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Analysis on Radioactive Waste Transmutation at a Clean Fusion-Fission Hybrid Reactor

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1. Introduction

The concept of clean nuclear power plant is gaining attention with time, as the researchers realize that with growing energy demand the nuclear energy may not be clean with long-lived high-level radioactive waste (LLHLW). Fusion-fission hybrid concept may be an attractive and efficient solution for the transmutation of stockpiled LLHLW from existing nuclear plants. Hybrid can burn waste during electricity generation as well as tritium breeding. Many conceptual designs have been proposed by many research teams. However, most hybrids focused to burn the trans-uranium isotopes (TRUs) only.

The impacts of blanket geometry change and cross section libraries on performance parameters such as tritium breeding ratio(TBR) and waste transmutation ratio(WTR) were evaluated previously and it was shown that they are very small. The dependency of TBR and WTR on neutron energy was also evaluated [1].

In this study, objective of a clean hybrid reactor is to burn the TRUs along with fission products (FPs). A preliminary depletion analysis of TRUs and FPs evaluated the transmutation performance and showed a feasibility of hybrid.

2. Concept of Hybrid

The geometry and material composition of fusion-fission hybrid named as Fusion based TRU Burner Reactor (FTBR) are shown in Fig.1 and Table 1 respectively.

Table 1. Material composition of fusion-fission hybrid

Zone	Material and volume fraction	Thickness (cm)
First & Structure Wall	ODS Steel (MA957): 70%, He-gas: 30%	5
TRU zone Vol % per Fuel Assembly	TRU: 3.56%, Zr: 7.04%, LiPb: 59.91%, SiC: 4.45%, Clad ODS steel: 9.98%, Na-Bond: 15.06%	50
FP zone	I-129: 0.5%, Cs-135: 1.7%, Tc-99: 0.8%, SiC: 2.5%, C: 78%, He-gas:16.5%	30
Beryllium layer	Be: 60%, He-gas: 40%	10
Reflector	C: 90%, He-gas:10%	20

The FTBR is based on a low power tokamak (100 MW max) and annular ring shaped TRU core, consists of hexagonal fuel assemblies with metal fuel (TRU 60 w/o, Zr 40 w/o). The TRU core was designed at 2,000 MWth fission power level with design parameters shown in table 2 [2]. The material composition for TRU and FP are assumed to be same with those of spent fuel from 1,000 MWe PWR with 10 years cooling time [3].

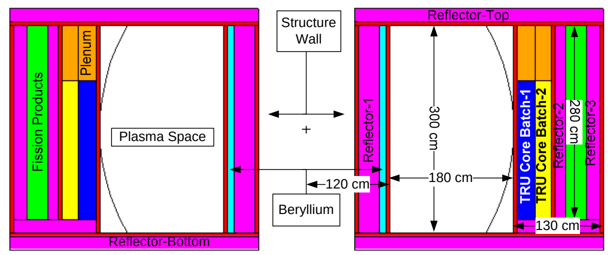

Fig. 1. Geometry of fusion–fission hybrid

Table 2. TRU core design parameters

fuel diameter (TRU 60%; Zr 40%)	0.36 cm
Na bond thickness	0.1 cm
clad (MA957 steel) thickness	0.05 cm
SiC coating thickness	0.02 cm
assembly width	6.0 cm
fuel pin pitch	1.0 cm
fuel length	200 cm
volume ratio of plenum/fuel	≈ 1
core fission power level	2,000 MWth
number of fuel assembly	1,000
avg. power density (MW/m^3)	106.917
linear power density (kW/m)	9.259

3. Transmutation Analysis

Calculations were performed using MCNPX 2.6 [4] with BURN card. Cycle length for TRU and FP burning is 3 years (1,100 days). The TRU core was designed to remain subcritical with fresh fuel. The fission power (2,000 MW) should be kept constant through the burn cycle. Therefore, with TRU-loaded core option, reduced reactivity of fission part should be compensated by the increase of fusion power level.

TRU and FP transmutation were analyzed by calculating TRU mass burned per full power year (fpy), support ratio and percentage of TRU mass burned per fpy. The same parameters were also used to analyze the FP transmutation. To account for the FP produced in TRU core, net FP mass burned per fpy was also calculated. FP transmutation was analyzed with two kinds of FP zones; 30 cm and 50 cm thickness of FP zone. TRU transmutation was compared with another design option, subcritical advance burner reactor (SABR) [5][6].

Fig. 2 shows the change in k-eff over the burn cycle and change in fusion power compensating it to make hybrid critical. The rate of change in fusion power was not small from 10 to 88 MWt. Required fusion power was calculated using the mathematical formula used by W.M.Stacey [5].

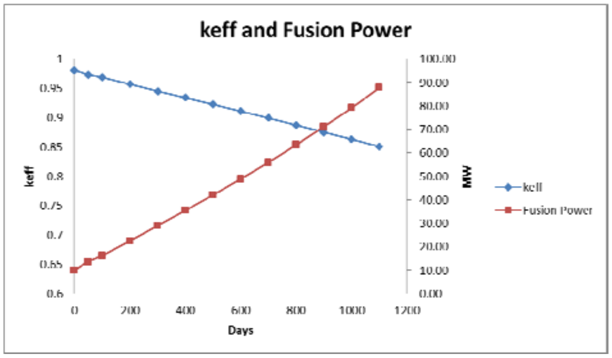

Fig. 2. Fusion power and k-eff variation during cycle

Table 3. TRU depletion analysis of FTBR & SABR

	FTBR	SABR[6]
Fusion Power (MWt)	10-88	99-175
Fission Power (MWt)	2000	3000
Power Density (MWt/m^3)	106	72.5
Max. k-eff	0.98	0.95
Range of k-eff variation	0.979-0.850	0.89-0.83
Irradiation Time (days)	1100	750/cycle
TBR	1.49	1.16
TRU inventory (kg)	14250	36000
Total TRU mass-burned (kg)	2251	2170/cycle
TRU mass-burned/yr (kg/fpy)	747.11	1060
% TRU burned/yr	5.24%	2.94%
TRU produced/yr in 1,000 MWe PWR (kg) [6]	250	
Support Ratio for 100% availability	2.99	4.2
Support Ratio for 75% availability	2.24	3.2

The summary of TRU transmutation over burn cycle is shown in table 2. TRU burnup rate in %/fpy and support ratio are the primary performance parameters of any waste burning reactor. TRU loss amount per fpy was 747 kg and TRU burnup rate is 5.24%/fpy. Those values should be increased for efficient and optimized design. The support ratio is more than 2 with 75% availability which means that current hybrid design can transmute waste from two PWRs. This parameter should be maximized under the design constraints. The tritium breeding ratio (TBR) of FTBR is 1.49 which shows self-sufficiency of fusion fuel.

TRU transmutation analysis of SABR is also shown in table 2 for comparison. The fusion power and TRU loading of FTBR is less than half of SABR but the support ratio and TRU mass-burned per fpy of FTBR is more than half of SABR. However, burnup rate in %/fpy is much higher in FTBR which shows the optimized burning of TRUs in FTBR.

Table 3 shows the summary of FP depletion analysis for two kinds of FP zone thickness; 30 and 50 cm. For 50 cm zone, FPs were loaded more by almost twice of amount in 30 cm FP zone. Increase in FP loading does not improve the performance parameters; both in FP burnup rate and support ratio. FP burnup amount is increased slightly by the increase of loading amount, but burnup rate in %/fpy is reduced significantly.

Table 4. FP depletion for two kinds of FP zone layers

FP zone Thickness (cm)	30	50
Total FP loaded (kg)	2930.60	5010.30
Total FP burned (kg)	380.01	392.92
FP mass-burned/yr (kg/fpy)	126.09	130.38
% of FP burned/yr	4.30%	2.60%
FP produced in TRU (kg)	162.25	162.25
Net FP mass-burned (kg)	217.77	230.68
Net FP mass-burned/yr (kg/fpy)	72.26	76.54
% of Net FP burned/yr	2.47%	1.53%
FP produced/fpy in 1000MWe PWR (kg) [1]	39.90	39.90
FP support Ratio 100% availability	1.81	1.92
FP support Ratio 75% availability	1.36	1.44

4. Conclusions

This preliminary study shows that a clean plant concept has good potential for waste transmutation. The efficiency of a hybrid concept for waste burning was analyzed by comparing support ratio, TRU amount burnt and TRU burning rate.

Optimization in TRU fuel can be further improved using 2- or 3- batch strategies. FP burning also needs to be optimized to attain same support ratio as for TRU. Toxicity analysis will also be performed for detailed performance assessment of hybrid design.

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