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Analysis on Radioactive Waste Transmutation in Light Water cooled Hyb-WT

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1. Introduction

Nuclear fusion energy is one of the most attractive sources of energy in 21st century. It is believed that fusion energy is limitless and clean without long-lived radioactive waste. However, realization of fusion energy is very challenging within a few decades because of short continued operation of plasma tokamak and limitation of material integrity under high neutron irradiation with high heat deposition, etc.

Whereas Fusion-Fission Hybrid Reactor (FFHR), as bridging stage between fission and fusion has less limitations compared to pure fusion reactor. It can be operated using small-sized fusion tokamak and produce less radiation damage to structure materials. Therefore, a feasibility of realization is much higher in FFHR compared with pure fusion. A combination of plasma fusion source for neutrons with a subcritical reactor at the blanket side has much higher capability in transmutation of waste as well as reactor safety compared with fission reactor options.

Fusion-Fission Hybrid Reactor (FFHR) uses various coolants depending on the purpose. It is important that coolant being used should be suitable to reactor purpose, because reactor performance and the design constraints may change depending on the coolant. There are basically two major groups of coolants for FFHR. One group of coolant does not contain Li. They are Na, Pb-Bi, H_2O and D_2O. The other group contains Li for tritium breeding. They are Li, LiPb, LiSn, FLIBE and FLiNaBe.

Currently, the issue in FFHR is its implication for radioactive waste transmutation (FFHR for WT). Because radioactive wastes of spent nuclear fuel (SNF) are transmuted using fusion neutron source. Therefore a suitable coolant should be used for effective waste transmutation. . In FFHR for WT, LiPb coolant is being used mainly because of tritium production in Li and high neutron economic through (n, 2n) reaction in Pb. However different coolants use such as Na, Pb-Bi are used in fast reactors and accelerator driven systems (ADS) having same purpose.

In this study, radioactive waste transmutation performance of various coolants mentioned above will be compared and analyzed. Through this study, the coolants are judged primarily for their support to waste transmutation disregarding their limitation to reactor design and tritium breeding capability.

First, performance of the light water coolant regarding radioactive waste transmutation was analyzed among various coolants mentioned above.

2. Characteristics of light water coolant

Light water is the cheapest material compared to the natural Li and FLiBe, also it has even more operational database because of being used as coolant in LWR up to now. Light water coolant possess good technical foundation, therefore it is the most feasible coolant. And do not require insulation coating in order to reduce MHD pressure drop in coolant flow channels because MHD pressure drop exist only for metal coolants with high electrical conductivity.

On the other hand, if it is used as coolant in FFHR operated at high temperature, departure from nucleate boiling (DNB) problem occurs because of low boiling temperature and vapor pressure of light water [1]. Therefore pressurized light water should be used, but it exert more pressure to first wall, structure wall, fuel pin, etc. which reduce the lifetime of reactor. To solving this problem, there is reactor which designs first wall and second wall in flowing pressurized light water region the front and the rear or uses pressure tube [1][2].

Water-cooled Pressure Tube (WPET) reactor uses pressure tube. Pressurized light water flows only inside of the pressure tube filled with fuel pins. It is separated from first wall and structure wall. WPET, study showed that max temperature of the first wall is 377C, lower than the operational temperature of FW (700C) composed V4Cr4Ti alloy. And the max thermal stress is 370.19MPa, satisfying the operation limit of the material [3]. These results can be seen useful for the coolant choice of FFHR. However, using pressure tube brings some disadvantage such as inefficient use of the space between the pressure tube. Ceramic breeder blanket is another hybrid reactor designed with pressurized water coolant in Japan. It utilizes packed small pebbles of fuel and coolant flows inside the pipe filled with fuel [2]. Considering design limitation mentioned above, light water has fatal disadvantage.

Also neutron spectrum softening caused by high moderation capability of light water by means elastic collision reaction is effective in production of fissile fuel and energy. Neutron spectrum softening enhance the breeding reaction of $^{238}U(n,\gamma)^{239}Pu$, $^{240}Pu(n,\gamma)^{241}Pu$ and fission reaction rate of fissile [1]. While it is not favored in radioactive waste transmutation which requires fast neutrons.

3. Methods and Results

3.1 Blanket design

Hybrid reactor for waste transmutation (Hyb-WT) is designed to incinerate the high level waste of transuranic (TRU) and fission products (FP) from PWR spent fuel [4][5]. The fuel is composed of PWR spent fuel reaching to burn-up grades of 33,000MWd/t. It is reference in case of performance analysis of the light water. In Hyb-WT, LiPb of 54.53% volume fraction uses as the coolant, no need separated tritium breeding zone due to function of Li as the coolant and tritium breeder.

Table Ⅰ. Hyb-WT and light water cooled Hyb-WT composition

Region	Thickness (cm)	Composition(%)
TRU Fission Core	45	TRU: 4.25(Np237, Am241, Am243, Cm244, Pu); Zr: 8.42; LiPb: 54.53; SiC: 4.91; Clad ODS steel: 11.05; Na-Bond: 16.84
Structure Wall	5	ODS steel(MA957):70; He-gas:30
FP Zone	30	CsI (129I: 0.42; 135Cs: 1.76); 99Tc: 0.82; SiC: 2.5; C: 78; He-gas:16.5
Tungsten Shield	10	W (W182:26.5; W183:14.3 W184:30.7; W186:28.5)
B_4C Shield	5	Be(Be10:16; Be11:64; C:20)
Super conductor Toroidal MF Coil	20	Nb93:70; Sn116:5; Sn117:2.6; Sn118:8.3; Sn119:2.9; Sn120:1.1;
Reflector	20	C:90; He-gas:10
Fission core Reflector	4	Li6:0.14; Li7:0.54; Pb204:24; Pb206:22; Pb208:52
Tritium Breeding Zone	20	Li6:17.7: Li7:82.3

TableⅡ. TRU fission core fuel design

	Case 1	Case 2	Case 3
H_2O Vo1. %	54.53	60.27	97.94
Fuel Diameter (mm)	3.8	3.2	2.18
Na bonding thickness(mm)	1	1	1
Cladding thickness(mm)	0.5	0.5	0.5
SiC coating thickness(mm)	0.2	0.2	0.2
Pitch(mm)	9.8	9.8	16.3
Fuel Height(cm)	200	200	200

In case of the light water cooled Hyb-WT, light water of 54.53, 60.27, 97.94 volume fraction design by change of fuel diameter and pitch in order to know performance depending on quantity of coolant. Also, light water does not exist tritium breeder, so inner reflector redesigns tritium breeding zone composed natural lithium.

Fig. 1 shows geometrical design of light water cooled Hyb-WT modeled in MCNPX and Table 1 shows compositions of each region [6]. Table 2 shows TRU fission core fuel design depend on volume fraction of the light water.

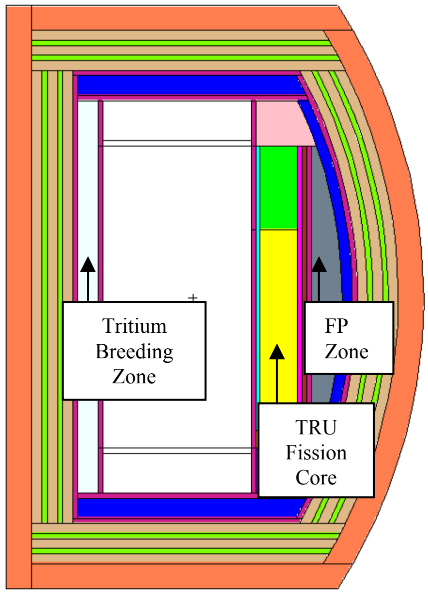

Fig. 1 Light water cooled Hyb-WT

3.2 Results of Analysis

Table 3. shows performance parameters of Hyb-WT for LiPb and light water and three case studies are designed for light water coolant with different volume fractions.

Table Ⅲ. Performance parameters of Hyb-WT for LiPb and light water coolant

	Reference	Case 1	Case 2	Case 3
Coolant / vol.%	LiPb / 54.53	H_2O / 54.53	H_2O / 60.27	H_2O / 97.94
K-eff [BOC / EOC]	0.96949 / 0.94596	1.07509 / 1.05305	1.02607 / 0.99794	0.97033 / 0.41558
Required Fusion Energy (MW)	12.6 ~ 23.06		~ 0.81	11.8 ~ 550
Loaded TRU Mass (ton)	14	14	12	0.38
LLTRU Transmutation (kg/fpy)	684.38	1040.5	991.5	526.96
ML TRU Transmutation (kg/fpy)	86	-230	-187	30
Total TRU Transmutation (kg/fpy)	748.25	784.25	748.25	546.37
Loaded FP Mass (ton)	34.3	34.3	34.3	34.3
FP Transmutation (kg/fpy)	300	-43	-38	3
TBR	1.84		3.19	0.38
Fis/Cap	2.52	0.74	0.78	0.13

* LL TRU : half-life of TRU nuclide $\geq$ 100years
* ML TRU : 10years $\leq$ half-life of TRU nuclide < 100years

Capture and fission reaction rate of TRU isotopes is increased, shown in Fig. 3 and 4, because of neutron spectrum softening, shown in Fig. 2 which increased the k-eff value. Case 1 is not subcritical system, therefore it does not required fusion power and tritium production. It is out of the scope of hybrid reactor. In a subcritical hybrid system fusion power as neutron source is the driving force to maintain the fission power level with the burning of fissile nuclides and consequent reduction of k-eff value. In case 3, the change in subcritical level is very large so the required fusion power reached up to 550 MW at EOC. The transmutation performance of LL TRU transmutation is better with light water than LiPb. LL TRU transmutation is increased by 1.5 times in case 1 as compared to LiPb. However, the transmutation performance of ML TRU is worse than LiPb, even ML TRUs are generated due to increased capture reaction rate. Consequently, total TRU mass transmutation is same.

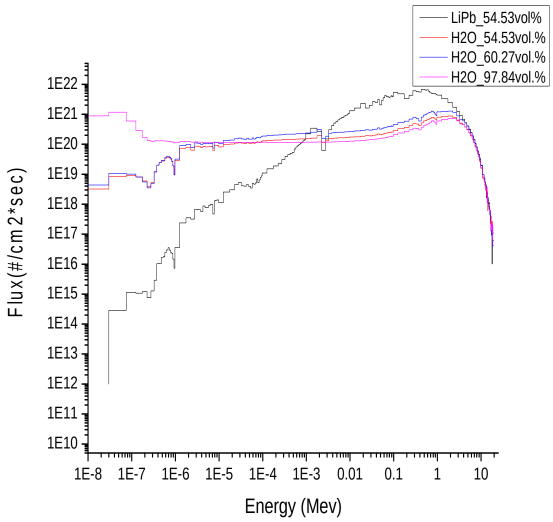

Fig. 2 Flux in TRU fission core depending on different coolant and vol.%

Fig. 2 shows flux distribution in TRU fission core and Fig. 3 and 4 shows fission and capture reaction rate per unit volume for loaded TRU nuclides. In Fig. 2, neutron spectrum is hardened with LiPb. Fast neutrons flux is much higher compare to thermal neutron flux. While flux with light water is softened due to neutron moderation. There is small difference between case 1 and case 2. In case 3, thermal neutron flux is very high compared to case 1 and case 2. Fig. 3 and 4 shows large fission reaction rate of ^{239}Pu and ^{241}Pu for case 1. Capture reaction rate of almost all TRU nuclides is increased especially of ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu through fertile capture reactions of Pu. When results are compared for different volume fraction of light water coolant, fission and capture reaction rates both increase significantly in case 1, because of large TRU mass. In case 3, fission and capture reaction rate are very low due to small mass of TRU fuel since the TRU massed decreased with the increase of coolant volume fraction. Mass of TRU loaded in TRU fission core is only 0.38ton for case 3, while it is more than 10tons for other cases. Thus TRU transmutation decreases significantly for case 3 as compared to other cases.

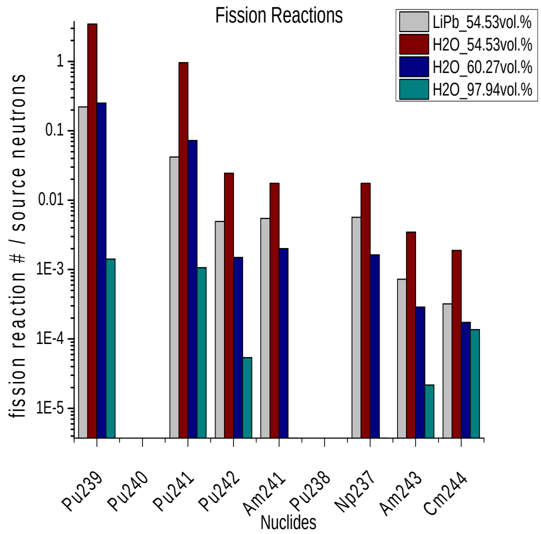

Fig. 3 Number of fission reactions per source neutrons of TRU nuclides in TRU fission core

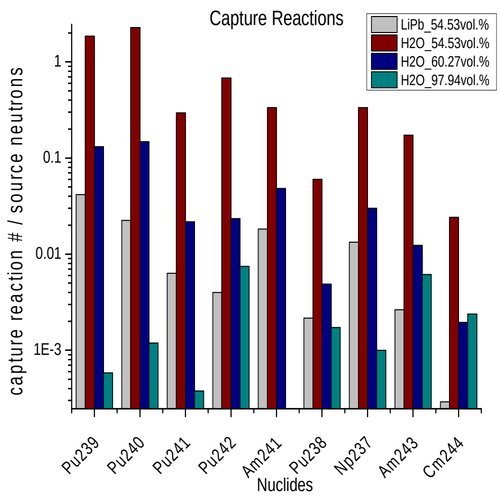

Fig. 4 Number of capture reactions per source neutrons of TRU nuclides in TRU fission core

Fig. 5 shows flux distribution in FP zone. Flux distribution is similar regardless of coolant material and coolant volume fraction. Neutrons produced from fusion source reach FP zone through TRU fission core with decreasing neutron energy. Whereas in case of light water coolant, most neutrons are not reached FP zone, because of excessive moderation in TRU fission core. Capture reaction rate is much higher in case of LiPb as compared to other cased as shown in Fig. 6. As a result, performance of FP transmutation is very low and FP increases through TRU transmutation in fission core in case of light water coolant.

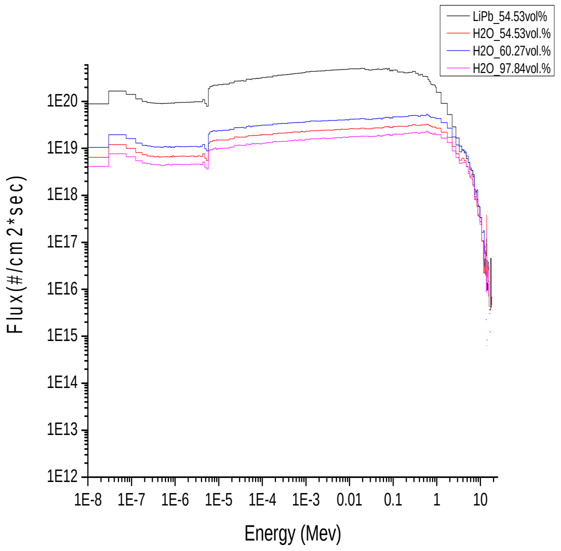

Fig. 5 Flux in FP zone depending on different coolant and vol.%

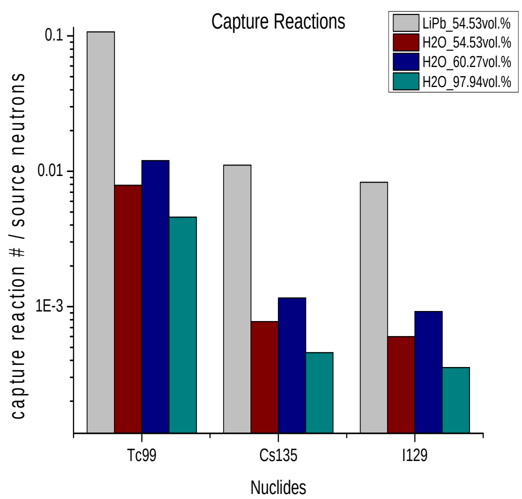

Fig. 6 Number of capture reactions per source neutrons of FP in FP zone

Fig. 7 shows percentage distribution of fission and capture reactions subsequent to neutron absorption in TRU nuclides. In the LiPb, 72% of neutron absorptions in TRU nuclides lead to fission and 28% lead to capture. Fission reactions occurs about 2.5 times more than capture reactions. In other words, TRU transmutation using fast neutrons is favorable. In case of light water coolant, capture reactions occur much more than fission reactions after neutron absorption. And percentage of capture reaction increases with increasing coolant volume fraction. In other words, most of absorbed neutrons lead to capture, so TRU nuclides is not incinerated but existed.

In case of large coolant volume fraction of light water, performance of TRU transmutation through direct fission reaction is decreased.

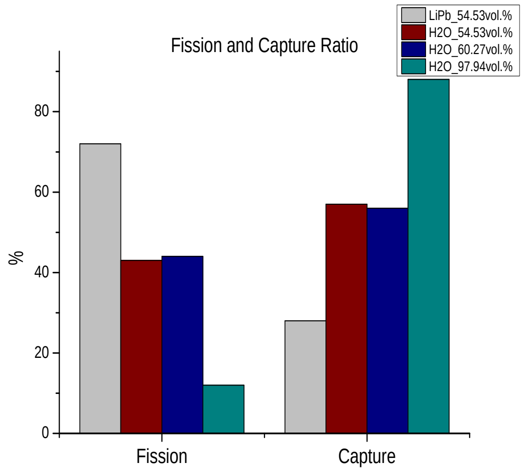

Fig. 7 Average distribution of fission and capture reactions subsequent to neutron absorption in TRU nuclides for different coolant materials and vol.%

Minimum value of TBR is 1.05 to satisfy tritium self-sufficient. Case 1 dese not required tritium due to not subcritical. LiPb and case 2 easily satisfy this condition. In case 2, tritium is produced from BOC to EOC, but tritium is consumed only EOC. Because k-eff has subcitical level only at EOC. Thus, TBR is relatively high. In case 3, required fusion power is large due to large decrement in k-eff, so more of the tritium is consumed than it produced

4. Conclusions

In this paper, performance of radioactive waste transmutation can be known depending on different volume fractions (54.53, 60.27, 97.94vol.%) of the light water. Light water dose required fusion power lower than LiPb due to high k-eff. However, case 3 only is the true depiction of light water cooled FFHR for WT. By neutron spectrum softening, fission and capture reaction rate of TRU nuclides increase. However, TRU is not incinerated using fission but transformed to other TRU nuclides due to higher capture reaction rate than fission.

Therefore, the light water coolant is not suitable to FFHR for WT.

REFERENCES

[1]S. Unalan, T. Ayata, S. O. Akansu, A. Erisen, A. Bolukbasi, "Light and heavy water cooled hybrid reactors for rejuvenation of LWR spent fuels", Energy Conversion and Management 44 (2003) 2567–2587

[2] Xinli Gao, Tiejun Zu, Wensi Tian, Suizheng Qiu, Guanghui Su, Hongchun Wu, "Thermal-hydraulic design of water-cooled pressure tube blanket for a fusion driven subcritical reactor", Fusion Engineering and Design 2013.

[3] Hongchun Wu, Tiejun Zu, Suizheng Qiu, Youqi Zheng, Liangzhi Cao, Wenxi Tian, "A fusion-fission hybrid reactor with water-cooled pressure tube blanket for energy production", Progress in Nuclear Energy 64 (2013) 1-7

[4]M. T. Siddique and M. H. Kim, “Performance Analysis of Hyb-WT with Homogenous and Heterogeneous Core Design,” Transactions of the Korean Nuclear Society Autumn Meeting Gwangju, Korea, May 30-31,, 2013, pp. 30–31.

[5] M. T. Siddique and M. H. Kim, “Conceptual design study of Hyb-WT as fusion–fission hybrid reactor for waste transmutation,” Ann. Nucl. Energy, vol. 65, pp. 299–306, Mar. 2014.

[6] M. T. Siddiqque and M, H. Kim, “Optimization of Surrounding Reflector Material for Hyb-WT”, Transaction of the Korean Nuclear Society Autumn Meeting Gyeongju, Korea, October 24-25, 2013