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Comparative Performance Evaluation of ITER TBM Concepts

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1. Introduction

Waste management of high level radioactive waste is an unresolved worldwide issue for recent nuclear industry. Geological disposal option to an isolated repository has been suggested as the final solution, however it is not feasible to some countries and it is not the best option. Partitioning and transmutation of high level radioactive isotopes has been studied as an alternative option with many kinds of burner concepts.

Fast reactors, accelerated driven subcritical reactor (ADSR), and fusion-fission hybrid reactor (FFHR) are major choices of concept for waste transmutation. Systems of ADSR and FFHR are dependent on subcritical reactor whereas fast reactor is an independent critical reactor. It is known that subcritical reactors are much more efficient and safe compared with critical reactors. Recent works showed transmutation capability of FFHR [1].

Korea is now running a Korea Superconducting Tokamak Advanced Research (KSTAR) project and is also participating with International Thermonuclear Experimental Reactor (ITER) project. The infrastructure for FFHR option is well ready and transmutation with FFHR can be a plan-B of the fast critical reactor option or ADSR.

Final purpose of this research is to make a design concept for hybrid test blanket module (HTBM) as a test bed for FFHR. Current design concept should be adapted to a feasible machine, ITER. The purpose of ITER Test Blanket Modules (TBM) is to test physical performance of tritium breeding, whereas the purpose of HTBM should be different, to test transmutation performance of high level radioactive waste. Therefore HTBM should be loaded with TRU isotopes which were separated from nuclear spent fuel by pyro-processing.

As a preliminary study, neutronic characteristics will be studied for TBM instead of HTBM. Lots of countries participating with ITER program have already designed many concepts of TBM, but did not yet for HTBM. Analyzed results from TBM study will be used for the next step work concerning the design of HTBM. Furthermore, this study will be a chance to learn a performance and characteristic of FFHR module design before designing full sized FFHR system.

Out of six candidate design concepts for ITER TBM, 4 concepts were selected in this study [2]. They are Lead-Lithium cooled Ceramic Breeder (LLCB) of India and Russia, Helium Cooled Ceramic Breeder (HCCB) of China, Helium Cooled Pebble Bed (HCPB) of EU, and Water Cooled Ceramic Breeder (WCCB) of Japan. The purpose of this study is not to compare existing TBMs for the best but to understand neutronic characteristics of their design features. Neutronic calculation is done with MCNPX 2.6.0 with ENDF/B-Ⅶ.0 neutron cross section library.

2. Geometrical Modeling of TBM Plug

Geometrical configuration of ITER with TBM is very complex because current design includes detail layout of coolant path, structural internals and shielding blocks. In order to analyze the performance of TBM, calculation model should include all space from plasma tokamak zone to the outer magnet coils. However, it may not be efficient to cover the whole geometry for this study. Therefore, effect of boundary conditions surrounding the TBM was tested in order to make a simpler calculation model. Performance parameters are average neutron flux at the first wall (FW) and tritium production rate (T/cm^3-sec).

2.1 Simplification of Plug Geometry

Two same sized TBMs are installed in ITER TBM port as shown in Fig. 1 [3]. However we designed a TBM port plug having one TBM to make calculation model simple.

In addition, cooling pipe systems behind the back side of TBM was assumed to be removed. Calculation boundary include the shield blocks as shown in Fig. 2.

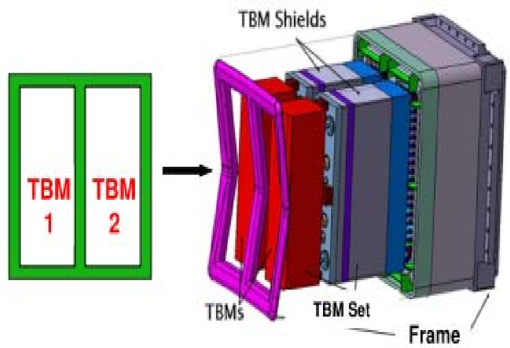

Fig.1. ITER TBM Port Plug.

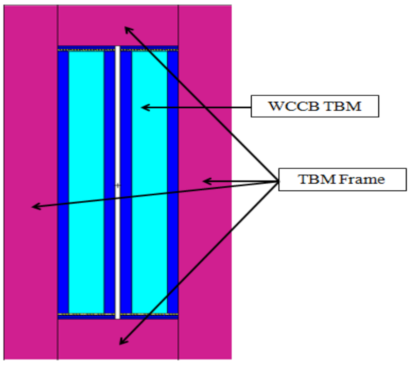

Fig. 2-a. MCNPX Model of Front View

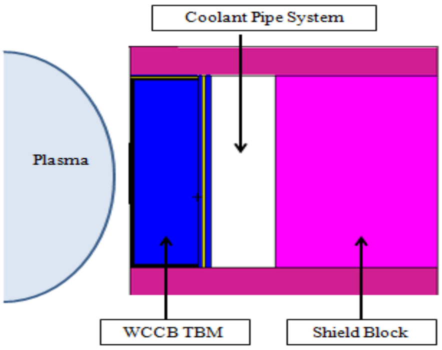

Fig. 2-b. MCNPX Model of Side View

TBM in port plug for this modeling study is chosen as Japanese WCCB TBM model. Information about TBM was obtained from open source literatures. However, many unknown parameters for modeling were decided based on reasonable assumptions. In this case, assumptions were made to make tritium production rate higher.

Effect of boundary conditions was tested from thin layer of shield to thick layer by expanding calculation area to both toroidal and poloidal direction as shown in Fig. 3. Material composition and design parameters of boundary condition test are shown in Table 1.

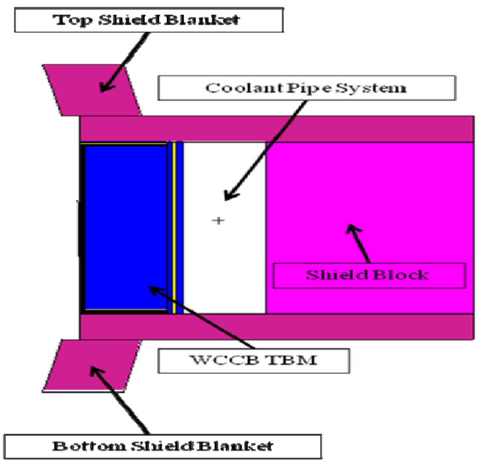

Fig. 3- a. Boundary Condition Model; xz plane

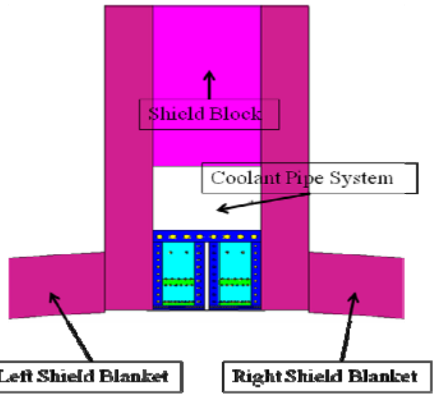

Fig. 3- b. Boundary Condition Model; yx plane

Table 1. Size and Material Composition of Model for Boundary Condition Test [4-6]

	Size (t:torodial direction p: poloidal direction r: radial direction, cm)	Material Composition (vol. %)
TBM	48.4(t) x 166(p) x 60(r)	
Shielding Block	48.4(t) x 166(p) x 120(r)	SS316 LN-IG(60), water(40)
TBM Frame	171 (t) x 216 (p) x 227.9(r)	SS316 LN-IG(85), water(15)
Shield Blanket	21.5~645(t) x 25~750(p) x 45(r)	SS316 LN-IG(85), water(15)

2.2 Effect of Boundary Conditions

Average flux in the fusion plasma FW and tritium production rate in the TBM were compared as the area of outer boundary zone is increased. They are summarized in Fig. 4. Reference scale of shielding blanket thickness in x-axis of Fig. 4 is the thickness of TBM frame (21.5cm T x 25cm P).

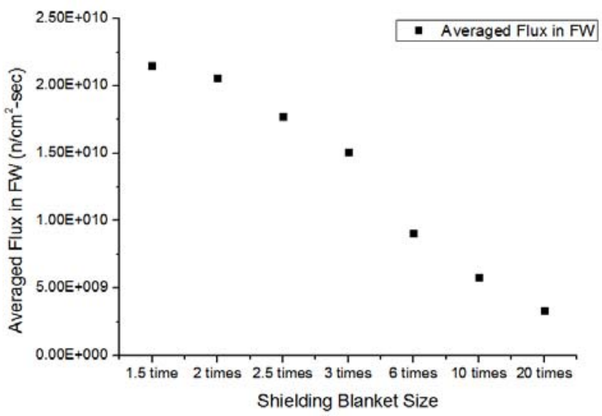

Fig. 4-a. Average flux in the fusion plasma FW

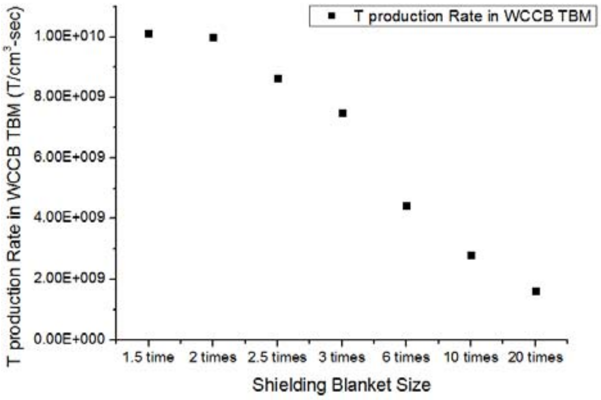

Fig. 4-b. Tritium production rate in the TBM

Flux in FW and tritium production rate in TBM decrease with increasing shielding blanket size. Especially when the size of shielding blanket is larger than 6 times of thickness of TBM frame, flux in FW and tritium production rate are sharply decreased. Hence, it is assumed that shield blanket size be three times of thickness of TBM frame.

3. Design Characteristics of ITER TBM Concepts

3.1 Modeling of TBM for ITER

Design characteristics are analyzed and compared with simplified geometrical model with boundary condition selected in the previous section 2.2. This problem is different from real TBM problem. Four concepts were modeled; Lead-Lithium cooled Ceramic Breeder (LLCB) of India and Russia, Helium Cooled Ceramic Breeder (HCCB) of China, Helium Cooled Pebble Bed (HCPB) of EU, Water Cooled Ceramic Breeder (WCCB) of Japan.

Assumed design data of each TBM model are shown in Table 2.

Table 2. Design Parameters of each TBM model

WCCB	
Country	Japan
Size(mm), (w x h x t) [7]	484 x 1660 x 600
Structural material [7]	F82H
Tritium Breeder [10]	Li_2TiO_3 Pebble
Li-6 enrichment	90%(assumed)
Packing fraction	67%
Neutron multiplier	Beryllium Pebble
Packing fraction	67%
Coolant	Water(H_2O)
LLCB	
Country	RF & India
Size(mm), (w x h x t) [5]	462 x 1670 x 559
Structural material [11]	In-RAFMS
Tritium Breeder [12]	
Ceramic breeder	Li_2TiO_3 Pebble
Li-6 enrichment	60%
Packing fraction	60%
Liquid breeder	Pb-17Li
Li-6 enrichment	90%
Neutron multiplier	Pb-17Li
Coolant	He(FW), Pb-17Li
HCPB	
Country	EU
Size(mm), (w x h x t) [17]	484 x 1660 x 710
Structural material [17]	EUROFER
Tritium Breeder	Li_4SiO_4 Pebble
Li-6 enrichment [17]	90%
Packing fraction [19]	64%
Neutron multiplier	Beryllium Pebble
Packing fraction [19]	64%
Coolant	Helium
HCCB	
Country	China
Size(mm), (w x h x t) [20]	484 x 1660 x 675
Structural material [20]	CLF-1
Tritium Breeder	Li_4SiO_4 Pebble
Li-6 enrichment [20]	80%
Packing fraction [2]	62%
Neutron multiplier	Beryllium Pebble
Packing fraction [24]	61%
Coolant	Helium

Modeling of test blanket module (TBM) is based on open source literatures as indicated in Table 2. However some unknown parameters for modeling were decided based on reasonable assumptions. All assumptions were made to make tritium production higher. Also, round shaped TBM is assumed to be rectangular for simplicity in analysis.

Performance parameters to be compared are averaged flux in FW, tritium production rate (T/cm^3-sec) and (n, 2n) reaction rate (reaction/cm^3-sec) in TBM module.

3.1.1 Water Cooled Ceramic Breeder (WCCB)

WCCB TBM modeling was conducted based on reference [7]. Total size of TBM is 48.4cm (width) x 166cm (height) x 60cm (thickness) [7]. However, unknown parameters were assumed as the followings;

- Coolant pipe parts at top and bottom of TBM is skipped in a red box in Fig. 5-a [8], however extended breeder zone and multiplication zone are designed as shown in Fig. 5-b.

- Pitch of coolant channels within TBM is assumed based on reference [9].
- Packing fraction of Beryllium pebbles in multiplication zone is assumed same as packing fraction of Li pebbles in breeder zone [10].

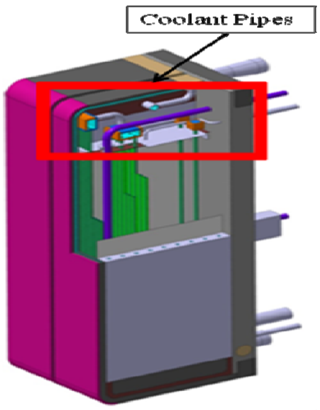

Fig. 5-a. WCCB Design

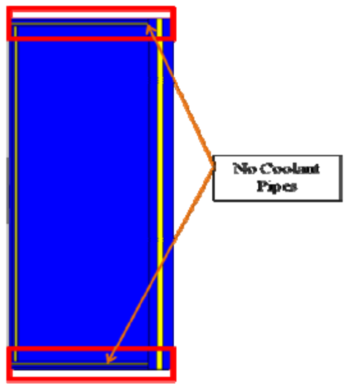

Fig 5-b. Modeling of WCCB; yz plane

There are two sub-modules in WCCB, each sub-modules is designed to have 2 breeder zone filled with Li_2TiO_3 pebble for tritium breeding and 2 multiplication zone filled with Beryllium pebble for neutron multiplication as shown Fig. 6. H_2O as a coolant is cooling the TBM through coolant pipe. Back wall at the rear of TBM is designed in order to combine 2 sub-modules [7, 10].

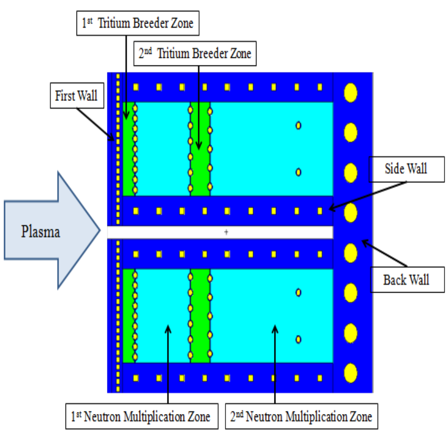

Fig.6. MCNPX Model of top view of WCCB

Design parameters of WCCB are shown in Table 3.

Table 3. Design parameters of WCCB [7-10].

Region	Size (cm)
First Wall Coolant Pipe	3 (thickness) 0.8 x 0.8 1.1 (pitch)
Side Wall Coolant Pipe	4.5 (thickness) 1 (diameter) 5.2 (pitch)
1st Tritium Breeder Zone Coolant Pipe	2.7 (thickness) 0.12 (diameter) 1.54 (pitch)
2nd Tritium Breeder Zone Coolant Pipe	4.2 (thickness) 0.12 (diameter) 2.84 (pitch)
1st Neutron Multiplication Zone Coolant Pipe	12.3 (thickness) 0.12 (diameter) 2.36 (pitch)
2nd Neutron Multiplication Zone Coolant Pipe	27.7 (thickness) 0.12 (diameter) 7.1 (pitch)
Back Wall Coolant Pipe	9 (thickness) 3 (diameter) 6 (pitch)

3.1.2 Lead-Lithium cooled Ceramic Breeder (LLCB)

LLCB TBM modeling was conducted based on reference [5, 11-12]. Total size of TBM is 46.2cm (width) x 167cm (height) x 55.9cm (thickness) [5]. LLCB TBM consists of 4 Ceramic breeder filled with Li_2TiO_3 Pebble and Pb-17Li coolant. FW is cooled by 80bar Helium. 65 Helium coolant channels are in FW and cross section of channel is 2cm x 2cm [5]. MCNPX models of LLCB are shown in Fig. 7.

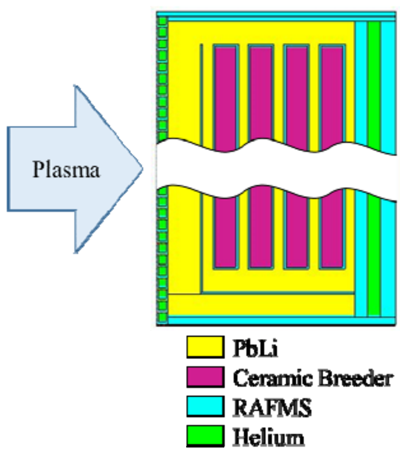

Fig. 7-a. LLCB MCNPX Modeling; xz plane.

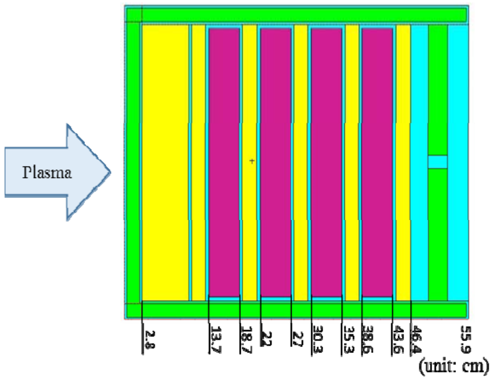

Fig. 7-b. LLCB MCNPX Modeling; xy plane.

3.1.3 Helium Cooled Pebble Bed (HCPB)

HCPB TBM modeling was conducted based on reference [13-19]. Total size of TBM is 48.4cm (width) x 166cm (height) x 71cm (thickness). But the ceramic breeder tube is changed from having rounded edges as shown in Fig. 8 to 90 degree angles based on reference [13-14, 17].

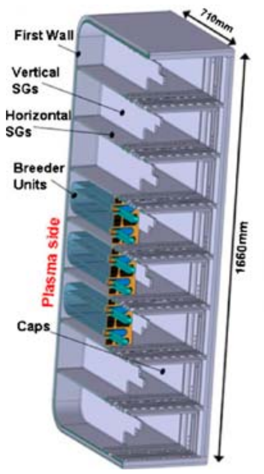

Fig. 8-a. HCPB TBM design [13].

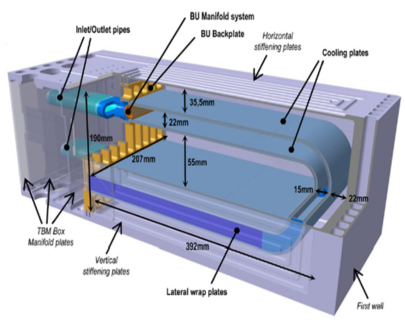

Fig. 8-b. HCPB TBM Breeder Unit design [14].

HCPB TBM has 16 Breeder Units. Breeder unit numbering rule was taken from reference [17]. Each breeder unit has ceramic breeder filled with Li_4SiO_4 pebble and ceramic breeder is covered with Beryllium pebbles. Helium is cooling FW, Beryllium pebble, cooling plates, grid, and covering side walls with 8MPa pressure [13]. MCNPX models of HCPB are shown in Fig. 9.

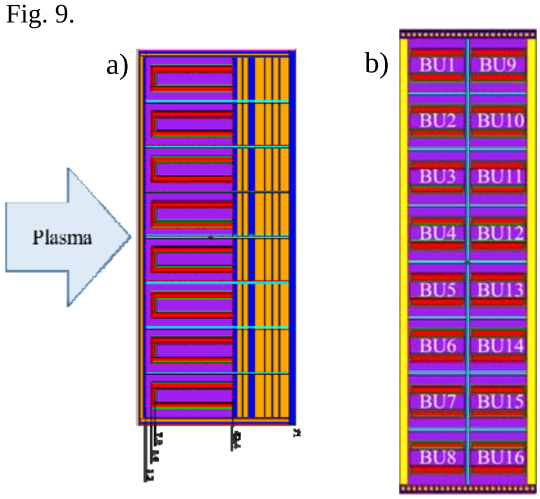

Fig. 9-a. HCPB MCNPX Model; xz plane.
Fig. 9-b. HCPB MCNPX model; yz plane & Breeder unit number

3.1.4 Helium Cooled Ceramic Breeder (HCCB)

HCCB TBM modeling was conducted based on reference [20-24]. Total size of TBM is 48.4cm (width) x 166cm (height) x 67.5cm (thickness) [20]. HCCB design is shown in Fig. 10. But ceramic breeder length is unknown parameter, so it is assumed that it reaches to FW of breeder unit.

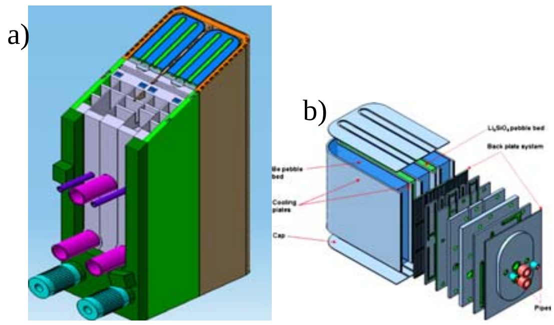

Fig. 10-a. HCCB TBM design [20]
Fig. 10-b. HCCB TBM Breeder Unit design [20]

HCCB TBM has 12 Breeder Units. Breeder unit numbering rule was taken from reference [23]. Each breeder unit has two plate shape ceramic breeders filled with Li_4SiO_4 pebble and ceramic breeder is covered with Beryllium pebbles. Helium is cooling FW, Beryllium pebble, cooling plates, grid, and covering side walls with 8MPa pressure [20] same as HCPB TBM. MCNPX models of HCCB are shown in Fig. 11.

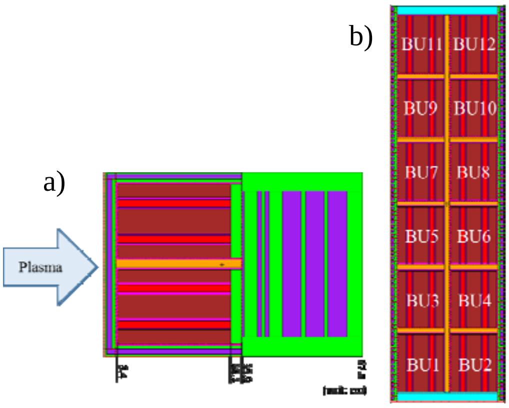

Fig. 11-a. HCCB MCNPX Model; xy plane.
Fig. 11-b. HCCB MCNPX model; yz planet & Breeder unit number

3.2 Neutronic Analysis of TBM Models

Performance parameters are summarized for different TBM concepts as shown in Table 4.

Table 4. Performances parameters of TBM concepts

TBM	WCCB	LLCB	HCPB	HCCB
Average Flux in FW (n/cm^2-sec)	3.19E+10	6.08E+10	4.89E+09	3.08E+10
T Production Rate (T/cm^3-sec)	1.04E+11	1.35E+11	6.00E+10	7.71E+11
Breeder Vol.%	7.85	59.59	8.8	6.31
Li Vol.%	1.75	11.0	2.5	1.74
(n, 2n) reaction Rate (reaction/cm^3-sec)	5.05E+8	6.41E+08	4.42E+08	1.91E+07
Multiplication Vol.%	48.53	32.69	39.92	21.29
Be or Pb Vol.%	29.35	26.5	25.5	13

First of all, average flux on FW with LLCB is the highest on the other hand average flux on FW with HCPB is the lowest.

LLCB, HCPB, and HCCB TBM which are using helium coolant in FW have similar neutron flux spectrum shape as shown in Fig. 12. WCCB TBM which is using water coolant in FW has similar neutron flux spectrum shape in fast neutron energy region however has really different shape in thermal neutron energy region. WCCB TBM has more thermal neutron flux amount than helium coolant using TBM in FW because of moderation effect by water. Compare only total amount of neutron flux in FW, In-RAFMS and F82H are better for HTBM FW material because of having high flux.

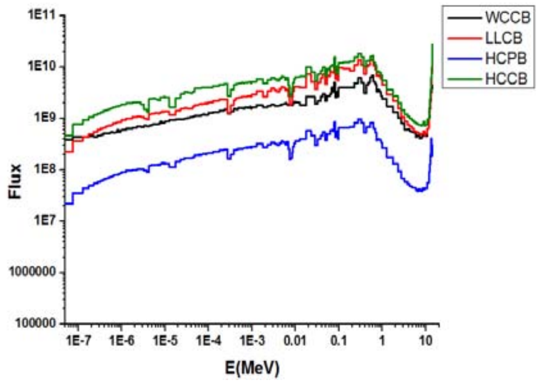

Fig. 12. Average Flux Distribution in FW of each TBM

WCCB and LLCB are using Li_2TiO_3 as a ceramic tritium breeding material. HCPB and HCCB are using Li_4SiO_4 as a ceramic tritium breeding material. Thus, comparison of tritium production rate with each TBMs can divide into two groups. LLCB TBM is using Li_2TiO_3 and PbLi for tritium breeding. Tritium production rate with LLCB TBM is high because of its large Lithium volume fraction. Tritium production rate with HCPB TBM is low because of low neutrons population by low neutron flux in FW. WCCB TBM and HCCB TBM have similar lithium volume fraction. Tritium production with HCCB TBM is higher than WCCB. Therefore, Li_4SiO_4 is better tritium breeding material than Li_2TiO_3.

In terms of (n, 2n) reaction rate, there are 2 groups. One is LLCB TBM using Pb and the other is WCCB TBM, HCPB TBM and HCCB TBM using Be as neutron multiplication material. Pb is more effective about neutron multiplication because (n, 2n) reaction rate with LLCB is high compared to volume fraction of Pb.

4. Conclusions

In this paper, design characteristics of 4 TBMs; WCCB, LLCB, HCPB, HCCB are analyzed before design of HTBM for waste transmutation.

F82H of WCCB TBM and In-RAFMS of LLCB TBM are more effective as FW material as a result of TBMs modeling. Also, Li_2SiO_4 is better than Li_2TiO_3 as tritium breeder and Pb is better than Be in terms of neutron multiplication.

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