Experimental Studies on Tungsten-armor Impact on Nuclear Responses of Solid Breeding Blanket

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Abstract. In order to experimentally evaluate the tungsten armor impact on tritium production of the solid breeding blanket being developed by JAERI for tokamak-type DEMO reactors, neutronics integral experiments have been performed by using DT neutrons at Fusion Neutron Source (FNS) facility of JAERI. Solid breeding blanket mockups relevant to the DEMO blanket have been applied in this study. The mockups are constructed by a set of layers consisting of 0 - 25.2 mm thick tungsten, 16 mm thick F82H, 12 mm thick Li_2TiO_3 and 100 - 200mm thick beryllium with cross-section of 660 x 660 mm in maximum. Pellets of Li_2CO_3 are embedded inside the Li_2TiO_3 layers to measure the tritium production rate. By installing the 5, 12.6 and 25.2 mm thick tungsten armors, sum of the integrated tritium productions at the pellets are reduced by about 2, 3 and 6 % relative to the case without the armor, respectively. Numerical calculations have been conducted using the Monte Carlo code. Calculation results for sum of the integrated tritium productions in the case with the tungsten armor agree well with the experiment data within 4 % and 19 % under condition without and with a neutron reflector, respectively.

1. Introduction

In fusion DEMO reactors, the blanket is required to provide a tritium breeding ratio (TBR) of more than unity. The solid breeding blanket being developed by JAERI for tokamak-type DEMO reactors consists of lithium titanate (Li_2TiO_3) or other lithium ceramics as the tritium breeder material, beryllium as the neutron multiplier material, reduced activation ferritic steel F82H as the structural material and water as the coolant [1, 2]. Neutronics integral experiments had been conducted in the previous studies using blanket mockups composed of these materials in order to verify the accuracy of the tritium production rate (TPR) [3 - 6]. In the blanket design proposed by JAERI, the local TBR is around 1.4 - 1.5 for the case without armor on the first wall. From the sputtering damage of the first wall point of view, tungsten armors are the effective materials for the protection. However, from the tritium production viewpoint, tungsten armors may reduce the TBR, and TBR might not satisfy the requirement in this case [7]. There are a number of scattering and resonance capture reactions in tungsten, so it is required to carefully conduct the TBR estimation taking into account the effect of the tungsten armor. No experimental studies have been reported so far about the impact of the tungsten armor on tritium production. In order to evaluate this issue experimentally, neutronics integral experiments have been performed using DT neutrons at the FNS facility of JAERI [8]. These experiments have been performed using blanket mockups with a one and two layers breeder under conditions with and without a neutron reflector.

2. Experiment

Five DT neutron irradiation experiments were performed by using FNS 80° beam line in this study. Three mockups were irradiated by neutrons from the DT source with a neutron reflector, and two mockups were irradiated by neutrons without a neutron reflector. In the experiments with a neutron reflector, the mockups were composed of one layer breeder, and various tungsten armor thickness (0, 12.6 or 25.2 mm). In the experiments without a neutron reflector, the mockups were composed of two layers breeder, and tungsten armor thickness (0 or 5 mm).

Figure 1 shows a schematic view of the experimental assembly for a one layer breeder mockup with a neutron reflector. This mockup is constructed by a set of layers of 0, 12.6 or 25.2 mm thick tungsten, 16 mm thick F82H, 12 mm thick Li_2TiO_3 (^6Li enrichment of about 40 %) and 200 mm thick beryllium with cross-section of 660 x 660 mm in maximum. The front surface of the F82H layer is approximately a 450 mm distance from the DT neutron source. This mockup is installed in the mockup enclosure made of SS316. In the opposite region of the mockup, the neutron reflector is also installed surrounding the DT neutron source. The beam duct is bored through the center of the neutron reflector. Experiments were performed keeping 450 mm of the distance from the DT neutron source to the F82H layer surface.

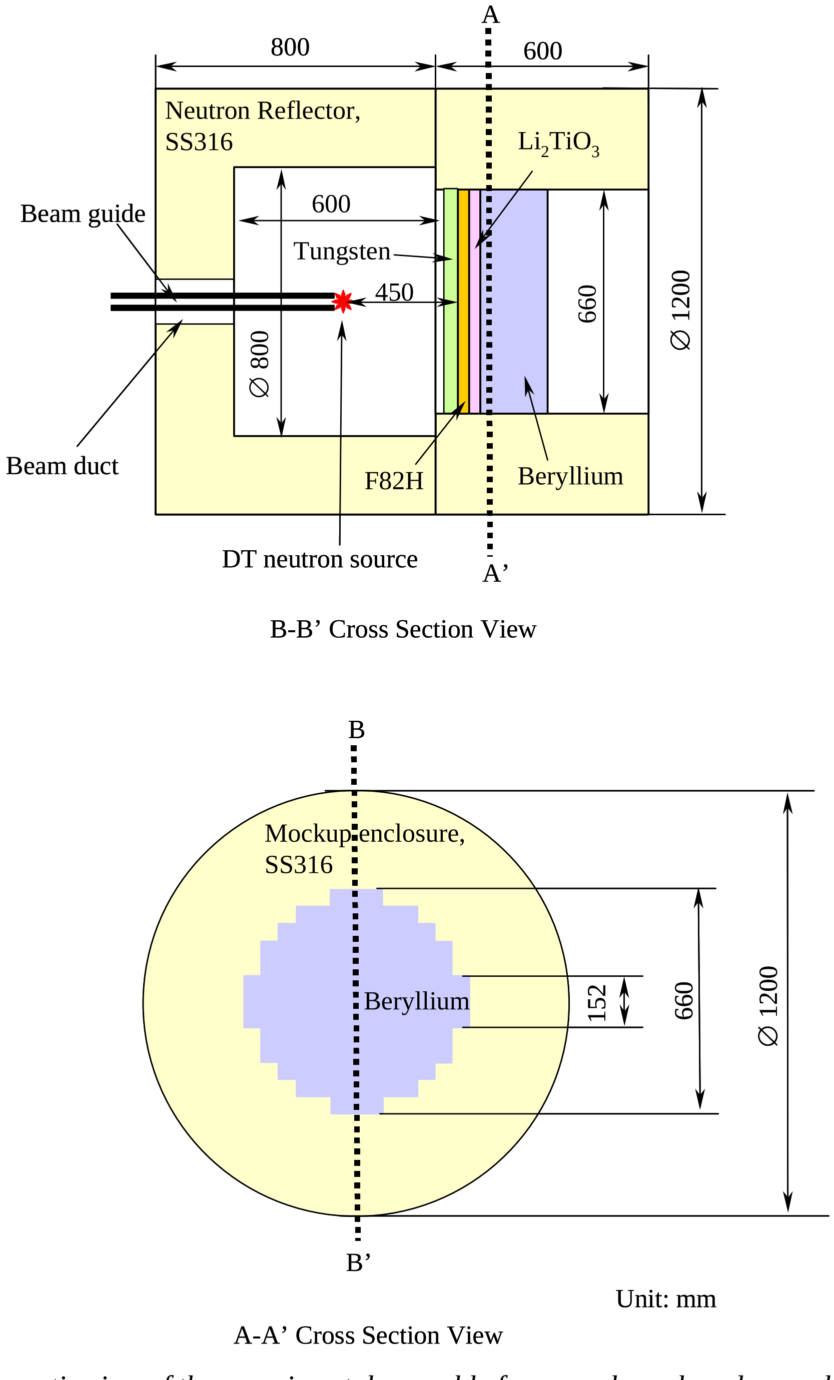

FIG. 1. A schematic view of the experimental assembly for a one layer breeder mockup with a neutron reflector.

Figure 2 shows a schematic view for a two layers breeder mockup without the reflector. This mockup is constructed by a set of layers of 0 or 5 mm thick tungsten, two layers of 12 mm thick Li_2TiO_3 (^{6}Li enrichment of about 40 %) and three layers of 100 mm thick beryllium. The Li_2TiO_3 layers are sandwiched by the beryllium layers. The front surface of the first beryllium layer is approximately a 100 mm distance from the DT neutron source. The neutron reflector is not installed. The experiments were performed keeping distance from the DT neutron source to the first beryllium layer surface.

The DT neutron yield at the target was about 1 x 10^{11} neutrons/s on average, which was monitored by the associated alpha particle measurement with a silicon surface barrier detector installed in the beam guide. Two or three days irradiation experiments, ten hours per day, were performed, with the integrated irradiation period of 20 or 30 hours, respectively, in total.

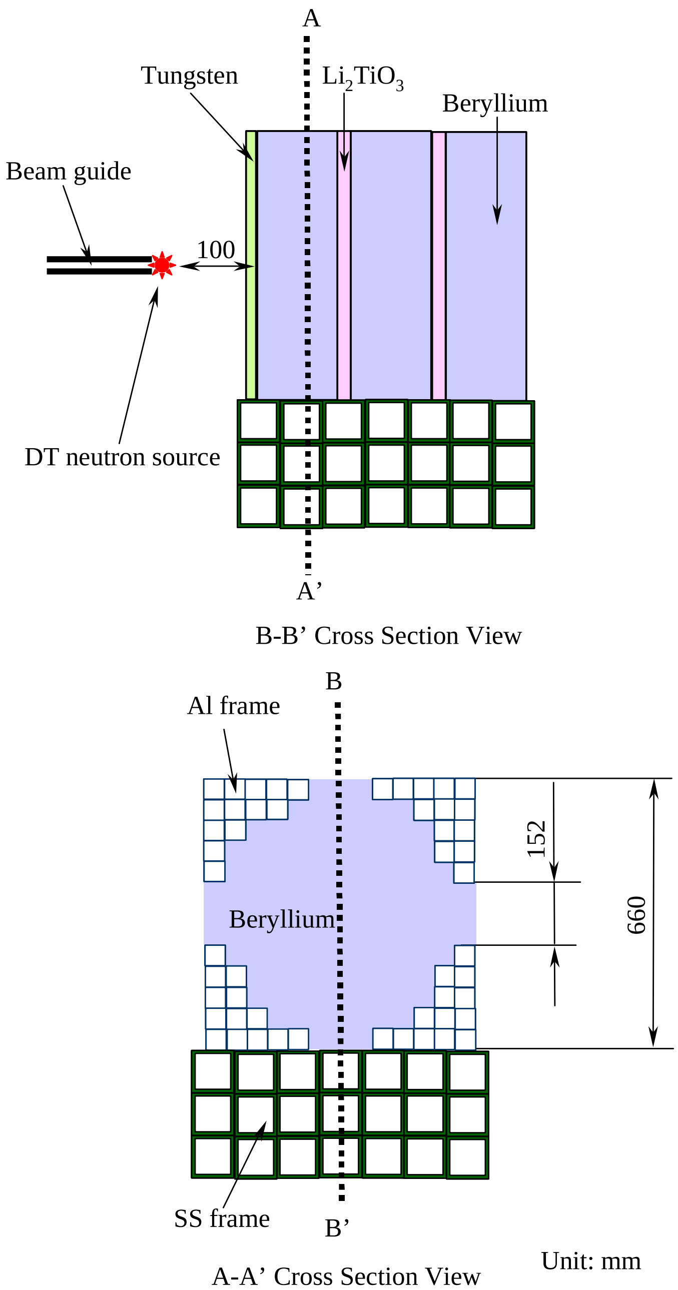

FIG. 2. A schematic view of the experimental assembly for a two layers breeder mockup without a neutron reflector.

Fifteen slices of Li_2CO_3 pellets, with a ^{6}Li enrichment of about 40 %, 13 mm in diameter and 0.5 - 2 mm in thickness, were embedded inside each Li_2TiO_3 layer. After the irradiation, induced radioactivities were measured by beta ray intensity of these pellets with a liquid scintillation spectrometer after the wet-chemistry treatment procedure [9], thus evaluating the TPRs.

3. Results

Figure 3 shows distributions of the local TPR from ^{6}Li for the one layer breeder mockup under condition with a neutron reflector. The experimental error is about 7 % [6]. The TPRs almost show the same tendency among the cases without the tungsten armor and with one. The TPRs increase when coming closer to the beryllium layer. The integrated tritium productions from ^{6}Li in the diagnostic pellets are 3.05 x 10^{-5}, 2.98 x 10^{-5} and 2.87 x 10^{-5} Bq/source neutron in the cases with 0, 12.6 and 25.2 mm thick tungsten armor, respectively. Figure 4 shows distributions of the ratio of the local TPR from ^{6}Li for the case with the tungsten armor to that without one. The ratios are in the range of 0.88 – 1.04 and 0.87 – 1.00 in the cases of 12.6 and 25.2 mm thick tungsten armor, respectively. By installing 12.6 and 25.2 mm thick tungsten armors, the local TPRs are reduced by about 9 and 13 % relative to the case without the armor, respectively, at the pellets adjacent to the beryllium layer. The local TPRs are reduced by about 2 and 3 % at the pellets adjacent to the F82H layer. The integrated tritium productions are reduced by about 3 and 6 %. The impacts of the tungsten armor on the local TPR at the pellet adjacent to the beryllium layer are larger than those on the integrated tritium production. This is probably because the mean free path of the thermal neutron is very small for the tritium production reaction in the Li_2TiO_3 layer. It is about 0.8 mm. As a result, the impacts of the tungsten armor on the tritium production increase when coming closer to the beryllium layer.

Figure 5 shows distributions of the local TPR from ^{6}Li in the first and second Li_2TiO_3 layers for the two layers breeder mockup under condition without a reflector. The TPRs increase

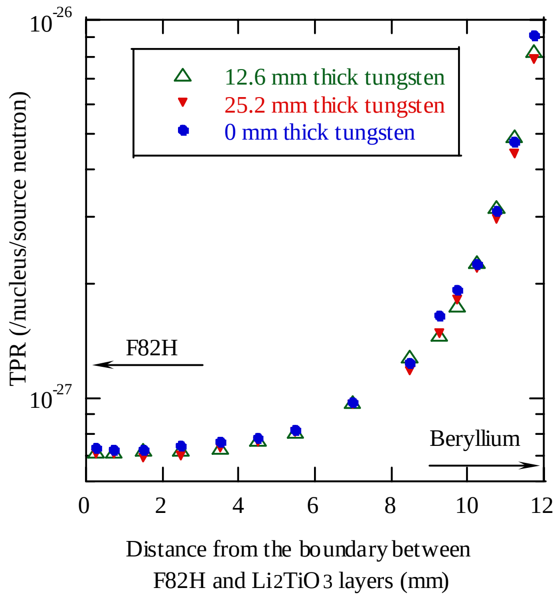

FIG. 3. Distributions of the local TPR from ^{6}Li for the one layer breeder mockup with the 0, 12.6 and 25.2 mm thick tungsten armor under condition with a neutron reflector.

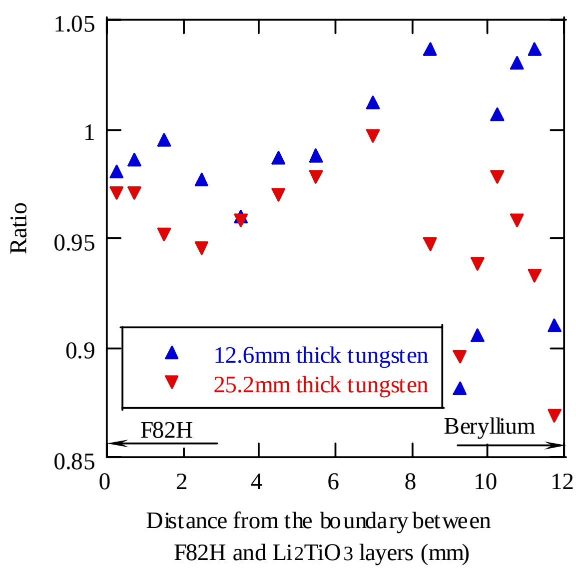

FIG. 4. Distributions of the ratio of the local TPR from ^{6}Li for the one layer breeder mockup with the tungsten armor to that without one.

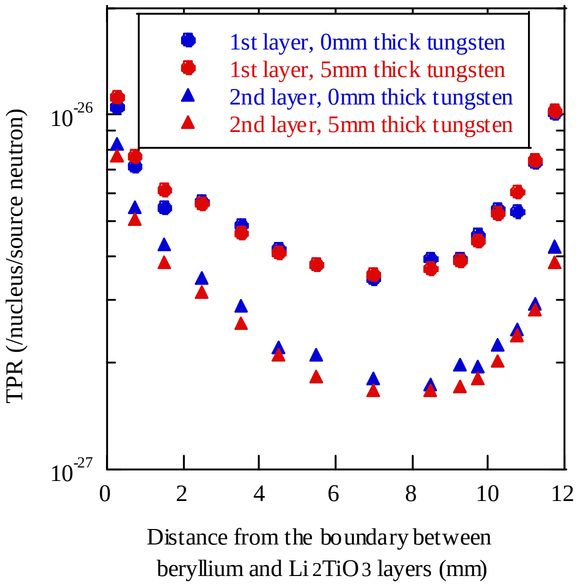

FIG. 5. Distributions of the local TPR from ^{6}Li for the two layers breeder mockup with the 0 and 5 mm thick tungsten armor under condition without a neutron reflector.

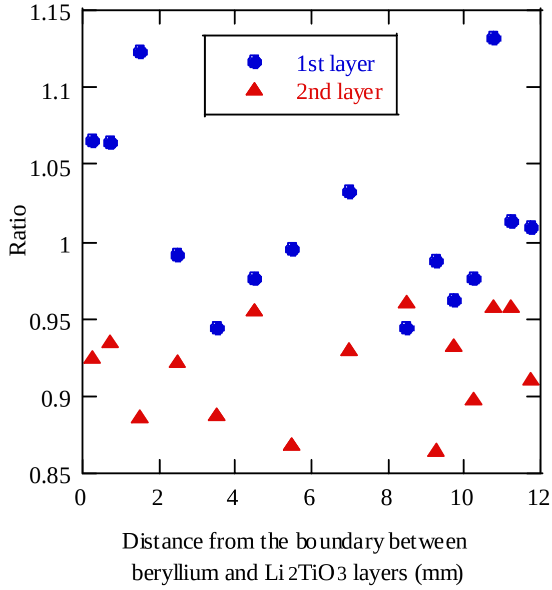

FIG. 6. Distributions of the ratio of the local TPR from ^{6}Li for the two layers breeder mockup with the 5 mm thick tungsten armor to that without one.

when coming closer to the beryllium layers in both sides. The integrated tritium productions in the first and second Li_2TiO_3 layers are 1.00 x 10^{-4} and 5.65 x 10^{-5} Bq/source neutron, respectively, in the case without the armor. These are 1.02 x 10^{-4} and 5.19 x 10^{-5} Bq/source neutron in the case with the 5 mm thick tungsten armor. Figure 6 shows distributions of the ratio of the local TPR from ^{6}Li for the case with the 5 mm thick tungsten armor to that without one. The ratios are in the range of 0.94 – 1.13 and 0.87 – 0.96 in the first and second Li_2TiO_3 layers, respectively. By installing 5 mm thick tungsten armor, the integrated tritium production increases by 2 % relative to the case without the armor in the first layer, and it decreases by 8 % in the second layer. It is expected that the thermal neutron flux increases due to the neutron multiplier reaction in the tungsten, so the tritium production increases in the first layer. On the contrary, the fast neutron flux decreases due to the scattering reaction in the tungsten, thus reducing neutron multiplier reaction in the beryllium, so the tritium production decreases in the second layer. By installing 5 mm thick tungsten armor, sum of the integrated tritium productions in the first and second layers is reduced by 2 %.

4. Discussions

Numerical calculations were conducted using the Monte Carlo neutral particle transport code MCNP-4C [10] and the Japanese Evaluated Nuclear Data Library JENDL-3.2 [11]. As for beryllium, S(α, β) was considered for En < 4eV on the scattering cross section of the thermal neutron. Figures 7, 8 and 9 show the neutron spectra at each boundary for the cases without armor and with 25.2 mm thick tungsten armor. These figures show the results for the one layer breeder mockup under condition with a neutron reflector. Both, fast neutron fluxes of the energy above 10 MeV and thermal neutron fluxes are reduced at all boundaries by installing the tungsten armor. It is expected that fast neutron fluxes are reduced by scattering of the tungsten, therefore thermal neutron fluxes are reduced by the reduction of neutron multiplying reactions due to interactions between beryllium and the fast neutron of the energy above 3 MeV. In addition, capture reactions of the tungsten itself are also expected to contribute to reduction of thermal neutron fluxes. So, while tungsten has large neutron multiplier reactions itself, it can be concluded that the tritium productions are reduced by above-mentioned effects. Figure 10 shows the ratio of the tritium productions from ^{6}Li for the case with the tungsten armor to that without one as a function of the tungsten armor thickness obtained by this experiment. This figure shows the results for the local TPR at the pellets adjacent to the beryllium layer, that to the F82H layer, and sum of the integrated tritium production. The results for the local TPR are obtained by the experiments with the one layer breeder mockup, and those for sum of the integrated tritium production are obtained by the experiments with the one and two layers breeder mockups. In the blanket design proposed by JAERI, it is expected that the reduction of the TBR is less than 2 %, since the thickness of tungsten armor is less than 5 mm.

Figure 11 shows distributions of the ratio of the calculation result to the experiment one (C/E) for the local TPRs from ^{6}Li in one layer breeder mockup with the 12.6 and 25.2 mm thick tungsten armor under condition with a neutron reflector. The C/Es are in the range of 1.14 – 1.33 and 1.11 – 1.26 in the cases with the 12.6 and 25.2 mm thick tungsten armors, respectively, for the local TPRs. The both C/Es are 1.19 for the integrated tritium productions.

Figure 12 shows distributions of the C/E for the local TPRs from ^{6}Li in two layers breeder mockup under condition without a reflector. The C/Es in the first and second Li_2TiO_3 layers are in the range of 0.98 – 1.06 and 1.02 – 1.11, respectively, in the case with 5 mm thick tungsten armor for the local TPRs. The C/Es are 1.02 and 1.06 for the integrated tritium productions. The C/E is 1.04 for sum of the integrated tritium productions. It is concluded that the integrated tritium productions can be accurately predicted for the condition without a reflector. Uncertainties of calculation results for the case with a reflector are larger than those without one. It is assumed that this occurs due to uncertainties of the cross section data about the back-scattering neutron from the SS316 of the reflector.

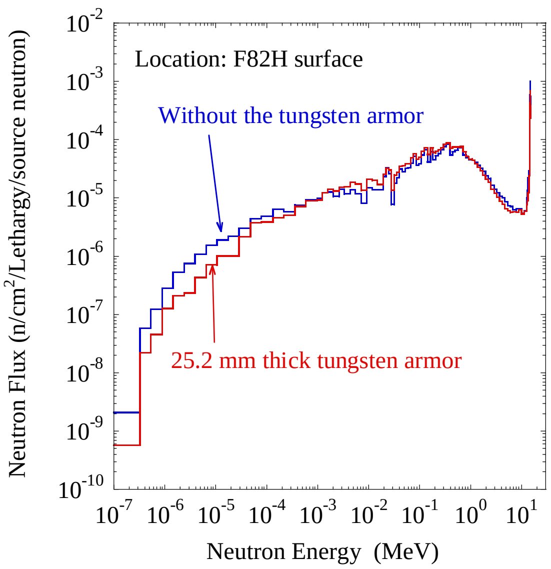

FIG. 7. Neutron flux spectra at the F82H layer surface for the cases without tungsten armor and with 25.2 mm thick tungsten armor obtained by numerical calculations.

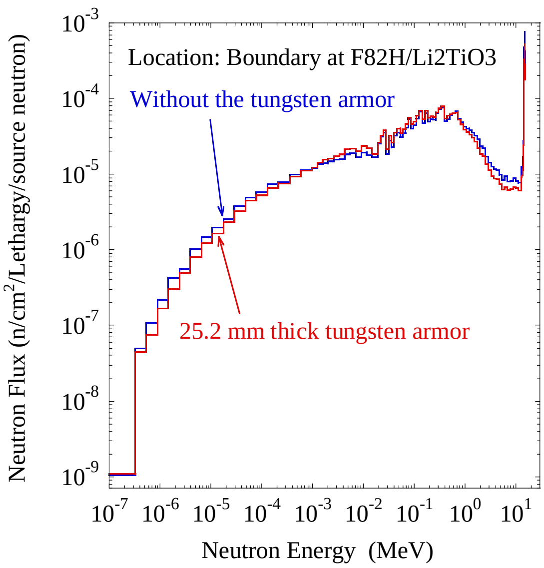

FIG. 8. Neutron flux spectra at the boundary between F82H and Li_2TiO_3 layers for the cases without tungsten armor and with 25.2 mm thick tungsten armor obtained by numerical calculations.

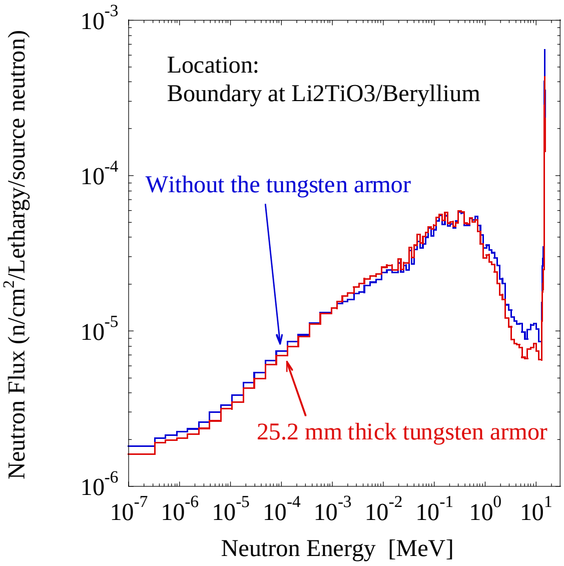

FIG. 9. Neutron flux spectra at the boundary between Li_2TiO_3 and beryllium layers for the cases without tungsten armor and with 25.2 mm thick tungsten armor obtained by numerical calculations.

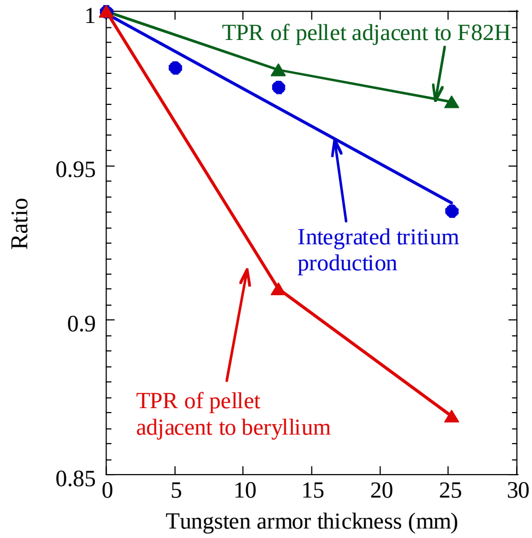

FIG. 10. Ratio of the tritium production from ^{6}Li for the case with the tungsten armor to that without one as a function of the tungsten armor thickness obtained by this experiment.

5. Summary

Neutronics integral experiments have been performed using DEMO blanket mockups with the tungsten armor. By installing the 5, 12.6 and 25.2 mm thick tungsten armors, sum of the integrated tritium production are reduced by about 2, 3 and 6 % relative to the case without the armor, respectively. Also, by installing 12.6 and 25.2 mm thick tungsten armors, the local TPRs are reduced by about 9 and 13 % relative to the case without armor, respectively, at the pellet adjacent to the beryllium layer. The impacts of the tungsten armor on the local TPR at the pellet adjacent to the beryllium layer are larger than those on the integrated tritium production. Numerical calculations have been conducted using the Monte Carlo code MCNP-4C with the nuclear data library FENDL-2. Calculation results of the fast and thermal neutron fluxes are also reduced at all boundaries by installing the tungsten armor. It is expected that fast neutron fluxes are reduced by scattering of the tungsten, therefore thermal neutron fluxes are reduced by the reduction of neutron multiplying reactions due to interactions between beryllium and the fast neutron. In addition, capture reactions of the tungsten itself are also expected to contribute to reduction of thermal neutron fluxes. So, while tungsten has large neutron multiplier reactions itself, it can be concluded that the tritium productions are reduced by above-mentioned effects. The C/Es for the sum of integrated tritium productions in the cases with the tungsten armor are 1.04 and 1.19 under conditions without and with a neutron reflector, respectively.

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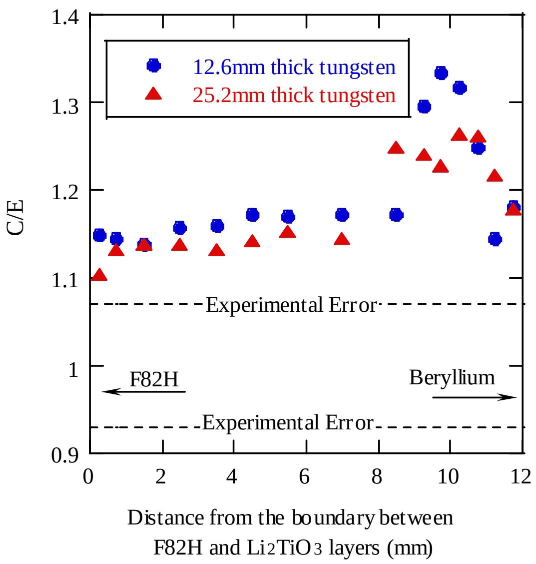

FIG. 11. Ratio of the calculation result to the experiment one (C/E) for the local TPRs from ^{6}Li in one layer breeder mockup with the 12.6 and 25.2 mm thick tungsten armor under condition with a neutron reflector.

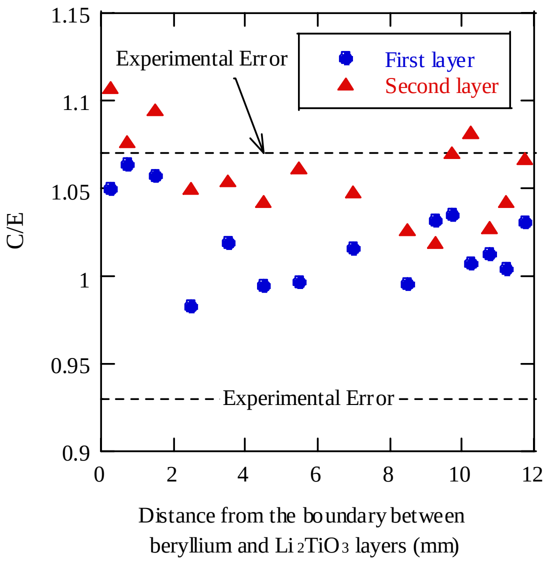

FIG. 12. Ratio of the calculation result to the experiment one (C/E) for the local TPRs from ^{6}Li in the first and second Li_2TiO_3 layers in two layers breeder mockup with the 0 5 mm thick tungsten armor under condition without a neutron reflector.

References

[1] YANAGI, Y., et al., “Nuclear and Thermal Analyses of Supercritical-water-cooled Solid Breeder Blanket for Fusion DEMO Reactor”, J. Nucl. Sci. Technol., **38** (2001) 1014.

[2] ENOEDA, M., et al., “Design and technology development of solid breeder blanket cooled by supercritical water in Japan”, Nucl. Fusion, **43** (2003)1837.

[3] OCHIAI, K., et al., “Neutronics Experiment of ^{6}Li-enriched Breeding Blanket with Li_2TiO_3/Be/F82H Assembly Using D-T Neutrons”, J. Nucl. Sci. Technol., **Suppl.2** (2002) 1147.

[4] KLIX, A., et al., “Tritium Measurement for ^{6}Li-Enriched Li_2TiO_3 Breeding Blanket Experiments with D-T Neutrons”, Fus. Sci. Technol., **41** (2002) 1040.

[5] SATO, S., et al., “Neutronics Experiments for DEMO Blanket at JAERI/FNS”, Nucl. Fusion, **43** (2003) 527.

[6] VERZILOV, Y., et al., “Integral Experiments for Verification of Tritium Production on the Beryllium/Lithium Titanate Blanket Mock-up with a One-Breeder Layer”, JAERI-Research 2004-015, Japan Atomic Energy Research Institute, Ibaraki (2004).

[7] SATO, S., et al., “Impact of armor materials on tritium breeding ratio in the fusion reactor blanket”, J. Nucl. Mater, **313-316** (2002) 690-695.

[8] http://fnshp.tokai.jaeri.go.jp/.

[9] VERZILOV, Y., et al., “A Novel Method for Solving Li_2CO_3 by Binary-acid for TPR Measurement”, J. Nucl. Sci. Technol., **33** (1996) 390.

[10] BRIESMEISTER, J. F., “MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C”, LA-13709-M, (2000).

[11] NAKAGAWA, T., et al., “Japanese evaluated nuclear data library version 3 reversion-2: JENDL-3.2”, J. Nucl. Sci. Technol., **32**, 1259 (1995).