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Benchmark experiment on bulk shield of SS316/water with simulated superconducting magnet

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Abstract

A bulk shielding experiment was performed at the D-T neutron source FNS, using the assembly simulating shield blanket, vacuum vessel and toroidal field coil (superconducting magnet) of ITER. The objective was to investigate the influence on nuclear parameters due to the nuclei involved in the toroidal field coil and the effect of B_4C/Pb. The analysis was performed by MCNP4-A and the DOT3.5 (P_5S_{16} approximation, 175-n and 42-γ groups with and without self-shielding correction) with JENDL Fusion File (JENDL-FF) and FENDL/E-1.1. All of the MCNP calculations and DOT calculations with self-shielding correction agreed within $\pm 40\%$ with the measurements. It was found that the influence of self-shielding mainly due to copper and tantalum in the DOT calculations was large for neutrons less than 10 keV. It is concluded that the uncertainty of nuclear designs by MCNP-4A and DOT3.5 with JENDL-FF and FENDL/E-1.1 on the bulk shield of ITER is approximately 40% in the toroidal coil region. The analysis suggested that it was quite important to deal with heavy nuclei of small quantity such as tantalum precisely in the shielding design. © 1998 Elsevier Science S.A. All rights reserved.

1. Introduction

The toroidal field coil of ITER which is to be made of a super conducting magnet (SCM) includes various nuclei such as niobium, copper and tantalum. The nuclear heating in SCM is the critical issue for ITER design. A bulk shielding experiment with the assembly simulating shield blanket, vacuum vessel and toroidal field coil of ITER was carried out as one of ITER/EDA (engineering design activities) R&D tasks. The objectives of this experiment were to examine the influence of these compositions on nuclear parameters and to investigate the calculation accuracy, since the bulk shielding performance of shield blanket for ITER was already studied in the previous SS316/water bulk shielding experiment [1–3]. The similar partial mock-up experiment [4], where the coil simulation was coarse, was also conducted at ENEA/Frascati, Italy.

2. Experiment

The experiment was performed at the Fusion Neutronics Source (FNS) facility [5] of the Japan

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Atomic Energy Research Institute (JAERI). The D-T neutrons were produced by bombarding a water-cooled 3.7×10^{11} Bq tritiated-titanium target with a 350 keV d^+ beam. The total D-T neutron yield was determined absolutely with an accuracy within 3% by an associated alpha-particle counting method (α-monitor) [6].

The test region of the experimental assembly (assembly No. 1) consisted of type 316 stainless steel (SS316)/water layers, which simulated shield blanket and vacuum vessel for ITER, and SCM region as shown in Fig. 1. The structure of the SCM region was modeled based on the Japanese Home Team design [7] for ITER SCM in 1993. The heterogeneous structure was replaced in a layered structure. Optimal material composition of the conductor region was selected according to the pre-analysis by DOT3.5 [8] with JSSTDL-3.1 [9] (n: 42 groups, γ: 21 groups). The volume fractions (%) of the conductor region were 36.4: 8.1: 6.5: 1.2: 18.3: 29.5 for Cu, Ti, Nb, Ta, Insulator and Void, respectively. Ta was involved in each strand in order to prevent the diffusion of Sn. Void was a substitute of liquid helium and epoxyglass was adopted as an insulator. The details of the SCM region are shown in Fig. 2. The assembly (assembly No. 2) where the SS316 of 51 mm in thickness before the SCM region was replaced with a B_4C/Pb layer (volume ratio 1:3) was used to study the effect of B_4C/Pb which was proposed as an auxiliary shield in ITER/CDA (conceptual design activities) [10].

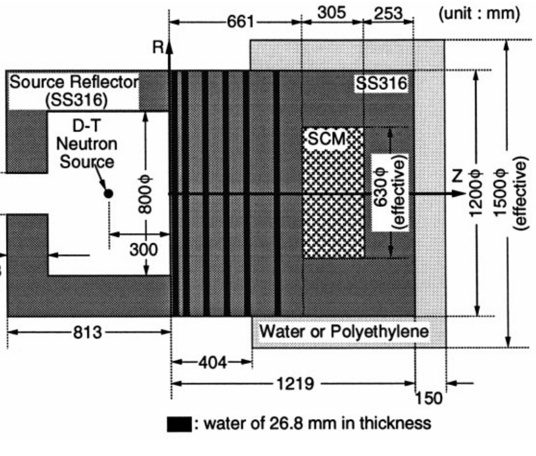

Fig. 1. The schematic view of the experimental assembly No. 1.

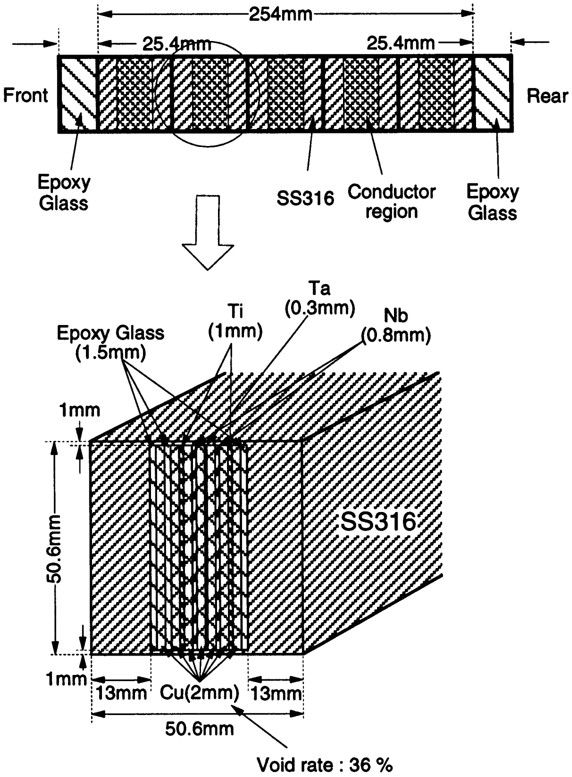

Fig. 2. Detailed structure of the SCM region.

Various experimental data were measured mainly in the simulated SCM region, since the data in the front SS316/water region were considered to be the same as those in the previous SS316/water experiment [1]. The measurement items and methods are as follows: (1) neutron spectra from 10 keV to 1 MeV with a small proton recoil gap proportional counter; (2) neutron spectra below 10 keV with the slowing down time (SDT) method; (3) dosimetry reaction rates of ^{27}Al(n,α)^{24}Na, ^{93}Nb(n,2n)^{92m}Nb, ^{115}In(n,n$'$)^{115m}In, ^{197}Au(n,γ)^{198}Au with the activation foil method; (4) dosimetry reaction rates of ^{10}B(n,α)^{7}Li with a BF_3 gas proportional counter; (5) fission rates of ^{235}U and ^{238}U with micro fission chambers; (6) gamma-ray spectra with a BC537 liquid organic scintillation counter; and (7) gamma-ray heating rates of epoxyglass, SS316 and copper with thermoluminescence dosimeters.

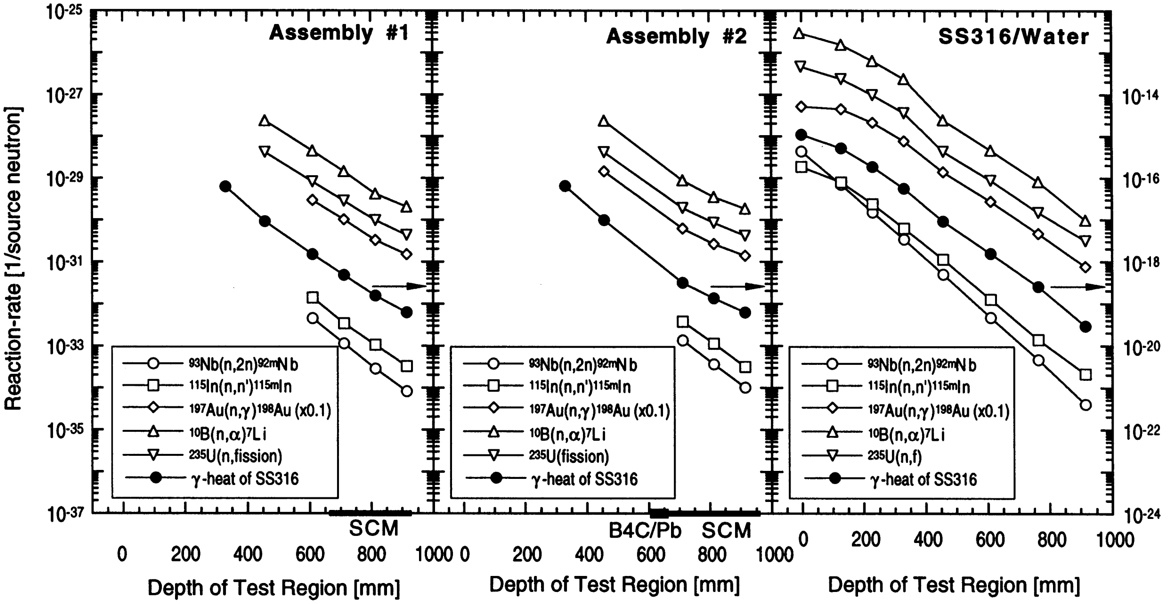

Fig. 3. Distribution of the measured reaction rates of ^{10}B(n,α)^{7}Li, ^{93}Nb(n,2n)^{92m}Nb, ^{115}In(n,n′)^{115m}In and ^{197}Au(n,γ)^{198}Au, fission rates of ^{235}U and gamma-ray heating rates of SS316 with those in the previous SS316/water bulk shielding experiment.

The detailed descriptions for the measurement techniques are in the previous report [1].

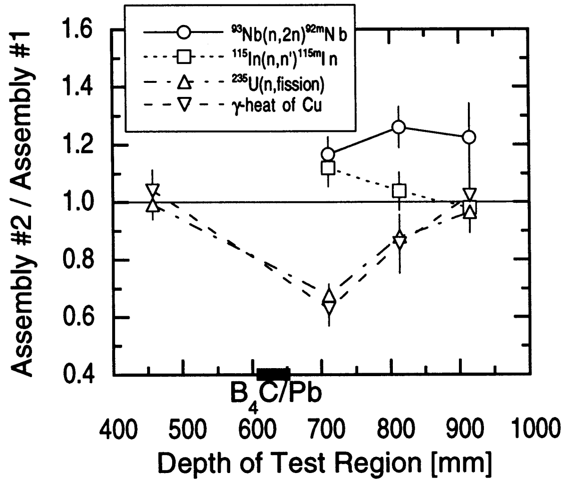

Fig. 4. Ratios of the measured reaction rates for ^{93}Nb(n,2n)^{92m}Nb and ^{115}In(n,n′)^{115m}In, fission rates of ^{235}U and gamma-ray heating rates of copper in the assembly No. 2 to those in the assembly No. 1.

3. Analysis

The analysis of this experiment was carried out with two transport codes which are used in ITER/EDA; one was the continuous energy Monte Carlo code MCNP-4A [11], the other was the 2D S_N transport code DOT3.5 with the modified GR-TUNCL code [12]. The nuclear data libraries of JENDL Fusion File (JENDL-FF) [13] and FENDL/E-1.1 [14] were adopted in this analysis since FENDL/E-1.1 was used in ITER/EDA and JENDL-FF was one of the candidates of the next version of FENDL/E-1.1. The processed libraries for the MCNP code were FSXLIB-JFF [15] and FENDL/MC-1.1 [16], respectively. The multi-group library (175-n and 42-γ groups, P_5 Legendre expansion) of FENDL/E-1.1 for DOT3.5 with or without the self-shielding correction was made by using the TRANSX 2.15 code [17] from revised FENDL/MG-1.1 [18]. Those of JENDL-FF were also obtained with the TRANSX 2.15 code from the matxs files of JENDL-FF newly processed by the NJOY 91.128 code [19] with the same process condition as that in the revised FENDL/MG-1.1. The experimental assemblies were modeled in the

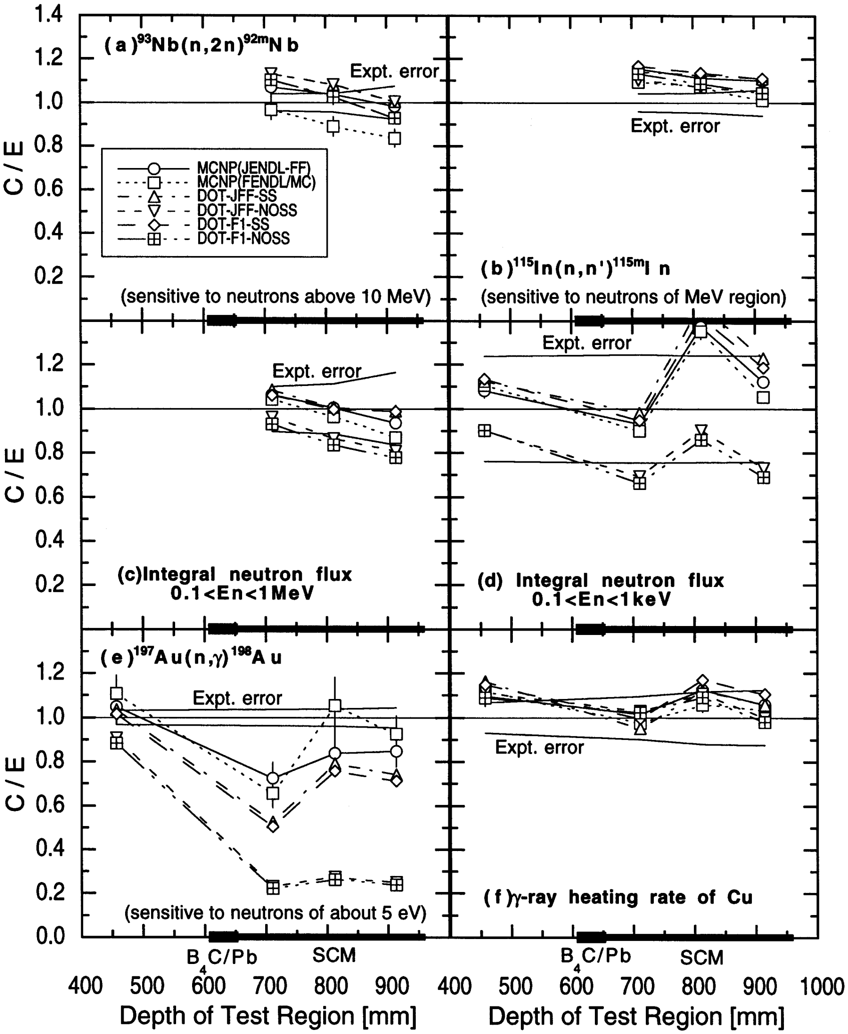

Fig. 5. Comparison between the calculations and the measurement for the reaction-rates of: (a) ^{93}Nb(n,2n)^{92m}Nb and (b) ^{115}In(n,n′) ^{115m}In, integral neutron fluxes of (c) 0.1–1 MeV and (d) 0.1–1 keV, reaction rates of (e) ^{197}Au(n, γ)^{198}Au and (d) gamma-ray heating rates of copper.

R-Z cylindrical shape. The conductor region which consisted of thin foils of several materials as shown in Fig. 2 was homogenized in the analysis. The angular quadrature of S_{16} was adopted in the DOT calculation.

4. Results and discussion

Some measured results are shown in Fig. 3 with those of the previous SS316/water bulk shielding experiment [1]. The measured data of assembly No. 1, 2 and SS316/water assembly at the depth of 457 mm are almost the same as each other, while those deeper than 650 mm are different depending on the assembly configuration. Fig. 4 shows the ratios of the measured data in assembly No. 2 to those in assembly No. 1. These ratios demonstrate the effect of B_4C/Pb. It is found that B_4C/Pb effectively decreases neutron fluxes in the eV region and gamma-ray heating rate.

Fig. 5 shows the ratios of the calculated to

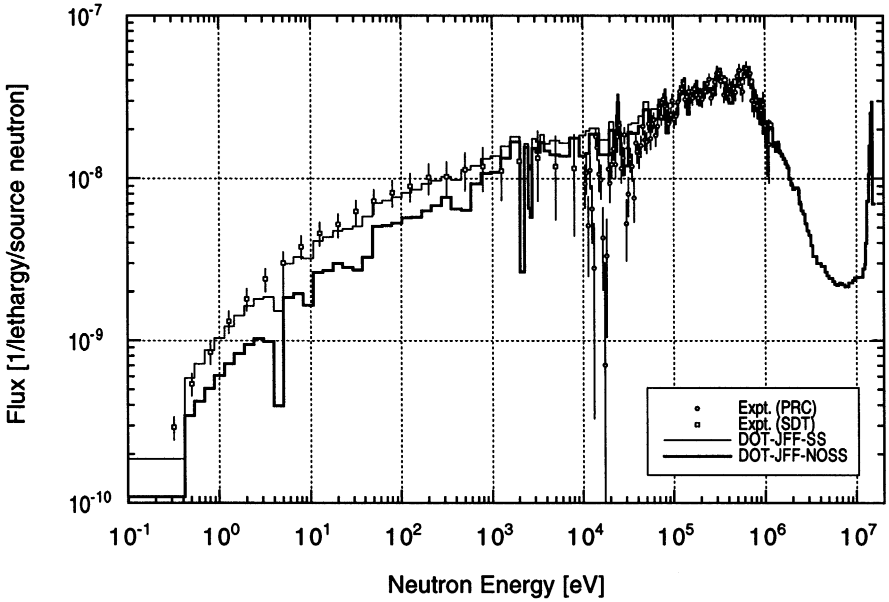

Fig. 6. Neutron spectra of DOT-JFF-SS and DOT-JFF-NOSS with the measured ones at the depth of 711 mm in the assembly No. 1.

measured data (C/E) for reaction-rates, neutron fluxes and gamma-ray heating rate in the assembly No. 2. The C/E trends were almost the same as those in assembly No. 1. MCNP-JFF, MCNP-F1, DOT-JFF and DOT-F1 mean the calculations by MCNP-4A and DOT3.5 with JENDL-FF and FENDL/E-1.1, respectively. The sub names SS and NOSS in the DOT calculations correspond to the DOT calculation with and without self-shielding correction, respectively. Both the MCNP calculations agree within 40% with the measurements. The DOT calculations with the self-shielding correction show almost the same accuracy as the MCNP calculations. The influence of self-shielding is large for neutrons, less than 10 keV in the DOT calculations, although it was small in the previous SS3 16/water bulk shielding experiment [2,3]. Fig. 6 shows the measured and calculated (DOT-F1) neutron spectra at the depth of 711 mm in assembly No. 1. Since the neutron spectra of DOT-F1-NOSS have the large dips around a few keV and 4 eV which correspond to the large resonances of copper and tantalum, respectively, the nucleus leading to the self-shielding are considered to be mainly copper and tantalum. The influence of self-shielding for γ-heating rate is seemingly small as shown in Fig. 5 (f). This is probably due to the cancellation of underestimated low energy neutrons and overestimated gamma-ray production (neutron capture) cross-sections.

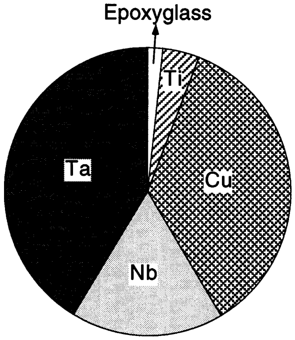

Fig. 7. The estimated contribution of the nuclei involved in the conductor region to the gamma-ray heating rate.

The DOT calculations were additionally carried out with the library (self-shielding corrected) processed from the revised FENDL/MG-1.1 which omitted the gamma-ray production data in the matxs file of the specified nucleus (e.g. tantalum) included in the conductor region. The contribution of the nuclei involved in the conductor region to the gamma-ray heating rate was estimated as the difference between the gamma-ray heating rates of the additionally calculated DOT and DOT-F1 with self-shielding correction. Fig. 7 shows the result at a depth of 711 mm in assembly No. 2. It is remarkable that the contribution of gamma-rays emitted from tantalum to the gamma-ray heating rate in the SCM region was more than 30%, although the volume fraction of tantalum in the conductor region was only 1.2%.

5. Concluding remarks

The benchmark experiment on bulk shield of SS316/water with simulated SCM was performed at FNS. The various experimental data for neutron and gamma-ray, particularly neutron spectra less than 1 MeV and gamma-ray heating rate, were measured at the simulated SCM region. The effect of B_4C/Pb was examined experimentally using the assemblies with and without B_4C/Pb. It was demonstrated that B_4C/Pb was quite effective at reducing neutrons below 1 keV and gamma-ray heating by a factor of two. From the comparison of the measured and calculated results, it was concluded that the accuracy of nuclear designs by MCNP-4A and DOT3.5 with JENDL-FF and FENDL/E-1.1 on the bulk shield of ITER was assured within 40%. The analysis suggested that it was quite important to deal with heavy nuclei of small quantity such as tantalum precisely in the shielding design.

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