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Dogleg Duct Streaming Experiment with 14 MeV Neutron Source

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There are several vacant channels for diagnosis, RF heating, etc. through the shielding structure in fusion reactors. Some of them consist of dogleg ducts, and the streaming effect has not been experimentally investigated yet. The present work was conducted to study the behavior of neutrons streaming through the ducts and estimate the uncertainties of calculations for the design of fusion reactors such as ITER on the basis of the experiments with the FNS facility at JAERI. The experimental assembly was an iron slab 180 cm in thickness. A doubly bent duct 30 cm × 30 cm in the cross section was shaped in the assembly. The lengths of the 3 legs were 115 cm, 60 cm and 65 cm respectively. The experiment was analyzed with the Monte Carlo transport calculation codes MCNP-4B, -4C, the nuclear data libraries FENDL-2 and JENDL-3.3. In the analysis, the calculated neutron spectra agreed with measured data within the statistical errors. The reaction rates for ^{93}Nb(n,2n)^{92m}Nb and ^{115}In(n,n')^{115m}In showed relatively favorable agreement within 30 - 70 % between calculated and measured results, while those for ^{197}Au(n,γ)^{198}Au did within a factor of 2 pointing out the difficulties of the calculation in the low energy range. As a result, the present calculation method turned out to be sufficient enough for the design of fusion reactors.

KEYWORDS: Dogleg duct, Streaming experiment, D-T neutron, fusion reactor, Neutron spectrum, Reaction rate, MCNP-4c, FENDL/2, JENDL-3.3

I. Introduction

There exist several penetrations such as diagnostics port, neutral beam injector (NBI) port, divertor port etc. through the shield in fusion reactors. From the viewpoint of the global shield of the reactors, it is essential to investigate the influence of neutron streaming through those ports on the radiation dose. Previously, the streaming experiments for straight ducts had been successfully conducted with the FNS (Fusion Neutronics Source) facility at the Japan Atomic Energy Research Institute (JAERI) as the R&Ds for the shielding design of ITER/EDA.[1-3] In those experiments, streaming effects of a bent duct were not investigated. Thus, in order to study the behavior of the neutrons streaming through a dogleg duct, which represents the typical complex ports in a fusion reactor such as ITER, an experiment was conducted for a doubly bent duct with the rotating neutron target (RNT) of the FNS/JAERI.

Analyses of the experiment were carried out with the continuous energy Monte Carlo codes MCNP-4B and -4C,[4] which had been used for miscellaneous radiation shielding calculations in the design of ITER/EDA. The aim of the analyses was to study the dogleg duct streaming effect on the local nuclear responses, and demonstrate the capability of the Monte Carlo transport calculations in the design of the fusion reactor shielding. Two sets of nuclear data FENDL/2[5] and JENDL-3.3[6] were employed for the study. The former is the data used for the design of ITER/EDA and the latter is the newly evaluated data released in 2002. This report describes the experimental procedures, the measured data and the results of the analysis.

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II. Experiment

1. Arrangement and measurement

The experiment was conducted with the FNS facility at JAERI. There are 2 target rooms in FNS. The target that provides a neutron yield as large as about 4×10^{12} n/s at full beam current was used in the experiment. The layout of the room is shown in **Fig.1**. The experimental assembly was constructed in the wall separating the two target rooms. The outline of the assembly is an iron slab 1700 mm in height, 1400 mm in width, and 1800 mm in thickness. A doubly bent duct 300mm × 300mm in cross section was shaped through the assembly. The geometrical configuration of the dogleg duct streaming experiment is shown in **Fig.2**. The first horizontal leg of the duct was set as high as the D-T neutron source. The second leg was connected vertically to the first with a right angle, and the third was horizontally to the second. The lengths of the legs were 1150 mm, 600 mm and 650 mm respectively.

Neutron spectra above 2 MeV were measured at several positions by a spherical NE213 scintillation spectrometer 40 mm in diameter. The two-gain method was adopted in the electronics system to make a wider energy range available. Neutron and gamma-ray signals were separated by a pulse shape discrimination technique based on the differences in rise time of the signal. The pulse height spectrum of recoil protons which represent neutron events was unfolded with the FORIST code[7] to obtain the neutron energy spectrum. The reactions of ^{93}Nb(n,2n)^{92m}Nb, ^{115}In(n,n')^{115m}In and ^{197}Au(n,γ)^{198}Au were employed as neutron activation dosimeters. The first reaction is effective to evaluate the 14 MeV neutron flux, the second is sensitive to fast neutrons above 1 MeV, and the third helps to understand the amount of the thermal and epithermal neutron flux.

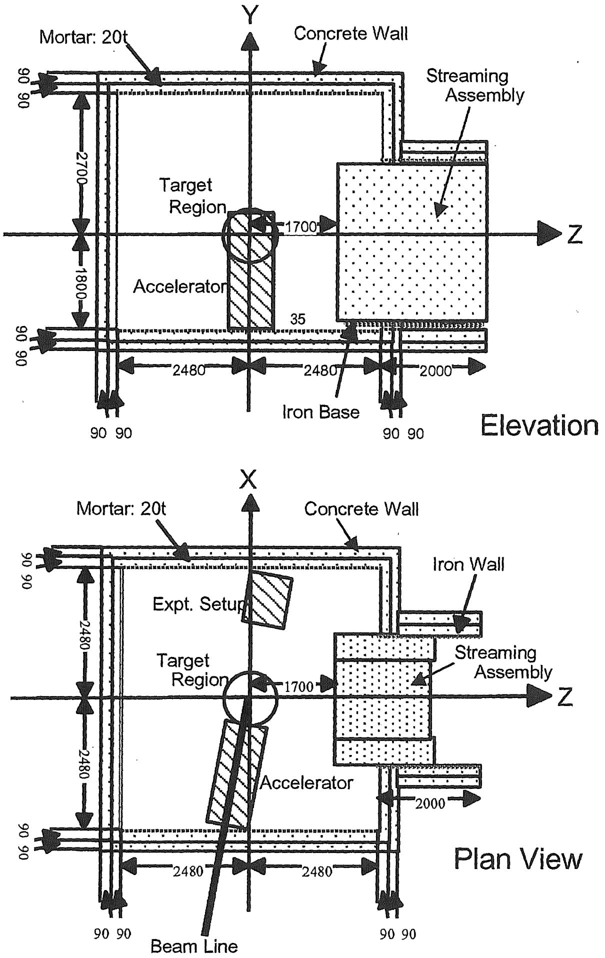

Fig.1 Layout of the target room.

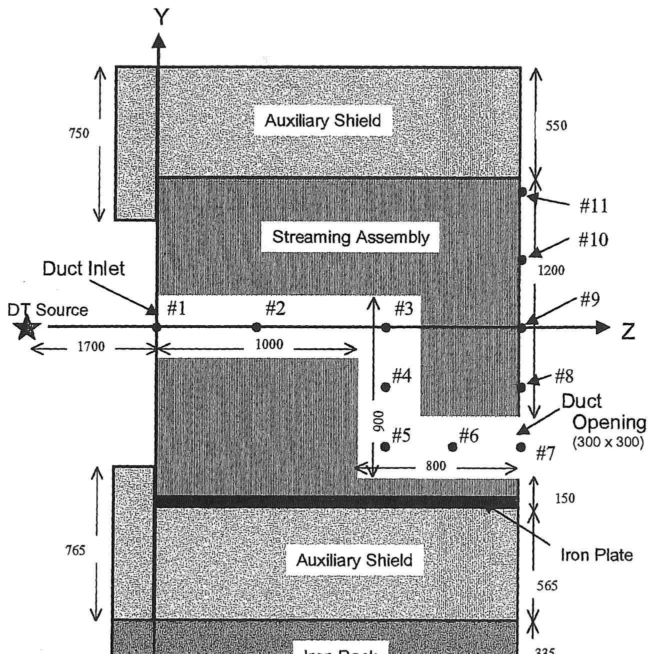

Fig.2 Schematic view of the experimental assembly.

2. Measured results

Measured neutron spectra are shown in **Fig.3**. The D-T neutron source intensity was normalized to unity. Positions of #3, #5 and #7 are located in the duct, and the spectrum becomes softer as the path along the duct from the inlet grows larger. As for the spectrum at the position #9, it is higher than that at the position #7, because the position #9 is located on the extension of the first leg and the shield between positions #3 and #9 is only 50 cm. It is noteworthy that the 14 MeV peak at position #9 is even larger than that at position #7.

Reaction rates measured with activation foils in the bent duct and on the back surface of the assembly are shown in **Fig.4** under the same normalization as the spectrum. It is observed that the reaction rates of ^{93}Nb(n,2n)^{92m}Nb and ^{115}In(n,n')^{115m}In caused mainly by fast neutrons prominently decrease after the duct bends, while those of ^{197}Au(n,γ)^{198}Au do not show clear change around the bends.

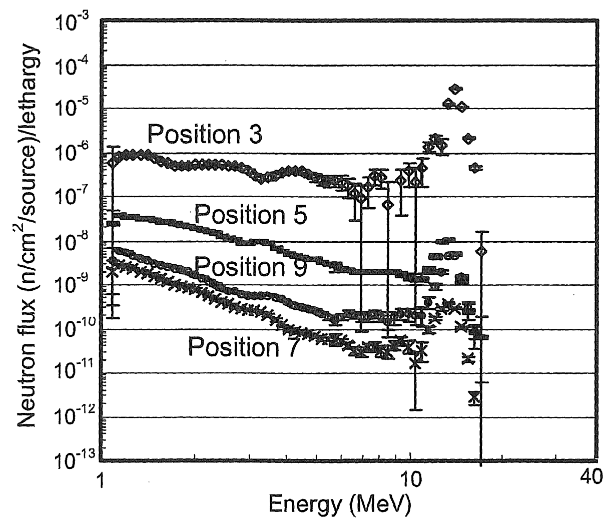

Fig.3 Neutron spectra measured at positions #3, #5, #7 and #9.

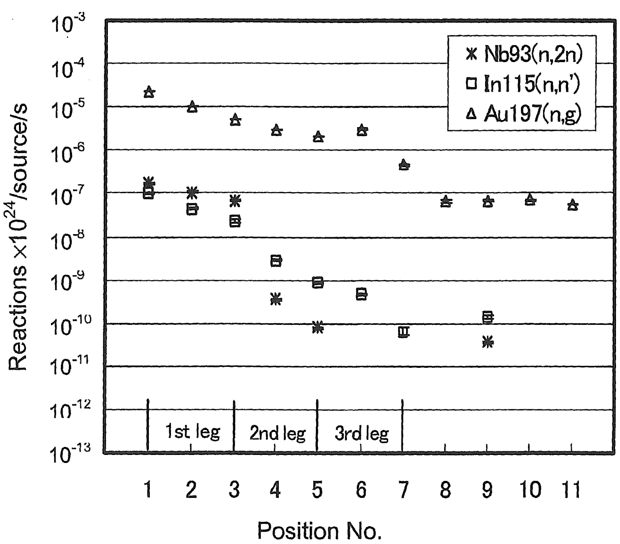

Fig.4 Reaction rates measured in the duct and behind the assembly.

III. MCNP analysis

1. Calculation procedure

All of the structures in the target room used for the experiment illustrated in **Fig.1** were accurately modeled in the calculation. The model includes the rotating neutron target (RNT) assembly, the experimental room and the streaming duct assembly separating the two target rooms. The Monte Carlo transport codes MCNP-4B and -4C with a special rou- tine to generate D-T neutrons were used for the calculations. The source routine consists of a simulation program for deu- terons slowing down in the titanium-tritium target and the kinematics of the ^{3}T(d,n)^{4}He reaction. It has been used for analyzing many experiments conducted at FNS such as shielding benchmark experiments etc., and the validity of the calculation procedure has been confirmed in those previous experiments and analyses.[1-3] Thus, the focus could be placed on estimating uncertainty ranges in the dogleg duct streaming calculations by the Monte Carlo method and providing reliability for local nuclear responses. The nuclear data libraries FENDL/2 and JENDL-3.3 were employed for the present study. Both calculated neutron spectra and reaction rates were normalized so that the ^{93}Nb(n,2n)^{92m}Nb reaction rate is consistent with the measured value at the duct inlet.

2. Neutron Spectrum

Neutron spectra calculated by the Monte Carlo method with FENDL/2 nuclear data are compared with measured spectra above 1 MeV in **Figs.5 - 8** at positions #3, #5, #7 and #9, respectively. The spectra calculated by JENDL-3.3 agreed with those by FENDL/2 within the statistical errors of the Monte Carlo calculations, and they were omitted in the figures. Although the comparisons are only in the higher energy range, the agreements are excellent except for 20 - 30 % underestimation at position #3. The discrepancy was made by the difficulty in the unfolding of the almost mono-chromatic measured data at the position where the target assembly can be directly observed, however, the bumps are relatively small compared with 14 MeV peak. As a general result of the spectra analysis, the calculation by MCNP-4B and -4C code together with FENDL/2 or JENDL-3.3 data was found suitable for the design calculation of ITER.

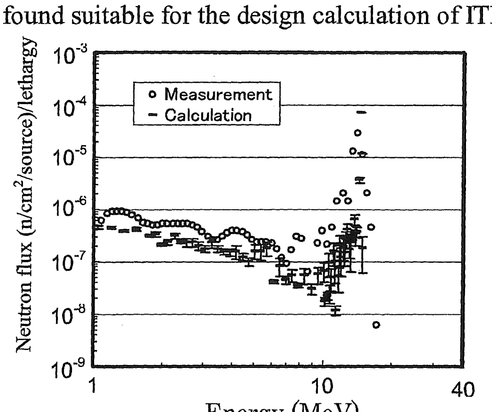

Fig.5 Spectra measured and calculated with FENDL/2 at pos. #3.

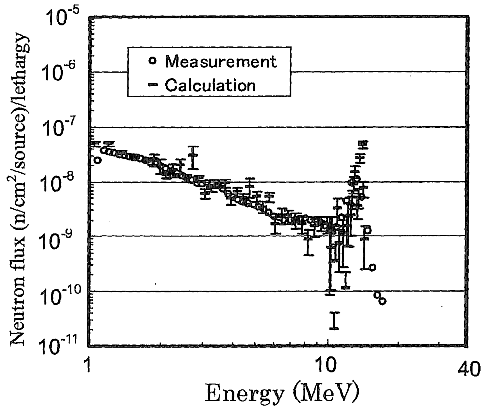

Fig.6 Spectra measured and calculated with FENDL/2 at pos. #5.

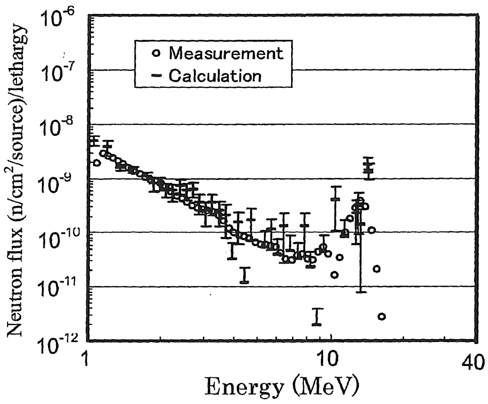

Fig.7 Spectra measured and calculated with FENDL/2 at pos. #7.

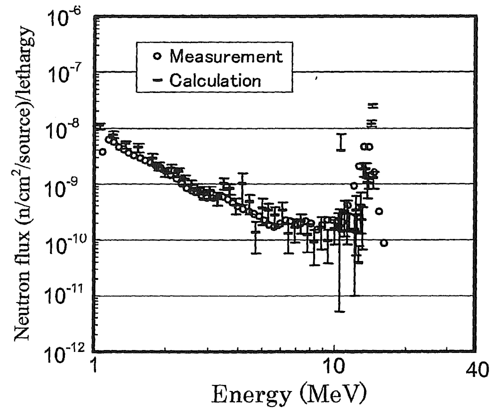

Fig.8 Spectra measured and calculated with FENDL/2 at pos. #9.

3. Reaction rates

Ratios of calculated and measured reaction rates in the duct and behind the assembly for ^{93}Nb(n,2n)^{92m}Nb, ^{115}In(n,n')^{115m}In and ^{197}Au(n,γ)^{198}Au are shown in Figs.9 - 11, respectively. Two Monte Carlo calculations were conducted with FENDL/2 and JENDL-3.3 nuclear data, and a third was done under the total absorption of the neutrons in the concrete wall of the target room with FENDL/2 nuclear data. The third case provides the knowledge as to the important component in source spectrum that dominates neutron flux in the duct and behind the assembly. In addition, it is advantageous to save the computer processing time.

The calculated reaction rates of ^{93}Nb(n,2n)^{92m}Nb agreed well with measured values except for those at positions #4 and #5. Since the positions are located in the second leg and the reaction rates become more than 2 orders of magnitude smaller than that at position #3 as was shown in Fig.4 due to the duct bend, the overestimation of about 40 - 70 % is relatively small. The reaction rates of ^{115}In(n,n')^{115m}In were generally underestimated except for those at positions #4 and #5. The underestimation may have been caused by the difficulty in dealing with the anisotropy of angular neutron flux. It is interesting that the calculated values obtained disregarding the reflection on the concrete wall agreed well with the other results except the values in the first leg. Calculated reaction rates of ^{197}Au(n,γ)^{198}Au generally agreed with measured values, however, the calculation made clear the difficulty to obtain accurate data with sufficiently small statistical errors. It is noteworthy that even the values calculated without wall reflection provided considerably good results.

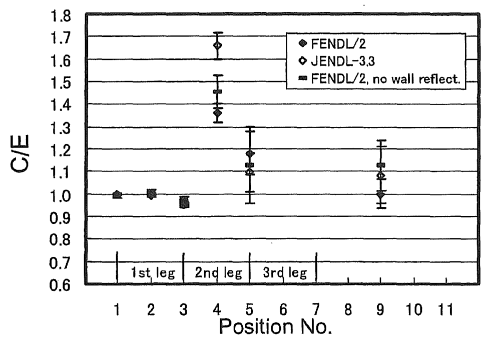

Fig.9 C/E values of ^{93}Nb(n,2n)^{92m}Nb reaction rates in the duct and behind the assembly.

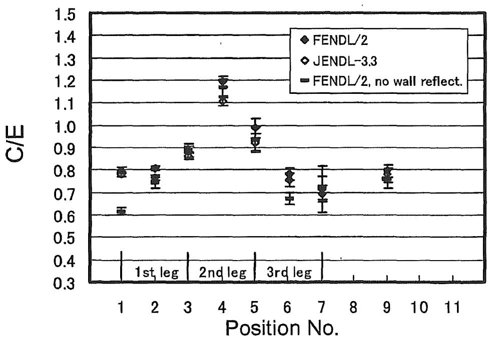

Fig.10 C/E values of ^{115}In(n,n')^{115m}In reaction rates in the duct and behind the assembly.

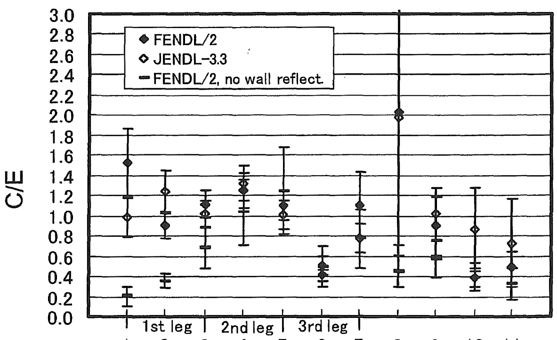

Fig.11 C/E values of ^{197}Au(n,γ)^{198}Au reaction rates in the duct and behind the assembly.

IV. Conclusion

A doubly bent duct streaming experiment was conducted at the FNS facility of JAERI in order to estimate the streaming effect through dogleg ducts upon shielding performance and evaluate the accuracy of calculation tools for the design of a fusion reactor such as ITER. The experiment was performed with a duct 30cm × 30cm in cross section penetrating an iron assembly 1.8 m in thickness. Neutron spectra above 2 MeV and reaction rates for ^{93}Nb(n,2n)^{92m}Nb, ^{115}In(n,n')^{115m}In and ^{197}Au(n,γ)^{198}Au were measured, and the experiment was analyzed by the Monte Carlo code MCNP, nuclear data libraries FENDL/2 and JENDL-3.3. The agreements between calculated and measured values were generally within the statistical errors of the Monte Carlo calculations, and the results show that the code and the nuclear data libraries are sufficiently reliable means to provide values accurate enough for estimating the streaming effects in the shielding design of fusion reactors.

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