Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 1, p. 263–267 (March 2000)

Investigation on Prediction Capability of Nuclear Design Parameters for Gap Configuration in ITER through Analysis of the FNS Gap Streaming Experiment

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As an R&D Task of shielding neutronics experiment under the Engineering Design Activities of the International Thermonuclear Experimental Reactor (ITER), streaming experiments with simulating a gap configuration formed by two neighboring blanket modules of ITER were carried out at the FNS facility. In this work, prediction capability of various nuclear design parameters was investigated through analysis of the experiments. The Monte Carlo transport calculation code MCNP-4A and the FENDL/E-1.0 and JENDL Fusion File cross section data libraries were used for the analysis with detailed modeling of the experimental conditions. As a result, all the measured quantities were reproduced within about ± 30 % by the calculations. It was concluded that these calculation tools were capable of predicting nuclear design parameters, such as helium production rates at connection legs of blanket modules to the back plate and nuclear responses in toroidal field coils, with uncertainty of ± 30 % for the geometry where gap streaming effect was significant.

KEYWORDS: ITER, FNS, gap streaming, blanket module, Analysis, MCNP, FENDL/E-1.0, JENDL Fusion File, nuclear design

I. Introduction

In the current design of the International Thermonuclear Experimental Reactor (ITER), a D-T fusion experimental reactor, blanket modules are attached to back plates with connection legs. This fabrication method makes a gap between every pair of neighboring blanket modules. The gaps, which are typically 20 mm in width, degrade considerably shielding performance of the blankets due to the streaming effect of radiations through the gaps. Hence, accurate prediction of shielding design parameters is required to protect adequately various components against radiations. Especially, accurate prediction of peaking factors for 14-MeV neutrons is important from an engineering point of view.

To investigate prediction capability of nuclear design parameters for such gap configuration in ITER, gap streaming experiments[1] were carried out at the Fusion Neutronics Source[2] (FNS) facility in Japan Atomic Energy Research Institute (JAERI), as a part of an R&D task of shielding neutronics experiment (T-218) under the Engineering Design Activities (EDA) of ITER.

Experimental details are described in a separate paper[1], and this paper deals with analytical parts of the experiments to validate the prediction capability.

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II. Brief Description of the Experiments

The experiments simulated a gap between two neighboring shielding blanket modules of ITER as shown in **Fig. 1**. In the experimental assembly, a gap (22 mm x 500 mm) was made up to the 300 mm depth of a bulk iron. The gap was followed by a cavity region (140 mm x 500 mm x 100 mm) that corresponded to the open space near the connection legs. The bulk iron layer of 100 mm in thickness attached behind the cavity corresponded to the back plate.

The experiments were separated into two parts, experiment-1 and experiment-2. The experiment-1 aimed at investigating validity of design calculations for estimation of helium production rates at the connection legs. The top and the bottom side of the cavity in the experimental assembly corresponded

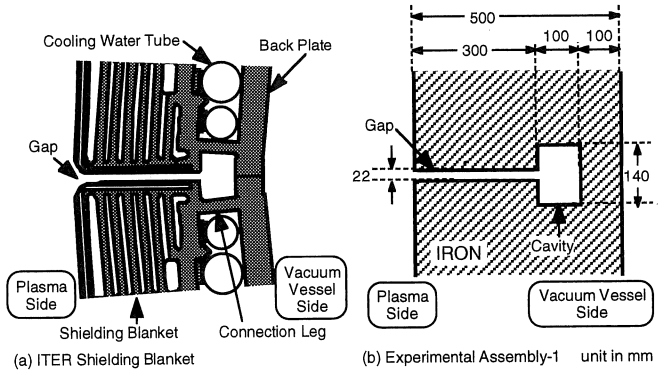

Fig. 1 Section view of the ITER shield blanket modules and the experimental assembly-1.

to the connection legs. Various nuclear responses were measured mainly inside the gap and the cavity.

On the other hand, the experiment-2 aimed at validating design calculations for estimation of various nuclear responses on toroidal field coils (TFCs) located behind the vacuum vessel. A bulk iron block of 300 mm in thickness that simulated the vacuum vessel of ITER was added to the experimental assembly-1. The rear surface of the assembly, the total thickness of which was 800 mm, was the position where TFCs were assumed to be located, and various nuclear responses were measured there.

For both the experiment-1 and -2, two positions of the point D-T neutron source were adopted: the first position was on the gap center line (direct gap configuration) and the second was shifted upper by 200 mm relative to the gap (offset gap configuration) as shown in **Fig. 2**. Additional measurements were also performed with filling up the gap and/or cavity with iron blocks.

Before the main experiments, an experiment was also performed to characterize precisely source neutron fluxes that entered into the gap streaming assembly without setting the gap streaming assembly. This was needed because neutrons scattered by a rotating target assembly and room walls as well as those directly coming from the target could be sources which influence on measured results.

III. Analysis

1. Code and Data

The continuous energy Monte Carlo transport calculation code MCNP-4A[(3)] was used for all the analyses because it could treat precisely the 3-dimensional geometries of the gap streaming assemblies, and was identified as one of the standard nuclear design codes for ITER.

Two transport cross section libraries for MCNP were used: FENDL/MC-1.0[(4)] and FSXLIB-JFF[(5)] derived from the Fusion Evaluated Nuclear Data Library (FENDL/E-1.0, abbreviated as FENDL-1)[(6)] and Japanese Evaluated Nuclear Data Library (JENDL Fusion File, abbreviated as JENDL-FF)[(7)], respectively. The FENDL-1 library has been assigned as the standard cross section library for ITER/EDA. For the photon transport and dosimetry cross section libraries, the MCPLIB[(3)] library and a library derived from JENDL Dosimetry File[(8)], respectively, were used.

2. Modeling of D-T Neutron Source and Surrounding Environment

A D-T neutron source driven by a deuteron-beam accelerator is roughly characterized as an isotropic mono-energy 14-MeV neutron source. The real D-T neutron source is, strictly speaking, characterized by followings, (i) neutron energy and intensity depend on the emission angle of the neutron with respect to the deuteron beam direction, and (ii) primary D-T neutrons are scattered by structural materials of the target. Therefore, for the first stage of the analysis, the D-T neutron source was simulated with a precise model of the D-T reaction kinematics and the target structure to provide an adequate source term for successive streaming calculations.

Figure 3 shows calculated angular distributions of source neutrons and mean neutron peak energy. When the target structure is omitted, the angular distribution is given by a smooth line which is slightly enhanced to the forward angle. In the distribution with modeling the target assembly, a large dip is clearly seen around 90 degree where about 30 % of source neutrons are scattered away by the target assembly. This indicates necessity of the detailed treatment of the source neutron condition because the gap openings see neutrons emitted toward ~ 80 degree where the scattering loss of neutrons is significant.

Next, the experimental room walls and additional objects inside the room such as the accelerator components and other experimental setups were considered because neutrons were scattered by these objects and impinged into the experimental assembly. A rough sketch of the calculation model is illustrated in **Fig. 4**. The model, however, involved some ambiguities in a chemical composition of concrete, especially a number of hydrogen atoms included in the concrete, and modeling of the additional objects. Hence, the calculation model was adjusted by changing two parameters, i.e., thickness of the room walls and the hydrogen content in the concrete, so as to reproduce adequately the results of the source characterization experiment.

3. Analysis of the Gap Streaming Experiment

The gap streaming assembly was modeled precisely with

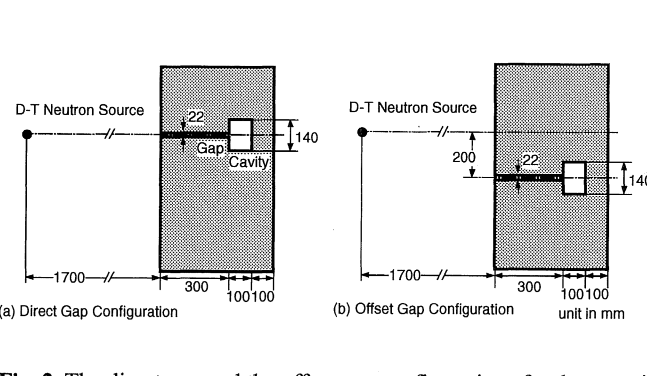

Fig. 2 The direct gap and the offset gap configurations for the experiment-1.

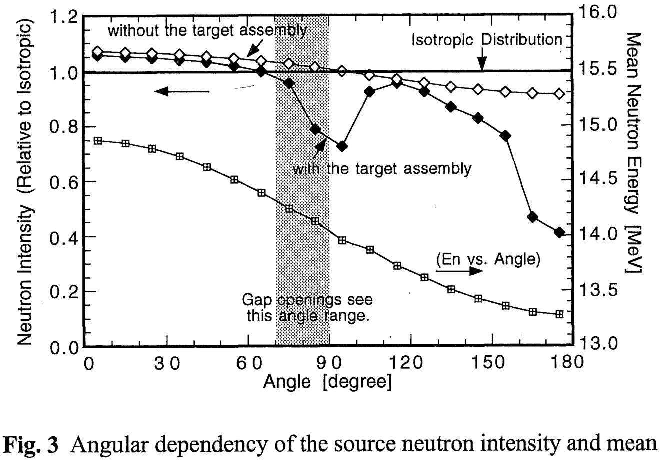

Fig. 3 Angular dependency of the source neutron intensity and mean peak energy.

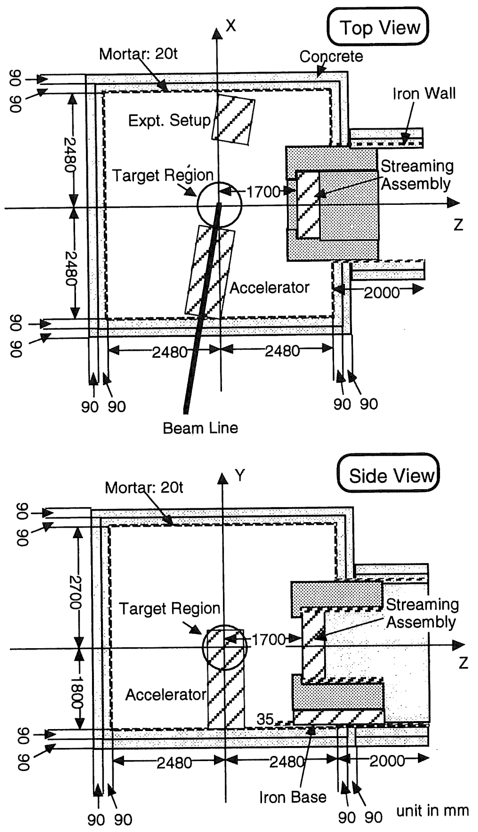

Fig. 4 Outline of the whole calculation model including room walls, experimental setups and the streaming assembly-1.

the neutron target assembly, the experimental room, etc. as shown in Fig. 4. In the calculation, cell detectors were distributed in the assembly at all positions where experimental data were obtained.

The source biasing method and the particle splitting and Russian roulette method with cell importance parameters were used as variance reduction techniques. Source neutrons were produced with a high probability for a direction toward the gap with adjusting appropriately particle weights. The cell importance parameters in the gap streaming assembly were increased by a factor of 2 for every 100 mm thicknesses. The cell importance parameters were adequate for low energy neutrons and gamma-rays while not for high energy neutrons. To solve the problem, cell importance parameters were changed as they increased by a factor of 3 for every 100 mm thicknesses, and all the calculations were repeated only for high energy neutrons with a cut-off energy at 0.3 MeV.

For the MCNP calculations, three engineering work stations (two HP9000/735 and one HP9000 C160) and a 256 parallel computers "Paragon" at Naka Research Establishment of JAERI were used. Usually, 32 nodes (processor elements) of Paragon were used for one MCNP calculation, and four MCNP calculations with 128 nodes were executed simultaneously. The Paragon computer with 32 nodes was ~ 6 times as fast as the work stations due to the parallel processing.

Finally, answers for all the quantities corresponding to the experiments were obtained with appropriate statistical errors.

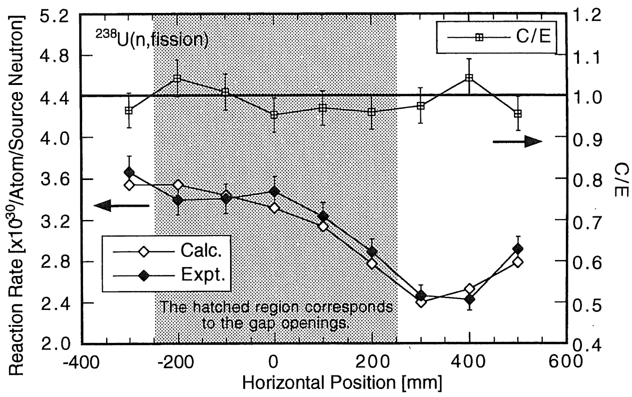

Fig. 5 Horizontal distribution of the ^{238}U(n,fission) rate and C/E ratios along the horizontal line where the open mouth of the direct gap is to be located.

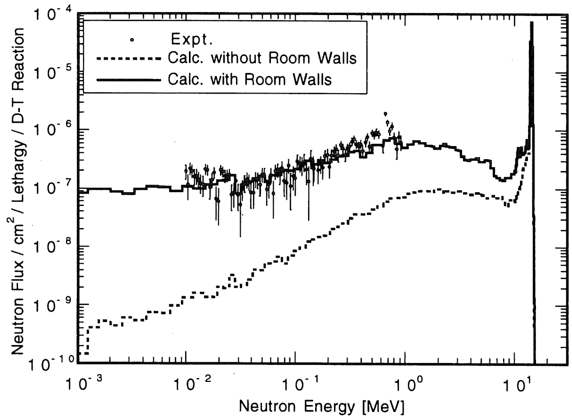

Fig. 6 Neutron flux spectra at the entrance position of the direct gap measured, and calculated with and without modeling the room walls, etc.

IV. Results and Discussion

1. Results for the Source Characterization Experiment

Measured and calculated ^{238}U(n,fission) rates are shown in **Fig. 5** with ratios of calculated to experimental values (C/E) along a horizontal line where the opening of the direct gap is located. The calculation reproduces adequately the dip of fast neutron fluxes, most parts of which are 14-MeV neutrons actually, at around 300 mm made by the target assembly.

Figure 6 shows a neutron flux spectrum in the energy range from 0.01 to 1 MeV measured at the position that corresponds to the center of the open mouth of the direct gap. The spectrum is compared with calculated spectra with and without modeling the room walls, etc. It is clearly indicated that neutron flux in the energy range is increased significantly by room-scattered neutrons. The calculated spectrum with considering the room walls agrees very well with the experimental data.

When all the results for the source characterization experiment are considered, it can be stated that the present calculation model is valid for calculating high energy source neutrons entering into the gap streaming assembly with uncertainty of ± 10 %, and for low energy neutrons and gamma-rays within ± 20 %.

2. Results for the Experiment-1

(1) C/E Value

Figure 7 shows C/E values with the FENDL-1 calculation for the $^{93}Nb(n,2n)^{92m}Nb$ reaction rate that represents 14-MeV neutron flux. The calculated results agree very well with the experimental data at all the detector positions: most of C/E values range from 0.8 to 1.2. This good agreement is a general trend for all the threshold reaction rates.

As for measured quantities which are sensitive to low energy neutrons and gamma-rays, agreements between the experiment and the calculation are slightly worse than those for the threshold reaction rates. However, their C/E values are in a range from 0.7 to 1.3. Note that results by JENDL-FF are almost equivalent to those by FENDL-1 for all the measured quantities.

(2) Relaxation Factor for the Connection Legs

One of the key shielding parameters of ITER is the helium production rate at the connection legs of blanket modules to the back plate from a point of view of rewelding.[9] As shown in Fig. 1, the connection legs are located at the shaded positions from direct exposure of 14-MeV neutrons coming through the gap. Here, we define the relaxation factor (RF) as a ratio of a nuclear response at the connection leg to that at the gap center. The helium production in the connection legs is reduced by RF by moving them from the gap center to the shaded position. In the present experimental configuration, RF corresponds to a ratio of a nuclear response at the top or bottom of the cavity to the cavity center.

Figure 8 compares RF obtained by the experiment and the calculation with FENDL-1. It is obvious that the calculation predict adequately all RF although the relaxation effect is considerable for threshold reactions. The good prediction of RF assures that design calculations for estimation of helium production rates at the connection legs with the code and data used are valid.

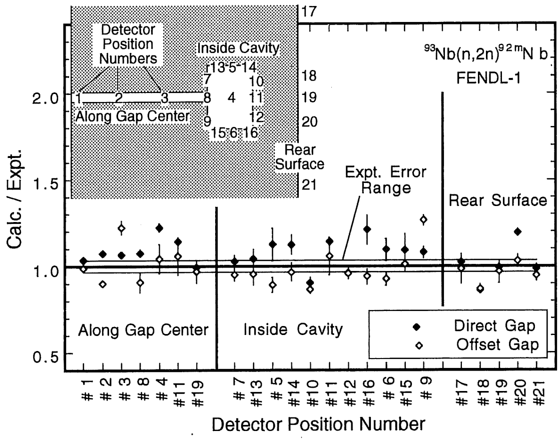

Fig. 7 C/E values for the $^{93}Nb(n,2n)^{92m}Nb$ reaction rates for the direct and offset configurations for the FENDL-1 calculation.

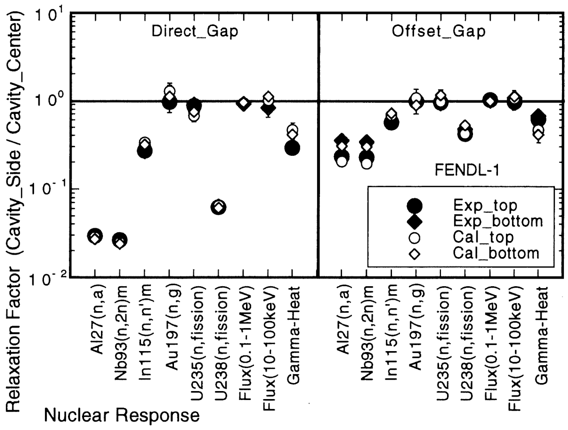

Fig. 8 Relaxation factors of various nuclear responses for the connection legs obtained by the experiment and the calculation with FENDL-1.

3. Results for the Experiment-2

(1) C/E Value

Figure 9 shows C/E values for the fission rate of ^{238}U and ^{235}U, which are sensitive to fast and slow neutrons, respectively, on the rear surfaces of the direct gap, offset gap and bulk assemblies. Some C/E values deviate significantly from 1.0 as found in Fig. 9 (b) and (e). The reason for those deviated C/E values is poor statistical accuracy in the Monte Carlo calculations because those deviated C/E values always associate with large statistical errors which are indicated in vertical bars in Fig. 9. Except for such particular cases, agreements of the calculations with the experimental data are generally good although the iron assembly is very thick as 800 mm and involves complicated geometries of the gap and cavity. When the statistical errors are considered, all the C/E values for both reactions and both cross section libraries range from 0.7 to 1.3. The good agreements are the general trend for other nuclear responses, such as neutron fluxes, activation foil reaction rates and gamma-ray heating rates.

(2) Peaking Factor

The gap and cavity make peaks in neutron flux distributions behind the iron assembly of 800 mm in total thickness where TFCs are assumed to be located. **Figure 10** shows peaking factors for integral neutron flux above 10 MeV at two cases; (a) only the cavity exists and (b) both the gap and cavity exist. According to the experiment, the largest peaking factor due to the cavity is 18 while that due to both the gap and cavity is 40. The peaking factors by the calculation with JENDL-FF are larger than those by the experiment: 22 and 60, respectively.

The overestimation of the peaking factors can be attributed to nuclear data. When deep penetration of a 14-MeV neutron flux through a bulk iron shield is calculated with JENDL-FF and also with FENDL-1, the 14-MeV neutron flux by the calculation attenuates faster than the experimental flux.[10] The underestimation of 14-MeV neutron flux for the bulk assembly is more remarkable than that for the assembly with the gap and cavity. Therefore, the peaking factors are calculated larger by the calculations. This problem can be solved by modifying

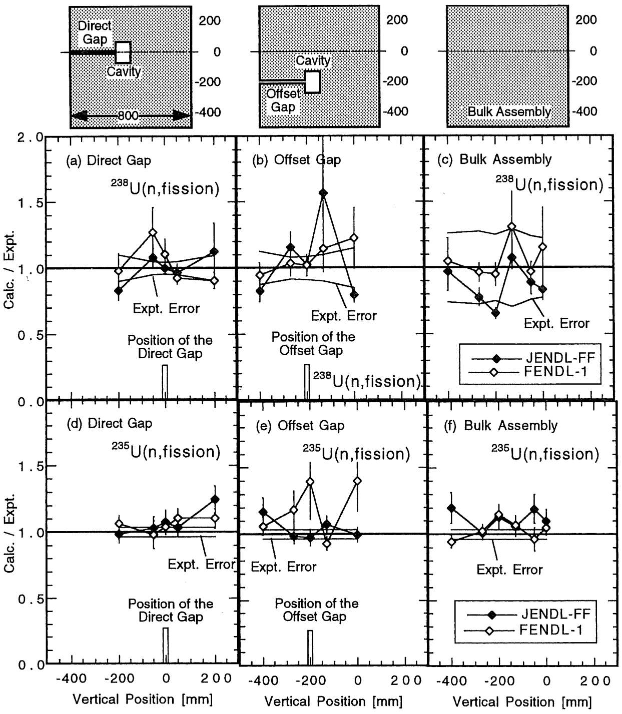

Fig. 9 C/E values for the fission rate of (a)~(c) ^{238}U and (d)~(f) ^{235}U on the rear surfaces of the direct gap, offset gap and bulk assemblies.

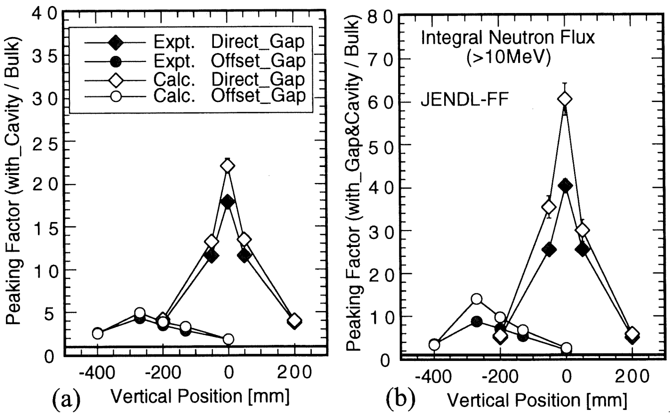

Fig. 10 Peaking factors for integral neutron flux above 10 MeV when (a) only the cavity exists and (b) both the gap and cavity exist.

the iron cross section in both JENDL-FF and FENDL-1 as suggested by Konno, et al.[11]

V. Concluding Remarks

From the comparisons of the calculated results with the experimental data, all the nuclear responses for all the gap configurations are predicted within ± 30 % by the MCNP code with FENDL-1 and JENDL-FF. Therefore, it is concluded that these calculation tools are capable of predicting nuclear design parameters, such as the helium production rate at the connection legs and nuclear responses in TFC, with uncertainty of ± 30 % for the gap geometry where gap streaming effect is significant.

ACKNOWLEDGMENT

This paper is an account of work undertaken within the framework of the ITER EDA Agreement. The views and opinions expressed herein do not necessarily reflect those of the Parties to the ITER Agreement, the IAEA or any agency thereof. Dissemination of the information included in this paper is governed by the applicable terms of the ITER EDA Agreement.

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