ELSEVIER

Fusion Engineering and Design 42 (1998) 235–245

Fusion Engineering and Design

Verification of ITER shielding capability and FENDL data benchmarking through analysis of bulk shielding experiment on large SS316/water assembly bombarded with 14 MeV neutrons

Mahmoud Z. Youssef [a,*], Anil Kumar [a], Mohamed A. Abdou [a], Chikara Konno [b], Fujio Maekawa [b], Masayuki Wada [b], Yukio Oyama [b], Hiroshi Maekawa [b], Yujiro Ikeda [b]

[a] *Mechanical and Aerospace Engineering Department, University of California, Los Angeles, CA 90095, USA*

[b] *Department of Reactor Engineering, Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken319-11, Japan*

Abstract

The recently developed FENDL-1 database, both in multigroup form (FENDL/MG-1.0) and continuous energy form (FENDL/MC-1.0) has been tested through analyzing a fusion integral experiment performed at the FNS facility, Japan, on a large bulk shielding assembly made of multilayers of SS316 and water. The assembly is a replica that simulates ITER shielding blanket and is bombarded by a 14 MeV source placed at 30 cm from the cylindrical assembly and housed inside a SS316 cylindrical can. This activity is undertaken as part of co-operation with JAERI on executing the required neutronics R&D tasks for ITER shield design. The objectives are (a) benchmarking FENDL-1 data and identifying any flaws that may exist in this newly developed database, and (b) examining the range of discrepancy between the calculated nuclear parameters inside the assembly and the measured ones in terms of the ratio of the calculated-to-experimental (C/E) data. Both differential and integral experimental data were analyzed along the central axis of the ~ 120 cm $D \times 140$ cm L assembly. The analyses with the multigroup data, MG also included library derived from ENDF/B-VI data base for comparison purposes. The MCNP Monte Carlo (MC) code was used with the FENDL/MC-1 data. The largest range of discrepancy between calculated and measured responses (reaction rates, neutron spectra, gamma ray heating, etc.) was found to be ~ 20–30% even though in most cases this discrepancy falls within the experimental errors.

1. Introduction

The recently developed FENDL-1 [1,2] database, both in multigroup form (FENDL/MG-1.0) and continuous energy form (FENDL/MC-1.0) has been tested through analyzing a fusion integral experiment performed at the Fusion Neutron Source (FNS) facility, Japan, on a large bulk shielding assembly made of multilayers of SS316 and water. The assembly is replica that simulates ITER shielding blanket and is bombarded by a 14 MeV neutron source. This activity is undertaken as part of co-operation with JAERI on executing the required neutronics R&D tasks for ITER shield design. The objectives are: (a) benchmarking FENDL-1 data and identifying any flaws that

* Corresponding author. Tel.: + 1 310 8252879.

0920-3796/98/$19.00
PII S0920-3796(98)00136-7

may exist in this newly developed database; and (b) examining the range of discrepancy between the calculated nuclear parameters inside the assembly and the measured ones in terms of the ratio of the calculated-to-experimental (C/E) data. These two objectives will guide designers with regard to the attenuation characteristics of ITER shield blanket and the involved uncertainties between measured and calculated data that should be implemented in the design process. Both differential and integral experimental data were analyzed along the central axis of the 1.2 m $D \times 1.4$ m L assembly. The analyses with the multigroup data, MG, (performed with 80n-24g, S8, P5, DORT [3] calculations with shielded and unshielded data) also included library derived from ENDF/B-VI data base [4] for comparison purposes. The MCNP (Los Alamos [5]) Monte Carlo (MC) code was used with the FENDL/MC-1 data (and JENDL-3.1 and 3.2 [6]). The present work is a continuation of previous analysis [7] performed on similar assemblies made solely of SS316.

In Section 2, description of the experimental set-up is given along with the measured items for which the analytical results were compared. The calculation procedures followed in the present work is described in Section 3. The results for analysis and the C/E values based on the MG and MC FENDL data bases are given in Section 4. Section 5 gives the main concluding remarks from the observed discrepancies between measurements and calculations.

2. Experimental set-up and measured items

The bulk shielding block is made of SS316 with seven layers of water (2.68 cm-thick) alternating with SS316 layers. The first water layer is at 1.2 cm from the front surface of the block. The SS316 layers that follow have the thicknesses of 2.4, 7.48, 7.48, 7.48, 12.56, 12.56 and 67.24 cm, in that order. The assembly has a source reflector can (20 cm-thick) to lessen room return effect and simulate low-energy reflected source neutron component. The cylindrical assembly is 120 cm in diameter and 137.16 cm in thickness and is slightly thicker than the thickness of the I/B blanket/shield and the vacuum vessel of ITER at the mid-plane. The volume ratio of SS316:water is $\sim 79.5{:}20.5$. Fig. 1 shows the dimensions of the assembly. The atomic density of the SS316 of the reflector and the SS316 of the assembly (can be found in [7]) is slightly different due to different manufacturing processes.

Measured parameters, covering the energy range from 14 MeV down to thermal energy, were taken inside the SS316 layers at locations as deep as 91.4 cm. Contribution from room return effect at this deepest location is $\sim 10\%$ [8]. Reduction of this effect could be achieved (1:10) with ~ 10 cm-thick polyethylene layer surrounding the back end of the assembly (not considered in the experiment). Calculated Parameters were compared to the following measured items: (1) neutron spectrum (measured by various detectors to cover wider energy range): 2 MeV $<$ En by measured by 14ϕ NE213 detectors, 3 keV $<$ En $<$ 1 MeV measured by proton recoil counter (PRC), and En $<$ 10 keV measured by BF3 counters, (2) foil activation rate: ^{93}Nb(n,2n)^{92m}Nb, ^{27}Al(n,α)^{24}Na, ^{115}In(n,n$'$)^{115}In, ^{197}Au(n,γ)^{198}Au, (3) fission rate: ^{235}U(n,f), ^{238}U(n,f), and (4) γ-ray heating rate measured by TLD. Measurements were taken at locations 0.0, 12.7, 22.86, 33.02, 45.72, 60.96, 71.12 and 91.44 cm. Additional location ($z = -1$ cm) is reserved for neutron spectrum measurements.

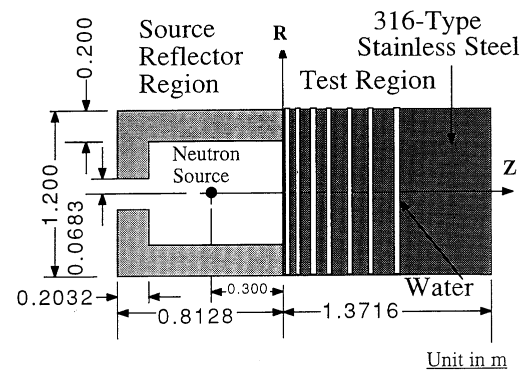

Fig. 1. The geometrical (R–Z) model of the SS316/water assembly.

3. Calculation procedures

The calculational tools used in the present work is the same described previously [7]. The 175n-42g FENDL/MG-1.0 in MATXS format (MacFarlane [9]) is the reference library used to generate a shielded and unshielded 80n-24g multigroup libraries (denoted here MATXS15). Likewise, the ENDF/B-VI (175n-42g) MATXS library is used to generate the counterpart 80n-24g libraries (denoted here MATXS 14). The dosimetry reactions in these libraries are based on ENDF/B-VI [4], however, for reactions that are not available in this library, the dosimetry file of JENDL-3.1 (J3DF) [10] of the 125n multigroup form was used instead in MATXS15 [e.g. ^{235}U(n,f), ^{238}U(n,f), ^{115}In(n,n′)^{115}In] or in MATXS14 [e.g. previous reactions plus ^{93}Nb(n,2n)^{92m}Nb]. These multigroup libraries were used in the 2-D R–Z discrete ordinates calculations (with P5S8 approximation) performed with DORT transport code [3] after generating the first collision source with the RUFF code [11] which was used as the external source to DORT runs to eliminate ray effect.

As in previous analysis [7], the MORSE-DD [12] code was used by JAERI to generate the angular/energy distribution of the emitted neutrons from the tritiated-titanium target in 125-n group structure and 37 angles spanning (in 5° intervals) the directions from $\mu = -1$ (180°) to $\mu = +1$ (0°) along the z-axis. This calculated neutron source was used as the incident spectrum on the assembly in both the MG and MC calculations. Factors such as the slowing down of deuteron ions in the TiT target, the shape of the deuteron beam, and the kinematics of the D–T reactions, were taken into consideration. The calculated incident source has a peak energy at 14.8 MeV in forward direction ($\mu = +1$, 0°) and a peak at 13.3 MeV in the backward direction ($\mu = -1$, 180°) with a non-negligible low-energy component in the source spectrum due to neutrons reflected by the source can. Because of multiplication in the target structure, the number of neutrons incident on the assembly is ~ 1.0295 per D–T reaction. In the MC calculations no self-shielding correction was needed since the FENDL/MC-1.0 data base is continuos in energy. The energy bins of the tallies used corresponds to the 125n-40g group structure of the Japanese library FUSION-J3 [13]. In treating the external neutrons by sampling from a source subroutine, the neutrons were considered to be emitted towards the whole solid angle. A typical detector size of the standard surface flux estimator is ~ 40 mm. The number of histories varied from 1–4 millions, depending on the type of response under consideration.

4. Results and discussion

In comparison to the previous large SS316 bulk shield experiments [7,13], attenuation power of neutron and gamma fluxes is much larger in the SS316/water assembly at the deepest location. Figs. 2 and 3 show the total neutron flux along the central axis of these assemblies calculated with the MG libraries for the shielded (SS) and unshielded data (No SS). At 90 cm depth, the flux in the SS316 assembly is ~ 15 times the corresponding flux in the SS316/water assembly with the shielded FENDL data. The shielded data at this depth give larger flux by a factor of 2 in the former assembly and by only ~ 1.08 in the latter, i.e. the impact of shielding the data is less pronounced in the SS316/water assembly. Similar features are observed with the ENDF/B-VI data, particularly in the former assembly. Larger fluxes are obtained with the shielded data due to the smaller total macroscopic cross-section of SS316. This cross-section has many resonances in the energy range keV to few MeV. Neutrons lose energies through either elastic (many collisions) or inelastic collisions and ignoring the presence of these resonances will give an inaccurate flux estimates in SS316, particularly at deep locations and for low-energy neutrons. The unshielded SS316 total macroscopic cross-section (infinite dilution) is a factor of 1.2–2 higher than the shielded one at several resonances leading to lower neutron flux at deep locations.

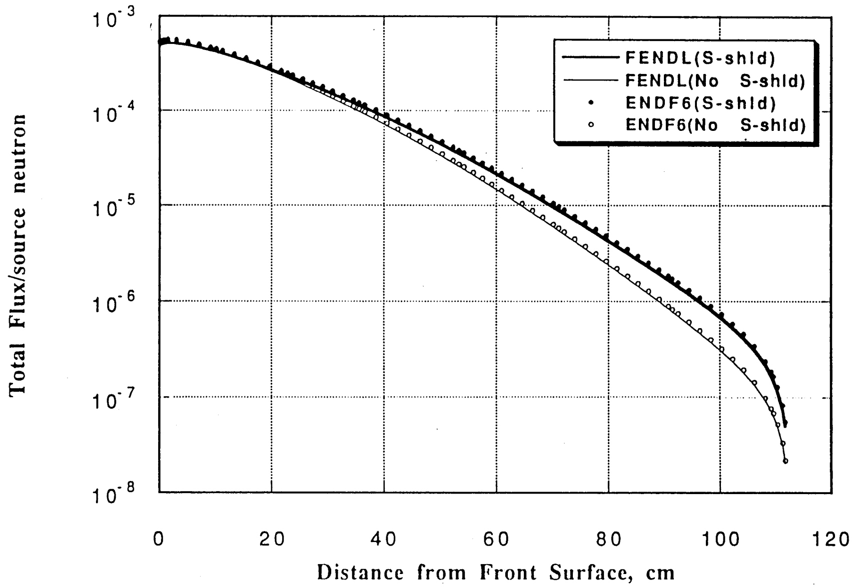

Fig. 2. Total neutron flux along the central axis of the SS316 assembly.

4.1. Integrated neutron spectrum and reaction rates

4.1.1. Energy rang En > 10 MeV and 1–10 MeV

The integrated spectrum >10 MeV is in a good agreement with the experiment within 5–10% at all locations with both the MG and MC data (within 5% with FENDL/MG, $\sim 10\%$ with ENDF6/MG, and $\sim 10\%$ with FENDL/MC). This can be seen from Figs. 4 and 5 where the calculated values are within the experimental error of 10%. (Note that the statistical errors of the MC calculations and their sizes are depicted in the corresponding figures). The under estimation of this component of 25–35% observed previously at deep locations with the MG data in a pure SS316 assembly do not exist. Reactions that are sensitive to this component such as $^{93}Nb(n,2n)^{92m}Nb$, $^{27}Al(n,\alpha)^{24}Na$, and $^{238}U(n,f)$ have also good prediction accuracy. Figs. 6 and 7 show the C/E values for the $^{93}Nb(n,2n)^{93m}Nb$ reaction where the prediction accuracy is ~ 2–10% with both the deterministic and the MC methods. It should be noted that about 97% of this reaction is attributed to neutrons above 10 MeV at practically all locations. About 90% of the $^{27}Al(n,\alpha)^{24}Na$ reaction is attributed to this component and the prediction accuracy is not as good (2–18% with FENDL/MG, 4–28% with ENDF6/MG, and 2–15% with FENDL/MC), particularly at location 91.4 cm. As for the $^{238}U(n,f)$ reaction, $\sim 50\%$ of it is due to neutron above 10 MeV with large contribution coming from neutrons in the energy range 1–10 MeV. This reaction has an accuracy of 2–15% with both MG and MC library. From Figs. 4–7 one can observe that self shielding correction has practically no impact on high-threshold reactions or the high-energy neutron spectrum. Also, as pointed out in Youssef et al. [7], the calculated integral spectrum and the reactions mentioned above are larger by ENDF6/MG than the ones obtained by FENDL/MG by ~ 5–7%, particularly at front locations.

The $^{115}In(n,n')^{115}In$ reaction is sensitive to neutrons in the energy range 1–10 MeV. The contribution from the energy range 1–5 MeV is large ($\sim 75\%$) whereas the contribution from neutrons above 10 MeV is small ($\sim 10\%$). The accuracy of the integrated spectrum in the energy range 1–10 MeV can be inferred from the C/E curves of this reaction shown in Figs. 8 and 9 where C/E values are within 2–15% (FENDL/MG and MC) and

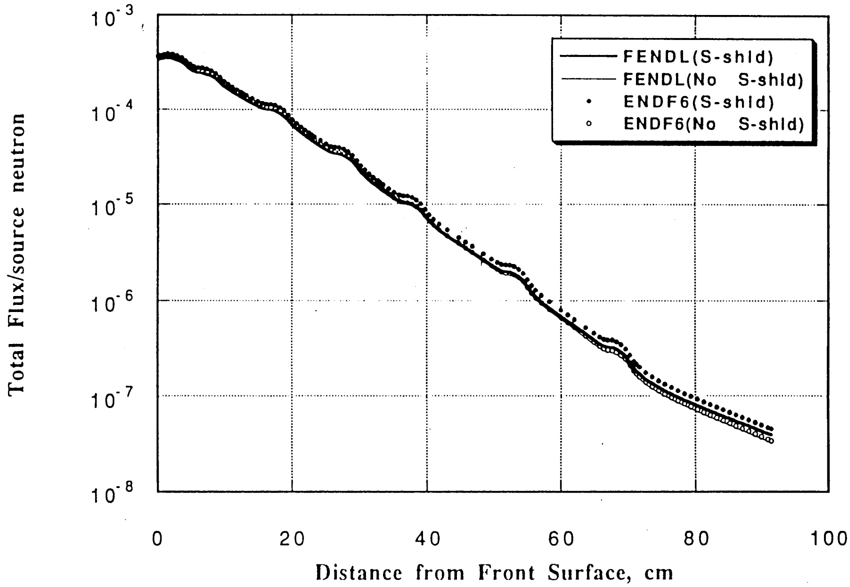

Fig. 3. Total neutron flux along the central axis of the SS3 16/water assembly.

2–25% (ENDF6/MG). The largest discrepancy in this reaction occurs at 76.2 cm depth.0

4.1.2. Energy range 0.1–1 MeV and 10–100 keV

In the SS316 assemblies, the large under estimation of ~60% and ~40% in the integrated spectrum in the energy range 0.1–1 MeV and 10–100 keV, respectively, obtained by the FENDL/MG shielded data at deep locations ($z = 91.4$ cm, [7]) are lessened to ~25% (see Figs. 10 and 11) and 10–15%, respectively, in the present SS316/water assembly. Note that the largest discrepancy occurs at the deepest location, particularly in the energy range 0.1–1 MeV and, on the average, the under estimation is observed at all locations in the energy range 10–100 keV (not shown). The agreement with the experiment is better at shallow locations (within 2–5% and 2–10% in these two energy ranges). The shielded MG data give better

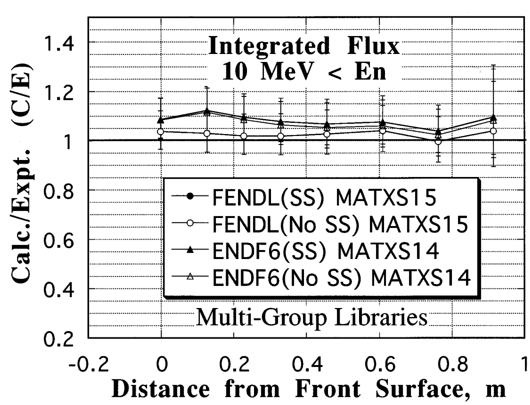

Fig. 4. The C/E values of the integrated neutron spectrum above 10 MeV—FENDL-MG.

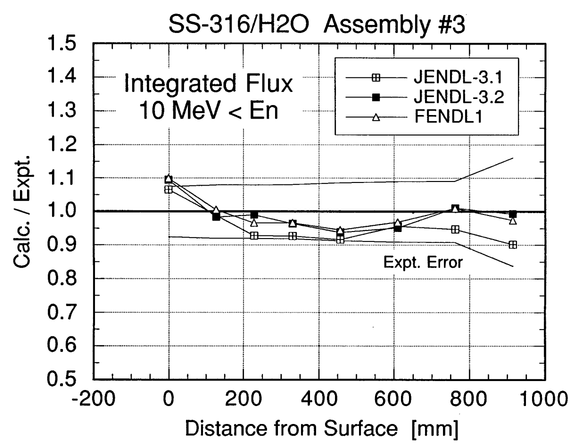

Fig. 5. The C/E values of the integrated neutron spectrum above 10 MeV—FENDL-MC.

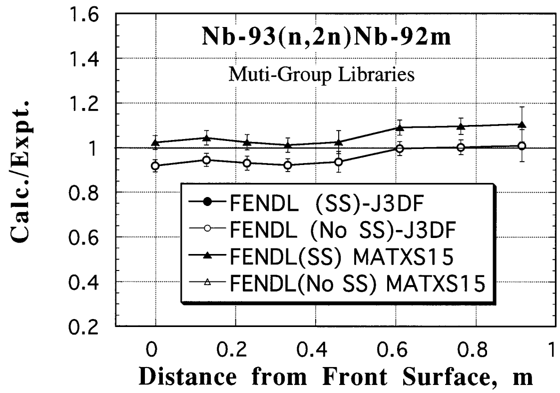

Fig. 6. The C/E values of the ^{93}Nb(n,2n)^{92m}Nb reaction—FENDL-MG.

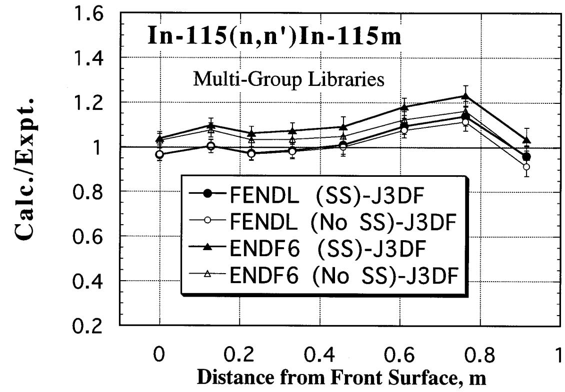

Fig. 8. The C/E values of the ^{115}In(n,n′)^{115}In reaction—FENDL-MG.

agreement with the experiment than the unshielded one, particularly at deep locations. This effect is less pronounced in the SS316/water assembly compared to the pure SS316 assembly since water tends to moderate neutrons and hence the spikes and valleys in the Fe shielded cross-sections are smoothed. The influence of the self-shielding correction is noticeable and more manifested at deep locations, particularly in the energy range 10–100 keV. The results based on ENDF6/MG are larger than that based on FENDL/MG by $\simeq 5–15\%$ $(0.1 < En < 1$ MeV) and by 5–20% $(10 < En < 100$ keV). This can also be seen from Fig. 12 which depicts the spectrum comparison with the experimental results at depth 91.4 cm. The results based on FENDL/MC have similar features (Fig. 11). The experimental error is $\cong \pm 5\%$. While the integrated spectrum in the energy range 0.1–1 MeV is within this error up to ~ 60 cm depth, the under estimation (by $\sim 25\%$) is still apparent at deeper locations. The integrated spectrum is also under estimated by $\sim 10–15\%$ with FENDL/MC at all locations in the energy range 10–100 keV.

4.1.3. Energy range 10–100 eV and 1–10 eV

In these energy ranges, the integrated spectrum agrees with the experimental data within the ex-

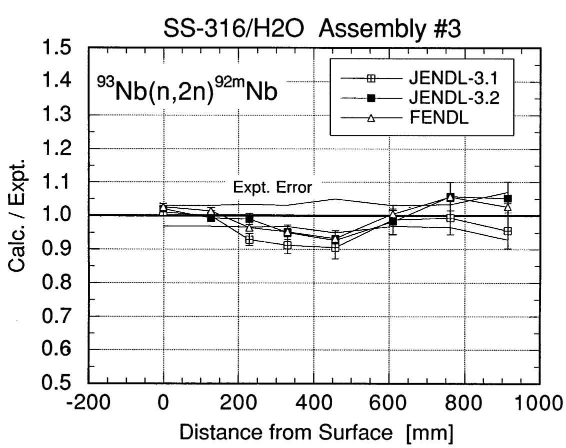

Fig. 7. The C/E values of the ^{93}Nb(n,2n)^{92m}Nb reaction—FENDL-MC.

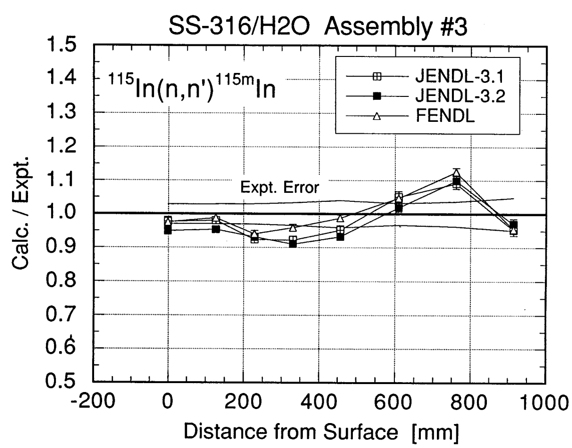

Fig. 9. The C/E values of the ^{115}In(n,n′)^{115}In reaction—FENDL-MC.

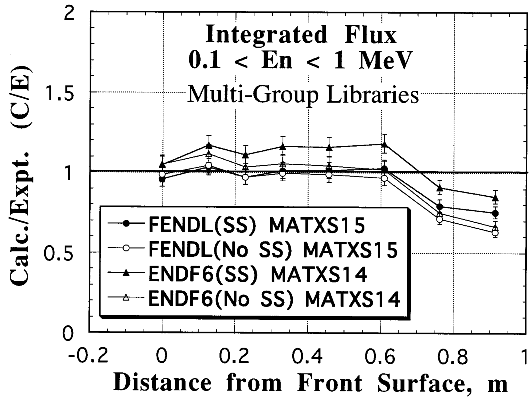

Fig. 10. The C/E values of the integrated neutron spectrum in the energy range 0.1–1 MeV (FENDL-MG).

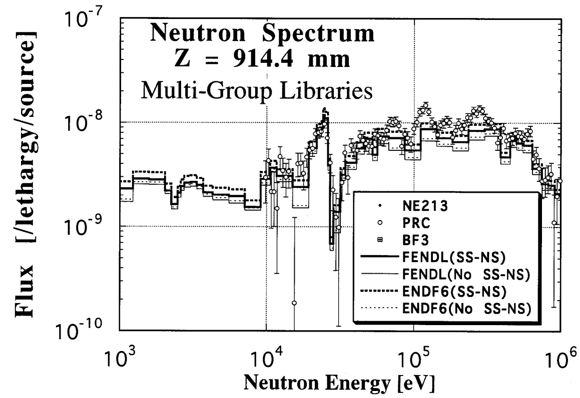

Fig. 12. Neutron spectrum comparison at 914.4 mm from the front surface.

perimental error. In the energy range 10–100 eV, the C/E values are lower than unity by 2–20% (FENDL/MG and FENDL/MC) but the experimental error is $\pm 20\%$. In the energy range 1–10 eV, the C/E values are lower than unity by ~ 2–10% with MG and MC FENDL libraries, and again, the prediction is within the experimental error of $\pm 10\%$. We recall that in pure SS316 assembly and in the energy range 1–100 eV, the integrated spectrum was found to be larger than unity by $\sim 30\%$ (FENDL/MG) up to a depth of 30 cm and lower than unity by ~ 35–40% (FENDL/MG) at depth $z = 91.4$ cm.

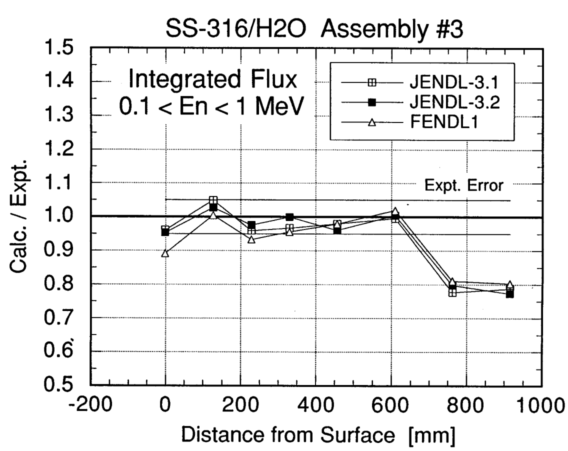

Fig. 11. The C/E values of the integrated neutron spectrum in the energy range 0.1–1 MeV (FENDL-MC).

4.1.4. Energy range below 1 eV

In this low energy range, the features of the C/E curves based on the multigroup and the MC continuous data are different. The C/E values are not within the experimental error of 10% as can be seen from Figs. 13 and 14. With he FENDL/MG library, the C/E values are lower than unity by ~ 10–30% whereas they are larger than unity by 2–15% with the FENDL/MC library, i.e. the results based on the MG data are smaller than those based on the MC data by ~ 12–45%. This could be attributed to the treatment of the thermal group in the multigroup libraries, as will be explained latter. To be also noted is the difference between results based on the shielded data of

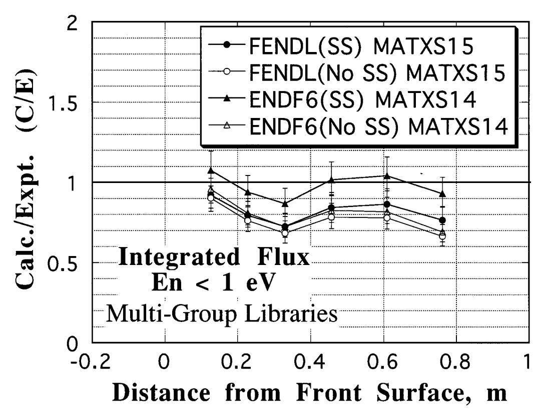

Fig. 13. The C/E values of the integrated neutron spectrum below 1 eV—FENDL-MG.

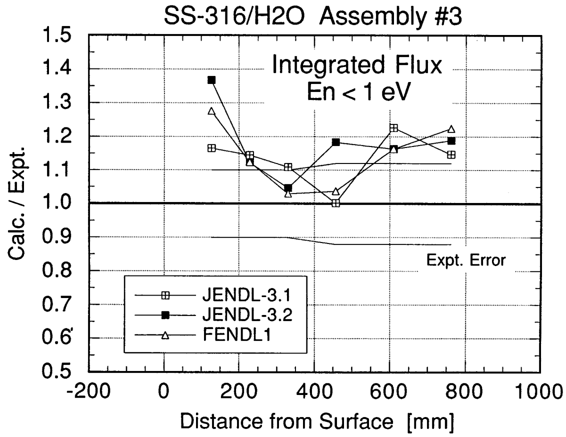

Fig. 14. The C/E values of the integrated neutron spectrum below 1 eV—FENDL-MC.

FENDL/MG and ENDF6/MG where the latter library gives values that are 20–25% larger than the former one at this low-energy range. Additionally, shielding the data in ENDF6/MG gives improvement by $\sim$15–30% in the integrated spectrum as compared to 2–10% improvement with the shielded FENDL/MG data. This is also apparent from the spectrum comparison shown in Fig. 15 where measurements are taken with the BF3 counters. The observed larger values obtained with the ENDF6/MG compared to FENDL/MG library [although the cross-sections of the main constituents of SS316 (FE, Cr, and Ni) are derived from the same pointwise data] has been discussed previously [7].

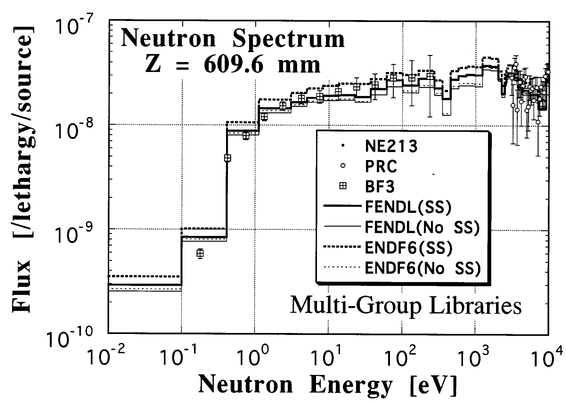

Fig. 15. Neutron spectrum comparison at 609.6 mm from the front surface.

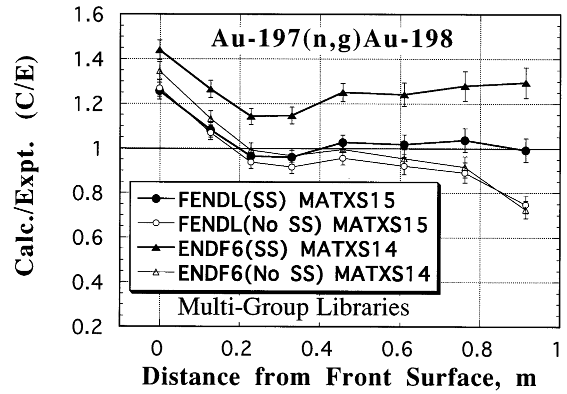

Fig. 16. The C/E values of the $^{197}Au(n,\gamma)^{198}Au$ reaction—FENDL-MG.

4.1.5. Non-threshold reactions

The features of the C/E curves for the integrated spectrum below 1 eV are to some extent reflected on the C/E curves for non-threshold reactions such as $^{235}U(n,f)$ and $^{197}Au(n,\gamma)^{198}Au$. Except at the front locations, the C/E values for the $^{235}U(n,f)$ are not within the experimental error of $\sim$5%, and based on the shielded FENDL/MG data, they are below unity by $\sim$10–20% whereas the under estimation is lessened (by $\sim$10%) with the FENDL/MC data. However, at $z = 0$ cm, the C/E values are $\sim$1.55 and 1.3 with the MG and MC data, respectively. The corresponding values for the $^{197}Au(n,\gamma)^{198}Au$ reaction at $z = 0$ cm are 1.25 and 1.15 (see Figs. 16 and 17), i.e. the MG shielded data gives larger calculated values than those obtained with the MC data by $\sim$25% and $\sim$10% for these two reactions, respectively. This could be caused by the rather larger value of the effective fission and absorption cross-section of thermal neutrons used in the MG calculation. These cross-sections are weighted with a maxwalian distribution for thermal neutrons rather than using the actual harder spectrum (as in pure SS316 media) as the weighting function. This leads to the over estimation of the $^{197}Au(n,\gamma)^{198}Au$ and $^{235}U(n,f)$ at the front surface. Larger absorption (and fission) rates at front locations leads to lower integrated spectrum for low-energy neutrons, as can be seen from Fig. 13. This inherent limitation in the discrete ordinates calculations should be observed unless the low-energy and thermal groups are properly evaluated. Note also that the C/E values for the $^{197}Au(n,\gamma)^{198}Au$ reaction have ascending trend towards back locations with the MC data whereas they have descending trend with the MG data. This was observed also in pure SS316 assembly [7].

4.2. Gamma-rays nuclear heating

The total heating in the SS316/water assembly is dominated by gamma ray heating at all locations in the assembly, particularly at rear locations where most of the gamma rays are generated from absorption reactions in the block constituents. Figs. 18 and 19 show the C/E values of gamma ray heating rate obtained by the MG and MC data. The gamma heating at the first measuring location (at front surface) calculated with the ENDF6/MG data is noticeably larger than the value obtained with the FENDL/MG data. The C/E values obtained with FENDL/MG and MC data are similar and within the experimental error of $\pm 20\%$. As shown, the C/E values tend to be larger than unity in the front part of the assembly with tendency to decrease at back locations by up to $\sim 20\%$. We recall that in pure SS316 assembly [7], the C/E values obtained with the FENDL/MG data were above unity (by 10% maximum) up till depth of 45 cm where they start to decrease rapidly with an under estimation of $\sim 40\%$ at depth 91.4 cm. This under estimation at deep locations is much lessened in the present assembly due to presence of water.

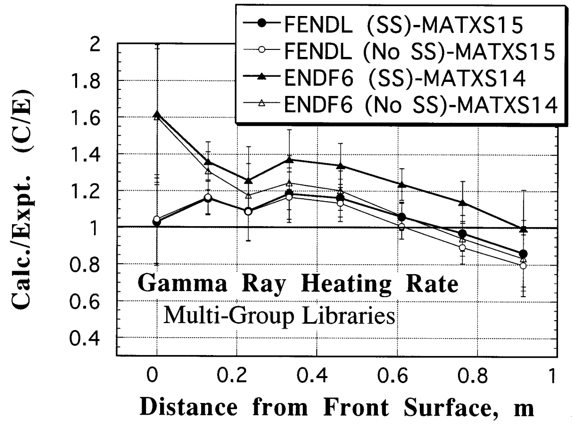

Fig. 18. The C/E values of gamma ray heating rate—FENDL-MG.

5. Summary and concluding remarks

FENDL-1 data base has been developed recently for use in ITER/EDA phase and other fusion-related design activities. It is undergoing extensive testing and benchmarking using experi-

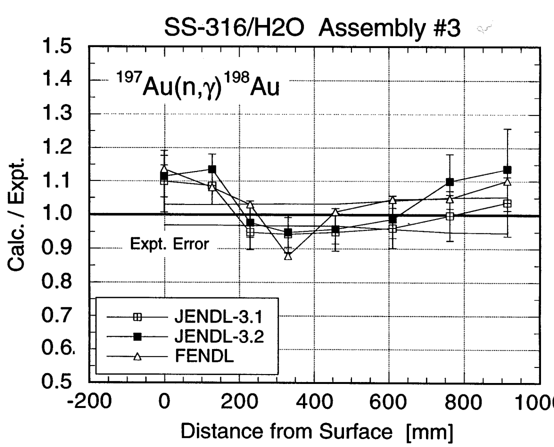

Fig. 17. The C/E values of the $^{197}Au(n,\gamma)^{198}Au$ reaction—FENDL-MC.

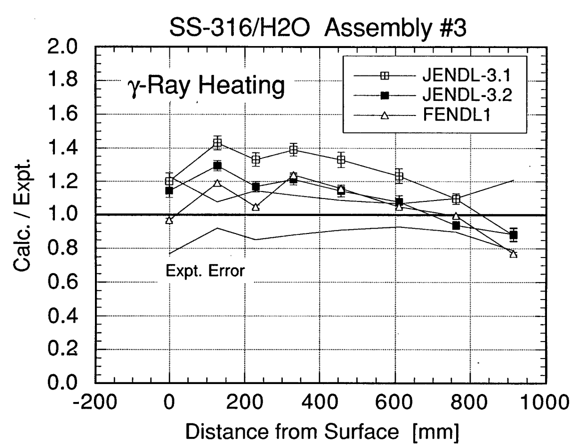

Fig. 19. The C/E values of gamma ray heating rate—FENDL-MC.

mental data of differential and integral measured parameters obtained from fusion-oriented experiments. As part of co-operation between UCLA (US) with JAERI (Japan) on executing the required neutronics R&D tasks for ITER shield design, three experiments were performed on cylindrical assemblies that resemble ITER shield blanket. The analysis of the first two assemblies that consisted solely of SS316 was previously reported [7,13]. The present work focuses on the third experiment performed with a bulk SS316/water assembly as a replica to ITER shield. Parallel effort has also been undertaken using the Frascati Neutron Generator (FNG, [14]). The data libraries considered for the benchmarking are the FENDL/MG-1 multigroup data base and FENDL/MC-1 continuous energy data base. The analyses with the multigroup data also included library derived from ENDF/B-VI data base for comparison purposes. The MCNP Monte Carlo code was used by JAERI with the FENDL/MC-1 data. Analysis with JENDL-3.1 and 3.2 was also performed although the present discussion capitalizes on FENDL-1 benchmarking. Although FENDL-1 data base is currently under testing and use by many investigators, the work on generating FENDL-2 has already started [15] to enrich FENDL data by the most recently evaluated data sets.

The integrated spectrum above 10 MeV is in a good agreement with the experiment within 5–10% at all locations with both the MG and MC data. The under estimation of this component of 25–35% observed previously at deep locations with the MG data in a pure SS316 assembly do not exist. Reactions that are sensitive to this component such as $^{93}Nb(n,2n)^{92m}Nb$, $^{27}Al(n,\alpha)^{24}Na$, and $^{238}U(n,f)$ have prediction accuracy of 2–10%, 2–18%, and 2–15%, respectively. The calculated integrated spectrum and these reaction rates are larger with ENDF/B-VI than FENDL/MG data by ~ 5–7%. The $^{115}In(n,n')^{115m}In$ reaction that is sensitive to the energy range of 1–10 MeV has also a prediction accuracy of 2–15%. The large under estimation of the integrated spectrum at deep locations of $\sim$ 60% (FENDL-MG/shielded, $0.1 < En < 1$ MeV) and $\sim 40\%$ (FENDL-MG/shielded, $1 < En < 100$ eV) observed in pure SS316 assemblies are much lessened to $\sim 25\%$ and 10–15%, respectively, in the present SS316/water assembly. The shielded MG data give better agreement with the experiment than the unshielded one, particularly at deep locations. This effect is less pronounced in the SS316/water assembly compared to the pure SS316 assembly. The C/E values of gamma-ray heating obtained by the MG and MC data are similar and within $\pm 20\%$ of the experiment. Generally, the results obtained with the MG data of FENDL have the same accuracy as those based on the MC data except for non-threshold reactions. This is due to the rather large effective absorption and fission cross-sections of the thermal group which leads to this discrepancy. One should evaluate these thermal cross-sections with the proper weighting spectrum to ensure consistency between the MG and MC results for the non-threshold reactions. Overall, the utmost discrepancy between FENDL calculations and measurements observed in the present study is ~ 20–30%, even though in most cases this discrepancy falls within the experimental error. One can therefore implement a factor of 1.2–1.3 as a design margin when calculating various responses for ITER shield design that utilizes combination of SS316 and water. The suggested factor for media consisting merely of SS316 was shown to be ~ 1.4 [7].

Acknowledgements

The present work is supported by the US Department of Energy grant # DOE-FG03-88ER52150. The experimental data has been provided by JAERI as a part of joint collaboration with the US according to the ITER Agreement reached in Garching March 21–26, 1994. This paper is partly an account of work assigned to the U.S. Home Team under Task Agreement T218: ‘Shielding Neutronics Experiment’ within the Agreement among the European Atomic Energy Community, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America on Cooperation in the Engineering Design Activities for the International Thermonuclear Experimental Reactor ('ITER EDA Agreement') under the auspices of the International Atomic Agency (IAEA).

References

[1] S. Ganesan, D.W. Muir, FENDL Multigroup Libraries, IAEA-NDS-129, International Atomic Energy Agency, July 1992.

[2] A.B. Pashchenko, Completion of FENDL-1 and start of FENDL-2, INDC(NDS)-352, IAEA Nuclear Data Section, International Atomic Energy Agency, March 1996.

[3] W.A. Rhoades, R.L. Childs, The DORT: two-dimensional discrete ordinates transport code, Nuc. Sci. Eng. 99 (May) (1988) 88–89; CCC-484, Radiation Shielding Information Center, 1988.

[4] P.F. Rose (Ed.), ENDF-201, ENDF/B-VI Summary Documentation, BNL-NCS-17541 [ENDF-201], 4th ed., Brookhaven National Laboratory, Oct. 1991.

[5] Los Alamos Monte Carlo Group, MCNP—A general Monte Carlo code for neutron and photon transport, Version 3A, LA-7396, Rev 2, Los Alamos National Laboratory, 1986.

[6] K. Shibata, et al., JENDL-3, JAERI-1319, Japan Atomic Energy Research Institute, 1990.

[7] M.Z. Youssef, A. Kumar, M.A. Abdou, C. Konno, F. Maekawa, M. Wada, Y. Oyama, H. Maekawa, Y. Ikeda, Benchmarking FENDL libraries through the analysis of bulk shielding experiments on large SS316 assemblies for the verification of ITER shielding characteristics, Fusion Technol. 30 (1996) 1101–1112.

[8] F. Maekawa, C. Konno, M. Wada, Y. Oyama, Y. Ikeda, Y. Uno, Y. Verzilov, H. Maekawa, Bulk shielding experiment on large SS316/Water assembly bombarded by D–T Neutrons, II: Analysis, JAERI-research 95-018, Japan Atomic Energy Research Institute, March 1995.

[9] R.E. MacFarlane, TRANSX2: A code for interfacing MATXS cross-section, libraries to nuclear transport codes, LA-12312-MS, UC-705 and UC-700 Issued: July 1992, Los Alamos National Laboratory, 1992.

[10] M. Nakazawa, et al., JENDL dosimetry file, JAERI-1325, 1992.

[11] L.P. Ku, J. Kolibal, RUFF—A ray tracing program to generate uncollided flux and first collision source moments for DOT4. A User's Manual. EAD-R-16, Plasma Physics Laboratory, Princeton University, 1980.

[12] M. Nakagawa, T. Mori, MORSE-DD, A Monte Carlo code using multigroup double differential form cross-sections JAERI-M84-126, Japan Atomic Energy Research Institute, July, 1984.

[13] F. Maekawa, C. Konno, K. Kosako, Y. Oyama, Y. Ikeda, H. Maekawa, Bulk shielding experiments on large SS316 assemblies bombarded by D–T neutrons, Vol. II: Analysis, JAERI-Research-94-044, Japan Atomic Energy Research Institute, July, 1994.

[14] P. Batistoni, M. Angelone, M. Pillon, L. Petrizzi, M. Gallina, H. Freiesleben, W. Hansen, D. Richter, K. Seidel, S. Unholzer, A. Santamarina, L. Benmansour, B. Gastaldi, R. Jacqmin, B. Campus, H. Philibert, U. Fischer, 2nd Intermediate Report on Measurements and Analysis: ITER Task 218 on Shielding Neutronics Experiment, Subtask A/EU Contribution, pros. n. 11/97 TECNINEU, ENEA C.R., Frascati, Italy, January 1997.

[15] A.B. Pashchenko, The IAEA Advisory Group Meeting on Extension and Improvement of the FENDL Library for Fusion Applications (FENDL-2), minutes of the meeting held March 3–7, 1997, International Atomic Energy Agency, Vienna, Austria, to be published, 1997.