

New integral experiments for a variety of fusion reactor materials with DT neutron source at JAEA/FNS

S. Sato¹, S. Kwon¹, M. Ohta¹, K. Ochiai¹, C. Konno²

¹National Institutes for Quantum and Radiological Science and Technology, Rokkasho-mura, Japan

²Japan Atomic Energy Agency, Tokai-mura, Japan

E-mail contact of main author: sato.satoshi@qst.go.jp

Abstract. In order to validate the nuclear data, we have performed integral experiments for a variety of fusion reactor materials with the DT neutron source at FNS in JAEA. The discrepancies between the calculated and experimental results were found in some experiments of the previous study, where the measured data might include background neutrons scattered in the concrete wall of the experimental room. Thus we perform new integral experiments with few background neutrons and validate nuclear data adequately in this study. It is found out that the nuclear data on tungsten and vanadium have no problems, while there are still concerns in the nuclear data on copper, molybdenum and titanium. We describe the details of the nuclear data on copper, molybdenum and titanium based on the experimental results in this study, and propose the modification of the nuclear data.

1. Introduction

Tungsten, vanadium, copper, molybdenum and titanium are important materials in fusion reactors. Tungsten is used as armor materials of the divertor and blanket, and is also used as radiation shield materials. Vanadium is a low activation material, and it is one of candidate materials of the structure material of the advanced blanket in DEMO reactor. Molybdenum is included in stainless steel which is used as a main shielding material in ITER. Copper is used as materials of the magnet. Titanium is used as tritium breeder material in the blanket. We performed integral experiments on tungsten, vanadium and copper with the DT neutron source at the Fusion Neutronics Source (FNS) facility in Japan Atomic Energy Agency (JAEA) over 20 years ago [1-5]. The calculated results of the dosimetry reaction rates sensitive to low energy neutrons such as that of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction largely underestimated the measured ones. Background neutrons scattered in the concrete wall of the experimental room may have caused these underestimations. In order to reduce the background neutrons and validate the nuclear data adequately, we perform new integral experiments with these materials covered with Li_2O blocks. Li has a very large absorption cross section for low energy neutrons, and it is very effective for reduction of the background neutrons. In addition, we confirmed that the nuclear data libraries of Li and O were good based on the Li_2O experiment at FNS [6]. We also newly perform integral experiments on molybdenum and titanium with Li_2O blocks.

2. Experiment and analysis

Figure 1 shows a new experimental assembly of the tungsten experiment. A rectangular tungsten assembly is covered with Li_2O blocks. Similarly to the tungsten assembly, Li_2O

blocks cover the vanadium, copper, molybdenum and titanium assemblies. The details of these assemblies are as follows;

- (1) Tungsten experiment: A rectangular tungsten assembly of 357 mm in width, 357 mm in height and 508 mm in thickness covered with Li_2O blocks of 51 mm in thickness for the front part, 153 mm in thickness for the side parts and 203 mm in thickness for the rear part. The distance between the DT neutron source and the front surface of the assembly is 150 mm.
- (2) Vanadium experiment: A rectangular vanadium-alloy (V-4Cr-4Ti) assembly of 152 mm in width, 136 mm in height and 152 mm in thickness covered with Li_2O blocks of 102 mm in thickness for the front part, 253 mm in thickness for the side and rear parts. The distance between the DT neutron source and the front surface of the assembly is 200 mm.
- (3) Copper experiment [7]: A quasi-cylindrical copper assembly of 630 mm in diameter and 608 mm in thickness covered with Li_2O blocks of 51 mm in thickness for the front and side parts, and 153 mm in thickness for the rear part. The distance between the DT neutron source and the front surface of the assembly is 149 mm.
- (4) Molybdenum experiment [8]: A rectangular molybdenum assembly of 253 mm in width, 253 mm in height and 354 mm in thickness covered with Li_2O blocks of 51 mm in thickness for the front part, 202 mm in thickness for the side parts and 253 mm in thickness for the rear part. The distance between the DT neutron source and the front surface of the assembly is 150 mm.
- (5) Titanium experiment [9]: A rectangular titanium assembly of 455 mm in width, 455 mm in height and 405 mm in thickness covered with Li_2O blocks of 51 mm in thickness for the front part, 101 mm in thickness for the side and rear parts. The distance between the DT neutron source and the front surface of the assembly is 151 mm.

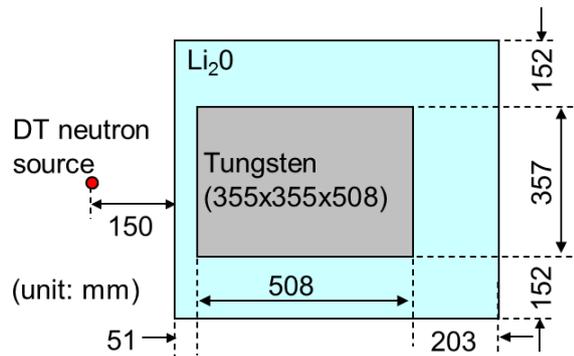


FIG 1. Experimental assembly of the new tungsten experiment.

Activation foils of Nb, Al, In, W and Au for dosimetry reaction rate measurement are installed into small spaces between blocks along the central axis in these assemblies. We measure the reaction rates of the dosimetry reactions; $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$, $^{186}\text{W}(n,\gamma)^{187}\text{W}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions. In addition, we install two micro fission chambers of 6.25 mm in outer diameter and 25.4 mm in active length in the measurement hole of 21 mm in diameter along the center of these assemblies, and measure the fission rates of ^{235}U and ^{238}U . We analyze these experiments by using the Monte Carlo code MCNP5-1.40

[10] with the recent nuclear data libraries, ENDF/B-VII.0 [11], ENDF/B-VII.1 [12], JEFF-3.2 [13], JENDL-4.0 [14], FENDL-3.0 [15] and JENDL Dosimetry File 99 [16].

3. Results and discussion

3.1. Tungsten experiment

Figure 2 shows the ratios of the calculation results with JENDL-4.0 and FENDL-3.0 to the experiment ones (C/Es) of the reaction rate of the $^{186}\text{W}(n,\gamma)^{187}\text{W}$ reaction. For comparison, this figure also shows the C/Es obtained in the previous experiment at FNS. The large underestimation observed in the reaction rates in the previous experiment is drastically improved in the present experiment. All the calculation results of the reaction rates of the $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$, $^{186}\text{W}(n,\gamma)^{187}\text{W}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions and the fission rates of ^{235}U and ^{238}U with ENDF/B-VII.1, JEFF-3.2, JENDL-4.0 and FENDL-3.0 generally show good agreements with the experiment ones. It is concluded that the nuclear data of tungsten have no problem.

3.2. Vanadium experiment

Figure 3 shows the C/Es of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction the ratios with JENDL-4.0 and FENDL-3.0 to in the previous and present vanadium experiments. Similarly to the tungsten experiment, the large underestimation observed in the previous experiment is drastically improved in the present experiment. All the calculation results of the reaction rates with the nuclear data libraries generally show good agreements with the experiment ones. It is concluded that the nuclear data of vanadium have also no problem.

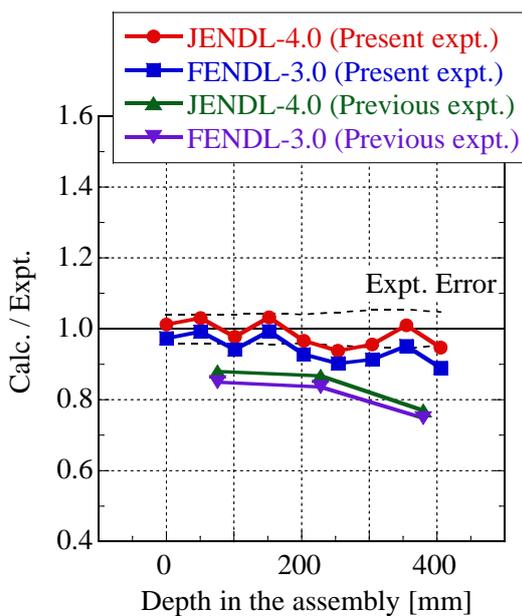


FIG 2. Ratio of the calculation results with JENDL-4.0 and FENDL-3.0 to the experiment ones of the reaction rate of the $^{186}\text{W}(n,\gamma)^{187}\text{W}$ reaction in the previous and present tungsten experiments.

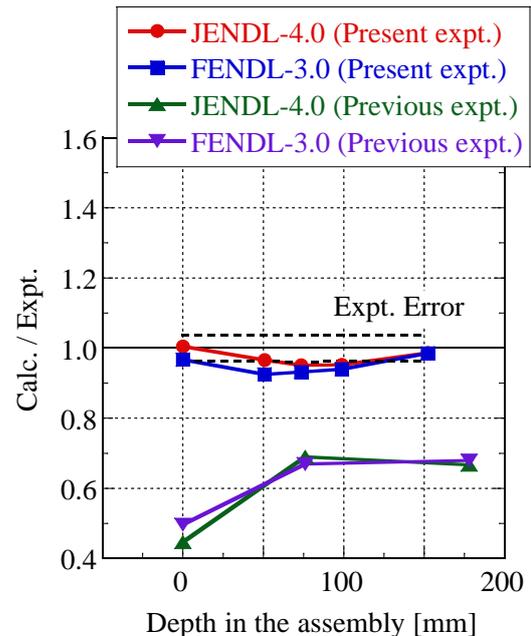


FIG 3. Ratio of the calculation results with JENDL-4.0 and FENDL-3.0 to the experiment ones of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction in the previous and vanadium experiment.

3.3. Copper experiment [7]

Figure 4 shows the C/Es with JENDL-4.0 of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction in the previous and present copper experiments. Similarly to the tungsten and vanadium experiments, the underestimation in the previous experiment is improved in the present experiment, but the calculation results still underestimate the experiment one with increasing distance from the front surface of the assembly. Similarly to the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction, the calculation results of the reaction rate of the $^{186}\text{W}(n,\gamma)^{187}\text{W}$ reaction underestimate the experiment one. In order to investigate reasons of the underestimation, we replaced the nuclear data libraries of ^{63}Cu or ^{65}Cu in JENDL-4.0 with those in ENDF/B-VII.1 or JEFF-3.2, and recalculated the reaction rates. Figure 5 shows the C/Es of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction using replaced the nuclear data libraries of ^{63}Cu and ^{65}Cu in JENDL-4.0 with those in JEFF-3.2. In case the ^{63}Cu data in JENDL-4.0 are replaced with those in ENDF/B-VII.1 or JEFF-3.2, the C/Es of the reaction rates of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and $^{186}\text{W}(n,\gamma)^{187}\text{W}$ reactions improve by about 10 %. On the other hand, in case the ^{65}Cu data in JENDL-4.0 are replaced with those in ENDF/B-VII.1 or JEFF-3.2, the C/Es worsen slightly. It is considered that the combination of ^{63}Cu data in JEFF-3.2 and ^{65}Cu data in JENDL-4.0 is the best. The $^{63}\text{Cu}(n,\gamma)$ reaction cross section data in JEFF-3.2 are smaller than those in JENDL-4.0 in the neutron energy from 100 eV to 0.3 MeV, while the elastic scattering cross section data of $^{65}\text{Cu}(n,\gamma)$ in JENDL-4.0 are larger than those in JEFF-3.2 in the neutron energy from 100 eV to a few keV. Thus we modified the elastic scattering and capture cross section data of the ^{63}Cu in JEFF-3.2 and ^{65}Cu data in JENDL-4.0 as follows; 10% larger elastic scattering cross section data and 10% smaller capture cross section data between 100 eV and 0.3 MeV. Figure 4 also shows the C/Es of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction with the modified cross section data. The C/Es drastically improve, and this finding strongly suggests that the elastic scattering and/or capture reaction cross-section data of copper should be evaluated.

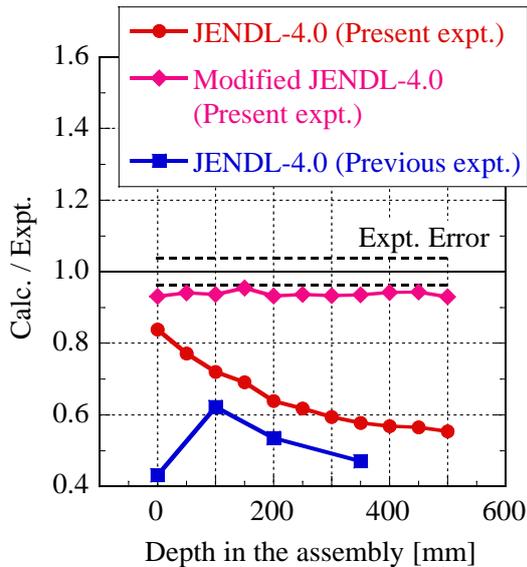


FIG 4. Ratio of the calculation results with JENDL-4.0 and modified JENDL-4.0 to the experiment ones of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction in the previous and present copper experiments.

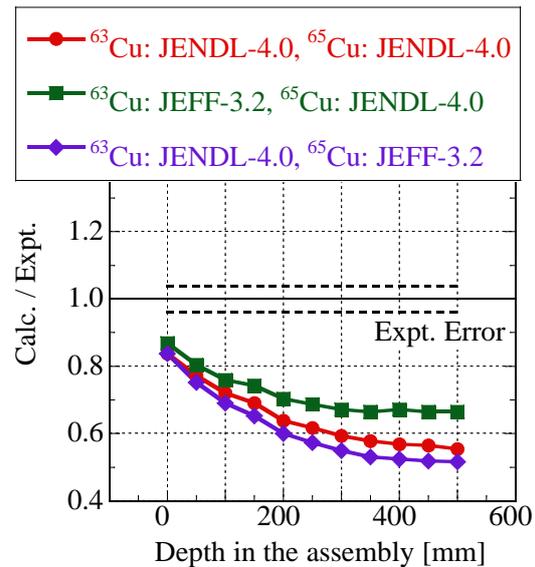


FIG 5. Ratio of the calculation results to the experiment one of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction using replaced the nuclear data libraries of ^{63}Cu and ^{65}Cu in JENDL-4.0 with those in JEFF-3.2 in the present copper experiment.

3.4. Molybdenum experiment [8]

Figures 6 and 7 show the C/Es of the reaction rate of the $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions, respectively, with JENDL-4.0 and JEFF-3.2 in the molybdenum experiment. The C/Es generally decrease with increasing distance from the front surface of the assembly for all the nuclear data libraries. Comparing the (n,2n) cross section data of $^{\text{nat}}\text{Mo}$ with the experimental data, those in JEFF-3.2 are more consistent with the experimental data by Frehaut [17] than those in JENDL-4.0. We replace the (n,2n) cross sections of all the Mo stable isotopes in JENDL-4.0 with those in JEFF-3.2. Although the (n, γ) cross section data of $^{\text{nat}}\text{Mo}$ in JENDL-4.0 are consistent with the experimental data by Stravisskly [18], they are larger than those by Fricke [19]. Additionally we multiply the (n, γ) cross section data above 200 eV of all the Mo stable isotopes except for ^{98}Mo in JENDL-4.0 by 0.7 as a trial. Figures 5 and 6 also show the C/Es with the modified JENDL-4.0. The C/Es drastically improve, and this finding strongly suggests that the molybdenum data in JENDL-4.0 should be revised based on the modified ones.

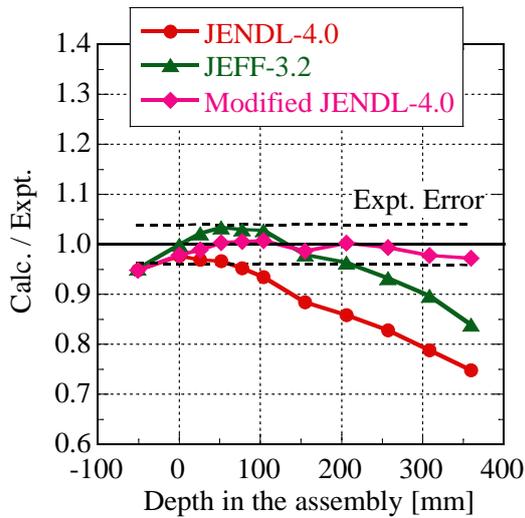


FIG 6. Ratio of the calculation results with JENDL-4.0, JEFF-3.2 and modified JENDL-4.0 to the experiment ones of the reaction rate of the $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ reaction in the molybdenum experiment.

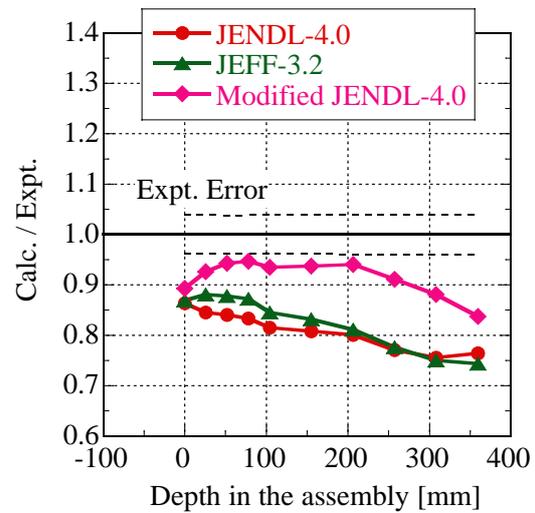


FIG 7. Ratio of the calculation results with JENDL-4.0, JEFF-3.2 and modified JENDL-4.0 to the experiment ones of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction in the molybdenum experiment.

3.5. Titanium experiment [9]

Figures 8 and 9 show the C/Es of the reaction rate of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions, respectively, with JENDL-4.0, JENDL-4.0u1, ENDF/B-VII.0 and ENDF/B-VII.1 in the titanium experiment. From the C/Es of the reaction rates of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions and the fission rate of ^{235}U , the calculated result with ENDF/B-VII.1 agrees with the measured one the best. In order to investigate which reaction in titanium isotopes in ENDF/B-VII.1 mainly improved the agreement between the measured and calculated reaction rates, we calculate the reaction rates with temporarily modified nuclear data where only specified reaction cross sections in the original ENDF/B-VII.0 are replaced with those in ENDF/B-VII.1. It is found out that two reactions of (n,2n) and (n, n'_{cont}) for ^{48}Ti contribute to the improvement of C/E of the reaction rate of the $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ reaction with

ENDF/B-VII.1. The shapes of the resonance cross section data of ^{48}Ti are very different among the nuclear data libraries, which drastically affect the calculated reaction rates of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and $^{235}\text{U}(n,\text{fission})$ reactions. It is also found out that the calculated result with JENDL-4.0u1 agrees with the measured reaction rates for the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ and $^{235}\text{U}(n,\text{fission})$ reactions better than that with JENDL-4.0 because of the improved resonance representation.

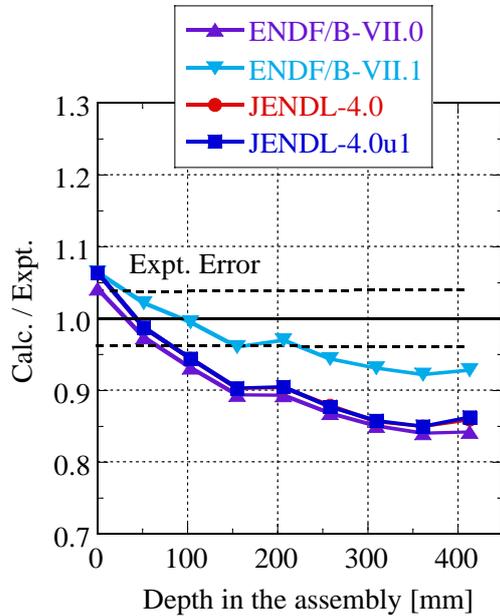


FIG 8. Ratio of the calculation results with JENDL-4.0, JENDL-4.0u1, ENDF/B-VII.0 and ENDF/B-VII.1 to the experiment ones of the reaction rate of the $^{115}\text{In}(n,n')^{115m}\text{In}$ reaction in the titanium experiment.

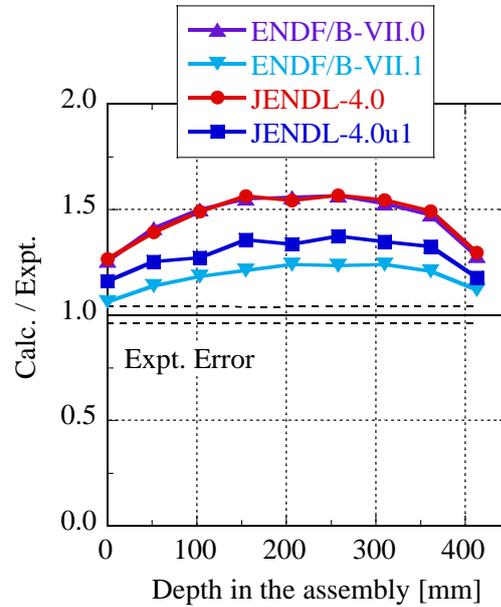


FIG 9. Ratio of the calculation results with JENDL-4.0, JENDL-4.0u1, ENDF/B-VII.0 and ENDF/B-VII.1 to the experiment ones of the reaction rate of the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction in the titanium experiment.

4. Summary

In order to verify the nuclear data for fusion reactor materials, we performed new integral experiments using the assemblies of tungsten, vanadium, copper, molybdenum and titanium with DT neutron source at FNS in JAEA. All the assemblies were covered with Li_2O blocks to reduce the background neutrons scattered by the wall of the experimental room. We measured the dosimetry reaction rates using the activation foils and the fission rates using the micro fission chambers along the center of the assembly. We calculated these reaction rates and fission rates by using the Monte Carlo code MCNP5-1.40 with the recent nuclear data libraries JENDL-4.0, ENDF/B-VII.1, ENDF/B-VII.0 and JEFF-3.2. The underestimations of the calculation results sensitive to low energy neutrons observed in the previous tungsten and vanadium experiments without Li_2O blocks drastically improved in the present experiment, and all the calculation results agreed very well with the experiment results. It was found out that the nuclear data of tungsten and vanadium had no problem. Although the underestimations obtained in the previous copper experiment were also improved in the present experiment, all the calculation results still underestimated the experiment ones with

increasing distance from the front surface of the assembly. The elastic scattering and/or capture reaction cross section data of copper should be evaluated to improve the calculation results. In the molybdenum experiment, the C/Es generally decreased with increasing distance from the front surface of the assembly for all the reaction rates and all the nuclear data libraries. It was found out that the (n,2n) cross section data for all the Mo stable isotopes in JEFF-3.2 were more suitable than those in JENDL-4.0 and the capture reaction cross section data of ^{92}Mo , ^{94}Mo , ^{95}Mo , ^{96}Mo , ^{97}Mo , and ^{100}Mo in JENDL-4.0 should be decreased. In the titanium experiment, the calculated results with ENDF/B-VII.1 agreed with the measured ones the best. This was because the (n,2n) and (n,n'_{cont}) reaction cross section data and resonance parameters in ENDF/B-VII.1 were the most suitable.

Acknowledgments

The authors would like to thank S. Tanaka, Y. Abe, Y. Oginuma, S. Kakizaki and S. Urai, JAEA, for the operation of the FNS accelerator.

Reference

- [1] MAEKAWA, F., et al., “Benchmark Experiment on Tungsten Assembly Bombarded with D-T neutrons”, Proc. of Int. Conf. on Nucl. Data for Sci. and Technol., **59** (1997) 1220.
- [2] MAEKAWA, F., et al., “Benchmark Experiment on Vanadium with D-T neutrons and Validation of Evaluated Nuclear Data Libraries by Analysis of the Experiment”, J. Nucl. Sci. Technol., **36** (1999) 242.
- [3] MAEKAWA, F., et al., “Benchmark Experiment on Vanadium-alloy Assembly with D-T neutrons - In-situ Measurement - ”, Fus. Technol., **34** (1998) 1018.
- [4] MAEKAWA, F., et al., “Benchmark Experiment on a Copper Slab Assembly Bombarded by D-T neutrons”, JAERI-M 94-038, Japan Atomic Energy Research Institute, (1994).
- [5] KONNO, C., et al., “Benchmark test of JENDL-4.0 based on integral experiments at JAEA/FNS”, Progr. Nuc. Sci. Technol., **2** (2011) 346.
- [6] MAEKAWA, H., et al., “Fusion blanket benchmark experiment on a 60 cm-thick lithium-oxide cylindrical assembly”, JAERI-M 86-182, Japan Atomic Energy Research Institute, (1986).
- [7] KWON, S., et al., “A New Integral Experiment on Copper with DT Neutron Source at JAEA/FNS”, Fus. Eng. Des., **109** (2016) 1658.
- [8] OHTA, M., et al., “Integral experiment on molybdenum with DT neutrons at JAEA/FNS”, Fus. Eng. Des., **109** (2016) 1644.
- [9] OHTA, M., et al., “Benchmark experiment on titanium with DT neutrons at JAEA/FNS”, Fus. Eng. Des., **89** (2014) 2164.
- [10] X-5 MONTE CARLO TEAM, “MCNP – A General Monte Carlo N-Particle Transport Code, Version 5”, LA-UR-03-1987, Los Alamos National Laboratory, (2003).
- [11] CHADWICK, M.B., et al., “ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology”, Nucl. Data Sheets **107** (2006) 2931.

- [12] CHADWICK, M.B., et al., “ENDF/B-VII.1 Nuclear data for science and technology: cross sections, covariances, fission product yields and decay data”, Nucl. Data Sheets **112** (2011) 2887.
- [13] CABELLOS, O., et al., “Processing of the new JEFF-3.2T4 Cross Section Library with the NJOY Code System into Various Formats for Testing Purposes”, NEA Report, (2014).
- [14] SHIBATA, K., et al., “JENDL-4.0: a new library for nuclear science and engineering”, J. Nucl. Sci. Technol., **48** (2011) 1.
- [15] FORREST, R.A., et al., “FENDL-3 Library – Summary Documentation”, INDC(NDS)-0628, (2012).
- [16] KOBAYASHI, K., et al., “JENDL Dosimetry File 99 (JENDL/D-99)”, JAERI 1344, (2002).
- [17] FREHAUT, J., et al., “Status of (n,2n) cross section measurements at Bruyeres-le-Chatel”, INDC(USA)-84, (1) (1980) 399.
- [18] STAVISSKIY, Yu.Ya., et al., “Neutron spectroscopic investigation of separated tungsten and molybdenum”, Neitronnaya Fizika, Moskva (1961) .
- [19] FRICKE, M., et al., “Measurements of cross-sections for the radioactive capture of 1-keV to 1-MeV neutrons by Mo, Rh, Gd, Ta, W, Re, Au and ²³⁸U”, Nuclear data for Reactors Conf., Helsinki (1970) .