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ARTICLE

Benchmark Test of JENDL-4.0 Based on Integral Experiments at JAEA/FNS

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The major revised version of Japanese Evaluated Nuclear Data Library (JENDL), JENDL-4.0, was released in May, 2010. As the benchmark test of JENDL-4.0 in the shielding and fusion neutronics fields, we analyzed many integral benchmark experiments (in-situ and Time-of-Flight (TOF) experiments) with DT neutrons at JAEA/FNS with the MCNP code and JENDL-4.0. The experiments with assemblies including beryllium, carbon, silicon, vanadium, copper, tungsten and lead, nuclear data of which were revised in JENDL-4.0, were selected for this benchmark test. As a result, it is demonstrated that JENDL-4.0 improves some problems pointed out in JENDL-3.3. JENDL-4.0 is comparable to ENDF/B-VII.0 and JEFF-3.1.

KEYWORDS: JENDL-3.3, JENDL-4.0, benchmark test, integral experiment, MCNP, FNS

I. Introduction

The major revised version of Japanese Evaluated Nuclear Data Library (JENDL), JENDL-4.0,[1)] was released in May, 2010. It is essential to validate JENDL-4.0 through analyses of integral benchmark experiments. Many integral benchmark experiments[2,3)] for nuclear data verification have been carried out with DT neutrons at the Fusion Neutronics Source (FNS) facility in Japan Atomic Energy Agency (JAEA) for 25 years. Thus we analyzed these experiments with JENDL-4.0 as one of benchmark tests of JENDL-4.0 in the shielding and fusion neutronics fields. Analyses with the recent other nuclear data, JENDL-3.3,[4)] JEFF-3.1[5)] and ENDF/B-VII.0,[6)] were also carried out in order to uncover whether JENDL-4.0 was better or not. This paper describes these benchmark tests.

II. Overview of Integral Experiments at JAEA/FNS

Two types of integral experiments for nuclear data verification with DT neutrons have been performed for 25 years at JAEA/FNS. One is an in-situ experiment[2)] and the other is a Time-of-flight (TOF) experiment.[3)]

A typical experimental configuration of the in-situ experiment is shown in **Fig. 1**. The shape of most of the experimental assemblies is a quasi cylinder as shown in Fig. 1. The effective diameter of the assembly is 630 mm. The thickness of the experimental assemblies is different each experiment depending on material volume which we own. Neutron spectra, reaction rates of dosimetry reactions, gamma heating rates and so on are measured inside the experimental assembly in this experiment. We have experimental data of lithium oxide, beryllium, graphite, silicon carbide (SiC), vanadium, iron, a type 316 stainless steel (SS316), copper, tungsten, etc.

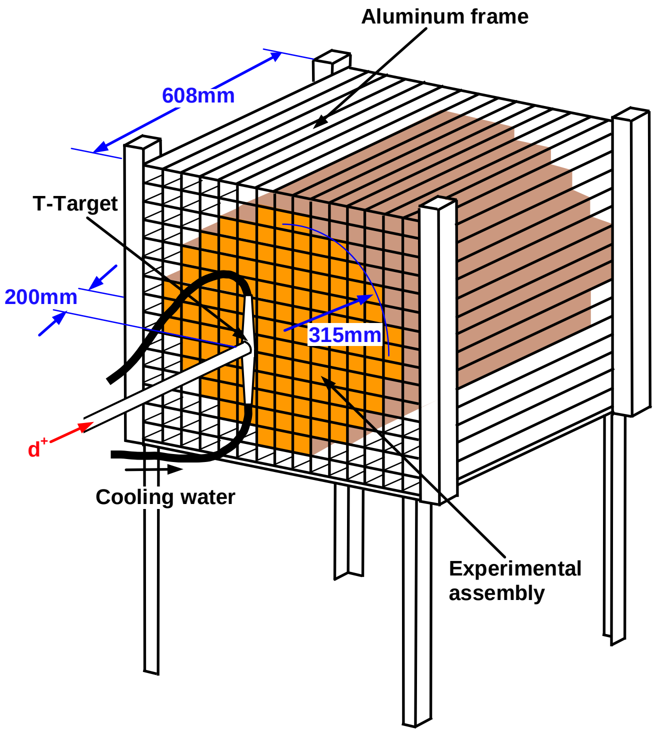

Fig. 1 Experimental configuration of in-situ experiment.

A typical experimental configuration of the TOF experiment is shown in **Fig. 2**. Angular neutron spectra above 100 keV leaking from thinner assemblies than those as shown in Fig. 1 are measured for lithium oxide, beryllium, graphite, liquid-nitrogen, liquid-oxygen, iron, lead, etc. by

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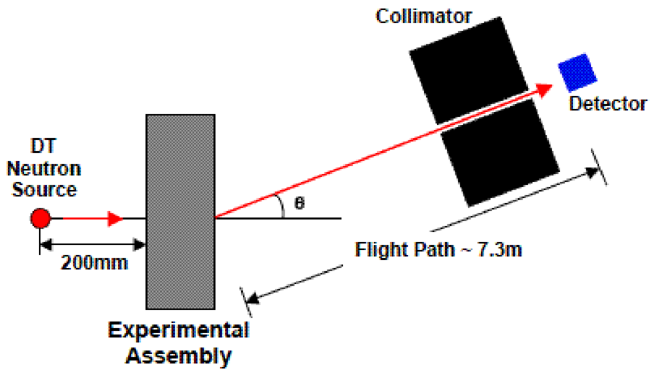

Fig. 2 Experimental configuration of TOF experiment.

using the collimator system in this experiment. The size of experimental assemblies is different each experiment depending on material volume which we own.

III. Analysis

The Monte Carlo code MCNP-4C[7] and the A Compact ENDF (ACE) file FSXLIB-J40[8] of JENDL-4.0 were used for the analysis of the experiments. Calculations with the ACE files of the following nuclear data libraries were also carried out for comparison.

- JENDL-3.3 (ACE file : FSXLIB-J33[9])
- JEFF-3.1 (ACE file : MCJEFF3.1NEA[10])
- ENDF/B-VII.0 (ACE file : endf70 in MCNP Data[11])

JENDL Dosimetry file 99[12] was adopted as the reaction cross section data for calculation of dosimetry reaction rates.

All the nuclear data in JENDL-3.3 are not modified in JENDL-4.0. The experiments with assemblies shown in **Table 1** including beryllium, carbon, silicon, vanadium, copper, tungsten and lead, nuclear data of which were revised in JENDL-4.0, were selected for this benchmark test. Iron data are also modified in JENDL-4.0, but the benchmark results for the iron experiments with JENDL-4.0 have been reported[13] already.

Table 1 Experimental assemblies

Experiment		Assembly: Shape	Assembly: Size
Be	in-situ	Quasi cylinder	630 mm in effective diameter 455 mm in thickness
	TOF	Quasi cylinder	630 mm in effective diameter 51, 152 mm in thickness
Graphite	in-situ	Quasi cylinder	630 mm in effective diameter 608 mm in thickness
	TOF	Quasi cylinder	630 mm in effective diameter 51, 202, 405 mm in thickness
SiC	in-situ	Rectangle	457 mm x 457 mm x 711 mm in thickness
V	in-situ	Rectangle	254 mm x 254 mm x 254 mm in thickness covered with 50 mm thick graphite
Cu	in-situ	Quasi cylinder	630 mm in effective diameter 608 mm in thickness
W	in-situ	Quasi cylinder	575 mm in effective diameter 507 mm in thickness
Pb	TOF	Quasi cylinder	630 mm in effective diameter 51, 203, 406 mm in thickness

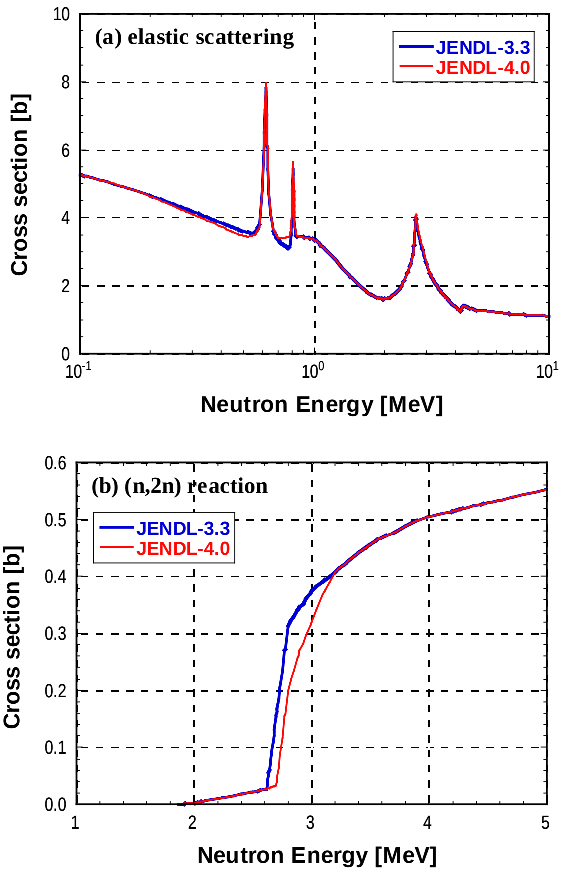

Fig. 3 Cross section data of ^{9}Be.

IV. Results and Discussion

1. Beryllium Experiments

The main modifications of the ^{9}Be data from JENDL-3.3 to JENDL-4.0 are the followings; 1) the elastic scattering cross section data are re-calculated and slightly modified around the peak of ~ 600 keV as shown in **Fig. 3**, 2) the (n,2n) reaction cross section data are revised only near the threshold energy as shown in Fig. 3, 3) the (n,γ) reaction cross section data increase by ~10%.

Therefore the difference between the calculation results with JENDL-3.3 and -4.0 for the beryllium TOF and in-situ experiments is not so large. **Figure 4** shows the measured and calculated angular neutron spectra leaking from the beryllium slab of 152 mm in thickness in the beryllium TOF experiment. All the calculated spectra agree with the measured ones very well. **Figure 5** plots ratios of calculation to experiment (C/E) for reaction rates of the $^{93}Nb(n,2n)^{92m}Nb$, $^{115}In(n,n')^{115m}In$, $^{6}Li(n,\alpha)T$ and $^{235}U(n,$ fission) reactions, which are mainly sensitive to neutrons above 10 MeV, neutrons above 0.3 MeV, thermal neutrons and thermal neutrons, respectively. It is noted that the overestimation for the reaction rates of the $^{6}Li(n,\alpha)T$ and $^{235}U(n,$ fission) reactions in the calculation result with JENDL-3.3 reduces by ~ 5% in that with JENDL-4.0.

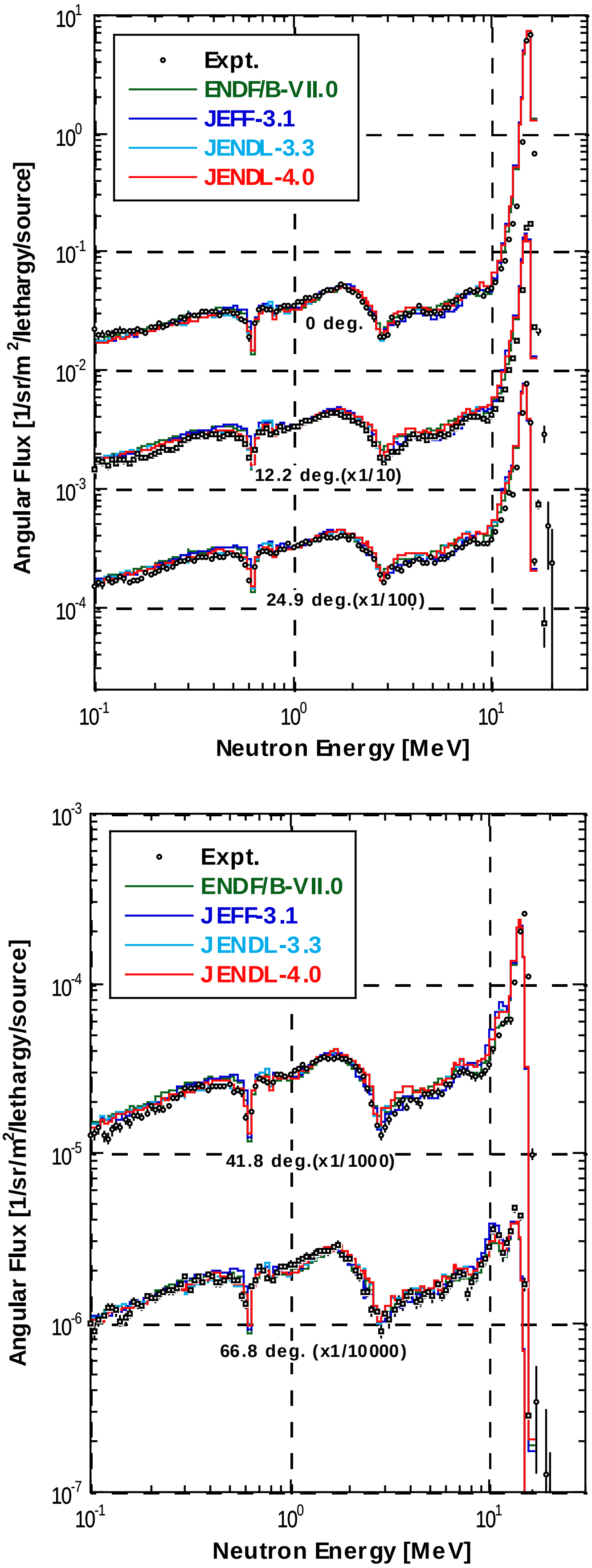

Fig. 4 Angular neutron spectra leaking from beryllium slab of 152 mm in thickness in beryllium TOF experiment.

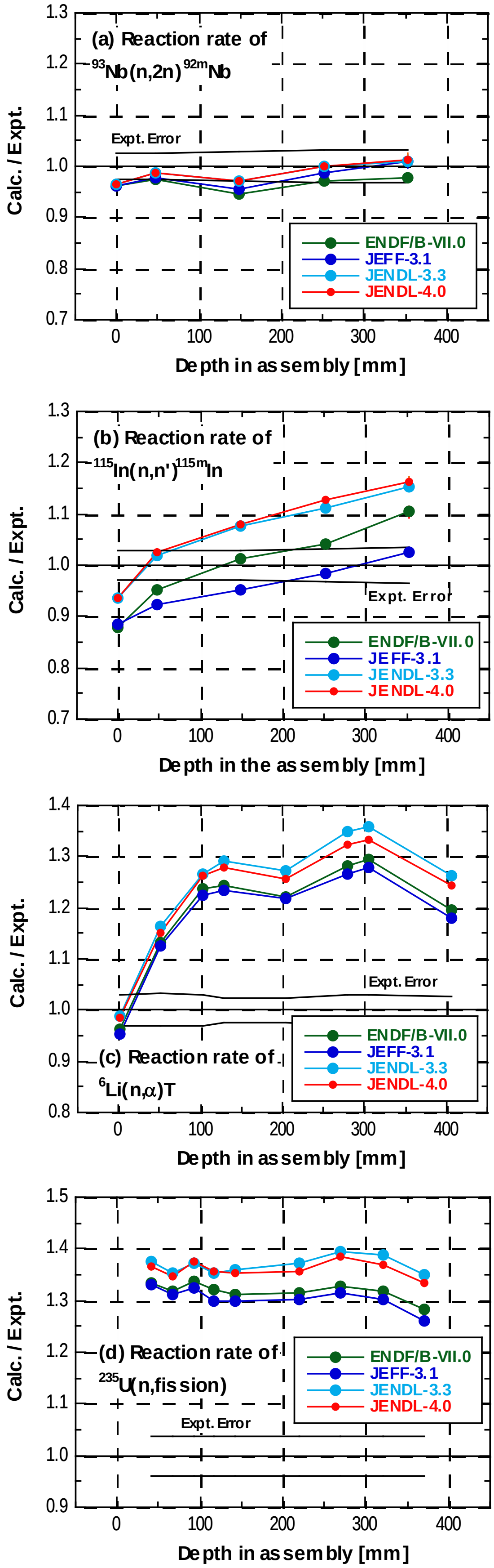

Fig. 5 C/E in beryllium in-situ experiment.

2. Graphite Experiments

The main modifications of the ^{nat}C data from JENDL-3.3 to JENDL-4.0 are the followings; 1) the (n,γ) reaction cross section data increase by ~10% in the 1/v part, 2) the angular distribution data of the elastic scattering are taken from JENDL-3.2 as shown in **Fig. 6**. Thus the difference between the calculation results with JENDL-3.3 and -4.0 for the graphite TOF and in-situ experiments is not so large as shown in **Figs. 7** and **8**.

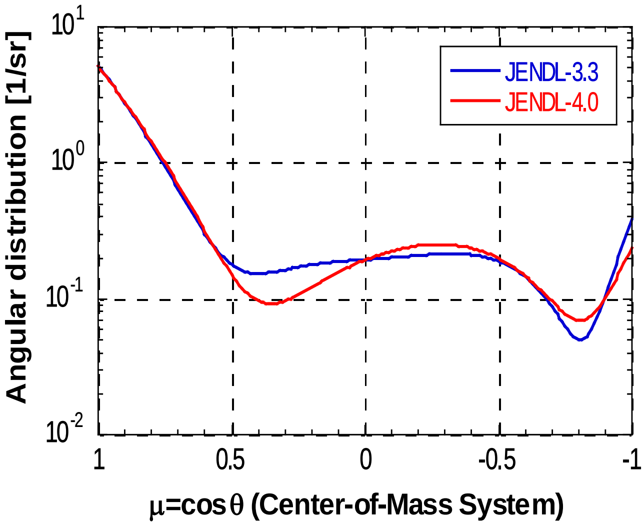

Fig. 6 Angular distribution data of elastic scattering of ^{nat}C for 14 MeV neutron.

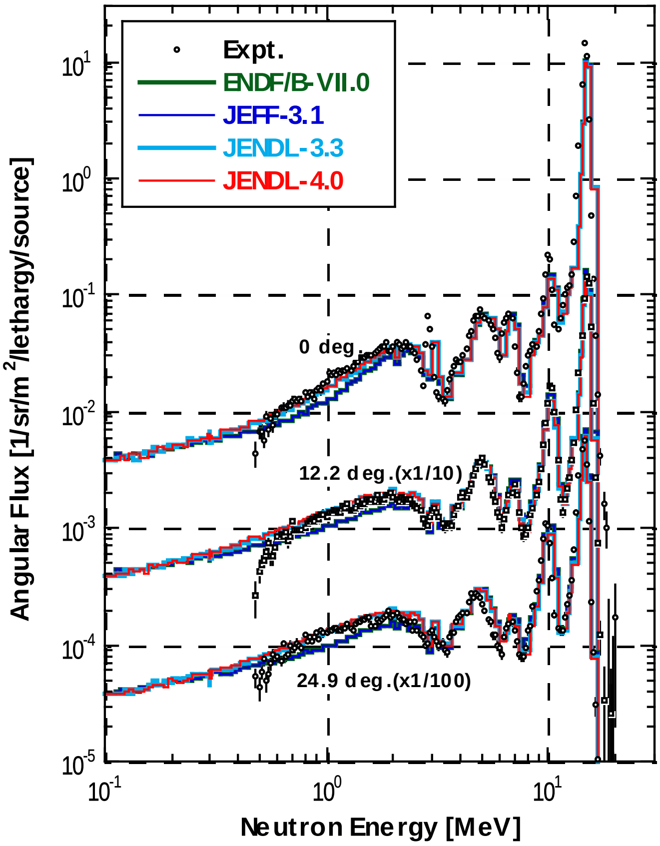

Fig. 7 Angular neutron spectra leaking from graphite slab of 203 mm in thickness in graphite TOF experiment.

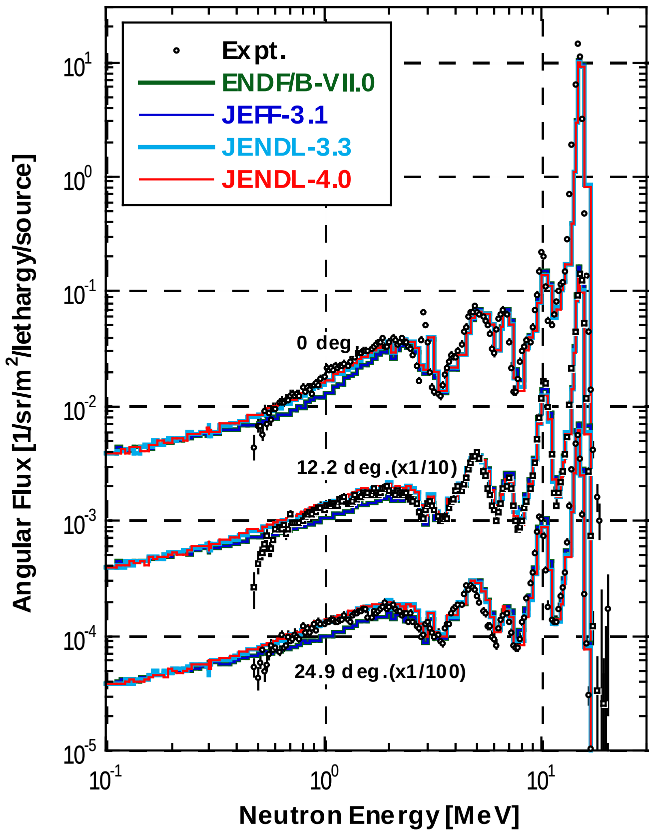

Fig. 7 (Continued).

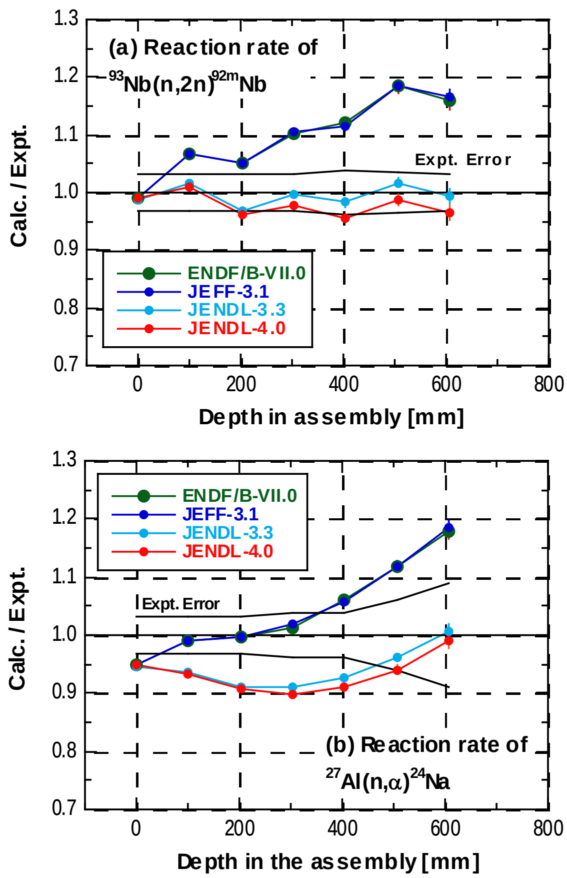

Fig. 8 C/E in graphite in-situ experiment.

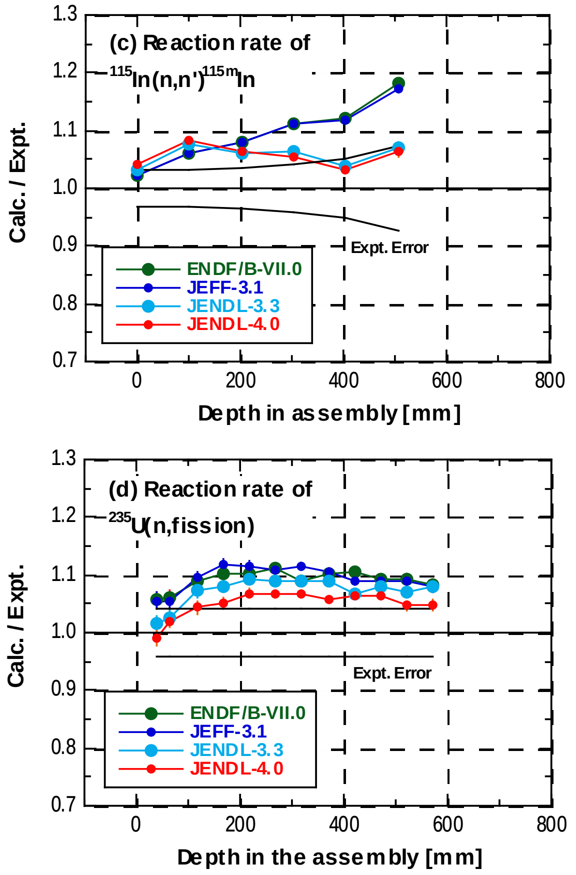

Fig. 8 (Continued).

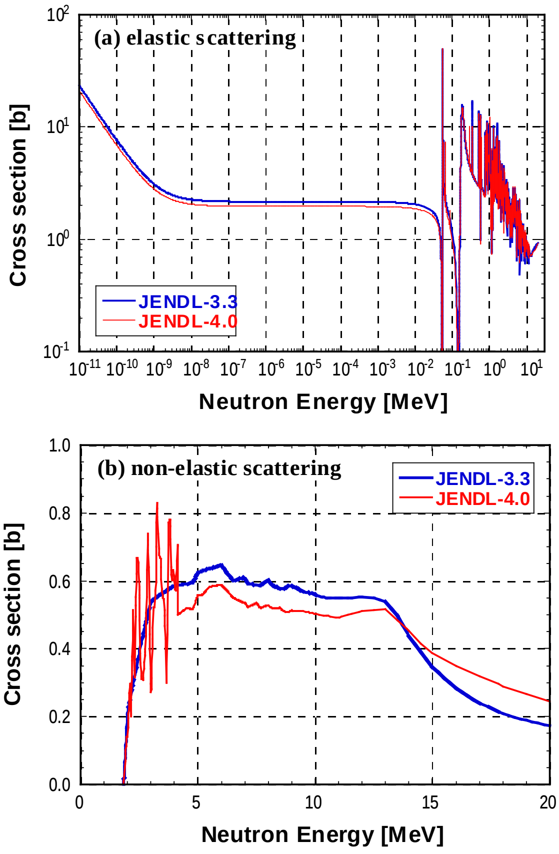

Fig. 9 Cross section data of ^{28}Si.

3. SiC Experiment

The main modifications of the ^{nat}C data from JENDL-3.3 to JENDL-4.0 are described above. The Si isotope data in JENDL-4.0 were newly evaluated by using the TNG code.[14)] The resolved resonance parameters were taken from ENDF/B-VII.0. Thus there are many modifications in the Si isotope data of JENDL-4.0. As an example, the total and non-elastic scattering cross section data of ^{28}Si, the abundance of which is over 90%, are shown in **Fig. 9**. However the difference between the calculation results with JENDL-3.3 and -4.0 for the SiC in-situ experiment is small as shown in **Fig. 10**.

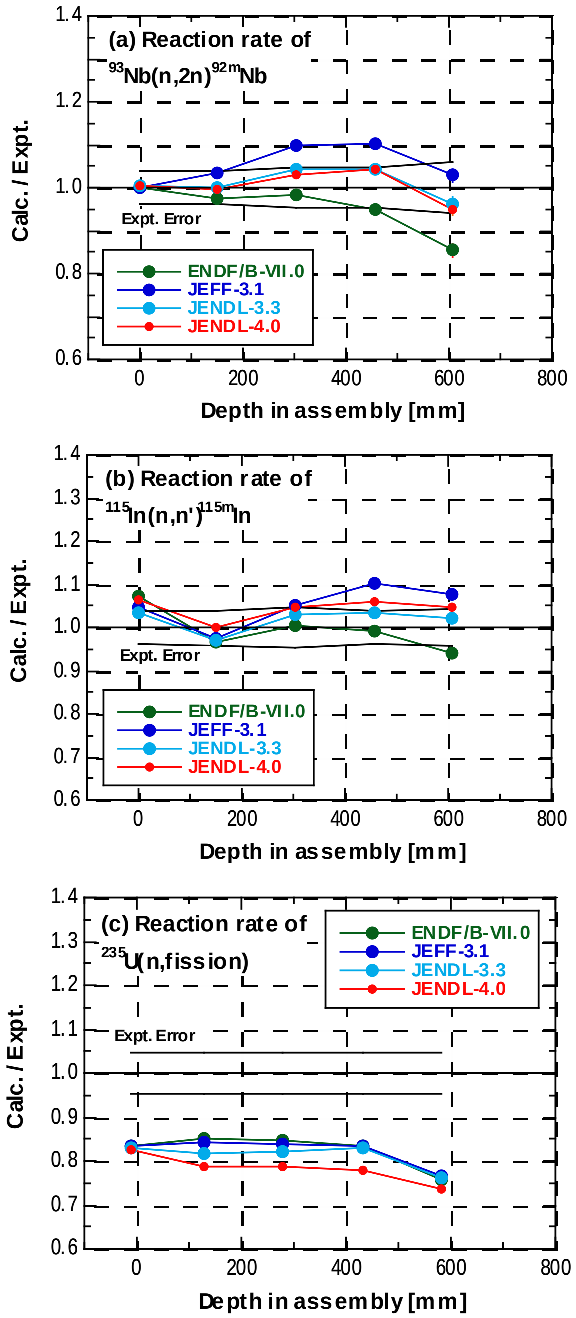

Fig. 10 C/E in SiC in-situ experiment.

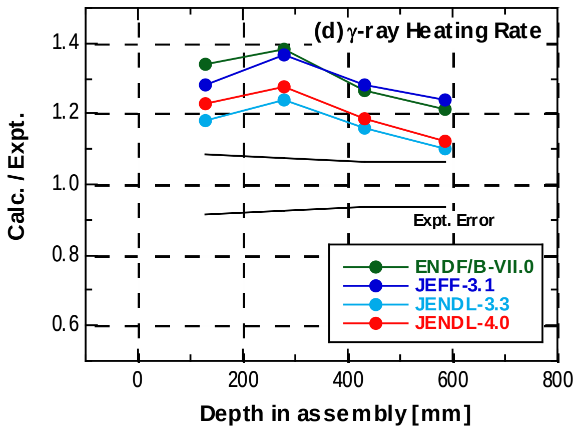

Fig. 10 (Continued).

4. Vanadium Experiment

The vanadium data in JENDL-4.0 were newly evaluated as ^{50}V (abundance : 0.25%) and ^{51}V (abundance : 99.75%) by using the CCONE code,[15] while those in JENDL-3.3 were evaluated as ^{nat}V. There are many modifications in the vanadium in JENDL-4.0 as shown in **Fig. 11**.

The calculation results for the vanadium in-situ experiment are compared with the measurement in **Figs. 12** and **13**. The underestimation for the reaction rate of the ^{115}In(n,n')^{115m}In reaction and for neutrons below a few keV in the calculation result with JENDL-3.3 is slightly improved in that with JENDL-4.0.

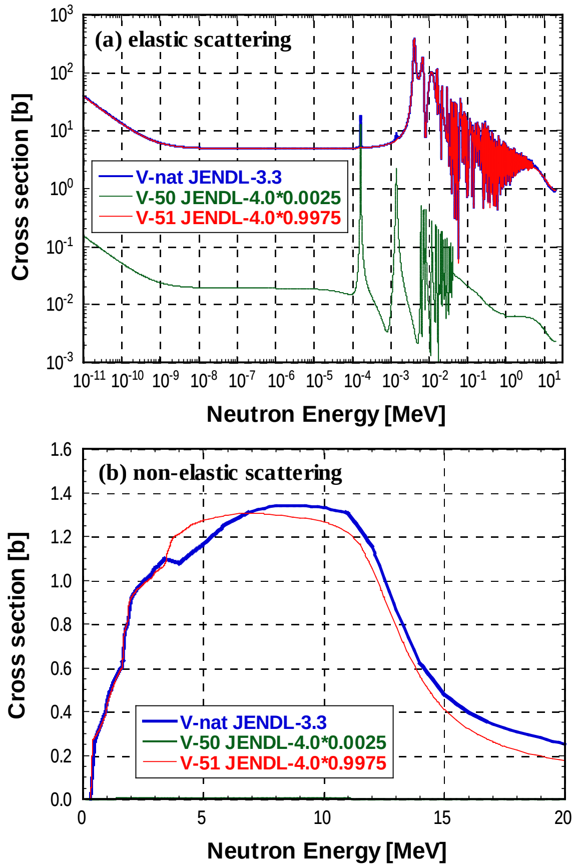

Fig. 11 Cross section data of V.

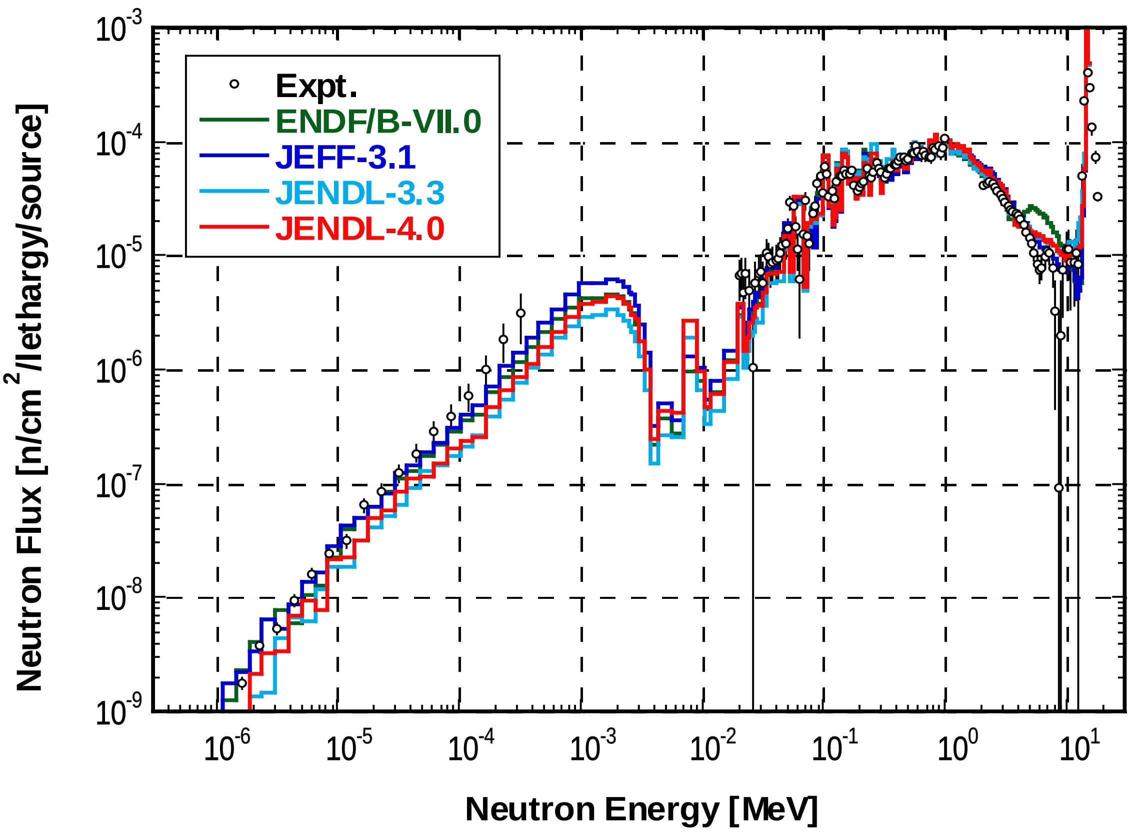

Fig. 12 Neutron spectra at depth of 78 mm in vanadium in-situ experiment.

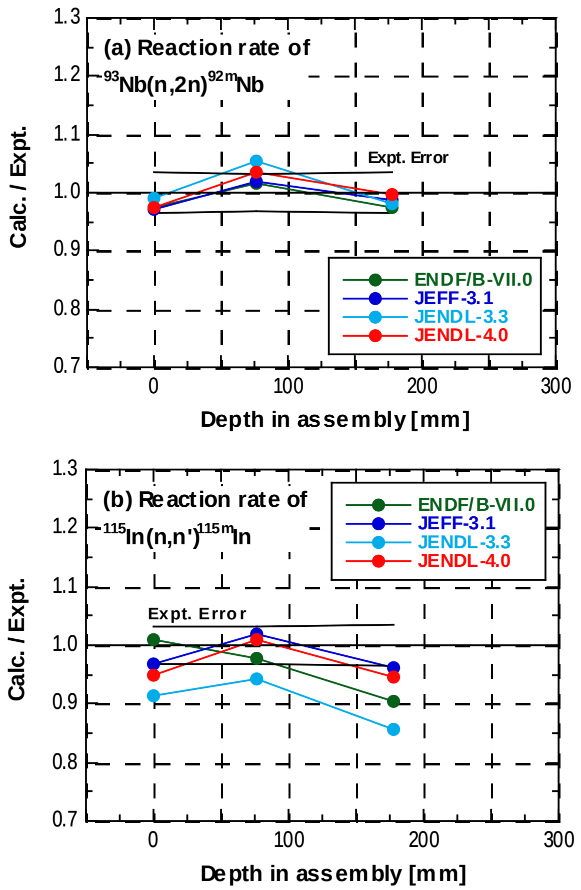

Fig. 13 C/E in vanadium in-situ experiment.

5. Copper Experiment

The modifications of the ^{63}Cu and ^{65}Cu data from JENDL-3.3 to JENDL-4.0 are only the cross section and angular distribution data of the elastic scattering as shown in **Figs. 14** and **15**.

The calculation results for the copper in-situ experiment are compared with the measured ones in **Figs. 16** and **17**. It is noted that the overestimation for neutrons from 10 keV to 100 keV in the calculation result with JENDL-3.3 reduces in that with JENDL-4.0, while the underestimation for neutrons below 1 keV in that with JENDL-3.3 is slightly enhanced in that with JENDL-4.0.

6. Tungsten Experiment

The tungsten isotope data in JENDL-4.0 were newly evaluated with CCONE. There are many modifications in the tungsten isotope data in JENDL-4.0. Particularly the (n,2n) reaction cross section data of the tungsten isotopes in JENDL-4.0 are different from those in JENDL-3.3 as shown in **Fig. 18**.

The calculation results for the tungsten in-situ experiment are compared with the measured ones in **Figs. 19** and **20**. The underestimation for the reaction rate of the ^{115}In(n,n')^{115m}In reaction in the calculation result with JENDL-3.3 is improved in that with JENDL-4.0, while neutrons above 10 MeV are slightly overestimated with the depth in the calculation result with JENDL-4.0.

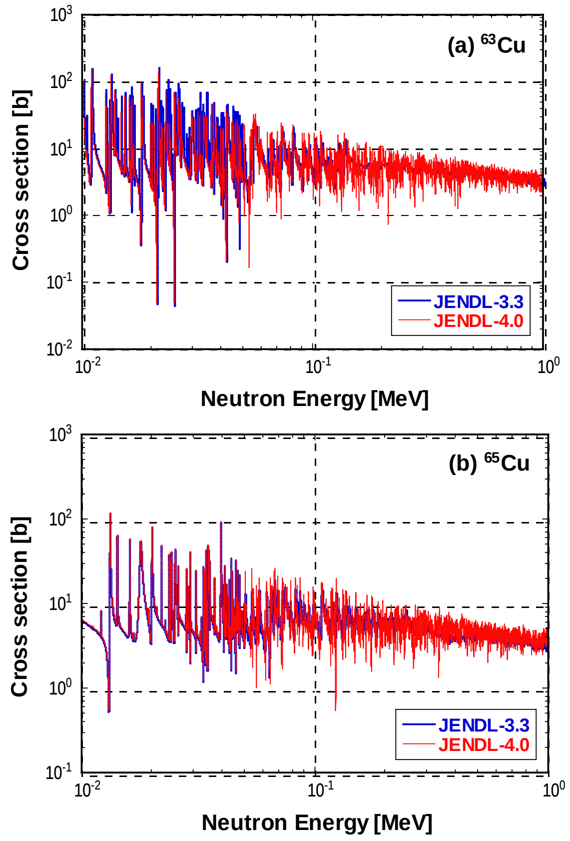

Fig. 14 Elastic scattering cross section data of Cu isotopes.

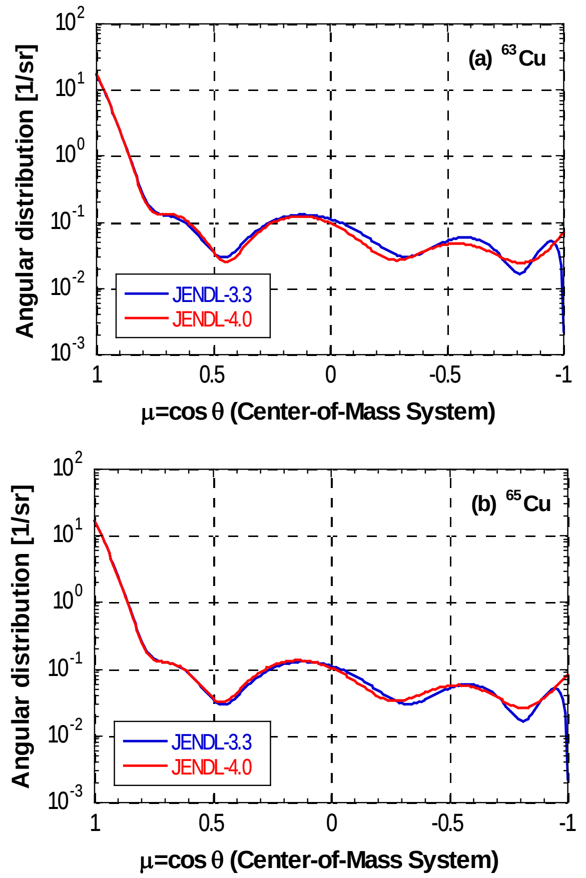

Fig. 15 Angular distribution data of elastic scattering of Cu isotopes for 15 MeV neutron.

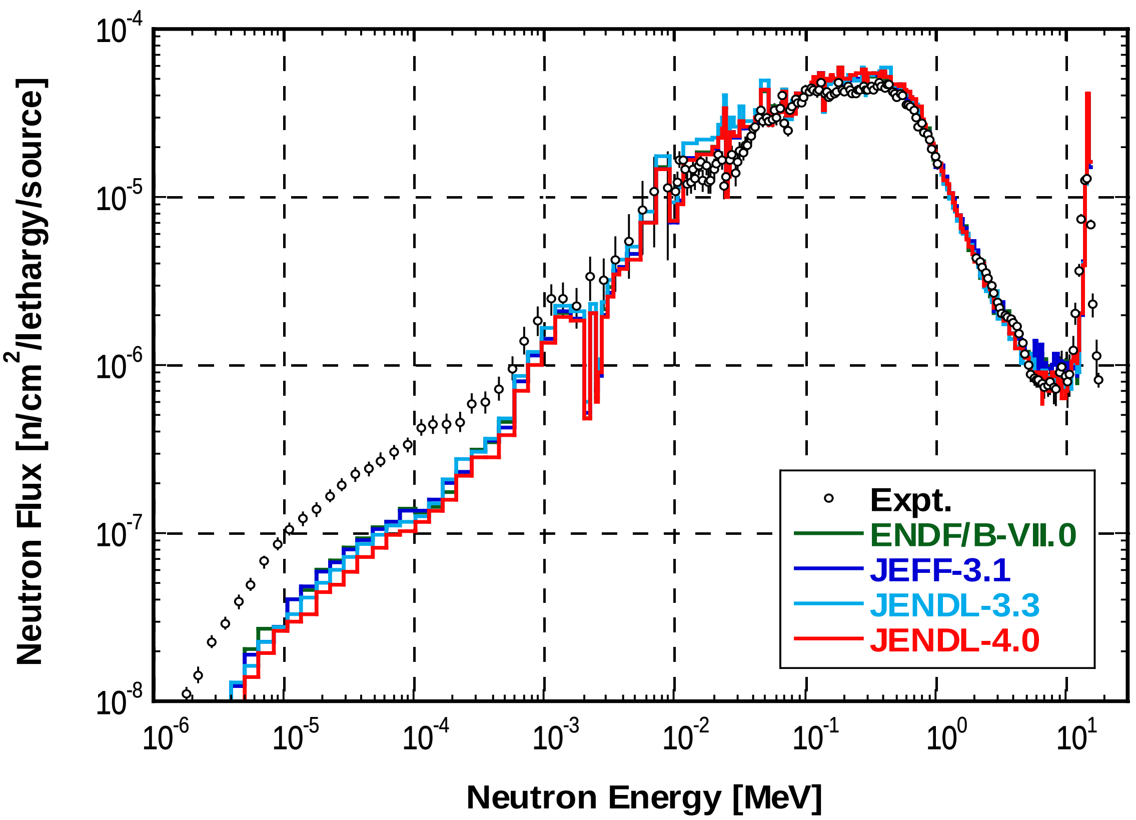

Fig. 16 Neutron spectra at depth of 228 mm in copper in-situ experiment.

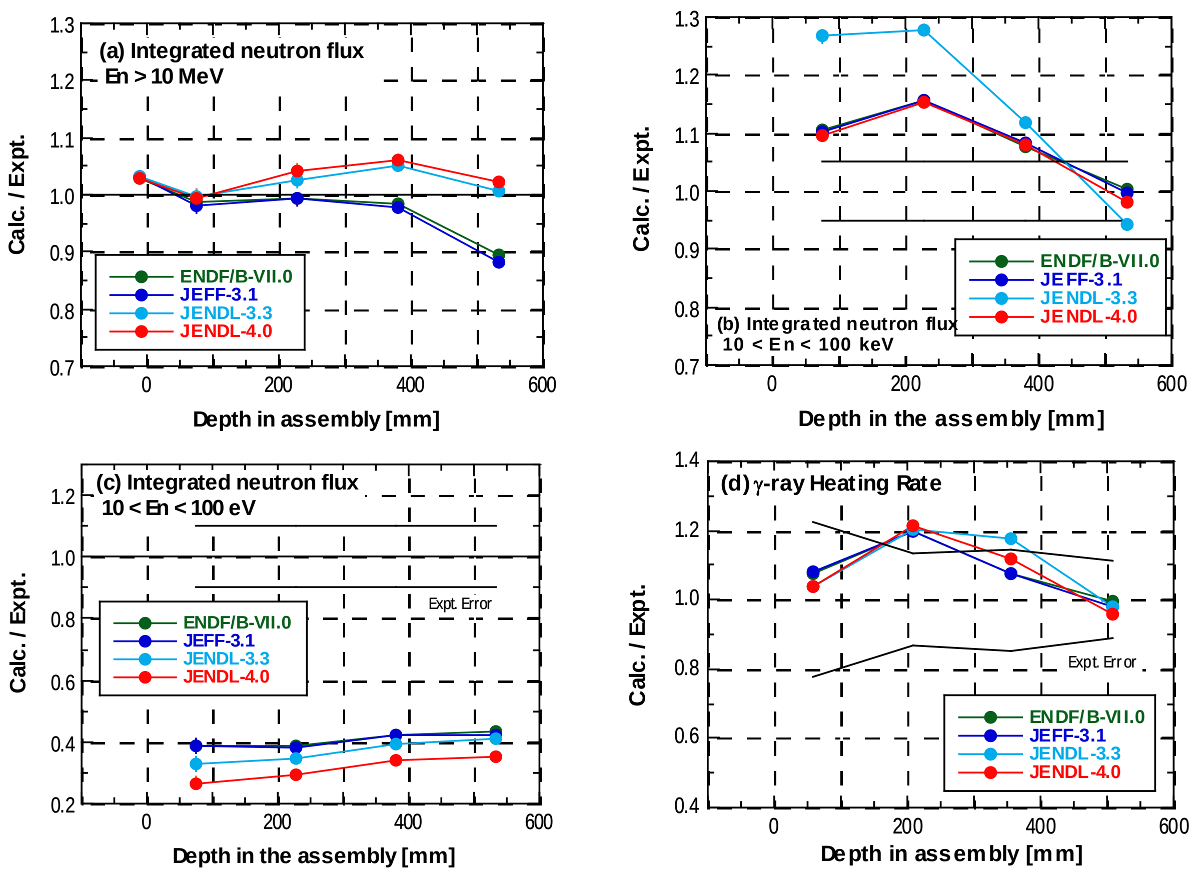

Fig. 17 C/E in copper in-situ experiment.

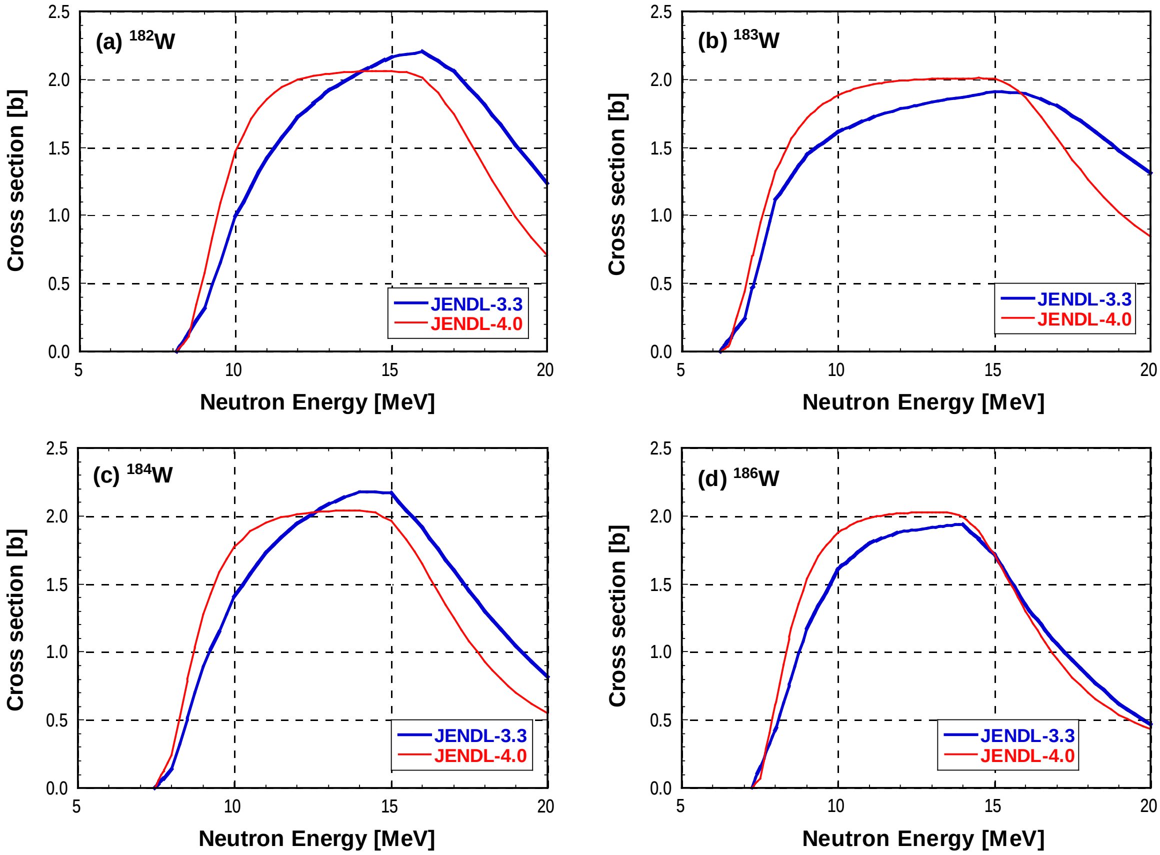

Fig. 18 (n,2n) reaction cross section data of W isotopes.

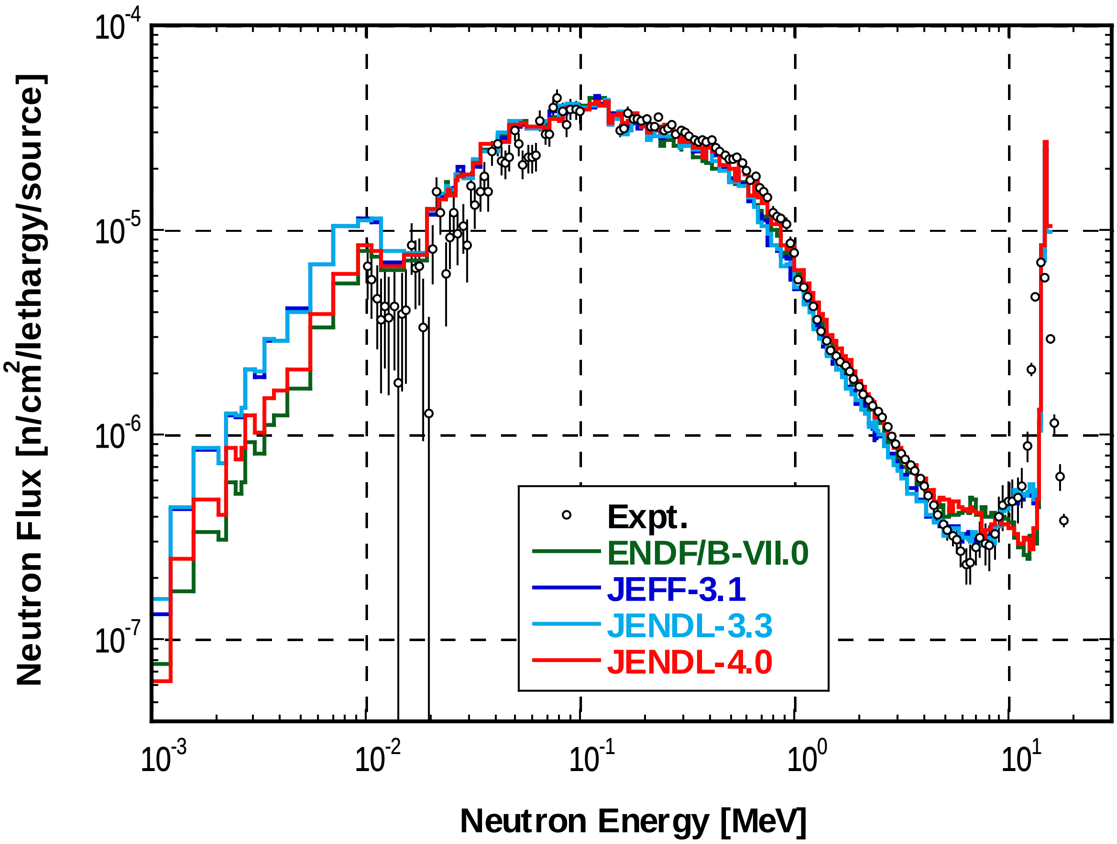

Fig. 19 Neutron spectra at depth of 228 mm in tungsten in-situ experiment.

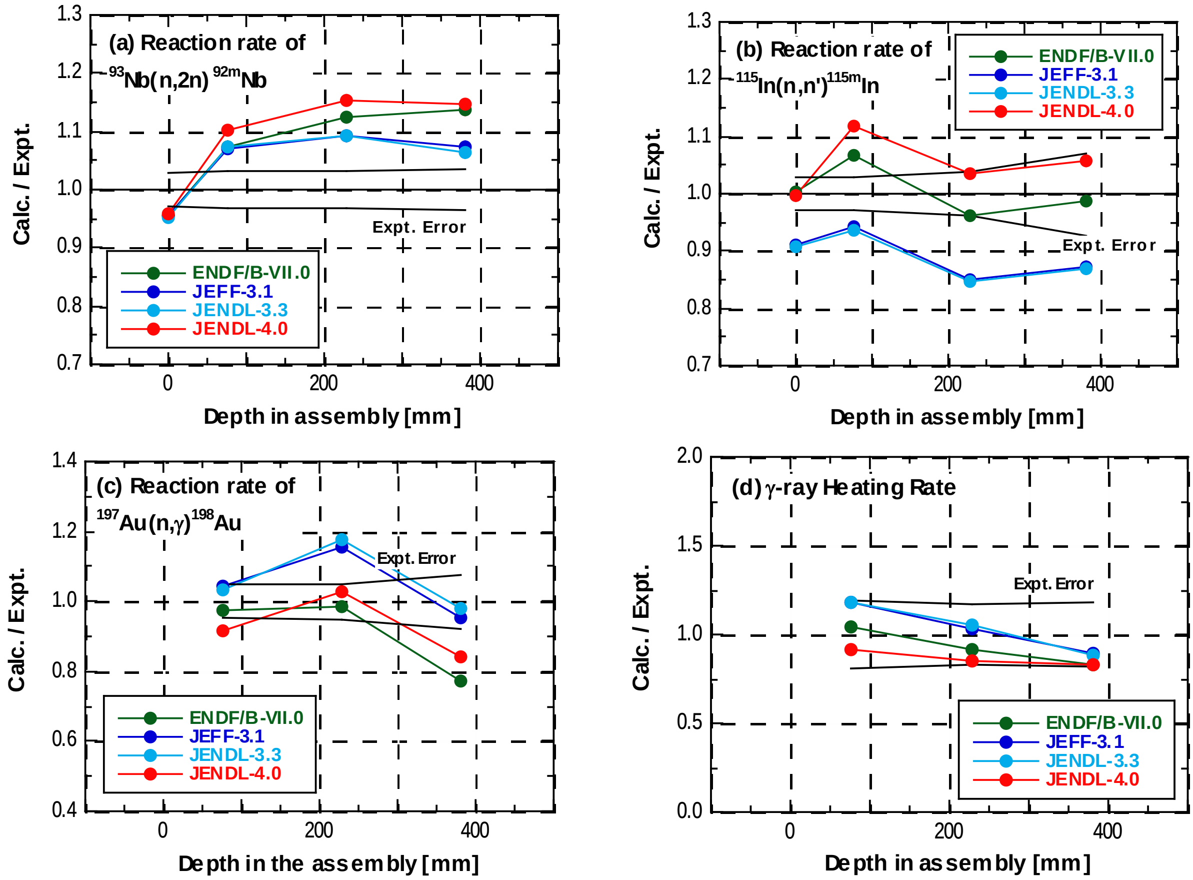

Fig. 20 C/E in tungsten in-situ experiment.

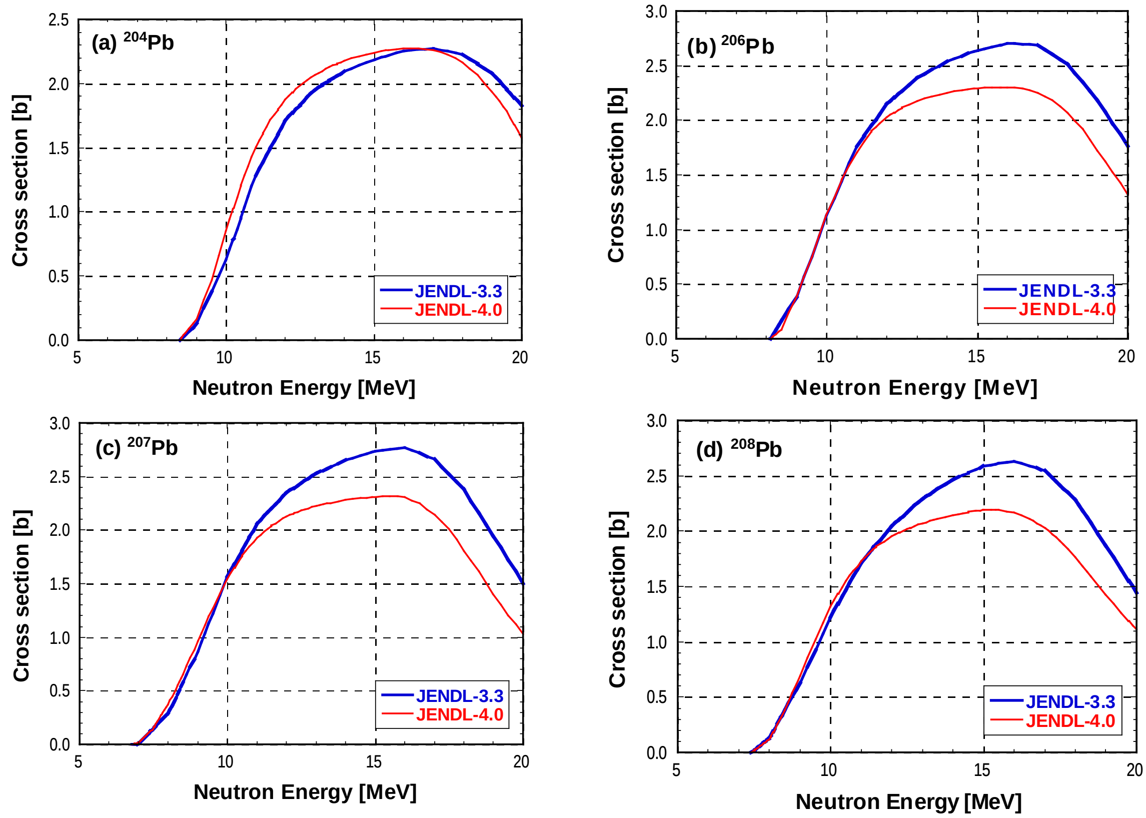

Fig. 21 (n,2n) reaction cross section data of Pb isotopes.

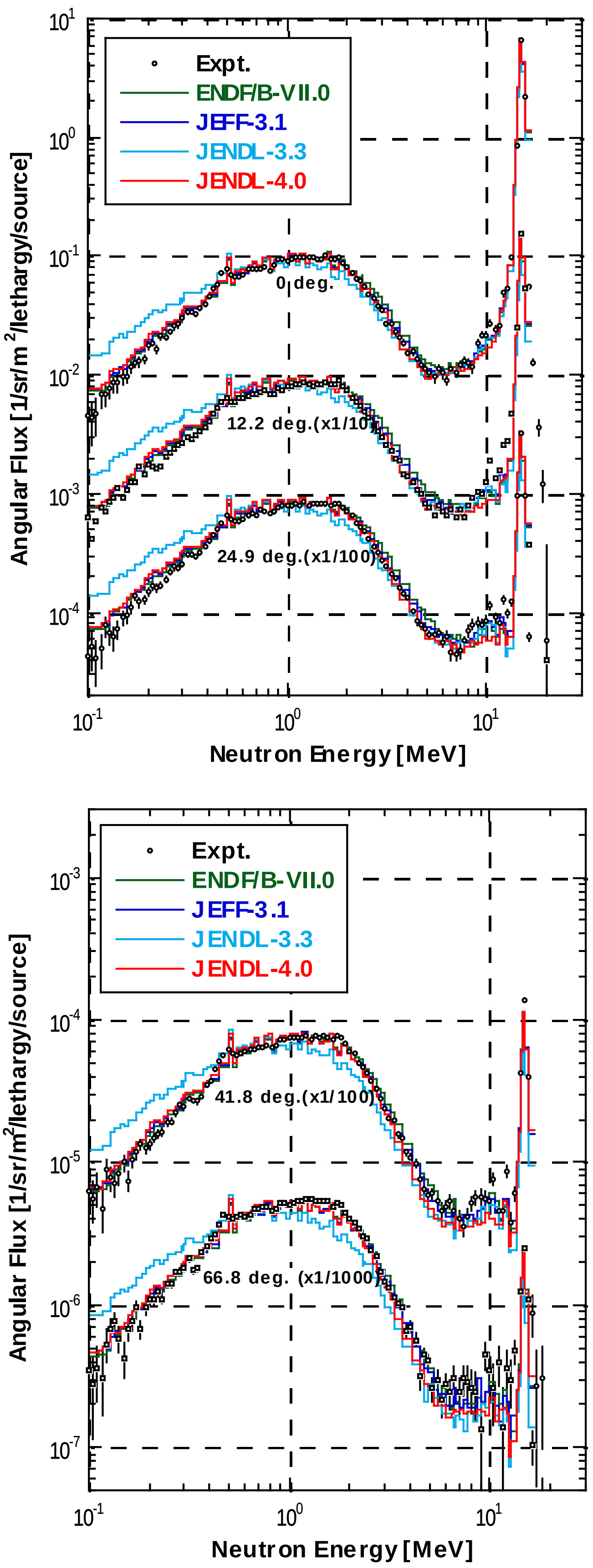

Fig. 22 Angular neutron spectra leaking from lead slab of 203 mm in thickness in lead TOF experiment.

7. Lead Experiment

The lead isotope data in JENDL-4.0 were also newly evaluated with CCONE. There are many modifications in the lead isotope data in JENDL-4.0. Particularly the (n,2n) reaction cross section data of the lead isotopes in JENDL-4.0 are different from those in JENDL-3.3 as shown in **Fig. 21**.

The calculation results for the lead TOF experiment are compared with the measured ones in **Fig. 22**. The underestimation for neutrons above 1 MeV and the overestimation for neutrons below 1 MeV in the calculation result with JENDL-3.3 are resolved in that with JENDL-4.0.

V. Conclusion

We analyzed the fusion neutronics integral experiments at JAEA/FNS with JENDL-4.0 as one of benchmark tests of JENDL-4.0 released in May, 2010. Through the comparison with the calculation results with JENDL-3.3, the followings are found out.

1) Beryllium experiments : The overestimation for the reaction rates of the ^{6}Li(n,α)T and ^{235}U(n, fission) reactions, which are mainly sensitive to thermal neutrons, in the calculation result with JENDL-3.3 by ~ 5% reduces in that with JENDL-4.0.
2) Graphite and SiC experiments : The calculation results with JENDL-4.0 are almost the same as those with JENDL-3.3.
3) Vanadium experiment : The underestimation for the reaction rate of the ^{115}In(n,n')^{115m}In reaction and for neutrons below a few keV in the calculation result with JENDL-3.3 is slightly improved in that with JENDL-4.0.
4) Copper experiment : The overestimation for neutrons from 10 keV to 100 keV in the calculation result with JENDL-3.3 reduces in that with JENDL-4.0, while the underestimation for neutrons below 1 keV in that with JENDL-3.3 is slightly enhanced in that with JENDL-4.0.
5) Tungsten experiment : The underestimation for the reaction rate of the ^{115}In(n,n')^{115m}In reaction in the calculation result with JENDL-3.3 is improved in that with JENDL-4.0, while neutrons above 10 MeV are slightly overestimated with the depth in the calculation result with JENDL-4.0.
6) Lead experiment : The underestimation for neutrons above 1 MeV and the overestimation for neutrons below 1 MeV in the calculation result with JENDL-3.3 are drastically improved in that with JENDL-4.0.

It is concluded that some problems in JENDL-3.3 are resolved in JENDL-4.0. Moreover it is demonstrated that JENDL-4.0 is comparable to ENDF/B-VII.0 and JEFF-3.1.

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