Integral Benchmark Experiments of the Japanese Evaluated Nuclear Data Library (JENDL)-3.3 for the Fusion Reactor Design

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Abstract. JENDL-3.3 is a neutron cross section data library of 337 nuclei evaluated from the latest experimental data. JENDL-3.3 introduces double differential cross sections, which are energy- and angle-dependent ones of the scattered secondary neutrons, and are important for anisotropic neutron transport calculations for the fusion reactors design. This paper overviews benchmark experiments carried out for key fusion related nuclei such as Iron and Vanadium, and the results of analyses with JENDL-3.3, together with JENDL-3.2 and FENDL-2 for a comparison purpose. The experiments have been carried out at the Fusion Neutron Source (FNS) of JAERI. During the neutron injection into the assemblies, neutron and secondary gamma-ray spectra have been measured inside and outside the assemblies. For the test assemblies, we have used Iron, Copper, Vanadium and Tungsten as a single element material, and $LiAlO_2$ and SiC as a compound material. From the integral benchmark experiments it was confirmed that the accuracy of JENDL-3.3 has been improved well compared with JENDL-3.2 and FENDL-2 by the re-evaluation using latest experimental data, and JENDL-3.3 is suitable for the nuclear analysis of the fusion reactor.

1. Introduction

The precise evaluation of the nuclear heating rate and the radiation dose rate is one of the most important issues on the ITER machine design. For the DEMO reactor and fusion power reactors, the design of the blanket whose tritium breeding ratio is more than unity is a critical issue to provide tritium by themselves. Those nuclear design works rely not only on computational tools but also nuclear data libraries.

Many efforts have been conducted on the development of nuclear data libraries for the fusion application, notably in EU (European Fusion File, EFF[1]) and in Japan (Japanese Evaluated Nuclear Data Library – Fusion File, JENDL-FF[2]). JENDL-FF includes 82 nuclides data with double differential cross-sections, which are energy- and angle-dependent ones of the scattered secondary neutrons and are important for anisotropic neutron transport calculations for the fusion reactors design. In US and the Russian Federation, nuclear data evaluations applicable for the fusion have been integrated to the general purpose nuclear data files ENDF/B-VI and BROND, respectively. IAEA compiled the Fusion Evaluated Nuclear Data Library, FENDL [3] based on the existing nuclear data files mentioned above. Now the present version FENDL-2 [4] is in use as standard data library for fusion design applications.

In Japan, a general purpose nuclear library JENDL-3.2 [5] has been revised to JENDL-3.3 [6], which is a neutron cross section data of 337 nuclei evaluated from the latest experimental data. JENDL-3.3 introduces double differential cross sections from JENDL-FF with some revision. Also it employs cross section data for each isotope, and co-valiance data which is necessary for uncertainty analyses of the nuclear design such as a tritium breeding ratio. This paper overviews benchmark experiments carried out for key fusion related nuclei such as Iron and Vanadium, and the results of analyses with JENDL-3.3, together with JENDL-3.2 and the FENDL-2.

2. Experiment

The experiments have been carried out at the Fusion Neutron Source (FNS) [7] of JAERI Tokai, which is an accelerator based 14 MeV neutron generator. Slab assemblies of fusion related materials, with geometry several times thicker than the mean free pass of 14 MeV neutrons, have been installed in front of the tritium target for the neutron generation. Figure 1 shows the typical experimental arrangement.

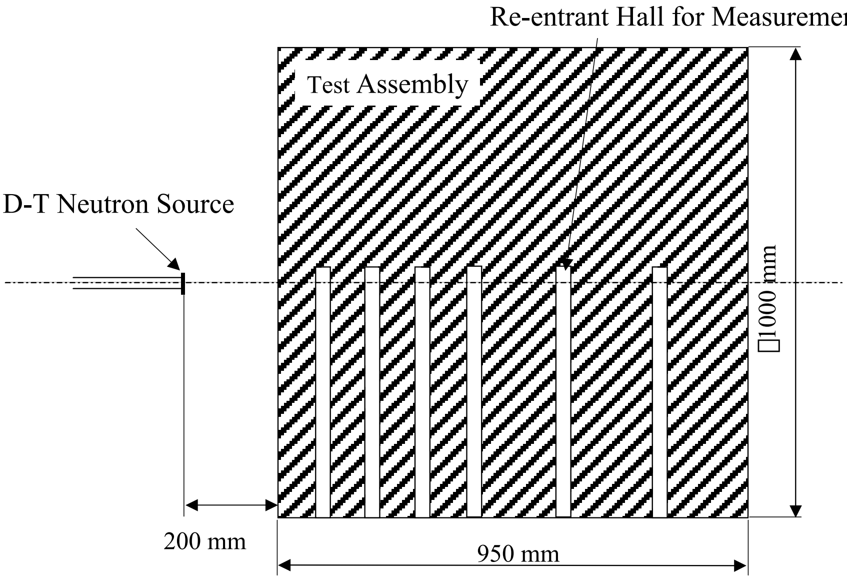

FIG. 1. The schematic view of the typical arrangement for the integral benchmark experiments.

During the neutron injection into the assemblies, neutron and secondary gamma-ray spectra have been measured inside and outside the assemblies. The neutron spectrum has been measured with a NE213 liquid scintillation detector in the energy range above 1 MeV, and a proton recoils counter(PRC) in the energy range 10 keV - 1 MeV. Figure 2 shows a schematic view of the compact NE213 liquid scintillation detector to be inserted into the re-entrant hall of the assembly for the inside neutron spectrum measurement. In some experiments, slowing down time (SDT) method has been employed for neutron spectra in the energy range 0.3 - 10 keV. The γ-ray spectrum has been measured with a BC537 liquid scintillation detector and a NaI scintillation detector. BC537 is a deuterated organic scintillator in order to avoid capture gamma-rays of hydrogen inside the scintillator itself. The typical neutron yield of the FNS neutron generator was approximately 2×10^{11} n/s, which was monitored by the associated alpha particle measurement with a silicon surface barrier diode installed in the beam line.

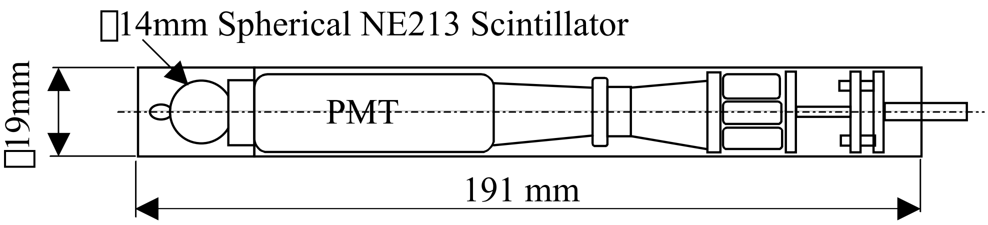

FIG. 2. The schematic view of the compact NE213 liquid scintillation.

For the test assemblies, we have used Iron, Copper, Vanadium and Tungsten as a single element material, and $LiAlO_2$ and SiC as a compound material.

3. Analyses

Results of the benchmark integral experiments were analyzed by a three-dimensional Monte Carlo Code MCNP-4C [8] with JENDL-3.3 and also JENDL-3.2 and FENDL-2. The experimental assembly was 3-dimensionally modeled in MCNP calculations.

4. Results

4.1 Iron

Iron is one of the most important nuclei as a major component of the structural material such as reduced activation ferritic steel. In JENDL-3.3, total cross sections of iron were revised in the energy range of 0.85 – 7 MeV based on the recent measurement. Figure 3 shows the experimental [9] and calculated neutron spectra in the energy range of 10 keV – 1 MeV at the position of 210 mm depth in the iron assembly. Calculated values by JENDL-3.3 show better agreement with the experimental values compared with the results by JENDL-3.2 and FENDL-2 .

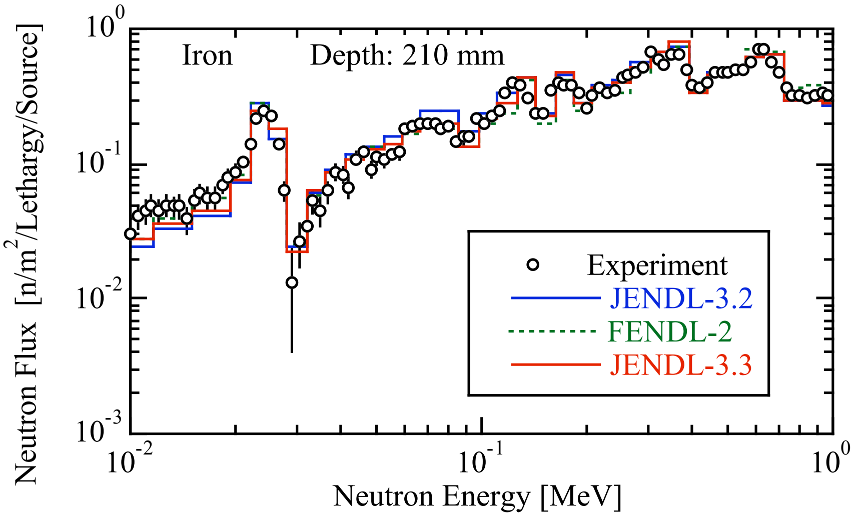

FIG. 3. Neutron spectra in the energy range of 10 keV – 1 MeV in the iron assembly.

The depth distribution of the energetic neutron flux is very important from the radiation shielding point of view. Figure 4 shows the ratio of the calculated value against the experimental one (C/E) for the energetic neutron flux measured by the activation foil method using ^{27}Al(n,α)^{24}Na reaction with a threshold energy of 4.9 MeV, as a function of the depth from the assembly surface. Calculated values by JENDL-3.2 underestimate the energetic neutron flux in deeper position, which is due to the underestimation of elastic scattering cross section for 14 MeV neutrons in JENDL-3.2. In JENDL-3.3, this feature is improved.

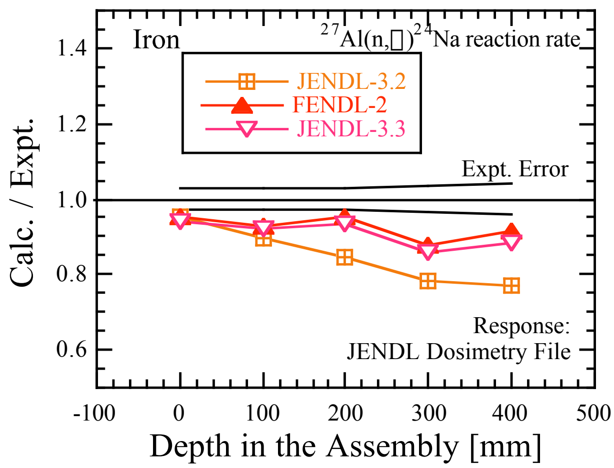

FIG. 4. C/E ratio of ^{27}Al(n,a)^{24}Na reaction rate in the iron assembly.

4.2 Vanadium

Vanadium is a candidate structural material of the liquid metal blanket. Figure 5 shows the experimental [10] and calculated neutron spectra in the energy range of 1 eV – 14 MeV at the position of 178 mm depth in the vanadium assembly. In JENDL-3.3, cross sections of vanadium were re-evaluated at the whole energy region. In the energy range of 10 keV – 14 MeV, there is a good agreement among the experimental values and calculated values with JENDL-3.2 and FENDL-2 which is equivalent to JENDL-3.2 for vanadium. Calculated values by JENDL-3.3 still underestimate the measured values by a slowing-down time methods, but show significant improvement relative to JENDL-3.2 and FENDL-2, which is due to the re-evaluation of the cross section around 1 keV for vanadium.

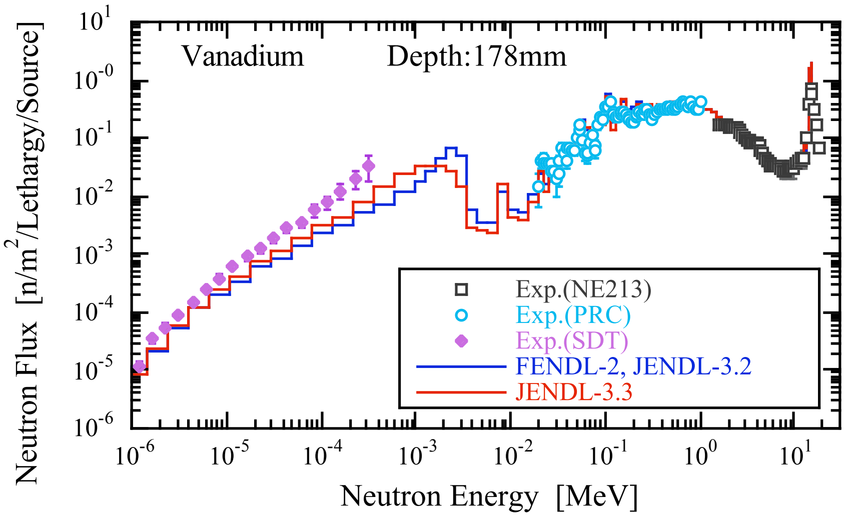

FIG. 5. Neutron spectra in the energy range of 1 eV – 14 MeV in the vanadium assembly.

Figure 6 shows the leakage gamma-ray spectrum from the 101.6 mm thick vanadium slab assembly. The calculated values with FENDL-2 (JENDL-3.2) underestimate the gamma-ray flux in the energy range above 3 MeV. The calculated values with JENDL-3.3 agrees well to the experimental values in the all energy range.

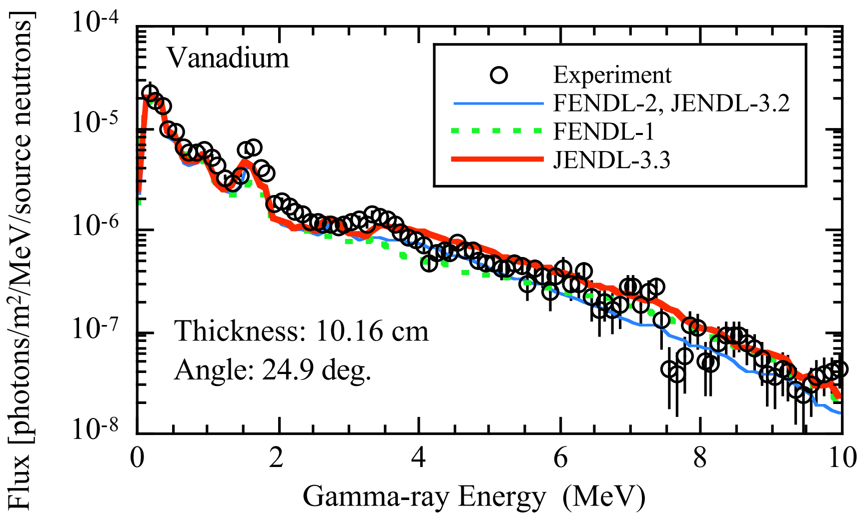

FIG. 6. Leakage gamma-ray spectrum from the 101.6 mm thick vanadium slab assembly.

4.3 Copper

Copper will be used as a heat conduction material in the plasma facing components. Also copper is used in super-conducting coils as a stabilizing material. Figure 7 shows the experimental [9] and calculated neutron spectra in the energy range of 100 keV – 14 MeV at the position of 228 mm depth in the copper assembly. There is a good agreement among the experimental values and calculated ones with JENDL-3.2, -3.3 and FENDL-2.

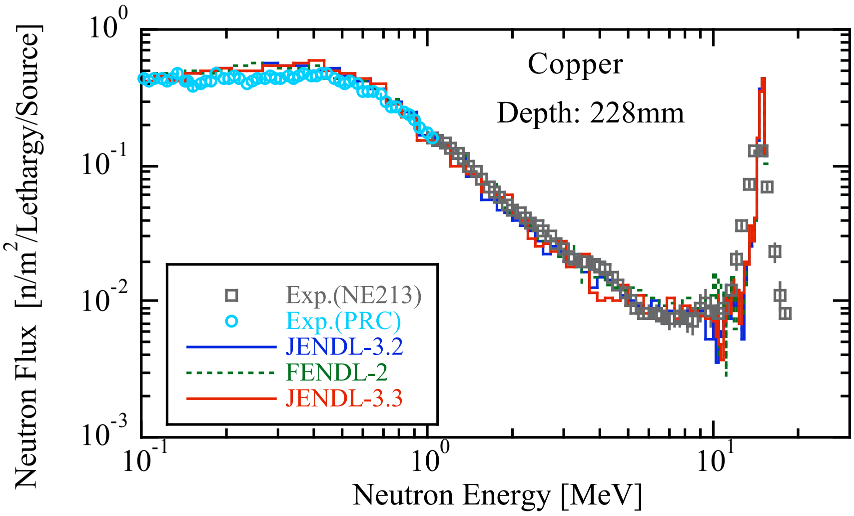

FIG. 7. Neutron spectra in the energy range of 100 keV – 14 MeV in the copper assembly.

4.4 Tungsten

Tungsten is the most promising armor material, and also important component of the ferritic steel F82H. Figure 8 shows the experimental [11] and calculated neutron spectra in the energy range of 1 keV – 14 MeV at the position of 380 mm depth in the tungsten assembly. The calculated values with JENDL-3.3 slightly underestimate the experimental ones in the energy range above 150 keV, whole calculated values with FENDL-2 are a little bit closer to the experimental ones. In the energy range below 150 keV, there is not significant difference among JENDL-3.3, -3.2 and FENDL-2.

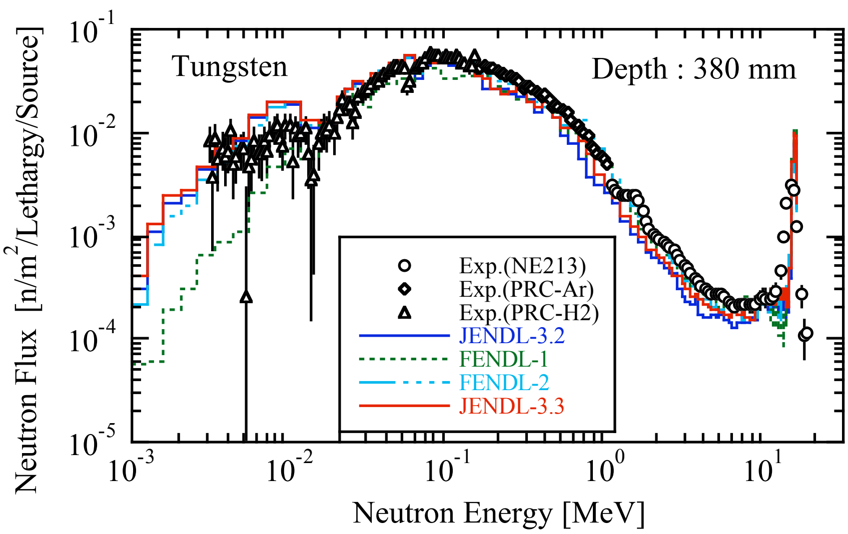

FIG. 8. Neutron spectra in the energy range of 1 keV – 14 MeV in the tungsten assembly.

4.5 Lithium Aluminate

Lithium aluminate ($LiAlO_2$) is a candidate of the tritium breeding material. Figure 9 shows the leakage gamma-ray spectra from 101.6 mm thick $LiAlO_2$ slab [12]. There is a good agreement among the calculated values by three libraries, and experimental values in the neutron spectra. JENDL-3.2 and FENDL-2 calculations underestimate the peak measured at approximately 6 MeV, which is due to the underestimation of a cross section of prompt gamma-ray production from ^{16}O. JENDL-3.3 calculation reproduces well the gamma-ray peak, which indicates the gamma-ray production cross section has been improved well.

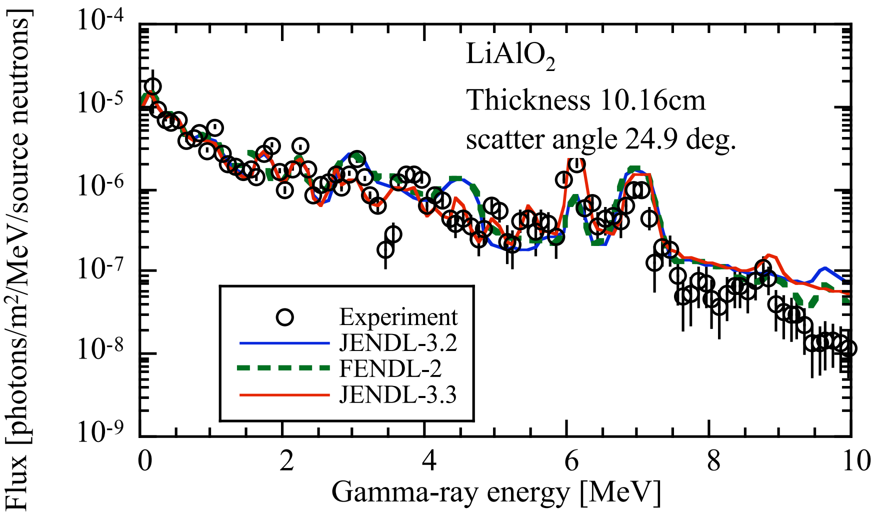

FIG. 9. Leakage gamma-ray spectrum from the 101.6 mm thick $LiAlO_2$ slab assembly.

4.6 Silicon Carbide

Silicon carbide (SiC) composite is one of the most promising candidate of the advanced structural material for the blanket. Figure 10 shows the experimental [13] and calculated neutron spectra in the energy range of 1 keV – 14 MeV at the position of 279 mm depth in the SiC assembly. Generally, there is rather good agreement among the experimental values and calculated ones with JENDL-3.2, -3.3 and FENDL-2. However, all calculations overestimate the neutron spectra in the energy range of 1 – 1.5 MeV, which is now under discussion.

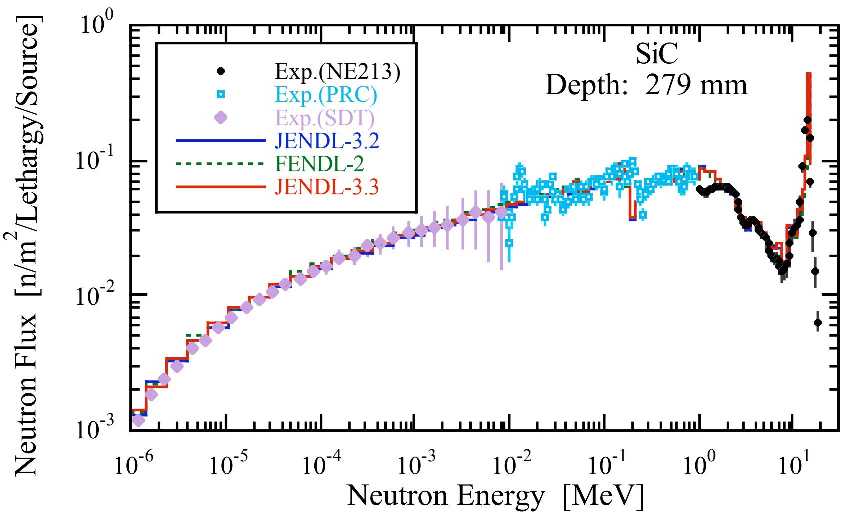

FIG. 10. Neutron spectra in the energy range of 1 eV – 14 MeV in the SiC assembly.

The depth profile of the energetic neutron flux has been measured with the activation foil method. Figure 11 shows the C/E ratio of the $^{93}Nb(n,2n)^{92m}Nb$ reaction rate, whose threshold energy is 9 MeV, as a function of the depth from the assembly surface. Calculated values by JENDL-3.2, -3.3 and –FF coincide each other, and agree with the experimental ones within the experimental error. Calculated values by FENDL-2 slightly underestimate the reaction rate in deeper position, which is due to the underestimation of elastic scattering cross section for 14 MeV neutrons in FENDL-2.

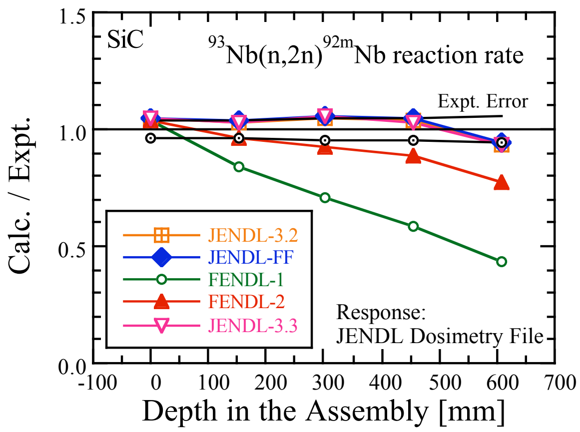

FIG. 11. C/E ratio of $^{93}Nb(n,2n)^{92m}Nb$ reaction rate in the iron assembly.

5. Conclusion

From the integral benchmark experiments it was confirmed that the accuracy of JENDL-3.3 has been improved well compared with JENDL-3.2 and FENDL-2 by the re-evaluation using latest experimental data, and JENDL-3.3 is suitable for the nuclear analysis of the fusion reactor. In response to this improvement, the consultants meeting to maintain FENDL library held in November 2003, at IAEA Vienna has recommended to revise the FENDL-2 library for 17 nuclei, where nuclear data of the JENDL-3.3 is to be applied for 9 nuclei (D, ^{12}C, ^{23}Na, Ti, ^{51}V, ^{55}Mn, Mo, W, ^{181}Ta).

The compilation work of JENDL-4, which is a next version of JENDL-3.3, is already started. We hope some problems of JENDL-3.3 pointed out in this paper will be improved in JENDL-4.

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