Benchmark Experiments on Advanced Breeding Blanket Materials and SiC with 14-MeV Neutrons

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Fusion neutronics benchmark experiments were conducted for a low-activation structural material (SiC) and three advanced tritium breeding blanket materials ($LiAlO_2$, Li_2TiO_3, Li_2ZrO_3). Neutrons and secondary gamma-rays were measured in experimental assemblies with impinging D-T neutrons. Validity of cross section data in recent evaluated nuclear data files were tested by the analyses of the experiment. Serious problems were pointed out in FENDL/E-1.0 for silicon and ENDF/B-VI for zirconium. As far as JENDL Fusion File, JENDL-3.2 and FENDL/E-2.0 were concerned, no significant problems were found for the four materials, and these data could be used adequately for fusion reactor designs.

1. Introduction

In recent designs of fusion reactors, use of advanced tritium breeding materials and low-activation structural materials is indispensable to accomplish technically feasible and attractive fusion reactors. However, benchmark tests of nuclear data for these materials have not been performed sufficiently because of lack of benchmark experimental data. To ameliorate this situation, benchmark experiments on three advanced tritium breeding materials ($LiAlO_2$, Li_2TiO_3, Li_2ZrO_3) and a low-activation structural material (SiC) were conducted by using the 14-MeV neutron source facility FNS in JAERI. A part of the experiments for measurements of neutron and gamma-ray spectra leaking from the experimental assemblies are reported elsewhere [1-3]. This paper deals with in-situ measurement experiments and results of benchmark tests with the experimental data for recent evaluated nuclear data files.

2. Experiment and Analysis

Experimental assemblies were produced by piling up sintered blocks in dimensions shown in Fig. 1. Figure 2 shows experimental assembly made of lithium zirconate in a pseudo-cylinder shape of 457 mm in diameter and 577 mm in thickness. D-T neutrons generated by FNS were impinged into the experimental assembly, and neutrons and gamma-rays were measured at several positions in the assembly. Measured quantities were neutron spectra from 14-MeV down to 0.3 eV, reaction rate distributions, gamma-ray spectra and gamma-ray heating rates. These quantities are measured frequently in similar experiments at FNS, and details of the measurements have been described in Ref. [4].

The continuous energy Monte Carlo transport calculation code MCNP-4B [5] was used for experimental analysis. Evaluated nuclear data files tested were JENDL-3.2 [6], JENDL Fusion File [7] (hereafter, JENDL-FF), ENDF/B-VI [8], FENDL/E-1.0 [9] and FENDL/E-2.0 [10]. Cross section data for some of elements in JENDL Fusion File, and all the data in FENDL/E-1.0 and FENDL/E-2.0 originated in other data sources as shown in Table 1.

3. Results and Discussion

3.1. Silicon Carbide (SiC)

Figure 3 compares measured and calculated neutron spectra at a 432 mm depth in the SiC assembly. Results by JENDL-FF and FENDL/E-2.0 agree satisfactory with the experimental data. The FENDL/E-1.0 calculation gives neutron flux intensity above 10 keV smaller than the measured values. This reason can be attributed to elastic scattering cross section of silicon at ~ 14-MeV as shown in Fig. 4. Total cross section in the three data files are close to each other while elastic scattering cross section in FENDL/E-1.0 at 14-MeV, ~ 0.5 b, is much smaller than the other values, ~ 0.75 b. When a 14-MeV neutron is scattered elastically, a produced secondary neutron is most likely to penetrate toward deep inside of the SiC assembly compared with secondary neutrons produced by other nuclear reactions. This is due to the anisotropic angular distribution of secondary neutrons for the elastic scattering reaction that is enhanced to forward directions. Hence, when the silicon data in FENDL/E-1.0 are used, the 14-MeV neutron flux is calculated smaller as penetration thickness increases compared with other two data files. The experimental results indicate that the elastic scattering cross section in FENDL/E-1.0 is too small.

Another problem is found in the silicon data in FENDL/E-1.0. Neutron fluxes below 1 MeV calculated with FENDL/E-1.0 near the D-T neutron source are larger than the experimental data. Figure 5 compares double differential neutron emission cross section (DDX) of silicon at 14.1 MeV in the three data files with the experimental data [11]. There is a strange peak below 1 MeV in the DDX of FENDL/E-1.0, and this is the reason for the overestimation of neutron fluxes below 1 MeV.

No problem is found in secondary gamma-ray data in all the data files tested.

3.2. Lithium Titanate (Li_2TiO_3)

Since neutron transport cross section for Li_2O has been already validated in previous benchmark studies [12], benchmarking on Li_2TiO_3, Li_2ZrO_3 and $LiAlO_2$ is suitable for testing cross section data for Ti, Zr and Al, respectively. As for secondary gamma-rays, a problem has been pointed out [3] in oxygen data in JENDL-3.2 that the most prominent gamma-ray peak at 6.13 MeV produced by 14-MeV neutron interaction with ^{16}O is given much smaller. This affects on calculated results for gamma-rays for the three blanket materials commonly when the oxygen data in JENDL are used.

Figure 6 compares measured and calculated neutron spectra at a 279 mm depth in the lithium titanate assembly. All the calculations give nearly the same results, and they agree well with the experimental data. The good agreements are consistent with results of the leakage neutron spectrum measurement above 50 keV at FNS [1, 2]. On the other hand, overestimation of calculated neutron fluxes in an energy region of 0.1 - 1 MeV by more than 50 % is reported [12] for the OKTAVIAN pulsed sphere experiment on titanium. The FNS and OKTAVIAN experiments are inconsistent each other, and there might be a problem in the OKTAVIAN experiment on titanium if we rely on the FNS experiments.

3.3. Lithium Zirconate (Li_2ZrO_3)

Neutron spectra at a 177 mm depth in the lithium zirconate assembly measured and calculated are shown in Fig. 7. Figure 8 shows ratios of calculated to experimental reaction rates (C/E values) for the $^{93}Nb(n,2n)^{92m}Nb$, $^{115}In(n,n')^{115m}In$ and $^{235}U(n,fission)$ reactions which are mainly sensitive to 14-MeV, 1 - 10 MeV and eV - keV neutrons, respectively. The calculation with ENDF/B-VI overestimates 14-MeV neutron fluxes with penetration depth increases as indicated in the $^{93}Nb(n,2n)^{92m}Nb$ reaction rate. The reason is that the elastic scattering cross section at 14 MeV for Zr is given larger in ENDF/B-VI. The overestimation of the $^{115}In(n,n')^{115m}In$ reaction rate by ENDF/-VI is attributed to inadequate DDX data at

14-MeV for Zr. Although slight overestimation of neutron fluxes in an energy range from 0.1 to 10 MeV is found in the JENDL-FF and FEND/E-2.0 calculations, it is not so significant. These results for MeV energy neutrons are consistent with the leakage neutron spectrum measurement [1, 2].

Although low energy neutron fluxes are calculated smaller than the experimental values as shown in Fig. 7 and the $^{235}U(n,fission)$ reaction rate in Fig. 8, the reason has not been identified.

3.4. Lithium Aluminate ($LiAlO_2$)

Figure 9 compares measured and calculated neutron spectra at a 279 mm depth in the lithium aluminate assembly. All the calculations give nearly the same results, and they agree almost satisfactory with the experimental data. The good agreements are consistent with results of the leakage neutron spectrum measurement [1, 2] and the OKTAVIAN pulsed sphere experiment [12].

4. Summary

Fusion neutronics benchmark experiments were conducted for a low-activation structural material (SiC) and three advanced tritium breeding blanket materials ($LiAlO_2$, Li_2TiO_3, Li_2ZrO_3). As a result of benchmark tests for cross section data in recent evaluated nuclear data files, serious problems were pointed out in FENDL/E-1.0 for silicon and ENDF/B-VI for zirconium. As far as JENDL Fusion File, JENDL-3.2 and FENDL/E-2.0 were concerned, no significant problems were found for the four materials, and these data could be used adequately for fusion reactor designs.

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Table 1 Origin of cross section data for each element in the five evaluated nuclear data files.

Evaluation	Si	C	Li	O	Al	Ti	Zr
JENDL-3.2	J-3.2	J-3.2	J-3.2	J-3.2	J-3.2	J-3.2	J-3.2
JENDL Fusion File	J-FF	J-FF	J-3.2	J-3.2	J-FF	J-FF	J-FF
ENDF/B-VI	B6	B6	B6	B6	B6	B6	B6
FENDL/E-1.0	BROND	B6	B6	B6	J-3.1	J-3.1	BROND
FENDL/E-2.0	B6	J-FF	B6	J-3.2	J-3.1	J-3.1	J-FF

J-3.1: JENDL-3.1 J-3.2: JENDL-3.2 J-FF: JENDL Fusion File
B6: ENDF/B-VI BROND: BROND-2

SiC
Sintered blocks, 3.16 g/cc
457 mm x 457 mm, 711 mm ^{t}

Li_2TiO_3
Sintered blocks, 2.77 g/cc
254 mm x 254 mm, 254 mm ^{t}

Li_2ZrO_3
Sintered blocks, 3.72 g/cc
475 mm ϕ, 577 mm ^{t}

$LiAlO_2$
Sintered blocks, 1.98 g/cc
254 mm x 254 mm, 254 mm ^{t}

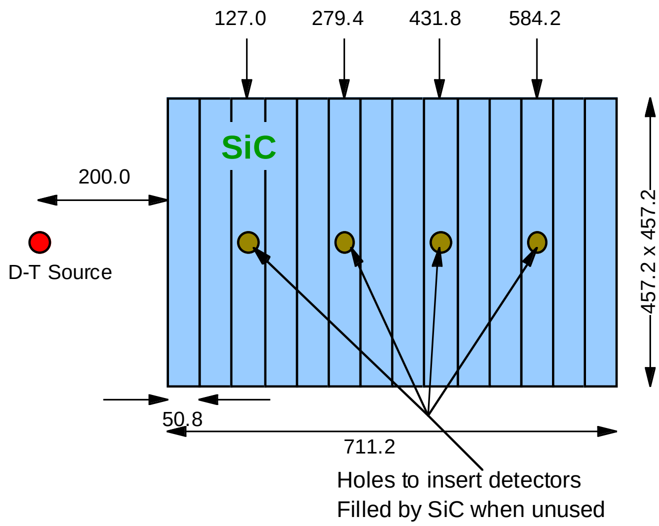

Fig. 1 Specifications for the experimental assemblies (left) and a schematic drawing of the SiC assembly (right).

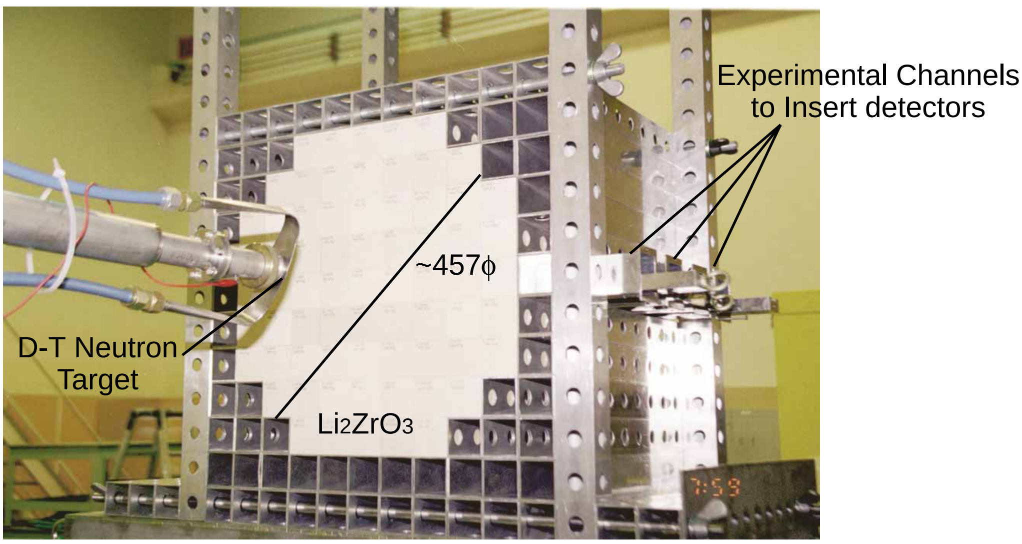

Fig. 2 Experimental assembly made of lithium zirconate.

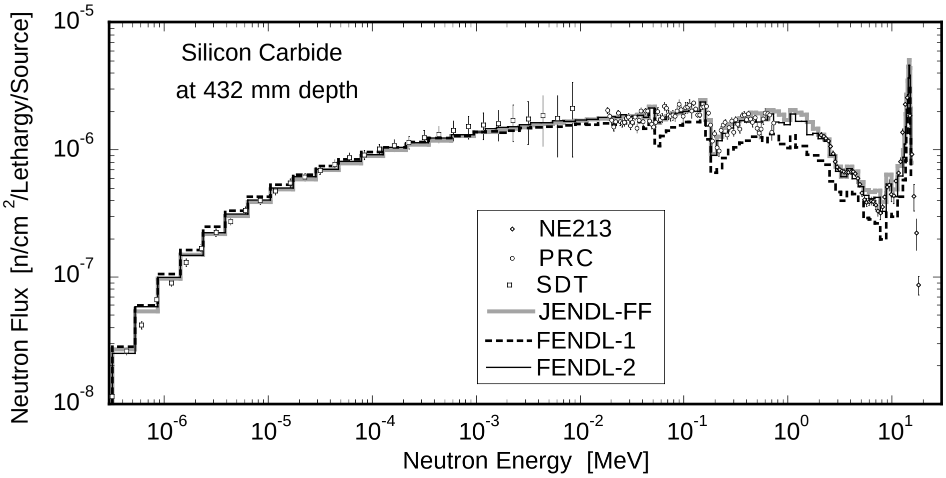

Fig. 3 Neutron spectra in the silicon carbide (SiC) assembly measured and calculated with three cross section files.

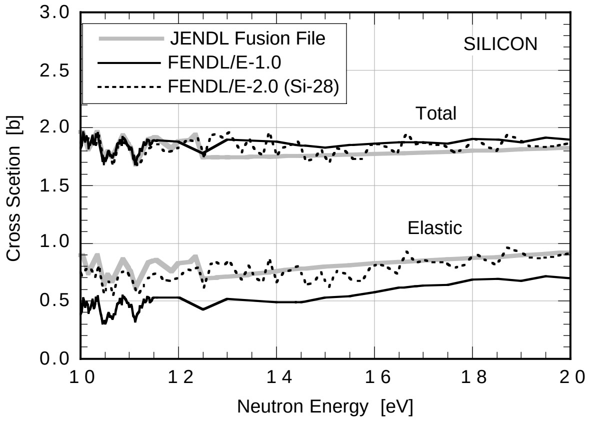

Fig. 4 Total and elastic scattering cross sections of silicon in JENDL Fusion File, FENDL/E-1.0 and FENDL/E-2.0. Data for the main silicon isotope (Si-28, 92.2 %) are plotted for FENDL/E-2.0 instead of silicon data in natural abundance.

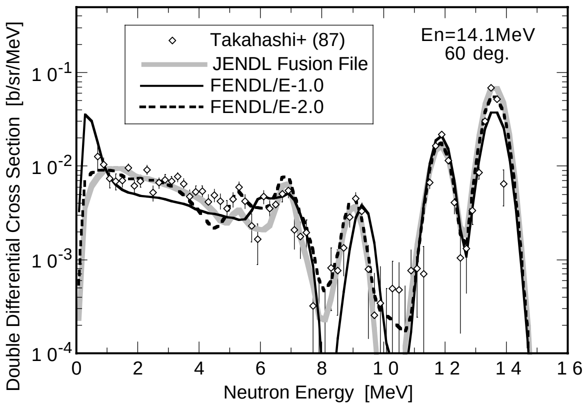

Fig. 5 Double differential neutron emission cross section of silicon at En=14.1 MeV for a scattering angle of 60 degrees measured by Takahashi, et al. [11] and that in the three cross section files .

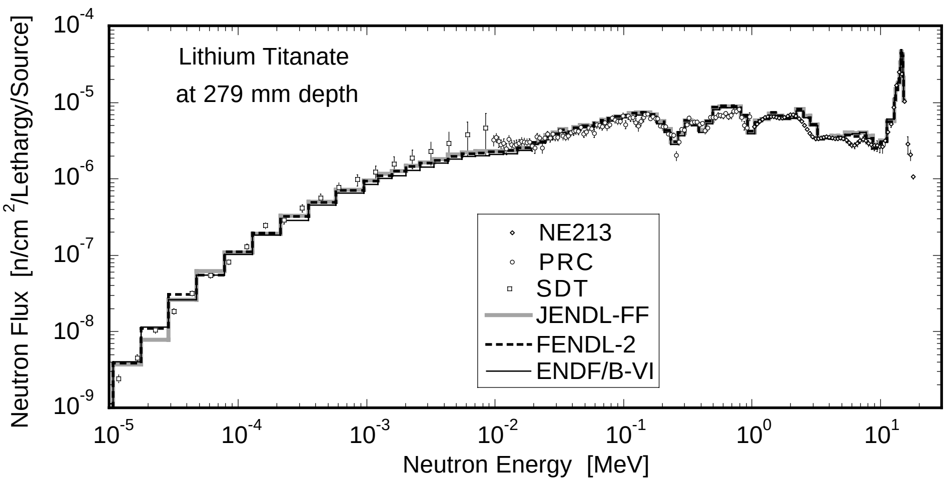

Fig. 6 Neutron spectra in the lithium titanate (Li_2TiO_3) assembly measured and calculated with three cross section files.

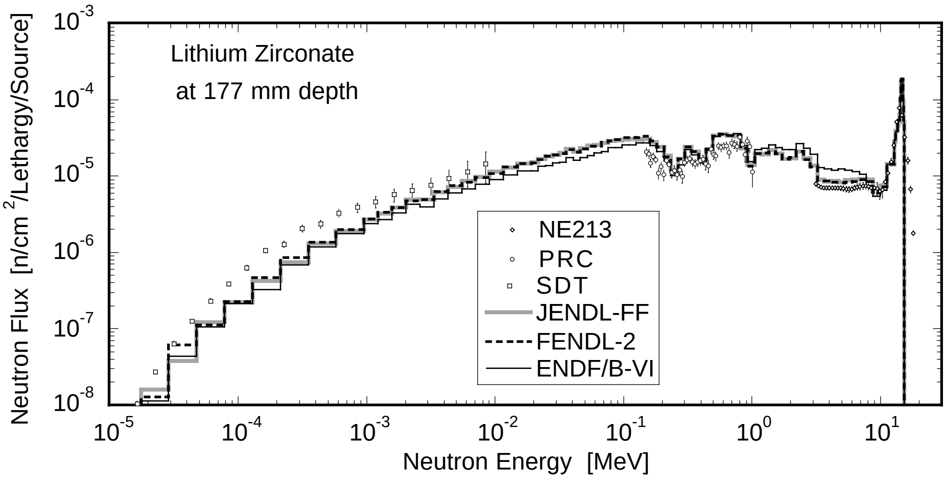

Fig. 7 Neutron spectra in the lithium zirconate (Li_2ZrO_3) assembly measured and calculated with three cross section files.

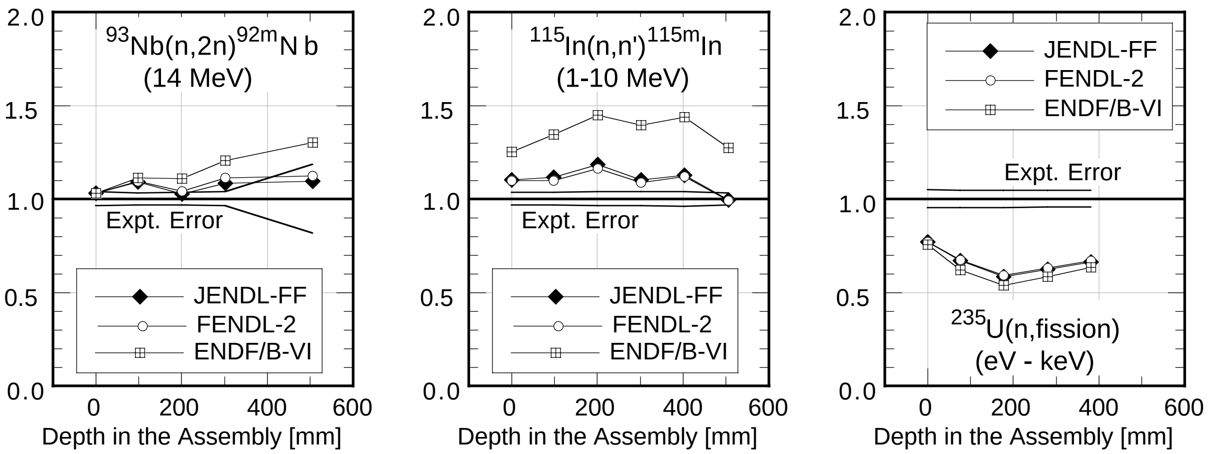

Fig. 8 C/E values for the three reaction rates in the lithium zirconate (Li_2ZrO_3) assembly.

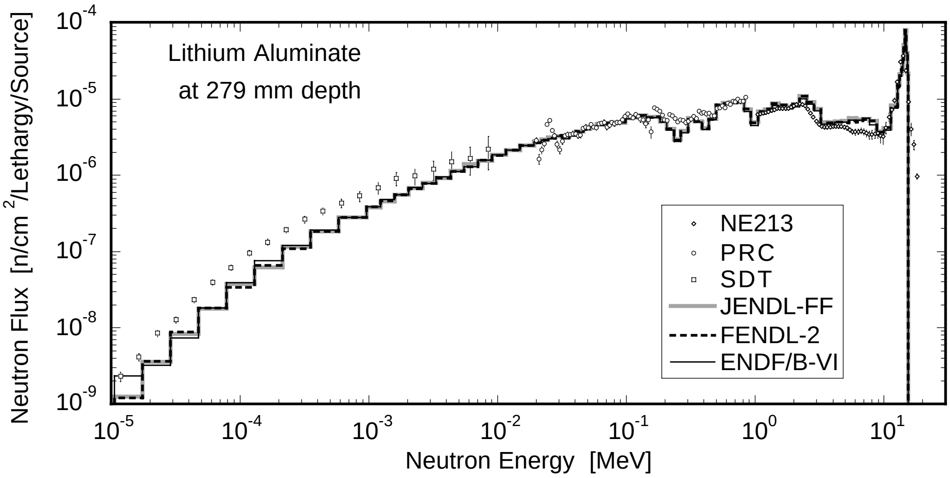

Fig. 9 Neutron spectra in the lithium aluminate ($LiAlO_2$) assembly measured and calculated with three cross section files.