Shielding benchmark of CENDL-3.2

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1. Introduction

The latest version of the Chinese Evaluated Nuclear Data Library, CENDL-3.2[1], was officially released to the public on June 12, 2020. Compared to the previous version of CENDL-3.1[2], the number of nuclides has increased from 240 to 272, resulting in a significant improvement in data quality and types. Out of all 272 materials, the data for 135 materials are totally new or partly updated evaluations. In order to verify the physical rationality, systematic comparisons between CENDL-3.2 and other major evaluated libraries (e.g. ENDF-B[3], JENDL[4], JEFF[5]) as well as experimental data available have been implemented on four types of shielding benchmark experiments, including Oktavian[6], LLNL pulsed-sphere[7], FNS[8] and ALARM-Cf[9] benchmarks.

2. Brief Description of the Experiments

The shielding benchmarks systematically examined the influence of nuclear data of various nuclides such as fission materials, neutron value-added materials, tritium-producing materials, and structural materials on the calculation of important integral parameters such as neutron value-added and γ generation under fusion and Cf-252 fission spectroscopy. It is of great significance for nuclear engineering applications. In addition, due to the high purity of the shielding sample materials and the single or small number of elements, the analysis of the neutron and γ leakage spectrum of sample materials can clearly indicate the data that needs to be improved. It can examine the cross-section and secondary neutron emission spectrum of elastic scattering, inelastic scattering, and (n, 2n) reactions; The γ leakage spectrum measured by the experiment is mainly composed of the instantaneous γ of the (n, n') and (n, 2n) reactions, so the γ leakage spectrum of the shielding reference experiment can be used to test the reliability of the non-elastic cross-section.

2.1 Oktavian

Oktavian is built by Osaka University and consists of a strong current deuterium beam accelerator, which can generate D-T pulse neutrons or 3 neutrons per 10^3/1.5ns × 10^{12}/s continuous D-T neutrons. In order to conduct basic research on the neutron transport characteristics of D-T fusion, many fusion neutronics experiments have been conducted. Between 1984 and 1989, several spherical shielding materials neutron and γ leakage spectrum have been measured using the Time of Flight (TOF) method.

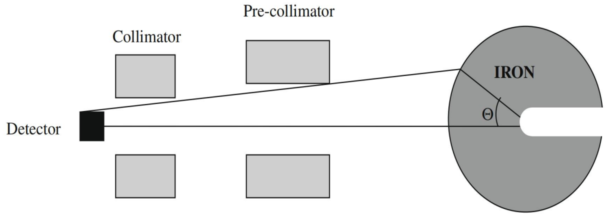

Fig.1 Simplified layout of the Oktavian experimental setup

The materials for which benchmark calculations have been performed are listed in Table I.

Table I: The materials used in the Oktavian shielding benchmarks.

Material	Diameter (cm)	Material	Diameter (cm)
Al	40	Mo	61
Co	40	Si	60
Cr	40	Ti	40
Cu	61	W	40
LiF	61	Zr	61
Mn	61		

2.2 LLNL pulsed-sphere

The pulsed-sphere experiment was conducted by the Lawrence Livermore National Laboratory in 1974, using an insulated core transformer accelerator neutron device (ICT neutron device) to accelerate deuterium ion beams and hit tritium titanium targets to produce (D, T) neutrons.

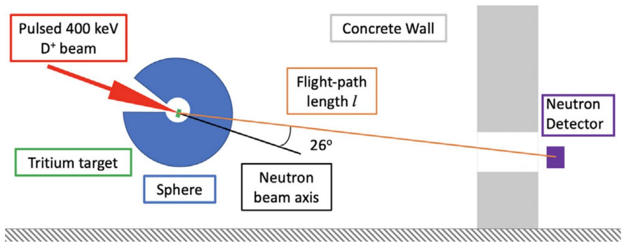

Fig.2 Simplified layout of the LLNL pulsed-sphere experimental setup

The materials for pulsed-sphere calculations have been performed are listed in Table II.

Table II: The materials used in the pulsed-sphere shielding Benchmarks.

Material	Diameter (MFP)	Material	Diameter (MFP)
Al	0.9	O	0.7
	2.6	Li7	0.5
C	0.5		1.6
	1.3	Mg	0.7
	2.9		1.9
D2O	1.2	N	1.1
	2.1		3.1
Fe	0.9	Pb	1.4
	3	teflon	0.9
	4.8		2.9
Li6	0.5	Ti	1.2
	1.6		3.5
Be	0.8		

2.3 FNS experiment

The FNS experiment was completed by the Fusion Reactor Physics Laboratory of the Japan Atomic Power Research Institute in the 1980s. The time of flight (TOF) method was used to measure the leakage neutron angular flux of D-T neutrons passing through plate-like samples such as lithium oxide, beryllium, graphite, iron, and lead.

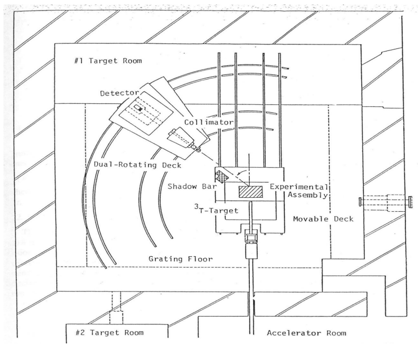

Fig.3 FNS target room and experimental setup

The materials for FNS benchmark calculations have been performed are listed in Table III.

Table III: The materials used in the FNS Benchmarks.

Material	Radius (cm)	Material	Radius (cm)
Be	5	C	5
	15		20
N	20		40
O	20	Fe	5
Pb	5		20
	20		40
	40		60

2.4 ALARM-Cf

In the 1980's at the Institute of Physics and Power Engineering (IPPE) in Obninsk, Russia, several experiments were executed to study the spectra of neutrons and gamma-ray photons flowing away from iron spheres of different diameters with a ^{252}Cf radionuclide source placed at the center of these spheres (References 1 - 3). Measurements of the spectra were made outside the spheres.

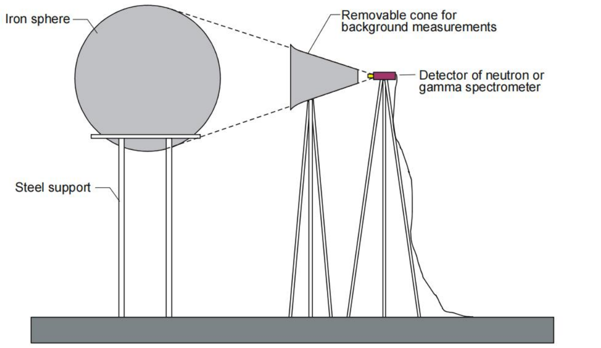

Fig.4 Scheme of ALARM-Cf experimental setup

The Fe and Pb have been performed on ALARM-Cf benchmarks, with the radius of 10, 15, 20, 25, 30, 35 for Fe, and 10, 20, 30 for Pb.

3. Methods and Results

3.1 Processing and testing of ACE file for CENDL-3.2

Using the nuclear data processing program NJOY2016[10], 272 nuclides from CENDL-3.2 were processed into ACE files. In order to check the integrity of the ACE files, drawing checks have been conducted. The content of the drawing check mainly includes all cross-sections, angular distributions, secondary particle emission spectra, etc. in the ACE document, and the results are saved in a PostScript file. No abnormalities were found during all drawing checks.

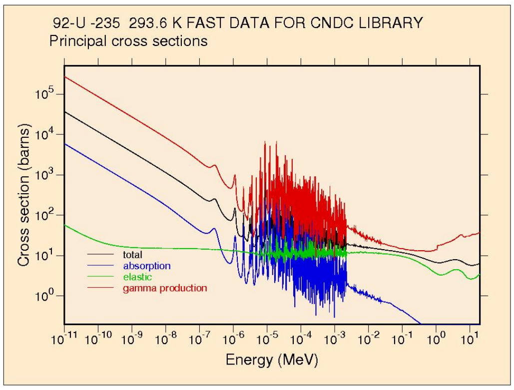

Fig.5 drawing test of U-235 cross section

In order to test the availability of ACE file for each nuclide in CENDL-3.2, simple particle transport problems were tested. The testing problem is to calculate the neutron surface flow rate generated by the irradiation of a white light neutron source in the energy range of 10^{-9}-20 MeV at the center of a sample sphere with a radius of 1 cm and a density of 2.0g/cm^3. After testing, 272 ACE files can operate MCNP[11] normally and provide reasonable results.

3.2 Shielding benchmark results of CENDL-3.2

Verification calculations were also conducted on ENDF/B-III. 0, JENDL-5.0, JEFF-3.3, and CENDL-3.1. The experimental results are processed using formulas (1) and (2) to convert flight time into energy.

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m(\frac{l}{t})^2 \qquad (1)$$

$$t = \sqrt{m/2E} \times l \qquad (2)$$

All experimental data refer to the ConDERC[12] website and ICSBEP.

From the results of the oktavian benchmarks, it can be seen that the results of CENDI-3.2 are in good agreement with the experimental data. Among them, the data of Al has been reevaluated, with the addition of P, D, He-3 production cross-sections and other data. The calculated results are closer to the experimental data than CENDL-3.1. W uses isotope nuclides to replace the previous natural nuclide data, and the calculated results are more in line with experimental data than before.

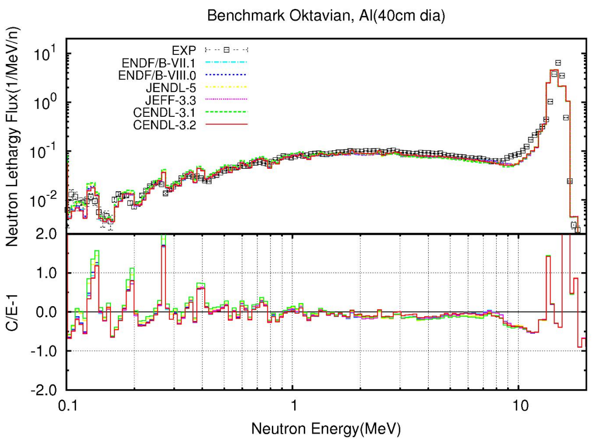

Fig.6 Neutron flux results of Oktavian Al benchmark

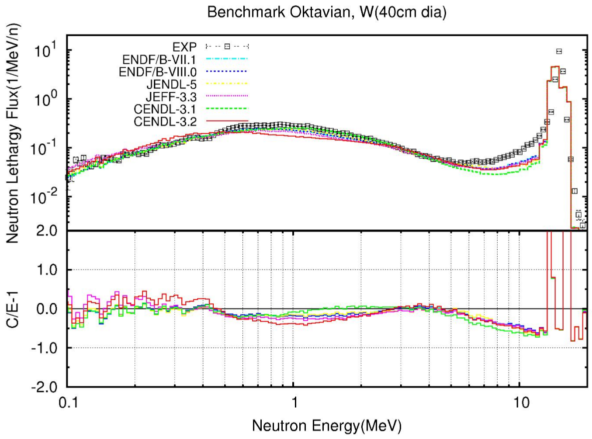

Fig.7 Neutron flux results of Oktavian W benchmark

In the results of the LLNL benchmark, Li-7, Mg, and Fe provided better calculation results, but there were differences between the calculation results of Be and other data and the experimental results.

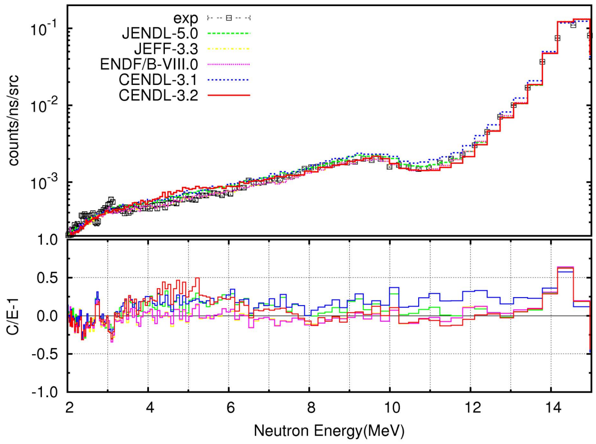

Fig.8 Results of LLNL pulsed sphere Li-7 benchmark

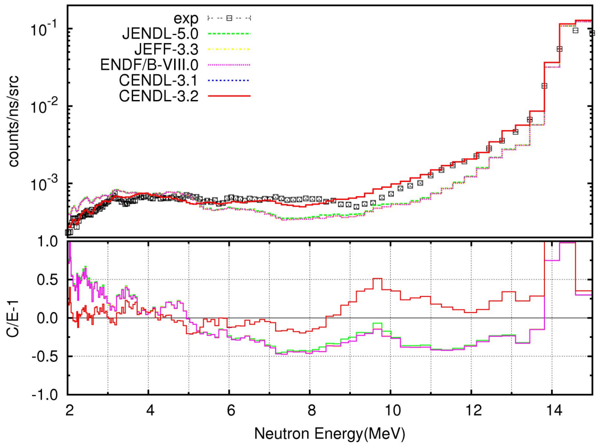

Fig.9 Results of LLNL pulsed sphere Mg benchmark

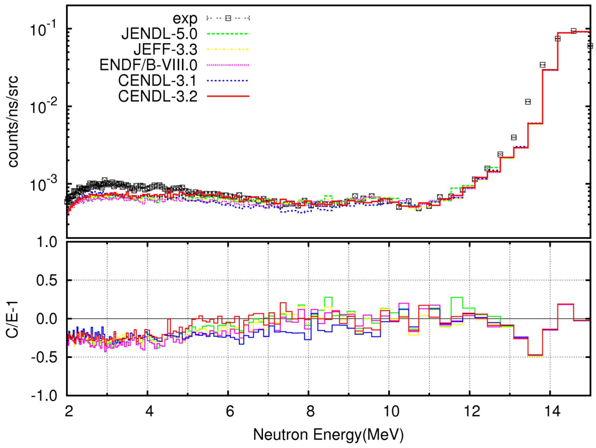

Fig.10 Results of LLNL pulsed sphere Fe benchmark

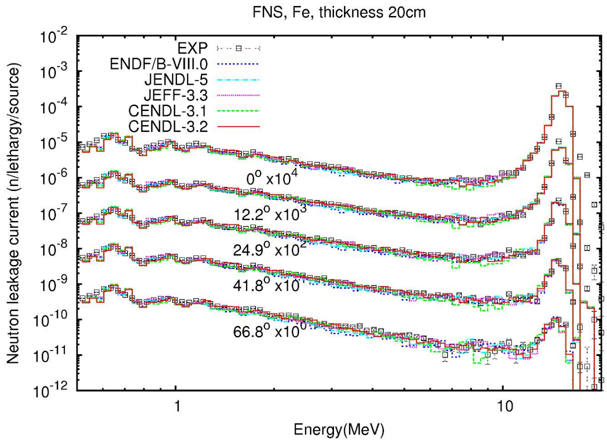

Fig.13 Results of FNS Fe benchmark

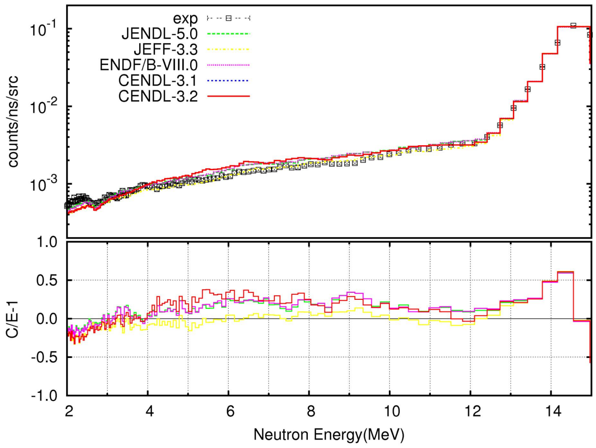

Fig.11 Results of LLNL pulsed sphere Be benchmark

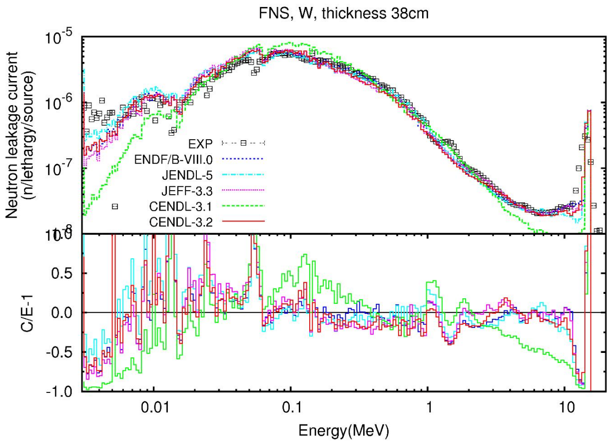

Fig.14 Results of FNS W benchmark

The FNS benchmarks have give the same trend as the Oktavian and pulse ball experiments.

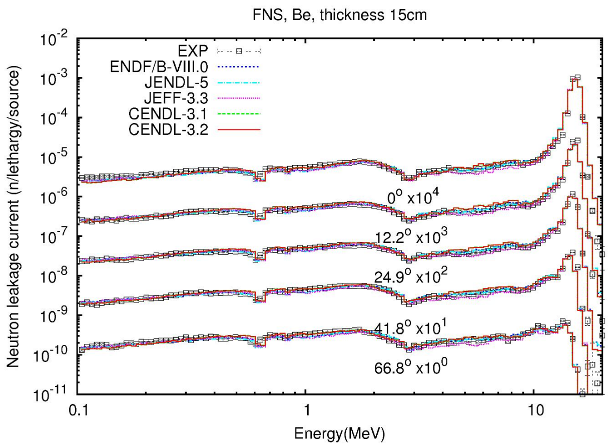

Fig.12 Results of FNS Be benchmark

The ALARM-Cf benchmark results for Fe and Pb with different radii are shown in the following figures.

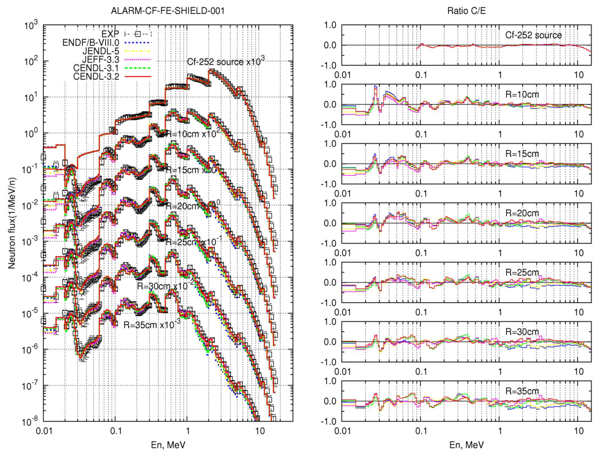

Fig.15 Results of ALARM-Cf Fe benchmark

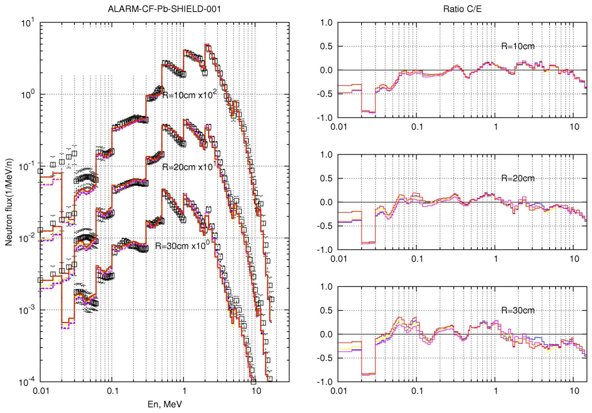

Fig.16 Results of ALARM-Cf Pb benchmark

4.Conclusions

A series of verification calculations were conducted on the neutron evaluated nuclear data of 31 nuclides in the latest version of CENDL-3.2 based on shielding benchmark experiments, Oktavian, LLNL pulsed-spheres, FNS and ALARM-Cf. The benchmark results show that the calculation results of CENDL-3.2 on the four types of shielding benchmark experiments are more in line with the experimental data compared to CENDL-3.1. Among them, data such as ^{7}Li, Mg, Fe, W have significantly improved the reliability of the calculation of neutron leakage spectra of shielding materials.

This work only conducted benchmarks of the shielding experiments for a part of nuclides in CENDL-3.2, and there are still most nuclides that have not undergone benchmark of the shielding experiments. In future work, it is necessary to conduct more benchmarks of more nuclides on more types of integral experiments to ensure the reliability and accuracy of the data.

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