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The high-energy multi-group HEST1.0 library based on ENDF/B-Ⅶ.0: development, verification and preliminary application*

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Abstract: ENDF/B-Ⅶ.0, which was released by the USA Cross Section Evaluation Working Group (CSEWG) in December 2006, was demonstrated to perform much better than previous ENDF evaluations over a broad range of benchmark experiments. A high-energy (up to 150 MeV) multi-group library set named HEST1.0 with 253-neutron and 48-photon groups has been developed based on ENDF/B-Ⅶ.0 using the NJOY code. This paper provides a summary of the procedure to produce the library set and a detailed description of the verification of the multi-group library set by several shielding benchmark devices, in particular for high-energy neutron data. In addition, the first application of HEST1.0 to the shielding design of the China Spallation Neutron Source (CSNS) is demonstrated.

Key words: ENDF/B-Ⅶ.0, multi-group library, 150 MeV, HEST1.0, SN method

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1 Introduction

China Spallation Neutron Source (CSNS) complex is designed to provide multidisciplinary platforms for scientific research and applications for national institutions, universities and industries. The baseline design of the CSNS consists of an accelerator system capable of delivering a 1.6 GeV (25 Hz) proton beam with 100 kW of beam power into a single target station.

In order to develop the main concepts of the accelerator-driven systems and the corresponding nuclear waste management, it is necessary to know the nuclear data on spectra and reaction cross sections for structural materials, actinides and fission products in a very broad energy range. In practice, the energy interval from thermal energies to a few thousand MeV should be covered [1]. The status of available nuclear data differs strongly for the energy regions below and above 20 MeV. Huge efforts have been made to create libraries of evaluated neutron data for the low-energy region below 20 MeV. In spite of some differences between the evaluations, most data are reasonable enough and their accuracies satisfy the requests of major current applications. However, the data for energies higher than 20 MeV are rather scarce and not yet systematized. Therefore, the energy region from 20 to 150 MeV requires special consideration, and corresponding evaluated data files should be prepared for the most important materials in the same manner as for the energy region below 20 MeV [1]. In accordance with that, the evaluated data files for about 30 nuclides of the most important structural and shielding materials were extended in the ENDF/B-Ⅵ library up to 150 MeV by the Los Alamos group [2]. The latest version of ENDF/B-Ⅶ.0 was demonstrated to

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perform much better than previous ENDF evaluations over a broad range of benchmark experiments, especially in the 20 to 150 MeV energy region of structural and shielding materials [3].

Due to these improvements, a high-energy multi-group data library, namely HEST1.0, has been developed mainly on the basis of ENDF/B-Ⅶ.0 for the neutron source CSNS target shielding design. As shown in Table 1, 28 nuclides from ENDF/B-Ⅶ.0 and 2 nuclides (^{1}H and ^{16}O) from ENDF/B-VI are included in HEST1.0. The neutron energy is up to 150 MeV, and it divides into 253 groups, which include 172 groups from 0 to 20 MeV and 81 groups from 20 to 150 MeV. The photon energy range is up to 100 MeV, which is divided into 48 groups. The weight function of the multi-group library set is taken from the Vitamin-e library [4] (thermal + 1/e + fission + fusion) and the max Legendre order of the scattering matrix is 6. The created thermal scattering data obeying the free-gas scattering law are prepared for all the nuclides, and 10 Bondarenko background cross sections are considered to generate self-shielded multi-group cross sections (1010, 104, 103, 300, 100, 30, 10, 1, 0, 1, and 10-3) under a temperature of 293 K. The cross-section data are stored in the MATXS format [4] in this work.

2 The HEST1.0 development procedure [5]

The procedure for HEST1.0 development is shown in Fig. 1. The NJOY nuclear data processing system [4] is the standard tool for processing basic nuclear data into multi-groups or point-wise libraries for various applications. NJOY can work with neutrons, photons and charged particles, and can produce libraries for a wide variety of particle transport and reactor analysis codes. The NJOY system consists of a set of modules, with each performing a well-defined processing task. Each of these modules is essentially a separate computer program.

NJOY's standard output files in MATXS format are processed by the BBC code [6] to generate a single large file containing the data of all the nuclides. The TRANSX code [6] is used to pre-treat the MATXS file to a simple library which can be used by the SN codes directly, such as ANISN [7] and DORT [8].

Table 1. The nuclides of HEST1.0.

nuclide							
1-H-1	1-H-2	6-C-12	8-O-16	13-Al-27	14-Si-28	14-Si-29	14-Si-30
20-Ca-40	20-Ca-42	20-Ca-43	20-Ca-44	20-Ca-46	20-Ca-48	24-Cr-50	24-Cr-52
24-Cr-53	24-Cr-54	26-Fe-54	26-Fe-56	26-Fe-57	28-Ni-58	28-Ni-60	28-Ni-61
28-Ni-62	28-Ni-64	74-W-182	74-W-183	74-W-184	74-W-186		

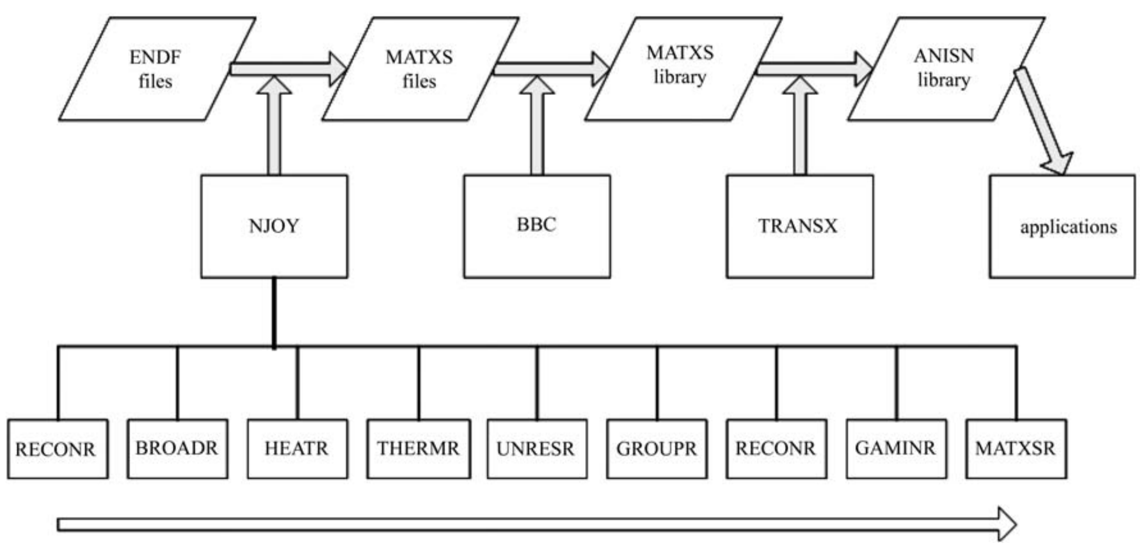

Fig. 1. Flow diagram for generating multi-group and point-wise libraries.

3 The methodologies of verification and validation

Verification and validation consists of a few steps: 1) The correctness of the procedure to produce a multi-group set library, such as tool upgrading, checking the documents and graphics produced by the tools, comparing the keff parameters, fission rate, capture rate, fluence rate, spectrum and angular distribution with basic critical and shielding calculations; and 2) the applicability and rationality of the multi-group set library, such as the selection of group structure and weight function, and checking the temperature and resonance self-shielding parameters.

This paper verifies the procedure of producing a multi-group set library, and analyzes the high-energy neutron cross sections and resonance parameters with serial shielding benchmarks. This work chooses two typical benchmarks from SINBAD [9], namely the 65p benchmark [10] and the OKTAVIAN benchmark [11–13]. The 65p benchmark is mainly used for the verification of high-energy multi-group data, and the OKTAVIAN benchmark is mainly used to verify the cross sections of Fe, Ni and W under 20 MeV.

4 Results

4.1 The 65p benchmark

The 65p benchmark experiments were performed at the AVF cyclotron of the Research Center of Nuclear Physics of Osaka University. A 1.0 cm-thick copper target was used. The secondary neutrons and photons were collimated by a 7.5 cm diameter, 50 cm long iron-lined concrete hole. The shielding materials of concrete and iron were placed very close to the collimator exit. In the 65p benchmark, the shields are slabs about 40×40 cm in cross section and 10 to 100 cm thick. This work chooses three points with distances 20, 40 and 60 cm from the source in the iron shields. It also chooses three points in concrete shields with distance of 20, 50 and 100 cm. The measured and calculated neutron fluxes for slabs of different thickness are compared and shown in Fig. 2. The comparisons demonstrate good consistency for the whole energy range in the distances 20 and 40 cm from the neutron source. As seen in Fig. 2, the spectra calculated with the use of HEST1.0 cross sections show a considerable discrepancy from the measured ones in the 20–50 MeV energy region. This is mostly caused by uncertainties of the measurements, and this inconsistency has also been noted previously [10].

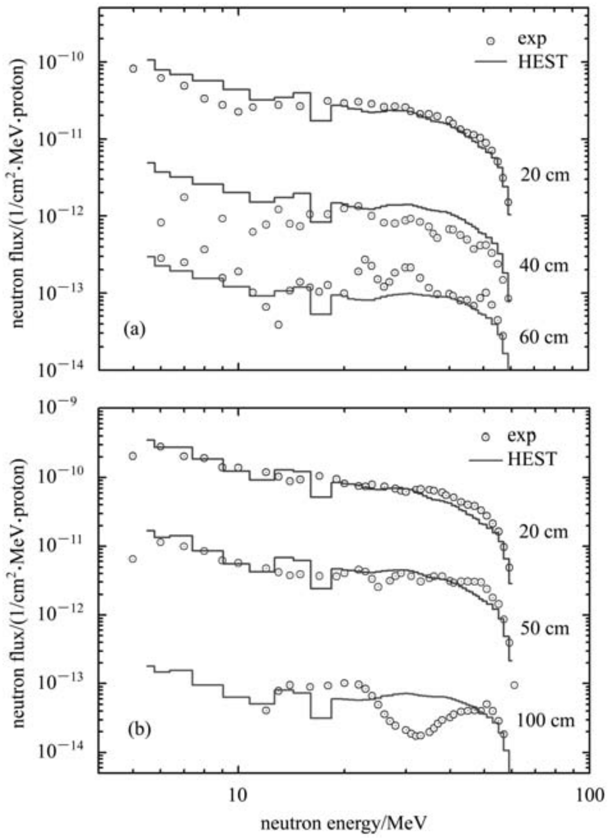

Fig. 2. Calculated neutron flux for iron (a) and concrete (b) slabs vs. experimental results.

4.2 The OKTAVIAN benchmark

A Cockcroft-Walton type accelerator, OKTAVIAN, at Osaka University was used to accelerate deuterons to a kinetic energy of 245 keV. The deuteron beam was led through a narrow tube to the center of the sphere, where pulsed 14.1 MeV monochromatic neutrons were produced by the d-t fusion reaction. The lower energy component of the source spectrum was about 5% of the 14 MeV main components. Therefore, the source was regarded to be 14 MeV monochromatic.

In the OKTAVIAN benchmark, three spheres are chosen with different materials to calculate the leakage. The measured and calculated neutron leakages for spheres of different materials are compared in Fig. 3. The comparisons show good consistency for the nickel and tungsten spheres in the 0.1–10 MeV energy range. As is seen, the consistency of the calculated and measured results is not good for neutron leakage from the iron spheres, especially in the 0.1–10 MeV energy range.

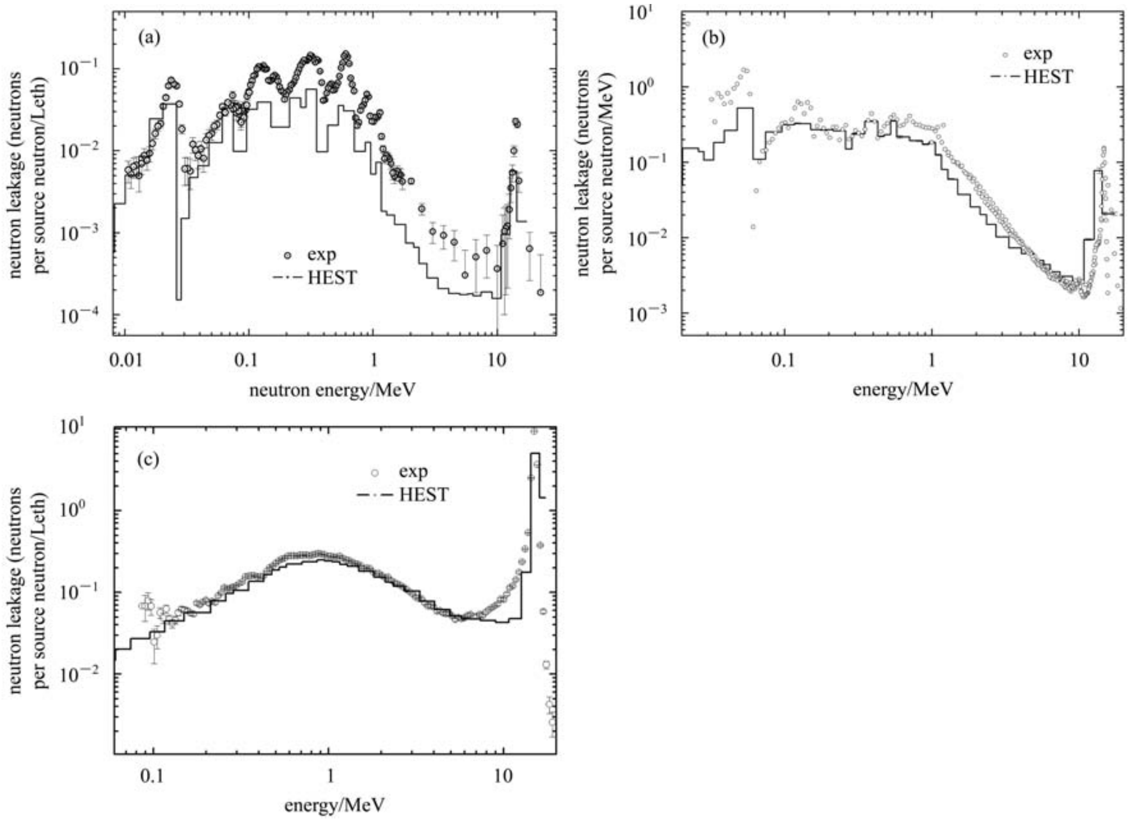

Fig. 3. Calculated neutron leakage in (a) iron, (b) nickel and (c) tungsten spheres vs. experimental results.

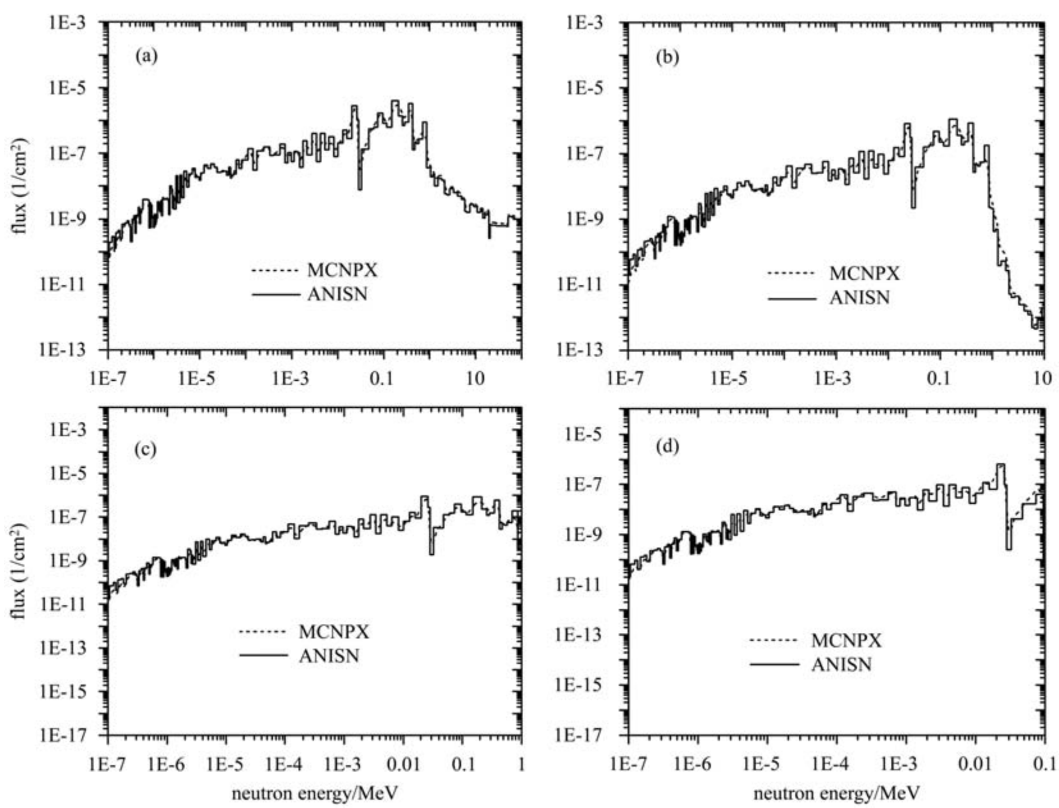

Fig. 4. Neutron flux calculated by ANISN and MCNPX with different sources, (a) 100, (b) 10, (c) 1 and (d) 0.1 MeV.

The calculated neutron leakage from the iron sphere has a large disparity with the measured one. In the 1–20 MeV energy range, it is mostly caused by a 7%–20% reduction in the inelastic cross-section of Fe [14]. And in the resonance energy range, it is caused by the dividing energy groups method.

4.3 The iron sphere benchmark

Surface neutron flux of the 2 diameter iron spheres is calculated in two independent ways. One uses the 1-D SN code ANISN with HEST1.0, and the other the Monte Carlo particle transport code MCNPX [15] with ENDF/B-Ⅵ data. The neutron source is in the center of the sphere, and its energy is 100, 10, 1 and 0.1 MeV, respectively, in the different models.

The surface neutron flux of the 2 diameter iron sphere with different sources is shown in Fig. 4. The ANISN code results with resonance correction are accordant with MCNPX calculations.

5 Application to the CSNS shielding design

5.1 The CSNS target station monolith shielding design

The CSNS target monolith [16] is the primary structure that contains the target–moderator–reflector complex (TMRC) and the shutters. Outside the reflector plug assemblies is the bulk shield, comprised of low carbon steel, which is surrounded by a high-density concrete biological shield. The calculation model consists of a 500 cm-thick steel shield and a 100 cm-thick concrete layer. Fig. 5 presents the DORT calculation results for the energy distribution of the neutron flux densities. The figure clearly shows the attenuation of the neutron spectra with increasing shield thickness.

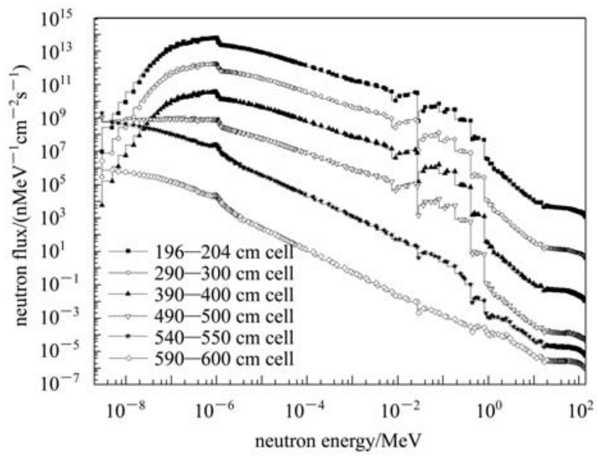

Fig. 5. The neutron flux density energy spectra for the calculation model.

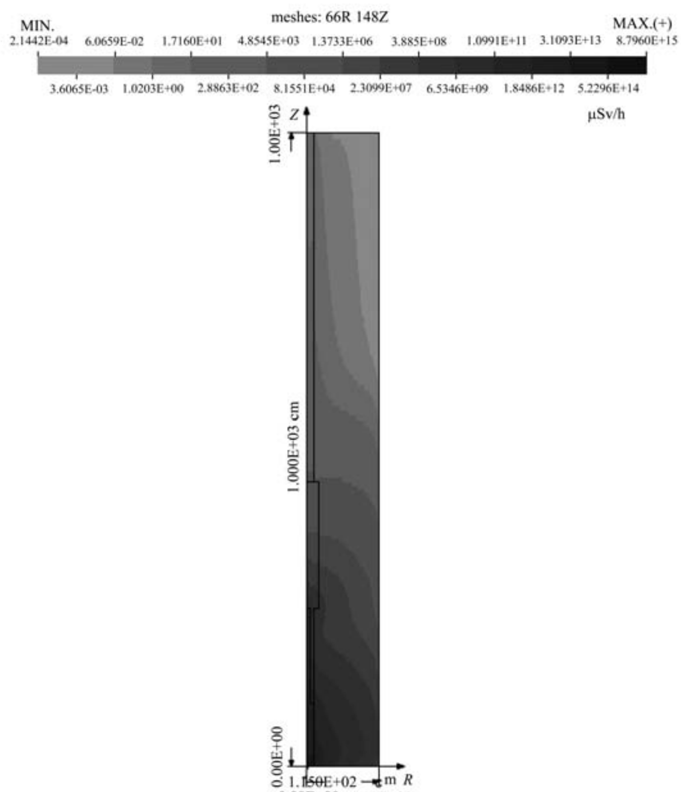

Fig. 6. The isodose contours of 316 stainless steel shutter neutron beam stop.

5.2 The CSNS target station shutter neutron beam stop design

The neutron beam stop models [17] have a radius of 11 cm, and the thickness of the low carbon steel is 104 cm. The neutron beam stop ranges from 250 to 450 cm of the moderator face, and the core vessel insert placed in the neutron beam line between the shutter and the moderators is 150 cm long. The inside radius of the core vessel insert is 5 cm and the outside radius is 11 cm. The model with isodose contours is shown in Fig. 6.

6 Conclusion

This paper summarizes the development, verification and validation of the high-energy multi-group cross-section library, HEST1.0. In addition, the preliminary application to the CSNS neutron source is also demonstrated.

The results show that HEST1.0 is a rational fit for CSNS target shielding research. Another library with energy up to 1 GeV should be developed for the accurate design of CSNS.

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