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Benchmark analysis of fission-rate distributions in a series of spherical depleted-uranium assemblies for hybrid-reactor design

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ABSTRACT

The nuclear performance of a fission blanket in a hybrid reactor has been validated by analyzing fission-rate experiments with a series of spherical depleted-uranium assemblies. Calculations were made with the Monte–Carlo transport code MCNP5 and the ENDF/B-V.0 continuous-energy cross sections and compared to the measured results. The ratios of calculated to experimental values (C/E) for the fission rate and the fission-rate ratio of ^{238}U to ^{235}U are presented along with a discussion of the validation of the ENDF/B-V.0 library regarding its use in the design of the fission blanket. Overestimations are observed in the calculation of the ^{238}U and ^{235}U fission rates at all positions, except the ones near the outer surfaces of the assemblies, and the C/Es of the fission rate decreased as the thickness of the depleted-uranium (DU) layer increased, while most of the C/Es of the fission-rate ratio of ^{238}U to ^{235}U were close to unity, being within the range of 0.95–1.05.

1. Introduction

Because the time scale on which fusion energy will become available is uncertain, hybrid fusion–fission reactors can represent an alternative to fill the gap between the present nuclear technology and future fusion reactors (Li, 2010; Jiang et al., 2010). Several different fusion–fission hybrid reactors have been proposed to date and are being developed for energy production (Shi and Peng, 2010). China is highly interested in developing this technology as a potential new source of energy, and several activities have been launched to study the problem. A fusion–fission reactor mainly consists of a fusion neutron source and a sub-critical blanket made with fissile material. The fusion-reactor core generates 14-MeV neutrons by the D-T fusion reaction, and the sub-critical blanket is designed to be fueled with natural uranium or spent fuel generated by PWRs (Pressurized Water Reactors) in the form of a U/Zr alloy, while light water is proposed as a coolant (Peng and Shi, 2010). Integrated experiments and analyses are required (Fischer et al., 2005; Sawan et al., 2010) to benchmark the nuclear data involved in the design calculation. As one of the key elements in the fission blanket, uranium has attracted special concern. Based on prior fission-rate experiments on a series of spherical depleted-uranium assemblies, the computational analysis in this paper was performed with the ENDF/B-V.0 nuclear libraries and the Monte–Carlo code MCNP5. Comparisons between the calculated (C) and measured (E) quantities are reported in terms of the C/E ratio, and a discussion of the results is also presented.

2. Overview of experiments

2.1. Experimental configuration

In this series of benchmark experiments on spherical assemblies of depleted uranium, six benchmark assemblies were constructed using a combination of spherical shells. The various assemblies consisted of different layers of shells. The inner radius (IR) of each assembly was 4.0 cm, while the outer radii (OR) ranged from 18.1 cm to 30.0 cm, and the density was 18.8 g/cm^3. The experimental configuration of the fusion-neutronics-benchmark experiment with a spherical assembly of depleted uranium with an outer radius of 30 cm (Wang et al., 1984) is shown in Fig. 1. The assembly's support was made of a 9-mm-thick iron plate. Neutrons with an energy of 14 MeV were generated at the center of the assembly from a Ti–T target (90 GBq) bombarded with deuterons with an energy of 250 keV and a current of 100 μA. The intensity was approximately 3×10^{10} neutrons/s. There were five channels for detectors and one channel for a drift tube. The experimental channel, through which the plate fission chambers were inserted to specific positions for the fission-rate measurement, was perpendicular to the direction of the incident D^+ beam. All other channels were filled with cylindrical depleted-uranium blocks. The distance

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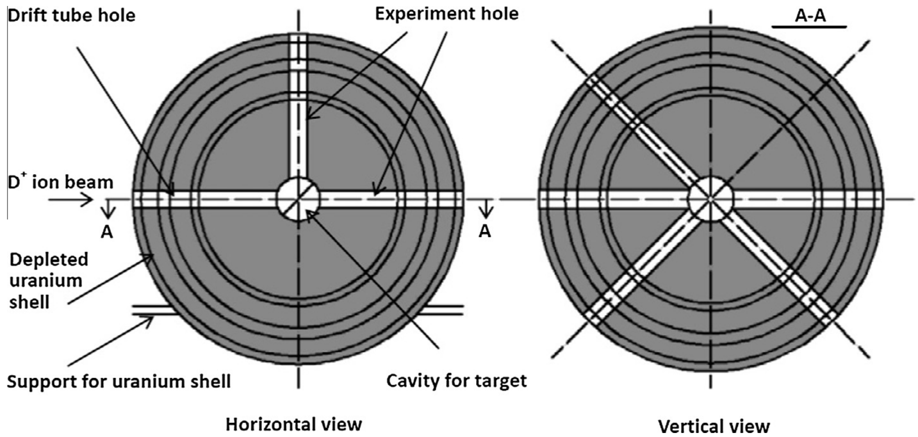

Fig. 1. Cross-sectional view of the experimental assembly with an outer radius of 30.0 cm.

Table 1
The dimensions of the six models.

Models	EX1 (cm)	EX2 (cm)	EX3 (cm)	EX4 (cm)	EX5 (cm)	EX6 (cm)
Inner radius (IR)	4.0	4.0	4.0	4.0	4.0	4.0
Outer radius (OR)	18.08	19.39	23.34	25.39	28.48	30.0

Table 2
Elements and atom densities.

Component	Element	Atom density (cm^{-3})
Depleted-uranium assembly	U-238	4.7355×10^{22}
	U-235	1.9754×10^{20}
	U-234	1.6169×10^{18}
	U-236	9.6918×10^{17}
Air	Nitrogen-14	4.2545×10^{19}
	Oxygen-16	1.1311×10^{19}

between the D–T neutron source of the assembly and the nearest concrete wall was more than 350 cm.

2.2. Experimental method and data processing

The absolute strength of the D–T neutron source was determined via the associated particle method (Evans et al., 1997). The alpha particle associated with neutron emission was measured with a silicon surface-barrier detector, which was mounted at 178.2° from the deuteron beam line. The absolute neutron yield was determined from the alpha count rate and the solid angle of the detector (Liu et al., 1999). Measurements of the reaction-rate distributions for ^{238}U(n, f) and ^{235}U(n, f) were made in the depleted-uranium assemblies using plate fission chambers. The outer diameter and length of the fission chamber were 3.0 cm and 2.5 cm, respectively, and the active area was 4.524 cm^2. The enrichment was 90.27% for ^{235}U in the enriched sample, while the material in the ^{238}U fission chamber was identical to that in the experimental assemblies. Before the uranium fission chambers were fabricated, the absolute number of atoms of the fissile deposits was obtained from the alpha count rate of both the ^{235}U and ^{238}U deposits by means of a silicon detector. These values were $(3.07 \pm 0.04) \times 10^{18}$ atoms for ^{238}U and $(2.26 \pm 0.03) \times 10^{18}$ atoms for ^{235}U. The detector efficiency was thus calculated by considering the self-absorption of the fission products in the thin fissile coating and the counts lost in the lower channels of the fission spectrum. Because of this accurate determination of the number of U atoms, the thickness of the uranium layer in the fission chamber was accurately measured, and the efficiency of the fission chambers was obtained with an uncertainty of ±1.0%.

The fission rate, $f_x(r)$, was obtained as a function of position in the assembly using the equation:

$$f_x(r) = N_f(r)/(\varphi m \eta),$$

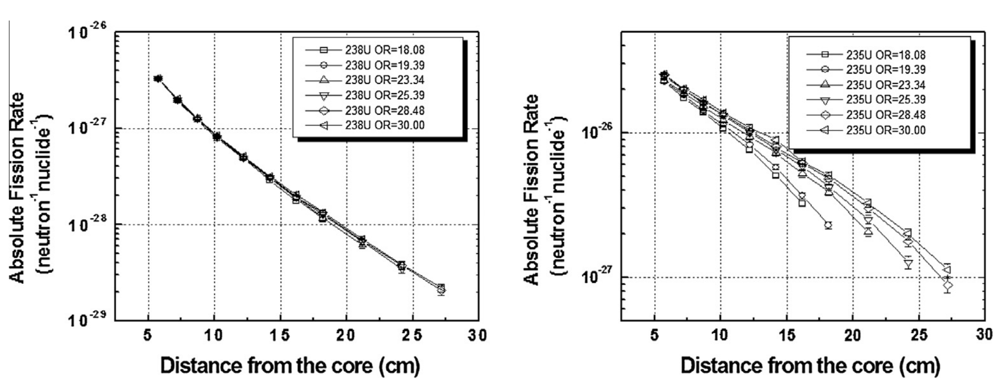

Fig. 2. The measured ^{238}U and ^{235}U fission rates in the six assemblies.