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Measurement and calculation of U and Th reaction rates in uranium mock assemblies

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ABSTRACT

The conceptual blanket based on a subcritical reactor for a fusion–fission hybrid energy reactor with magnetic confinement fusion is being studied. To validate nuclear data and code of neutronics calculation for the blanket design, measurement of reaction rates for U and Th is performed by integral experiments. Based on the fission blanket, the uranium mock assemblies are established, and include the depleted uranium shell, the depleted-uranium/polyethylene/graphite shell and the natural uranium cube. A depleted-uranium/polyethylene/graphite assembly of 131 mm in inner radius and 365 mm in outer radius consists of three layers of depleted uranium shells, two layers of polyethylene shells and a graphite shell, and these shells are arranged alternatively. A D–T fusion neutron source is centered of the spherical assemblies. The U reaction rates for capture, fission and ratio of capture to fission in the assemblies are measured by depleted uranium foils and an HPGe gamma spectrometer. The ^{232}Th reaction rates for capture, fission and ratio of capture to fission are measured by ThO_2 foils put into the depleted uranium shell. The measured results are compared to the calculated ones by using MCNP code with ENDF/B-VII.0 library data.

1. Introduction

The fusion–fission hybrid energy reactor is that fusion energy is multiplied by released fission energy from the subcritical reactor as the blanket (Shi and Peng, 2010; Li et al., 2012). The conceptual design can increase the utilization rate of uranium resources. The subcritical reactor is mainly loaded with natural uranium (UZr alloy) as nuclear fuel and lithium material (Li_4SiO_4) as tritium breeder. In the fission fuel region, the uranium and light water are arranged alternately. Light water is coolant and moderator. The volume ratio of uranium to light water is about 2:1. In the uranium, fertile nucleus ^{238}U is used to breed ^{239}Pu by ^{238}U capture reaction, and fission nuclei are used to multiply fusion energy by fission reaction. With the development of fusion technology, depleted uranium and thorium could be selected as the fission fuel, in which fertile nucleus ^{232}Th is used to breed ^{233}U by ^{232}Th capture reaction. Meanwhile, the conceptual design of a hybrid reactor based on the Th/U cycle should be a candidate for new energy system. In conceptual design stage, it is essential to perform sufficient neutronics experiments for validating nuclear data and code used in the design and checking neutron property of the conceptual blanket.

Referred to the blanket, we have established a series of the mock assemblies and performed benchmark integral experiments (Liu et al., 2012, 2014a,b). Aiming at researching the neutron property of the blanket, the ways for establishing the mock assemblies are that the neutron spectra, material and structure are relevant for the conceptual blanket. The mock assemblies consist of uranium and polyethylene, alternately. Polyethylene has similar property to light water as a neutron moderator (Liu et al., 2012). The plutonium production rates, uranium fission rates, tritium production rates in the assemblies and leakage neutron energy spectra from the assemblies were measured. The experimental results were calculated by the MCNP code employing ENDF/B-V and ENDF/B-VI library data, and the ratios of calculation to experiment (C/E) were obtained. The results indicate that the code and relevant nuclear data were applicable to analyze the integral experiments and conduct neutronics calculation for the blanket. The results of integral experiments support the feasibility of the conceptual design.

The neutron spectra in the mock assemblies are very complicated, because of polyethylene strongly moderating 14 MeV neutrons. For making experimental results more reliable, it is demanded to carry out further research for validating nuclear data with new library and verifying the method of measuring uranium reaction rates. Moreover, it is very little that the integral experiment of ^{232}Th reaction rates with D–T fusion neutron had

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been done. It is essential to develop the experimental technique of thorium neutronics parameters in a macro assembly.

In this paper, the recent progress in research on the integral experiments in representative assemblies is described. The uranium mock assemblies include the depleted uranium shell, the depleted-uranium/polyethylene/graphite shell and the natural uranium cube. The integral experiments in the mock assemblies have been performed. The ^{238}U capture rates, uranium fission rates and ratio of capture to fission are measured in the spherical assemblies, separately. The ^{238}U capture reaction rates in cubic fission mockup are re-analyzed. The ^{232}Th capture rates, fission rates and ratio of capture to fission are measured in the depleted uranium shell. The measured results are calculated by using MCNP code with ENDF/B-VII.0 library data.

2. Mock assemblies

2.1. Spherical fission assembly

The kind of mock assemblies based on materials available is spherical, and the neutron spectra in the assemblies are near to ones in the fission blanket. This mockup consists of depleted-uranium (~99.6% ^{238}U, ~0.4% ^{235}U)/polyethylene/graphite, alternately, as shown in Fig 1. Its volume ratio of depleted uranium (DU) to polyethylene (PE) is about 0.94:1. The assembly is 131 mm and 365 mm in inner radius (IR) and outer radius (OR), as listed in Table 1. The outer graphite shell are also used to shield background neutrons and increase counts at far positions to core. The abundance of uranium in the assembly is the same as ones in detectors of the DU foils (Liu et al., 2012). The detectors in the spherical assembly are at an angle of 90° to incident D^+ beam direction.

A D–T fusion neutron source is placed at the center of the assembly. In the 14 MeV neutron generator, the energy of D^+ ions is 225 keV and neutrons are produced by D^+ beam bombarding a tritium–titanium (T–Ti) target. The yield is about 3×10^{10} neutrons/s. The absolute yield of the neutron source is measured by the associated α particle method. An Au–Si surface barrier semiconductor detector is at an angle of 178.2° to incident D^+ beam direction in drift tube and used to measure the yield.

2.2. Depleted uranium shell

The kind of assembly without polyethylene is spherical and consists of the depleted uranium. The neutron spectra in the assembly are relatively simple. It is used to check measuring method and nuclear data. The assembly are 194 mm and 300 mm in IR and OR, respectively, as shown in Fig. 2. A D–T fusion neutron source is same as described above.

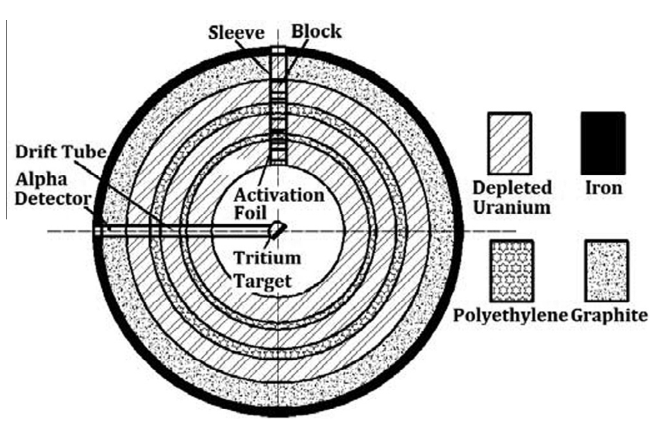

Fig. 1. Spherical fission assembly with depleted-uranium/polyethylene/graphite shells.

Table 1
Radius and materials of spherical fission assembly.

IR/OR (mm)	131/181	181/194	194/233	233/254	254/300	300/350	350/365
Materials	DU	PE	DU	PE	DU	Graphite	Iron

2.3. Cubic fission mockup

In the conceptual design of the blanket, the fuel region loaded with UZr alloys of natural uranium (NU) (Shi and Peng, 2010; Li et al., 2012). The structure of the fuel region is lattice cell. Whereas, the kind of mockup is cubic, and its material and structure, besides neutron spectra, are basically consistent with ones of the fission blanket. The cubic fission mockup with lattice cell structure consists of NU (~99.3% ^{238}U, ~0.7% ^{235}U) and PE as shown in Fig. 3 (Liu et al., 2014b). The length and height of the mockup are 467.5 mm and 460 mm, the thickness 206 mm, respectively. The 195 holes of 8.5 mm radius are equably distributed in the NU mockup. The PE tubes in the shape of hollow cylinder of 6 mm IR and 8.5 mm OR are placed in the holes. A D–T fusion neutron source is placed at normal distance of 100 mm to the center of the cubic mockup surface. The detector is placed in holes of 230 mm height to the central level surface of mockup. The abundance of uranium in the mockup is the same as ones in detectors of the NU foils in ring shape.

3. Result in spherical fission assembly

3.1. ^{238}U capture reaction rates

The fertile nuclide ^{238}U capture reaction rate indicates breeding of fissile fuel ^{239}Pu. ^{238}U (n, γ) ^{239}U capture reaction rates by measuring 277.6 keV γ rays emitted from ^{239}Np (^{239}U decay) in DU foils, i.e., the production rate of ^{239}Pu (^{239}Np decay), can be deduced (Liu et al., 2012; Yan et al., 2012).

The 7 slices of DU foils with 24 mm in diameter and 0.174–0.248 mm in thickness are put in the radial channel of the spherical mockup at a 90° direction to incident D^+ ion beam as shown in Fig. 1. The source neutron yield during irradiation is measured by an auto-timing counts system and corrected by the decay factor (Liu et al., 2012; Yan et al., 2012). The self-absorption correction factors of a DU foil to 277.6 keV γ rays are measured with the HPGe gamma spectrometer and ^{243}Am γ ray source. The values obtained by the least square method are 91.1–88.4% depending on thicknesses of DU foils.

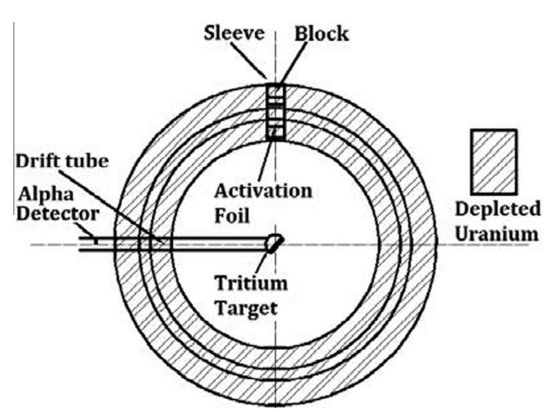

Fig. 2. Depleted uranium shell.