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Reaction rates in blanket assemblies of a fusion-fission hybrid reactor

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Abstract To validate neutronics calculation for the blanket design of fusion-fission hybrid reactor, experiments for measuring reaction rates inside two simulating assemblies are performed. Two benchmark assemblies were developed for the neutronics experiments. A D-T fusion neutron source is placed at the center of the setup. One of them consists of three layers of depleted uranium shells and two layers of polyethylene shells, and these shells are arranged alternatively. The ^{238}U capture reaction rates are measured using depleted uranium foils and an HPGe gamma spectrometer. The fission reaction rates are measured using a fission chamber coated with depleted uranium. The other assembly consists of depleted uranium and LiH shells. The tritium production rates are measured using the lithium glass scintillation detector which is placed in the LiH region of the assembly. The measured reaction rates are compared with the calculated ones predicted using MCNP code, and C/E values are obtained.

Key words Simulating assembly, Integral experiment, Reaction rates, Fusion-fission, MCNP

1 Introduction

A fusion-fission hybrid reactor for energy production consists of a sub-critical reactor and magnetic confinement fusion device[1]. The CAEP conceptual design of hybrid reactor has a blanket of a sub-critical reactor loaded with natural uranium to breed ^{239}Pu, and a tritium production blanket with ^{6}Li to breed tritium.

It is important to study the neutron spectra in the blanket for verifying and/or improving the neutronics design of the blanket. The integral neutronics experiment[2] with simulating assemblies is a main approach to check the neutronics design. The integral quantities measured in experiments can be used to validate nuclear data and nuclear codes that are used in calculations. The ^{238}U capture reaction rate, i.e. ^{239}Pu production rate, is used to estimate the breeding rate of fissile isotopes. The fission rates of ^{235}U and ^{238}U are used to estimate the energy production. Tritium production rate is used to estimate the quantity of tritium produced. For these reasons, we established two benchmark simulating assemblies in the blanket. The experiments for measuring the integral quantities are studied with a D-T fusion neutron source. The fission assembly consisting of three shells of depleted uranium and two PE (polyethylene) shells, arranged alternatively, is used to measure the ^{238}U capture reaction rate and the fission reaction rates of ^{235}U and ^{238}U. The tritium production assembly, which is a LiH shell enclosing a depleted uranium shell, is used to measure the tritium production rate.

2 Benchmark assemblies

2.1 The fission assembly

According to the conceptual design of the hybrid reactor[1], the fission blanket consists of natural uranium (~0.7% ^{235}U) and light water. The volume ratio of natural uranium to water is approximately 2:1~1:1. For the purpose of this study, an experimental assembly is set up to simulate the fission blanket in this reactor and this assembly consists of DU (depleted uranium, ~0.4% ^{235}U) and PE, due to the unavailability of natural uranium. PE has similar property to water

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as a neutron moderator. Structure of the assembly is referred to the conceptual design. The volume ratio of DU:PE is ~2:1.

Fig.1 shows schematically the benchmark fission assembly to measure the DU fission rates and ^{238}U capture reaction rate. The inner radius (IR) is 131 mm and the outer radius (OR) is 300 mm. Each PE shell is sandwiched between two DU shells. From inner to outer, the three DU shells are 50, 39 and 46 mm in thicknesses, respectively; while the the two PE shells are 13 and 21 mm in thicknesses, respectively. The 225 keV deuteron beam comes from a D-T fusion source of about 3×10^{10}/s.

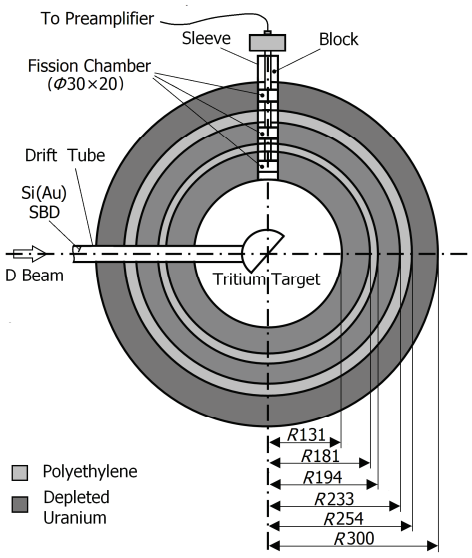

Fig.1 Schematic diagram of the fission assembly

2.2 The tritium production assembly

The tritium production assembly is shown in Fig.2. It is of 40-mm IR and 300-mm OR, with a DU shell of 91 mm thicknesses and a LiH shell of 169 mm thickness. The DU shell is used to simulate fission blanket so that neutrons with fission spectrum can leak into the LiH region of tritium production. The portion of ^{6}LiH in LiH is 8.7%. A D-T fusion neutron source is used for measuring tritium production rates in the LiH region.

3 The reaction rates

3.1 ^{238}U capture reaction rate

In the fission assembly, the process of ^{238}U capturing neutron and decaying into ^{239}Pu is that nuclide ^{239}U (half life of 23.54 min) produced decays into ^{239}Np (half life of 2.335 d), and ^{239}Np into ^{239}Pu. By measuring 277.6 keV γ-ray of ^{239}Np, the production rate of ^{239}Pu can be deduced. The reaction rate indicates multiplication of fissile fuel. An uranium foil is used to measure ^{238}U capture reaction rate[3] , i.e., plutonium production rate, $P(r)$, *via* the ^{238}U(n,γ) ^{239}U reaction. It can be expressed as

$$P(r)= N(r)/[m_{U}bg\varepsilon\Phi A(d)] \quad (1)$$

where, r is the position of a DU foil in a radial channel; $N(r)$ is the gamma activity of DU foil at the position r and in irradiation time of t_0; m_U is the number of ^{238}U atoms in the uranium foil; b is the isotope abundance; g is the emission rate of 277.6 keV γ-ray from ^{239}Np decay, ε is the efficiency of an HPGe detector, calibrated by ^{243}Am 277.6 keV γ-ray in its decay (half life of 7954 a) into ^{239}Np; Φ is the absolute yield of the neutron source, measured by the associated α particle method and corrected by decay of the activated foils during irradiation; and $A(d)$ is the correction factor of self-absorption of the uranium foil to 277.6 keV γ-ray, and d is thickness of the uranium foil. The capture reaction rates are normalized to one source neutron and one ^{238}U atom in a foil.

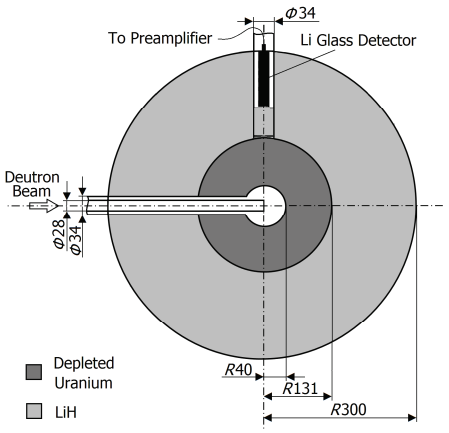

Fig.2 Schematic diagram of the tritium production assembly.

The uranium foil is of Φ24 mm, and so is the ^{243}Am γ-ray source, which is located at 25.6 mm above the HPGe detector, with an efficiency of 5.46% at 277.6 keV. During irradiation, an activated nuclide in the foils decays simultaneously. To obtain gamma activity of the foil in the irradiation time, the source neutron yield must be corrected by the decay factor[3] relevant to the decay constants of ^{239}U and ^{239}Np, the irradiation time, cool time, and measuring time.

The self-absorption factors of the uranium foils to 277.6 keV γ-ray measured with the HPGe detector and the ^{243}Am source, using the least square method, are 93.3%~89.8% for the uranium foils of 0.122−0.193 mm in thickness.

The fission assembly in Fig.1 was located at the experimental hall with the neutron generator. The HPGe detector in a shielding chamber at the measuring room was used to measure γ-rays from an irradiated foil off-line, using the MAESTRO code for data collection and analysis. Seventeen slices of DU foils were irradiated in the radial channel of the assembly at 90°to the D^+ beam incidence. The ^{238}U(n,γ)^{239}U reaction rates were obtained using Eq. (1), with an uncertainty of the reaction rates of 3.5%−3.7%.

The distribution of plutonium production rates measured is shown in Fig.3. Because of the PE moderation of the neutrons, and thresholdless of the ^{238}U(n,γ)^{239}U reaction, the distribution of the reaction rates emerges peaks in two PE regions. The ^{238}U capture reaction rates in the fission assembly are calculated using MCNP5 code and ENDF66c library data, as shown in Fig.3.

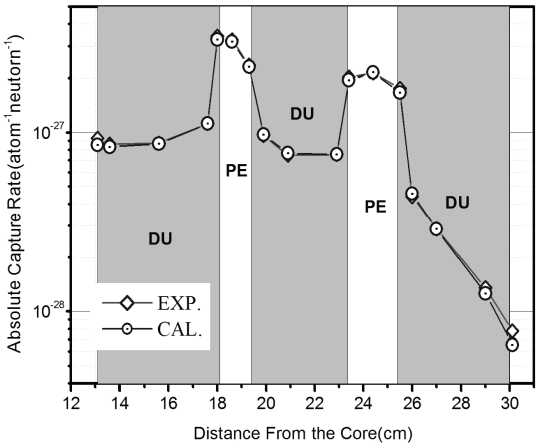

Fig.3 Distribution of ^{238}U capture reaction rates (DU, depleted uranium; PE, polyethylene)

The model is completely consistent with the structure and ingredient of the assembly contained the target chamber. The distribution of the source neutron energy with angle is described. The number of sampling particles is about 1×10^8. The run time is about one week. The calculated capture reaction rates are normalized to one source neutron and one ^{238}U atom. The calculated error is less than 1%. The C/E (ratio of the calculated data to the experimental data) is 0.92−1.04. As for effect of background neutrons, we had the C/E=0.84 in outer surface of assembly. The total plutonium production rate in the three DU shells of the assembly can be obtained by integrating capture rates in the DU regions and correcting them by the structural materials effects in the target chamber and the hole of the drift tube. The total Pu production rate in the DU shells is 2.240, with an uncertainty of 4.1%.

3.2 U fission reaction rate

In the fission assembly, the U fission reaction rate indicates the energy amplification and neutron multiplication. The DU fission chamber of Φ30 mm×20 mm was used to measure fission rates[4]. A cable was connected to the preamplifier. The abundance of the ^{238}U isotope in the DU coating of Φ24 mm in the chamber is 99.579%. It was placed in the radial channel, at a 90°to D^+ beam incidence. The fission rate can be expressed as

$$F(r)= N_f(r) /(m_U \Phi \eta) \quad (2)$$

where, r is the position of a fission chamber in a radial channel; $N_f(r)$ is fission count measured by a fission chamber; m_U is the number of uranium atoms; η is the efficiency of recording fission fragment; and Φ is the absolute yield of the neutron source in the center of the spherical shell, measured by the associated α particle method. A Au-Si surface barrier detector (SBD) is placed at 178.2° to the D^+ beam incidence in drift tube. The fission reaction rates are normalized to one source neutron and one U atom in the fission chamber.

The absolute fission rates of DU were measured by the fission chamber in 8 positions in the three DU shells (Fig.1), with an uncertainty of about 4.7%. The distributions of DU fission rates measured and calculated are shown in Fig.4. The fission rates in the three DU regions of the assembly were calculated using MCNP5 code and ENDF/B-V library data. The model is completely consistent with the structure and ingredient of the assembly contained the target chamber, with the calculated error of less than 2%, and C/E = 0.98−1.14. Integrating the distribution of DU fission rates in the three DU regions of the assembly, the total fission rate is 1.11. The total fission rate is related to the energy multiplication factor M, which is defined as the ratio of the fission energy release in the assembly to per unit source neutron energy. In the

fission assembly, M is approximately equal to the fission energy divided by 14.1 MeV, and the value is about 16.

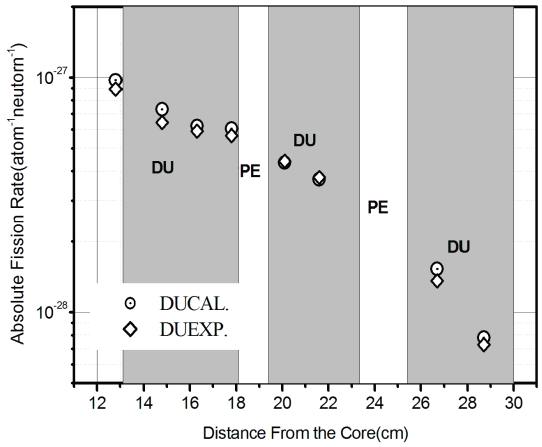

Fig.4 Distribution of depleted uranium fission rates. (DUEXP represents experimental results. DUCAL represents calculated results)

3.3 Tritium production rate

In the tritium production assembly, the ^{6}Li(n,α)T reaction takes place. The reaction rate, indicating the tritium production rate, was measured by ^{6}Li glass scintillator[5] (Fig.2). The detector with ^{6}Li glass of Φ20 mm× 1 mm was placed in the radial channel of the assembly at 90° to D^{+} beam incidence. The tritium production rate is in proportion to the number of ^{6}Li(n,α)T events and can be expressed as

$$T(r)= N_t(r) /(m_{Li}\Phi) \quad (3)$$

where, r is the position of a detector in a radial channel; N_t(r) is ^{6}Li(n,α)T reaction number measured by a ^{6}Li glass detector; Φ is the absolute yield of the neutron source in the center of the spherical shell; and m_{Li} is the number of ^{6}Li atoms in a lithium glass. The reaction rates are normalized to one source neutron and one ^{6}Li atom in the ^{6}Li glass detector.

In a mixed neutron-γ radiation field, the responses of ^{6}Li glass with 95% abundance differ from ones of ^{7}Li glass with 99.99% abundance. However, the γ responses of ^{6}Li glass and ^{7}Li glass are almost the same. The counts from rays as background in a ^{6}Li glass detector are subtracted by the counts from γ-rays in a ^{7}Li glass detector. The lithium glass detector was placed at 16 positions in 10-mm intervals. When the reaction rate was measured on-line at a position, a hole in the front of the detector is filled using small LiH cylinders.

The tritium production rates in the lithium region of the assembly were obtained according to Eq.(3), with an uncertainty of about 5.4%. The distribution of tritium production rates is shown in Fig.5. Because of leakage neutron spectrum from the DU shells is hard (Fig.6) and thresholdless of the ^{6}Li(n,α)T reaction, the reaction rates increased with increasing radial distance before the third position, where it began to decrease with increasing distances. The distribution of leakage neutron spectrum from DU shell is calculated by MCNP5 code and ENDF66c library data, and normalized to one source neutron. The result shows that the neutron spectrum below 10 MeV is similar to fission spectrum as shown in Fig.6. Because of the U(n,2n) and U(n,f) reaction multiplying neutrons in the depleted uranium shell, there are more 1 MeV neutrons than 14 MeV ones.

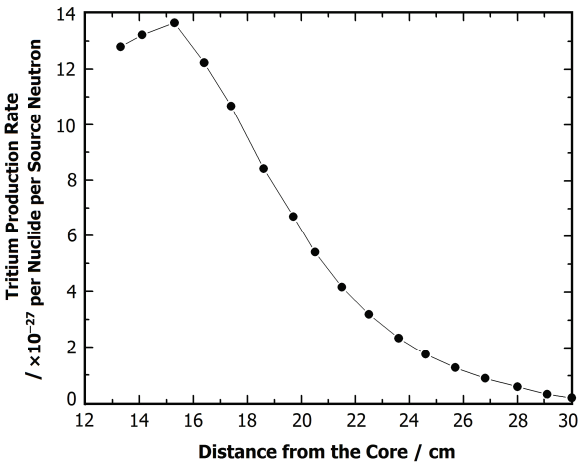

Fig.5 Distribution of tritium production rates

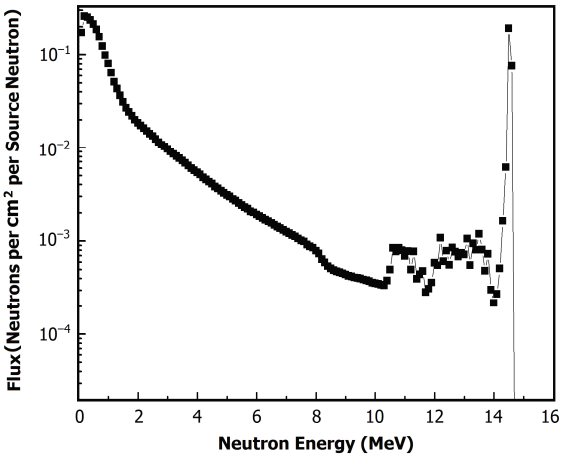

Fig.6 Distribution of leakage neutron spectrum from the depleted uranium shell.

The number of ^{6}Li(n,α)T reaction per volume in the detector is proportional to tritium production rates in lithium region of the assembly. The proportional factor is value of ^{6}Li atom number per volume in the detector to one in LiH shell. The total tritium production rate in lithium region of the assembly can be obtained by integrating ^{6}Li(n,α)T reaction rates and corrected by the proportional factor and the self-shield factor of ^{6}Li glass to neutrons.

4 Conclusions

To validate the neutronics design of the fusion-fission hybrid reactor with sub-critical blanket and tritium production blanket, two benchmark assemblies based on materials available are established. Experiments for measuring reaction rates by integral methods are performed. The distributions of fission rates, and Pu and tritium production rates in the benchmark assemblies are measured by different techniques. The experimental results show that the C/E values of the ^{238}U capture reaction rates are 0.92−1.04, and the depleted uranium fission rates are 0.98~1.14. The results are beneficial to perform the integral neutronics experiments in further simulation of the assemblies.

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References

1 Shi X M, Peng X J. Nucl power eng. 2010, **31:** 5–7.

2 Liu R, Jiang L, Zhu C X, *et al*. Proceedings of international conference on nuclear data for science and technology, Nice, France, April 2007, 969–971.

3 Wang D L, Chen S H, Kang W, *et al*. Atom Energy Sci Tech, 1997, **31:** 229–233.

4 Liu R, Lin L B, Wang D L, *et al*. Nucl Tech, 2000, **23:** 851–855.

5 Yamaguchi S, Oyama Y, Nakamura T, *et al*. Nucl Instru Meth Phys Res, 1987, **A254:** 413–418.