Neutronics Experiments for DEMO Blanket at JAERI/FNS

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Abstract. In order to verify the accuracy of the tritium production rate (TPR), neutron irradiation experiments have been performed with a mockup relevant to the fusion DEMO blanket consisting of F82H blocks, Li_2TiO_3 blocks with a ^{6}Li enrichment of 40 and 95 %, and beryllium blocks. Sample pellets of Li_2TiO_3 were irradiated and the TPR was measured by a liquid scintillation counter. The TPR was also calculated using the Monte Carlo code MCNP-4B with the nuclear data library JENDL-3.2 and ENDF-B/VI. The results agreed with experimental values within the statistical error (10 %) of the experiment. Accordingly, it was clarified that the TPR could be evaluated within 10 % uncertainty by the calculation code and the nuclear data. In order to estimate the induced activity caused by sequential reactions in cooling water pipes in the DEMO blanket, neutron irradiation experiments have been performed using test specimens simulating the pipes. Sample metals of Fe, W, Ti, Pb, Cu, V and reduced activation ferritic steel F82H were irradiated as typical fusion materials. The effective cross-sections for incident neutron flux to calculate the radioactive nuclei (^{56}Co, ^{184}Re, ^{48}V, ^{206}Bi, ^{65}Zn and ^{51}Cr) due to sequential reactions were measured. From the experimental results, it was found that the effective cross-sections remarkably increases with coming closer to polyethylene board that was a substitute of water. As a result of the present study, it has become clear that the sequential reaction rates are important factors to accurately evaluate the induced activity in fusion reactors design.

1. Introduction

In the nuclear fusion DEMO (demonstration) reactor, the blanket is required to provide a tritium breeding ratio larger than unity by neutron-induced reactions in lithium in the blanket. Solid breeder blankets being developed by JAERI for tokamak-type DEMO reactors utilize Li_2O or Li_2TiO_3 as tritium breeder material, beryllium as neutron multiplier, reduced activation ferritic steel F82H (2% W, 8% Cr and 90% Fe) as structural material and water as coolant [1,2]. Neutrons are captured by the structural material, water and the divertor, and escape to the outside through ducts. To ensure tritium breeding ratio larger than unity is a critical issue in the development of the blanket and the fusion reactor design. Also important is to develop a blanket with a low activation level. It was pointed out recently that the activation processes via not only primary neutron reactions but also sequential reactions should be considered in activation calculations [3,4]. In order to experimentally evaluate these issues, neutronics experiments have been performed by using DT neutrons at Fusion Neutron Source (FNS) [5] facility of JAERI.

2. Tritium production experiments

The ^{6}Li-enriched Li_2O or Li_2TiO_3 is proposed as prospective candidate of breeding materials for the DEMO reactor blanket. The tritium production rate for the blanket design, however, has never been evaluated experimentally with the D-T neutron source, and tritium production experiments with blanket assemblies using ^{6}Li-enriched (40 and 95 %) Li_2TiO_3, Be and F82H, were carried out at JAERI-FNS to evaluate the tritium production rate (TPR).

Figure 1 shows a schematic view of the experimental assembly. As no reflector was set around the D-T source, incident neutrons on the left surface are monochromatic at 14 MeV. The tritium-titanium (TiT) target generates 1.7 x 10^{11} D-T neutrons/s on average via ^{3}H(d,n)^{4}He reaction. In order to measure the D-T neutron generation rates, the associated

α particles were monitored with Si surface barrier detectors. The test assembly was mounted on thin aluminum support frames and a steel deck. The distance between the surface of the assembly and the TiT-target was 200 mm. The thickness of the first F82H, Li_2TiO_3, second F82H and beryllium layer were 16, 12, 3, and 200 mm, respectively. The lateral side of Li_2TiO_3 region was covered with 12 mm thick B_4C. The size of the assembly was about 500 x 500 mm^2 in area with a total thickness of 231 mm. The assembly was surrounded by 100-150 mm thick nat-Li_2CO_3 to shield the neutrons reflected by the experimental room walls. Square holes 50 x 50 mm^2 in area were provided for the fluence measurement through the centerline of the first and second F82H layers. Laminated F82H sample sheets 1.6 and 1 mm in thickness were filled in the center holes of the first and second F82H layers, respectively, to measure the activation distribution in the F82H. Pellets of Li_2TiO_3, 12 mm in diameter and 2 mm in thickness, were located in a bore in the $^6Li_2TiO_3$ layer as detectors to measure the TPR distribution. A liquid scintillation counter system (Aloka-5500) was employed to measure the β-radiation from the yielded tritium [6], and a high purity Ge detector was used to measure the gamma ray emitted from the activated foils [7].

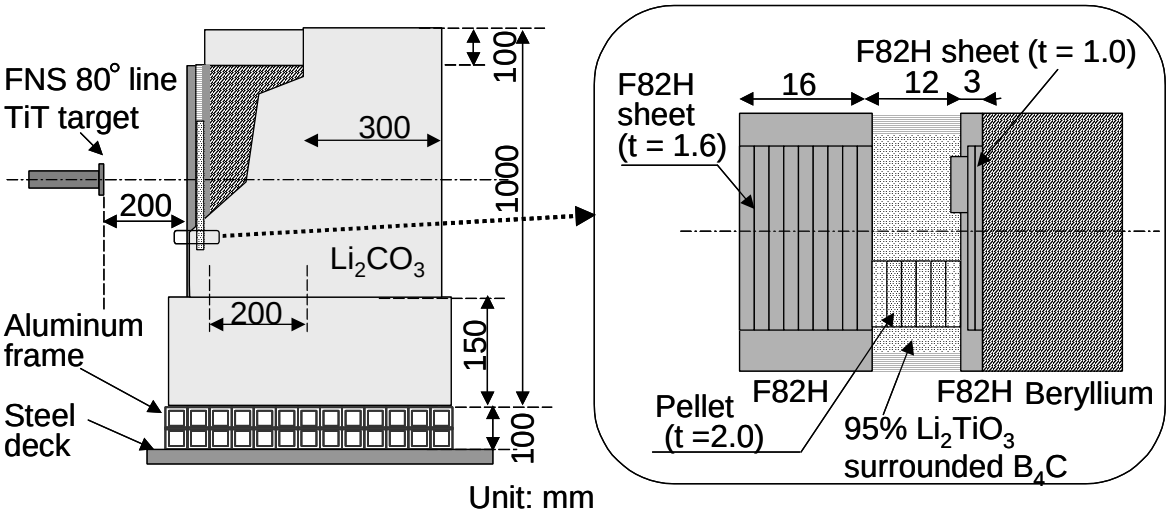

FIG. 1 The schematic view of experimental assembly with the D-T neutron and the configuration of Li_2TiO_3, F82H and Be layers.

Monte Calro transport codes MCNP-4B and -4C were used to calculate the TPR and foil activations with JENDL-3.2 and ENDF-BVI nuclear data libraries. Figure 2 shows the TPR for Li_2TiO_3 pellets obtained by the experiment and calculations. The pellet nearest to the beryllium zone shows the highest TPR. For all the other pellets, TPRs are nearly constant except for a little larger value of the pellet adjacent to the first F82H layer. Although plenty of thermal neutrons are produced by the beryllium zone, a fairly large ratio of them must be captured in the Li_2TiO_3 pellet nearest to the beryllium zone because of the large thermal cross section of $^6Li(n,\alpha)$ reaction. On the other hand, TPRs in the medium locations are expected to be created mainly by $^6Li(n,\alpha)$ reactions of giant resonance cross section at 240 keV. Thus, the important matter for the reliable calculation seems to be how excellently the reaction rate is reproduced around the resonance. In Fig. 2 the calculated TPRs agreed well with the experimental values within the experimental error of about 10 %, which means TPR can be calculated by the Monte Carlo method within the uncertainty of 10 %. As for the nuclear data, significant difference was not observed between JENDL-3.2 and ENDF/B-VI.

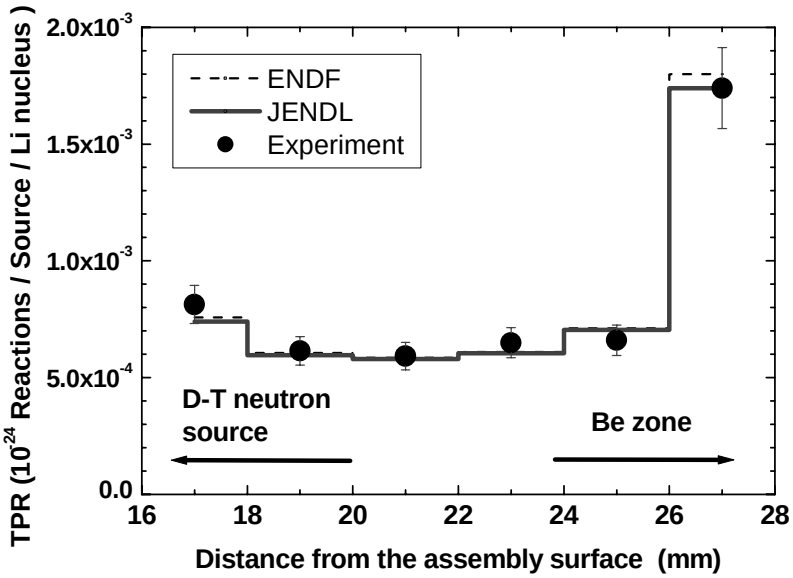

FIG. 2 Distribution of the measured and calculated TPR produced in Li_2TiO_3 pellets. The origin position (0 mm) is the surface of the 16 mm F82H zone which is nearest to the TiT-target point.

3. Sequential Reaction Experiments

Recently it was pointed out that the activations via sequential charged particle reactions (SCPRs) defined as the reactions induced by secondary charged particles should be considered in activation calculations for safety designs of future D-T fusion reactors [3,4]. As for the SCPRs induced by charged particles emitted from primary neutron reactions in homogeneous materials, some experimental results have been reported by Ikeda et al. [8] and Maekawa et al. [9]. However, a special consideration of the SCPRs will be required in the boundary region between different materials. Around the surface of a cooling water pipe, it is expected that the radioactivity production via SCPRs would be enhanced by recoiled proton from hydrogen in the water. The enhancement of the radioactivity production makes corrosion products more activated. It gives rise to critical issues because the corrosion products may be transported along coolant loops into regions outside the biological shield. Thus, the experimental studies have been performed with test specimens simulating the cooling water pipe.

A typical arrangement of the test specimens is shown in Fig. 3. Each irradiation foil was laminated on a polyethylene board 3 mm in thickness that simulates water flowing inside a cooling pipe. The size of the foil was 10 x 10 x (0.05-0.25) mm^3. Natural Fe, W, Ti, Pb, Cu, V and low activation ferritic steel F82H were employed as samples. The radioactive nuclei generated from these materials by the irradiation of secondary protons have sufficiently long half-lives, and the energies of the emitted decay gamma rays are suitable for measurement. Neutrons bombarded the sample materials at the magnitude of 10^{10} order $n/cm^2/s$ flux for 23-40 hours. In order to determine the neutron flux incident on each laminated sample, niobium foils of 10 x 10 x 0.1 mm^3 were attached on both sides of it. A ^{232}Th fission chamber located at the ceiling of the target room was used as a monitor for generated neutrons. After a suitable cooling time, the gamma rays emitted from the irradiated foils were measured by a high purity Ge detector, and the peaks corresponding to the radioactive nuclei (^{56}Co, ^{184}Re, ^{48}V, ^{206}Bi, ^{65}Zn and ^{51}Cr) produced by the SCPRs in Fe, W, Ti, Pb, Cu and V were identified in the measured spectra, respectively.

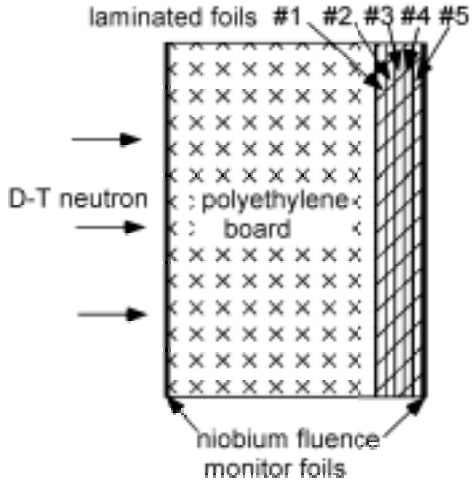

FIG. 3 Typical arrangement of the irradiated sample.

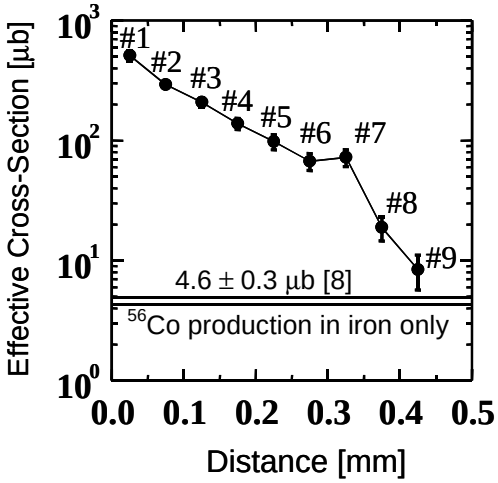

FIG. 4 The effective cross-sections for the ^{56}Co production in Fe foils with respect to the distances from the surface of the polyethylene board.

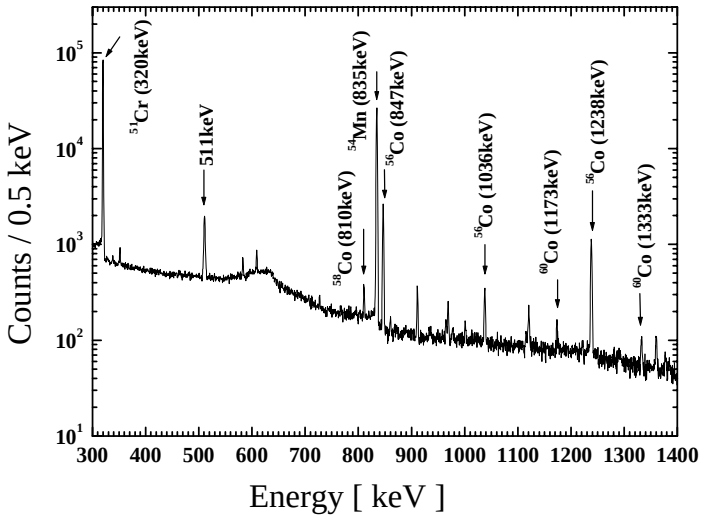

FIG. 5 The gamma-ray spectrum of the F82H foil attached close to the polyethylene board measured after 2 months of cooling time.

The effective cross section was defined as the sequential reaction rate per target atom of natural abundance per neutron flux [10]. For tungsten and lead, the effective cross-sections associated with SCPRs have been measured for the first time. The sequential reaction rate averaged over the thickness of the foil was experimentally derived from the full-energy peak counts by using the full-energy peak efficiencies, well-known decay constant, and gamma ray emission probabilities. Figure 4 shows the derived effective cross-sections for the ^{56}Co production in Fe foils with respect to the distances from the surface of the polyethylene board. With coming closer to the board, an exponential increase of the effective cross-sections is clearly observed in the region between positions #1 and #6. The values around the distance range from 300 to 450 μm are rapidly dropping. This is because the flight range of 14-MeV protons is about 450 μm. During the flight, protons lose the energy down to 5.35 MeV, that is the Q value of the ^{56}Fe(p,n)^{56}Co reaction [11]. Figure 5 shows the gamma ray spectrum of the F82H foil attached close to the polyethylene board measured 2 months after the irradiation. The gamma rays corresponding to ^{56}Co due to the ^{56}Fe(p,n) sequential reaction were clearly observed. It is noteworthy that the intensity of the 847-keV gamma ray from ^{56}Co is about

10 % as large as that of the 835-keV gamma ray from ^{54}Mn due to ^{54}Fe(n,p) reaction by primary neutrons. In the equilibrium, the activity of ^{56}Co whose half-life is 77 days was calculated at about 3 % of the activity of ^{54}Mn (312 days, likewise) on the basis of the effective cross section obtained in this experiment. Because the contact dose rate factor per unit activity for ^{56}Co is about 4 times larger than that for ^{54}Mn, the contribution of ^{56}Co to the spatial radiation dose rate must be about 10 % of that of ^{54}Mn. During the operation before the equilibrium is attained, the contribution must be larger than the value, so that it cannot be neglected in the safety design.

4. Summary

In order to verify the accuracy of the tritium production rate (TPR), neutron irradiation experiments have been performed with an assembly simulating the fusion DEMO blanket. The TPR was also calculated using the Monte Carlo code MCNP-4B and -4C with the nuclear data library JENDL-3.2 and ENDF-B/VI. It was clarified in the experiment that the TPR was drastically enhanced in the breeder regions adjacent to the beryllium blocks due to an increase of thermal neutrons in the beryllium blocks. The TPRs derived from the calculation results agreed with those from the experiment within 10 %, which corresponds to the statistical error in the experiment. Further experiments are planned with Li_2TiO_3 in a form of small pebbles as proposed in the DEMO blanket, and the evaluation accuracy for the pebble configuration will be examined.

Undesirably long-lived radioactive nuclei are expected to be generated by sequential reactions induced by secondary charged particles. In the present study, neutron irradiation experiments have been performed for test specimens simulating cooling water pipes in the DEMO blanket. Sample metals of Fe, W, Ti, Pb, Cu, V and F82H were irradiated. The effective cross-sections for producing the radioactive nuclei (^{56}Co, ^{184}Re, ^{48}V, ^{206}Bi, ^{65}Zn and ^{51}Cr) generated by the sequential reactions were measured. In the present study, it has been clarified that the sequential reaction rates are enhanced, by taking into account the recoiled protons from water, by more than 10 times compared with those induced by the charged particles emitted from the primary neutron reactions in the metals themselves. From the present study, it has been clarified that the sequential reaction rates are of great importance to evaluate the shut-down dose rates and the activated corrosion products.

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