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Blanket Experiments Using Enriched Li_2TiO_3/Ferritic Steel/ Beryllium Assemblies and D-T Fusion Neutrons

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Abstract

At Fusion Neutronics Source (FNS), we have done experiments with thermal-type breeding blanket mock-ups using lithium titanate as breeder material, beryllium as neutron multiplier, and reduced activation ferritic steel F82H simulating structural material. The objective of the experiments is the neutronics performance evaluation of candidate materials for fusion reactor designs as well as the validation of neutron transport code and available neutron data libraries for these materials. A method for the direct measurement of the produced tritium based on liquids cintillation counting was developed. The activation of chromium, tungsten, and iron in F82H steel and titanium in lithium titanate was measured.

Keywords:

advanced breeder material, lithium titanate, thermal blanket, tritium breeding ratio

1. Introduction

A sufficient tritium production of the breeding blanket is of crucial importance for the operation of a fusion reactor. Materials for recent designs for the fusion DEMO reactor blanket include beryllium, ^{6}Li-enriched Li_2TiO_3 ceramics and reduced activation ferritic steels (F82H: Cr 8%, W 2%, Fe balance). The cross section for the important tritium-producing reaction in these thermal-type blankets, $^6Li(n,\alpha)T$, is very high at thermal and subthermal neutron energies. Therefore the fraction of those neutrons as well as their flux should be as high as possible in the breeding material.

Beryllium acts as neutron multiplier and moderator for fast neutrons. Irradiation experiments with beryllium-containing assemblies have been carried out, see for example [1]. However, these assemblies never included lithium titanate. Therefore irradiation experiments with thermal-type blanket models including lithium titanate and D-T fusion neutrons are currently performed at Fusion Neutronics Source (FNS) of JAERI. Preliminary MCNP calculations suggested a ^{6}Li enrichment above 40% in order to obtain sufficient high tritium production rates (TPR). The use of F82H steel will decrease the TPR due to the presence of tungsten. The reaction $^{186}W(n,\gamma)\ ^{187}W$ causes absorption of thermal neutrons needed for tritium breeding.

We have been measuring material activation of chromium, tungsten, iron, and titanate as well as the tritium production in breeding assemblies containing one layer of Li_2TiO_3 with a ^{6}Li enrichment of 95% and 40%. The tritium production measurement was done using liquid scintillation counting techniques. The experimentally obtained tritium production and activation of chromium and tungsten agreed well with

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MCNP [2] calculations using ENDF/B-VI [3] and JENDL3.2 [4] nuclear data files, whereas ^{54}Fe showed a C/E ratio of about 1.2.

We obtained a tritium production profile as one would expect for a thermal blanket, i.e., the tritium production decreases with increasing distance from the surface of the breeding layer due to self-shielding.

2. Experimental Setup

The blanket neutronics experiments have been carried out at FNS using its 80 degree target which can supply up to $4*10^{11}$ D-T neutrons per second. Three different arrangements of layers of F82H steel, beryllium, and lithium titanate ceramics were used, Fig. 1 shows one arrangement as example. Neutron fluence verification was done by means of activation foils located on the beam axis between each layer.

Lithium titanate blocks of 50 mm × 50 mm × 12 mm forming a layer of 12 mm thickness were used as breeding material. To obtain the tritium production in the layer, pellets of lithium titanate with the same ^6Li concentration and a size of 12 mm diameter and 2 mm thickness were inserted into a bore in one of the lithium titanate blocks, see also Fig. 1. Six pellets fit into the bore and allowed to obtain the longitudinal tritium production distribution with a resolution of 2 mm. The pellets were 35 mm off the beam axis. The titanate block carrying the pellets was wrapped in aluminum foil to suppress contamination.

For the metal activation measurement, sheets of F82H steel of 1.6 mm and 1.0 mm thickness and a size of 50 mm × 50 mm were inserted into the F82H layers.

The total size of the blanket assembly was 1000 mm × 1000 mm with a thickness of 500 mm including an outer layer of lithium carbonate to shield the assembly from room-returned neutrons. The D-T neutron source was 200 mm away from the first steel layer. The layer arrangements used in the experiments are shown in Table 1. For the results presented here the total source neutron yield was about 10^{16} neutrons per experiment. It was monitored by two solid-state α - detectors for the D-T reaction.

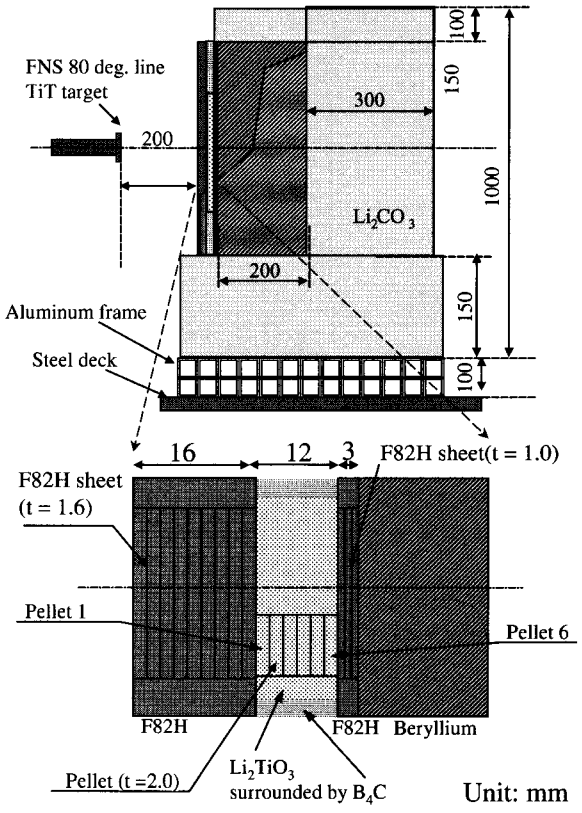

Fig. 1 Cross sectional view of one of the assemblies. Three different layer arrangements were used, see Table 1 for details.

Table 1 The layer arrangements and thicknesses used in the experiments. Zeroes mean the layer was not present, see also Fig. 1. All thicknesses in mm.

Breeding layer ^6Li enrichement	Exp. #	Layer thickness in mm F82H	Be	F82H	Li_2TiO_3	F82H	Be
95%	1	0	0	16	12	3	200
	2	0	0	16	12	9	200
	3	16	50	3	12	9	150
40%	4	0	0	16	12	3	200
	5	16	50	3	12	9	150

3. Experimental Results

3.1 Tritium sample preparation

The tritium production was measured by means of liquid scintillation counting (LSC) of the accumulated tritium activity in the pellets. The electrons emitted during the decay of the tritium nucleus have a maximum energy of 18 keV with a range of a few μm in liquids and solids. Therefore it is necessary to bring the tritium into close contact with a scintillator. The lithium titanate pellets were dissolved in concentrated hydrochloric acid. The low pH value of the solution caused incompatibility with the used scintillator so that the solution was neutralized with sodium hydroxide before incorporation into the liquid scintillation cocktail. The current accuracy of the method is estimated to be 10%. Further validation is in progress, especially during the current series of experiments we will obtain TPR values also from lithium carbonate detectors for which a well established treatment already exists, see for example [5].

3.2 Tritium production

Experimentally obtained TPR values in 95% ^{6}Li enriched lithium titanate sandwiched between F82H and beryllium (experiment 3, Table 1) are presented in Fig. 2. The spatial resolution was 2 mm. The tritium distribution in the layer is characteristic for a thermal-type blanket. The tritium concentration decreases with increasing distance from the surface inside the breeding layer. That is caused by a strong shielding effect due to the very high cross section for the reaction ^{6}Li(n,α)T at low neutron energies. The neutron spectrum is depleted in slow neutrons inside the layer. Figure 3 shows calculated TPR spectra inside the layer and near the surface to illustrate this effect.

It was also noted that the TPRs in all six pellets in experiment 2 were slightly lower than the corresponding TPRs of experiment 1 indicating depletion of thermal and subthermal neutrons in the spectrum by F82H.

3.3 Activation of titanium

The measured activation of titanium is mainly caused by (n,p) and (n,np) reactions, the product is scandium. These reactions are threshold reactions. Verification of the cross section of the reactions ^{46}Ti(n,p)^{46}Sc and ^{47}Ti(n,np)^{46}Sc at neutron energies around 14 MeV can be found for example in ref. [6].

The measurement was done two days after irradiation, therefore isotopes with a short lifetime had already decayed. Three isotopes of scandium, 46, 47, and 48, were found by γ-spectroscopy of the pellets.

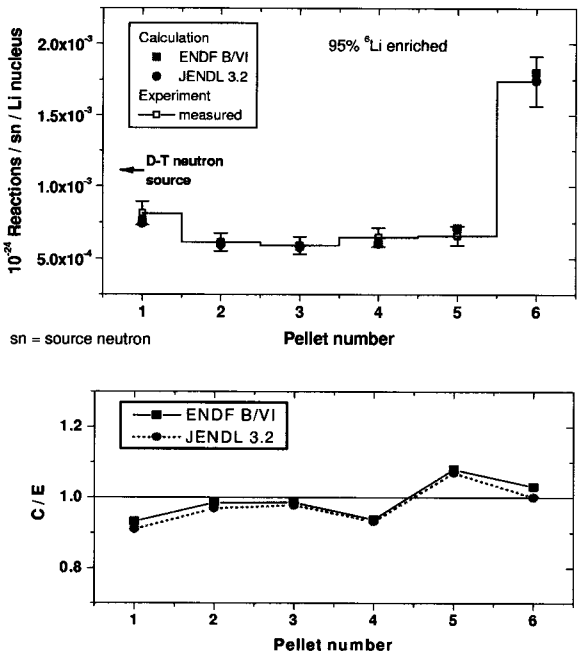

Fig. 2 Experimentally obtained tritium production rate compare to MCNP calculations from experiment 3, see Table 1.

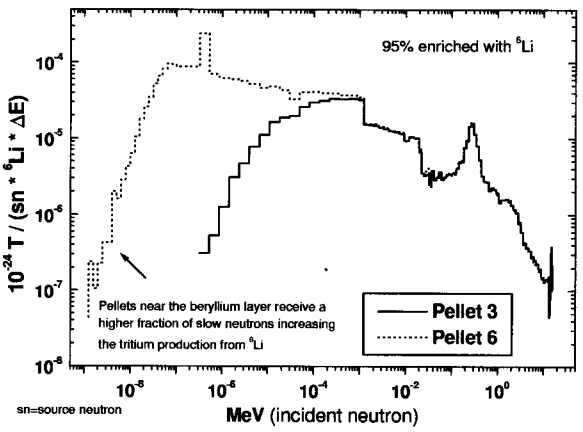

Fig. 3 Calculated TPR spectrum of two pellets in the assembly illustrating the shielding effect in the breeding layer. Pellet 6 is near the surface, pellet 3 is inside the layer.

Their half-life time is 83.8, 3.4, and 1.82 days, respectively. The activation of titanium could impose a major source of background noise for the LSC tritium measurement because its activity is higher than that of the tritium. However, the obtained tritium spectra do not show a significant gamma background. That indicates that the scandium isotopes are not in solution despite

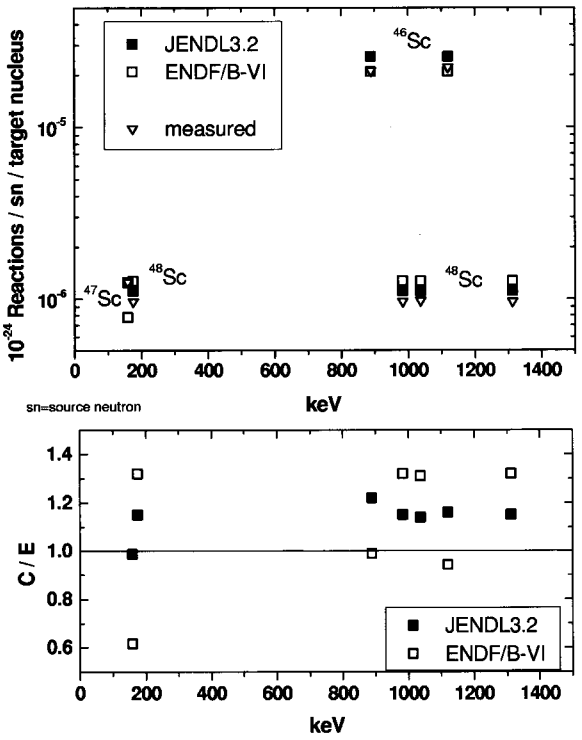

Fig. 4 Activation of titanate in the breeding layer. The x-axis shows the energies of the gamma lines used for the activity measurement.

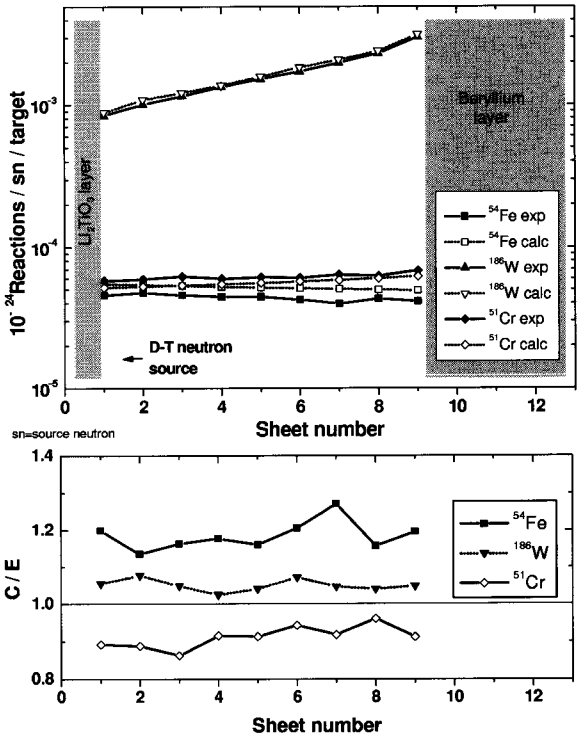

Fig. 5 Reaction rates in a layer of F82H steel between the breeding layer and the beryllium layer. The total thickness of the layer was 9 mm, each sheet had a thickness of 1 mm.

their low concentration of the order of 10^8 nuclei per gramm lithium titanate.

The main contribution to the activation comes from ^{46}Sc with a production rate about ten times higher than that of the other two isotopes, and ^{48}Sc with a lower production rate but higher activity due to its short lifetime.

The measured values were compared to calculations with the neutron transport code MCNP-4B and the ENDF/B-VI and JENDL3.2 data libraries. Figure 4 shows the results. The calculations included the (n,p) and (n,np) reactions. The generation of ^{46}Sc is better described by the calculation based on the ENDF/B-VI libraries whereas ^{47}Sc and ^{48}Sc are better described by JENDL3.2.

3.4 Activation of F82H steel

The structural material F82H was analyzed for activation of iron, chromium, and tungsten. Figure 5 shows measured activities arising from the reactions ^{54}Fe(n,p)^{54}Mn, ^{186}W(n,γ)^{187}W, ^{50}Cr(n,γ)^{51}Cr, and ^{52}Cr(n,2n)^{51}Cr.

The figure shows the case of a nine millimeter layer of F82H steel between the breeding layer of 95% ^{6}Li enriched lithium titanate and the beryllium layer. The neutron spectrum near the lithium titanate layer is depleted in slow neutrons due to absorbtion. Near the beryllium the fraction of slow neutrons is higher because they originate mainly by moderation of fast neutrons in the beryllium.

The reaction ^{54}Fe(n,p)^{54}Mn is a threshold reaction, the spatial reaction rate in the steel layer does not depend on the location.

^{50}Cr(n,γ)^{51}Cr and ^{52}Cr(n,2n)^{51}Cr both lead to the production of ^{51}Cr. The first reaction is also a threshold reaction but the cross section for the second reaction behaves similar to that of ^{6}Li. That is why the reaction rate increases towards the beryllium layer. Natural chromium consists of 84% ^{50}Cr and 4.5% ^{52}Cr. The contribution from ^{52}Cr is not so high, therefore the reaction rate increases only slightly towards the beryllium layer.

Excellent agreement between calculation and experiment was found for ^{186}W. The cross section for the considered reaction behaves similar to that of ^{6}Li.

The reaction rate appears to decrease exponentially with distance from the beryllium layer. That is due to absorption of slow neutrons in F82H mainly because of the presence of ^{186}W. The source of slow neutrons is the beryllium layer, the high ^{6}Li concentration in the titanate layer does not allow a significant contribution of slow neutrons.

4. Conclusion

Irradiation experiments with a thermal-type breeding blanket model and D-T neutrons were performed at FNS. The breeding material was lithium titanate enriched with ^{6}Li. A method for the direct measurement of the tritium production was developed. Experimental values and calculations done with MCNP-4B and the JENDL3.2 and ENDF/B-VI data libraries agreed well within the estimated experimental error of 10%.

The activation of titanium was also measured. It was found that the calculations with JENDL3.2 show less scattering and a C/E ratio of about 1.2. The ENDF/B-VI calculations are more scattered, but the $^{46}Ti(n,p)^{46}Sc$ reaction, which contributes mostly to the total ^{46}Sc, is better described with ENDF/B-VI.

Activation of iron, chromium, and tungsten in F82H steel was obtained by γ-spectroscopy. Excellent agreement of experimental and calculated values was found for ^{186}W. The activation of ^{50}Cr, ^{52}Cr, and ^{54}Fe showed discrepancies up to 25% or a C/E ratio of up to 1.25.

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