Evaluation of Tritium Breeding and Irradiation Damage for the EU Water-Cooled Lithium-Lead Test Blanket Module in ITER-FEAT

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Abstract. Comprehensive neutronic analyses have been carried out for the EU water-cooled lithium-lead test blanket module (TBM) integrated into ITER-FEAT to assess tritium generation and parameters relevant to the lifetime performance of the TBM, such as helium and atomic displacement production. The analyses have been performed utilizing models representing the complex ITER and TBM structure close to reality. The Monte Carlo transport code MCNP-4C and cross-sections from the FENDL-2.0 data library have been used in the analyses. Theoretical estimates of the radial distribution of tritium production density, total tritium production rate, radial distribution of helium and displacement formation along the TBM, and poloidal distribution of helium and displacement generation in demountable hydraulic connections of the TBM have been obtained.

1. Introduction

The ITER-FEAT reactor, whose programmatic objective is to demonstrate the scientific and technological feasibility of fusion energy, is an intermediate step toward the first demonstration fusion power reactor, DEMO. Among the main objectives of ITER are plasma studies, testing of components for a future reactor and testing of tritium breeding module concepts in a true fusion environment, i.e. 14 MeV neutron wall loading on the first wall > 0.5 MW/m^2 and fluence > 0.3 MWa/m^2 [1].

The water-cooled lithium-lead (WCLL) DEMO blanket is one of the European blanket concepts to be further considered for manufacturing a test blanket module (TBM) for testing in ITER-FEAT. One of the aims of the testing is to evaluate the neutronic behaviour of the TBM and to validate the computer code estimates [2].

The WCLL TBM is similar to the equatorial part of an inboard segment of the corresponding DEMO blanket and is designed for casing in one vertical half of port #18 at the midplane of ITER-FEAT. It is intended to be tested in ITER-FEAT under operational conditions of ≈0.8 MW/m^2 neutron wall loading (500 MW fusion power), 0.25 MW/m^2 surface heat flux and a neutron fluence of ≥0.3 MWa/m^2. The TBM uses liquid Pb-17Li with 90% ^{6}Li enrichment as a breeder and neutron multiplier, EUROFER-97 9% Cr steel as a structural material and light water as a coolant. It consists of a directly cooled steel box serving the function of Pb-17Li container reinforced by radial and toroidal stiffeners. The breeder region is cooled by an independent water flow in double-walled C shaped tubes (DWTs) immersed in the breeder pool [2].

This work presents the results of three-dimensional calculations of tritium generation in the TBM and radiation damage of the structure through helium, hydrogen and atomic displacement production, and estimates of the amount of atomic displacement and helium production at the demountable hydraulic connections, utilizing the Monte Carlo code MCNP-4C [3].

2. Modelling and Method of Calculation

The model of the TBM and the frame [4] set up for use with the MCNP code has been updated and integrated into the existing three-dimensional 20^0-geometry sector model of ITER-FEAT, which uses two reflecting surfaces at the boundaries [5]. All relevant components of the ITER machine are accounted for in the geometrical description: the shielding blanket, vacuum vessel, divertor cassette, ports (equatorial, divertor, cryopump, upper) and magnet system are described in detail [5]. The model of the TBM and the frame has been inserted into the equatorial outboard test blanket port #18, accounting for 2 cm gaps between the shielding blanket and the frame walls and for a 2 cm reset from the first wall of ITER and the front of the TBM.

The TBM components (breeder region, steel container, breeder DWTs and stiffeners) are described adequately in the model except that the cooling region of the segment box is represented by a homogeneous approximation. The vertical collectors of the first wall cooling system located behind the backplate (BP) and the inlet and outlet headers of the breeder zone cooling circuit were modelled as parts of semi-cylinders. To evaluate helium and atomic displacement production at the welding of DWTs on the BP, tubes through the BP with the same diameters as those in the breeder region were modelled. The responses were calculated in the horizontal parts of DWTs in the back 1/8 of the breeding zone with a depth of 7.55 cm, hereafter referred to as DWTs close to the BP, and in the modelled tubes in the BP, referred to as DWTs in the BP. The radial-toroidal cross-section of the TBM model, integrated in ITER-FEAT, at z = 57.25 cm from the center of the TBM, and the radial-poloidal cross-section at the center of the TBM are presented in Fig. 1.

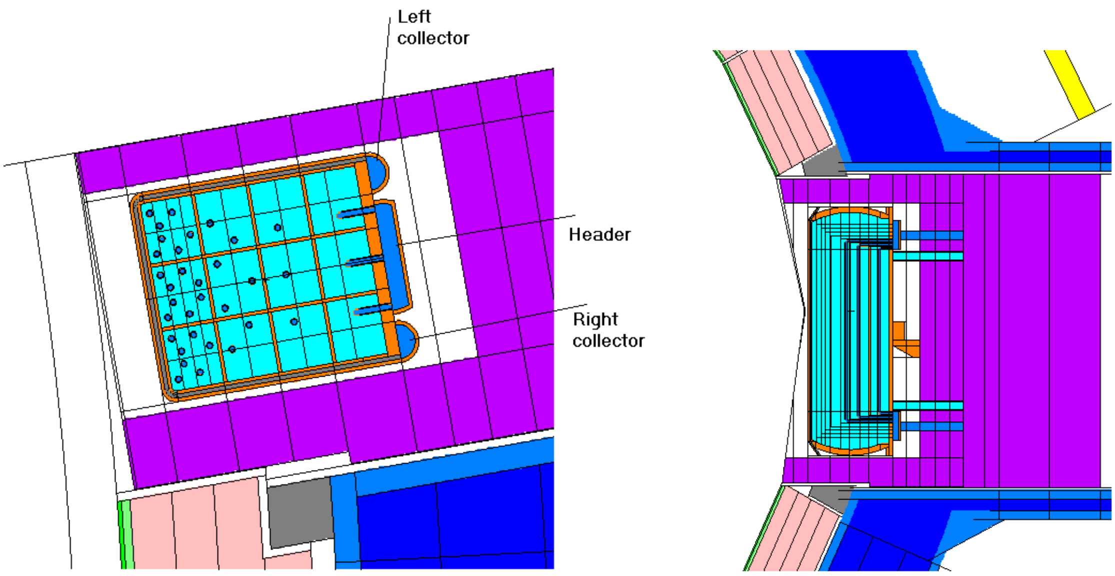

FIG. 1. Radial-toroidal cross-section view of the TBM model at z = 57.25 cm from the TBM center (left) and radial-poloidal cross-section view at the center of the TBM model (right).

Detailed three-dimensional radiation transport calculations utilizing the MCNP-4C code and cross-sections from the FENDL-2.0, FENDL/A-2.0, EFF2.3 and IRDF-90 data libraries have been performed. To carry out the analyses a realistic D-T plasma neutron source has been used in the calculations [5].

The neutron responses were scored until sufficient statistical accuracy was obtained. Relative errors of less than 5% have been achieved for the radiation damage responses. Tritium production has been calculated with a maximum relative error of less than 0.6%, owing to the high requirement for accuracy of that neutronic characteristic.

3. Results

3.1. Tritium Production

Assuming 90% ^{6}Li enrichment and a 22% duty cycle (400 s burn length, a pulse repetition period of 1400 s), the tritium production rate was estimated to be 3.8738 x 10^{16} T atoms/s (16.62 mg/d). As tritium production depends on ^{6}Li enrichment, the effect of using different ^{6}Li enrichment on tritium generation has also been assessed. The results are listed in Table I, which shows the decrease of tritium production with decreasing ^{6}Li enrichment. The neutron wall loadings (NWL) of 0.8 MW/m^2 and 1.1 MW/m^2 specified in the table are the estimated values on the first wall of the TBM and the design value [2] respectively. The last column of the table gives the percentage change of tritium production with ^{6}Li enrichment compared with that at 90% enrichment. As is seen from the table, decreasing ^{6}Li enrichment from 90% to 60% results in a 12% decrease in tritium production. Since the WCLL blanket strongly depends on blanket coverage and inhomogeneities, a thorough analysis of the blanket taking into account the ports and penetrations would clarify what level of ^{6}Li enrichment is sufficient to ensure self-sustaining tritium production of the DEMO WCLL blanket.

The radial distribution of tritium production density has been calculated in order to provide data useful for permission barrier analyses. The result is shown in Fig. 2. The decrease of tritium breeding density with increasing depth correlates with the decrease of neutron flux of energy < 0.01 MeV, which contributes the most to the tritium production.

TABLE I: TRITIUM PRODUCTION RATE IN THE TBM AT DIFFERENT ^{6}Li ENRICHMENT.

NWL (MW/m^2)	**0.8**	**1.1**	**Ratio (T production/T production at 90% ^{6}Li)**
T production at 7.5% ^{6}Li (mg/d)	8.27 (0.006)[a]	11.37 (0.006)	0.498
T production at 40% ^{6}Li (mg/d)	13.29 (0.006)	18.27 (0.006)	0.800
T production at 60% ^{6}Li (mg/d)	14.64 (0.006)	20.13 (0.006)	0.881
T production at 90% ^{6}Li (mg/d)	16.62 (0.004)	22.85 (0.004)	1.000

[a)] Relative error.

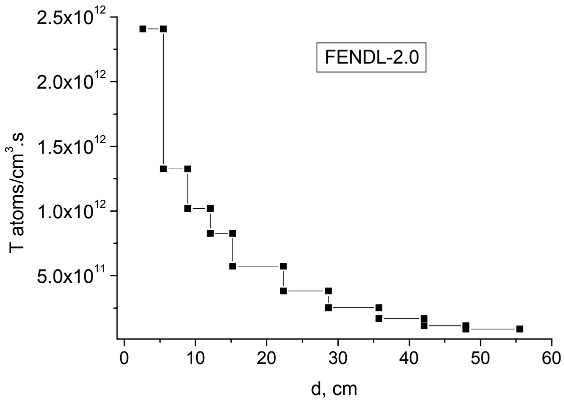

FIG. 2. Radial distribution of tritium production density in the breeder region. The d stands for the distance from the front of the TBM.

3.2. Radiation Damage

The two main sources of radiation damage in a fusion reactor are the atomic displacement and gas production through transmutation, and knowledge of these is essential to determine the components' useful lifetime. The helium, hydrogen and atomic displacement production (displacements of Fe, Cr and Mn-55 atoms) in the steel structure of the TBM has been calculated and the radial distribution of these has been estimated in the DWTs, the stiffeners and the box. To assess helium and dpa production at the weldings of demountable hydraulic components, i.e. of DWTs on the BP, in inlet/outlet headers of the breeder zone cooling circuit and in vertical collectors of the first wall cooling system, the poloidal distributions of helium and dpa production in DWTs close to the BP, in DWTs in the BP and in the headers, as well as the toroidal-poloidal distribution in the collectors, have been assessed.

The spatial/energy distribution of neutron flux has been calculated using FENDL/2.0 cross-section data. The (n,α), (n,n'α), (n,p) and (n,n'p) cross-sections for each nuclide have been taken from the FENDL/A-2.0 activation library. The atomic displacement cross-sections of the EFF2.3 and IRDF-90 libraries have been used to calculate the displacement of Fe, Cr and Mn-55 atoms.

It was found that the maximum of radiation damage takes place in the first wall first steel layer. This is because of the high fast neutron flux of $E_n > 0.1$ MeV and the highest 14 MeV neutron flux in the first wall arising from the D-T source and reflection by the Pb-17Li (Fig. 3). The He and H production in that location amounts to 19.3 appm/0.3MWa/m^2 and 103 appm/0.3MWa/m^2 respectively, as seen in Fig. 4, where the radial distributions of helium and hydrogen production in the box are shown. A large helium and hydrogen production rate in the structure of the front of the breeder region is also observed: the helium production rate in the stiffeners is 13.3 appm/0.3MWa/m^2, while in the first row of DWTs it totals 12.3 appm/0.3MWa/m^2, and the hydrogen production is 66 appm/0.3MWa/m^2. The largest atomic displacement is located in the first wall first steel layer and amounts to 2.77, 2.79 and 2.45 dpa/0.3MWa/m^2 for Fe, Cr and Mn-55 atoms respectively (Fig. 5). The second highest atomic displacement found is in the stiffeners in the front part of the breeder zone, totalling 2.44, 2.51 and 2.26 dpa/0.3MWa/m^2 for Fe, Cr and Mn-55 atoms respectively (Fig. 5).

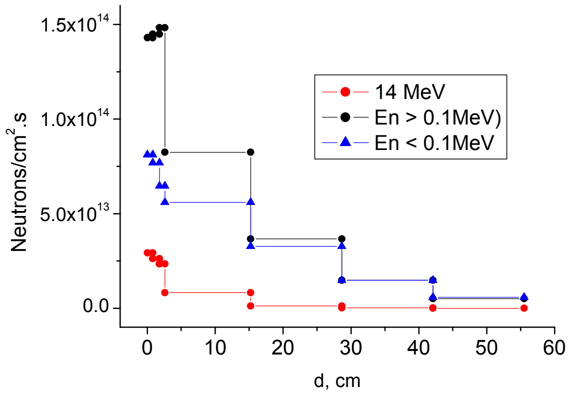

FIG. 3. Radial distribution of neutron flux in the box. The d stands for the distance from the front of the TBM.

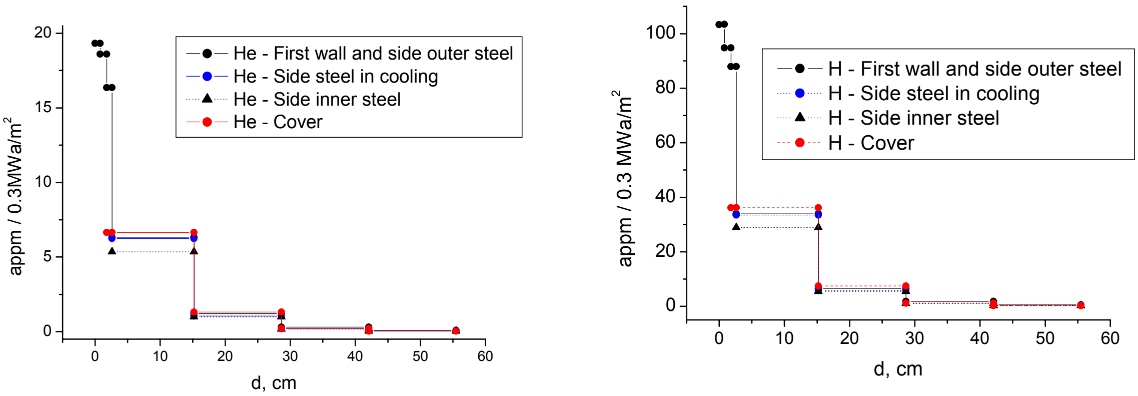

FIG. 4. Radial distribution of helium (left) and hydrogen (right) production in the box. The d stands for the distance from the front of the box.

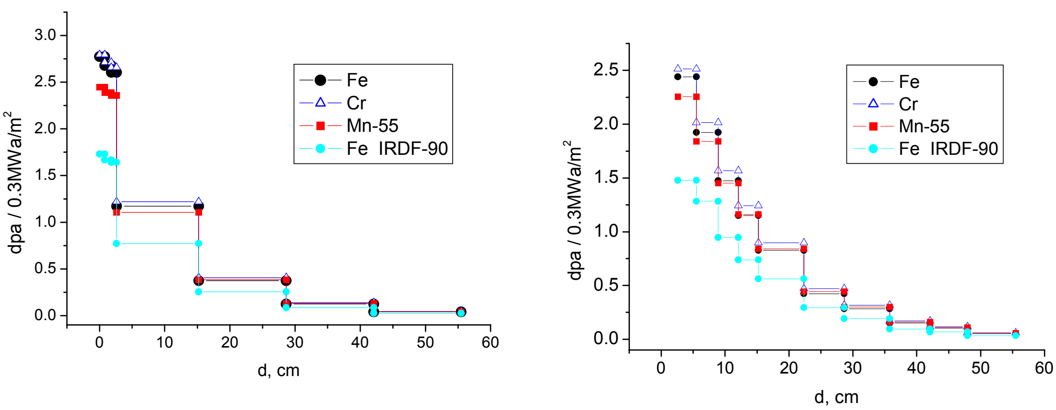

FIG. 5. Radial distribution of atomic displacement in the box (left) and in the stiffeners (right). The d stands for the distance from the front of the box.

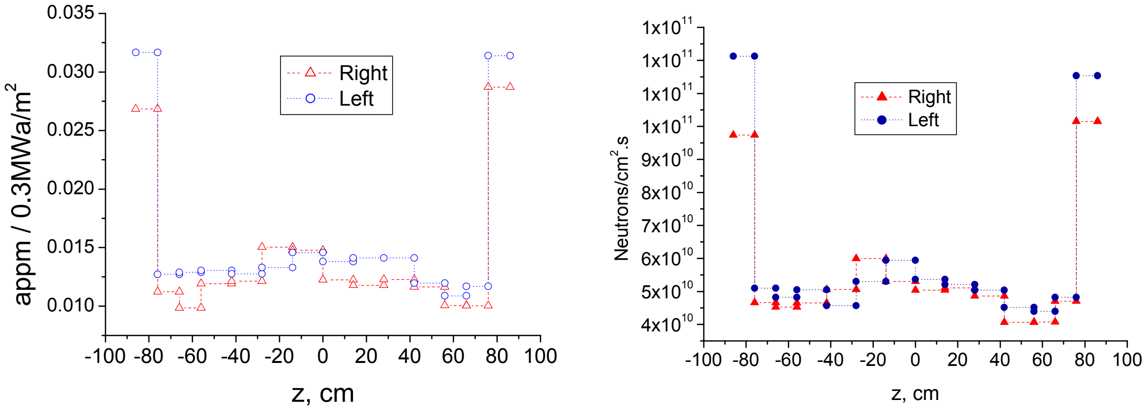

FIG. 6. Toroidal-poloidal distributions of helium production (left) and neutron flux of E_n > 3 MeV (right) in the vertical collectors. The distance z is measured from the center of the TBM.

At demountable hydraulic connections the largest helium content is in the vertical collectors, amounting to 0.032 appm/0.3MWa/m^2, and is located in the upper and lower parts of the left side collector if facing the front of the TBM (Fig. 6). This is due to the higher fast neutron flux in the left side collector than in the right side one, as is seen in Fig. 6.

The largest values of atomic displacement obtained in demountable hydraulic connections are located in DWTs close to the back plate (in the inner rows of DWTs centered at z = ±57.25 cm from the TBM center) and are 0.039, 0.044 and 0.042 dpa/0.3MWa/m^2 for Fe, Cr and Mn-55 atoms respectively (Fig. 7). The poloidal distributions of fast neutron flux (E_n > 0.1 MeV) and of the flux of neutrons with energy < 0.1 MeV averaged over the cells of DWTs close to the BP and of DWTs in the BP are shown in Fig. 7. It is seen from the figure that the contribution of fast neutrons to the displacement production in DWTs close to the BP is higher than that in DWTs in the BP, where neutrons with energy < 0.1 MeV dominate owing to the better slowing down capability of steel than of Pb-17Li.

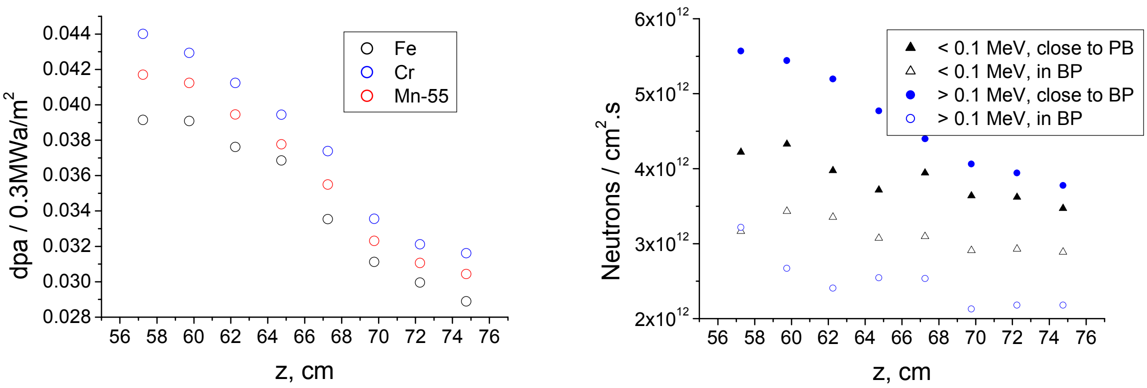

FIG. 7. Poloidal distribution of atomic displacements (left) in DWTs close to the BP and poloidal distribution of neutron flux averaged over the cells of DWTs close to the back plate and of DWTs in the BP (right). The distance z is measured from the center of the TBM.

4. Conclusions

Theoretical estimates of the radial distribution of tritium production density, the total tritium production rate, the radial distribution of helium, hydrogen and displacement formation along the TBM structure, and the poloidal distribution of helium and displacement generation in demountable hydraulic connections of the TBM have been obtained employing the three dimensional Monte Carlo radiation transport code MCNP.

The estimate of tritium production is intended for validation of the Monte Carlo code and cross-sections used in tritium related experiments in ITER-FEAT and for intercomparison with the other TBM concepts. The estimates of the helium, hydrogen and atomic displacement production presented in this work are of relevance for assessment of the terms of TBM structure replacement and the reweldability of the demountable hydraulic connections taking into account the radiation lifetime of EUROFER-97 and the required limit for weldability of the steel structure.

References

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