Initial Three-dimensional Neutronics Calculations for the EU Water Cooled Lithium-Lead Test Blanket Module for ITER-FEAT[1]

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Abstract. The paper summarizes the main results of the initial three-dimensional radiation transport analysis of the EU water-cooled lithium-lead test blanket module performed using the Monte Carlo code MCNP. Estimates of tritium production rate, nuclear energy deposition and cumulative fluence effects such as radiation damage through atomic displacement and production of He and H are presented.

1. Introduction

The water-cooled lithium-lead (WCLL) DEMO relevant blanket is one of the two European blanket concepts to be further developed for manufacturing a test blanket module (TBM) to be tested in ITER-FEAT. One of the objectives of the testing is to evaluate the neutronic behaviour of the TBM and to validate the computer code estimates [1]. The WCLL TBM is intended to be tested in ITER-FEAT under operational conditions of 1.1 MW/m^2 neutron wall loading, 0.25 MW/m^2 surface heat flux and a neutron fluence of $\geq$0.3 MWa/m^2. It is designed for casing in one vertical half of Port #18 at the midplane of ITER-FEAT. The TBM uses liquid Pb-17Li with 90% ^{6}Li enrichment as a breeder and neutron multiplier, 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 independent water flow in double-walled C shaped tubes (DWTs) immersed in the breeder pool. The TBM is attached to the back wall of the water-cooled steel frame directly supported by the ITER-FEAT vacuum vessel [1].

2. Modeling of the TBM and Method of Calculation

A three-dimensional model that adequately represents the complex geometric arrangement of the module and the frame has been developed for use with the MCNP code. The breeder region, steel container, breeder cooling tubes and stiffener geometries are described adequately in the model, while the cooling region of the box is represented by a homogeneous approximation. The radial-toroidal cross-section of the model at the midplane of the TBM and the frame and corresponding toroidal-poloidal cross-section view of the model are displayed in Fig. 1. The blanket of the whole machine has been approximated by a 10^0 (half-sector) model using the TBM and the frame model with white boundary conditions at the upper, bottom and back frame surfaces and reflection at its side surfaces.

The source neutrons with energy of 14.1 MeV have been sampled uniformly over the frame front surface and directed using cosine angular distribution. An importance sampling has been used as an appropriate variance reduction technique. A maximum relative error of less than 5% has been achieved for all responses.

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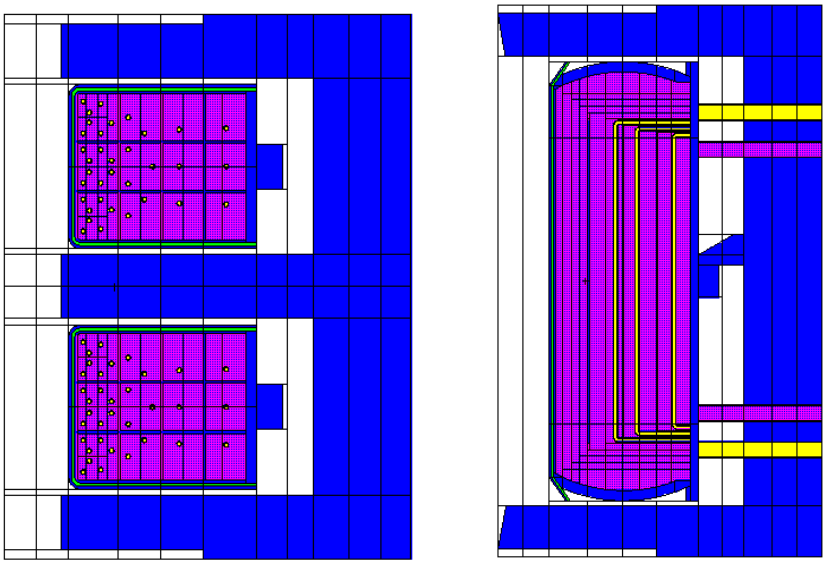

FIG. 1. Radial-toroidal cross-section of the model at the midplane of the TBM (left) and toroidal-poloidal cross-section view of the model (right).

Detailed three-dimensional radiation transport calculations based on the Monte Carlo code MCNP-4C [2] have been performed to predict the radiation characteristics of the TBM. Point-wise cross-sections from ENDF/B-VI and FENDL-2.0 data libraries have been used in our calculations. The FENDL/A-2.0, IRDF-90 and photon interaction MCPLIB2 evaluated data sets have also been used in continuous energy calculations.

3. Results

The tritium production rate has been assessed using the ENDF/B-VI and ENDL/2.0 cross-section data to calculate the spatial/energy distribution of neutron flux in the breeder region and the response. The estimated tritium production rate amounts to 6.1566×10^{17} T atoms/s/1.1MW/m^2 (58.11 mg/day, 22% duty cycle) and does not show a dependence on the cross-section data used. The radial distribution of tritium breeding density along the breeding zone, needed for tritium permeation analyses, is shown in Fig. 2.

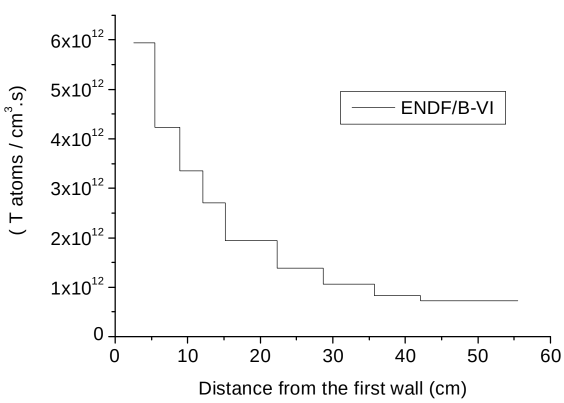

FIG. 2. Radial distribution of tritium breeding density.

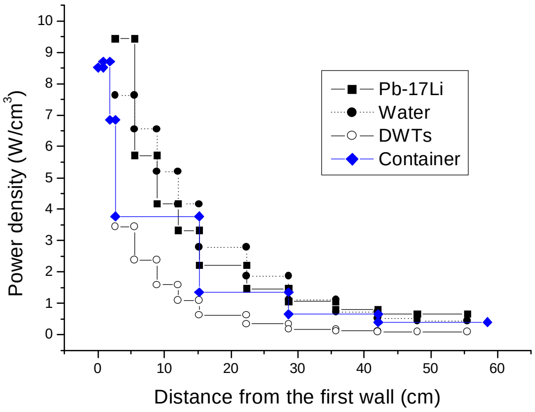

FIG. 3. Nuclear power density distribution in the TBM.

Coupled neutron–gamma calculations have been carried out using ENDF/B-VI and MCPLIB2 cross-section data sets to obtain the spatial dependence of neutron and gamma heating rates. The calculated nuclear power density distributions in the TBM components are shown in Fig. 3 as a function of the distance from the front of the container. The total power deposition in the TBM has been estimated to be 1.09 MW, of which 0.277 MW is in the breeder container and 0.813 MW in breeding zone. Table I lists the nuclear heating rate in the separate components of the TBM.

TAB. I: NUCLEAR HEATING RATE IN TBM COMPONENTS.

Region	**W / 1.1 MW/m^2**
1st wall 1st steel layer	5.9565×10^4
1st wall cooling zone	6.9951×10^4
1st wall 2nd steel layer	3.8836×10^4
Top and bottom covers	2.7353×10^4
Side of the container	7.5033×10^4
Steel of breeder cooling tubes (DWTs)	7.0023×10^3
Water in breeder cooling tubes	3.4710×10^4
Stiffeners	1.6915×10^4
PbLi17	7.5398×10^5
Total	1.0912×10^6

Tritium production and nuclear energy deposition rates have been calculated using other boundary conditions, namely void at the top, bottom and rear surfaces of the frame and reflection at its side surfaces, in order to assess the effect of the assembly coverage upon these parameters. The estimated tritium production rate amounts to 19.86 mg/day (22% duty cycle). The nuclear heating rate totals 0.597 MW, of which 0.418 MW is in the breeding zone and 0.179 MW in the breeder container. Eliminating the infinite scatterer results in lowered tritium breeding and nuclear heating rates by factors of 3 and 1.8, respectively.

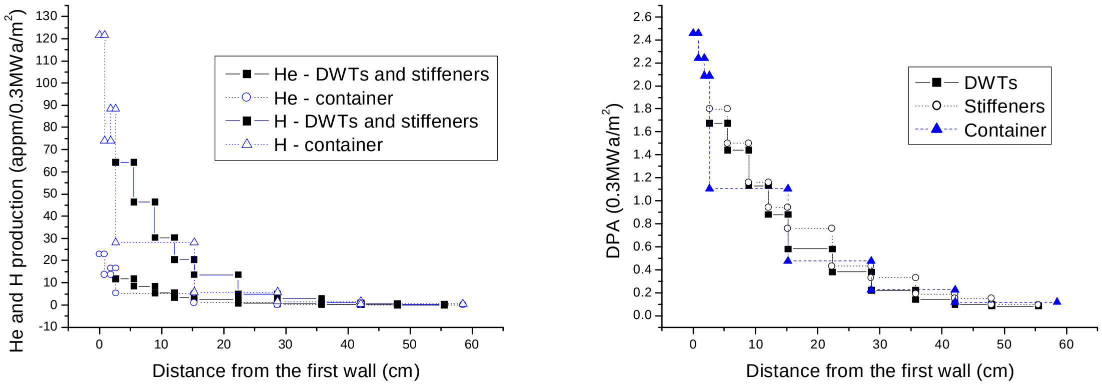

FIG. 4. Radial distribution of He and H production (left) and displacement of iron (right) in the steel structure of the TBM.

Knowledge of displacement and gas production is essential for characterizing the radiation damage in reactor materials and for determining the components' useful lifetime. He and H production and atomic displacement in different module components and in the frame have been calculated on the basis of ENDF/B-VI cross-section data to estimate the spatial/energy distribution of the neutron flux. Cross-sections of (n,xp) and (n,xα) reactions from FENDL/A-2.0 and atomic displacement cross-sections of iron in steel EUR standard from IRDF-90 data libraries have been utilized to assess the gas generation and displacement. The radial distribution of He and H production and displacement of iron in the steel structure are presented in Fig. 4. As seen from the figure, the largest H and He production and atomic displacement (121.6 appm H, 22.7 appm He, 2.46 dpa) take place in the first wall. Calculation of radiation damage using void boundary conditions at the top, bottom and rear surfaces of the frame results in decreased values of dpa by a factor of around 1.4, while He and H production remains unaffected.

4. Conclusions

Three-dimensional coupled neutron–gamma transport calculations using the Monte Carlo radiation transport code MCNP-4C have been performed to assess the neutronic performance of the EU WCLL TBM. A 10^0 half-sector model utilizing an adequately presented geometric arrangement of the TBM and the frame has been used. The main responses, namely tritium production and nuclear energy deposition rates and radiation damage, have been estimated. It was found that tritium production rate is the parameter most sensitive to the blanket coverage, while nuclear heating rate and dpa are affected to a smaller extent. The results given above present a preliminary estimate of the neutronic performance of the TBM. Comprehensive analyses will be carried out after the module is inserted into a suitable model of the ITER machine in order to provide theoretical estimates of TBM neutronic characteristics for comparison with the results measured during the testing in ITER-FEAT.

5. References

[1] POITEVIN, Y., et al., "Status of the Design and Testing Programme of the WCLL Test Blanket Module for ITER-FEAT", CEA Rep. SERMA/RT/01-3019/A (December 2001).

[2] BRIESMEISTER, J.F. (Ed), MCNP^{TM}, A General Monte Carlo N-Particle Transport Code, Version 4C, LA-13709-M (December 2000).