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Water-cooled Pb–17Li test blanket module for ITER: Impact of the structural material grade on the neutronic responses

G. Vella [a,*], G. Aiello [a], M.A. Fütterer [b], L. Giancarli [b], E. Oliveri [a], F. Tavassoli [c]

[a] *Dipartimento di Ingegneria Nucleare (DIN), Università degli Studi di Palermo, Viale delle Scienze, 90128 Palermo, Italy*

[b] *CEA – Saclay, DRN/DMT/SERMA, 91191 Gif-sur-Yvette, France*

[c] *CEA – Saclay, CEREM, 91191 Gif-sur-Yvette, France*

Abstract

The Water-Cooled Lithium Lead (WCLL) DEMO blanket is one of the two EU lines to be further developed with the aim of manufacturing by 2010 a Test Blanket Module for ITER (TBM). In this paper results of a 3D-Monte Carlo neutronic analysis of the TBM design are reported. A fully 3D heterogeneous model of the WCLL–TBM has been inserted into an existing ITER model accounting for a proper D–T neutron source. The structural material assumed for the calculations was martensitic 9% Cr steel code named Z 10 CDV Nb 9-1. Results have been compared with those obtained using MANET. The main nuclear responses of the TBM have been determined, such as detailed power deposition density, material damage through DPA and He and H gas production rate, radial distribution of tritium production rate and total tritium production in the module. The impact of using natural Lithium on the TBM system operation has also been evaluated.

1. Introduction

The ITER reactor [1], whose main specifications are recalled in Table 1, is currently foreseen to be the only intermediate step towards a DEMOnstration reactor (DEMO). This means that, apart from plasma studies and component testing, it shall be used as a test facility for DEMO relevant tritium breeding blankets. The Water Cooled Lithium Lead (WCLL) DEMO blanket [2] is one of the two EU lines to be further developed in the next decade, with the aim of manufacturing a Test Blanket Module (WCLL–TBM) [3,4] for ITER. First tests are currently scheduled for the beginning of the Basic Performance Phase of the ITER reactor, prior to D–T operation. The objectives are in particular the demonstration of tritium breeding, recovery and confinement, and the extraction of high grade heat suitable for electricity generation.

For a design data completion, in the frame of a research collaboration CEA–DIN, a detailed 3D neutronic and photonic analysis of the most recent design of the WCLL–TBM has been performed. The results are presented in this paper.

2. Brief description of the WCLL–TBM [4]

The WCLL–TBM is to be installed into one of the ITER equatorial ports. The test port is 260 cm high × 160 cm wide and is equipped with a separately water cooled stainless steel interface frame, 20 cm thick on all sides. This frame divides the port in two toroidal halves: the EU TBM occupies one toroidal half, the other being allocated to the water cooled Japanese ceramic test module. Accounting for the circumferential gaps (2 cm) between the shielding blanket and the interface frame and between the interface frame and the TBM, the external TBM dimensions become 212 cm in poloidal and 44 cm in toroidal direction. Its radial depth is 58.5 cm, approximately the same as the DEMO Inboard blanket of which the TBM is meant to be representative.

* Corresponding author. Tel.: +39 91 232255; fax: +39 91 232215; e-mail: vella@din.din.unipa.it.

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Table 1
Main ITER specifications

Fusion power	1500 MW (pulsed operation)
Pulse time	2200 s
Burning time	1000 s (45% duty cycle)
Major/minor radius	8.1/3.0 m
Impurity control	Divertor, single null

The WCLL–TBM relies on the liquid eutectic Pb–17Li (90% ^{6}Li enriched) as both tritium breeder and neutron multiplier and water, at 15.5 MPa and 325°C maximum outlet temperature, as coolant.

The present design uses a steel box, reinforced by radial and toroidal stiffeners, as Pb–17Li container. The box is directly cooled with an independent toroido-radial water circuit, whose vertical collectors are located behind the backplate. A 5 mm thick Be layer covers the First Wall (FW) for compatibility with the ITER environment.

The stiffeners form a system of U channels for the eutectic which is slowly circulated for tritium extraction, purification and Li adjustment taking place in specific units outside the blanket. The Pb–17Li pool (breeder zone) is poloidally cooled by double-walled U tubes (DWTs – inner tube diameters 11/13.4 mm, outer tube diameters 13.6/16.5 mm, gap filled with Ti or Fe). The Pb–17Li flows in counter-current with the cooling water and therefore the inlet temperature of the eutectic is close to or slightly higher than the outlet temperature of the breeder zone cooling water, i.e. 325°C.

The breeder zone is delimited on the top by a tube plate and closed on the bottom with a steel cap welded to the box walls. The header for the cooling system of the breeder zone is located on the top of the tube plate, while the Pb–17Li is distributed into the channels through a system of horizontal and vertical perforations obtained in the plate itself. All pipework leaves from the rear. The box is designed to withstand the nominal coolant pressure of 15.5 MPa. The structural material is martensitic steel currently under development. For design purposes it is assumed to be equal to the Mod. 9% Cr–1Mo steel, referenced in RCC-MR as Z 10 CDV Nb 9-1 [5].

3. Models and results

The neutronic and photonic calculations were performed with the MCNP ver. 4a Monte Carlo transport code [6] together with the FENDL transport cross section library [7]. A pre-existing model of ITER was used for the analysis [8]. The model comprises 1/40 of the whole reactor (9° sector) with proper reflective surfaces at the boundaries. The shielding blanket, the vacuum

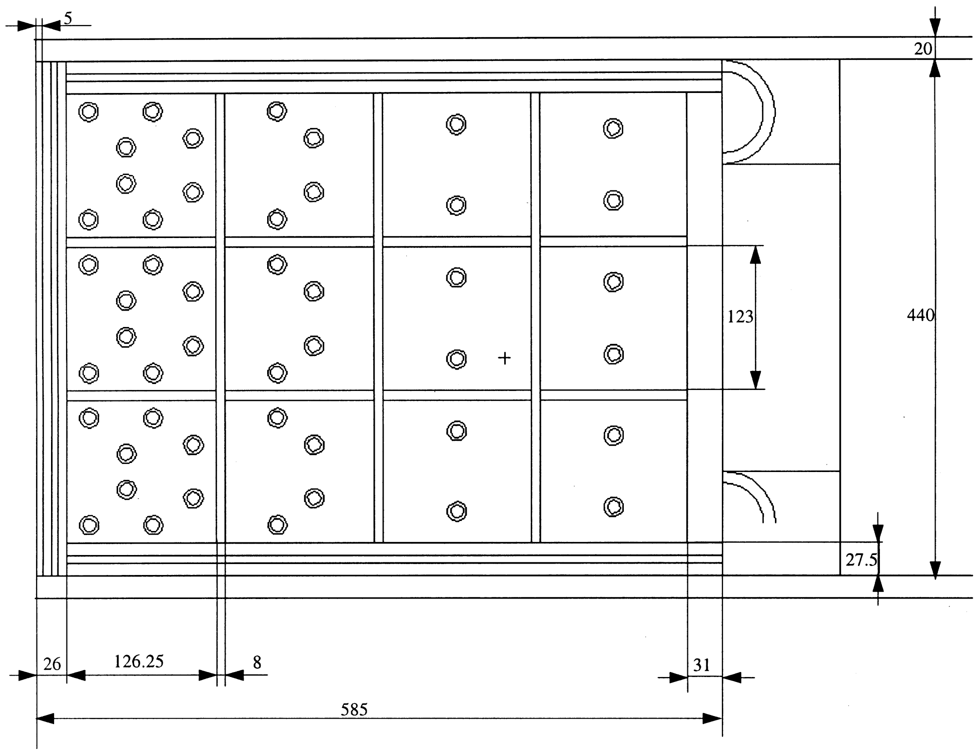

Fig. 1. Horizontal section of the model used for the analyses, details of the TBM.

vessel, the magnet system and the divertor cassette are described in detail. The three major ports through the vacuum vessel are included. A proper D–T plasma neutron source was used [9]. A fully 3D heterogeneous model of the WCLL–TBM has been defined and inserted into the central outboard test blanket port. The presence of the interface frame has been taken into account. The model is a comprehensive description of the TBM, including the gaps around the module, the Be layer on the FW, the toroido-radial cooling system of the steel box and the cooling system of the breeder zone. In Fig. 1 details of the model are shown. The DWTs inside the Pb–17Li pool have been described as single wall tubes. The tube plate and the bottom cap have been modelled as two steel slabs, while the header has been represented as a set of adjoining heterogeneous volumes made of steel, water and Pb–17Li.

The principal macroscopic material densities in operating conditions are: steel 7.76 g/cm^3, Pb–17Li 9.51, water 0.7, Be 1.85 g/cm^3. The assumed structural material is Z 10 CDV Nb 9-1; some of the analyses have been repeated using MANET [10] instead of 9% Cr steel in order to assess the main differences between these materials.

The main nuclear responses of the TBM have been evaluated: heat deposition, tritium production, He and H gas production rate and DPA in the structural material. To speed up calculations, exploiting the multiprocessing capability of the MNCP code, the PVM [11] software was used on a cluster of IBM RS-6000 workstations. The statistical uncertainties are lower than 5%.

3.1. Nuclear power deposition

Total power deposition in the whole TBM resulted to be about 1.05 MW. Detailed contributions are reported in Table 2. In order to provide useful data for thermo-mechanical analysis, the radial and poloidal nuclear power density distributions in the TBM have been evaluated. Selected results are reported in Figs. 2 and 3.

For the purposes of analysis the whole TBM has been subdivided in five poloidal sectors, each about 42 cm high, with the uppermost containing also the volumes constituting the header. The poloidal power density distribution in the first wall is reported in Table 3. As expected, the maximum values of the power density are located in the central sector. The peak into the FW steel in the upper part of the box is due to the water in the breeder zone header which slows down the remaining fast neutrons with a consequent considerable production of γ rays. These are then absorbed by the surrounding steel, causing an increase in the power density deposition in the box walls, in the tube plate and in the uppermost part of the breeder zone.

On the basis of the obtained values, thermo-mechanical analyses to determine the required thickness of the header and of the bottom cap are in progress. Further analyses, substituting MANET for 9% Cr steel,

Table 2
Nuclear power deposition in the WCLL–TBM

Segment box	0.32 MW
Breeder zone	0.63 MW
Header	0.10 MW
Total	1.05 MW

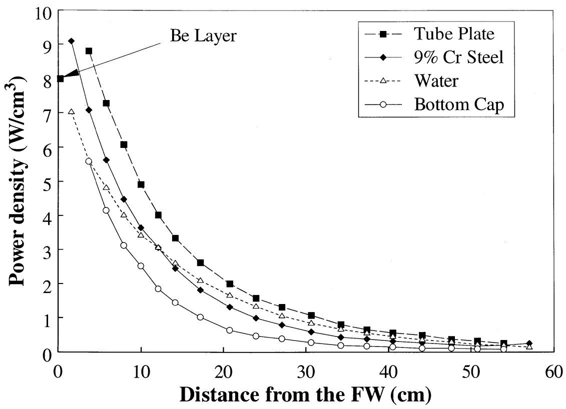

Fig. 2. Power density distribution in the box of the WCLL–TBM.

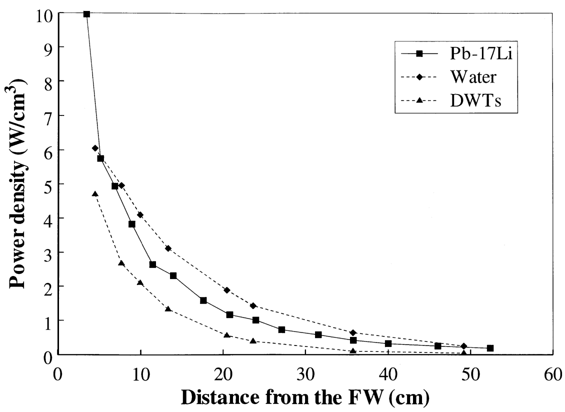

Fig. 3. Power density distribution in the breeder zone of the WCLL–TBM.

Table 3
Poloidal power distribution in the FW (W/cm^3)

	Be	Steel	Water
Poloidal sector V	7.76	10.01	6.50
Poloidal sector IV	8.35	9.23	7.47
Poloidal sector III	8.47	9.42	7.55
Poloidal sector II	8.19	8.95	7.21
Poloidal sector I	7.19	7.85	6.43

have been performed to evaluate the impact of the structural material grade. As expected, the results showed that heat deposition in the module is substantially unaffected.

3.2. Tritium production

In order to test tritium breeding, recovery and confinement capability, adequate tritium must be produced inside the TBM. Total tritium production in the whole module resulted to be about 67 mg/day, assuming continuous operation with a duty cycle of 45% and nominal ^{6}Li enrichment (90%). The impact of using different ^{6}Li enrichment on the TBM system operation has also been considered. The results show that increasing the Li enrichment from 60% to 90% has little influence on the overall tritium production (T production rate increases from 60 to 67 mg/day, that is by about 10%), while between 7.5% (natural Li) and 60% tritium production rate nearly doubles (from 32 to 60 mg/day). This somewhat confirms previous analyses [12] which showed that a ^{6}Li enrichment of about 50% would still ensure tritium breeding self sufficiency for the WCLL DEMO blanket.

In order to provide useful data for tritium permeation analyses, the radial distribution of tritium production rate has been evaluated. Results are shown in Fig. 4. Also to this scope H gas production rate along the box and in the DWTs has been calculated and is reported in Section 3.3.

3.3. Radiation damage

During plant operation, interactions between the highly energetic fusion neutrons and the atoms of the structural material lead to two main damage mechanisms: (a) displacements of atoms from their lattice sites as a result of collisions, and (b) gas production resulting from diverse nuclear reactions, mainly (n,p) and (n,α). While the hydrogen isotopes diffuse out of the metallic lattice or form metal hydrides, α-particles remain trapped in the metal and generate helium gas bubbles. These processes lead to unfavourable changes of mechanical properties (such as embrittlement), limit the lifetime of the structural material and affect reweldability.

Material damage through displacement per atom (DPA) has been evaluated using the MCNP code together with the displacement cross section for iron taken from ASTM standards [13]. Fig. 5 shows DPA per year of pulsed full power operation (45% duty cycle) in the structural material (9% Cr steel) of the TBM.

Radial distribution of He and H gas production rate (in appm/year of pulsed full power operation, 45% duty cycle) along the box of the TBM is reported in Fig. 4. He and H gas production rate in the first row of the DWTs resulted to be about 30 and 105 appm/year respectively. The same analyses have been repeated using MANET instead of 9% Cr steels. The results showed that, although gas production rate is always lower in Z 10 CDV Nb 9-1 steel, the differences are in most cases low enough (about 5%) to be negligible.

4. Conclusions

A detailed 3D neutronic and photonic analysis of the most recent design of the WCLL–TBM has been performed with the MNCP code. The nuclear power deposition in the TBM with the reference material Z 10 CDV Nb 9-1 was calculated to be 1.05 MW to which must be added 0.466 MW due to the surface heat flux (0.5 MW/m^2). The He and H production, as well as the expected dpa, were equally determined. At the end of the ITER Basic Performance Phase (expected neutron fluence 0.3 MWa/m^2), corresponding to 240 days of pulsed full power operation, expected maximum values are

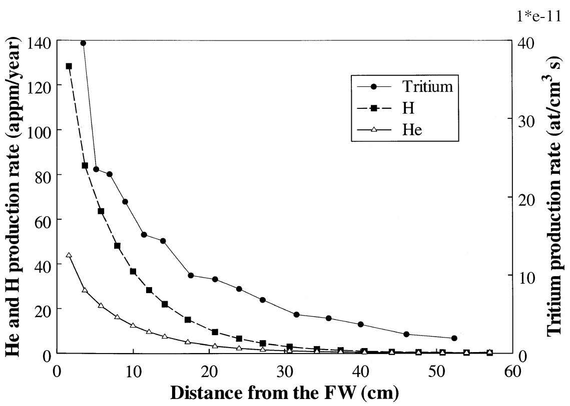

Fig. 4. Radial distribution of He and H gas production rate in the structural material (9% Cr steel) and of the tritium production rate inside the breeder zone of the TBM.

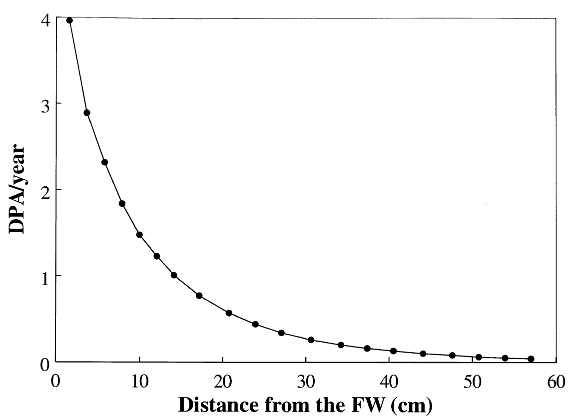

Fig. 5. DPA per year in the box of the WCLL–TBM.

approximately 2.6 dpa, 85 appm H and 30 appm He. All maxima are located in the First Wall.

Even with naturally abundant ^{6}Li, the daily tritium production is still almost half as high (32 mg/d) as with 90% enrichment (67 mg/d). Most of the test objectives could thus be attained with natural abundance so that a high enrichment is not a first order necessity for the WCLL–TBM. The maximum Li consumption would be 0.134 g/d which, during the BPP, would lead only to a minor composition change of the liquid alloy. Comparing Z 10 CDV Nb 9-1 steel to MANET proved that the heat deposition is basically the same. Although the gas production rate in Z 10 CDV Nb 9-1 is always lower than in MANET, the differences are only approximately 5%.

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