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# On the thermo-mechanical behaviour of DEMO water-cooled lithium lead equatorial outboard blanket module

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## HIGHLIGHTS

- Numerical study of DEMO WCLL equatorial blanket module steady state thermo-mechanical performances.
- Adoption of a qualified commercial code based on the Finite Element Method.
- Assessment of module thermo-mechanical behaviour under normal operation and over-pressurization loading scenarios.
- Assessment of thermal and stress states compliance with the prescribed design criteria.

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## ABSTRACT

Within the framework of EUROfusion R&D activities an intense research campaign has been carried out at the University of Palermo, in close cooperation with ENEA Brasimone, in order to investigate the thermo-mechanical performances of the DEMO water-cooled lithium lead breeding blanket (WCLL). In particular, attention has been paid to the most recent geometric configuration of the DEMO WCLL outboard equatorial module, as designed by WCLL project team during 2015, endowed with an attachment system based on the use of radial pins, purposely outlined to connect the module back-plate to its back-supporting structure, that have been properly considered to simulate more realistically the module thermo-mechanical behaviour.

The research campaign has been mainly focused on the investigation of the module thermo-mechanical performances under the Normal Operation (Level A) and Over Pressurization (Level D) steady state loading scenarios envisaged for the DEMO WCLL.

A theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified ABAQUS v. 6.14 commercial FEM code has been adopted.

Thermo-mechanical results obtained have been assessed in order to verify their compliance with the design criteria foreseen for the structural material. To this purpose, a stress linearization procedure has been performed along the most critical paths located within the module structure, in order to check the fulfilment of both Level A and Level D rules prescribed by the SDC-IC structural design code. Results obtained are herewith presented and critically discussed, highlighting the open issues and suggesting the pertinent modifications to DEMO WCLL outboard equatorial module design aimed to obtain the complete fulfilment of the prescribed design criteria.

## 1. Introduction

Within the framework of the DEMO nuclear fusion reactor R&D activities [1–3], the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (DEIM) has been involved, long time now, in the theoretical-numerical assessment of the thermo-mechanical behaviour of several breeding blanket concepts [4–10]. More recently, following the outcomes of these previous studies, a research campaign has been launched, framed within the Working Package Breeding Blanket of EUROfusion action [11], to investigate the steady state thermo-mechanical performances of the 2015 baseline configuration of the DEMO water-cooled lithium lead breeding blanket (WCLL) outboard equatorial module. The assumptions and methodology adopted as well

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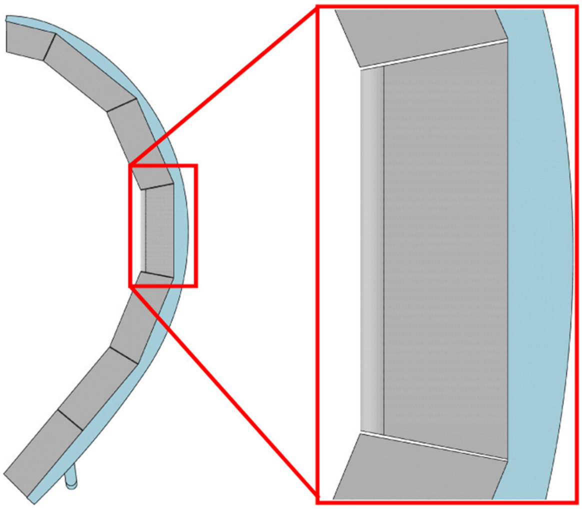

**Fig. 1.** WCLL outboard segment.

as the results obtained are herewith reported and critically discussed.

## 2. WCLL breeding blanket

The research campaign has been focussed on the assessment of the thermo-mechanical behaviour of the WCLL outboard equatorial module directly welded to the ribs of the Back-Supporting Structure (BSS), purposely lengthened till the back of the module. Moreover, the mechanical effect of the other outboard segment modules has been taken into account by means of the use of “dummy” modules directly tied to the BSS (Fig. 1).

The WCLL outboard equatorial module mainly consists of an external Segment Box (SB), composed by a First Wall (FW) directly exposed to the plasma, two Side Walls (SWs), a Top Cap (TC) and a Bottom Cap (BC) that close the SB in the upper and lower part and a Back Plate (BP) that delimits the module in the radial direction. FW, SWs and caps are cooled by means of square channels in which it flows subcooled water at the pressure of 15.5 MPa (PWR conditions). The SB is reinforced with a set of Stiffening Plates (SPs), which divide the module in 16 toroidal-radial slices along the poloidal direction, and filled with the Pb-Li liquid metal eutectic alloy, acting as breeder and neutron multiplier. SB internals are cooled by means of bundles of Double-Walled Tubes (DWTs) where water coolant flows under PWR conditions (Fig. 2). Finally, each toroidal-radial slice foresees a further plate, called baffle plate, which acts as a guide for the liquid breeder in its path inside the Breeder Zone (BZ).

The whole of SB, stiffening grid and DWTs are made of the reduced activation ferritic martensitic steel Eurofer. A linear elastic model has been adopted for the Eurofer steel, while regarding the thermo-physical properties of both Pb-Li and Eurofer, they have been assumed depending uniquely on temperature [12,13].

A theoretical-numerical approach based on the Finite Element Method (FEM) has been followed and the qualified FEM code Abaqus v.6.14 has been adopted. To this purpose, it has been set-up a FEM model of the WCLL outboard equatorial module, consisting of a mesh composed of $\sim 13.6{\cdot}10^6$ nodes connected in $\sim 23.2{\cdot}10^6$ linear tetrahedral and hexahedral elements [14].

## 3. Thermo-mechanical loads and boundary conditions

The loading conditions relevant to the steady state scenarios of Normal Operation (NO) and Over Pressurization (OP), classified as Level A and Level D, respectively, in the SDC-IC [15] design rules, have been investigated.

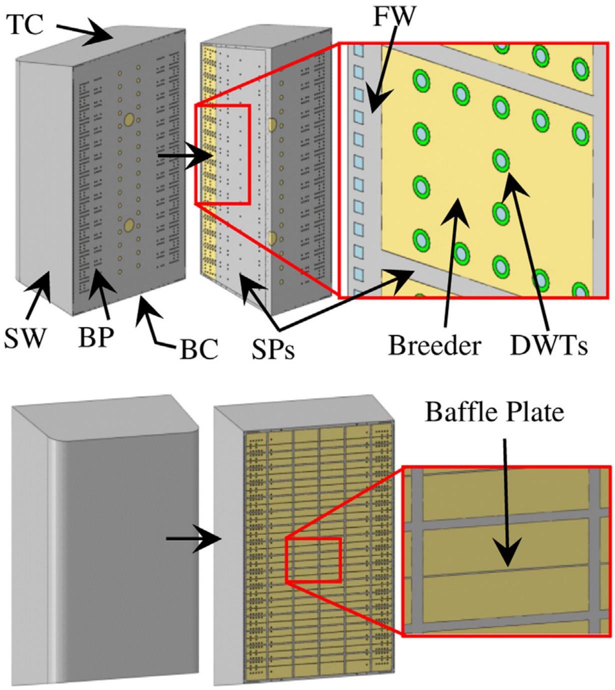

**Fig. 2.** SB internal and external components.

From the thermal point of view, two different loading conditions have been taken into account, differing each other as to the heat flux applied onto the FW plasma-facing surface of the outboard equatorial module. The first, named Case 1, has foreseen a maximum value of 0.5 MW/m$^2$ imposed onto the straight surface of the FW, while in the second, named Case 2, a maximum value of 1.4 MW/m$^2$ has been imposed onto the same surface. Concerning the bend FW surfaces, a cosine-dependent law has been adopted for them [14]. The non-uniform normal heat flux has been applied to the FW plasma-facing surface by means of a purposely set-up FORTRAN routine. A non-uniform spatial distribution of heat power volumetric density has been applied to the model to simulate the nuclear-deposited power density taking into account the nuclear heating reported in [14].

Forced convective heat transfer between the structure and the coolant has been simulated with the simplified “frozen” flow field approach. In particular, the water flow domain (cooling channels and tubes) has been meshed by means of 8-node DCC3D8-forced convection/diffusion elements, where the heat transfer convective-diffusive transport equation has been supposed to hold. The coolant velocity field has been assumed to be known and, typically, the mass flow rate for unit area has been prescribed at each material point, so that the velocity could be automatically code-calculated by means of the mass density. The heat flux entering the coolant domain across the steel walls has been prescribed by means of a thermal contact model, which allows the temperatures of coolant and channel walls to be coupled by means of the following equation:

$$q''_{ij} = h\left(T_i^{wall} - T_j^{coolant}\right) \tag{1}$$

where $q''_{ij}$ is the heat flux flowing through the coupled nodes i and j, belonging to the steel walls and the water-coolant, respectively, and h is the heat transfer coefficient. Mass flow rates through channels and DWTs have been calculated, by means of a purposely set-up iterative procedure, so to obtain a uniform water temperature increase of 40 °C ($\Delta T_{Design}$) between their inlet and outlet

**Table 1**
Mass flow rates and heat transfer coefficients.

| | Case 1 | |
|---|---|---|
| | G [kg/s] | HTC [W/m$^2$ °C] |
| FW channel | 0.0676 | 18801.84 |
| TC channel – Min | 0.0071 | 3083.43 |
| TC channel – Max | 0.0262 | 8793.57 |
| BC channel – Min | 0.0079 | 3375.73 |
| BC channel – Max | 0.0251 | 8509.74 |
| DWT – Min | 0.0046 | 2103.37 |
| DWT – Max | 0.0736 | 19205.32 |
| Case 2 | | |
| FW channel | 0.1464 | 34877.51 |
| TC channel – Min | 0.0081 | 3436.48 |
| TC channel – Max | 0.0213 | 7475.66 |
| BC channel – Min | 0.0092 | 3803.85 |
| BC channel – Max | 0.0213 | 7475.66 |
| DWT – Min | 0.0046 | 2103.37 |
| DWT – Max | 0.0736 | 19205.32 |

Bold values are reported values higher than unity indicating safety rules not verified.

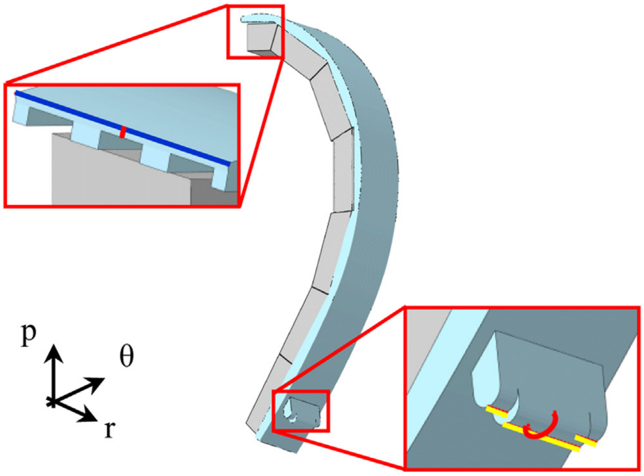

**Fig. 3.** Mechanical constraints.

sections [8]. The inlet coolant temperature has been set equal to 285 °C. Moreover, heat transfer coefficients have been calculated adopting the Dittus & Bölter correlation [16] according to the predicted mass flow rates. Mass flow rate (G) and heat transfer coefficient (HTC) values, computed according to the aforementioned procedure, are reported in Table 1.

Concerning the breeder, no buoyancy effects have been taken into account, assuming Pb-Li to be still, while the thermal interaction between breeder and internal SB surfaces, as well as between breeder and DWTs outer surfaces have been simulated implementing a linear thermal contact model, characterized by a thermal conductance of $10^5$ W/m$^2$ °C.

As to dummy modules, a non-uniform thermal field linearly depending on the distance from FW has been imposed. In particular, temperature values ranging from 500 °C on the FW to 300 °C on the BP have been assumed. This spatial distribution of temperature has been drawn from preliminary analyses performed on the WCLL outboard equatorial module [10].

From the mechanical point of view two different loading conditions have been taken into account for each thermal case, according to the scenario considered. Regarding the NO loading scenario, the mechanical effect of the water coolant flowing into FW, SW and cap channels, as well as DWTs has been reproduced imposing a pressure of 15.5 MPa to all water-wetted surfaces. A pressure of 0.5 MPa has been foreseen for the breeder-wetted surfaces in order to model the mechanical interaction between the breeder and both SB internal surfaces and DWT external ones. As far as the OP loading scenario is concerned, a pressure of 18.6 MPa, equal to the coolant pressure increased by 20% [15], has been imposed onto all wetted surfaces in order to take into account a coolant leak inside the box. Moreover, the thermal deformation field arising within the model as a consequence of its non-uniform temperature distribution and its isotropic thermal expansion tensor has been considered as to both the loading scenarios investigated. Finally, the weight force has been applied to the whole model. Both the WCLL outboard equatorial module and the 6 dummy modules have been considered directly welded to the BSS ribs. In order to reproduce the mechanical effect of the outboard segment attachment system to the Vacuum Vessel, the displacements of some sets of nodes have been prevented in both NO and OP loading scenarios. In particular, the displacement along the radial direction has been forbidden for nodes highlighted in blue in Fig. 3, the toroidal ones for nodes highlighted in red, while radial and poloidal displacements have been prevented for nodes highlighted in yellow.

## 4. Results

Un-coupled steady state analyses have been run to assess the thermo-mechanical behaviour of the WCLL outboard equatorial module, as well as to verify that structural design criteria are met [15].

From the thermal point of view, results have shown that temperatures remain below the Eurofer maximum allowable value (550 °C) except in Case 2, where this value is exceeded in restricted areas located nearby cap corners and a peak of 582 °C is reached (Fig. 4). As to SB, the hottest parts are located at the interface between baffle plate extremities and breeder, probably due to the fact the breeder circulation has not been modelled.

Moreover, the thermal field calculated for the coolant has shown that, regarding water flowing into SW-FW and cap channels, the maximum temperatures are reached in correspondence of the bend regions of the channels, as a consequence of the counter-current flow. The minimum coolant margin against saturation is predicted in Case 2 and it amounts to 5.6 °C. Conversely, concerning BZ tubes, water flowing into the bundles of DWTs located in the boundary slices experiences temperature values higher respect to those reached in the coolant of the DWTs situated in the inner slices.

As far as mechanical results are concerned, a stress linearization procedure has been carried out along some significant paths of the SB in order to verify whether the Level A and Level D design criteria are fulfilled.

In particular, paths lying on the toroidal mid-plane have taken into account for FW and BP (Fig. 5), while paths lying on different poloidal and radial planes have been considered for the SPs (Fig. 6).

Mechanical results of NO scenario have been shown, for both cases, that the most critical areas are located within SPs and near the caps, where the criterion against plastic flow localization is not fulfilled. This is probably due to resistance exerted by vertical SPs against thermal expansion of horizontal SPs and vice versa, as well as to the compression exerted by BP and caps on the FW, due to their lower poloidal thermal expansion with respect to this latter (Table 2).

Concerning the OP loading scenario, paths located near the caps do not satisfy again the design criteria, especially in Case 2 where high temperatures reached on the FW cause also failure for creep damage. On the other hand, only few SP paths fail to fulfil the criteria, probably due to the effect of the higher pressure imposed on the internal SB surfaces. All paths located within the BP successfully fulfil the design criteria in every loading scenario investigated.

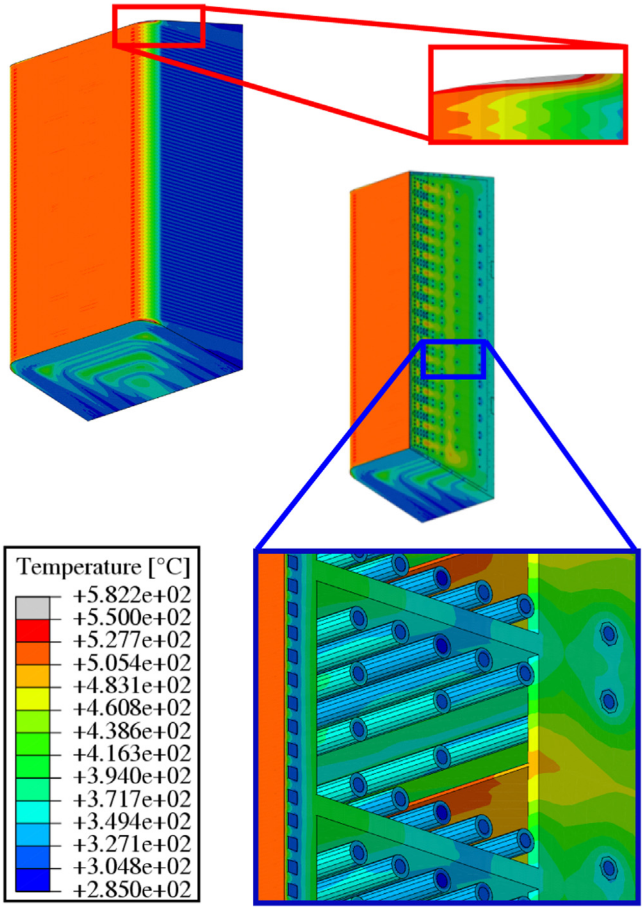

**Fig. 4.** Case 2 thermal results.

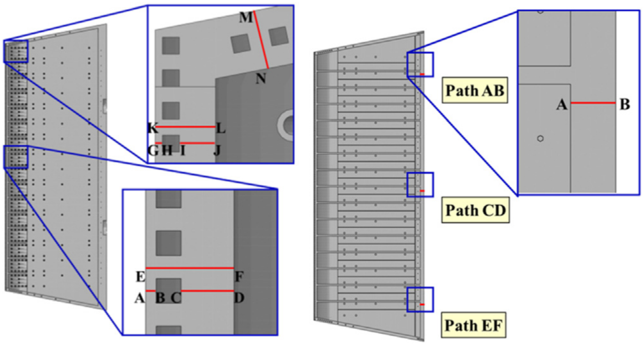

**Fig. 5.** FW and BP paths at toroidal mid-plane.

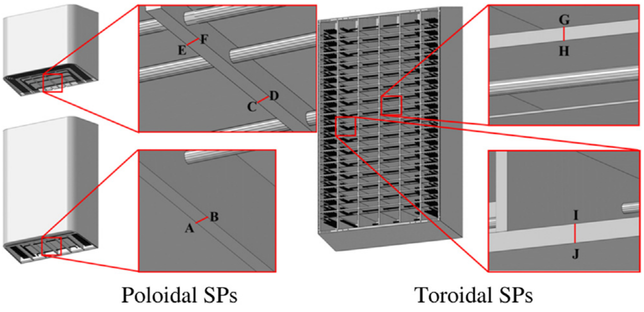

**Fig. 6.** Paths located within SPs.

**Table 2**
SDC-IC criteria in critical paths [15].

| Case 1 | Stress linearization path | | | |
|---|---|---|---|---|
| | $FW_{GH}$ | $FW_{IJ}$ | $SP_{AB}$ | $SP_{CD}$ |
| $T_{Max\text{-}Path}$ [°C] | 407.7 | 404.2 | 411.7 | 456.3 |
| Level A criteria | | | | |
| $P_m/S_m$ | 0.074 | 0.094 | 0.052 | 0.046 |
| $(P_m+P_b)/K_{eff}\,S_m$ | 0.070 | 0.077 | 0.035 | 0.034 |
| $(P_m+Q_m)/S_e$ | **2.030** | 0.521 | **1.490** | **1.680** |
| Level D criteria | | | | |
| $P_m/\sigma_{lim}$ | 0.676 | **1.200** | 0.714 | 0.858 |
| $(P_m+P_b)/K_{eff}\,\sigma_{lim}$ | 0.616 | **1.350** | 0.477 | 0.574 |
| $(P_m+Q_m)/2\,S_e$ | **1.690** | **1.370** | **1.020** | 0.269 |
| $W_t[1.35\,(P_m+P_b/K)]$ | – | – | – | **36.10** |
| Case 2 | | | | |
| $T_{Max\text{-}Path}$ [°C] | 520.6 | 397.3 | 410.4 | 456.3 |
| Level A criteria | | | | |
| $P_m/S_m$ | 0.090 | 0.093 | 0.052 | 0.046 |
| $(P_m+P_b)/K_{eff}\,S_m$ | 0.084 | 0.077 | 0.035 | 0.031 |
| $(P_m+Q_m)/S_e$ | **3.640** | 0.526 | **1.456** | **1.656** |
| Level D criteria | | | | |
| $P_m/\sigma_{lim}$ | 0.832 | **1.190** | 0.713 | 0.859 |
| $(P_m+P_b)/K_{eff}\,\sigma_{lim}$ | 0.784 | **1.340** | 0.476 | 0.574 |
| $(P_m+Q_m)/2\,S_e$ | **2.680** | **1.350** | **1.010** | 0.275 |
| $W_t[1.35\,(P_m+P_b/K)]$ | **2.470** | – | – | **36.30** |

## 5. Conclusions

A research campaign has been carried out at DEIM in order to investigate the thermo-mechanical performances of the DEMO WCLL outboard equatorial module whether connected to the BSS under both NO and OP steady state loading scenarios. Two load cases have been investigated differing as far as the heat flux on the FW-SWs plasma facing surface is concerned.

From the thermal point of view, results obtained in case of a heat flux of 0.5 MW/m$^2$ show that an acceptable temperature distribution is reached within structure, breeder and coolant domains, while in case it is increased up to 1.4 MW/m$^2$, hotspots are predicted in a poorly-cooled restricted area located in the bottom and top corners of FW.

From the mechanical point of view, results obtained in both cases show that a revision of the SPs has to be performed in order to limit their secondary stresses, possibly by changing their thickness and number, as well as to enforce the FW top and bottom corner regions to avoid their failure due to immediate plastic flow localisation.

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