Preliminary design of the top cap of DEMO Water-Cooled Lithium Lead breeding blanket segments

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Within the framework of EUROfusion R&D activity, a research campaign has been carried out at the University of Palermo, in close cooperation with ENEA labs, in order to preliminary design the top cap foreseen for the DEMO Water-Cooled Lithium Lead (WCLL) breeding blanket segments. Due to the high heat and pressure loads acting on such component, its design results particularly demanding and a specific multi-physics approach is needed, covering several aspects from design to thermal-hydraulic and structural assessments. Preliminary detailed CAD model of the cap integrated into the upper region of the WCLL breeding blanket outboard central segment has been set-up, equipped with proper cooling circuits as well as manifold and attachment systems according to the design of the equatorial elementary cell. An detailed numerical model has been set-up with the aim of simulating both the thermal-hydraulic and thermo-mechanical behaviour of the above-mentioned system. A thermal-hydraulic assessment has been performed to investigate the cooling system performances, verifying the effectively extraction of nuclear heat power herein deposited while complying with the prescribed thermal-hydraulic requirements (outlet temperature, pressure drop, etc.). Finally, the thermo-mechanical response of the upper breeding blanket region has been evaluated in terms of stress and temperature distributions, verifying that the structural material maximum temperature stays below its limit value and that structural integrity is ensured by means of the fulfilment of design rules reported in RCC-MRx structural design code.

Keywords: DEMO; WCLL, breeding blanket, multi-physics, cap.

1. Introduction

Within the framework of DEMO R&D activities envisaged by the EUROfusion action [1-4], the University of Palermo is involved in the thermo-mechanical design of the Water Cooled Lithium Lead Breeding Blanket (WCLL BB) concept, candidate as driver blanket for the EU-DEMO fusion reactor.

The WCLL BB is articulated into 16 toroidal sectors, each one occupied by three outboard and two inboard segments. For each segment, two different architectures have been developed: the Multi Module Segmentation (MMS) and the Single Module Segmentation (SMS). This latter, characterized by a poloidal stack of elementary toroidal-radial cells, guarantees enhanced thermo-mechanical performances with respect to the MMS one, increases tritium production and permits a better breeder drainage and helium extraction [5].

The WCLL BB Outboard Central (OBC) segment, endowed with the manifold layout conceived by ESTEYCO [6], is composed of an EUROFER Segment Box (SB), articulated in a First Wall (FW) and two Side Walls (SWs) covered by a Top and a Bottom Cap (TC, BC), and a Breeder Zone (BZ), where Pb-Li eutectic alloy flows allowing tritium production to take place due to breeding reactions.

The SB is structurally reinforced against internal loads by a system of Stiffening Plates (SPs) arranged in poloidal-radial and toroidal-radial direction, with a thickness of 16 mm and 12 mm, respectively. Moreover, horizontal baffle plates are alternately located between toroidal-radial SPs to route the breeder radial-poloidal-radial flow without playing any structural role. Sub-cooled pressurized water under typical PWR conditions (150 bar and inlet/outlet temperatures of 295/328°C) is foreseen as the coolant.

The design of a TC preliminary model for this blanket concept is one of the most important issue in the WCLL BB R&D activities, due to the high heat and pressure loads acting on such component.

A research campaign has been, hence, performed at the University of Palermo and, due to the complexity of the geometry as well as to the non-uniform heat load distribution, a methodology based on a Design-by-Analysis approach has been followed. In particular, a theoretical-numerical approach, based on the Finite Element Method (FEM) has been followed and a qualified commercial FEM code, ABAQUS v6.14 [8], has been adopted.

To this purpose, FEM model of the WCLL BB top cap, equipped with a proper set of Double Walled Tubes (DWTs) aimed at BZ cooling and a set of square channels intended to refrigerate both FW and caps, has been set up and their thermo-mechanical performances have been investigated under Normal Operation (NO) and Over-Pressurization (OP) steady state loading scenarios, the former related to nominal operations and the latter to accidental conditions caused by an in-box

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LOCA due to a DWT failure. The proposed TC design structural integrity has been, finally checked against the design criteria of RCC-MRx structural design code [9].

2. OBC Top Cap

2.1. Geometrical model

In order to obtain a realistic simulation of the TC thermo-mechanical behaviour while saving calculation time, a model composed of 1 elementary cell plus the remaining upper region (Fig. 1) has been selected as the minimum needed to make the cap model independent from boundary conditions.

Therefore, the model has been obtained cutting the OBC segment conceived by ESTEYCO, including the manifolds region. In this concept, Pb-Li leaves the Top Cap following the path coloured in blue in Fig. 1.

Due to the model toroidal symmetry, only one half of the TC domain has been simulated and, in order to enhance its mechanical performances, a TC thickness of 40 mm has been chosen.

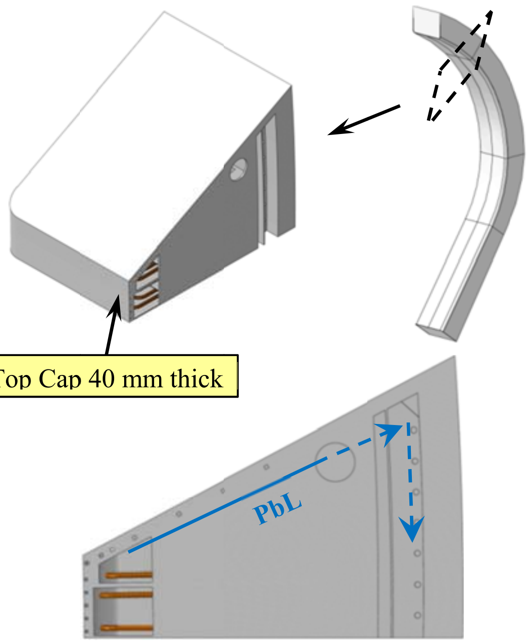

Fig. 1 TC geometric model.

Moreover, 4 square cooling channels (7x7 mm), arranged with a poloidal pitch of 33.6 mm, have been considered for the elementary cell in order to provide the FW-SW-FW region with an effective cooling. Conversely, one channel for the analogous region of the TC upper cell has been assumed with similar dimensions. Counter-current water flow has been assumed inside these channels from an inlet temperature of 295 °C to an outlet one of 328 °C.

Furthermore, in order to remove the nuclear heat power therein deposited, the TC region has been equipped with 7 square channels, preliminary dimensioned with a side equal to 10 mm, where water coolant flows with the same thermal-hydraulic conditions of the FW-SWs cooling channels. Figure 2 shows the TC cooling water path, from the FW inlet manifold to the outlet manifold.

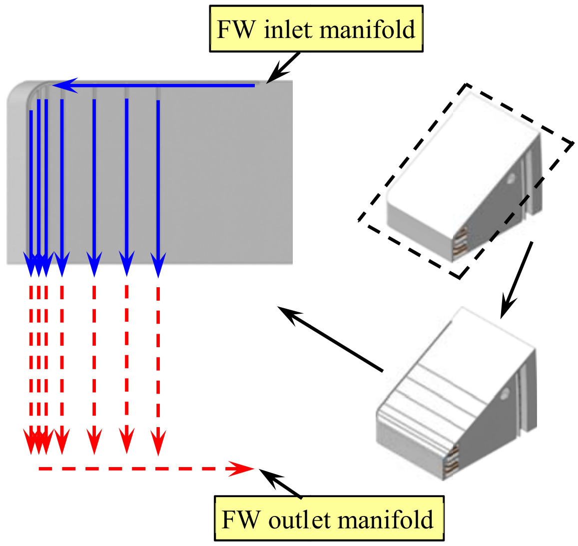

Fig. 2 TC cooling channels.

With the aim to cool the BZ, the WCLL 2019 DWT layout (24 tubes) [10] has been implemented into the TC model, as depicted in Fig. 3. In particular, due to Pb-Li manifolds configuration, no DWTs have been foreseen in the upper region.

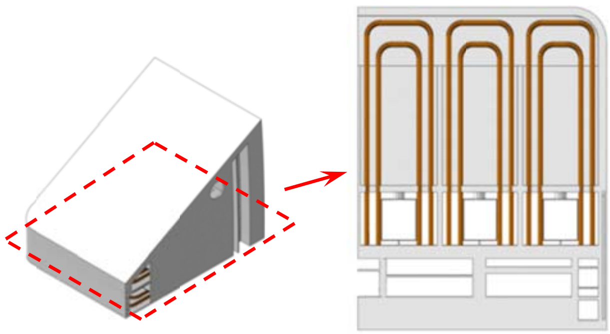

Fig. 3 DWTs adopted in TC model.

In order to improve its mechanical performances, a TC plate thickness of 42 mm (including 2 mm-thick Tungsten armour) has been foreseen, unlike elementary cells of the segment where the FW thickness amounts to 27 mm (including the 2 mm-thick W armour) (Fig. 4).

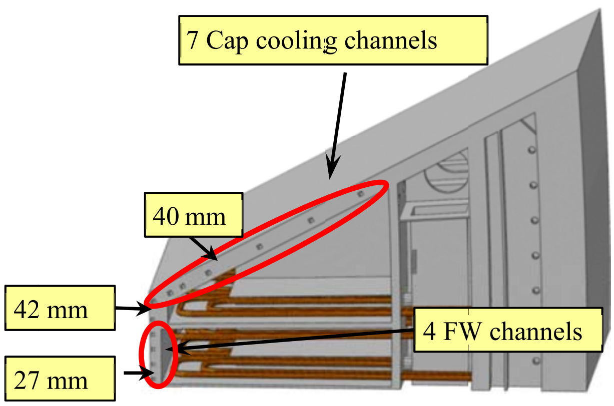

Fig. 4 Detailed view of the TC geometric model.

Finally, the mesh set up for this detailed geometric model, including structure, DWTs and breeder, has been composed with ~2.8M nodes connected in ~5M linear elements, has been realised.

2.2. Materials, loads and boundary conditions

As regards the materials adopted, EUROFER, a reduced activation Ferritic/Martensitic (RAFM) steel, has been assumed as structural material, except for the 2 mm-thick FW armour supposed as made of tungsten [11], in order to safeguard the FW and reduce the sputtering effect. Materials have been considered uniform, isotropic and linearly elastic and their thermo-mechanical properties have been assumed to depend only on temperature [9].

From the thermal point of view, an heat flux of 0.66 MW/m^2 [12] has been applied onto FW plasma facing surface. A non-uniform spatial distribution of heat power volumetric density [Figs. 5-7] has been applied to the model to simulate the deposited nuclear power density [12].

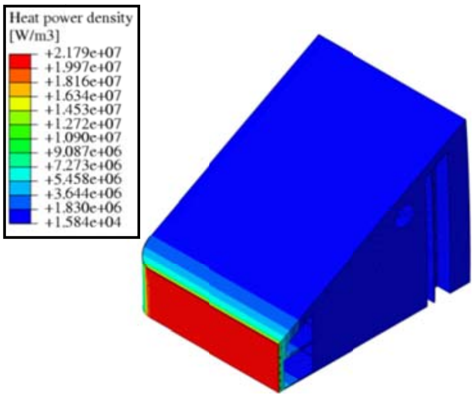

Fig. 5 Volumetric density of nuclear heat power field on SB.

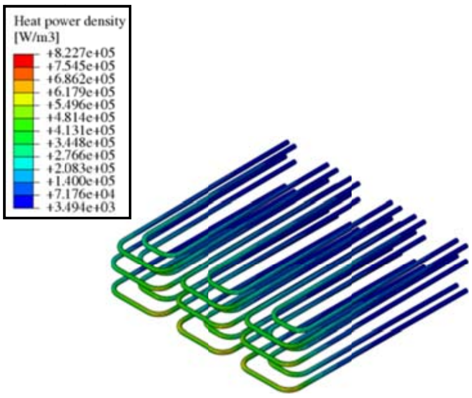

Fig. 6 Volumetric density of nuclear heat power field on DWTs.

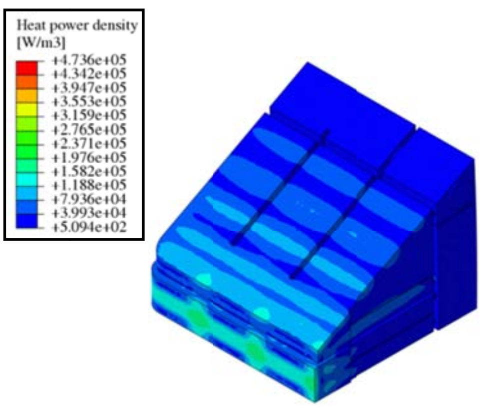

Fig. 7 Volumetric density of nuclear heat power field on Pb-Li.

The forced convective heat transfer in the SB channels and BZ DWTs, between wetted walls and coolant, has been simulated adopting a proper thermal contact model considering a bulk temperature equal to 311.5 °C, which is the average value between inlet and outlet temperatures. In particular, an iterative procedure has been adopted:

- First step, an analysis runs with uniform bulk temperature (set on 311.5 °C) and Heat Transfer Coefficients (HTCs) calculated by Dittus & Bölter correlation[13], to calculate the coolant thermo-physical properties at its average temperature,
- Second step, the power extracted by the coolant flowing through each DWT, FW and Cap channel is assessed together with the related mass flow rates, assuming a nominal thermal rise equal to 33 °C in the coolant.
- Third step, an analysis runs with the reviewed HTCs calculated on the basis of the new mass flow rates assessed in the previous step.

It is to be noticed that this iterative procedure didn't require more than two iterations to converge. The convective boundary conditions for DWTs, FW and Cap cooling channels are reported in table 1 in which the symbol G represents the mass flow rate.

Table 1 Cooling circuits parameters.

	G [kg/s]	HTC [W/(m^2 °C)]
FW	0.8387	39356
Cap	0.6306	11727
DWTs	0.6684	27060

Moreover, considering the breeder as stagnant, assumption already adopted in previous analyses [14][15], the thermal contact of the Pb-Li with the internal SB surfaces and the DWTs outer surfaces have been modelled imposing a conservative thermal conductance value of 10^5 W/m²°C, while the Pb-Li thermal conductivity has been obtained by a proper correlation [16]. From the mechanical point of view, two different loading scenarios have been taken into account, Normal Operation (NO) and Over Pressurization (OP). In particular, in order to simulate the mechanical action of the water flowing inside the FW cooling channels, a pressure of 15.5 MPa has been set onto all these surfaces. In order to simulate the presence of the Pb-Li flowing inside the BZ, a pressure of 0.5 MPa has been applied onto all internal breeder-wetted surfaces. As far as the OP scenario is considered it has been simulated considering a pressure of 18.6 MPa, equal to the coolant pressure increased by 20% [17] onto all internal wetted surfaces. Moreover, the thermal field derived by the thermal analyses previously carried out has been considered. With the aim to simulate the poloidal continuity and the presence of the other toroidal half of the domain, two symmetry conditions have been imposed respectively to the poloidal and the toroidal surfaces of the structure (Fig. 8).

Finally, a restraint in radial direction have been applied to a set of nodes identified on the BP, in order to simulated the attachment systems acting on the structure, as shown in figure 8.

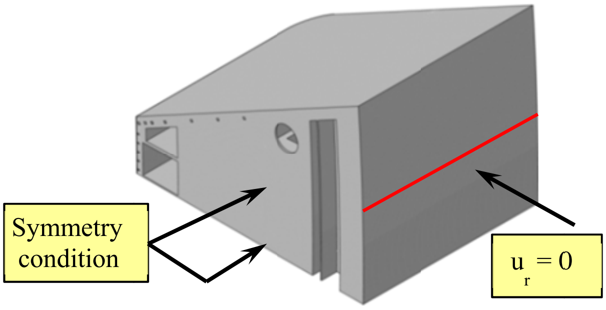

Fig. 8 Mechanical constraints.

3.3. Results

Steady state analysis of the Top Cap model set-up have been performed in order to investigate its thermo-mechanical behaviour under the thermal loads and boundary conditions envisaged for both NO and OP loading conditions. Then, it has been verified the fulfilling of the safety criterion based on the EUROFER maximum temperature and the RCC-MRx structural design criteria safety rules. Thermal analysis results show that the temperature values exceed the maximum allowable value, set on 550 °C [18], in some horizontal SPs regions, as depicted in figure 9. Instead, figures 10 and 11 depict the Von Mises stress field calculated in NO and OP loading scenarios, respectively. These mechanical analysis results indicate that the most stressed regions are located within the toroidal-radial SPs and near the FW and Cap channels. Therefore, a stress linearization procedure has been performed along 8 critical paths located within FW, Cap and toroido-radial and poloido-radial SPs (figs. 12 and 13), to verify the fullfillment of the design rules reported in the RCC-MRx code [9]. In particolar, Levels A and D have been taken into account for the NO and the OP scenarios, moreover, both high and low temperature rules have been considered according to whether the mean temperature along the paths exceeded or not the temperature of of 375°C [9].

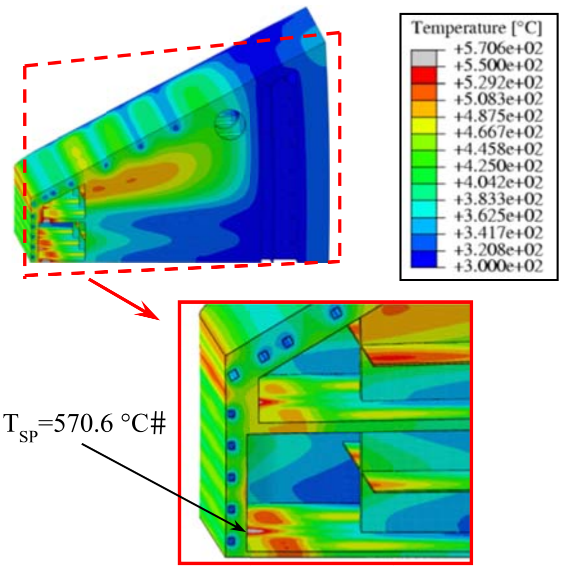

Fig. 9 Thermal field on SB.

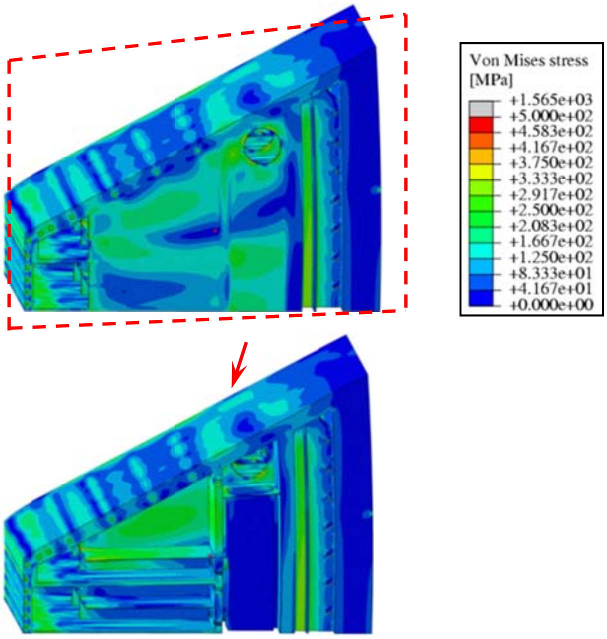

Fig. 10 Von Mises stress field under NO scenario.

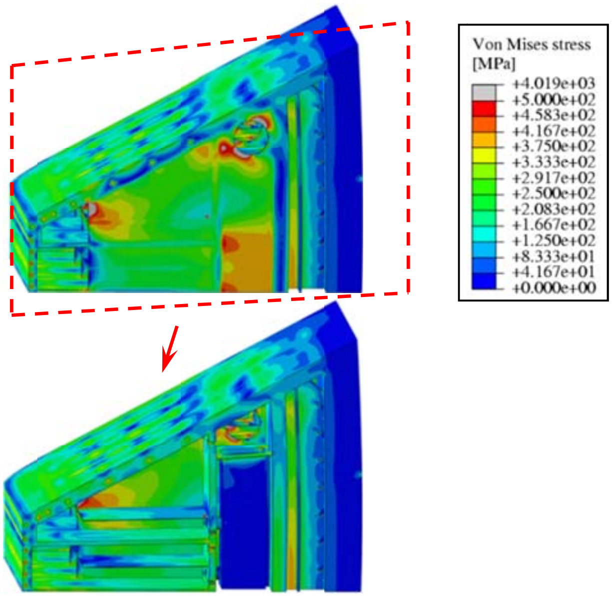

Fig. 11 Von Mises stress field under OP scenario.

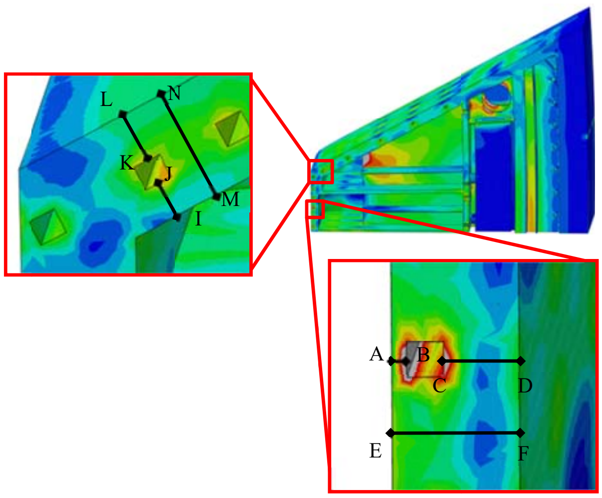

Fig. 12 Stress linearization paths on FW and Cap.

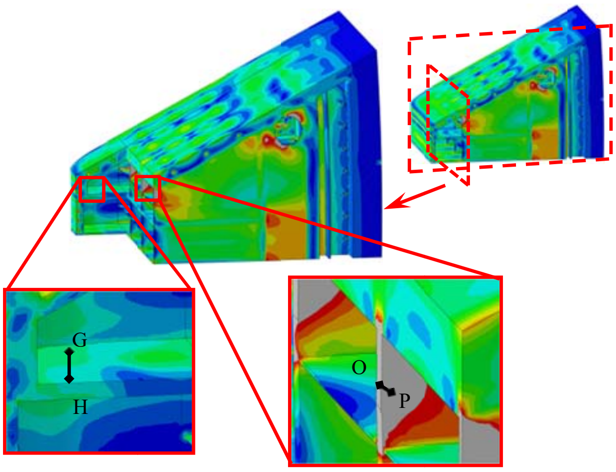

Fig. 13 Stress linearization paths on SPs.

Stress linearization results indicate that RCC-MRx Level A criteria, concerning nominal loading condition, are fulfilled with wide margin along all paths taken into account. As regards, RCC-MRx Level D criteria, they result to be generally fulfilled. Table 2 and 3 report the stress linearization results under the two loading scenario investigated. It can be observed that the most critical regions are located within the FW and the poloidal-radial SP, where both the primary and total membrane stress criteria are not fulfilled, moreover, it is to be highlighted that Level D criteria against the thermal creep has not been verified.

Table 2 Stress Linearization results under NO loading scenario - Level A RCC-MRx safety criteria.

		Low Temperature rules				High Temperature rule
Path	$T_{Ave\text{-}Path}$ [°C]	P_m/S_m	$(P_m+P_b)/K_{eff}\,S_m$	$(P_m+Q_m)/S_e$	$(P_m+P_b+Q+F)/S_{et}$	$(P_m+P_b/K_t)/S_t$
AB	376.43	0.22	0.16	0.69	0.20	0.15
CD	373.86	0.09	0.12	0.08	0.22	//
EF	453.97	0.07	0.06	0.34	0.12	0.07
GH	437.55	0.10	0.06	0.53	0.08	0.08
IJ	430.47	0.18	0.14	0.52	0.15	0.16
KL	338.22	0.07	0.09	0.65	0.16	//
MN	411.11	0.06	0.06	0.63	0.10	0.06
OP	503.82	0.16	0.11	0.78	0.12	0.17

Table 3 Stress Linearization results under OP loading scenario - Level D RCC-MRx safety criteria

		Low Temperature rules			
Path	$T_{Ave\text{-}Path}$ [°C]	P_m/S_m	$(P_m+P_b)/K_{eff}\,S_m$	$(P_m+Q_m)/S_e$	$(P_m+P_b+Q+F)/S_{et}$
AB	376.43	1.06	0.84	1.06	0.26
CD	373.86	0.43	0.55	0.33	0.24
EF	453.97	0.40	0.42	0.40	0.13
GH	437.55	0.37	0.25	0.49	0.07
IJ	430.47	0.75	0.52	0.62	0.15
KL	338.22	0.34	0.37	0.59	0.14
MN	411.11	0.32	0.28	0.55	0.08
OP	503.82	1.40	0.94	1.38	0.22

3. Conclusions

Within the framework of the DEMO R&D activities, a research campaign has been carried out at University of Palermo to investigate thermo-mechanical performances of a proposed preliminary design of the Top Cap of the WCLL OBC segment, verifying its structural integrity by the design criteria reported in the RCC-MRx standards.

From the thermal point of view, results obtained show that an acceptable temperature distribution is reached within structure except in the SPs where temperature exceeds the maximum allowable value of 550 °C.

As far as the mechanical behaviour is concerned, the selected thickness (40 mm) of the Top Cap allows it to withstand mechanical loads as all the RCC-MRx safety criteria are verified while, with regard to the SB, some small regions of the FW and the vertical SP .don't fulfil the considered criteria in the OP scenario.

The promising results obtained, lead to a further development of the work to study the Top Cap thermal-mechanical response considering a more detailed nuclear heating distribution to optimize its BZ cooling circuit layout and then to improve its mechanical behaviour.

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expressed herein do not necessarily reflect those of the European Commission.

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