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Vacuum Vessel Upper Port design assessment of the European DEMO

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The present work focuses on the design assessment of the DEMO Upper Port. The size of the upper port is defined by the available space in between the toroidal field coils and the required space to integrate a thermal shield between the vacuum vessel (VV) port and the coils. As the large breeding blanket (BB) segments will require periodic replacement via the upper vertical ports the space inside the upper port needs to be maximized. For this reason the optimization and verification of the upper port design is a critical aspect in the development of DEMO project. The work here presented investigates the possibility to have an upper port with single walled sidewalls to increase the space inside the port available for the integration of pipe work and to allow the handling of the BB segments. The work carried out evaluates the feasibility of the design solution from the structural and thermal point of view verifying the upper port structure against nuclear heating, in-vessel pressure, and electromagnetic loads due to a toroidal field coil fast discharge and plasma disruptions according to nuclear codes.

Keywords: DEMO, Vacuum Vessel, Electromagnetic analysis, Upper Port, FEM.

1. Introduction

Previous studies on DEMO configuration addressed both the structural scheme of the main vessel [1], [2] and the lower port structures taking into account the most severe loads acting on them [3]. The present work focuses on the design and analysis of DEMO upper port structure.

One of the main drivers in design of the DEMO Upper Port (UP) structure consists of the definition and optimization of its dimensions. Since the Breeding Blanket (BB) segments will require periodic replacement via the upper vertical ports at the top of the vacuum vessel, the optimization of the UP design is a critical aspect in the design of DEMO. Moreover the remote handling of the BB sector will be challenging due to its scale (∼10 m high and presently assumed to weigh up to 80 t) [4].

The size of the UP is constrained by the position of the toroidal field (TF) coils [5]. Much of the toroidal space in the area of the UP is taken up by the TF coils. In addition a thermal shield must be integrated between the UP and the coils with the necessary clearances. Independent of the poloidal location, the sizes of the TF coil, thermal shield, and port wall are constant and towards the inboard increasingly narrow down the remaining space inside the port [5].

This article summarizes the design studies of the UP structure. In order to maximize the space inside the UP an UP port with single-walled sidewalls is proposed. The structural integrity is verified considering the most critical loads conditions acting on the UP. The UP structure is verified according to the design rules defined in RCC MRx [6].

2. Design of DEMO Upper Port Structure

The Upper Port has been conceived with single-walled sidewalls, and has a double walled structure with ribs and shells at inboard and outboard side. The material of the VV, the UP and the UP plug is the austenitic steel AISI 316 L(N) [7]. The DEMO 2015 configuration has been used as reference for design studies [3]. The sidewalls shells have thickness of 60 mm, while, at the inboard and at the outboard side the ribs are 40 mm thick and the shells have thickness of 60 mm (Fig. 1).

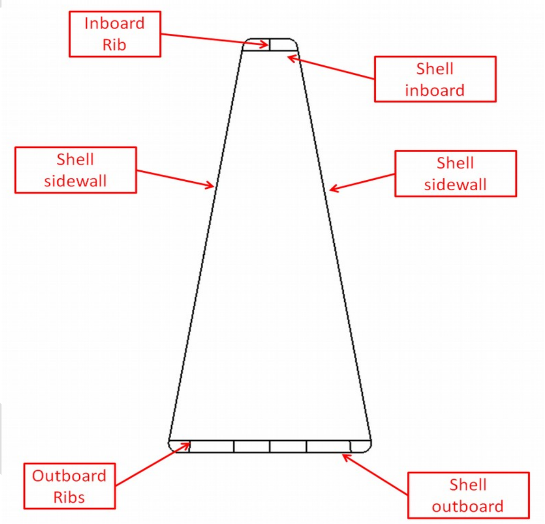

Fig. 1 Top View of the upper port with layout of ribs and shells

In previous studies preliminary analyses have been conducted [8] [9] to assess the feasibility of the UP design concept shown in Fig. 1. The results showed that some improvements are needed to assure the structural integrity of the UP against the design loads. The results pointed out the need of reinforcements at the inboard side of the port and at the single-walled port side-walls. In particular the sidewalls require stiffening structures to limit deformation in toroidal direction.

In order to face these issues the authors propose to add welded flange with "L" shape placed on the upper extremity of the port, see Fig. 2. The flanged geometry could be obtained sweeping an "L" profile with 60 mm of thickness all around the upper edge of the UP. The flange

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was hence considered with the dimensions shown in Fig. 2. The flange allows the extension of the in-port space in the upper part of the UP and provides stiffness to the UP sidewalls.

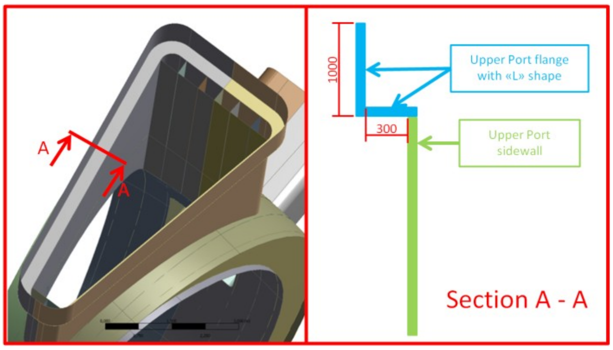

Fig. 2 Upper port flange with "L" shape, dimensions are in “mm”

The flange is placed about 500 mm above the profile of poloidal field (PF) coil n°1, see Fig. 3.

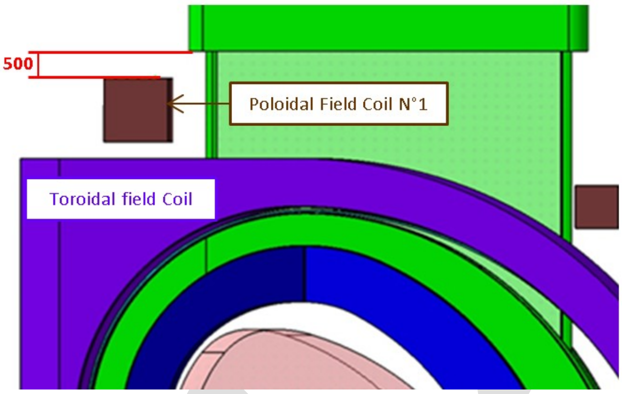

Fig. 3 UP flange above the top surface of PF1 - dimensions are in “mm”

3. Structural integrity assessment

3.1. Load cases

Four load cases have been identified to be critical to the design of the UP: (i) the neutrons generated during normal plasma operation cause volumetric heating of the non-actively cooled UP sidewalls, (ii) during a TFCFD electrical currents are induced in the port sidewalls and also in the upper port plug, (iii) eddy currents are induced in the UP structures in upward VDEs during both the thermal quench and the current quench phases, and (iv) in-vessel coolant leaks can cause over-pressurization of the VV up to 2 bar [10].

During a magnet fault event (e.g. detected loss of superconductivity) or in case of an abnormal working condition a fast discharge of the coils is initiated. The coil currents are ramped down rapidly and their energy is dissipated on quench resistors located outside of the tokamak building. The TFCFD induces poloidal currents in the passive structures. The currents interacting with the magnetic field generate loads. During the plasma operation a TFCFD event will trigger also a Major Disruption (MD) or a VDE. The EM loads acting on the VV and the in-vessel components (IVCs) caused by these events are main design drivers [11]. According to the current configuration of DEMO reactor, the TF coil discharge was assumed exponential with a time constant of 27 s [12].

For the VDE up the thermal quench time was assumed to be 1.4ms, the linear current quench time to be 71ms. A TFCFD usually triggers a central disruption but can also trigger a VDE. The latter combination is classified as category III event and level C criteria has to be applied [10].

3.2. Electromagnetic analysis

The distribution of the electromagnetic (EM) forces in the UP structures has been calculated in EM analyses and was transferred to the structural finite element (FE) model of the VV with UP structures. The port plug has been considered as electrically connected to the UP structures. The electrical contacts have been placed at the level of the plug structure see Fig. 4.

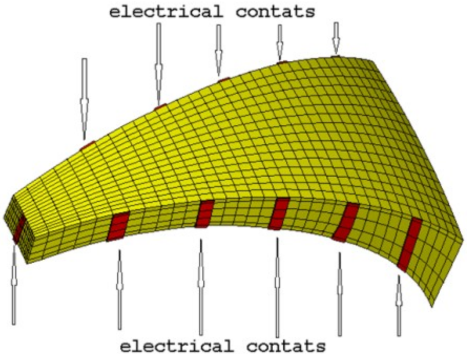

Fig. 4 FE model of the UP port plug with electrical contact [13]

The behavior of the resultant forces and moments vs time and their peak values at thermal and current quench (t=60.174 and t=60.25-60.7s) are shown in Fig. 5 and Fig. 6.

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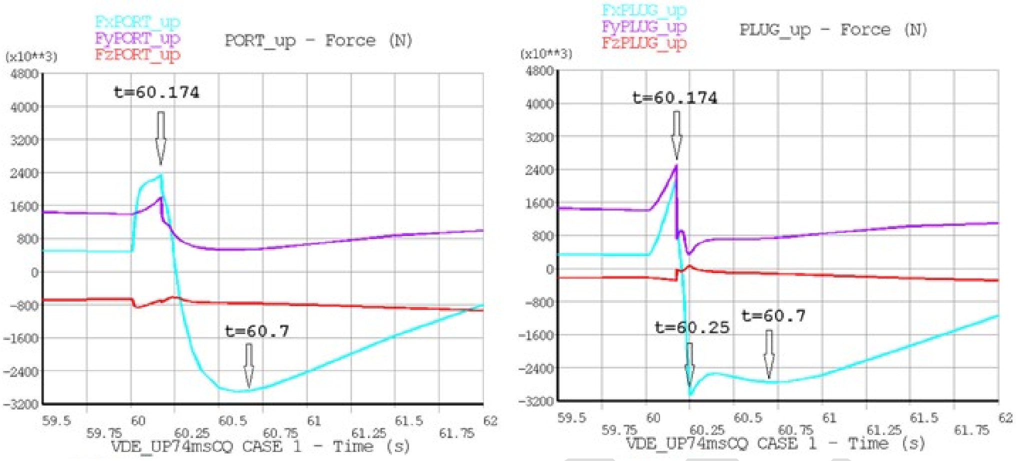

Fig. 5 Resultant forces during a TFCFD with consequent VDE upward (thermal quench at t=60.174s, peak loads due to plasma current quench at t=60.25-60.7s) – the "y" direction is aligned with the vertical axis of DEMO machine [13]

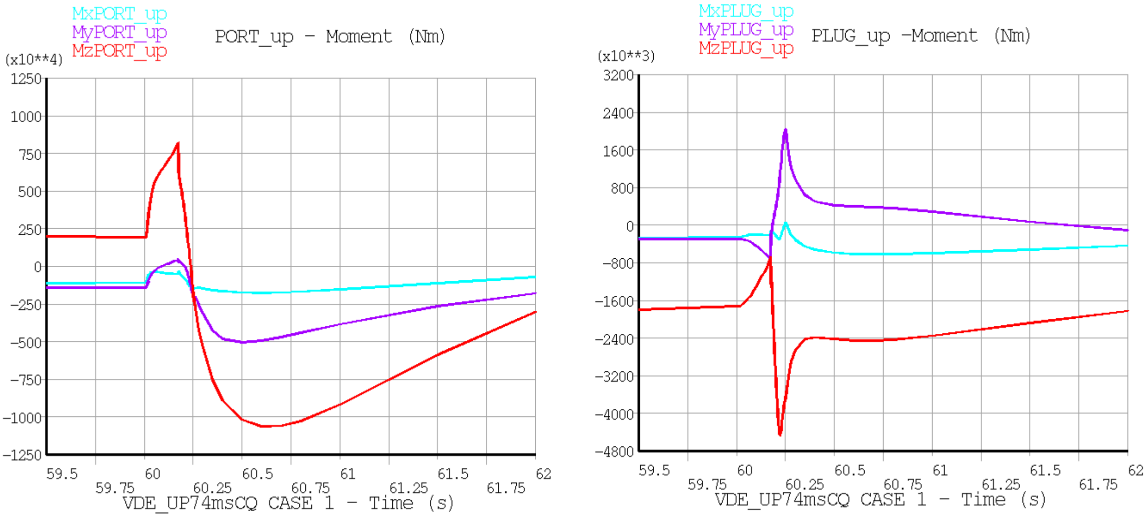

Fig. 6 Moments during a TFCFD with consequent VDE upward (thermal quench at t=60.174s, peak loads due to plasma current quench at t=60.25-60.7s) in upward direction – the "y" direction is aligned with the vertical axis of DEMO machine [13]

The values of the resultant forces and moments acting both on the UP and the UP plug are listed in Tab. 1 and Tab. 2.

Tab. 1 Resultant forces on UP and UP plug, the "y" direction is aligned with the vertical axis of DEMO machine [13]

TIME	**ID time**	**Upper Port**			**Upper Port Plug**		
		Fx [MN]	**Fy [MN]**	**Fz [MN]**	**Fx [MN]**	**Fy [MN]**	**Fz [MN]**
52.5	**T1**$_{TFCFD}$	**0.81**	**2.32**	**-0.84**	**0.55**	**2.35**	**-0.28**
60.174	**T2**$_{TFCFD+TQ}$	**2.35**	**1.81**	**-0.69**	**2.19**	**2.51**	**-0.29**
60.25	**T3**$_{TFCFD+CQ1}$	**0.14**	**0.89**	**-0.64**	**3.05**	**0.35**	**0.07**
60.7	**T4** $_{TFCFD+CQ2}$	**-2.86**	**0.55**	**-0.76**	**-2.75**	**0.74**	**0.00**

Tab. 2 Resultant moments on UP and UP plug, the "y" direction is aligned with the vertical axis of DEMO machine [13]

TIME	**ID time**	**Upper Port**			**Upper Port Plug**		
		Mx [MNm]	**My[MNm]**	**Mz [MNm]**	**Mx [MNm]**	**My [MNm]**	**Mz [MNm]**
52.5	**T1**$_{TFCFD}$	**-1.34**	**-1.75**	**-3.15**	**-0.33**	**-0.36**	**-2.87**
60.174	**T2**$_{TFCFD+TQ}$	**-0.50**	**0.47**	**8.22**	**-0.20**	**-0.70**	**-0.68**
60.25	**T3**$_{TFCFD+CQ1}$	**-1.45**	**-1.98**	**-1.90**	**0.06**	**2.03**	**-3.67**
60.7	**T4** $_{TFCFD+CQ2}$	**-1.73**	**-5.06**	**-10.2**	**-0.29**	**-0.34**	**-1.20**

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Since the induced currents are predominately poloidal, the electrical straps have a minor effect on the EM loads due to the TFCFD. For each time step a dedicated FEM analysis has been carried out applying the field of loads coming from the EM analyses.

3.3. Structural design criteria

TFCFD, VDE up and in-vessel LOCA cause primary stresses and the structure is therefore verified against type P damage for these loads [10]. The types of analysis employed for this verification are linear elastic or elastoplastic. In the elastic analysis the membrane plus bending stress of the VV material is limited to 195 MPa assuming a VV temperature of 200°C [6].
Nuclear heat loads due to normal plasma operation cause thermal and hence secondary stresses. The structure is therefore verified against type S damage for this load case according to RCC MRx [6].

4. FE Assessment

4.1. FE model

A FE model of a single VV sector has been developed. It includes the UP with UP plug for the purpose to verify the UP structures.
The FEM analysis takes into account not only the loads acting on the UP structure but also those acting on the UP plug. The study and analysis of the UP plug is not in the scope of the present work, despite that, it has been modeled to take into account the loads transferred by the UP plug to the UP structures. (Fig. 7)

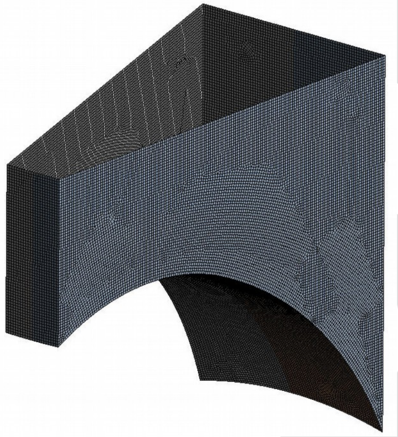

Fig. 7 3d mesh of DEMO UP plug

4.1.1. Boundary Conditions

Cyclic boundary condition has been applied on the side edges of the VV sector. In order to consider the VV supports at the lower port two nodes were restrained against the translation in toroidal and vertical direction
The UP plug is joined to the UP through the edges of the "L" shape flange. In that area the edges of the UP and UP plug are assumed as fully bonded. Moreover the UP and UP plug nodes placed on the edges labelled "a" in are constrained together in such a way that they can slide mutually along the vertical axis.

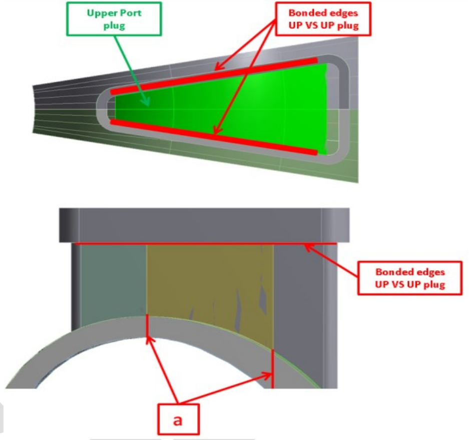

Fig. 8 Boundary conditions UP plug

4.2. Analysis results - TFCFD, VDE up

The stress distributions of two of four time step are shown in Fig. 9 and Fig. 10. The results of FEM linear elastic analyses showed that in all time steps (Tab. 1 and Tab. 2) the membrane plus bending stress is lower than the limit imposed (i.e. 195 MPa) by the RCC MRx in case of P type damage evaluation and Level A design criteria.

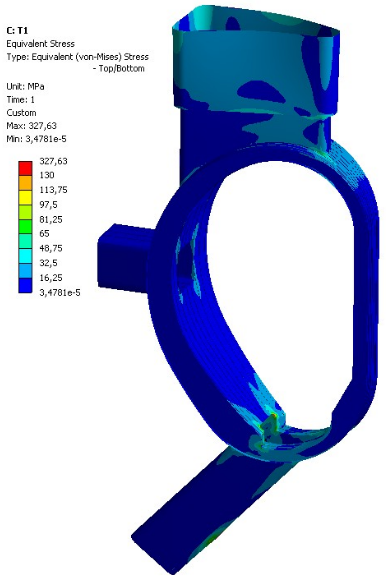

Fig. 9 Membrane plus bending stress distribution a T1 - only TFCFD effect

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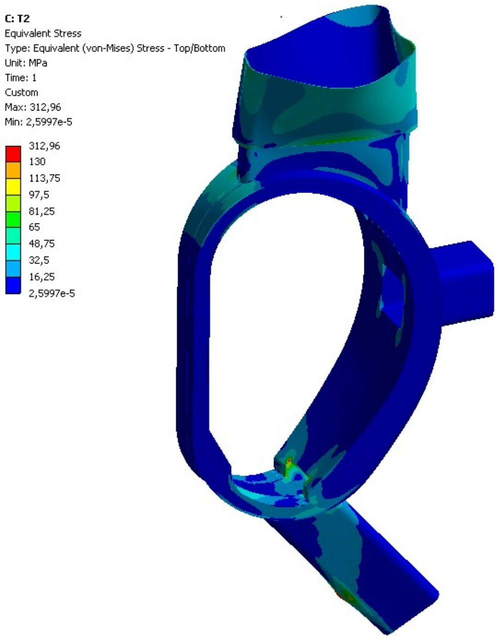

Fig. 10 Membrane plus bending stress distribution a T2

4.3. Analysis results – in-vessel LOCA

FEM analyses have been carried out to define the maximum vacuum chamber pressure of DEMO VV. Two different methods of analysis have been adopted; the elastoplastic method has been used to take into account of the beneficial effect due to steel hardening behavior, while the linear elastic method and analytical calculation procedure have been adopted to check the consistency of the previous results.

4.3.1. Elastoplastic analysis

The structural verification is carried out using also the elastoplastic analysis procedure according to RCC MRx rules [6], applying the load progressively to the deformed structure up to plastic collapse. Gravity acceleration has been applied to the FE model to take into account weights of all VV structures. The boundary conditions used in these analyses are the same reported section 4.1.1. The Minimum true stress-strain data of SS 316L (N) have been applied to the material type inside the FEM model [7]Error: Reference source not found. The nominal value considered as pressure load is 10 bar, the pressure was applied step by step on deformed structure. Each step increased the load of 20% while the gravity acceleration applied is constant for each step and equal 2.5 times the nominal value. The results of the analysis showed that the VV and the UP structures as such as conceived can withstand to a pressure higher than 10 bar in case of P type damage evaluation through a level C Criteria [6].

4.3.2. Linear elastic analysis

In order to check the consistency of the previous analyses, FEM linear elastic analyses have been carried out. The FE model and boundary conditions are the same of the previous, the material type has a linear elastic behavior. In Fig. 11 is shown the maximum value for Von Mises stress at 2 bar, this value meets the RCC-MRx rules [6]. In particular the maximum bending plus membrane stress is about 122 MPa, this value is lower than 1.5Sm (i.e. 195 MPa in the case of austenitic steel [6]).

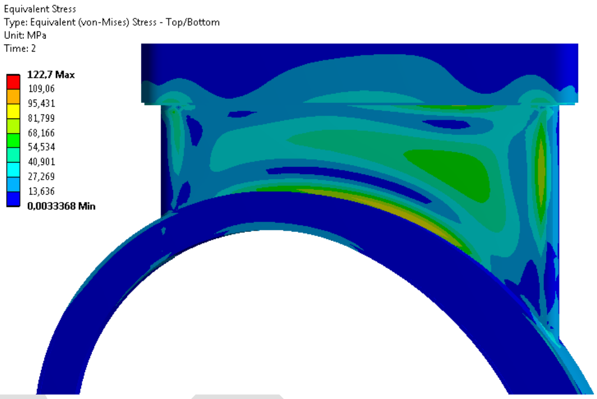

Fig. 11 Von Mises Stress on the upper port with pressure at 2 bar

In Fig. 12 the results of similar analysis with pressure of 6 bar is shown. As we can observe, also in this case the RCC-MRx rules are meet. The maximum bending stress plus membrane stress is about 181 MPa, this value is lower than the limit of 195 MPa imposed by RCC-MRx rule [6]Error: Reference source not found in case of austenitic steel. The calculation confirms that the upper port can withstand the pressures applied.

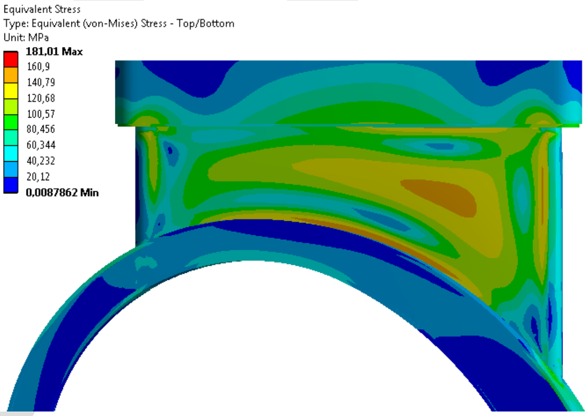

Fig. 12 Von Mises Stress on the upper port with pressure at 6 bar

Since the maximum vacuum chamber pressure during an In-Vessel Loss of Coolant Accident (LOCA) is assumed to be higher than 1 bar [14], a pressure of 2 bar has been chosen (as in ITER) as maximum vacuum chamber pressure considering limitations of other components part of the DEMO primary confinement and hence primary vacuum boundary, (e.g. the diamond disks of the EC launcher, the bellows of the torus vacuum pumps, the neutral beam vessel and the fuel injector vessel).

4.4. Analysis results – Normal operation

The sidewalls of upper port are the only components of DEMO VV single walled and, at the moment, not actively cooled. Due to this a thermal steady state FEM analysis has been carried out to evaluate the level of thermal stress induced by the thermal heat load distribution provided by

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PMU [15]. The consistency of the results has been checked also analytical models according to Fourier Law [16].

The nuclear heating distribution is shown in Fig. 13. The values of heat load varies in the range 0.1kW/ m^3 -1kW/ m^3 at inboard near to the BB. All the other UP surfaces are set at 200°C since they are assumed as actively cooled.

The thermal steady analysis was conducted in the conservative hypothesis that the heat is transferred just through conduction.

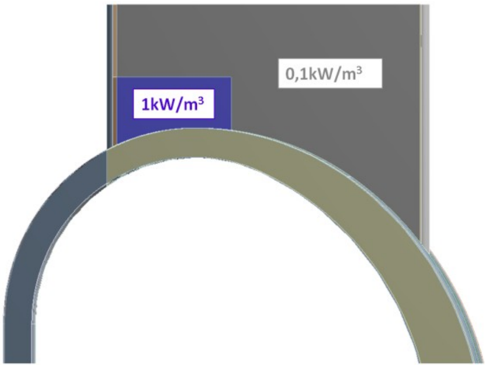

Fig. 13 Heat load distribution on the UP sidewalls

In Tab. 3 are listed the boundary condition set in thermal steady state analysis.

Tab. 3 Boundary conditions of Thermal Steady State

FE model characteristics	Units	[mm,°C]
	Element Type	Shell131
	N° of elements	94285
	N° of nodes	92986
	Average element size [mm]	50
Material Properties	Material	AISI 316 L(N)
	Thermal conductivity [W/m·K] at 200°C	16,98 [6]

The results of the thermal analysis are shown in Fig. 14. The maximum value of temperature is about 224°C (Fig. 14). The thermal stress induced in the structure can be neglected since the difference between the maximum and minimum temperature is about 24°C.

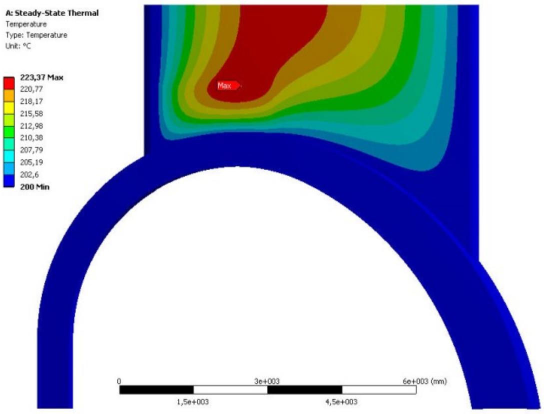

Fig. 14 Temperature distribution on the upper port sidewall

The results have been checked to be consistent through the Thermodynamic Fourier Law [16]. The heat transfer problem has been schematized as a plate, with dimensions similar to the sidewall of the upper port (Fig. 15). The thermal load acting on the upper port sidewall has been calculated through a volume weighted average. The value obtained is 0.14 kW. The two extremities have been set at 200°C (Fig. 15) since the others UP structures have been assumed as actively cooled.

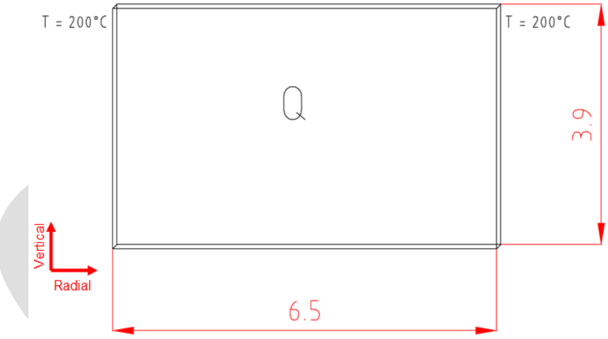

Fig. 15 thermal scheme of the upper port sidewall, dimensions are in meters

The thickness of plate shown in Fig. 15 is set 0.06m equal to the upper port sidewall thickness. In this configuration according with Fourier postulate [16] the maximum temperature will be near the midline of the plate and is about 260°C. The calculation based on the Fourier Law gives a more conservative estimation of the maximum temperature, nevertheless the two results has the same order of magnitude. Both analyses confirmed that no active cooling system is needed for the UP sidewalls.

5. Conclusion

The work here presented addressed the feasibility of the design solution proposed considering the most critical load condition. In particular the analysis conducted to check the structural integrity of the UP against a TFCFD with consequent VDE in upward direction demonstrated that the level of stress on the UP structures meets the codes. The VV and UP structures can withstand a maximum vacuum chamber pressure of about 10 bar even though 2 bar was chosen as reference pressure for the vacuum chamber to take into account the limitation of the other components of DEMO. Finally the results thermal analysis showed no active cooling is needed for the UP structures since the maximum temperature is near the center of the UP sidewalls. The relatively low nuclear heating in the area causes a temperature increase of the non-actively cooled structure by only 24°C.

Acknowledgments
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References

[1] Mozzillo, R., Marzullo, D., Tarallo, A., Bachmann, C., &

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author's email: rocco.mozzillo@unina.it

Di Gironimo, G. (2016). Development of a master model concept for DEMO vacuum vessel. Fusion Engineering and Design, 112, 497-504.

[2] Mozzillo, R., Tarallo, A., Marzullo, D., Bachmann, C., Di Gironimo, G., & Mazzone, G. (2016). Preliminary structural assessment of DEMO vacuum vessel against a vertical displacement event. Fusion Engineering and Design, 112, 244-250.

[3] Mozzillo, R., Bachmann, C., & Di Gironimo, G. (2017). Structural assessment on DEMO lower port structure. Fusion Engineering and Design, 121, 348-355.

[4] Keep, J., Wood, S., Gupta, N., Coleman, M., & Loving, A. (2017). Remote handling of DEMO breeder blanket segments: Blanket transporter conceptual studies. Fusion Engineering and Design.

[5] C. Bachmann et al, Issues and strategies for DEMO in-vessel component integration, Fusion Eng. Des. Volume 112, 15 November 2016, Pages 527-534, http://dx.doi.org/10.1016/j.fusengdes.2016.05.040

[6] RCC-MRx 2012, Design And Construction Rules For Mechanical Components Of Nuclear Installations 2012 Edition, Paris – France.

[7] Appendix A to ITER SDC-IC, Materials Design Limit Data, Iter_222RLN, PRIVATE COMUNICATION.

[8] F. Lucca, Structural analysis of upper port, EFDA_D_2LM782, PRIVATE COMUNICATION.

[9] F. Villone, Upper port electromagnetic analysis, EFDA_D_2LC2PP, PRIVATE COMUNICATION.

[10] Bachmann, C., Biel, W., Ciattaglia, S., Federici, G., Maviglia, F., Mazzone, G., ... & Taylor, N. (2017). Initial definition of structural load conditions in DEMO. Fusion Engineering and Design, 124, 633-637.

[11] Sannazzaro, G., Bachmann, C., Campbell, D. J., Chiocchio, S., Girard, J. P., Gribov, Y., ... & Taylor, N. (2009, June). Structural load specification for ITER tokamak components. In Fusion Engineering, 2009. SOFE 2009. 23rd IEEE/NPSS Symposium on (pp. 1-4). IEEE

[12] C. Bachmann, DEMO Plant Structural Load Specification, EFDA_D_2MY7H3, PRIVATE COMUNICATION.

[13] Massimo Roccella, Giuseppe Ramogida, Fabio Villone. EM DGM including TFCs and EM analyses of Plasma disruptions plus TFCs FD, EFDA_D_2NAZYR.

[14] Bachmann, C., Biel, W., Ciattaglia, S., Federici, G., Maviglia, F., Mazzone, G., ... & Taylor, N. (2017). Initial definition of structural load conditions in DEMO. Fusion Engineering and Design, 124, 633-637

[15] B. Caicchi, Nuclear Heating on the Upper Port Wall_2107, PRIVATE COMUNICATION.

[16] Taler, J., & Duda, P. (2010). Solving direct and inverse heat conduction problems. Springer Science & Business Media.

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author's email: rocco.mozzillo@unina.it