Fusion Engineering and Design 124 (2017) 882–886

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

A new HCPB breeding blanket for the EU DEMO: Evolution, rationale and preliminary performances

F. Hernández[a,*], P. Pereslavtsev[a], Q. Kang[a], P. Norajitra[a], B. Kiss[b], G. Nádasi[c], O. Bitz[a]

[a] Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology (INR), Germany
[b] Institute of Nuclear Techniques, Budapest University of Technology and Economics, Budapest, Hungary
[c] Wigner Research Center for Physics, Budapest, Hungary

ARTICLE INFO

Article history:
Received 1 October 2016
Received in revised form 10 January 2017
Accepted 3 February 2017
Available online 22 February 2017

Keywords:
HCPB
Breeding blanket
DEMO
TBR

ABSTRACT

The Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) is one of the 4 BB concepts being investigated in the EU for their possible implementation in DEMO. During 2014 the former "beer-box" BB concept based on the ITER's HCPB Test Blanket Module suffered several design changes so as to meet the different counteracting nuclear, thermohydraulic and thermomechanical requirements. These studies evidenced that the concept is too rigid to meet the tight TBR requirements imposed for the EU DEMO (i.e. TBR $\geq$ 1.10). Additionally, the complex manifold system with unbalanced helium mass flow in each of the 2 parallel cooling loops made the concept thermohydraulically complex. However, parametric studies during 2015 revealed that the HCPB concept have potential for a better nuclear performance, as well as margin for a significant simplification of the cooling internals by redefining the cooling plates and the architecture of the blanket, building a symmetric flow scheme.

This paper describes the new HCPB concept based on an integrated FW with the breeding zone thermo-hydraulics and helium manifold systems. The former complex manifold backplates have been compacted and integrated in the cooling plates, releasing $\approx$300 mm of radial space that can be used now to increase breeder zone, the neutron shielding, to reinforce the Back Supporting Structure (BSS) or basically to reduce the reactor size. Detailed neutronic analyses have yielded a TBR of $\sim$1.20 for the baseline design. Initial analyses show a correct thermohydraulic behavior. Preliminary thermomechanical analyses also indicate that the design can potentially withstand an in-box LOCA at 9 MPa at a level C according to the RCC-MRx code. Future consolidation activities are described, which shall lead to a concept meeting the BB requirements.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

During 2011–2013 initial conceptual studies on the HCPB breeding blanket (BB) have been performed in the framework of the EFDA Power Plant Physics & Technology. These activities led to a HCPB BB design [1,2] based on the concept developed for the PPCS study [3]. That concept consisted on a modular arrangement of vertical and horizontal stiffening grids, creating a grid of cuboids where the BU's are located (the so-called "beer box" architecture, more details in the BU's arrangement e.g. in [4] and [5]).

A preliminary exercise with the "beer-box" HCPB architecture has been performed during 2014 with a first DEMO tokamak configuration [6]. During this first exercise it has been evidenced that the "beer-box" architecture has a poor nuclear performance, both in terms of TBR and shielding capabilities [7]. Additionally, the thermohydraulic scheme of this architecture is based on an unsymmetrical flow distribution between the different blanket module subcomponents, where the flow is collected in a complex system of manifolds at the rear side of the blanket, complicating its assembly, reducing its reliability and leading to relatively high pressure drops.

Due to these poor performance figures and the current uncertainties still present in the DEMO tokamak design [8] it has been concluded that a more flexible architecture that can offer larger design margins for risk mitigation is needed. This paper describes the new proposed HCPB architecture for the EU DEMO which simplifies the former configuration and improves the basic performance figures of the blanket.

* Corresponding author.
E-mail address: francisco.hernandez@kit.edu (F. Hernández).

http://dx.doi.org/10.1016/j.fusengdes.2017.02.008
0920-3796/© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

2. The new HCPB BB baseline design

2.1. General architecture

The proposed HCPB BB for DEMO (Fig. 1) is based on a multi-module segment configuration, formed by 7 inboard (IB) and 7 outboard (OB) blanket modules per segment. Each blanket module is formed by a box defined by the First Wall (FW), the backplate and an arrangement of parallel cooling plates (CP) that separate alternate layers of Li_4SiO_4 (breeder material) and Be (neutron multiplier), both in form of pebble beds (Ø(0.25 ÷ 0.63) mm for Li_4SiO_4 and Ø1 mm for Be).

At the top and bottom of each blanket module there is the so-called "double caps". Due to the lack of vertical stiffening grids in this architecture the ≈25 mm thick caps of the "beer-box" concept are not enough to withstand an event of an in-box LOCA at the lowest safety criteria (level D after RCC-MRx code). In order to cope with such accidental events, the implementation of "double-caps" are necessary, which is a tandem of 24 mm thick caps joined by a zig-zag planar structure inspired in the Warren-truss concept in civil engineering structures. This planar zig-zag structure is not actively cooled, but the total thickness of the "double-caps" is limited to ≈84 mm so as to keep the temperature of this subcomponent under the design limit of 550 °C set due to loss of creep strength considerations [15].

Each blanket module is assembled to the so-called Back Supporting Structure (BSS, Fig. 1). It acts as main structural support for the blanket segments, as well as a manifold for the purge gas and the helium coolant distributed to each of the blanket modules. The manifold is built upon concentric pipe arrangement, where the outlet helium flows in the inner oval pipe and the inlet helium flows between this pipe and the BSS manifold. In order to avoid heat losses, the inner pipe is covered by ≈3 mm layer of a thermal insulator.

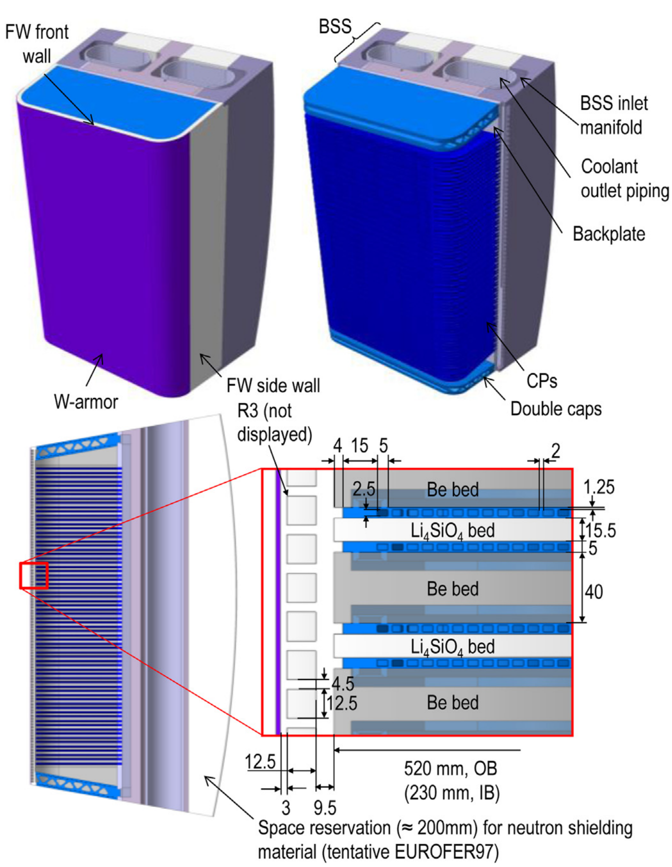

Fig. 1. HCPB BB based on a "sandwich" architecture. Detailed pictures for the equatorial OB module.

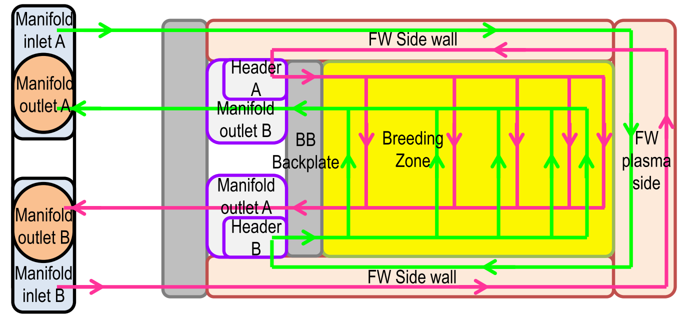

Fig. 2. Flow scheme (top) and cut-off detail of the CP and the flow paths for the 2 parallel helium loops.

The general dimensions of the blanket module are detailed in Fig. 1. A 2 mm layer of W is foreseen as armor for the FW against sputtering and erosion due to charged particles from the plasma. The creation of this layer of W is yet to be defined but plasma spray is preliminarily considered. The blanket subcomponents are designed upon the experience gathered during the development of the HCPB-TBM for ITER and are mainly based on spark erosion (for the FW), die sink electric discharge machining and spark erosion (FW and CP) and electron beam as the joining technique.

2.2. Purge gas system

A purge gas sweeps the Li_4SiO_4 and Be pebble beds separately. It is composed by He with an addition of 0.1% wt H_2 as doping agent to promote an isotopic exchange between the tritium (T) bred in the pebbles and the doping agent to form HT, helping to the T release and extraction. A low purge gas pressure is preferred in order to help reducing the T permeation into the coolant. However, a too low pressure can decrease the purge gas thermal conductivity due to the Smoluchowski effect, worsening the effective bed conductivity. This has been experimentally observed to occur at purge gas pressures below 0.15 MPa [9]. Therefore the purge gas pressure at the breeder zone (BZ) is set to 0.2 MPa. The addition of H_2O instead of H_2 as doping agent would promote tritiated water, drastically reducing the T permeation to negligible values. However, the use of Be as neutron multiplier may not allow purging with this doping agent due to the hydrolisation of Be at high temperatures, at least in that pebble bed. Purging with He + 0.1% wt H_2O may be possible with $Be_{12}Ti$ due to the temperature shift of its reactivity with H_2O or not needed at all for an alternative neutron multiplier with negligible or no (n,T) reaction.

2.3. Coolant parameters and flow scheme

The new HCPB BB architecture resembles to past designs developed during the 90's [10,11]. However, one of the main differences is in the CPs, which have been now designed to work as manifolds, so as to release space at the back of the blanket, simplifying the former complex manifold system of the "beer-box" concept.

The blanket coolant is He at 8 MPa. This pressure is a trade-off between a minimization of primary stresses, flow speeds (hence pressure drops), piping dimensions and the expansion tank size in an event of an in-vessel LOCA. The He inlet and outlet temperatures are 300 °C (to avoid working close to the shifted DBTT due to neutron irradiation) and 500 °C (to avoid working close to the creep strength drop temperature), respectively.

Fig. 2 shows the flow path with the new architecture. The subcomponents are cooled by two parallel He flows. Contrarily to the

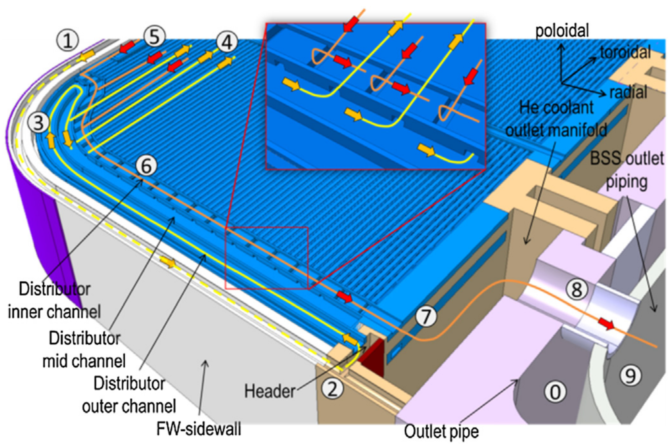

Fig. 3. Flow scheme (top) and cut-off detail of the CP and the flow paths for the 2 parallel helium loops.

"beer-box" concept, these 2 flows are symmetric, sharing 50% each of the total blanket module mass flow.

In Fig. 3 the inlet He flows through the BSS manifold inlet, marked as (0), flows through the FW (1) and it is collected in the headers (2). From the headers the coolant enters the CP distributor (3), where the He flows to the cooling channels of the CP (4). The He from the other parallel symmetric loop flows in counter-flow (5) and it is collected also at the distributor, exiting the CP and collected in the He outlet manifold (7), where it is transferred (8) to the BSS outlet piping (9).

3. Basic blanket performance figures

3.1. Neutronics

An extensive neutronics campaign has been conducted with the new HCPB architecture developed for the latest EU DEMO tokamak show e.g. in [8] (fusion power of 2037 MW). These analyses have driven the design from a zero-th (V0) version to the baseline design (version V3) described in the previous section. Details of the methods and results are described in [12].

Fig. 4 shows the design iterations from V0 to V3, with an indication of the TBR obtained in each case. V0 started with a preliminary arrangement of Li_4SiO_4 and Be beds thicknesses of 11 mm and 33 mm, respectively. The radial built of the HCPB BB is here 450 mm for the IB modules and 820 mm for the OB ones. The caps are here as in the "beer-box" and CP are inserted in the region between the caps and the first adjacent CP. V1.1 is as V0 but implementing

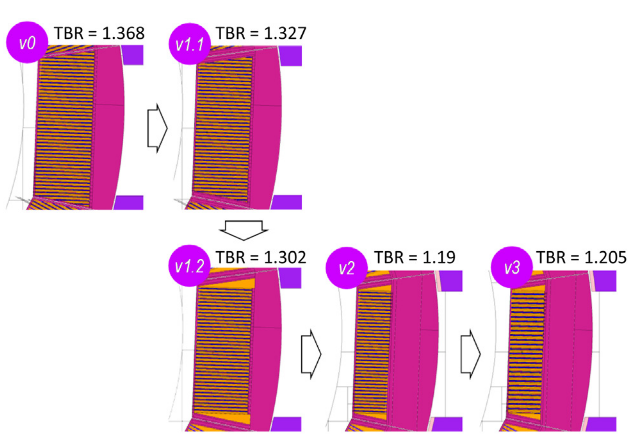

Fig. 4. Design iterations with the new HCPB concept.

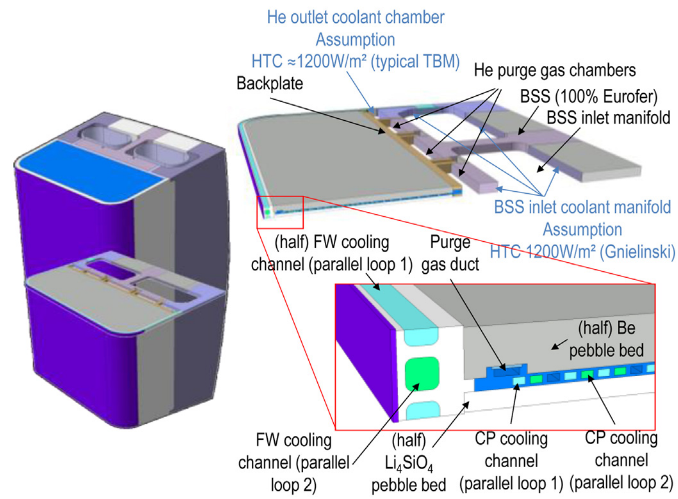

Fig. 5. Slice model for thermohydraulic analyses.

the double-caps, while V1.1 is as V1.2 with the removal of the CP between the caps and the first adjacent CP, as they are increase the complexity of the assembly and the thermohydraulics. Due to the high TBRs obtained from V0 to V1.2 it has been decided to reduce the BZ, so as to reduce the inventory of functional materials, as well as to increase the BSS radial build. V2 has therefore radial builds of 230 mm in the IB and 520 mm in the OB. V3 is as V2 but with bed thicknesses of 15.5 mm and 40 mm for the Li_4SiO_4 and Be beds, respectively. This last V3 (baseline) resulted in a TBR $\approx$ 1.205.

The BSS in V3 is thick enough to leave a space for additional neutron shielding material. Different materials have been studied (EUROFER, WC, graphite stacks and graphite pebbles). As EUROFER has already shown good shielding figures (fast neutron flux in the toroidal field coil (TFC) < 10^9 cm^{-2} s^{-1}), it has been chosen as shielding material for the V3. The power density in the TFC is <50 W/m^3 and the dpa damage in the vacuum vessel (VV) is <0.2 dpa/fpy, as required.

3.2. Thermohydraulics

Some preliminary results are available for the V0 with some assumed mass flow distributions and 1D fluid flow models in [13]. Here, detailed CFD analyses are reported, which have been conducted on a slice model of the HCPB equatorial OB blanket module (Fig. 5). This model comprises 1 CP and 2 halves of Li_4SiO_4 and Be beds and the resulting slice of the FW and BSS.

The total reactor thermal power obtained after the neutronic analyses for the baseline design is 2796.4 MW. This thermal power assumes a homogeneous FW heat flux of 0.5 MW/m^2. Taking into account the heat capacity of He and ΔT through the blanket this corresponds to a mass flow of 2690.4 kg/s ($\approx$70% to OB, $\approx$30% IB). The mass flow in the equatorial OB module (OB4) is 6.33 kg/s and $\approx$0.051 kg/s though 1 cooling channel of the FW of the OB4. A roughness (R_a) of 13.5 μm has been considered as typical value for spark eroded and machined channels.

The temperature distribution in the different materials is shown in Fig. 6. The maximum temperature in the EUROFER, the Li_4SiO_4 and the Be are 578.3 °C, 935.4 °C and 671.7 °C, respectively. The hot spot in the EUROFER is very localized in at the purge gas ducts, where the CP stresses are small. The hot spots in Be and the Li_4SiO_4 are about 20 °C outside the design limits defined for these materials [17] but they can be easily reduced by rearranging the cooling channels to have a slightly more density of channels at the front side of the blanket, reducing it at the back or also by slightly reduc-

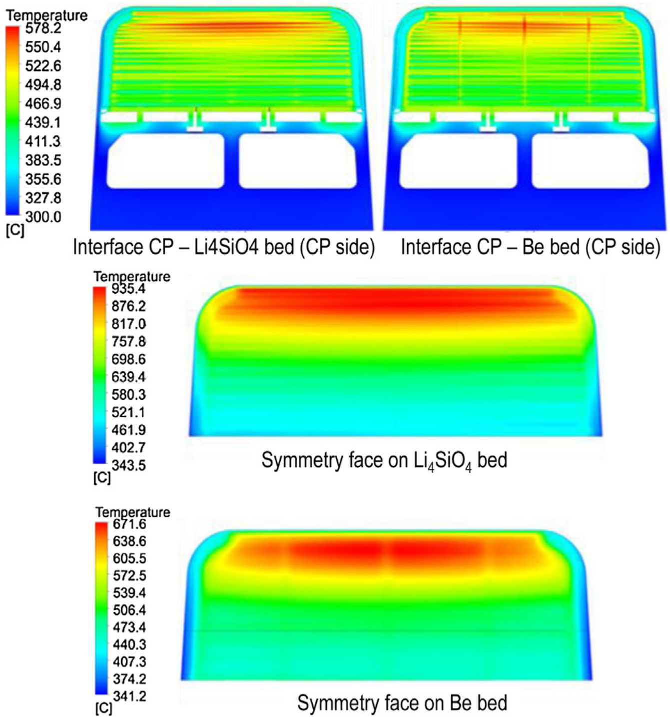

Fig. 6. Temperature distribution of the HCPB DEMO (baseline design).

ing the height of the pebble beds bed a few mm, which will not significantly change the TBR from the current value of ≈1.20.

Special attention has been paid at the pressure drop of the blanket system, as the circulation power needed for helium cooled blankets is considered a concern for the overall net plant efficiency. The resulting pressure drop of the OB4 is ≈0.2 MPa. A complete CFD analysis of the BSS and the piping up to the VV upper and lower ports for the OB and IB segments has been as well performed. The results show that the overall pressure drop in the blanket system with this architecture and the current DEMO tokamak parameters is ≈0.26 MPa.

A quick evaluation of the required pumping power P_{pump} needed considering an average He density of about 6 kg/m^3 and an additional typical pressure drop of ≈0.1 ÷ 0.2 MPa for the rest of the PHTS loop yields $P_{pump} = Q_{tot}\Delta P_{drop} \approx 160 \div 200$ MW. Comparing this to the required 200 ÷ 250 MW in the former "beer-box" concept (blanket + BSS pressure drop ≈0.36 MPa and considering the same fusion power coolant parameters), the simplifications done in this architecture should lead to a sensible improvement in the net plant efficiency.

3.3. Thermomechanics

3.3.1. Accidental event (in box LOCA)

Together with the neutronics performance, the event of an in-box LOCA has been the second main design driver of the blanket. For this, structural analyses with an internal pressurization of the OB4 module box has been conducted, with a pressure of 9 MPa (8 MPa coolant pressure + ≈10% to account for uncertainties). For the sake of simplicity only damage modes regarding primary stresses (membrane P_m and bending P_b) have been assessed and therefore, an isothermal condition of 500 °C has been defined. Further analyses will add the effect of the thermal field, but in the experience of the authors, the maximum allowable stress S_m is usually more stringent than the S_{em} used for assessing the effect of the combination of primary membrane and secondary stresses (P_m + Q).

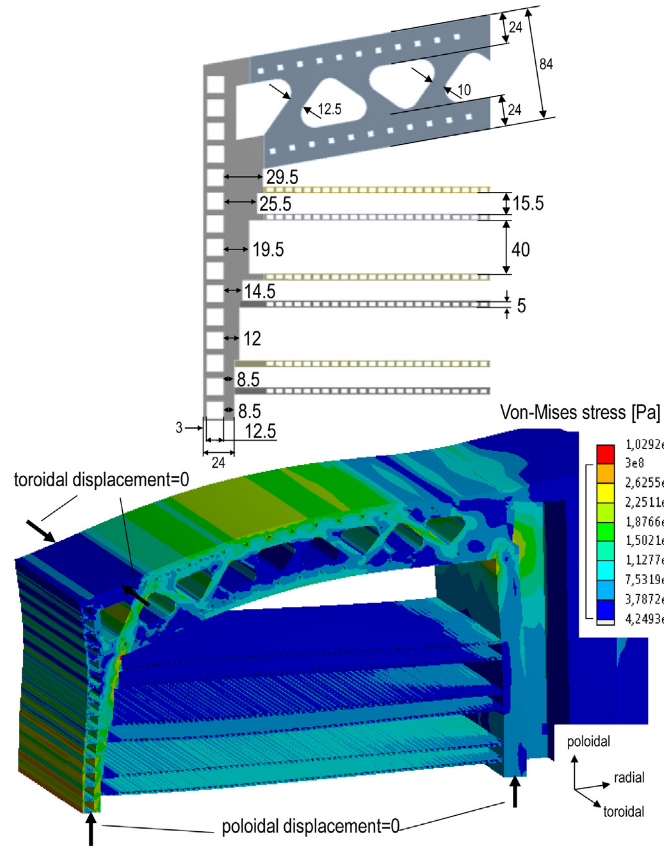

Fig. 7. Stress analysis for in-box LOCA event.

As it can be seen in Fig. 7, the internal pressurization of the blanket is only a concern at the cap region. After several design iterations a redesign of the cap to the current "double-cap" has been performed. Due to the significant difference in the thicknesses between the "double cap" (84 mm) and the FW (25 mm), a stepped arrangement as shown in Fig. 7 top is needed in the FW. After the stress assessment on this design to a simplified slice of the blanket (Fig. 7 bottom), the structure can potentially fulfill the RCC-MRx [16] rules at a level C.

3.3.2. Normal operation

Some preliminary results are available for the V0 in [14]. Here, a more detailed stress analysis for the normal operation has been conducted to the baseline HCPB architecture (V3) and the temperature distribution from the CFD analysis of Section 3.2. The stress analysis has included the calculation of the primary and secondary stresses and the assessment of these by means of the RCC-MRx code at a level A.

Fig. 8 shows a picture of the same slice model as in Section 3.2 of the OB4 used for the stress analysis. A coolant pressure of 8 MPa has been set up at the cooling channels of the CP and FW. The temperature distribution for the Q stresses has been the one obtained in Section 3.2. At the bottom surface of the slice a symmetry condition has been imposed while at a parallel motion with respect to the bottom surface of the slice has been set up.

A good global structural behavior is observed, with the exception of the distributors, where the P stress fails by plastic collapse and instability. A thicker plate will be required in future versions of this new blanket. The immediate plastic flow localization is also not fulfilled at the connecting bridges of the BZ and FW with the BSS due to the differential thermal expansion of the hot BZ and the

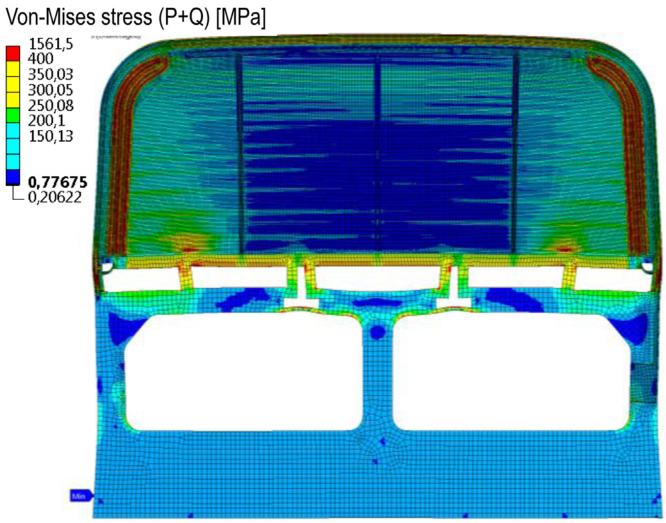

Fig. 8. Stress analysis for normal operation.

cold BSS. A more flexible structure will have to be implemented in a more consolidated design.

4. Conclusions

A new DEMO HCPB BB architecture has been presented in this paper. This blanket is based on a repeating "sandwich" structure of CP and alternate breeder and multiplier pebble beds. The former complex manifold backplate system has been integrated directly in the CP, simplifying the flow scheme (which is now fully symmetric), releasing about 300 mm at the back of the blanket and reducing the pressure drop about 30% in comparison to the former "beer-box" concept Neutronic, thermohydraulic and thermomechanical analyses have shown correct performance figures, especially for the TBR, which makes the current architecture much well prepared to mitigate future tokamak scenarios that may lead to significant reduction of the blanket surface coverage, e.g. larger divertor, implementation of detached FW configurations, double null architectures, integration of many in-vessel systems, etc.

Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme2014–2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] D. Carloni, L.V. Boccaccini, F. Franza, S. Kecskes, Requirements for helium cooled pebble bed blanket and R&D activities, Fusion Eng. Des. 89 (7–8) (2014) 1341–1345.
[2] J. Aktaa, S. Kecskes, P. Pereslavtsev, U. Fischer, L.V. Boccaccini, Non-linear failure analysis of HCPB blanket for DEMO taking into account high dose irradiation, Fusion Eng. Des. 89 (7–8) (2014) 1664–1668.
[3] D. Maisonnier, I. Cook, P. Sardain, L.V. Boccaccini, L. Di Pace, et al., DEMO an fusion power plant conceptual studies in Europe, Fusion Eng. Des. 81 (8–14) (2006) 1123–1130.
[4] F. Hernandez, F. Cismondi, B. Kiss, Thermo-mechanical analyses and assessment with respect to the design codes and standards of the HCPB-TBM Breeder unit, Fusion Eng. Des. 89 (7–8) (2012) 1111–1117.
[5] F. Hernandez, J. Rey, H. Neuberger, S. Krasnorutskyi, R. Niewöhner, A. Felde, Manufacturing pre-qualification of a Short Breeder Unit mockup (SHOBU) as part of the roadmap toward the out-of-pile validation of a full scale helium cooled pebble bed breeder unit, Fusion Eng. Des. 98–99 (2015) 1779–1783.
[6] C. Bachmann, G. Aiello, R. Albanese, R. Ambrosino, F. Arbeiter, et al., Initial DEMO tokamak design configuration studies, Fusion Eng. Des. 98–99 (2015) 1423–1426.
[7] P. Pereslavtsev, C. Bachmann, U. Fischer, Neutronic analyses of design issues affecting the tritium breeding performance in different DEMO blanket concepts, Fusion Eng. Des. 109–111 (2016) 1207–1211.
[8] M. Coleman, F. Maviglia, C. Bachmann, J. Anthony, G. Federici, et al., On the EU approach for DEMO architecture exploration and dealing with uncertainties, Fusion Eng. Des. 109–111 (2016) 1158–1162.
[9] S. Pupeschi. R. Knitter. M. Kamlah, Effective thermal conductivity of advanced ceramic breeder pebble beds, this conference.
[10] M. Dalle Donne, DEMO-relevant Test Blankets for NET/ITER. Part 2: BOT Helium Cooled Solid Breeder Blanket. Volume 2: Detailed Version, KfK 4929, Kernforschungszentrum Karlsruhe, 1991.
[11] M. Dalle Donne, European DEMO BOT Solid Breeder Blanket, KfK 5429, KFK 1994.
[12] P. Pereslavtsev, U. Fischer, F. Hernández, L. Lu, Neutronic analyses for the optimization of the advanced HCPB breeder blanket design for DEMO, this conference.
[13] G. Zhou, F. Hernandez, L.V. Boccaccini, H. Chen, M.Y. Ye, Preliminary steady state and transient thermal analysis of the new HCPB blanket for the EU DEMO reactor, Int. J. Hydrogen Energy 41 (17) (2016) 7047–7052.
[14] G. Zhou, F. Hernandez, L.V. Boccaccini, H. Chen, M.Y. Ye, Preliminary structural analysis of the new HCPB blanket for the EU DEMO reactor, Int. J. Hydrogen Energy 41 (17) (2016) 7053–7058.
[15] B. van der Schaaf, F. Tavassoli, C. Fazio, et al., The development of EUROFER reduced activation steel, Fusion Eng. Des. 69 (2003) 197–203.
[16] AFCEN, RCC-MRx, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2012.
[17] J. Reimann, R. Knitter, G. Piazza, New compilation of Material Data Base and Material Assessment Report, EFDA Reference TW5-TTBB-006 Deliverable Nr. 2.