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WCLL breeding blanket design and integration for DEMO 2015: status and perspectives

A. Del Nevo[a*], P. Agostini[a], P. Arena[b], G. Bongiovì[b], G. Caruso[c], G. Di Gironimo[d], P. A. Di Maio[b], M. Eboli[e], R. Giammusso[a], F. Giannetti[c], A. Giovinazzi[e], E. Martelli[c], G. Mariano[c], F. Moro[f], R. Mozzillo[d], A. Tassone[c], D. Rozzia[e], A. Tarallo[d], M. Tarantino[a], M. Utili[a], R. Villari[f]

[a] *ENEA FSN-ING-PAN C.R. Brasimone, 40032 Camugnano (Bo), Italy*
[b] *University of Palermo, Viale delle Scienze, Edificio 6, 90128 Palermo, Italy*
[c] *DIAEE, Sapienza University of Rome, Corso Vittorio Emanuele II, 244, 00186, Roma, Italy*
[d] *CREATE, University of Naples Federico II, DII, P.le Tecchio 80, 80125, Napoli, Italy*
[e] *DICI, University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy*
[f] *ENEA FSN-FUSTEC-TEN, C.R. Frascati, via E. Fermi 45, 00044 Frascati, Italy*

Water-cooled lithium-lead breeding blanket is considered a candidate option for European DEMO nuclear fusion reactor. ENEA and the Linked Third Parties have proposed and are developing a multi-module blanket segment concept based on DEMO 2015 specifications. The layout of the module is based on horizontal (i.e. radial-toroidal) water cooling tubes in the breeding zone, and on lithium lead flowing in radial-poloidal direction. This design choice is driven by the rationale to have a modular design, where a basic geometry is repeated along the poloidal direction. The modules are connected with a back supporting structure, designed to withstand thermal and mechanical loads due to normal operation and selected postulated accidents. Water and lithium lead manifolds are designed and integrated with a consistent primary heat transport system, based on a reliable pressurized water reactor operating experience, and the lithium lead system. Rationale and features of current status of water-cooled lithium-lead breeding blanket design are discussed and supported by thermo-mechanics, thermo-hydraulics and neutronics analyses. Open issues and areas of research and development needs are finally pointed out.

Keywords: WCLL, Breeding Blanket, DEMO

1. Introductory remarks

The Breeding Blanket (BB) is a major system of a fusion reactor. The features of the blanket system will impact the DEMO (DEMOnstration Power Station) [1] plant design, availability, safety and environmental aspects and cost of electricity. Being the main objective of a fusion reactor the production of electricity, the primary function of the breeding blanket is to interface the plasma, to remove the heat generated in the tokamak plasma and to transfer it to the Primary Heat Transfer System (PHTS), ensuring an efficient power conversion. Moreover, the breeding blanket shall also breed the tritium (T) used in the fusion reaction, thus ensuring the self-sufficiency of the reactor, and shield the Vacuum Vessel (VV) and the superconducting coils. Water-Cooled Lithium-Lead (WCLL) BB is considered a candidate option for the European DEMO nuclear fusion reactor [2]. It relies on EUROFER as structural material, liquid Lithium-Lead (PbLi) 6Li enriched at 90% as breeder, neutron multiplier and tritium carrier, and water as coolant at Pressurised Water Reactor (PWR) conditions. Design activities are pursued to develop and to deliver a feasible and integrated conceptual design of the WCLL BB in the framework of the H2020 EUROfusion Project [3].

An outline of the current status of WCLL BB conceptual design is discussed, providing rationale and features and presenting sample and meaningful thermo-mechanics (TM), thermo-hydraulics (TH) and neutronics analyses. Open issues and areas of research and development (R&D) needs are finally pointed out.

author's email: alessandro.delnevo@enea.it

2. Main design requirements

The reference configuration is DEMO 2015 [4]. It has 18 TF coils and the toroidal segmentation consists of 54 and 36 segments for the outboard and inboard, respectively. The thickness of the blanket varies with the poloidal direction. The operational concept is DEMO 1, which assumes nine pulses with a burn time of 2 hours per day. During the pulse mode, the thermal power calculated with PROCESS code is 2436 MW. The Neutron Wall Load distribution (average 1 MW/m^2) and radial nuclear power densities in materials are calculated by MCNP 5 code[6] [7]. An average first wall (FW) heat flux (HF) of 0.22 MW/m^2 is assumed for the evaluation of the thermal balance and an HF of 0.5 MW/m^2 is used for the design of the equatorial outer module. Irradiation limit of material during operation is assumed as 20 dpa. Tritium breeding ratio (TBR) larger / equal to 1.1 is a requirement. Reference primary system thermodynamic cycle is based on coolant (water) at inlet/outlet temperatures respectively equal to 285 °C and 325 °C, at 15.5 MPa. The design of the cooling system accounts for the maximum temperature limit of 550°C. The cooling system is designed for a nominal pressure of 15.5 MPa, the PbLi pipelines, manifolds and breeding blanket box are verified to withstand a pressure of 15.5 MPa + 10%, as Class IV condition.

3. WCLL breeding blanket system

3.1 Segmentation

The WCLL BB 2015 is based on the Multi-Module-Segment (MMS) concept. This is currently the approach pursued in EUROfusion working package (WP) BB[2]. According with the MMS concept, both inner and outer segments are divided into 7 boxes with straight surfaces, attached to a common back supporting structure (BSS). The breeding blanket boxes are constituted by the breeder zone (BZ) and the First Wall (FW). The segmentation has been defined with a three steps method: 1) definition of input data and assumptions; 2) modelling design solutions; 3) evaluation of the solutions and selection of the reference. Therefore, the reference geometrical configuration of the BB segmentation is selected through six figures of merit (FOM), correlating in a qualitative way the geometrical features with physical and/or technological quantities[8]. Current geometrical layout based on the MMS concept implies that the complete drainage of the PbLi and removal of He in the BZ are not possible. Thus, studies are needed to solve or minimize issues.

3.2 First Wall

The FW is in the front part of the WCLL BB. It is an integrated part of BB module and it is cooled with an independent water system at the reference coolant thermodynamic conditions. The FW is an U-shape plate bended (150 mm) in radial direction (Fig. 1). The thickness is of 25 mm, plus 2 mm of protective tungsten layer. The water flows in counter current direction in square channels with dimension of 7x7 mm and pitch of 13,5 mm. The channels are 3 mm inside the steel along the radial-toroidal direction. The FW cooling geometry is the result of an optimization procedure, accounting for steady state thermal and TM analyses, done with a 3D FEM models [9]. The results demonstrate that it is possible to withstand an heat flux of 2.0 MW/m^2 reducing the thickness of material from the FW steel edge to the cooling channels boundary up to 1mm.

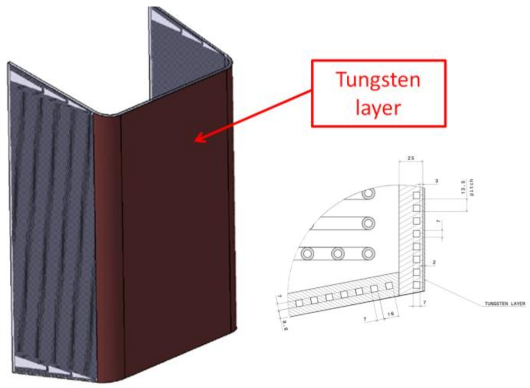


Fig. 1. Layout of U-shaped FW and geometry

3.3 Module box

Each module box has a "quasi" modular geometry. Basically, an "elementary cell" is repeated along the poloidal direction up to the lower and upper caps, which represent a discontinuity. The equatorial outer central module (EOCM) is considered as the reference for the geometrical description and the analyses (Fig. 2). The EOCM is divided in 16 "elementary cells" in poloidal direction and 6 channels in toroidal direction. Each "elementary cell" has a baffle plate at the mid-plane: the PbLi enters in the bottom, flows in radial-poloidal direction and exits from the top. The BZ water cooling tubes are placed along a toroidal-radial direction (Fig. 2). They are double walled (DWT) and have the internal and external diameters equal to 8 mm and 13,5 mm, respectively. The layout and the number (21) of the tubes is repeated in each elementary cell. Preliminary analyses were carried out to demonstrate the feasibility of the design choices, to evaluate the performances, and to derive indications and feedbacks, triggering enhancements, modifications and the plan for 2016 activities.

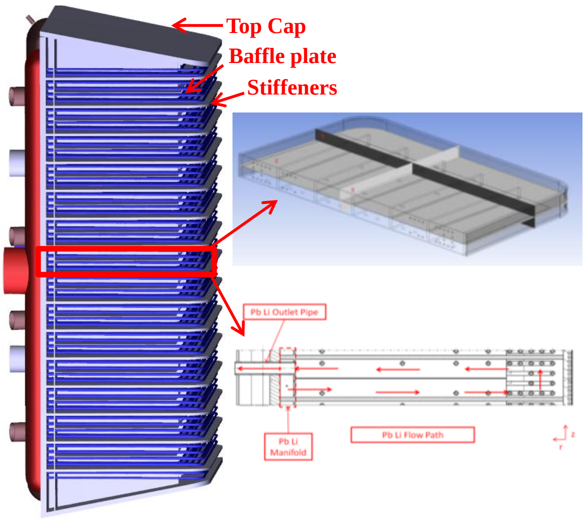
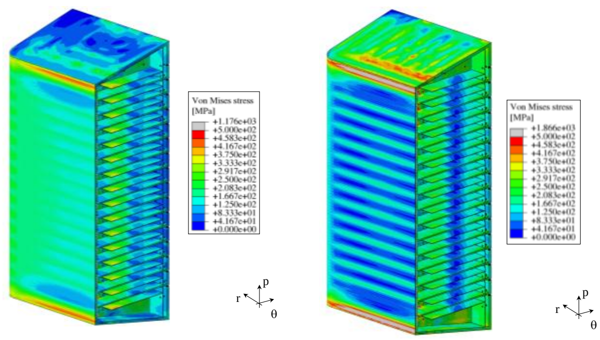


Fig. 2. WCLL BB 2015 v0.2 equatorial outboard central module

Thermal analyses by 3D FEM code provided indications of the influence of the number of tubes in the breeding zone on the temperature field of the module box [10]. Results with the full model of the EOCM box demonstrate the design is able to fulfill the temperature limit of 550°C (i.e. max temperatures in breeder and EUROFER materials are 542.7 °C and 538.0 °C, respectively). The TM analyses (Fig. 3) have addressed both normal operation (NO) and over-pressurization (OP) scenarios evaluating the requirements prescribed by safety codes. Results shows that critical areas, located within the stiffening plates (SP) and near the Caps, where the criterion against plastic flow localization is not fulfilled [11].

A CFD analysis[12] of the breeder unit was carried out, focusing on the "elemetary cell". The model reproduces a central toroidal-radial slice of the module and includes six parallel breeder cells in the toroidal direction. The mesh accounts for solid structures, (i.e. SP, baffle plate, DWT and FW) fluids (i.e. water coolant and PbLi breeder). Results confirm that the FW and the preliminary layout of the DWT is effective in cooling the BZ. Moreover, the temperature field (Fig. 4) has a maximum calculated temperature of about 410 °C, which is more than 100 °C lower than the maximum temperature calculated in the FEM analysis (and with the CFD neglecting the PBLi buoyancy forces[12]). Therefore, the CFD analyses of the cells at top and bottom zones would be useful to calculate a more realistic temperature field that would reduce the conservativeness of the FEM analyses. It was observed that the unidirectional flow in the BZ implies higher temperatures in the front part of the module (where larger volumetric power is deposited) outlet side. Because of the buoyancy forces, the PbLi tends to move faster creating a depression from adjacent parallel breeder cells, which may impact the optimal functioning of the outlet manifold. In view of this, a simplification of the PbLi manifold systems and the improvement of the BZ cooling system in order to reduce the thermal gradients in radial direction have to be studied.



(a) NO Scenario *(b) OP Scenario*

Fig. 3. TM results: Von Mises Stress Field

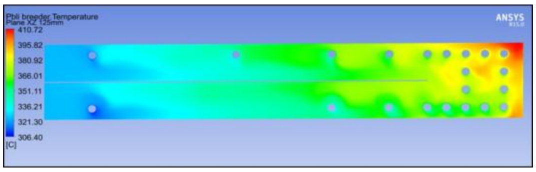


Fig. 4. Breeder temperature field by CFD code

Magneto-hydro-dynamic (MHD) effects in the breeding blanket impact the flow field of the liquid metal, thus perturbing also the temperatures. The design approach relies in reducing as far as possible the PbLi velocities in the BZ as well as in the manifolds and pipes. The PbLi velocity limits by design are: 0.25mm/s in the BZ, 5mm/s at manifolds orifices and 50mm/s in pipelines. Preliminary MHD analyses are pursued to analyze the BZ of the “elementary cell”[13]. The results confirm that insulating flow channel inserts (FCI) are not required to decouple the fluid and the duct walls. Calculated pressure drop in the BZ flow path is 178 Pa. A study with more realistic assumptions would be conducted, extending the analysis to the manifold region.

3-D neutronics calculations were performed using MCNP5 and JEFF 3.2 nuclear data[7]. Resulting maximum NWL is 1.33 MW/m^2, calculated in the outboard equatorial module. The global tritium breeding ration (TBR) is 1.127. The highest contribution is given by the EOM (i.e. TBR=0.142) and the contributions of outboard and inboard blankets are 71% and 29% respectively. The overall nuclear power deposited on the BZ of DEMO 2015 is 1805 MW. The EOM is the largest contributor with 4.5MW. The shielding performance of the system BB/manifold/BSS is sufficient to ensure the safe operation of the vacuum vessel (VV), i.e. damage is lower than 0.03 dpa/FPY (Fig. 5), and to reduce the nuclear heating deposited in the toroidal field coils (TFC) to acceptable level (<7x10-6 W/cm3).

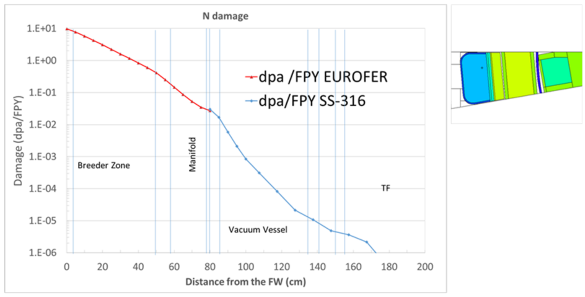


Fig. 5. Damage in EUROFER & SS316 (dpa /FPY) radial profile along inboard-midplane

3.4 Manifolds system

PbLi and water manifolds systems are in charge to connect the modules with the main pipelines. The PbLi inlet manifold is internal to the module box, between the Back Plate (BP) and the breeding zone. It ensures the PbLi distribution in the elementary cells through 6 orifices on the toroidal-poloidal plate. The system has been designed with the support of CFD [14]. MHD effects were neglected. The PbLi enters from 8 pipes exits through 32 pipes. Two manifolds (inlet and outlet) are placed on the back wall of the module box. They are connected with the BZ cooling system and with the main pipelines. Both manifolds are 1750mm high and 326mm width. The inlet and outlet pipes are placed in centre and are DN 100. The FW cooling zone is fed by two manifolds (inlet and outlet). These are bended pipes DN40 and are joined to the FW cooling channels through tubes.

3.5 Back supporting structure

The BSS is a poloidal-toroidal plate having maximum radial thickness of 200 mm attached to the modules by means of 4 ribs (Fig. 5). It share with the main pipelines and the manifolds the space on the backside of the modules.

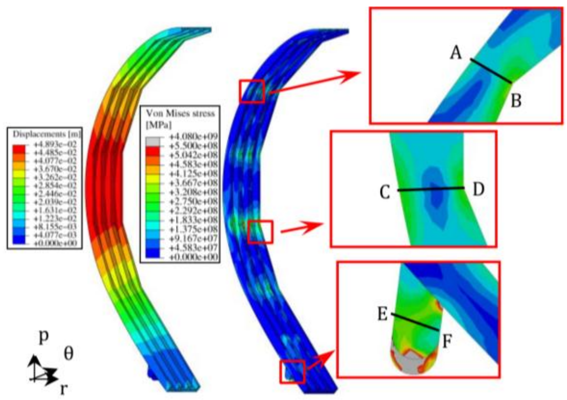


Fig. 6. TM analyses of BSS against EM loads.

The structure has been analyzed [15] considering the gravity, the thermal and the preliminary EM loads. Results have shown that EM loads make the BSS rotate clockwise in the poloidal-toroidal plane. Safety verifications, according to SDC-IC codes, are totally satisfied as far as each single load is concerned and also when the total load is taken into account, even if with a lower margin.

3.5 Integration with PHTS and PbLi system

Six main pipes feed and collect the fluids of the module boxes. They are successfully integrated in the DEMO 2015 CAD without interferences. FW and BZ cooling systems are separated, thus two pipes enters from the lower port to fed the modules and other two pipes exit from the upper port to deliver the hot coolant to the PHTS. Dimensions of the pipelines are calculated according with the velocity limit of 7 m/s. The overall primary system coolant mass flow rate is 9035 kg/s. PbLi pipes (inlet and outlet) are routed from the upper port. The flow area of these pipes is the results of the total mass flow rate equal to 956.30 kg/s, calculated assuming 10 recirculation per day and the velocity limit considered in the main pipelines (50mm/s).

4. Conclusive remarks and future activities

A preliminary conceptual design of the WCLL BB based on DEMO 2015 specifications has been developed and analyzed. It takes advantage from R&D activities done in '90 and '00, but it is based on a different rationale and, therefore, proposes different solutions in terms of layout and integration. This required the preparation of a new CAD of the segment as well as a detailed model of the EOCM. 3D FEM, CFD, and neutronic models have been developed to evaluate the design solutions and to provide feedbacks on the performances. Results demonstrate that the new layout (e.g. horizontal BZ coolant scheme, PbLi flow path in the module, modularity in poloidal direction, etc.) is promising. Main outcomes are:

- The integrated FW has large margins of operation, being able to withstand an HF of 1.4MW/m^2.
- The EOCM has the capability to fulfill the requirements prescribed by safety codes in NO and OP conditions, with few exceptions. The criticalities might be solved either with design modifications, including the investigation of the SSM approach, or considering a more realistic temperature field (max. temperature used in the analysis is 540 °C).
- The BSS has the capability to successfully withstand, the preliminary EM loads available for the design.
- Thermo-hydraulic analyses provided the temperature field of the "elementary cells" in the EOCM box, demonstrating that the maximum temperature is about 410 °C.
- Sufficient breeding (TBR=1.127) and shielding performances are demonstrated with the neutronic calculations

Issues are identified and countermeasures are under evaluation and analyses. The most relevant are:

- MMS approach has drawbacks: it does not allow the complete PbLi drainage, it might make difficult the He removal from modules in some zones, it has discontinuities between modules which may be the cause of hot spot temperatures and, thus, of reduced material resistance, and of neutrons streamline producing localized higher damage to VV materials and TFC;
- proposed design of BSS needs active cooling in inboard segment, which is affected by a power deposition about one order of magnitude larger than the outboard;
- manifolds and feeding/discharging pipes scheme shall be improved and simplified.

Acknowledgments

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