WPBOP-CPR(17) 17704

E Martelli et al.

# Study of EU DEMO WCLL Breeding Blanket and Primary Heat Transfer System Integration

Preprint of Paper to be submitted for publication in Proceeding of 13th International Symposium on Fusion Nuclear Technology (ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# Study of WCLL Breeding Blanket and Primary Heat Transfer System Integration

Emanuela Martelli[a]*, Fabio Giannetti[a], Gianfranco Caruso[a], Andrea Tarallo[b], Massimiliano Polidori[c] Luciana Barucca[d], Alessandro Del Nevo[e]

*[a]DIAEE, Sapienza University of Rome, Corso Vittorio Emanuele II, 244, 00186 Roma, Italy*
*[b]CREATE, University of Naples Federico II, DII, P.le Tecchio 80, 80125, Napoli, Italy*
*[c]ENEA CR Bologna, Via Martiri di Monte Sole 4, 40129, Bologna, Italy*
*[d]Ansaldo Nucleare, Corso Perrone 25, 16100 Genova, Italy*
*[e]ENEA FSN-ING-PAN, ENEA CR Brasimone, Località Brasimone, 40032 Camugnano (BO), Italy*

The Water-Cooled Lithium Lead breeding blanket is a candidate option for the realization of European DEMO power plant. One of the main function of the breeding blanket is to recover the thermal power from the first wall and the breeding zone and to drive it to the Primary Heat Transfer System. Moreover, due to the DEMO pulsed operation, an Energy Storage System is foreseen in order to ensure thermal energy availability and reduce cycling loading during dwell time. The blanket design must interface with the PHTS and ESS in an integrate solution with the aim of delivering feasible power plant, with high conversion efficiency.

This paper presents the recently updated modeling of WCLL breeding blanket conceptual design and its integration with PHTS. A thermal-hydraulic model of main components of WCLL PHTS is developed, using RELAP5 system code, to support the design and sizing. A RELAP5/Mod3.3 extended version has been set-up to implement PbLi and molten salt (HITEC) fluid proprieties, as well as the relevant heat transfer correlations. The results of preliminary applications provide a comprehensive set of thermo-hydraulic parameters (i.e. coolant inventory, pressure drops), relevant for the assessment of the design integration.

Keywords: DEMO, PHTS, WCLL, breeding blanket

## 1. Introduction

In a fusion power plant, the Breeding Blanket (BB) is a key component since it has to withstand severe conditions while ensuring tritium self-sufficiency, adequate neutron shielding, and the removal of the heat generated in the tokamak plasma and transferring it to the Primary Heat Transfer System (PHTS) and then to the Power Conversion System (PCS), assuring an efficient power conversion. The features of the blanket system will impact the DEMO (DEMOnstration Power Plant) [1] design, availability, safety and environmental aspects and cost of electricity. The Water-Cooled Lithium-Lead (WCLL) blanket concept [2] is one of the candidate option for the EU DEMO, which relies on Eurofer as structural material, liquid eutectic Lithium-Lead (PbLi) as breeder, neutron multiplier and tritium carrier, and water at typical Pressurized Water Reactor (PWR) conditions as coolant.

R&D activities are pursued, by ENEA and its linked third parties, to develop the new design of WCLL blanket concept and the preliminary design of the PHTS, connected with the Energy Storage System (ESS) to deal with the DEMO pulsed operation [1] , and of the PCS.

An outline of the recently updated design of WCLL blanket concept [3], and its PHTS is discussed. Moreover, the Balance of Plant (BoP) configuration, including the Intermediate Heat Transfer System equipped by the ESS and the PCS, is illustrated and the preliminary sizing of the main components is discussed.

## 2. WCLL design description

Starting from the main outcomes obtained from WCLL 2015 design and analyses [4][5][6], an advanced and optimized design has been developed in 2016, and analyses have been carried out to ensure the feasibility and to demonstrate its suitability, in particular, in terms of tritium production and shielding performances [7], thermo-mechanical performances both in normal and over pressurization conditions [8], and BZ and FW coolant efficiency [9].

The new WCLL blanket concept is based on the Single Module Segment (SMS) approach, maintaining the same internal structure, FW configuration and BZ coolant system layout of the previous design [2]. The manifolds region and Back Supporting Structures (BSS) has been adapted to the new configuration. The main geometry of the segments is simplified to face, as much as possible, manufacturing and remote handling issues.

The WCLL blanket segment, shown in Fig. 1, consists of an external box, composed by the First Wall (FW), directly exposed to the plasma and covered with a tungsten layer, the Side Walls (SWs), the bottom and top caps and the Back Plate (BP). The blanket segment is reinforced with a set of stiffeners: radial-toroidal stiffeners divide the segment in poloidal direction in slices, hereinafter called "breeding units", illustrated in detail in Fig. 1. Five radial-poloidal stiffeners divide the breeding units in 6 toroidal channels, where PbLi is distributed. A baffle plate, placed at half between two

*author's email: emanuela.martelli@uniroma1.it*

horizontal stiffeners, ensures the circulation of PbLi in radial-toroidal direction inside the breeding zone. The breeding units are filled with PbLi alloy and cooled by means of water, at PWR conditions, flowing in radial-toroidal Double Wall Tubes (DWTs) crossing vertical stiffeners. The FW and SWs are cooled by means of square channels, where water flows in counter-current direction at PWR conditions.

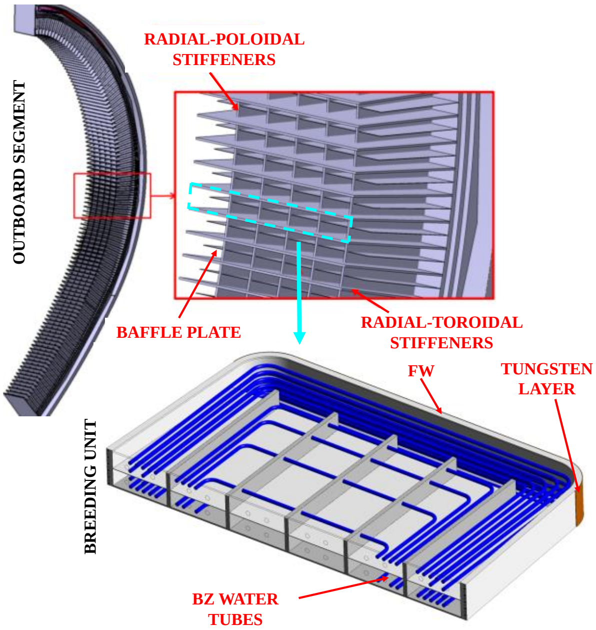


Fig. 1. WCLL BB 2016 design: outboard segment and breeding unit at equatorial plane.

The PbLi inlet and outlet manifolds are placed inside the segment structure, delimited by walls of 30 mm thick. The back walls of the segments are properly cut in the back area to save space for the BZ and FW cooling water manifolds. The BSS of the segments (inboard and outboard) have T-shape and are joined to the sidewalls and the back walls of the modules. The PbLi and water manifolds are linked with the in-vessel piping system, which consists of the feeding and collecting pipes of the two inboard and three outboard segments, as shown in Fig. 2. The FW and BZ water coolant pipes (inlet and outlet) are routed through the upper port of DEMO Vacuum Vessel (VV). The PbLi feeding pipes enters from the lower port and the collecting pipes exit from the upper port of the VV.

## 3. BZ and FW PHTS

### 3.1 PHTS configuration

The main function of the PHTS is to provide cooling water to the first wall and blanket systems and to transfer the thermal power to the PCS for its conversion into electricity.

The WCLL PHTS is constituted by two independent PHTSs: the BZ PHTS and the FW PHTS. During the pulse mode, the BZ primary system deliver the power (1577 $MW_{th}$) to the steam turbine by means of Once Through Steam Generators (OTSG). The FW primary system transfers the heat to the Energy Storage System (ESS) through two Intermediate Heat Exchangers (IHXs), using HITEC molten salt as fluid. The total power transferred from the FW to PHTS, and then to the ESS, is 467.6 $MW_{th}$. During the 30 minutes dwell time, the ESS transfers the heat, accumulated during the pulse mode, to four Steam Generators.

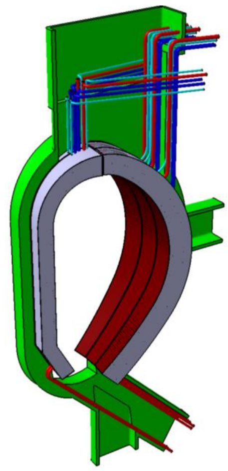

Fig. 2 DEMO WCLL BB sector integration with PbLi and coolant systems.

The cooling water is distributed and collected by means of four ring headers, hosted in a proper passage 7×7 m that runs all around the tokamak. The main pipeline diameters outside the vacuum vessel are calculated accounting for coolant velocity of 15 m/s, with a maximum limit of 20 m/s.

The primary coolant is pressurized by means of a pressurizer connected to the hot leg upstream of the steam generator. The type and location of this pressurizer were selected based on space considerations, pressure controllability and safety criteria.

Starting from the preliminary sizing, the FW and BZ PHTS CAD models have been developed and integrated in DEMO baseline CAD. The main pipes dimensions have been defined on the base of European standard regulation [11] and T/H design parameters. The two cooling loops are symmetrical with respect the radial-poloidal of the tokamak, located at a distance of 71 m from each other. The main PHTS components, and their position with respect the tokamak building, are shown in Fig. 3.

### 3.2 BZ PHTS OTSG preliminary sizing

The BZ PHTS transfers energy from the BZ of the BB to the PCS during the pulse mode (2 h, [1]) for a total power of 1.577 $GW_{th}$. Two OTSGs are heated by the primary water coolant coming from the breeding zone of the breeding blanket. The primary coolant inlet and outlet temperature are 295 °C and 328 °C, respectively, at 15.5 MPa. The total water mass flow rate is 8146.2 kg/s, calculated using the RELAP5 water properties [10].

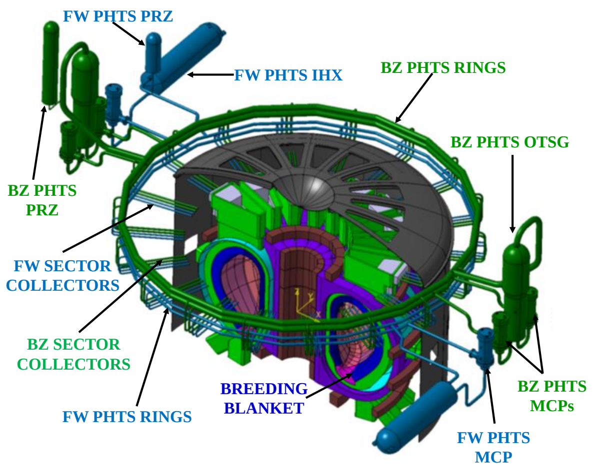


Fig. 3. WCLL PHTS front and top view.

In DEMO, the thermal power removed by one OTSG is 788.6 $MW_{th}$, the corresponding mass flow rate, of the primary system, is 4073.1 kg/s. The OTSG secondary side (water) pressure is assumed 6.41 MPa and the feedwater coolant inlet temperature is 238 °C. The objective is to produce super-heated steam at 299 °C. Therefore, the feedwater flow is fixed at 430.1 kg/s.

A RELAP5/Mod3.3 model of the OTSG is developed to perform the components sizing. The model includes the primary and secondary side. The tubes side is modeled with an equivalent PIPE component. The heat exchange between primary and secondary side is modeled with heat structures. The boundary conditions are set up using time depended volumes (TMDPVOL) and junction (TMPDJUN) components.

Scoping sensitivity analyses are performed to evaluate SG performances, changing the number of tubes, the p/D and the lattice (i.e. square and triangular lattices are considered). Based on the selected configurations further analyses are performed reducing the active tubes length from 15.87 to 12.99 m and tubes fouling factor from 1 to 0.5. The main thermal and geometrical design parameters of the selected SG configuration (clean condition) are reported in Table 2.

Table 2. BZ PHTS steam generator parameters.

| # | Parameter | Units | Value |
|---|---|---|---|
| 1 | BZ Power | $MW_{th}$ | 788.6 |
| 2 | Primary side water $T_{in}$ | °C | 328 |
| 3 | Primary side water $T_{out}$ | °C | 295 |
| 4 | Secondary side water $T_{in}$ | °C | 238 |
| 5 | Secondary side water $T_{out}$ | °C | 299 |
| 6 | No. of tubes | -- | 7569 |
| 7 | Tube $D_o$ | mm | 15.88 |
| 8 | Thickness | mm | 0.864 |
| 9 | Length of tubes | m | 12.987 |
| 10 | Lattice | -- | square |
| 11 | p/D | -- | 1.28 |
| 12 | Heat transfer area | $m^2$ | 4369 |
| 13 | V water tubes | $m^3$ | 20 |
| 14 | $D_{ext}$ vessel | m | 2.9 |

### 3.2FW PHTS IHX preliminary sizing

During the power pulse (2h) the FW system delivers the power (467.6 $MW_{th}$) to the PHTS through two water/HITEC heat exchangers, and the corresponding energy ($3.37\times10^6$ MJ) is accumulated in the ESS. The overall power transferred through each intermediate heat exchanger is 233.8 $MW_{th}$.

The reference configuration assumes the temperature cycle 295-328 °C for the primary water coolant system and 280-320 °C for the intermediate molten salt coolant system. The horizontal IHX is typical liquid-liquid heat exchanger tube and shell with two passes. Pressurized water coolant flows inside U-shape tubes, in counter current direction with respect the molten salt, which flows shell side with a cross flow path. The main parameters of the reference IHX are reported in Table 3.

In order to develop a dynamic model of the systems, an extended version of RELAP5/Mod3.3 code has been set-up with the implementation of the PbLi and HITEC fluid proprieties, as well as some relevant heat transfer correlations: i.e. Sieder-Tate, Zukauskas, Seban-Shimazaki and Ushakov.

A RELAP5/Mod3.3 model of the reference IHX has been developed to verify the preliminary sizing. The nodalization includes the shell and tubes sides of IHX. The tube side is modeled with an equivalent PIPE component. Boundary conditions are set-up with time dependent volume (TMDPVOL) and junction (TMPDJUN) components. The energy exchange between shell and tube side is modeled with RELAP5/Mod3.3 heat structures using Sieder-Tate heat transfer correlation.

Table 3. FW PHTS intermediate heat exchanger parameters.

| # | Parameter | Units | Value |
|---|---|---|---|
| 1 | FW Power | $MW_{th}$ | 233.8 |
| 2 | Primary side water $T_{in}$ | °C | 328 |
| 3 | Primary side water $T_{out}$ | °C | 295 |
| 4 | Secondary side HITEC $T_{in}$ | °C | 280 |
| 5 | Secondary side HITEC $T_{out}$ | °C | 320 |
| 6 | No. of tubes | -- | 5211 |
| 7 | Tube $D_o$ | mm | 15.88 |
| 8 | Thickness | mm | 0.864 |
| 9 | Length of tubes | m | 28.9 |
| 10 | Lattice | -- | Square |
| 11 | p/D | -- | 1.28 |
| 12 | Heat transfer area | $m^2$ | 6701 |
| 13 | V water tubes | $m^3$ | 23.7 |
| 14 | $D_{ext}$ vessel | m | 3.5 |

### 3.2 PHTS pumps

Considering both the BZ and FW PHTS, six Main Coolant Pumps (MCPs) are foreseen in the current preliminary PHTS design of DEMO: four MCPs, two per loop, in the cold legs of the BZ PHTS, two MCPs in the FW PHTS. According with the main design data of the PHTS, the calculated pressure drops in the systems are 0.88 MPa and 0.84 MPa respectively in the BZ and FW PHTSs. Considering a postulated efficiency of 78%, the power consumed by the pumps is of 3.081 MW and 1.764 MW, respectively for those installed in the BZ PHTS and in the FW PHTS.

## 4. ESS configuration

The pipelines connecting the IHX secondary sides to the hot and cold molten salt tanks (e.g. the ESS), the tanks themselves, the steam generator and the pumps constitute the Intermediate Heat Transfer System (IHTS). Considering the operation of DEMO, as well as the design requirement of continuous and near constant electrical power delivered to the grid in both pulse and dwell, the thermal power to be accumulated in the ESS is known and then the dimensions of hot and cold storage tanks of the ESS system are identified.

According with the current specifications, during the pulse (2 h) the mass flow of HITEC from cold to hot tanks is 6000 kg/s. During the dwell time, the mass flow of molten salt from hot to cold tanks is 24000 kg/s. The ESS contains a mass of molten salt equal to 43200 tons at the beginning of dwell, thus 23365 $m^3$ are needed to store this amount of molten salt.

During dwell time (0.5 h, [1]), the hot molten salt is delivered to four Helical Steam Generators (HCSGs). The total thermal power available during dwell time is 1870 $MW_{th}$. The hot molten salt flows in shell side and transfers energy to water flowing in the tubes side. The molten salt temperature cycle is 280-320 °C. The feedwater enters in the HCSG with an inlet temperature of 238 °C and exits with an outlet temperature of 299 °C at 6.41 MPa. Considering one HCSG the mass flow rate of HITEC is 7757.1 kg/s, and the feedwater mass flow rate, calculated with the enthalpy balance, is 255 kg/s.

The heat transfer between hot molten salt and PCS water is evaluated considering the conduction mechanism through the tubes thickness as well as the convection of the liquid water / steam and molten salt streams at the HCSG outer and inner tubes side. The molten salt Heat Transfer Coefficient (HTC) is calculated using the Zukauskas correlation. The water side convective heat transfer is evaluated using RELAP5/Mod3.3 implemented correlation. The HITEC salt velocity is selected accordingly with the geometry in a way that it is in the range between 1 and 1.5 m/s, which is a good compromise between the HTC performances and the pressure drop values and the potential for corrosion issues.

The main geometrical parameters of the selected HCSG of the ESS are reported in Table 4.

Table 4. ESS helical steam generator parameters.

| # | Parameter | Units | Value |
|---|---|---|---|
| 1 | FW Power | $MW_{th}$ | 467.5 |
| 2 | Primary side HITEC $T_{in}$ | °C | 320 |
| 3 | Primary side HITEC $T_{out}$ | °C | 280 |
| 4 | Secondary side water $T_{in}$ | °C | 238 |
| 5 | Secondary side water $T_{out}$ | °C | 299 |
| 6 | No. of tubes | -- | 1446 |
| 7 | Tube $D_o$ | mm | 16.0 |
| 8 | Thickness | mm | 0.8 |
| 9 | Length of tubes | m | 68.0 |
| 10 | Heat transfer area | $m^2$ | 4449 |
| 11 | V water tubes | $m^3$ | 16.0 |
| 12 | V HITEC | $m^3$ | 37.18 |
| 13 | $D_{ext}$ vessel | m | 3.0 |

## 5. PCS configuration

The thermodynamic cycle hypothesized is derived from the PWR cycles with OTSGs and it is shown in Fig. 4. The steam turbine is moved by superheated steam (299 °C at 6.4 MPa) generated into the two OTSGs during the pulse mode and into the four HCSGs during the dwell mode. The HCSG is part of IHTS and it produces steam mainly during the dwell using the energy from the FW, stored in the hot tank during the pulse phase as sensible heat of the molten salt.

Thanks to this double steam sources, that alternatively transfer the BB and FW generated thermal power to PCS, the steam turbine works in a continuous mode with a limited variation of the steam load during the pulse and dwell, being the system able to cope with the power “lost” in dwell caused by the pulsation of the low temperature heat sources (e.g DIV-PFU, DIV-Cassettes, VV). Consequently, no significant impact on turbine lifetime consumption is expected. Moreover, it is envisaged a reduction of the present large size of molten salt tank, reducing the dwell time (e.g.10 minutes), deriving from the DEMO recent development [12], and adapting the ESS operating system to the new conditions, with an increment of thermal power to the turbine due to the reduction of power needed into the heat storage. This could be possible, thanks to HCSGs work at reduced power during the pulse. An alternative solution could be the elimination of the tank in case of viability of the BOP option with a direct coupling of PHTS to PCS [13].

For an efficiency increment, feedwater preheaters train includes divertor and vacuum vessel Heat Exchangers belonging to correspondent PHTS.

A Gatecycle™ analysis was carried out, mainly focused on the efficiency estimation. The preliminary result is about 37.1% average gross electrical efficiency, considering both pulse and dwell phases. The electrical efficiency is reduced to around 34%, with the consideration of the electrical load (limited to PHTSs, ESS and PCS components for this analysis). An optimized analysis performed with Gatecycle™ is reported in [14].

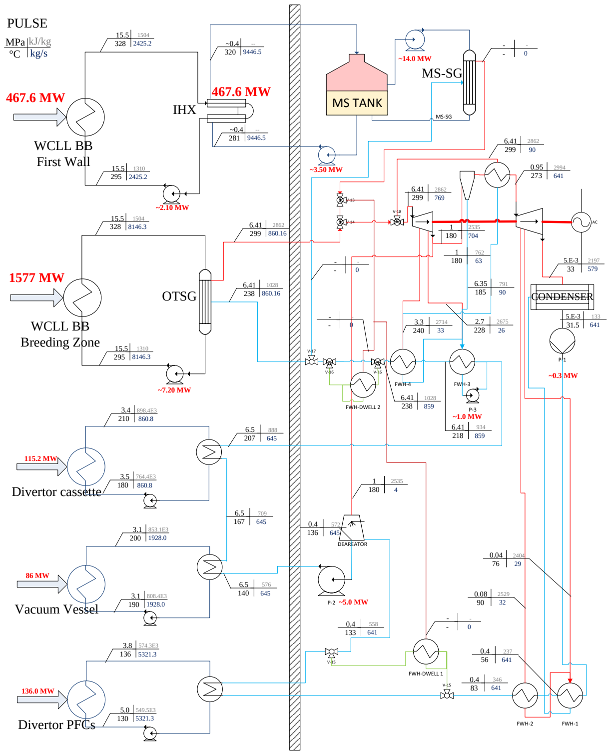


Fig. 4. Preliminary cycle configuration during pulse mode.

## 5. Conclusions

Starting from the design constraints and conditions of DEMO, and the WCLL blanket design features, ENEA and its linked third parties developed, in 2016, the preliminary design of the PHTS, connected with the Energy Storage System (ESS) to deal with the DEMO pulsed operation, and of the PCS. Main outcomes of the R&D activity are:

- The PHTS of the DEMO WCLL BB has been defined. The selected configuration relies on two separate PHTSs connected with the breeding zone (BZ PHTS) manifolds and the first wall (FW PHTS) manifolds, respectively. The PHTSs has been sized, and the data have been used to develop and integrate CAD into the DEMO baseline.
- SGs (e.g. OTSG and HCSG) and IHX have been preliminary sized and rely on existing technologies.
- A review of molten salt properties was carried out, and a RELAP5/Mod3.3 extended version has been set-up with the implementation of the PbLi and HITEC fluid proprieties, as well as the relevant heat transfer correlations: i.e. Sieder-Tate, Zukauskas, Seban-Shimazaki and Ushakov. Thanks to this activity, it will be possible to develop a dynamic model of the systems using one of the most widely used system code for PWR NPP simulation.
- The PFD of the PHTS, ESS and PCS has been developed and preliminary Gatecycle™ analyses have been carried out.
- Considering the design requirement of continuous and near constant electrical power delivered to the grid in pulse and dwell, the hot and cold storage tanks of the ESS system have imposed dimensions. Using HITEC fluid, the volume of one tank is about 23500 $m^3$. Improvements can be achieved reducing the dwell time (e.g. around 10 minutes) and modifying, coherently with the new conditions, the ESS operating system.

## Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

## References

[1] G. Federici et al., Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fusion Eng. Des. 109–111 (2016) 1464–1474

[2] E. Martelli et al., Advancements in DEMO WCLL breeding blanket design and integration. Int. J. Energy Res. (2017), doi: 10.1002/er.3750.

[3] A. Tassone et al., Recent progress in the WCLL breeding blanket design for the DEMO fusion reactor, IEEE Transactions on Plasma Science, July 2017 (Unpublished results).

[4] A. Del Nevo et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fusion Engineering and Design, 2017, http://dx.doi.org/10.1016/j.fusengdes.2017.03.020.

[5] R. Mozzillo et al., Rationale and method for design of DEMO WCLL breeding blanket poloidal segmentation, Fusion Engineering and Design, 2017, http://dx.doi.org/10.1016/j.fusengdes.2017.01.039.

[6] E. Martelli et al., CFD analysis of WCLL BB PbLi manifold, Fusion Engineering and Design, 2017, http://dx.doi.org/10.1016/j.fusengdes.2017.04.108.

[7] F. Moro et al., Neutronic analyses in support of the WCLL DEMO design development,( this conference).

[8] P.A. Di Maio et al., On the thermo-mechanical behaviour of DEMO water-cooled lithium lead equatorial outboard blanket module, Fusion Engineering and Design, 2017, http://dx.doi.org/10.1016/j.fusengdes.2017.05.051.

[9] E. Martelli et al., Thermo-hydraulic analysis of EU DEMO WCLL breeding blanket, Fusion Engineering and Design (Unpublished results).

[10] ISL Inc, RELAP5/MOD3.3 Code Manual Volume I: Code Structure, System Models, and Solution Methods, Nuclear Safety Analysis Division, July 2003.

[11] European Standard EN10220, CEN, December 2002.

[12] G. Federici et al., DEMO Design Activity in Europe: Progress and Updates, this conference.

[13] L. Barucca et al., Status of EU DEMO Heat Transport and Power Conversion Systems, this conference.

[14] L. Malinowski et al., Design and analysis of a new configuration of secondary circuit of the DEMO fusion power plant using GateCycle, this conference.