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Industry Supported Improved Design of DEMO BoP for HCPB BB Concept with Energy Storage System

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The DEMO BoP configuration studied in this work consists of the Primary Heat Transfer System, the Intermediate Heat Transfer System, using HITEC salt as coolant, equipped with a thermal Energy Storage System, and the Power Conversion System. This configuration is capable of producing electricity continuously through the pulse time (2 hours), as well as dwell time (10 min) of the plant operation. The DEMO BoP development process was supported by industrial partners: Siemens Power and Gas Division and Kraftanlagen Heidelberg. The efficiency of the proposed Rankine cycle of the PCS is obtained to be not less than 39%. While elaborating the improved DEMO BoP design, KIT developed a plant model using the industrial code EBSILON®.

Keywords: DEMO, Balance of Plant, Energy Storage System, Helium Cooled Breeding Blanket, pulsed operation

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1. Introduction

One of the Breeding Blanket (BB) concepts for a EU Demonstration Fusion Reactor (DEMO) [1] is the Helium Cooled Pebble Bed (HCPB) BB [2, 3], which is based on the use of pebbles of lithiated ternary compounds and Be or beryllides as tritium breeder and neutron multiplier materials, respectively, EUROFER97 as structural steel and He as BB coolant.

This paper presents an improved HCPB BB DEMO (18 sectors design) plant configuration (in comparison with 2016 design [4]) with IHTS/ESS, including conceptual designs of PHTS, IHTS/ESS and PCS [5]. The paper also presents key components of the PCS, including sizing and preliminary cost estimates. The industrial components for IHTS/ESS and PHTS are still to be specified. Currently, the foreseen IHTS/ESS and PHTS component designs are based primarily on the design calculations performed by WPBoP partners.

It is worth to mention, that no show stoppers were identified from the industrial side for the current DEMO BoP design.

Selection of the real equipment, final required space and costs evaluation are foreseen for the next two years. The final design of DEMO BoP might still be different, depending on the further research and development within the EUROfusion Project.

The step-wise thermal power production profile of DEMO (pulse time of 2 hours and dwell time of 10 min) has a strong influence on DEMO BoP components. All systems and components in the PHTS are subjected to unavoidable power cycles; however, efforts are put in the design of the BoP to avoid or at least to minimize power cycle effects on all the BoP components.

The main idea to solve the power cycles was the introduction of the IHTS with HITEC salt (7% $NaNO_3$ + 53% KNO_3 + 40% $NaNO_2$) [6] as heat transfer fluid between the BB PHTS and the PCS, where HITEC salt can store thermal energy during pulse operation and release it to PCS during dwell time period. Moreover, a thermal ESS would ensure flexibility to DEMO while supplying electricity to grid or for in-house needs.

The work described in this paper has been performed in the frame of the European Fusion Programme (EUROfusion), Power Plant Physics and Technology (PPPT) section, Balance of Plant (BoP) work package for EU DEMO Fusion Power Plant (FPP).

2. DEMO BoP Description

DEMO BoP for HCPB BB option consists of a chain of systems, including four PHTSs (BB, DIV-PFU, DIV-Cas and VV), IHTS with a thermal ESS to cope with dwell times, and PCS.

The current state of DEMO BoP (as of February 2018) for HCPB BB option is depicted in Fig. 1. Starting with 6 outboard and 3 inboard cooling loops, the energy of the helium is transferred by an intermediate heat exchanger (HX) to the HITEC salt, which transports it at low pressure out of the tokamak building to the ESS, which is an industrial 2-tanks design. Heat is then transferred from HITEC salt to the steam generator (SG) that boils and superheats the feedwater and delivers steam to the steam turbine. Steam generator of the proposed DEMO BoP configuration is a two stage steam generator. During pulse time first stage SG generates steam of ~282°C and 57.11 bar, while the second stage SG generates steam of ~446°C and ~130 bar. The steam parameters leaving the first stage of SG are being kept constant during the whole DEMO operation. This is done in order to be able to keep temperature of the cold HITEC salt returning to the cold salt tank at ~270°C. That temperature is required to avoid cooling of the HCPB BB below 300°C.

The other usable fusion related heat sources (i.e. DIV-PFU (plasma facing unit), DIV-Cas (cassettes) and VV (vacuum vessel)) are used to heat-up the PCS feedwater on the return line to the SG. Taking into account pulse/dwell times of 2 h/10 min, DEMO can operate permanently under ~91%/~103% power respectively, thus allowing flexible and continuous plant operation without interfering with plasma operation. Due to the live steam extraction for feedwater preheating from high and low pressure turbine stages, the efficiency of the PCS is increased, thus reducing the burden to the ESS also during the dwell time.

The steam turbine used in the current configuration follows the state-of-the-art concept proposed by Siemens for this HCPB DEMO BoP. In the previous BoP configuration [4] the SG considered was a one-stage SG, with the steam pressure of 58.5 bar. Current BoP configuration foresees a two-stage SG with the stages working nominal pressures of 57.11 bar and ~130 bar. This was done to obtain higher cycle efficiency, which is currently not less than ~39%.

** The magnitude of the blowers power during dwell time will depend on the possible and effective regulation of the pumping group.*

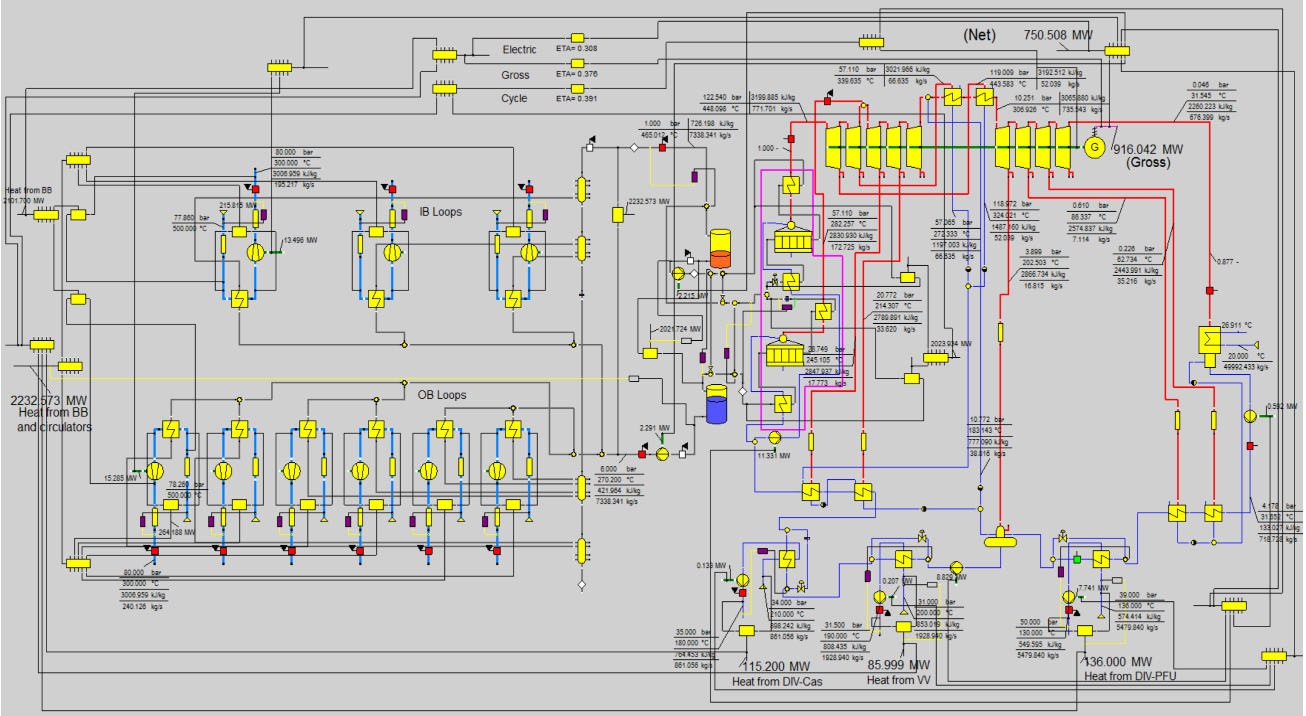

Fig. 1. DEMO BoP model in EBSILON® [7] (PHTSs, IHTS/ESS and PCS at 91 % (pulse time) operation) [5].

2.1 PHTSs

The main parameters of the four independent PHTSs receiving heat from BB, DIV-Cas, DIV-PFU and VV are shown in Table 1. Each of the 9 BB heat transfer loops has its own HX and 2 blowers to cope with partial Loss Of Flow Accident (LOFA) in case of a single blower failure. Each inboard blanket (IB) heat transfer loop extracts ~215.8 MW while each outboard blanket (OB) loop transfers ~264.2 MW.

During dwell time, helium flow rate is reduced as thermal energy deposited is drastically reduced down to the decay heat level. Consequently, pumping power in the helium compressors is expected to be significantly lower* than nominal (~132 MW during pulse time).

Table 1. Main parameters of the DEMO PHTSs.

	BB	DIV-Cas	DIV-PFU	VV
Coolant	Helium	Water	Water	Water
Thermal Power pulsed/dwell (MW)	2101.7/21.02	115.2/1.07	136/1.42	86/1.0
Mass flow rate pulsed/dwell (kg/s)	2026.4/27.1	861.1/861.1	5479.8/5479.8	1928.9/1928.9
BoP inlet temperature pulsed/dwell (°C)	500/450	210/195	136/133	200/195
BoP outlet temperature pulsed/dwell (°C)	300/300	180/194.7	130/132.8	190/194.9
Operational pressure (bar)	80	35	50	31.5

Each of the other 3 secondary heat sources (DIV-PFU, DIV-Cas and VV) has its own HX and a water pump. In order to ensure that the correct amount of heat is being transferred to the PCS and that the returning water has its design parameters, feedwater flow around the corresponding HXs is being split into the main flow and the by-pass flow.

The industrial components for the four PHTSs are still to be specified. The current PHTS component designs are based primarily on design calculations performed by WPBoP partners.

2.2 IHTS/ESS

HITEC salt tanks in the IHTS/ESS are used to accumulate the required amount of heat in the form of sensible heat, which replaces mainly the BB heat source, but also the power missing in the PCS from DIV-PFU, DIV-Cas and VV heat sources during dwell time, when DEMO is producing almost no heat. This is important to ensure the continuous operation of the power train composed of steam turbine and generator, thus producing electricity and keeping the whole PCS operational all the time.

The foreseen ESS of the DEMO is an industrial 2-tanks design commonly used in CSP plants [8]. HITEC salt in the hot tank is accumulated at 465°C, while the temperature in the cold tank is being kept at 270°C. With a duty cycle (pulse/dwell) time of 2 h/10

** The magnitude of the blowers power during dwell time will depend on the possible and effective regulation of the pumping group.*

min, thanks to ESS, DEMO can operate permanently under ~91%/~103% power thus allowing flexible and continuous plant operation. Estimated HITEC salt mass required for such an operation is ~5040 tons, which leads to a tank size of 24 m diameter and ~7 m height.

As in the previous case of PHTS, industrial components for the IHTS/ESS are still to be specified where the current component designs are primarily based on the calculations performed by the project partners.

2.3 PCS

PCS of DEMO is a commercial water-steam Rankine cycle (see Fig. 1). Parameters of the PCS were selected such that HITEC salt temperature returning back to the cold molten salt tank could be stable and equal to ~270°C both during pulsed and dwell operation. This HITEC temperature, in turn, is needed to have a stable He temperature of 300°C returning back to the BB, essential for the stable operation of He blowers, that will be selected later this year by ATEKO company from Czech Republic.

As one of the outcomes of the trilateral collaboration (KIT-INR, KAH and Siemens), established in 2016, the currently presented PCS Rankine cycle was optimized by Siemens. Steam extractions from the high and low pressure steam turbine stages used for feedwater preheating were optimized for a state-of-the-art steam turbine produced by Siemens. The DEMO BoP turbogenerator by Siemens consists of the steam turbine (SST5-6000) together with a condenser, including two steam re-heaters (SR), condensate drain and the electrical generator (SGen5-3000W).

Specifications for some other important DEMO PCS components, like feedwater heat exchanger, deaerator, feedwater pump aggregate and PCS circulation pump – both manufactured by KSB company were provided to us by our partners from Kraftanlagen Heidelberg (KAH). However, industrial components for all the remaining DEMO PCS equipment are still to be specified. The cycle net efficiency obtained with the current improved configuration is ~39%/~41% (for the pulse/dwell time).

The following improvements to the HCPB DEMO BoP configuration, when compared to 2016 design [4] could be mentioned here: 1) IHTS fluid was changed from solar salt to HITEC salt [6], which is beneficial as HITEC salt has a lower freezing point in comparison with the solar salt; 2) DEMO BoP configuration was adapted to include real steam turbine configuration proposed by Siemens; 3) Deaerator is now being operated at stabilized conditions; 4) Feedwater temperature at steam generator entrance was also stabilized; 5) The impact of DEMO pulsating mode of operation on all DEMO BoP components, first of all on the steam turbine and the electricity generator, was minimized; 6) When adopting new steam turbine configuration, Rankine cycle efficiency was increased from ~36% to ~40%; 7) Additional heat exchanger on the feedwater preheating line, working only during dwell time, was eliminated thanks to the optimized PCS configuration.

2.4 BoP components sizing and preliminary cost estimates

Specifications of space requirements and costs for DEMO BoP components are presented in Table 2. These specifications were provided by our DEMO-WPBoP partners, KAH colleagues and experts from Siemens Power and Gas Division. Many components have not been yet defined as existing on the market because of the lack of the responses from the industry. Thus, the missing equipment should still be defined when providing real design for DEMO BoP in the next phase of the project. The total costs of HCPB DEMO BoP could not be estimated because of the missing information on the existing industrial equipment.

3. Conclusions

A short overview of the current (as of February 2018) DEMO BoP design, for HCPB BB option (18 sectors design), being developed and improved at KIT is presented in this paper. Improvements to the DEMO PCS configuration, when compared to its previous design as of 2016 [4], are also listed above. Key PCS components, including their preliminary sizing and cost estimates were presented as well. These specifications were provided to us by our project partners, KAH colleagues and experts from Siemens Power and Gas Division.

Currently, the foreseen IHTS/ESS and PHTS component designs are based primarily on the design calculations performed by the project partners. Therefore, next steps in the WPBoP task include selection of the existing industrial equipment for DEMO BoP. Selection of the real equipment, final required space and costs evaluation are foreseen for the next two years.

Table 2. Space requirements and costs for DEMO BoP components [5].

DEMO BoP Component	Design dimensions, m			Space reservation, m			Weight, t	Costs*, M Euro
	Length	Width/Diam	Height	Length	Width/Diam	Height		
PHTS IB HX	12.2	3.5						2.4
PHTS OB HX	11.7	4						3
PHTS IB He blower + FI				17.5$^{(x2)}$	8$^{(x2)}$	3$^{(x2)}$	23	17
PHTS OB He blower + FI				17.5$^{(x2)}$	8$^{(x2)}$	3$^{(x2)}$	23	17
PCS DIV-PFU HX	6.5	1.7						0.4

** The magnitude of the blowers power during dwell time will depend on the possible and effective regulation of the pumping group.*

<table>
<tr><td>PCS DIV-PFU Pump</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PCS DIV-Cas HX</td><td>12.1</td><td>2.5</td><td></td><td></td><td></td><td></td><td></td><td>2.8</td></tr>
<tr><td>PCS DIV-Cas Pump</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PCS VV HX</td><td>10.8</td><td>1.5</td><td></td><td></td><td></td><td></td><td></td><td>0.7</td></tr>
<tr><td>PCS VV Pump</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>IHTS Hot Tank</td><td></td><td>23.8</td><td>6.8</td><td rowspan="4">71.4</td><td rowspan="4">35.7</td><td rowspan="4">8</td><td rowspan="4">-</td><td rowspan="4">16.6</td></tr>
<tr><td>IHTS Cold Tank</td><td></td><td>23.8</td><td>6.8</td></tr>
<tr><td>IHTS Pump 1</td><td></td><td></td><td></td></tr>
<tr><td>IHTS Pump 2</td><td></td><td></td><td></td></tr>
<tr><td>PCS FW1 HX</td><td>14.4</td><td>2.5</td><td></td><td></td><td></td><td></td><td></td><td>1.1</td></tr>
<tr><td>PCS FW2 HX</td><td>4</td><td>1.7</td><td></td><td></td><td></td><td></td><td></td><td>0.2</td></tr>
<tr><td>PCS FW3 HX</td><td>9.8</td><td>2</td><td></td><td>21</td><td>3.5</td><td>4</td><td>43.9</td><td>2.1</td></tr>
<tr><td>PCS FW4 HX</td><td>8.3</td><td>3.2</td><td></td><td></td><td></td><td></td><td></td><td>3.1</td></tr>
<tr><td>PCS SG1 PH</td><td>14.8</td><td>1.5</td><td></td><td></td><td></td><td></td><td></td><td>0.9</td></tr>
<tr><td>PCS SG1</td><td>11.7</td><td>3.6</td><td></td><td></td><td></td><td></td><td></td><td>9.0</td></tr>
<tr><td>PCS SG1 SH</td><td>3.9</td><td>1.4</td><td></td><td></td><td></td><td></td><td></td><td>0.4</td></tr>
<tr><td>PCS SG2 PH</td><td>25.8</td><td>2.9</td><td></td><td></td><td></td><td></td><td></td><td>6.9</td></tr>
<tr><td>PCS SG2</td><td>8.9</td><td>3.5</td><td></td><td></td><td></td><td></td><td></td><td>7.1</td></tr>
<tr><td>PCS SG2 SH</td><td>23.1</td><td>2.4</td><td></td><td></td><td></td><td></td><td></td><td>6.5</td></tr>
<tr><td>DRAIN</td><td></td><td></td><td></td><td rowspan="6">52</td><td rowspan="6">19</td><td rowspan="6">24</td><td rowspan="6">1285</td><td rowspan="6">90.7</td></tr>
<tr><td>PCS SR1 HX</td><td></td><td></td><td></td></tr>
<tr><td>PCS SR2 HX</td><td></td><td></td><td></td></tr>
<tr><td>PCS ST</td><td></td><td></td><td></td></tr>
<tr><td>PCS GENERATOR</td><td></td><td></td><td></td></tr>
<tr><td>PCS CONDENSER</td><td>23</td><td>8.8</td><td></td></tr>
<tr><td>PCS Pump 1</td><td></td><td></td><td></td><td>16</td><td>3.4</td><td>3</td><td>-</td><td rowspan="3">7.6</td></tr>
<tr><td>PCS Pump 2</td><td></td><td></td><td></td><td>16</td><td>3.4</td><td>3</td><td>-</td></tr>
<tr><td>PCS FW Pump</td><td></td><td></td><td></td><td>7</td><td>2.9</td><td>3</td><td>-</td></tr>
<tr><td>DEAERATOR</td><td>35</td><td>4</td><td></td><td>40</td><td>5</td><td>6</td><td>152</td><td>10.4</td></tr>
</table>

* Costs for pipework, valves, I&C, relay station, cooling towers, machine hall building and auxiliaries are not considered

Acknowledgments

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References

[1] https://www.euro-fusion.org/programme/

[2] F. A. Hernandez, F. Arbeiter, L. V. Boccaccini et al., Overview of the HCPB Research Activities in EUROfusion // IEEE Transactions on Plasma Science. ISSN 0093-3813 / 2018. Vol. 46/6. – P. 2247-2261.

[3] F. Hernandez, P. Pereslavtsev, Q. Kang et al., A new HCPB breeding blanket for the EU DEMO: Evolution, rationale and preliminary performances, Fusion Engineering and Design. ISSN 0920-3796 / 2017. Vol. 124. – P. 882-886.

[4] E. Bubelis, W. Hering, S. Perez-Martin. Conceptual designs of PHTS, ESS and PCS for DEMO BoP with helium cooled BB concept // Fusion Engineering and Design. ISSN 0920-3796 / in press, 2018.

[5] E. Bubelis, W. Hering. Final Report on Deliverable "DEMO HCPB BB with FW cooled in series with BZ & Plant configuration with IHTS+ESS – Conceptual designs and sizing of PHTS, IHTS, ESS and PCS components", KIT report No. INR-02/18, FUSION 493, February 2018.

[6] HITEC® Heat Transfer Salt. Coastal Chemical Co., L.L.C. Brenntag Company.

[7] https://www.steag-systemtechnologies.com/ebsilon_professional+M52087573ab0.html

[8] https://energy.gov/eere/energybasics/articles/concentrating-solar-power-thermal-storage-system-basics

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