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Design update of DEMO BOP for HCPB BB concept with an energy storage system

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ABSTRACT

An option for the Intermediate Coupling Design (ICD) of the European Demonstration Fusion Reactor (DEMO) Balance of Plant (BOP) configuration for Helium-Cooled Pebble Bed (HCPB) Breeding Blanket (BB) concept consists of the Primary Heat Transport System (PHTS), the Intermediate Heat Transfer System (IHTS), using HITEC salt as coolant, equipped with a thermal Energy Storage System (ESS), and the Power Conversion System (PCS). The aforementioned BOP configuration is capable of producing electricity continuously during the pulse time (2 h) and dwell time (10 min) of DEMO plant operation.

The present study reports on the current (2023) thermal system design of DEMO HCPB ICD BOP for 12 operational states defined by the DEMO Design Central Team (DCT) in 2021. It was shown that the PCS is able to accommodate all of the 12 operational points defined based on the uncertainties of the energy map, provided that an additional bypass line at the outlet of the Divertor Cassettes (DIV-CAS) Heat Exchanger (HX) towards the low-pressure part of the feedwater line (to the condenser in this investigation) is installed in the system. This line is activated only in the cases, where the feedwater flow to the low temperature DEMO heat sources HXs is needed to be higher than that necessary to remove BB power at the Steam Generators (SGs). In all the other cases, the bypass line remains unused. Additionally, perspective improvements of DEMO HCPB BOP regarding thermal ESS, as well as PCS are discussed.

1. Introduction

One of the Breeding Blanket (BB) concepts for the EU DEMO [1] is the 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 helium as BB coolant.

This paper reports on the current (2023) thermal system design of DEMO HCPB ICD BOP for 12 operational states (named as design points A1–0 to A2–2 for two values of fusion power (Pfus = 1.9 and 2.0 GW) in Tables 2 and 3 below) defined by the DEMO Design Central Team (DCT). The DEMO HCPB BOP design published in 2019 [4] contained the BB PHTS with 3 Inner Blanket (IB) and 6 Outer Blanket (OB) cooling loops, while the current DEMO HCPB BOP design includes BB PHTS with 8 combined IB+OB cooling loops [5]. In 2021 DCT issued "2021 Energy Map" [6], which defined the following: 1) BB PHTS power was varied slightly from the previous value of 2101.7 MWth and is now in the range from 1910 to 2117 MWth (difference of < 5%); 2) Divertor Plasma Facing Cassettes (DIV-PFC) PHTS power was increased significantly from the previous value of 136 MWth and is now in the range from 170 to 251 MWth; 3) DIV-CAS PHTS power was also increased significantly from the previous value of 115.2 MWth to the range from 181 to 216 MWth; 4) Vacuum Vessel (VV) PHTS power was decreased significantly from the previous value of 86 MWth and is now in the range from 45 to 48 MWth. Operating temperatures for almost all DEMO heat sources used for HCPB ICD BOP stayed at the same level [6]: the temperature range for BB is 300–520 °C, for DIV-PFC is 130–136 °C and for DIV-CAS is 180–210 °C. The only noticeable change is in the operation temperatures for VV heat source – the operating temperature range of 190–200 °C was lowered to 40–60 °C.

Based on the "2021 Energy Map" [6] data and on the performed EBSILON® analysis [7], it was decided (caused by the low grade operating temperature of VV PHTS) to eliminate the integration of VV PHTS HX from DEMO HCPB ICD BOP configuration for Work Package (WP) BOP activities beyond 2021, thus releasing heat transported by VV cooling circuit to the Component Cooling Water System. By doing so, a

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simplification of the low-pressure feedwater line of the PCS is achieved.

At the same time (in 2021), DEMO DCT defined also 12 operational states for HCPB ICD BOP [8], which resulted from the uncertainties in the defined parameters, presented in the “2021 Energy Map”. Two years later (in 2023), DEMO DCT slightly updated the 12 operational states for HCPB ICD BOP. Having all these increased PHTSs power values in mind, it become clear that DEMO HCPB ICD BOP configuration has to be re-analyzed using EBSILON® software [9] and improved with the aim to find a configuration able to manage all the operational points envisaged. This activity has been carried out also accepting advices and suggestions of our industrial partner Kraftanlagen Heidelberg (KAH) GmbH.

2. DEMO BOP 2023 description

DEMO HCPB ICD BOP current (2023) configuration, which was analyzed using EBSILON® software [9], is shown in Fig. 1. EBSILON® is a software package that simulates thermodynamic cycle processes and is used for engineering, designing, and optimizing of different kinds of power plants. EBSILON® supports the engineering processes from feasibility studies all through to the detailed dimensioning of a power plant. EBSILON® can be run either in a static or a quasi-static mode, thus real dynamic simulations of DEMO BoP are presently not possible.

With the aim to set up a bounding configuration, the design point of the current DEMO HCPB ICD BOP considers maximal PHTSs power values. As such the performed EBSILON® analysis used: 2117 MWth for BB PHTS power, 251 MWth for DIV-PFC power and 216 MWth for DIV-CAS power. Table 1 presents the 12 operational states of the DEMO HCPB ICD BOP configuration updated in 2023 for the thermal-hydraulic analysis by EBSILON® software.

As one can see from Fig. 1, DEMO HCPB ICD BOP (2023) configuration consists of 3 cooling loops: BB PHTS, IHTS and PCS. BB PHTS consists of 8 combined IB+OB cooling loops. The BB cooling system is operated with Helium of 520 °C in the feed line and of 300 °C in the return line. In the 8 Intermediate Heat Exchangers (IHXs) the heat carried by helium is transferred to the HITEC molten salt flow where the HITEC salt heats up from 270 °C to 465 °C. In the IHTS hot HITEC salt is kept in the hot tank, while cold HITEC salt returning from the SGs is collected in the cold tank. Both, cold and hot tanks, with the corresponding molten salt pumps belong to the IHTS. The main purpose of the IHTS is to store thermal energy (in the form of hot HITEC salt) during DEMO pulse time operation of 2 h, and release the stored thermal energy during DEMO dwell time operation of 10 min, thus enabling a continuous and constant PCS operation at ~91.3% of its nominal power during DEMO pulse and dwell time operation. PCS represents normal Rankine steam cycle, consisting of feedwater preheaters, steam generators (8 units of two-stages SGs), steam re-heaters, steam turbine with electricity generator, condenser, deaerator and feedwater piping. PCS efficiency during pulse time operation is 37.4% and electricity generator generates ~798 MWth of net electricity.

For proving the feasibility of the 12 operational states with the current DEMO HCPB ICD BOP configuration (see Fig. 1), multiple EBSILON® Sub-Design simulations were performed for all 12 operational points defined by DCT for HCPB ICD BOP. The obtained final results are presented in Tables 2 and 3.

The 12 operational states for DEMO HCPB ICD BOP (2023) configuration were analyzed on the assumption, that the main operational parameters (temperatures and pressures) of the SIEMENS steam turbine can vary slightly during the transition of DEMO operation through all 12

Table 1
Summary of the 12 operational states simulated for DEMO HCPB ICD BOP (2023) configuration. Below in the table P_{fus} is the fusion power.

	Case No.	BB *MW*	DIV-PFC *MW*	DIV-CAS *MW*
Pfus=2GW	**A1–0**	2035	225	215
	A1–1	2050	213	211
	A1–2	2009	251	216
	A2–0	2102	191	196
max	**A2–1**	2117	179	192
	A2–2	2076	217	197
Pfus=1.9GW	**A1–0**	1936	213	204
	A1–1	1950	202	200
min	**A1–2**	1910	239	205
	A2–0	1999	181	185
	A2–1	2013	170	181
	A2–2	1973	207	186

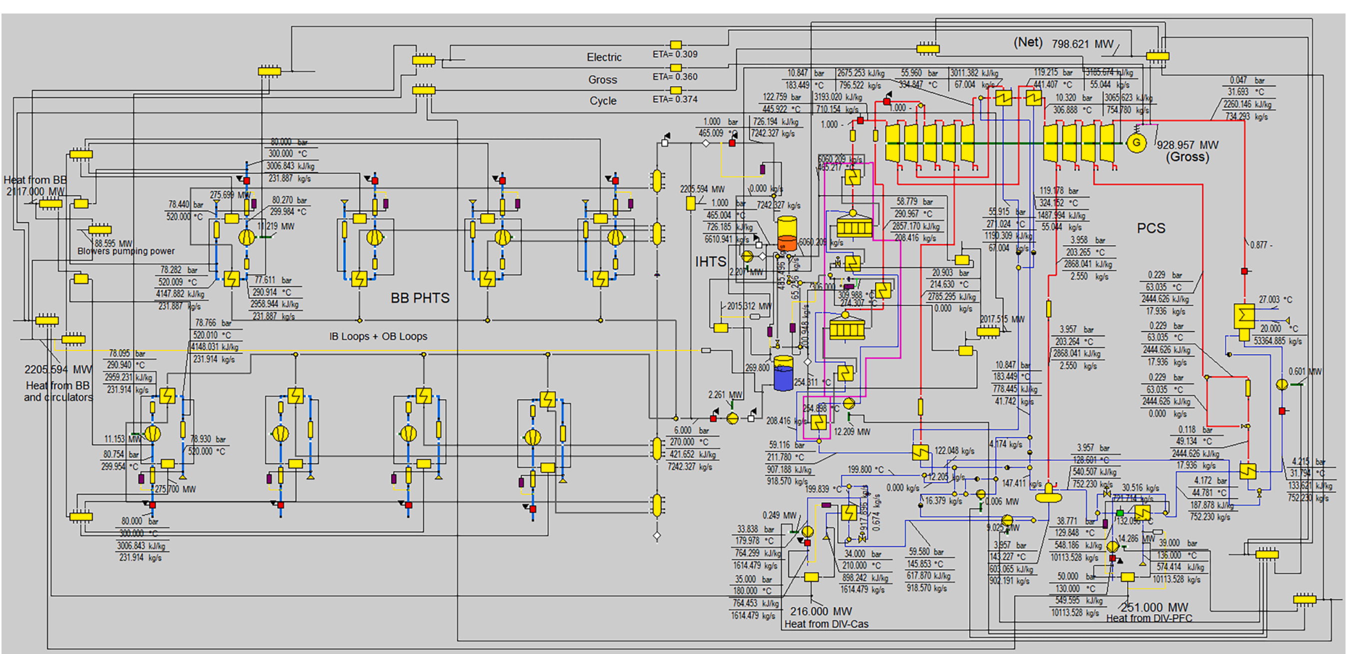

Fig. 1. HCPB ICD BOP: ~91.3% power transfer – pulse time. Design point, max power of all heat sources. Colors specification: pink/violet polygon represents 2-stages steam generator, light blue lines are for He, dark blue lines are for water, red lines are for steam, thick gray lines are for HITEC and thin black lines are for logic and control.

Table 2
Selected HCPB ICD BOP pulse time parameters for the design point, as well as 12 operational states (2023 update).

Case No.	BB power	DIV-CAS power	DIV-PFC power	FW temp. before deae-rator	FW temp. before SG	Steam flow to deae-rator	Deae-rator cond. flow bypass	Steam line to FW1 HX Δp	SG1 out. temp.	SG1 out. pres.	SG2 out. temp.	SG2 out. pres.	Pnet	ηcycle
	MW	MW	M W	° C	°C	kg/s	%	b ar	°C	b ar	°C	bar	MW	%
Design point, max power of all heat sources (Pfus = 2.0 GW)														
Design point	2117	216	251	128.6	211.8	2.550	10	0.111	291.0	58.8	445.9	122.8	798.6	37.4
Pfus = 1.9 GW														
A1–0	1936	204	213	121.6	209.6	6.056	9	0.1	288.0	58.0	445.8	116.2	727.7	37.4
A1–1	1950	200	202	117.7	209.3	12.520	14	0.1	288.1	58.0	445.6	116.6	729.4	37.5
A1–2	1910	205	239	122.6	209.1	12.024	32	0.1	287.9	57.9	446.1	115.3	712.1	36.6
A2–0	1999	185	181	110.0	204.8	22.540	17	0.1	288.1	58.1	445.2	117.8	735.2	37.7
A2–1	2013	181	170	106.1	203.4	27.092	17	0.1	288.2	58.1	445.1	118.1	735.9	37.8
A2–2	1973	186	207	119.2	207.8	14.977	37	0.1	288.1	58.1	445.4	117.2	733.4	37.6
Pfus = 2.0 GW														
A1–0	2035	215	225	122.1	208.8	3.823	1	0.106	288.4	58.3	444.6	119.5	762.8	37.3
A1–1	2050	211	213	118.1	205.6	5.291	1	0.106	288.3	58.3	444.6	119.6	762.4	37.4
A1–2	2009	216	251	120.4	208.2	18.288	25	0.115	288.3	58.2	444.9	118.6	741.5	36.4
A2–0	2102	196	191	110.4	204.8	22.532	1	0.106	288.5	58.5	444.0	121.3	771.4	37.7
A2–1	2117	192	179	106.4	203.5	27.495	1	0.106	288.5	58.6	443.9	121.7	772.2	37.8
A2–2	2076	197	217	119.2	207.4	14.479	17	0.106	288.5	58.5	444.2	120.7	769.6	37.5

Table 3
Selected HCPB ICD BoP dwell time parameters for the design point, as well as 12 operational states (2023 update).

Case No.	BB power	DIV-CAS power	DIV-PFC power	FW temp. before deae-rator	FW temp. before SG	Steam flow to deae-rator	Deae-rator cond. flow bypass	Steam line to FW1 HX Δp	SG1 out. temp.	SG1 out. pres.	SG2 out. temp.	SG2 out. pres.	Pnet	ηcycle
	MW	MW	M W	° C	°C	kg/s	%	b ar	°C	b ar	°C	bar	MW	%
Design point, max power of all heat sources (Pfus = 2.0 GW)														
Design point	22.0	1.8	0.8	58.7	196.3	57.407	10	0.0	290.5	58.6	446.3	122.1	780.0	40.2
Pfus = 1.9 GW														
A1–0	20.1	1.7	0.7	56.8	169.0	66.223	3	0.0	287.0	57.5	447.2	112.6	706.4	39.8
A1–1	20.2	1.6	0.6	56.6	169.6	68.649	1	0.0	287.1	57.5	447	113.1	712.7	39.8
A1–2	19.8	1.7	0.8	56.7	165.9	66.155	1	0.0	286.9	57.4	447.5	111.5	694.6	39.7
A2–0	20.9	1.5	0.6	56.4	171	71.427	3	0.0	287.3	57.7	446.4	114.9	732.5	39.9
A2–1	20.9	1.5	0.5	56.3	171.3	72.060	1	0.0	287.4	57.7	446.2	115.4	738.2	39.9
A2–2	20.6	1.6	0.7	56.9	170.2	69.573	1	0.0	287.2	57.6	446.7	113.9	721.4	39.8
Pfus = 2.0 GW														
A1–0	21.1	1.8	0.7	57.7	172.0	72.010	1	0.0	287.5	57.8	445.9	116.1	744.5	39.8
A1–1	21.9	1.8	0.7	57.5	172.4	72.995	1	0.0	287.5	57.9	445.7	116.7	751.1	39.9
A1–2	20.9	1.8	0.8	57.8	172.2	68.272	1	0.0	287.4	57.7	446.2	115.4	733.4	39.8
A2–0	21.9	1.6	0.6	57.3	173.7	75.798	1	0.0	287.7	58.1	445.1	118.5	771.8	39.9
A2–1	21.9	1.6	0.6	57.1	174.1	76.694	1	0.0	287.8	58.1	444.9	119.0	778.0	39.9
A2–2	21.6	1.6	0.7	57.8	173.0	74.055	1	0.0	287.6	58.0	445.4	117.6	760.7	39.9

defined operational states including transitions from pulse to dwell and dwell to pulse (see Tables 2 and 3 for details). When going from one operational state to another – additionally one needs to regulate steam flow from the low-pressure steam turbine to the low-pressure feedwater preheater, as well as amount of the condensate, coming from the drain, steam re-heaters, as well as high pressure feedwater preheater to the deaerator.

From Table 2 it is evident that for two defined operational points – cases A1–2 for P_{fus} = 1.9 and 2.0 GW – one change needs to be implemented into the current (2023) DEMO HCPB ICD BOP configuration. For these two cases, where BB PHTS power is not at its maximum, but powers of DIV-PFC PHTS and DIV-CAS PHTS are at their maxima or rather close to their maxima, in order to be able to remove the whole heat load from DIV-CAS cooling circuit, one needs to take part of the condensate after DIV-CAS HX and return it back to the condenser. For the case A1–2 for P_{fus}=1.9 GW this part is 8% of the condensate leaving DIV-CAS HX, while for the case A1–2 for P_{fus}=2.0 GW this part is 11% of the condensate leaving DIV-CAS HX. This measure reduces the efficiency of the PCS, however, allows the removal of the total heat load from DIV-CAS cooling circuit. The remaining 10 operational defined states are feasible with the current (2023) DEMO HCPB ICD BOP configuration (see Fig. 1), without a partly return of the condensate to the condenser.

Above-described difficulties with the defined operational states for DEMO HCPB ICD BOP – cases A1–2 for P_{fus} = 1.9 and 2.0 GW – are related only to pulse operation of DEMO (see Table 2 for more details), while no such difficulties were detected for the dwell operation of DEMO (see Table 3 for more details).

Concluding, one can say that the current (2023) HCPB ICD BOP configuration, with maximal power values of the heat sources as the design point is able to handle all 12 operational points but two. In fact, for 2 defined states (cases A1–2), changes in the DEMO HCPB ICD BOP (2023) configuration are required. In order to be able to remove the total heat load from DIV-CAS cooling circuit, the condensate after DIV-CAS HX needs to return back partially to the condenser. The latter reduces the efficiency of the PCS, but provides total heat removal from DIV-CAS cooling circuit.

3. Conclusions

Based on the performed analysis with EBSILON® software, as well as on optimization studies in cooperation with the industrial partner, the following changes in the HCPB ICD BOP (2023) configuration had to be implemented (in comparison to HCPB ICD BOP configuration for 2019 [4]):

1. Instead of the two feedwater preheaters, supplied by the steam from the low-pressure steam turbine, only one low pressure feedwater preheater is needed for the current HCPB ICD BOP configuration.
2. Steam to the single low pressure feedwater preheater still needs to be minimized, in order to be able to remove the whole heat transported by DIV-PFC PHTS.
3. Instead of the two feedwater preheaters, supplied by the steam from the high-pressure steam turbine, only one feedwater preheater is needed for the current HCPB ICD BOP configuration. This was done in order to maximize the steam supply to the deaerator during pulse and dwell time operation.
4. Certain part of the condensate, coming from the drain, steam reheaters, as well as a high-pressure feedwater preheater to the deaerator, should bypass the deaerator, in order for PCS to be able to remove the whole heat transported by DIV-CAS PHTS for the 12 operational points. The condensate is partially returned back to the feedwater line in front of the main condensate pump, not after it, as it was implemented in the 2022 configuration [10] of HCPB ICD BOP. This was done in order to optimize the operation of the PCS.
5. In order to fully remove the required power from DIV-CAS PHTS for the two DEMO HCPB ICD BOP operational points A1–2, a bypass of a certain amount of feedwater (right after DIV-CAS HX) to the condenser was proposed in 2022 [10]. Attempts were done in 2023 to optimize the PCS efficiency by relocating this above-mentioned bypass; however, the best end connection point for this bypass still remains the condenser.

The final conclusion from aforementioned presented research activity is as follows: the current (2023) HCPB ICD BOP configuration, defined on the basis of maximal power values of the used heat sources as design point, is feasible and operational for all defined operational states of HCPB ICD BOP. However, for 2 defined states (cases A1–2), one needs to implement one change into the configuration of DEMO HCPB ICD BOP. In order to be able to remove the whole heat load from DIV-CAS cooling circuit, one needs to take part of the condensate after DIV-CAS HX and return it back to the condenser. This measure reduces the efficiency of the PCS, however allows removal of the whole heat load from DIV-CAS cooling circuit. This measure is needed only for two operational states of DEMO HCPB ICD BOP, the occurrence of which is rather low, so no big influence on DEMO HCPB ICD BOP operation or efficiency in general is thus expected.

4. Perspective improvements of demo HCPB ICD BOP

Perspective improvements of DEMO HCPB ICD BOP consists of: 1) changing the design of the SGs – replacing 2-stage SGs with one stage SGs (producing steam only at 130 bar); 2) rearranging the positioning of ESS HITEC tanks (including re-sizing) and SGs, thus reducing their footprint by ~44%; 3) modification of PCS layout to ensure flexibility respect to all the envisaged operational points, 4) further optimization of the PCS design in order to increase the efficiency of the Rankine steam cycle.

CRediT authorship contribution statement

Evaldas Bubelis: Writing – original draft, Investigation, Data curation, Conceptualization. **Sebastian Ruck:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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