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Design Update of DEMO BoP for HCPB BB Concept with an Energy Storage System

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The EU Demonstration Fusion Reactor (DEMO) Balance of Plant (BoP) configuration for Helium-Cooled Pebble Bed (HCPB) Breeding Blanket (BB) concept studied consists of the Primary Heat Transfer 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). This updated BoP configuration is capable of producing electricity continuously through the pulse time (2 h), as well as dwell time (10 min) of DEMO plant operation. The DEMO BoP further development was supported by industrial partners.

The present study reports on the thermal system design of DEMO HCPB BoP 2023 for 12 operational states defined by the DEMO Design Central Team (DCT). This activity demonstrated that the PCS lay-out is able to accommodate all the 12 operational points generated by the uncertainties of the energy map, provided that an additional bypass line at the outlet of the Divertor Cassettes (DIV-CAS) Heat Exchanger (HX) - integrated in the PCS - toward the low pressure part of the feedwater line (to the condenser in this investigation) is installed in the system. This line activates in the cases where the feedwater flow to the low temperature DEMO sources HXs is higher than that to remove BB power at the Steam Generator (SG). In all the other cases, according to EBSILON® code results, this bypass line is not used. Additionally, perspective improvements of DEMO HCPB BoP regarding thermal ESS and PCS are presented as well.

HCPB Indirect Coupling Design (ICD) BOP Scheme

DEMO HCPB ICD BOP current (2023) configuration, which was analyzed using EBSILON® software, is shown in Figure 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.

As one can see from Figure 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. 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.

Table 1. PHTS parameters for the design point of the current DEMO HCPB ICD BOP

Parameter	BB PHTS	DIV-PFC PHTS	DIV-CAS PHTS
Power, MWth	2117	251	216
Tcool-in, °C	520	136	210
Tcool-out, °C	300	130	180
Pres., bar	80	50	35

The 12 operational states for DEMO HCPB ICD BOP (2023) configuration (see Table 2) 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 defined operational states including transitions from pulse to dwell and dwell to pulse (see Tables 3 and 4 for details).

Table 2. Summary of the 12 operational states simulated for DEMO HCPB ICD BOP (2023) configuration. Below in the table Pfus is the fusion power

	Case No.	BB	DIV-PFC	DIV-CAS
		MW	MW	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

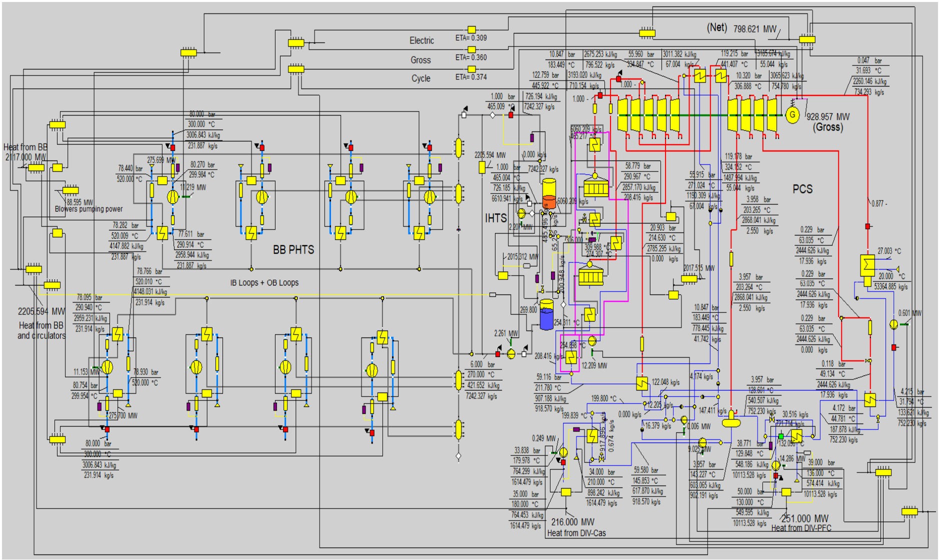

Figure 1. HCPB ICD BOP: ~91.3% power transfer – pulse time. Design point, max power of all heat sources. Colors specification: pink/violet polygon represents 2-stages steam generator, light blue lines are for He, dark blue lines are for water, red lines are for steam, thick grey lines are for HITEC and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

Table 3. 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 deaerator	FW temp. before SG	Steam flow to deaerator	Deaerator cond. flow bypass	Steam line to FW1 HX Dp	SG1 out. temp.	SG1 out. pres.	SG2 out. temp.	SG2 out. pres.	Pnet	ηcycle
	MW	MW	MW	°C	°C	kg/s	%	bar	°C	bar	°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 4. 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 deaerator	FW temp. before SG	Steam flow to deaerator	Deaerator cond. flow bypass	Steam line to FW1 HX Dp	SG1 out. temp.	SG1 out. pres.	SG2 out. temp.	SG2 out. pres.	Pnet	ηcycle
	MW	MW	MW	°C	°C	kg/s	%	bar	°C	bar	°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

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):

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 re-heaters, 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 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. 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.

<u>The final conclusion</u> 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.

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