WPSAE-CPR(17) 17279

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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.

BB LOCA analysis for the reference design of the EU DEMO HCPB blanket concept

Xue Zhou Jin

Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Following DEMO configuration in 2015 the design of the Helium Cooled Pebble Bed (HCPB) blanket concept has been significantly improved. For the reference design HCPB2015V3 and the associated primary heat transfer system (PHTS) the breeding blanket (BB) loss of coolant accident (LOCA) has been investigated as the design basis accident (DBA). System code MELCOR186 for fusion is used for the LOCA simulation. The LOCA can take place in the breeder zone (BZ) or in the first wall (FW) of the BB, and it is assumed to be in one affected equatorial blanket module (BM) on the outboard (OB). Different scenarios due to break sizes and plasma shutdown conditions are taken into account. He inventory during normal operation is determined as steady state results. Transient results of LOCA are evaluated for the mass flow rate, pressure, helium temperature, structure temperature and mass. Finally, issues encountered in this analysis are discussed.

Keywords: DEMO safety, HCPB, LOCA, MELCOR.

1. Introduction

Helium Cooled Pebble Bed (HCPB) blanket concept is one of four EU DEMO (Demonstration Power Plant) blanket concepts being developed in the current pre-conceptual design phase of the EUROfusion Consortium. In 2015, the blanket design was significantly improved based on the updated DEMO configuration with a fusion power of 2037 MW and 18 toroidal fields (TFs) [1], and the required tritium breeding rate (TBR) [2]. Deterministic safety analysis for the selected breeding blanket (BB) loss of coolant accident (LOCA) is essential for the reference design HCPB2015V3 and the associated primary heat transfer system (PHTS) in order to study the pressure behaviour in the blanket modules (BMs), in the connected loop and in the pressure relief systems; the temperature evolution of the coolant flow and the structures; and the helium (He) inventory. MELCOR 186 for fusion is used for the LOCA simulation [3]. Transient of the LOCA is initialized during the normal operation at steady state. Before the accidental study the design of the related systems is described firstly in the following.

2. Design of the related systems

The HCPB blanket system is subdivided into 18 sectors [2]. Each sector comprises three outboard (OB) and two inboard (IB) segments. Each IB or OB segment contains 7 BMs. HCPB2015V3 (Fig. 1) is a "sandwich-concept" instead of the ITER-like "beer-box-concept" in 2014 [4]. The equatorial BM OB4 with high heat load is selected as the affected module for the BB LOCA. The joint of the U-shaped first wall (FW), cooling plates (CPs) and back plates encloses the breeder zone (BZ), and forms a BM by fixing at the back supporting structure (BSS) and covering with caps. The parallel CPs create volume layers where the breeder ceramic pebble beds (Li_4SiO_4) and the neutron multiplier pebble beds (beryllium (Be)) are emplaced in alternate sequence. The FW has to absorb high heat fluxes from the plasma and it is cooled down by He in counter flow. The front wall is coated with a plasma facing component (PFC) tungsten (W) having a thickness of 2 mm. The cross section of the FW channel has square design with a side length of 12.5 mm. All cooling channels are made by EUROFER97. The design data for one OB4 are: mass flow rate of 6.3293 kg/s ($\dot{m}_{OB4}$), temperature of 300 °C (T_{OB_in}) and pressure of 8 MPa at the blanket inlet, 500 °C at the blanket outlet (T_{OB_out}), pressure drop of 0.22 MPa (dp), surface heat flux of 0.5 MW/m² (q_{OB4}), and thermal power of 5.072 MW.

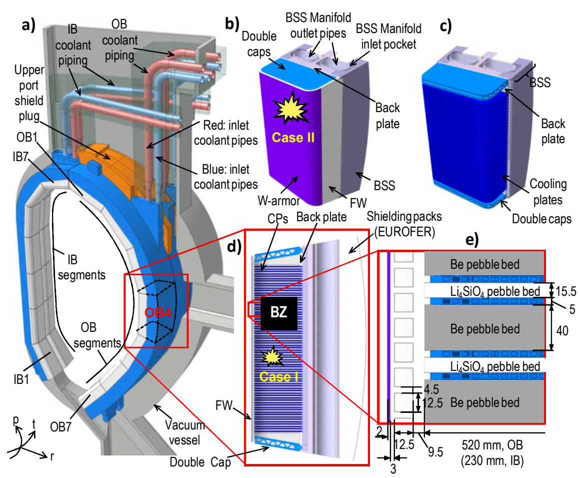


Fig. 1 HCPB2015V3 and LOCA locations: a) one sector; b) & c) 3D views of the OB4; d) section cut of the OB4; e) detail of the BZ [2]. *Coordinates: p = poloidal; t = toroidal; r = radial.*

The produced tritium is purged by Li_4SiO_4 and partially by Be in a He purge gas (PG) loop of the tritium extraction removal (TER) system operated at 0.2 MPa and 450 °C. A common PG supply at the inlet is located at the top of the blanket sector, and independent outlet lines for Li_4SiO_4 and Be pebble beds at the bottom

author's email: jin@kit.edu

(Fig. 2 a)). The TER system is prevented from the LOCA via double isolation valves, and its detailed design is being developed.

Fig. 2 b) shows the preliminary PHTS design serving the HCPB system [5]. It is designed with 6 loops for OB blankets and 3 loops for IB blankets. Each OB loop contains 3 sectors and each IB loop 6 sectors. Each loop is designed with one heat exchanger (HX) and two compressors in parallel for the redundancy. Types of the HX and compressor are not determined. The total mass flow rate of 6 OB loops is 1628.61 kg/s from the BB design that the averaged mass flow rate is 271.435 kg/s for each loop, 90.4783 kg/s for each sector, 30.1594 kg/s for each segment, and 15.0797 kg/s in one flow direction (I/II). The longest OB loop is selected for the simulation. The average surface heat flux of 7 BMs is 0.22 MW/m² ($q_{segment}$) in the loop instead of q_{OB4}.

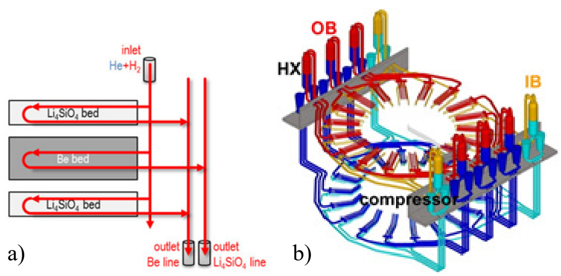


Fig. 2 Design: a) PG distribution [2], b) PHTS [5]

The vacuum vessel (VV) has a free volume of 2502 m³ and temperature of T_{OB_in} [6]. The suppression tank (ST) of the VV pressure suppression system (VVPSS) has a volume of 50000 m³ (V_{ST}), temperature of 20 °C and pressure of 4.5 kPa. It has the function of an expansion volume (EV) for the gas cooled concept. For small leak size, the bleed line (BL) connecting the VV to the ST will be triggered at a sub-atmospheric pressure limit of 90 kPa (p_{VV_BL}); for large leak size the rupture disc (RD) connecting the VV to the ST will be triggered passively at 150 kPa (p_{VV_RD}) to ensure the pressure limit of the VV at 200 kPa (p_{VV_limit}) (Fig. 3).

3. LOCA scenarios and assumptions

Cooling channels in a BM are located in the FW and BZ (Fig. 1). Thus two representative BB LOCA cases have been identified: case I in-BB LOCA for the failure of cooling channels in the BZ; case II in-vessel LOCA for the failure of cooling channels in the FW. The LOCA is assumed in one OB4 as the design based accident (DBA). Different scenarios due to the break sizes regarded as double-ended guillotine break (DEGB) (A_b) and plasma shutdown conditions are taken into account. Accidental sequences and assumptions are listed in Table 1. The typical break sizes are selected as (a) the smallest size with one cooling channel, (b) the largest size with one CP in the BZ or 10 cooling channels of the FW, which is assumed due to the runaway electrons (RE) in the worst case. It affects a surface area of 10 m² (A_{RE}) on the FW as continuous toroidal break at the equatorial level in strip form. At the LOCA initial the heat transfer coefficients (HTCs) of the FW and CP set to 0.0 without the convection. 3 s later the compressor is shut down due to the pressure measuring response time of at least 2 s. The plasma shutdown is assumed at 4 s (t_{plasma}) based on the FW temperature results in [7] that it is still below the design limit of 550 °C (T_{Eu_limit}) during the plasma burn at that time. Three plasma shutdown conditions are considered: (1) a fast plasma shutdown (FPSS) without the plasma disruption; (2) FPSS with the plasma disruption; (3) soft plasma shutdown for 60 s from ITER. In case I, the FPSS or soft plasma shutdown is activated at t_{plasma}. Case II leads to the inherent plasma shutdown by He ingress into the VV, which is assumed as the FPSS at t_{plasma} as well. The real time for the termination of the fusion power should be shorter than t_{plasma}. The total plasma disruption energy is assumed to be 0.5 GJ conservatively, which is evenly distributed over A_{RE} for a duration of 100 ms (t_{PD1}) or 10 ms (t_{PD2}). t_{PD1} leads to a FW surface power of 0.0926 GW in OB4.

Table 1. Accidental sequences and assumptions for the BB LOCA of DEMO HCPB blanket concept.

Case					I		II	
Failure condition					CP in BZ		FW	
Scenario					Ia	Ib	IIa	IIb
Assumptions	Nr. of the failed cooling channels				1	32 (1 CP)	1	10
	A_b (m²)				3.0e-5	9.6e-4	3.125e-4	3.125e-3
	He ingress into				PG		VV	
	PG line / Bleed line / RD				$p_{PG} > p_{PG\_limit}$		$p_{VV} > p_{VV\_BL} / p_{VV\_RD}$	
	A_PG / A_BL / A_RD (m²)				1.3254e-2		0.05 / 1.0	
Time evolution (s)	Steady state / LOCA				1000		1000	
	HTC = 0.0				> 1000		> 1000	
	Compressor shutdown				1003		1003	
	Plasma shutdown condition	FPSS	Plasma disruption	(1) no	1004 *(caseIa1)*	*(caseIb1)*	1004 *(caseIIa1)*	*(caseIIb1)*
				(2) 100 ms	1004 ~ 1004.1 *(caseIa2)*	*(caseIb2)*	1004 ~ 1004.1 *(caseIIa2)*	*(caseIIb2)*
				(2') 10 ms	-		1004 ~ 1004.01 *(caseIIa2')*	*(caseIIb2')*

(3) Soft plasma shutdown (60 s)	1004 ~ 1064 *(caseIa3)*	- *(caseIb3)*

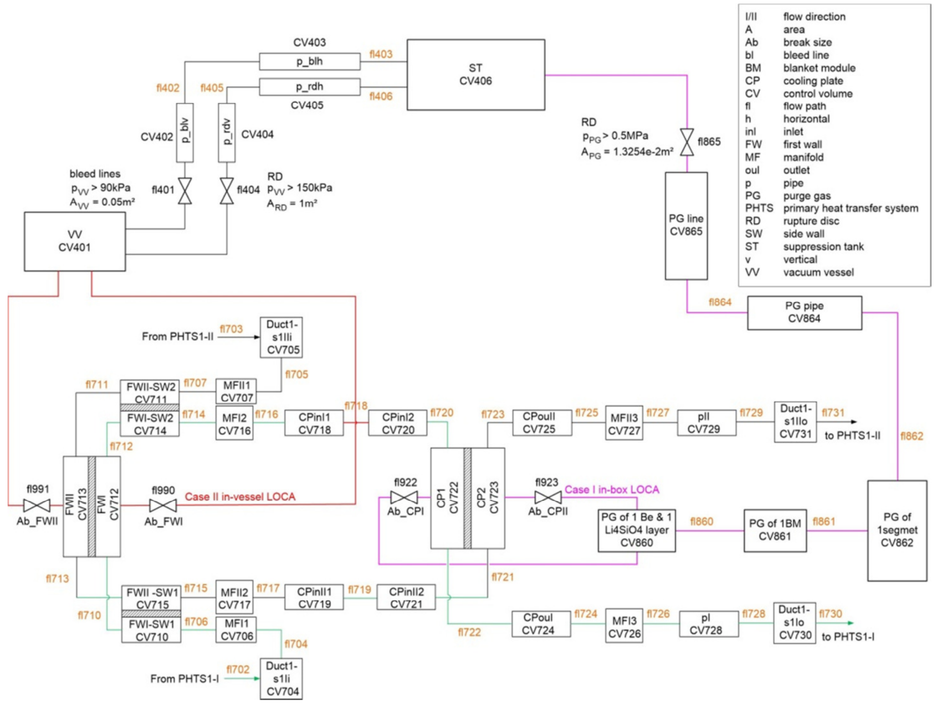


Fig. 3 MELCOR modelling for OB4 and LOCA conditions.

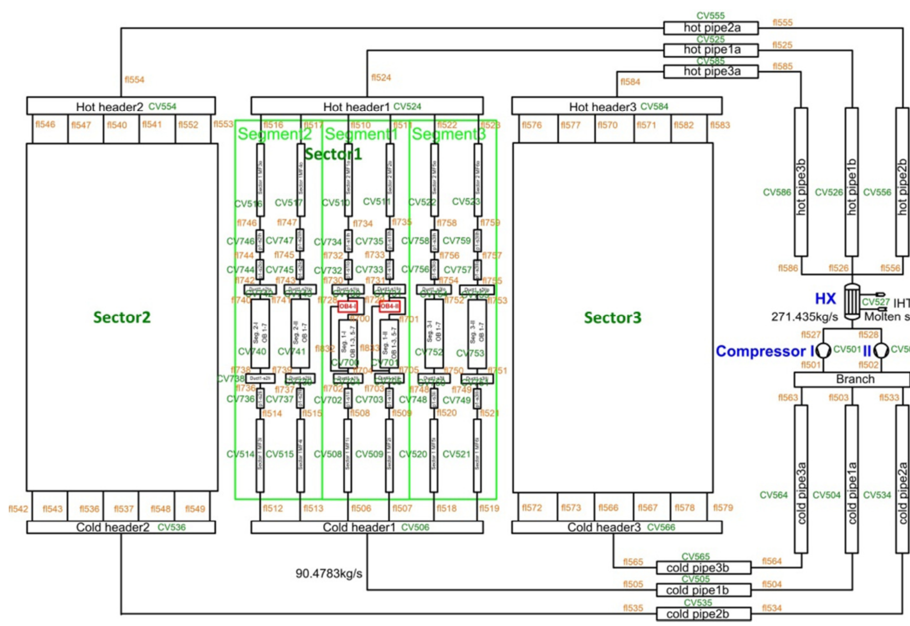


Fig. 4 MELCOR modelling for the loop with integrated OB4.

4. System modelling

Using MELCOR186 for fusion the system is modelled stepwise from single OB4 to one loop, and the integration of the OB4 in the loop.

Fig. 3 shows the modelling of one OB4 in two piping branches symmetrically. Components are modelled as control volumes (CVs) connected with flow path (fl) for the He flow. It is started with the inlet duct CV704 in PHTS-I and CV705 in PHTS-II for the counter flow. Heat structure (HS) is modelled one dimensional (1D) for the components such as the MFs, the FW, and the BZ considering the pebble beds volume. Convective boundary condition is applied with the HTC calculated by the HS package for the MFs, the FW HTC of 4212.2 W/m²K and the CP HTC of 4073.92 W/m²K in [2]. To avoid high FW temperature on the plasma side due to simple 1D-HS, heat exchange to other HSs for cooling channel fillets and FW rear side is modelled with MELCOR conduction function (FUN1) as well. The surface heat flux facing the plasma is multiplied with the surface area to be the surface power source. The nuclear power [8], the decay heat [9] and the power from the BZ to the FW rear side [2] are modelled as internal power source. At the shutdown, the maximum decay heat is 3.82% of the normal power in W, 2.67% in the FW, 1.63% in Be, 0.78% in Li_4SiO_4 and 3.13% in the CP. For modelling Be and Li_4SiO_4 pebble beds a packing factor (PF) of 63% is considered and properties of pebbles in He are used [10-12]. Material properties for EUROFER and W are taken from [13] and [14] respectively. Material temperature is limited at T_{Eu_limit} for EUROFER97, 650 °C for Be (T_{Be_limit}), and 920 °C for Li_4SiO_4 (T_{Li_limit}) in operation.

Fig. 4 shows the modelling of one OB loop with loop data from [5]. Two compressors (CV501 and CV502) are modelled with QUICK-CF pump model to evaluate the pressure boost. The HX (CV527) is modelled to remove enthalpy source that the flow is cooled down to the BM inlet temperature T_{OB_in}. One of three branches (fl503, fl533, fl563) supplies the flow into one of three sectors. After the cold header (CV506/CV536/CV566) the flow is distributed averaged in 6 branches due to 3 segments in counter flow. Before the integration of OB4 model, segment1 is modelled same as segment2 like CV740/CV741 that CV700/CV701 model 7 BMs. HSs associated to this CV are modelled based on the HSs of OB4 with respect to the FW in the front, side wall, fillet and rear side, Be pebbles and the bounded CPs, Li_4SiO_4 pebbles and the bounded CPs, and all remained structures (MFs). Since no detailed design of other 6 BMs is available, the surface area for the heat exchange is scaled based on the nuclear power distribution [8]. $q_{segment}$ is used in loop operation.

OB4 model between manifolds (MFs) CV706/CV707 and CV728/CV729 shown in Fig. 3 is integrated in the loop, which is represented as OB4-I and OB4-II in Fig. 4, and CV700 and CV701 model other 6 BMs in segment1 of sector1. Since the FW surface power for $q_{segment}$ is 44% of the power for q_{OB4}, keeping the same T_{OB_out}, the mass flow rate of OB4 in the loop ($\dot{m}_{OB4\_loop}$) is 5.5210 kg/s instead of $\dot{m}_{OB4}$. Energy loss coefficients are adjusted to achieve the required mass flow distribution in absence of valve control in the current design. The mass flow rate is controlled by the constant compressor velocity. Heat removal in the HX is controlled by control function (CF).

The VV is modelled with CV401 in Fig. 3 and HS. It is cooled by water to achieve 150 °C on the outer wall (T_{VV_ow}) and 200 °C on the inner wall. The related VV-PHTS is not modelled due to missing design. For running MELCOR, the VV is initialized with H_2 at 100 Pa and T_{OB_in}. CV406 models the VVPSS and it is assumed adiabatic, CV402 for the bleed line, and CV404 for the RD. fl401 models the pressure condition of the bleed line, fl404 for the RD, fl990 and fl991 for the FW failure, fl922 and fl923 for the failure of cooling channels of the CP. For the failure of one cooling channel fl991 or fl923 is closed. In the in-BB LOCA He ingresses into PG CV860, which models one Be and one Li_4SiO_4 layer with a free volume of 2.1555e-2 m³. Following the flow sequence, CV861 models one OB4 without the volume of CV860; CV862 with a volume of 3.0885 m³ models one segment without the volume of CV860 and CV861; CV864 for the in- and outlet pipes due to He ingress in both directions; CV865 for the PG line connecting the ST and fl865 for PG RD.

5. Simulation results

For the simulation He is used as working fluid. Time steps are selected between 0.1 ms and 0.1 s, which are suggested by the code developer. The normal operation is achieved with the results at steady state of 1000 s.

5.1 Steady state results

He inventory of the loop (m_{He_1loop}) is equal to 1.5848e3 kg for the total volume of 2.7491e2 m³, in which He mass of three sectors is 5.2509e2 kg including the in- and outlet piping, and the mass of the remained piping and components is 1.0597e3 kg. Results of the mass flow rate, pressure and He temperature are well comparable with the design data: 271.492 kg/s for the loop; 2.7640 kg/s for one segment in one flow direction; OB inlet pressure at 8.012 MPa and dp of 0.2214 MPa; OB inlet temperature at 300.10 °C and temperature increase of 199.36 °C to the outlet. The FW temperature on the boundary between EUROFER and W of OB4 (439.99 °C) is lower than the reference value of 544.0 °C due to $q_{segment}$. Correspondingly, OB4 FW outlet temperature of 361.0 °C is lower than the reference value of 380.45 °C for q_{OB4}. The FW temperature of sector2 (561.12°C) exceeds T_{Eu_limit}, because the CV representing one segment presents the outlet temperature of the blanket instead of the FW. Temperature of Be at ~565 °C and Li_4SiO_4 at ~663 °C are within their own ranges of the CFD reference.

5.2 Transient results

Transient start time of the LOCA is reset to 0.0 for the evaluation of all transient results. The transient is ended at 5 h (t_{end}). Decay heat at 1 h is adopted till t_{end}. Representative results are shown in Fig. 5, Fig. 6 and Fig. 7 for the pressure, temperature and mass respectively.

The break size has impact on He ingress with respect to the time evolution of the mass flow rate, pressure, temperature and mass. In the in-BB LOCA (case I), time to confine p_{PG_limit} is less than 1.0 s for the large break size, and 4.2 s only for the smallest break size (Fig. 5 (a)). Thus the TER system should be protected immediately after the LCOA by opening the RD. The pressure of CV860 reaches the maximum peak of 2.546 MPa at 8.3 s in caseIb. In the in-vessel LOCA (case II), time to confine p_{VV_BL} is 90 s for the smallest break size and the RD is inactive. For the large break size, time for p_{VV_BL} is 8.1 s and 15 s for opening the RD. The VV pressure reaches the maximum peak of 0.15 MPa at 14.7 s in caseIIb. The large break size causes fast pressure drop by the He loss in the BM (Fig. 5 (b)) and fast pressure increase in the ST (Fig. 5 (c)). The final pressure at equilibrium (p_{fin}) is achieved at 67 kPa in caseIb, at 62 kPa in caseIIa and at 60 kPa in caseIIb. Accordingly, He mass in the ST is 1.527e3 kg in caseIb, 1.465e3 kg in caseIIa, and 1.477e3 kg in caseIIb (Fig. 7). In caseIa, t_{end} is not long enough to reach the equilibrium. V_{ST} is large enough for the failure of one OB loop, since p_{fin} is below the atmospheric pressure. Additional simulation for case IIb shows that to obtain p_{fin} at p_{VV_limit}, the ST is reduced to 1.2476e4 m³ (V_{ST1}).

The plasma shutdown condition has impact on the FW temperature mainly. The highest heat flux load caused by t_{PD2} leads to a maximum temperature peak of 656 °C at 4.6 s in caseIIa2' (Fig. 6 (a)) and the duration of 16 s above T_{Eu_limit}. It should be clarified if this temperature and the duration could affect the FW integrity. Without the plasma disruption, the temperature peak is ~460 °C only. However, the simplified modelling of one segment or 6xBM in one CV leads to high temperature peak up to 575 °C (Fig. 6 (b)). Nevertheless, it saves large CPU time. Temperatures of Be and Li_4SiO_4 are below T_{Be_limit} and T_{Li_limit} respectively.

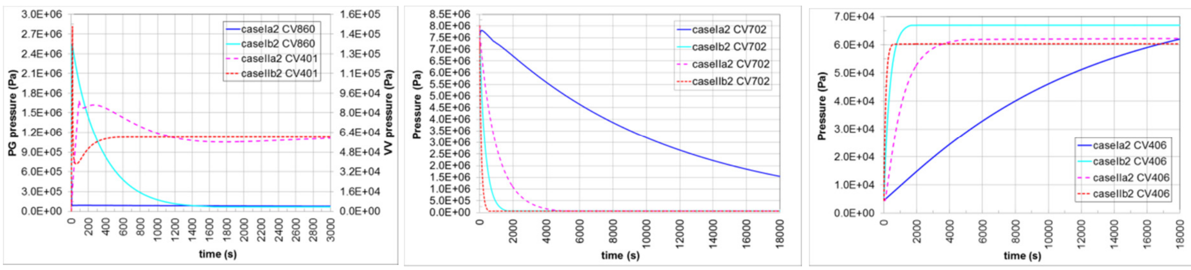
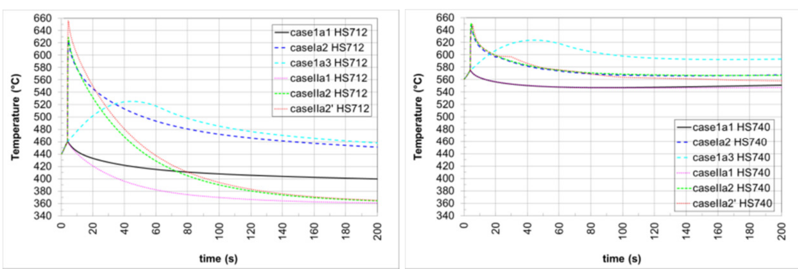


Fig. 5. Pressure: (a) PG or VV (b) BM inlet (c) ST



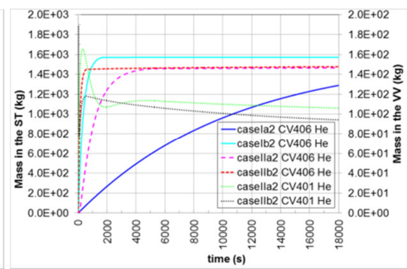


Fig. 6. FW temperature: (a) OB4 (b) CV for 7 BMs

Fig. 7. He mass

6. Summary

The BB LOCA in one OB4 of the HCPB2015V3 with the associated loop has been investigated using MELCOR 186 for fusion. Simulation of the loop including 3 OB sectors shows He flow behaviour at steady state comparable to the blanket design. Regarding m_{He_1loop} He inventory of all 6 OB loops can be 9.5090e3 kg, if the difference of piping arrangement for each loop is neglected. This large quantity is a challenge for dimensioning of the pressure relief systems in case of in-vessel, in-BB or ex-vessel LOCA. Based on the determined V_{ST1} for the in-vessel LOCA in one loop, the volume for the failure of all 6 loops can be 7.4856e4 m³. To reduce this volume, heat removal to the environment and to subcooled water in the same tank should be considered. The combined VVPSS and EV for both He and water are being explored in the EUROfusion safety program. The in-vessel LOCA affects the VV, while the in-BB LOCA can affect the TER system potentially. The break size has impact on the He ingress with respect to the time evolution of the mass flow rate, pressure, temperature and mass. Small break size decelerated the He loss speed, pressure drop, temperature change and He accumulation. The plasma shutdown condition has impact on the FW temperature. The high heat flux load caused by short disruption time leads to high temperature peak exceeding the design limit. To obtain local FW temperature distribution and hot spot, 3D thermal analysis should be investigated. The LOCA study will be improved with respect to the available system design and update accompanying DEMO development.

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.

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