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Preliminary accident analysis of ex-vessel LOCA for the European DEMO HCPB blanket concept

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In this study an ex-vessel LOCA is assumed with a double-ended guillotine break of a main pipe in an outboard loop of the primary heat transfer system (PHTS) that helium blows down into the tokamak cooling room (TCR). The reference designs are the HCPB2016 (helium cooled pebble bed) and the associated PHTS based on the European DEMO baseline 2015. For the design basis accident (DBA) a fast plasma shutdown (FPSS) followed by a plasma disruption is assumed at 3 s after the detection of the LOCA. Three main cases are considered with respect to three affected FW areas in one or two loops. An in-vessel LOCA is followed when the FW reaches 1000 °C. Eight scenarios are simulated using MELCOR 186 for fusion with respect to the mitigated or unmitigated plasma disruption conditions, the options of the dry or wet suppression tank (ST), the cooling ability of the vacuum vessel (VV), the emissivity of the radiation, and the transport of source terms performed for the BDBA. The transient results are discussed for the time evolution of the accident sequences, pressurization in the systems, temperature behavior in volumes and structures, and tritium and dust transport behavior.

Keywords: DEMO safety, HCPB, LOCA, MELCOR.

1. Introduction

Ex-vessel LOCA is one of the most critical events of the deterministic accident analysis within the EUROfusion WPSAE project. The potential evolution of this LOCA in an outboard (OB) loop of the PHTS with the integrated Helium Cooled Pebble Bed (HCPB) blanket concept in terms of pressurization of the tokamak cooling room (TCR), the vacuum vessel (VV) and the suppression tank (ST) needs to be evaluated. Radiological releases due to the aggravating in-vessel LOCA are studied as well. MELCOR 186 for fusion is used for this study [1].

2. Reference design

Following the European DEMO baseline 2015, HCPB2016 is the reference design [2]. Compared to HCPB2015V3 [4], the double-caps at the top and bottom of a blanket module (BM) are updated with 42 cooling channels in each cooling plate (CP). The channel cross section (A_c) is 5 mm x 5 mm. The same cooling channels number is also used in one CP of the breeder zone (BZ) with the unchanged A_c of 5 mm x 3 mm. The FW design is unchanged. The manifold from the FW to the BZ is extended to the cap. The main parameters of the equatorial BM (OB4) are the mass flow rate of 6.3293 kg/s ($\dot{m}_{OB4}$), the temperature of 300 °C (T_{OB_in}) and the pressure of 8 MPa at the blanket inlet, 500 °C at the blanket outlet (T_{OB_out}), surface heat flux of 0.5 MW/m² (q_{OB4}), and the thermal power of 5.07 MW. The pressure drops in the FW, the BZ, the cap, in- and outlet of the back supporting structure (BSS) are 6.3e4 Pa, 9.1e4 Pa, 4.0e3 Pa and 1.8e4 Pa respectively. The averaged heat transfer coefficients (HTC) in the FW, the cap and the BZ are 3862.92 W/m²K, 3072.0 W/m²K and 3284.7 W/m²K respectively. The PHTS designed with the inlet piping through the lower ports is adopted [3]. The averaged mass flow rate of each OB loop is 271.435 kg/s, 90.4783 kg/s in each sector, and 15.0797 kg/s in one flow direction of a segment (I/II). The average surface heat flux of 7 BMs is 0.22 MW/m² instead of q_{OB4}.

The vacuum vessel (VV) has a free volume of 2502 m³ and temperature of T_{OB_in} [5]. The suppression tank (ST) has a volume of 5.0e4 m³, temperature of 30 °C and pressure of 4.5 kPa. It has the function of an expansion volume (EV) for the gas cooled concept. Two options for the ST are selected. ST_1 is dry ST with air only, and ST_2 is wet ST filled with 100 m³ water as heat sink. Three relief pipes (RPs) and three rupture disc (RD) pipes from three neutral beam injection (NBI) ports connect the VV and the ST. The pressure limit of the RP and the RD are 90 kPa (p_{RP}) and 150 kPa (p_{RD}) respectively to avoid the VV exceeding 200 kPa (p_{VV}).

3. Ex-vessel LOCA assumptions and scenarios

The ex-vessel LOCA is assumed with a double-ended guillotine break (DEGB) of a cold pipe downstream of the compressor (Fig. 2). The break size (A_{b_ex}) is 0.622408 m². In case of the failure of two loops A_{b_ex} is assumed to be in each loop in order to determine the maximum pressurization of the TCR (Fig. 1). Actuation of the flow signal is defined at 80% of the nominal mass flow rate, at which the LOCA is detected (t_{sig}). Time for the fast plasma shutdown (FPSS) and compressor shutdown is assumed to be 3 s after t_{sig}. According to flow reduction the HTC is assumed to ramp down to 0.0 at t_{sig}. Table 2 shows three design basis accident (DBA) cases with the FPSS and one beyond design basis accident (BDBA) case (caseIV). Different disruption energies are applied for the mitigated or unmitigated

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plasma disruption related to failure of different FW surface areas. An aggravating in-vessel LOCA is assumed when the FW facing the plasma (EUROFER) reaches 1000 °C (T_{fail}). In CaseIV the plasma burns continuously until the FW fails at t_{fail}. Gas ingress into the VV causes the unmitigated plasma disruption for 4 ms before the plasma termination. The failure size of caseI is adopted. Concerning other options for the ST, the VV cooling abilities, the emissivity of the radiation from the FW to the VV, and the transport of source terms totally eight scenarios are taken into account. In MELCOR, He and water cannot be used as working fluids (WFs) in one system. Thus He is non-condensable gas (NCG) in use of ST_2. The VV cooling ability at steady state is assumed to be maintained during the transient except for caseIIIb and caseIVc, in which it is controlled to keep the VV temperature (T_{VV}) at T_{OB_in}. In caseIVd, the total W-dust inventory in the VV is 25 kg, and 5 kg dust due to the plasma disruption [5]. The maximum tritium inventory in the VV is 2450 g. Tritium mass in all BMs is 106.76 g and it is 0.640 g in each He loop. The mobilization fraction is 1.0.

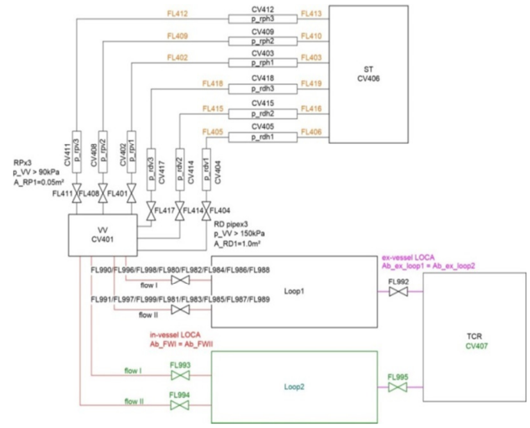


Fig. 1. System schema.

Table 2. Assumptions of the ex-vessel LOCA for DEMO HCPB blanket concept in different scenarios.

Case / scenario			I	II	IIIa	IIIb	IVa	IVb	IVc	IVd
FPSS			yes				no			
Plasma	mitigated 10 ms		7.5e-3	7.5e-2	-					
disruption	unmitigated	rise 1 ms	-		3 MJ	15 MJ	3 MJ			
energy		decay 3 ms	-		7 MJ	35 MJ	7 MJ			
Affected FW area (m²)			0.01	1.0	5.0		0.01			
Affected FW channels (OB4)			3	124 loop1, 84 loop2	992 8xOB4 loop1, 47 loop2		3			
ST			ST_2				ST_1	ST_2	ST_1	ST_1
Emissivity			0.25			0.8 (update)	0.25			
He			NCG				WF	NCG	WF	
VV cooling			steady			controlled	steady		controlled	steady
transport of source terms			-							yes

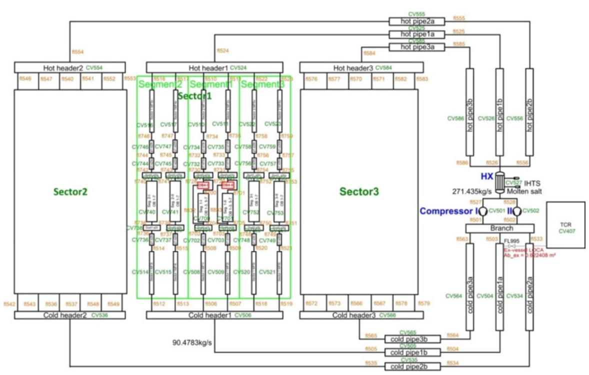


Fig. 2. MELCOR modeling for the loop with integrated OB4.

4. System modeling using MELCOR 186 for fusion

Fig. 1 shows the system schema modeled with the ex-vessel and the in-vessel LOCAs. Components are modeled as control volumes (CVs) connected with flow path (FL) for the He flow. Loop1 including three blanket sectors is modeled in detail in Fig. 2. One OB4 in segment1 of sector1 represented as two boxes (OB4-I and OB4-II) is modeled in detail in Fig. 3, and CV700 and CV701 model the other 6 BMs in parallel flow. Loop2 is modeled as duplication of loop1 by changing numbering of CV, FL, control function CF etc., and segment1 of sector1 is simplified without the OB4 model. LOCAs lead He ingress from both loops into the common TCR, VV and ST. System modeling has been described in detail in [4]. In the following only the updates are pointed out.

The ex-vessel LOCA is assumed with the break of cold pipe1a (CV504). Caps and BZ are modeled separately for HCPB2016 (Fig. 3). The nuclear data and the decay heat in [4] are adopted. The decay heat is extrapolated from 1 h to 1 day for the simulation. T_{VV} at T_{OB_in} is maintained by means of removing certain enthalpy source in the VV (Q_{VV}), while the VV outer wall temperature is defined at 200 °C. During the LOCA it is assumed that the VV cooling ability is unchanged as it at steady state except for caseIIIb and caseIVc. In these cases Q_{VV} is controlled to be large enough to keep T_{VV} at T_{OB_in}. 3 RPs and 3 RDs are modeled as well. CF401 in FL401, FL408 and FL411 models the pressure condition of the RP, and CF404 in FL404, FL414 and FL417 for the RD. FL990 and FL991 model the FW failure in loop1 when the FW temperature exceeds T_{fail}. CV407 models the TCR and its concrete walls are modeled as the heat structure (HS).

Radionuclide package is used for caseIVd. Dust and tritium in the VV are defined as aerosol sources by tabular function. Tritium mass of all BMs is distributed in BM CVs. Tritium in the loop is assumed to locate in the branch CV503. Dummy horizontal HSs are added by the required CVs for aerosol deposition on HS surface. Divertor cassettes surface for dust settling on is modeled as VV bottom surface.

5. Simulation results

Similar to [4], the He flow results are comparable with the blanket design at steady state of 1000 s. He inventory of one OB loop is 1.5848e3 kg. During the LOCA of both loops, doubled He inventory of 3.1696e3 kg will affect the TCR, VV and ST. Transient of the ex-vessel LOCA is initialized at steady state and it is ended at 9 h (t_{end}). The transient start time is reset to 0.0 for the evaluation of all transient results. Fig. 4 to Fig. 6 show the representative results.

He blowdown is detected at 0.0215 s (t_{sig}). The blanket pressure (Fig. 4 (a)) drops to the TCR pressure level (Fig. 4 (b)) within 10 s. The peak pressure of the TCR is 1.3072e5 Pa at 25 s from one loop, and 1.64465e5 Pa from two loops, while the maximum TCR temperature reaches 73.71 °C at 17 s and 109.56 °C respectively (Fig. 5 (b)). Due to the FPSS the in-vessel LOCA is 4 h 29 min 42 s delayed in comparison with the BDBA (caseI vs. caseIVb in Fig. 6). Consequently Opening of the RP is 4 h 46 min 34 s delayed (Fig. 4 (c)). Larger break size of the FW leads to the earlier in-vessel LCOA. The affected structure temperature decreases after reaching T_{fail} and then returns due to the decay heat (Fig. 6). In caseIVb this temperature increases up to 1024.67 °C, and then decreases. In Fig. 4 (c), for the small break size (caseI and caseIV) the VV pressure decreases significantly and the system equilibrium is not reached at t_{end}, while for the large break size (caseII) it increases again to reach the equilibrium. For the largest break size (caseIII) the VV pressure increases continuously after the RP opening to a peak value of 1.2077e5Pa. For all scenarios the equilibrium pressure does not exceed p_{RD} that the RD is closed all the time.

The in-vessel LOCA causes gas expansion from the affected volume at high temperature and high pressure (CV712) into the large VV, which leads to the temperature drop in CV712 (Fig. 5 (a)) and a temperature peak in the VV (Fig. 5 (c)). The largest peak is 1397.18 °C in caseIIIa. Because the VV contains the positive pV work term to the internal energy of the expanding gas, while CV712 contains the negative work term. In caseIIIa, keeping Q_{VV} of -7.9789e4 W required for steady state, the maximum VV temperature reaches 1397.18 °C at 16059 s and it is higher than T_{OB_in} in long term. To retain T_{VV} at T_{OB_in}, a controlled power up to -4.5106e6 W is removed (caseIIIb). The maximum VV temperature is 1344.71 °C; and the RP opening time of 16884 s is 812 s delayed against caseIIIa (Fig. 4 (c)). For the BDBA (caseIV), the maximum VV temperature reaches 889.47 °C at 142 s (caseIVa) by keeping Q_{VV} of -3.9960e4 W. To retain T_{VV} at T_{OB_in}, a controlled power up to -1.5183e6 W is removed (caseIVc). Hereby the maximum VV temperature is 860.05 °C; the RP opening time of 7563 s is 2210 s delayed against caseIVa; and the temperature in ST_1 up to 354.06 °C at t_{end} is 260 °C less than it in caseIVa (Fig. 5 (d)).

The ST pressure at the equilibrium (Fig. 4 (d)) is higher from the failure of two loops (caseII & caseIII) than it from one loop. The ST masses from the small break size are significant lower than they for the large break size, but the TCR masses are more due to less He loss into the VV. The maximum mass in the VV is below 1000 kg. The dry ST_1 leads to the ST temperature increase up to 613.93 °C at t_{end} (caseIVa) (Fig. 5 (d)). The wet ST_2 keeps the temperature at 44.50 °C after the peak temperature of 110.22 °C at 5445 s (caseIVb). In ST_1 (caseIVa) the He mass is 126.83 kg at t_{end} and the total mass is 6235.0 kg, while in ST_2 (caseIVb) the He mass is 133.39 kg, the total gas mass is 3902.2 kg, and the total mass including water is 1.03435e5 kg.

The most dust and tritium remain in the VV due to the small break size (caseIVd). 32.412 kg as all masses are deposited on the VV HS, and only 3.8410e-2 kg are deposited on all other HSs except for the VV HS. At t_{end} the total dust aerosol mass in the VV and on the VV HS is 29.9644 kg, and 4.7863e-3 kg dust is transported to the ST, but no dust is found in the TCR. The total tritium aerosol mass in the TCR and on the TCR_HS is 1.8845e-2 kg, 2.4478 kg in the VV, and 5.7207e-4 kg in the ST.

6. Summary

Eight scenarios have been simulated for HCPB2016 due to the ex-vessel LOCA followed by an in-vessel LOCA with respect to the FW failures sizes, the plasma disruption conditions, the ST options, the VV cooling abilities, the emissivity of the radiation, and the source terms transport in DBA or BDBA. He inventory of two loops has impact on the pressurization of the TCR, VV and ST that the He blowdown leads to a pressure peak of 1.64465e5 Pa in the TCR, which is 25.81% higher than it in one loop. In DBA, the in-vessel LOCA occurs between 4.46 h (caseIIIa) and 4.53 h (caseI). The BDBA leads to the in-vessel LOCA at ~134 s (caseIV). The larger break size leads to earlier opening of the RP, and the VV pressure reaches the maximum peak for the largest break size. Removing excessive power in the VV, T_{VV} retains at T_{OB_in}, also increase of the VV pressure is decelerated, which postpones the RP opening time. The VV pressure increased to the system equilibrium level does not affect the RD opening. Temperature in the wet ST can be reduced effectively, and the equilibrium pressure is sub-atmospheric. For the small break size, the dust and tritium stay mainly in the VV. Dust in the VV is not transported to the TCR, but tritium from the loop is transported to the TCR. In the next step, in-vessel LOCA due to thermal quench for large failure size in two loops should be investigated to determine the maximum pressurization of the VV, and source terms transport for the maximum releases. The VV should be modeled with detailed HSs to remove power sufficiently.

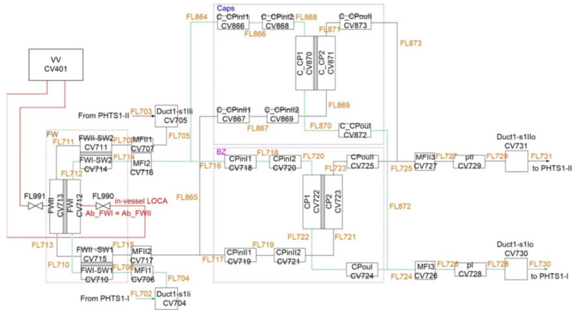


Fig. 3 MELCOR modeling for OB4 with the in-vessel LOCA

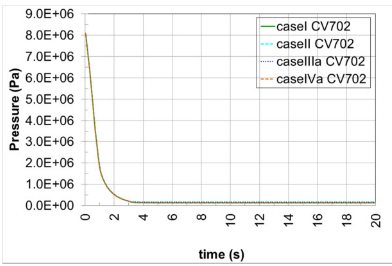
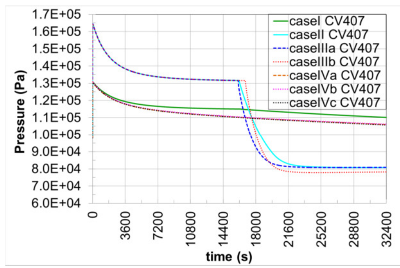
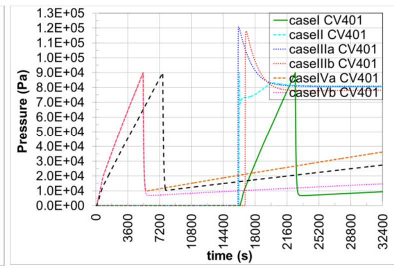


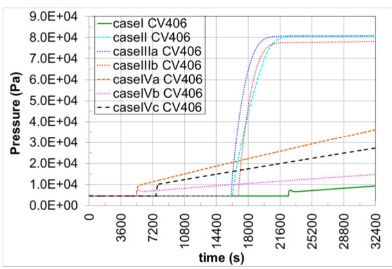
Fig. 4. Pressure: (a) BM inlet



(b) TCR



(c) VV



(d) ST

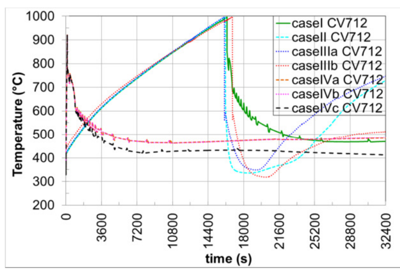
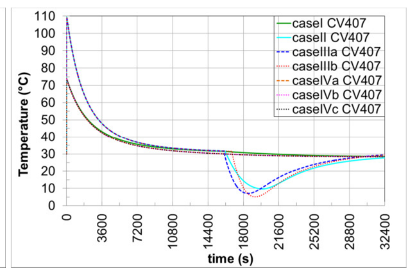
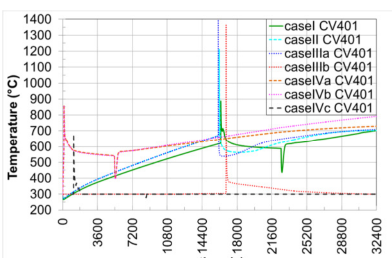


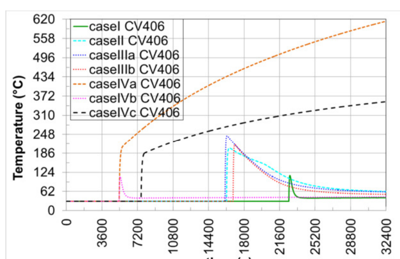
Fig. 5. He temperature (a) OB4 FW



(b) TCR



(c) VV



(d) ST

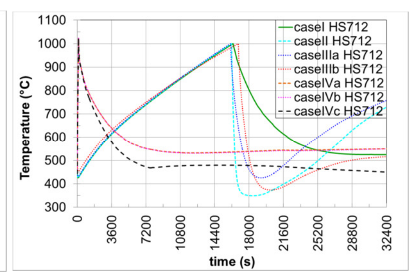


Fig. 6. FW temperature

Acknowledgments

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References

[1] B. J. Merrill et al., Recent development and application of a new safety analysis code for fusion reactors, Fusion Eng. Des. 109-111 (2016) 970-974.

[2] F.A. Hernández et al., Overview of the HCPB Research Activities in EUROfusion, IEEE Transactions on Plasma Science PP(99): 1-15 May 2018.

[3] F. Cismondi et al., Input data by BB - BOP for SAE-VVPSS, EFDA_D_2MWTX5_V4_0, 2016.

[4] X. Jin, BB LOCA analysis for the reference design of the EU DEMO HCPB blanket concept, Fusion Eng. Des. xxx (2018) xxxx–xxxx. In press

[5] M.T. Porfiri, G. Mazzini: DEMO BB Safety Data List (SDL), EFDA_D_2MF8KU_v2_0, 2016.