ANALYSES OF LOCAS IN THE PRIMARY HEAT TRANSFER SYSTEM OF THE HELIUM COOLED PEBBLE BED BLANKET CONCEPT

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ABSTRACT

The future introduction of fusion power plants requires also the demonstration that all the radiological risks, in term of potential hazards to the staff, the population and the environment, are below the limits established by national authorities in both normal and off-normal conditions. As for Light Water Reactors (LWR), one of the most challenging accidents is the Loss of Coolant Accident (LOCA), which causes the depressurization of the Primary Heat Transfer System (PHTS) and the pressurization of the confinement structures and components, as the Vacuum Vessel (VV), the Expansion Volume (EV), and the Tokamak Building (TB). Hence, a detailed analysis on the break area and on the location of the rupture should be executed to demonstrate that the confinement barriers are able to withstand the pressure peak within design limits and the residual cooling capabilities of the PHTS are sufficient to remove the decay heat coming from the in-vessel components. Nonetheless, basing on the results of these analyses, several improvements can be introduced in the systems design in order to improve the overall safety performances of the plant itself. For this purpose several Ex-vessel and In-vessel LOCA analyses for the PHTS of the DEMOnstration Power Plant (DEMO) Helium Cooled Pebble Bed (HPCB) blanket concept have been conducted. In particular, two PHTS designs have been investigated, the first developed in the 1992 which is actually considered the reference design for the HCPB blanket concept, and a new one (alternative design) developed basing on the preliminary safety analysis results of the reference design. The aim of the work is to compare the performances of the two designs basing on the pressure peak values within the confinement barriers and the release of He inventory from the PHTS. Finally, taking into account the results of these analyses, considerations are formulated on the design criteria of the confinement barriers.

KEYWORDS
HCPB, Ex-Vessel LOCA, In-Vessel LOCA, fusion power plant, DEMO.

1. INTRODUCTION

The exploitation of Fusion as energy source requires the demonstration of a limited impact in term of risk to the staff, the public, and the environment, well below the limits established by the national safety authorities. Hence, a systematic safety analysis has to follows the design development to demonstrate that the safety objectives are met for each solution proposed.

The first fusion reactor designed to prove the capabilities to produce electrical power in a safe and commercially acceptable way is DEMO. Several design solutions have been proposed for such reactor, basing on the blanket concepts investigated [1]. Parallel to the development of the blanket concepts, also several different PHTS designs have been developed. To date, HCPB blanket concept and its PHTS seems one of the most promising solutions proposed [2] [3] [4]. Although, in previous analyses some concerns have been highlighted due to the huge helium inventory contained inside its PHTS [5]. For this purpose, an alternative PHTS has been proposed and compared to the reference one [5]. The present work is then a prosecution of the previous analyses [5] employing an improved modelization of the PHTS and carrying out a code-to-code comparison among MELCOR 1.8.2 fusion version and ASTEC V2R3p2 codes. The capabilities of the old MELCOR 1.8.2 version (originally released in 1993) has been extended during the latest years to cover also some specific fusion related phenomena [6]. For this purpose, also if the original source code and modelling is quite old, the fusion version is still employed in fusion activities, and its capacities have been widely proven during the preliminary safety analyses for the ITER facility [7]. On the contrary, for ASTEC no specific fusion versions have been released so far, but works are under way to extend the capabilities of the code to model such plants [8].

The aims of this analysis can be listed as follow:

- Investigate, through the application of the MELCOR code, the influence of the break area and its position on the behaviour of the two HCPB PHTS. Several rupture sizes located in the main PHTS pipes have been investigated, spanning from Large Break LOCAs (LB-LOCAs) to Very Small Break LOCAs (VSB-LOCAs). The models employed in this task are characterized by a coarse description of the system, but sufficient to highlight the behaviour of the EV, the VV, and the two PHTS designs;
- Basing on the PHTS behaviours, propose easy but useful tips to reduce the severity of accidents through the actuation of safety valves and the application of accident management actions; and
- Execute a code-to-code comparison among MELCOR 1.8.2 (fusion version) and ASTEC V2R3p2. For MELCOR, a special version developed to cope with the fusion related phenomena has been employed [6], while for ASTEC the generic LWR version has been employed [9]. The aim of this comparison is to check the reliability of the results obtained, and to stress the different modelling approaches among the two codes. This last task is developed to asses eventual lacks of the ASTEC code when applied to helium cooled loops. To do so only the reference PHTS has been considered because the the modelisation assumptions behind the two designs are identical.

The following work is subdivided into six sections:

- The first section provides a short introduction of the work, its goals and the subdivision of the paper;
- The second section briefly present the HCPB concept, and the two PHTS designs;
- The third section describes the Ex-Vessel scenarios, the nodalisations employed, and the results of three hot header LOCAs;
- The fourth section describes the In-Vessel scenarios, the nodalisations employed, and the results of two LOCAs;
- The fifth, and last section, reports the main conclusions of the work.

2. THEORY

2.1. The Helium Cooled Pebble Bed Blanket Concept

The Helium Cooled Pebble Bed blanket concept is developed at Karlsruhe Institute of Technology (KIT), as part of the European efforts on the fusion technology researches [1]. This concept consists of a solid breeder material (Li_4SiO_4 or Li_2TiO_3) in form of pebbles employing helium as coolant. The blanket structure is composed by several boxes, which can be subdivided into three radial zones:

- The First Wall (FW) is made of EUROFER and protected through a Tungsten layer (W layer). The maximum temperature of the FW should not exceed 550 °C to preserve its microstructure and mechanical properties [10]. The W layer is added to reduce the erosion produced by the plasma. The aim of the FW is to protect the outer regions of the machine from the netruon damage, and to provide a suitable heat transfer area for the heat coming from the plasma.
- The Breeding Zone (BZ) is needed for the production of Tritium. The BZ is composed as a sandwich (in tangential direction) of pebble beds, cooling plates/pipes, and Be pebbles for neutron multiplication. This complex layout enable the attainment of a self-sufficient Tritium Breeding Ratio (TBR). However, the TBR is also influenced also by the thickness of the FW, which should be sufficiently small to reduce the neutron parassitic captures. Although, also if the box structure is quite complex, and the steel content is reduced as much as possible to increase the TBR, the overall box resistance is quite good and a maximum pressure of $\sim$2 MPa can be born.
- The Back Supporting Structure (BSS) hold the box in position, and it feed the box coolant circuits thanks to 4 manifold.

The arrangement of these boxes can be described as follows: the blanket is subdivided in 16 sectors each composed by three Out-Board (OB) and two In-Board (IB) segments, in turn composed by six poloidally-arranged blanket boxes each. In total 48 OB and 32 IB segments compose the blanket itself, and each sector covers an angle of 22.5° (Figure 1). Further details on the HCPB concept can be found in [11], and in [12].

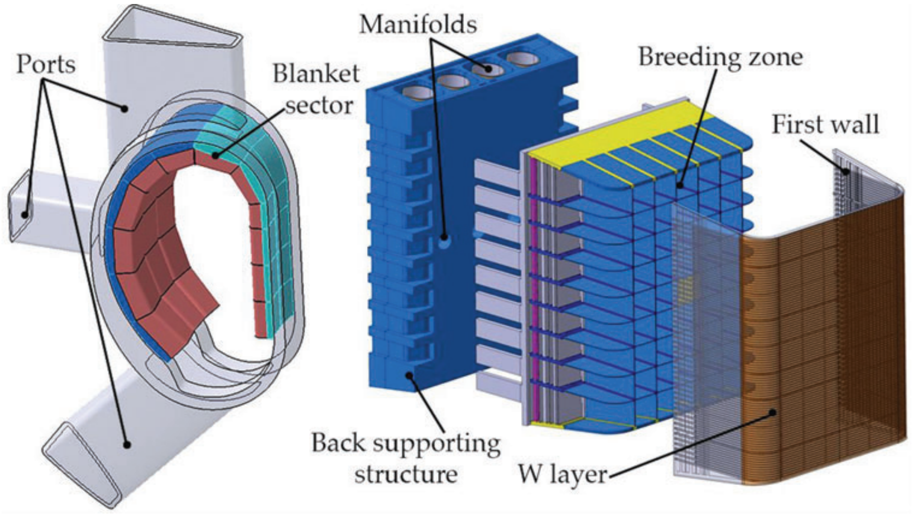

Figure 1. Blanket description.

2.2. The Primary Heat Transfer System

2.2.1. Reference design

The conceptual cooling strategy for the HCPB Blanket is based on the use of four independent cooling circuits: two for the OB segments and two for the IB ones. This layout allows the cooling of the FW channels in counterflow to increase the overall blanket heat transfer performances. These two cooling circuits are connected to the blanket segments via the manifolds in the BSS. Each cooling circuit consists of five Cooling Trains (CTs) plus one spare for the OB, and two CTs plus one spare for the IB. Each CT foreseen a Steam Generator (SG) and a compressor (Figure 2). The design data of the reference PHTS reported in Table I are taken from [3] except for the temperature range which is taken from [12].

The connection among the blanket OB segments and the PHTS is made through 48 pipes crossing the VV upper port. The pipes size is DN 250 inside and DN 350 outside the VV upper port to reduce the velocity of the coolant and the pressure drops. The coolant is then collected by four hot headers (200 m^3 each), which in turn re-distribute the coolant to the CTs (main pipes size DN 1200). Finally, four cold headers collect and re-distribute the coolant to the blanket segments (Figure 2). The size of pipes, compressors, SGs, and valves are the same for both the OB and the IB loops and the overall design layout rely on a quite good standardization. Further details on this design can be found in [3], [4], and [12].

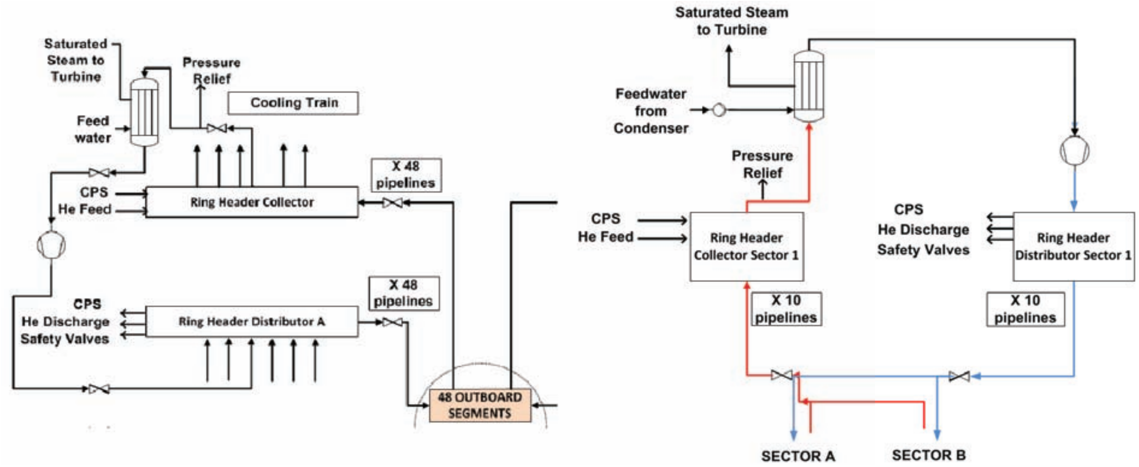

Figure 2. PHTS reference (left) and alternative (right) designs sketch.

Table I. PHTS reference and alternative design data of each cooling loop.

Characteristic	**Unit**	**Ref. design**	**Alt. design**
Power	[MW]	910.5	156.25
T_{in} - T_{out}	[°C]	300-500	300-500
Flow rate	[kg/s]	875.5	153.5
Nominal Pressure	[MPa]	8.0	8.0
Total Pressure Drop	[MPa]	$\sim$0.4	$\sim$0.4
n. of CTs		18	16
operational/spare CTs		14/4	16
Coolant volume	[m^3]	$\sim$1180.0	$\sim$186.0
Coolant mass	[kg]	$\sim$6800.0	$\sim$1070.0

2.2.2. Alternative design

The huge helium inventory contained in each coolant loops of the reference design poses several risks to the integrity of the EV and the VV during incidental conditions. For this purpose an alternative PHTS design has been proposed and developed at KIT [5]. This alternative design has been developed to reduce the helium inventory contained in each loop, and to increase the number of independent coolant loops.

The main differences among the two designs are the number of the coolant loops, and the reduced size of the hot and cold headers (Figure 2). From the blanket module 10 outlet pipes (5 from an IB sector and 5 from an OB sector) route the coolant to an hot header. In turn, a single coolant pipe drives the coolant fluid through a SG and and then to a cold header. Finally, the coolant is routed back to the blanket segments from the cold header through ten pipes. The blanket inlet and outlet pipes, as well as the main coolant pipe, have the same dimensions of the reference design ones, while the headers are scaled down to 10 m^3 (instead of 200 m^3).

This solution increases the number of independent coolant loops from 4 to 16, leading to a reduction of the coolant inventory contained inside each loop. For this purpose, thanks to the reduced helium inventory releasable, lower stresses to the EV and the VV are expected. The design data of the alternative PHTS are summarized in Table I.

3. EX-VESSEL SCENARIOS

3.1. Nodalisations & scenarios

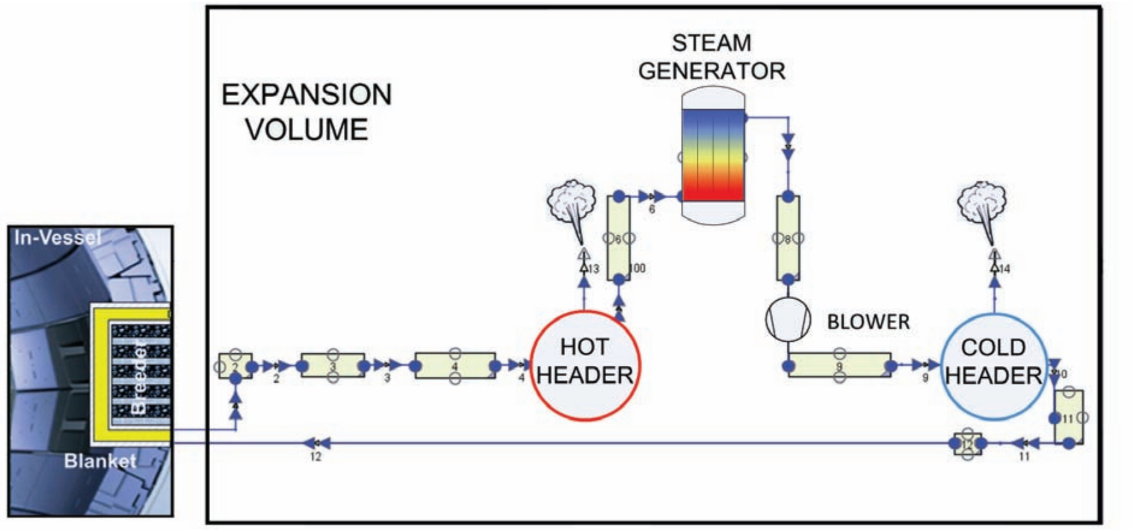

Figure 3. Ex-Vessel nodalisation.

As stated in [4], the most challenging Postulated Initiating Events (PIEs) are the LOCAs spanning from a double guillotine break to small leakages. In the following pages the results of three hot header LOCAs are briefly analysed.

The reference and the alternative designs have been simulated with a similar nodalisation, but with different dimensions to reflect the different size of their coolant loops. Figure 3 shows a sketch of the nodalisations employed, and in Tables II, III, and IV the main characteristics of Control Volumes (CVs), the Flow Path (FP) and the Heat Structures (HSs) are reported. The geometrical subdivision of the CVs has been performed to follow as close as possible the description reported in [3]. Similarly, the friction factors of the various flow paths have been set according to the geometrical features of the pipes layout reported in [3] and in [5].

In both models the pipes passing through the boxes are simulated as a single lumped CV (BL). This CV is then connected to the first of the three CVs simulating the blanket outlet pipes (BP1, EN, and BP2). The friction factor (in both direction) of the flow path connecting BL and BP1 is set to 15.4 to obtain the same total pressure drops reported in [3]. The last blanket outlet pipes CV (BP2) is connected with the hot header CV (HH), and in turn the hot header CV is connected to the main coolant pipes routing the coolant to the SGs (HL). As for the blanket outlet pipes, also the main coolant pipes are simulated a lumped CV subdivided into three parts: the first simulating the ”hot leg” from the hot header to the SG (HL), and the other two simulating the cold leg before and after the helium blower (CL1 and CL2). As for the blanket

Table II. Control Volumes main data.

	Reference design		Alternative design	
CV name	**Flow area [m^2]**	**Volume [m^3]**	**Flow area [m^2]**	**Volume [m^3]**
BL	0.5195	112.32	0.1039	23.4
BP1	2.171	2.171	0.4524	0.4524
EN	2.92	2.92	0.6083	0.6083
BP2	3.755	37.55	0.7823	7.82
HH	/	183.2	/	9.16
HL	4.58	206.1	0.9161	41.22
SG	0.5195	184.7	0.1039	36.9
CL1	4.58	91.6	0.9161	18.32
CL2	4.58	114.5	0.9161	22.9
CH	/	183.2	/	9.16
BP3	3.15	31.5	0.6555	6.56
RD	2.2	2.2	0.4581	0.4581
EV	/	70000.0	/	70000.0

Table III. Flow Paths main data.

			Reference design		Alternative design	
CV name	**From**	**To**	**Flow area [m^2]**	**Friction factor**	**Flow area [m^2]**	**Friction factor**
BLBP1	BL	BP1	2.171	15.4	0.452	22.4
BP1EN	BP1	EN	2.171	1.0	0.452	1.0
ENBP2	EN	BP2	3.75	1.0	0.7822	1.0
BP2HH	BP2	HH	3.75	1.5	0.7822	1.5
HHHL	HH	HL	4.58	1.0	0.9161	1.0
HLSG	HL	SG	4.58	5.2	0.9161	5.2
SGCL1	SG	CL1	4.58	15.77	0.9161	23.77
CL1CL2	CL1	CL2	4.58	2.1	0.9161	2.1
CL2CH	CL2	CH	4.58	2.7	0.9161	2.7
CHBP3	CH	BP3	3.15	1.0	0.6555	1,0
BP3RD	BP3	RD	3.15	1.5	0.6555	1.5
RDBL	RD	BL	1.42	0.5	0.4581	0.5

Table IV. Heat Structures main data.

Characteristic	**HSBLK**	**HSSG**	**HSEV**
Thickness	EUROFER 25 mm	AISI 316L 2 mm	AISI 304 1 mm, Concrete 1 m
Reference design			
Area [m^2]	2500.0	15000.0	7850.0
Boundary cond.	Injected 910.5 MW	Removed 910.5 MW	HTC calculated by the code
Alternative design			
Area [m^2]	3000.0	3000.0	7850.0
Boundary condition	Injected 153.5 MW	Removed 153.5 MW	HTC calculated by the code

piping, the SG pipes are simulated as single CV and the friction factors (in both directions) of the flow path connecting SG and CL1 are set to $\sim$15.8. In the following, the cold leg is connected to a cold header (CH), which redistribute the coolant to the blanket inlet pipes (BP3 and RD). As for the blanket outlet pipes also the inlet pipes are simulated lumped together, but subdivided into two parts instead of three.

The entire plant is placed inside a containment building called Expansion Volume (EV). The design of the EV has been not yet finalised, so its characteristics have been supposed similar to those employed for the Power Plant Conceptual Study [13].

In both models also three HSs are added:

- The first HS simulates the blanket piping (HSBLK). The inner side of this HS is attached to blanket piping CV (BL1), while at the outer side a power injection is employed as boundary condition.
- The second HS simulates the SG pipes. The inner side of this HS is attached to the SG CV, while at the outer side a power extraction is employed as boundary condition.
- The third HS simulates the EV walls. The inner side of this HS is attached to the EV, while at the outer side the HTC toward the outer environment is calculated by the code.

The data for the blanket and the SG piping (HSBLK and HSSG) have been taken from [3], while for HSEV the data assumed have been based on the Power Plant Conceptual Study.

The helium blowers have been modelled with the following characteristics:

- Maximum pressure head set to 3.82E5 Pa for the reference design, and at 3.6E5 Pa for the alternative one;
- Volumetric flow rate at zero pressure head set to 357.55 m^3/s for both designs;
- Volumetric flow rate at maximum pressure head set to 151.1 m^3/s for both designs.
- Blower trip occurring in the same instant of the rupture (at 10.0 s in the graphs).

The breaks among the PHTS and the EV have been simulated as a valve opening at 10.0 s, and the following slope for the decay power has been employed: [14]

- In 1.0 s the plasma power falls down from 100% to 5%;
- From 1.0 s to 3600.0 s the plasma power remains constant to 5%;
- From 3600.0 s to 7200.0 the plasma power decrease from 5% to 1%;
- From 7200.0 s till the end of the simulations the plasma power remains constant to 1%.

The data reported above are valid for both codes, but in ASTEC the initial temperatures of HSBLK (500 °C) and HSSG (300 °C) instead of the plasma power have been imposed as boundary conditions. The causes behind this modifications are:

- In ASTEC helium can be simulated only as an incondensable gas instead of a coolant; and
- Incondensable gases do not participate to heat exchange phenomena;

It should be also noted that the alternative design has been simulated only with the MELCOR code.

3.2. Results

Three hot header LOCA cases have been investigated:

- The first case characterized by a break size of 1.832 m^2 (200% of the hot header nominal area);
- The second case characterized by a break size of 9.161E-2 m^2 (10% of the hot header nominal area); and
- The third case characterized by a break size of 9.2E-4 m^2 (1% of the hot header nominal area).

In Figures 4 and 5 are reported the pressure trends for the PHTS and the EV for the reference and the alternative designs, respectively. In Table V a summary of the main results for both designs is shown.

As expected, the decrease of the break area lead to slower transient. For a break size of 1.832 m^2 the blowdown phase ends in less than 5 s in both designs, reaching a maximum pressure of 0.239 and 0.122 MPa for the reference and alternative designs, respectively. This difference can be explained considering the different different helium inventory contained inside the two PHTS designs.

For a break size of 9.2E-2 m^2 the blowdown phase ends in $\sim$70 s in the reference design, and in $\sim$15 s in the alternative one. The maximum pressures reached are 0.239 and 0.122 MPa for the reference and the alternative designs, respectively.

For a break size of 9.2E-4 m^2 the blowdown phase ends in $\sim$7200 s in the reference design, and in $\sim$2400 s in the alternative one. The maximum pressures reached are 0.323 and 0.122 MPa for the reference and the alternative designs, respectively. In this case the break area is small enough to produce a quite slow transient. The slow blowdown lead to a longer period in which helium is in contact with blanket piping HS (HSBLK). This phenomenon lead to a greater removal of the decay heat compared to the previous two break cases. Although, the slow transient increases also the influence of the heat exchange phenomena among the EV and the outer environment. The sum of these two phenomena is different in the two designs: in the reference design the heat exchange toward the outer environment it not sufficient to remove the decay power leading to a higher pressure (compared to the two previous cases), while in the alternative design the heat exchange toward the outer environment is sufficiently high to limit the maximum pressure to values comparable with the previous two cases.

Moreover, MELCOR and ASTEC predict slightly different trends due to the differences among them. In ASTEC helium is treated as an incondensable and it does not partecipate to the heat exchange phenomena. On the contrary, in MELCOR helium is a coolant. Thanks to this difference the MELCOR blowdowns are slower compared to the ASTEC ones because the heat extracted from the blanket HS (HSBLK) slightly reduces the severity of the helium expansion.

Another difference among the two codes can be found in the long-term behaviour of he EV. In MELCOR the EV total pressure slightly increases, while in ASTEC it decrease thanks to the heat exchange with the outer environment. This difference is due to the different Heat Transfer Coefficients (HTCs) calculated among the two codes. Although, a special mention should be made for the alternative design affected by a break size of 9.2E-4 m^2. As shown in Figure 5 the PHTS pressure around 1050 s starts to increase and the in decreases to the equilibrium pressure value. In the same time, in the EV the pressure remains quite constant. This behaviour is shown only in this case, and it may be due to the combination of the low decay power and the very small break size investigated. Probably, during this period the mass flow rates across the rupture are not sufficiently high and the decay heat remains inside the PHTS. Then, when a sufficient pressure difference is again reached among the PHTS and the EV, the mass flow rate across the break increases again and the decay power restarts to be transported to the EV. After this pressure peak the system reach equilibrium conditions, and such conditions is preserved till the end of the simulations. Although, his phenomenon may be a periodic behaviour characterized by cyclic increases and decreases of the PHTS pressure. However, such behaviour is not shown in the simulations carried out probably because the power decay slope employed covers the following pressure increases and decreases.

Under the safety point of view several remarks can be reported:

- The break sizes of 1.832 and 9.2E-2 m^2 lead to fast blowdown. These transients are too fast to perform any mitigative action, as for example the actuation of the safety valves placed on the main coolant pipes (the hot and cold legs). This lead to the complete release of the coolant inside the EV, which reaches quite high pressure value in the reference design (<0.3 MPa). On the contrary, in the alternative design the EV reaches lower values (<0.14 MPa), allowing the relaxation of the EV design limits.
- The break size of 9.2E-2 m^2 lead to a quite slow blowdown in both designs, allowing the execution of mitigative actions to reduce the severity of the transient. These actions are mandatory in the reference design because the heat exchange toward the outer environment is not sufficient to limit the maximum EV pressure. At the same time, in the alternative design the maximum pressure value is comparable with the previous two cases, thus mitigative actions may be also not performed.

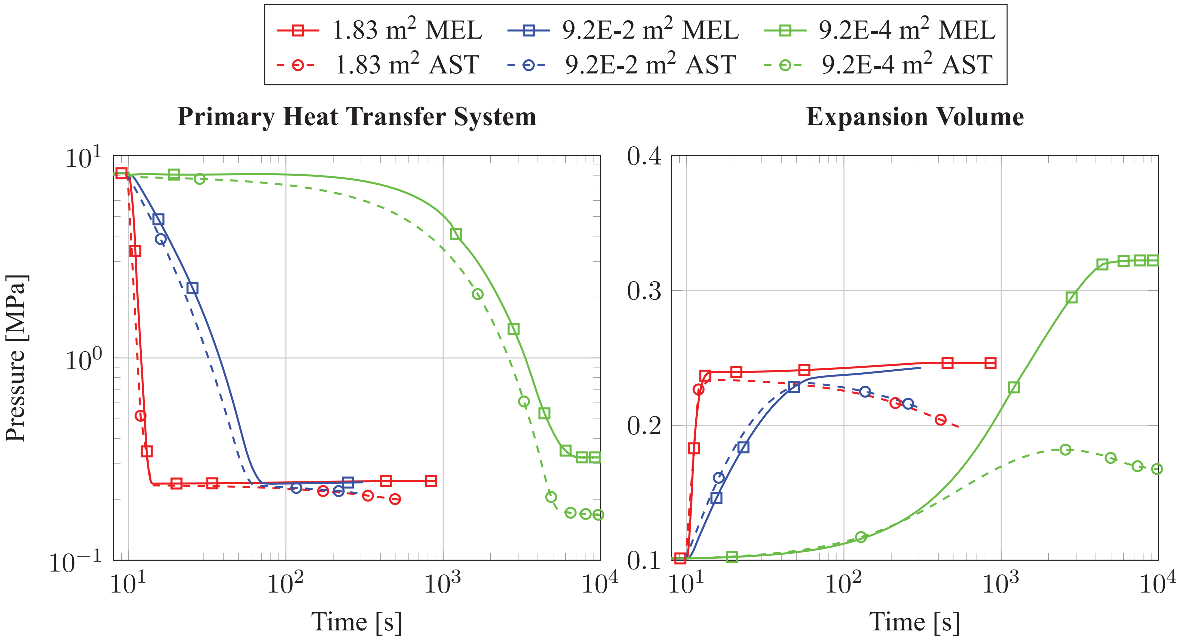

Figure 4. PHTS and EV total pressure trends during the Hot Header LOCA scenarios (reference design).

4. IN-VESSEL SCENARIOS

4.1. Nodalisations & scenarios

The In-Vessel scenarios are similar to the Ex-Vessel ones, but in this case the break is supposed to occur among the blanket piping CV (BL) and the VV, which is in turn connected to the EV through a rupture disk. The two PHTS designs and the EV have been simulated as in the Ex-Vessel scenarios (description in section 3.1). A CV with a total volume of 1860.0 m^3 [15] and initial boundary conditions set to 210 Pa and 200 °C has been added to model the VV. A rupture disk of 1.0 m^2 opening when the differential pressure among the EV and VV exceeds 0.15 MPa [16] has been also added. Moreover, inside the VV an HS (HSVV) has been introduced to simulate the boxes FW. This HS is made of EUROFER with a total

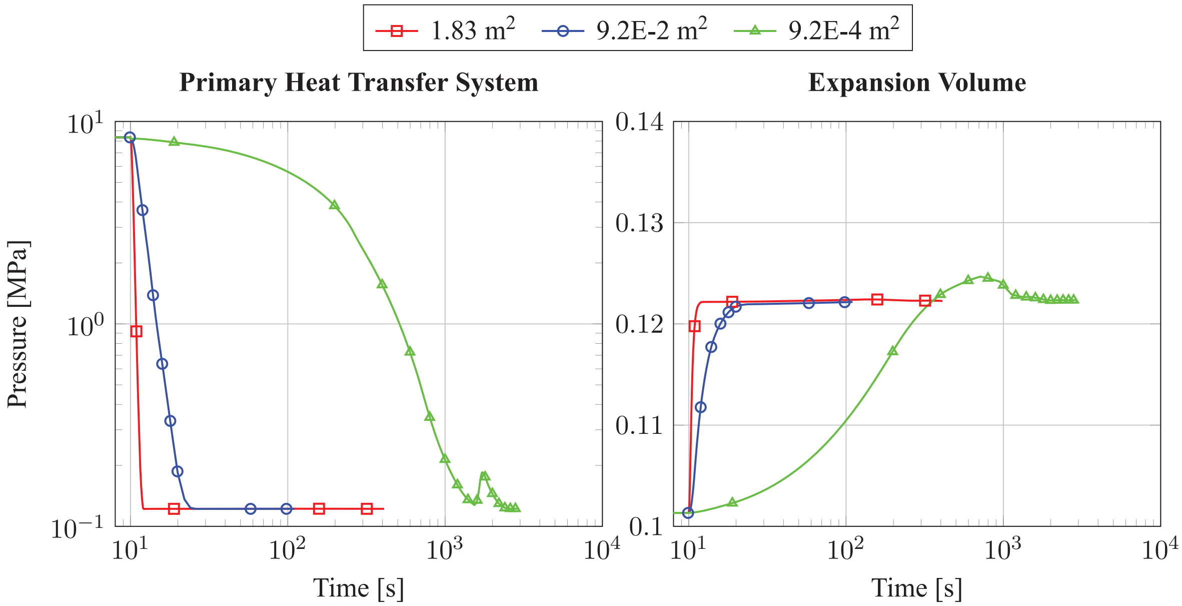

Figure 5. PHTS and EV total pressure trends during the Hot Header LOCA scenarios (alternative design).

Table V. Equilibrium pressure values reached inside the EV during the investigated LOCA scenarios.

	Reference design				**Alternative design**	
Hot header	**MELCOR**		**ASTEC**		**MELCOR**	
Area [m^2]	**T [s]**	**Pres. [MPa]**	**T [s]**	**Pres. [MPa]**	**T [s]**	**Pres. [MPa]**
1.83218	4.1	0.239	4.0	0.235	2.1	0.122
0.09161	70.0	0.239	60.0	0.232	16.0	0.122
0.00092	7200.0	0.323	5650.0	0.174	2416.0	0.122
In-Vessel						
0.12	60.0	0.274	50.0	0.257	14.0	0.123
1.0E-3	6100.0	0.173	5100.0	0.172	1140.0	0.117

area of 1000 m^2, a thickness of 30 mm, and with an adiabatic boundary condition at the outer side. The valve opening time, the power decay slopes have been set as in the the Ex-Vessel scenarios. It should be also noticed that the alternative design has been simulated only with MELCOR. In Figure 6 a sketch of the employed models is reported.

4.1.1. Results

Two In-Vessel LOCA cases have been investigated:

- The first case characterized by a break size of 0.12 m^2 (200% of the flow area of one manifold passing through the BSS; and
- The second case characterized by a break size of 1.0E-3 m^2.

In figures 7 and 8 are reported the pressure trends for the PHTS, the EV, and the VV for the reference and the alternative designs, respectively. In Table V a summary of the main results for both designs is shown.

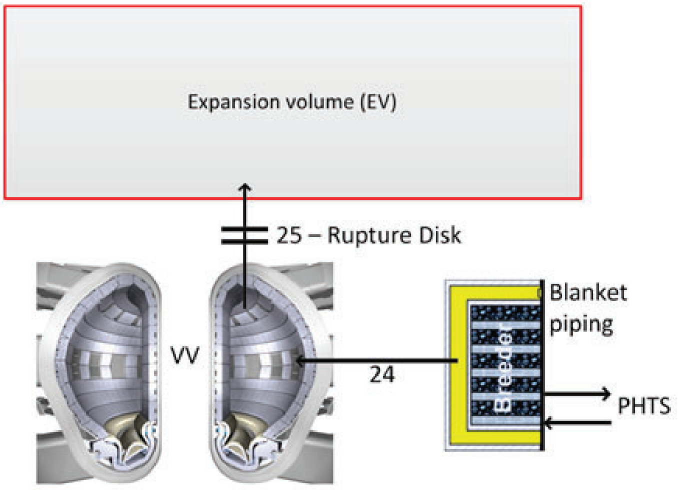

Figure 6. In-Vessel nodalisation.

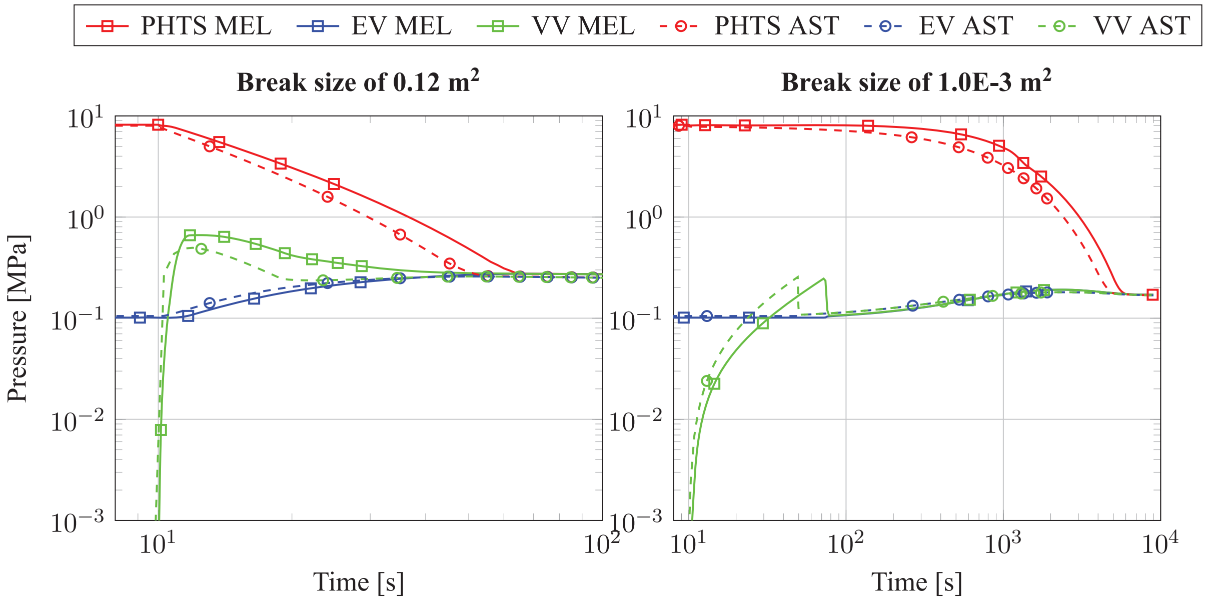

Figure 7. PHTS, VV, and EV total pressure trends during the In-Vessel LOCA scenarios (reference design).

For a break size of 0.12 m^2 the blowdown phase ends in $\sim$60 s in the reference design, and in $\sim$14 s in the alternative one. For both design the VV pressurization is quite fast, and the opening of the rupture disk is not able to decrease the severity of the pressurization rate. The maximum pressures reached inside the VV are 0.66 MPa and $\sim$0.47 MPa for the reference and the alternative designs, respectively. This difference can be explained considering the lower helium inventory contained inside the coolant loop of the alternative design ($\sim$1/6 of the reference one). The different helium inventory lead also to a different maximum pressure in the EV. In the reference design the total pressure inside the EV at the end of the blowdown phase is $\sim$0.272 MPa, while in the alternative design is $\sim$0.122 MPa.

For a break size of 1.0E-3 m^2 the blowdown phase ends in $\sim$6100 s in the reference design, and in $\sim$ 1140 s in the alternative one. On the contrary of the previous break case, after the rupture disk opening

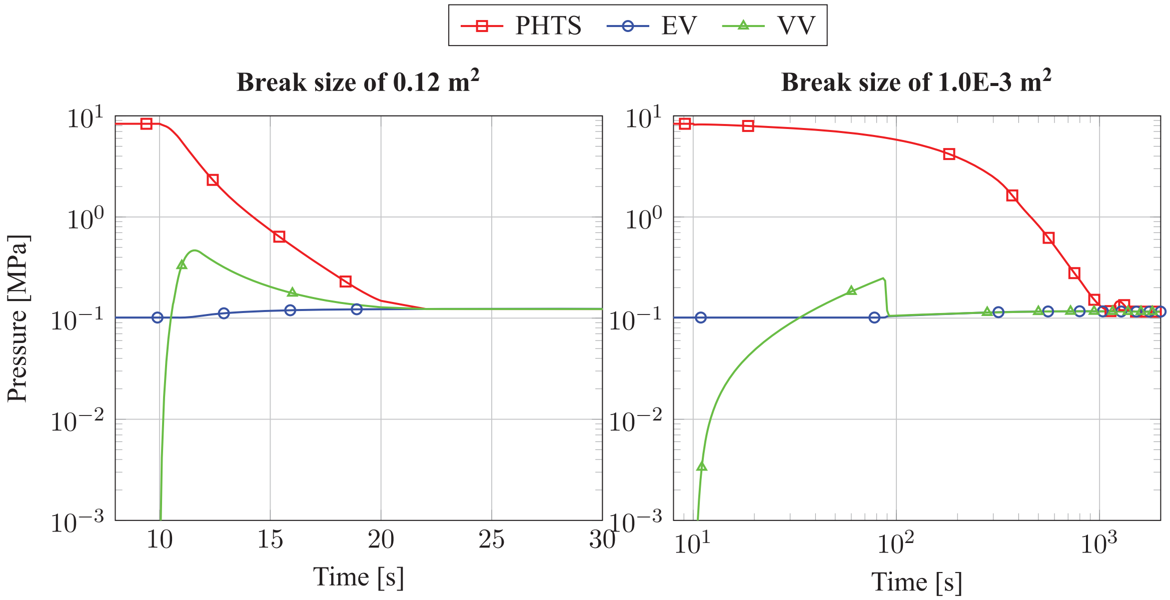

Figure 8. PHTS, VV, and EV total pressure trends during the In-Vessel LOCA scenarios (alternative design).

the VV pressurization suddenly changes slope. This behaviour is due to the reduced break area, which is able to reduce the severity of the helium ingress to a value that can be easily managed by the rupture disk. Moreover, this slower transient lead also to a reduced total pressure inside the EV pressure at the end of the blowdown phase thanks to the greater influence of the heat exchanges with the outer environment. For this purpose, in the reference design the total pressure inside the EV at the end of the blowdown phase is ∼0.173 MPa, while in the alternative design is ∼0.117 MPa.

Regarding the code-to-code comparison among ASTEC and MELCOR the remarks made for the hot header LOCAs are partially valid also for these scenarios. The ASTEC limitation regarding the helium behaviour still influences the blowdown phase, leading to lower VV maximum pressure values, and to shorter blowdown phases. This difference mainly influences the longer transient. For a break size of 0.12 m^2 the ASTEC blowdown phase lasts ∼10 s less then in MELCOR, while the VV reaches an overall equilibrium with the EV in ∼20 s instead of ∼45 s as in MELCOR. On the contrary, for a break size of 1.0E-3 m^2 the ASTEC blowdown phase ends ∼1000 s before the MELCOR one, and also the equilibrium among the VV and the EV is reached in different instants: ∼40 s in ASTEC, and ∼110 s in MELCOR. Although, in the long-term phase no clear differences are shown among the results provided by the two codes. This is quite surprising, because in the Ex-Vessel LOCAs the influence of the heat exchange phenomena with the outer environment was different. Although, no explanations have been found to justify the discrepancies among the In-Vessel and the Ex-Vessel LOCAs.

Finally, regarding more specific safety aspects, no major remarks can be drawn: the maximum pressure inside the VV is well below the design limit of 2 MPa, while the EV behaviour is comparable to that shown during the Ex-Vessel LOCAs (except for the long-term phase). For this purpose it can be remarked that the alternative design is able to reduce the stresses on the VV and the EV, thus allowing a relaxation of the design limits of both components/buildings. It can be also noted that, for smaller break areas, the actuation of the isolation valves along the main coolant pipes can be performed. This action, if executed in few seconds, may also avoid the opening of the rupture disk.

5. CONCLUSIONS

The aims of this work were:

- Calculate the maximum pressures inside the EV and the VV to provide an indication on its design limits;
- Demonstrate that alternative PHTS designs can be employed to reduce the stresses on the EV and the VV, as well as the size and the complexity of the plant; and
- Compare the results of two of the main Severe Accident (SA) codes: MELCOR 1.8.2 (fusion version) and ASTEC V2R3p2 in order to show the actual differences among them.

To stress the various points listed above several analyses have been carried out focusing on two PHTS designs: the reference design described in [3], and an alternative one proposed by KIT in 2014 [5]. These two designs have been investigated employing a simple model, but able to stress their main safety characteristics.

Although, the following limitations affecting the models employed should be avoided in future works:

- A complex logic for the blower trip should be implemented instead of suppose a trip occurring in the same instant of the break;
- Both the intact and the broken loops should be simulated to asses the capabilities of the intact loop to remove the whole decay heat instead of a 50% as supposed in this work. This improvement will also provide more realistic temperature and pressure trends and values.

Although, these limitations do not diminish the value of this work, keeping in mind that it was executed to provide only first-guess values and clear indications on the differences among ASTEC and MELCOR.

As conclusion, for the code-to-code comparison it can be stated that MELCOR is able to reproduce more realistically the whole transient, while ASTEC provides less realistic values due to the impossibility to simulate the heat exchange phenomena among helium and the surrounding HSs. Regarding more specific safety aspects, it can be stated that the alternative layout proposed is able to reduce the severity of the transient, as well as the size and the complexity of the plant. In the future the complexity of the transient investigated may be increased investigating the following scenarios:

- Multiple box pipes failure may be investigated for the In-Vessel scenarios; and
- The combined break of the blanket and divertor heat transfer systems releasing the coolants (helium for the blanket and water for the divertor) inside the VV.

At the same time, further investigations about the different behaviour of the Ex-Vessel and the In-Vessel scenarios during the long-term phase will be executed.

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