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(Article begins on next page)

Analysis of the Effects of Primary Heat Transfer System Isolation Valves in case of In-Vessel Loss-Of-Coolant Accidents in the EU DEMO

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As DEMO is the first European device planned to produce electricity from fusion, the volume of its Primary Heat Transfer Systems (PHTS) will be consistently larger if compared to present or next-generation tokamaks such as ITER. The consequences of an in-vessel Loss-Of-Coolant Accident (LOCA) would then be more important, and within the EUROfusion Consortium different possible mitigation measures are being investigated. Among these, the introduction of Isolation Valves (IsoVs) on the main cooling loops of the Breeding Blanket is being considered, in view of the many benefits they would introduce, not only in case of accidents, but also e.g. during the maintenance of the in-vessel components. Fast-closing IsoVs on the PHTS would help in relaxing not only the requirements of the VV pressure suppression system (VVPSS) design, but also those related to the expansion volumes that shall accommodate the contaminated coolant discharged from the PHTS after a LOCA.

In the present work, the GETTHEM code, the system-level thermal-hydraulic model developed for the EU DEMO at Politecnico di Torino, is used to assess the beneficial effects of the introduction of the IsoVs. The effects of the actuation time of the IsoVs and of their location are parametrically investigated, considering both water and helium as PHTS coolants, with particular reference to the reduction of the in-vessel space-averaged pressure and of the suppression system size.

Keywords: EU DEMO, VVPSS, in-vessel LOCA, safety, isolation valves

1. Introduction

The design of the EU DEMO reactor [1] considers, since the pre-conceptual phase, different accidental transients as basis for the design of the plant, according to the same approach adopted in the case of fission power plants. Among those transients, one is that resulting from the sudden occurrence of a break in one of the Primary Heat Transfer Systems (PHTS), causing an ingress of coolant inside the Vacuum Vessel (VV), i.e. an in-VV Loss-Of-Coolant Accident (LOCA). During this transient the coolant pressurizes the VV (normally operating under ultra-high vacuum conditions), the primary confinement barrier, which needs then to be evacuated to avoid its structural failure, see Fig. 1. Currently, a design pressure limit of 2 bar is considered [2]; note that this limit, driven by local considerations (i.e. the presence of diamond windows in the radiofrequency heating system), is presently assumed as upper bound for the entire object [2]. In order to reduce the amount of coolant released outside the PHTS, fast-closing isolation valves (IsoVs) may be used in the PHTSs. Such IsoVs have the double aim of reducing the peak pressure in the VV and the amount of contaminated coolant released outside the confinement. On the other hand, IsoVs would introduce an additional, non-negligible pressure drop in the PHTS, increasing the circulators power, which could already use a significant fraction of the total plant output (particularly true for a gas-cooled system) [3]. In addition, such valves may need to be redundant to ensure the reliability of the isolation function: as a consequence, the cost and complexity of the PHTS would increase further, as well as the plant unavailability due to the potential of spurious closures (and the consequent loss of flow). In ITER [4], where both issues are less relevant (being it an experiment rather than a power plant), IsoVs have been implemented.

2. Aim of the work and methodology

In the present work, the effectiveness of IsoVs located in the Breeding Blanket (BB) PHTS of EU DEMO is assessed, for both the Helium-Cooled Pebble Bed (HCPB) [5] and the Water-Cooled Lithium-Lead (WCLL) [6] BB concepts. The assessment aims at providing an estimation of the beneficial effects of IsoVs installation (a brief, qualitative discussion of the drawbacks is also reported). This is achieved evaluating the reduction of both the peak of the average pressure in the VV and the released coolant inventory outside the PHTS and VV.

To avoid an over-pressurization, the VV is equipped with three Burst Disks (BD, cross section 0.49 m²), which open when a given differential pressure threshold (1.5 bar) is reached between the VV and its expansion volume. The BDs are bypassed by active Bleed Valves (two per each BD, cross section 0.1 m²), which intervene in case of small leakages preventing large BDs to breach, see Fig. 1. In the case of the WCLL BB, where the coolant is water at 155 bar, 295-328 °C [6], the expansion volume is a water pool kept at low pressure in saturation

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conditions, similarly to the suppression pools used in Boiling Water Reactors. The flashed water exiting from the VV will reduce its volume by condensation in the pool itself. Relatively slow transients take place in this case, as the PHTS depressurizes and water starts flashing therein. In the case of HCPB, cooled by helium at 80 bar, 300-520 °C [5], the coolant will flow in a cool water pool (i.e. a "wet" expansion volume), connected with a large free volume downstream. The water pool would not condense the helium stream, but would help in reducing its energy and tritium content. Faster transients happen here, as the flow is always single-phase.

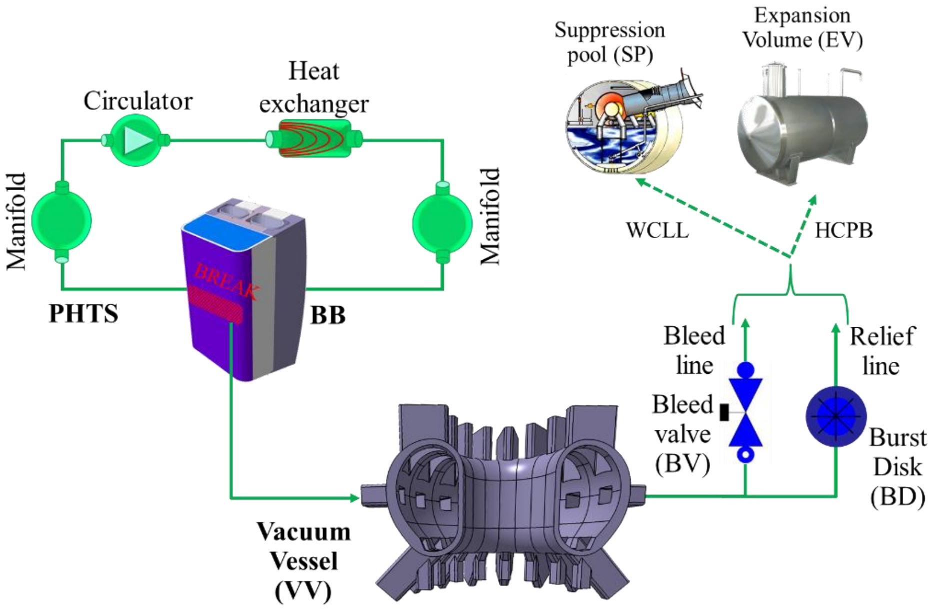

Fig. 1. Scheme of the EU DEMO VVPSS.

The work is carried out with the GEneral Tokamak THErmal-hydraulic Model (GETTHEM), the system-level thermal-hydraulic model developed for EU DEMO at Politecnico di Torino [7][8]. GETTHEM has already been used in the past within the EUROfusion Consortium to perform parametric studies on the EU DEMO VV Pressure Suppression System (VVPSS), considering both helium [9] and water-cooled [10] BBs. Thanks to its low computational cost, GETTHEM is applied here to analyze several scenarios, parametrically considering the effect of varying the location of the IsoVs and the time needed to fully isolate the line.

As a remark and caveat, the present analysis, done with a system-level (0D/1D) model (according to a widely-accepted practice in the fusion community [9]-[14]), allows evaluating the needed size of the VVPSS, which strongly affects its integration in the reactor building. It cannot provide an accurate evaluation of the load on the VV (and on the diamond windows in particular), which could result from a more detailed (and expensive) 3D Computational Fluid-Dynamic model (see e.g. [15]), but is beyond the scope of the present work.

3. Simulation setup and scenarios

The models used in the present work are the same as described in [9][10] and are summarized in Fig. 2, with the only difference of the inclusion of the IsoVs. Their effect is introduced in the model splitting the total PHTS volume in two parts (I) and (II), upstream and downstream the valve, respectively. In view of the lower pressure drop they would guarantee, gate valves are assumed to be used for the IsoVs [3], with a postulated linear characteristic.

Two different positions of the valves are considered, i.e. either on the manifolds or on the hot/cold legs, see Fig. 3. If IsoVs are installed on the manifolds, possibly more coolant can be confined, as they would isolate all the ex-VV PHTS components, as well as intact sectors belonging to the same loop. As an adverse effect, a very large number of valves would be needed, increasing the plant complexity, the risk of failures and maybe the total cost. On the other hand, valves installed on the legs would be in a much lower number, but the size of the single valve will be much larger. In the case IsoVs are installed on the manifolds, the volume of the part (II) in the GETTHEM model (see Fig. 2) only refers to the sector(s) where the break happens, whereas the other sectors are upstream the valve and thus considered in volume part (I). Note that a case considering IsoVs installed *both* on the manifolds and on the legs is not considered: indeed, it would not be able to confine significantly more volume with respect to the case with IsoVs installed on the manifolds, but would introduce the drawbacks of both solutions.

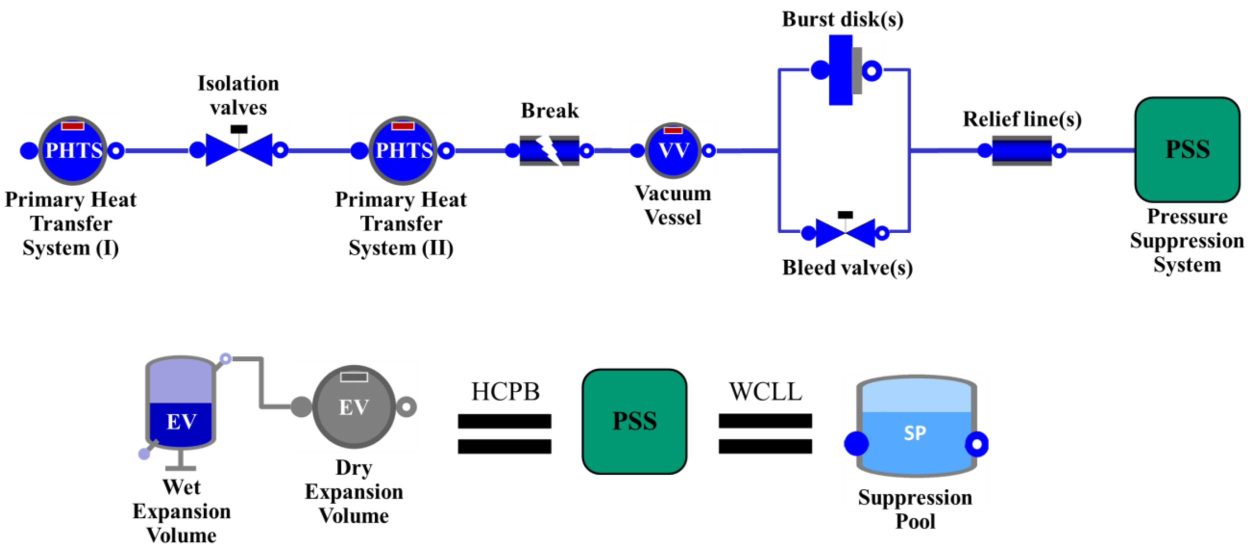

Fig. 2. (Top) GETTHEM model for the analysis of an in-VV LOCA. (Bottom) Two different PSS have been implemented in the model, for HCPB and WCLL, respectively. EV: Expansion Volume; SP: Suppression Pool.

The parameters adopted in the analysis, all taken from the EU DEMO BB Safety Data List (SDL) [17], are summarized in Table 1. The initiating event considered here is the opening of 1 m² break in the FW [17], which causes the double-ended guillotine break of 208 FW cooling channels in the case of HCPB (square cross section 12.5×12.5 mm² [5]) and of 262 FW cooling channels in the case of WCLL (square cross section 7×7 mm² [6]). In the case of the HCPB, this may cause the loss of coolant from either one or two BB PHTS cooling loops, so the worst case (release from two loops) is analyzed.

Concerning the IsoVs, in this work the time required to isolate the line is parametrically varied: a fixed delay of 3 s is assumed before the IsoVs start to close (time needed for PHTS depressurization detection and signal generation and transmission) [17], whereas different scenarios are considered for the actual closing time (or "actuation time"). Indeed, the minimum actuation time is limited by the need to avoid the "water hammer" effect: this limit, proportional to the speed of sound in the medium and to the line characteristic time, is estimated to be 0.1 s for helium and 2 s for water [3][18]. The maximum value has been chosen with the aim to have a fast valve and according to values provided by a survey done on existing nuclear-grade IsoVs [3][19] (1÷3 s for helium and 3÷8 s for water); the timeline of the transient is reported in Fig. 4. Three different values are considered for the sensitivity:

1. The minimum value to avoid water hammer (0.1 s for the HCPB, 2 s for the WCLL, respectively);
2. The lower bound of the maximum value estimated in [3] (1 s for the HCPB, 3 s for the WCLL, respectively);
3. The upper bound of the maximum value estimated in [3] (3 s for the HCPB, 8 s for the WCLL, respectively).

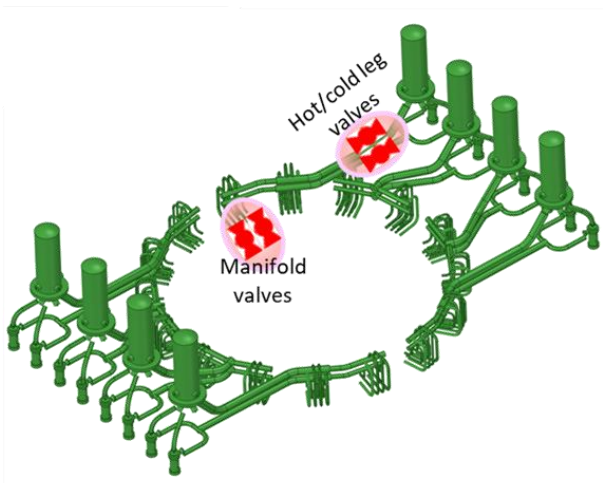

Fig. 3. Possible locations of IsoVs (adapted from [16]).

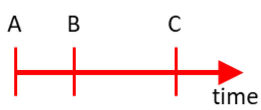

Fig. 4. Key line isolation times. A: Initiating event (large LOCA); B: event detection and valve actuation signal generation and transmission; B-C: needed time to close the valve (actuation time); C: line isolation.

Table 1. Parameters of the EU DEMO PHTS and VVPSS.

BB	Parameters	Value
HCPB and WCLL	Pressure limit VVPSS pressure VVPSS temperature	2 bar 4.5 kPa 20 °C
HCPB	Inventory PHTS temperature VVPSS size	431.0 m³ 300-520 °C 50000 m³ (0.2 % water)
WCLL	Inventory PHTS temperature VVPSS size	138.0 m³ 295-328 °C 2600 m³ (60 % liquid)

Since the sizes of the VVPSS expansion volume reported in Table 1, extracted from the SDL, were computed assuming a different scenario, i.e. involving all the BB segments (and consequently all the coolant inside the PHTS) [9][10][17], it may be a large overestimation of the needed size if the accident involves only part of the coolant, as in the present study. Indeed, a break causing a toroidally-continuous rupture all along the machine is presently considered impossible [20]. Therefore, as a starting point, the minimum possible size of the VVPSS without the intervention of the IsoVs is evaluated, for both scenarios on the basis of the actual released inventory. This approach is also conservative, as using the volumes reported in Table 1 would translate in a lager pressure suppression capability of the system, as compared to the VVPSS which will actually be found in the EU DEMO plant. IsoVs are then assumed to intervene, their location and actuation time being varied parametrically as explained above, and the reduction of peak average pressure and released inventory is evaluated. Finally, the possible reduction of the size of the VVPSS is estimated crediting the IsoVs actuation, allowing to draw conclusions about the effectiveness of their introduction.

4. Results

4.1 Reduction of the VVPSS size without IsoVs

As expected, the first transient analysis shows that the VVPSS EV size as reported in the SDL is overestimated in the present case, where much less coolant is lost during the LOCA. This is shown in Fig. 5, where the evolution of the VV pressure is reported: indeed, for the HCPB, the recovery pressure in the VVPSS is as low as 0.46 bar, whereas for the WCLL it is 0.18 bar. The peak average pressure in the VV is 1.70 bar for HCPB and 1.65 bar for WCLL. The low pressure values reached at equilibrium prove that it is possible to reduce the size of the VVPSS in both cases. GETTHEM is then applied repeatedly in order to identify the smallest possible size of the VVPSS which still guarantees a maximum pressure below 2 bar. The identified values are 7500 m³ for HCPB and 405 m³ for WCLL. As expected from previous analyses [9][10], this reduction does not affect the maximum pressure reached during the transient; it *does* affect the steady-state pressure, which is however not a concern as it is reached in a "controlled" manner. This is shown in Fig. 5. As a side remark, note that the peak pressure is reached in ~2.5 s for HCPB and ~5.3 s for WCLL: this implies that, if a 3 s delay is assumed for the IsoVs intervention, an effective reduction of the peak pressure is hardly achievable. This consideration worsens if considering that this is a 0D analysis computing average pressure values: a local (spatial) peak may be reached even before this time.

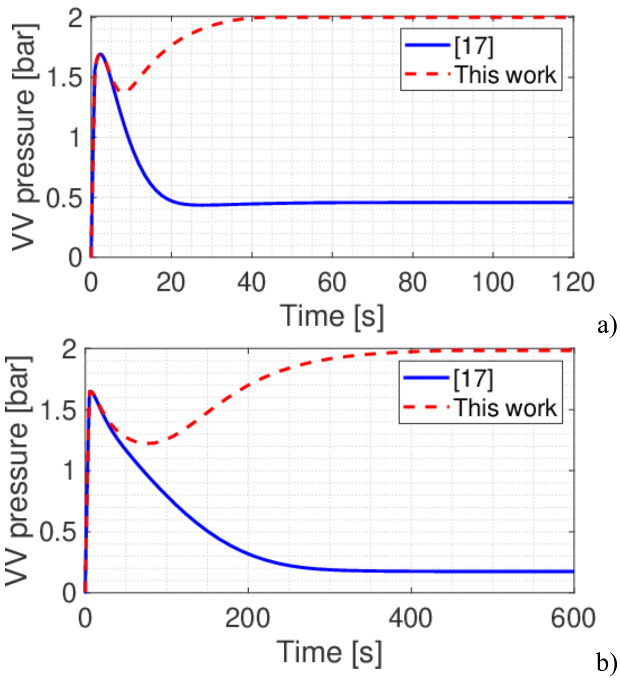

Fig. 5. Evolution of the VV pressure following a LOCA, for HCPB (a) and WCLL (b), with PSS volumes from [17] (solid lines) and PSS volumes computed in this work (dashed lines).

4.2 Sensitivity to IsoVs position and actuation time

Considering now as baseline values the newly computed VVPSS volumes, IsoVs are introduced, either on the manifold or on the legs, according to the rationale explained in section 3 above. The reduction of the coolant inventory released outside the VV ($R_{\%}$) is given by

$$R_{\%} = \frac{M_{r,no\ IsoV} - M_{r,IsoV}}{M_{r,no\ IsoV}} \quad (1)$$

where $M_{r,no\ IsoV}$ is the coolant mass released to the VVPSS if no IsoVs are present and $M_{r,IsoV}$ is the coolant mass released to the PSS taking into account the IsoV closure. The choice of this parameter highlights the effectiveness of the IsoVs in relative terms with respect to the case when no IsoVs are present. The values of $M_{r,no\ IsoV}$ are 1.42 t for the HCPB and 83.7 t for the WCLL.

The results of the sensitivity study are summarized in Table 2 for the HCPB BB and Table 3 for the WCLL BB, reporting the peak VV pressure, the VVPSS equilibrium pressure and the percent inventory reduction, for the different valve locations and actuation times, and in Fig. 6, where the first part of the pressure transients in the PHTS and VV are reported. The analysis quantitatively confirms, as qualitatively anticipated in the previous section, that the reduction of the peak pressure is negligible, independently of the valve actuation time, due to the large time needed to fully isolate the line, as evident from Fig. 6. As the peak pressure was already safely below the 2 bar limit, even without the intervention of the IsoVs, this conclusion turns out to be of limited practical relevance in the particular case considered here.

In view of the faster timescales characterizing the helium transient with respect to the water one, in the HCPB case the reduction of the coolant loss is always < 50 %. For the same reason, the valve actuation time is extremely important in this case: going from the minimum value of 0.1 s to the maximum of 3 s, almost ~10 % less coolant is kept inside the PHTS. Also the valve location plays an important role here, as ~12 % more coolant is kept upstream of the valve and is not released, if the valves are located on the manifolds. Hence, in the case of HCPB, a faster detection time, if achievable, is envisaged.

For the WCLL, in view of the much longer characteristic timescale, IsoVs are more effective, with minimum percent inventory reduction being > 60 % in the worst case. In addition, as the transient suddenly slows down after ~2 s, when water starts flashing [10] (see the slope change in the PHTS curves in Fig. 6b), the valve actuation time does not affect significantly the outcome, and even the slowest-closing valves considered here (8 s) would be effective. Conversely, the previous consideration about the location of the valves applies also here, with ~13 % more coolant confined, if the valves are put on the manifolds.

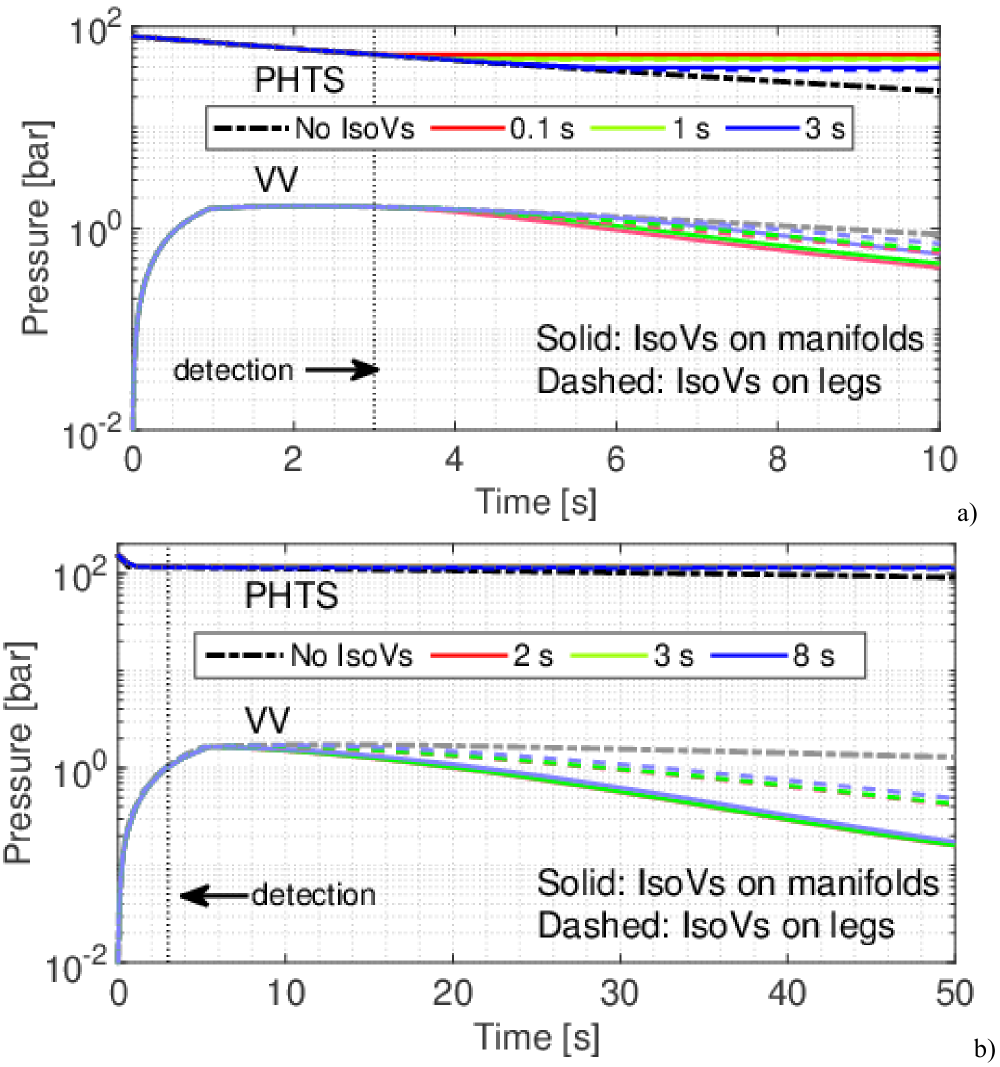

Fig. 6. Pressure evolution in the PHTS (upper set of curves) and VV (lower set of curves), in the first 10 s for the HCPB (a) and in the first 50 s for the WCLL (b). Different colors refer to different valve actuation times. For each actuation time, the solid lines refer to the case with IsoVs on the manifolds, whereas the dashed lines refer to the case with IsoVs on the hot/cold legs.

Table 2. Results of the sensitivity analysis for the HCPB.

IsoV position	IsoVs on manifolds			IsoVs on hot/cold legs		
Valve actuation time (s)	0.1	1	3	0.1	1	3
In-VV peak pressure (bar)	1.69	1.69	1.69	1.70	1.70	1.70
VVPSS recovery pressure (bar)	1.09	1.15	1.28	1.34	1.39	1.50
Coolant loss reduction (%)	46	43	36	33	30	24
Minimum needed VVPSS volume (m³)	2900	3200	3800	4000	4200	4700

Table 3. Results of the sensitivity analysis for the WCLL.

IsoV position	IsoVs on manifolds			IsoVs on hot/cold legs		
Valve actuation time (s)	2	3	8	2	3	8
In-VV peak pressure (bar)	1.56	1.56	1.56	1.59	1.59	1.62
VVPSS recovery pressure (bar)	0.23	0.23	0.24	0.37	0.38	0.43
Coolant loss reduction (%)	78	77	76	65	64	61
Minimum needed VVPSS volume (m³)	57	58	64	107	110	122

The different effectiveness of IsoVs in HCPB vs. WCLL are even more evident looking at how the total coolant mass is distributed among the three volumes (PHTS, VV and PSS) at steady-state: this is reported in Fig. 7a for the HCPB and in Fig. 7b for the WCLL. In the first case, in fact, a relatively large fraction (~15 %) of the total inventory is kept inside the PHTS+VV even without IsoVs. By introducing the valves, this value increases by a factor of 3 in the best case, as the denominator in eq. (1) is large. Conversely, for the WCLL, almost all the coolant (99.6 % of total) is released to the PSS if no IsoVs are introduced. When the IsoVs are considered, the amount of coolant which stays confined inside PHTS+VV increases by a factor of 8 (worst case) to 10 (best case), i.e. from 0.41 % to 3.2÷4.0 %. The good improvement highlighted in Table 3 is then mainly due to bad performance with no IsoVs (i.e. as the denominator in eq. (1) is in this case very small). In other words, IsoVs for the HCPB are less effective, but also less necessary than for the WCLL. Note that such result may also be significantly improved if a lower detection time is achievable.

Considering the reduced released inventory, it is then possible to reduce the VVPSS volume accordingly: following the rationale explained in section 4.1 above, GETTHEM is applied progressively reducing the VVPSS volume, until a recovery pressure of 2 bar is reached, knowing that the peak pressure is not affected by this parameter. The result of this analysis is reported in the last row of Table 2 and Table 3; the volume reduction is almost proportional to the inventory reduction, so that the final VVPSS volume can reach very small values (~60 m³) in the case of WCLL with IsoVs on manifolds. The reduction in the case of HCPB is less important in relative terms, but, considering the much larger volume required by helium, it is considerable in absolute value.

As a final remark, even if this is not the aim of the present work, the issues related to the introduction of IsoVs in the PHTS, such as additional pressure drop, cost and manufacturability, should be taken into account before making a final decision about their installation; these points are qualitatively summarized in Table 4. For the first issue, the pressure drop due to the presence of IsoVs has been estimated in [3] to be in the range of 0.2÷0.6 bar for HCPB and 2.6÷3.5 bar for WCLL, i.e. 7÷36 % of the total PHTS pressure drop in the first case and 30÷36 % in the latter. This raises concerns regarding the needed circulator power, which would cause a reduction of the plant efficiency. It is particularly true for the HCPB case, where the contribution of the circulator power is already significant even disregarding the presence of IsoVs. Concerning cost and manufacturability, it is worth noticing that if IsoVs are located on the manifolds, a much larger number of valves is needed (4 valves per tokamak sector, i.e. 72 valves, not accounting for redundancy). On the other hand, if valves are located on the legs, less valves would be needed (8 + redundancy), but with a much larger diameter: for the case of WCLL, DN-850 valves would be needed, which are larger than common IsoVs currently used in the nuclear industry. In the case of HCPB, even larger DN-1100 to DN-1300 valves would be required, posing serious questions about their manufacturability. Nevertheless, it has already been pointed out that valves on legs are less effective (and less necessary) in particular for HCPB, so their adoption is questionable regardless of the market availability.

5. Conclusions and perspective

The effectiveness of Isolation Valves (IsoVs) on the Primary Heat Transfer System (PHTS), to mitigate the consequences of an in-VV LOCA, has been assessed using the GETTHEM code. Adoption of IsoVs is being investigated for the EU DEMO, in particular to reduce the amount of contaminated coolant released outside the PHTS.

Table 4. Summary of pros and cons of IsoVs.

Issue	HCPB IsoVs on manifolds	HCPB IsoVs on legs	WCLL IsoVs on manifolds	WCLL IsoVs on legs
Percent volume reduction	Medium	Low	High	Medium
Absolute volume reduction	High	High	High	High
Pressure peak reduction	Negligible	Negligible	Negligible	Negligible
Additional pressure drop	High	Low	High	High
Needed valve size	Large	Very large	Medium	Large
Cost and complexity	High	Low	High	Low

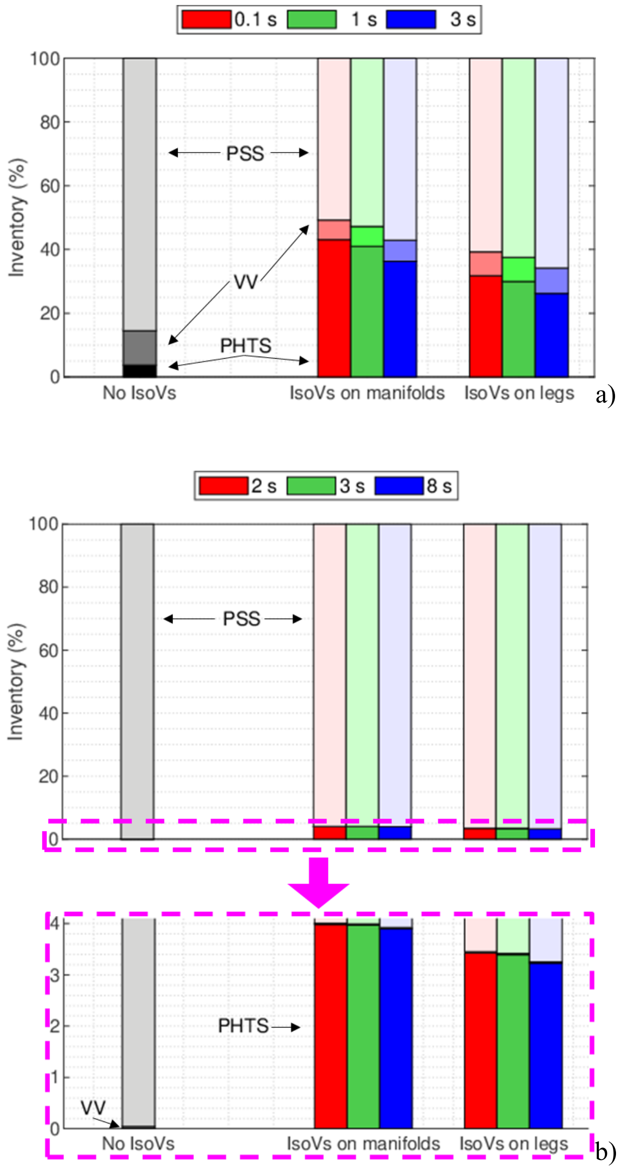

Fig. 7. Steady-state distribution of the coolant among the three volumes (PHTS, VV, PSS), for the HCPB (a) and the WCLL (b, with a zoom for values below 4 %). Different colors refer to different valve actuation times. For the WCLL, note that the inventory in PHTS with no IsoVs and in VV with IsoVs is negligible and not visible in the figure.

The analysis has shown that the valves are not effective in reducing the peak of the average pressure in the VV, mainly due to the long detection time presently considered. However, IsoVs could confine a relatively large amount of coolant in the PHTS. This would in principle allow reducing the size of the VVPSS Expansion Volume, partially relieving the integration issues arising from an oversized VVPSS.

The IsoVs effectiveness has been investigated for both the HCPB and the WCLL breeding blanket. In the first case, in view of the faster transients taking place during a LOCA, the valves may not allow a VVPSS size reduction larger than 50 %, even with a very fast-closing valve, at least if a detection time as large as 3 s is to be considered. Nevertheless, considering the large volumes needed for helium to expand, the effect in absolute terms is appreciable. Conversely, the longer timescales characteristic of the WCLL transient make the IsoVs more effective in this scenario, even at the slowest actuation time considered here. The final decision about the use of IsoVs, however, should take into consideration also other issues, such as limits on the release of radioactive materials, additional pressure drops, valve availability on the market, and costs; a qualitative comparison of such issues has been reported.

In perspective, a benchmark among system-level codes is being performed to confirm the validity of a 0D/1D approach in predicting the pressure evolution following a LOCA, with particular reference to the peak in-VV pressure – and its possible reduction with IsoVs.

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