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Tritium transport in the vacuum vessel pressure suppression system for helium cooled pebble bed

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ABSTRACT

In the frame of the safety studies for the EU-DEMO reactor, attention is paid to the hydrogen concentration in the vacuum vessel and connected volumes since it would lead to a possible hazard of releasing tritium and activated dust. The risk of explosion cannot be excluded a priori if H_2 stockpiles. For this reason, in both water (WCLL) and helium (HCPB) cooled breeding blanket concepts of EU-DEMO, the problem is under investigation with a cross-reference between the available technologies in fission (such as the Passive Autocatalytic Recombiners – PAR) and fusion application. In particular, the recent analyses pointed out the implementation of the PARs into the Vacuum Vessel Pressure Suppression System or linked systems.

This paper evaluates the Hydrogen behavior (main mobilized tritium source term) for the Helium-Cooled Pebble Bed (HCPB) VVPSS concept. The analyses preliminary investigate the stratification of the hydrogen mass inventory inside the PSS. In particular, a MELCOR 1.8.6 model of the PSS, based on past activities aimed at dust transport and thermohydraulic analyses, is adopted. The paper also introduces the applicability of PAR technology in the operation range of fusion devices, analyzing the problem of the recombination rate due to the dilution of Hydrogen after a Helium blowdown.

1. Introduction

Hydrogen production is one of the major issues affecting nuclear safety in fission and fusion nuclear reactor technology. As was demonstrated during Fukushima Daichi NPP (Nuclear Power Plant) accident [1,2], Hydrogen can lead to severe consequences on the integrity of the confinement building. In the European DEMOnstration Reactor (EU-DEMO), the hydrogen concern can derive from tritium mobilization and oxidation reaction of steam with plasma-facing components and breeder materials [3–5]. The design of the safety system, such as the Vacuum Vessel Pressure Suppression System (VVPSS), aims to assess the possible mitigative solutions depending on the scenarios. Several studies [6–8] have been carried out or are in progress.

For the Water-Cooled Lithium Lead (WCLL) EU-DEMO breeding blanket concept, the analyses reached advanced conclusions based on a sensitivity analysis involving the water level, tank dimensions, and location of passive recombiners [9,10]. In the case of the Helium Cooled Pebble Bed concept, these analyses started from the conclusion and assumptions adopted for the WCLL. For the WCLL, the Passive Catalytic Recombiners (PARs) have been located in the dry tanks connected to the VVPSS tanks.

A preliminary analysis was conducted to investigate if the recombination was effective when PAR are installed in the dry tanks. As follow back activity, the study continued with the preparation of sensitivity analyses evaluating the tritium behavior in the wet tanks, where the suppression pools and the scrubbers are installed.

Specific criteria have been adopted considering the VVPSS design and the PARs recombination phenomenon in a sensitivity analysis involving the volume distribution and the water level in the suppression pools.

This paper aims to present the results of the preliminary and sensitivity analyses used to simulate the in-vessel Loss of Coolant Accident (LOCA) in the HCPB [11].

2. VV and PSS MELCOR model

The VV and PSSs input deck was developed in the previous activities done in the EUROfusion project in EURATOM 8th Research Framework

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Programme (FP8). The model was initially used to analyze the thermohydraulic behavior during an In-Vessel LOCA, focusing on the pressure peak in the VV chamber and VVPSS. Such activity also included the transport of the tungsten dust from the VV chamber to the VVPSS tanks, where the helium flow was washed in the suppression tank, significantly reducing the mass inventory of the dust aerosols.

The VVPSS system is composed of two different components: the wet tanks and the dry tanks called Expansion Volumes (EV), which have to mitigate accident consequences by avoiding pressure exceeding the VV design pressure (2.0 bar) [7,8]. As shown in Fig. 1, the model is based on the PAR available data [12–15]. In the preliminary model, the wet tanks have 300 m^{3}volume and a pool level of 2.0 m. Tungsten (W) dust is not considered in these analyses. The blowdown boundary conditions were extracted from the data in [11].The in-vessel LOCA initiated at 0.0035 s after the steady state calculated with a separated model simulating the Breading Blanket circuit loops. The compressor trip is followed by the unmitigated plasma disruption at 0.0075 s. Due to the failure of 30 channels in the loop, the LOCA causes He to ingress into the VV with a peak mass flow rate of 21.403 kg/s at 1.104 (as shown in Fig. 2). It occurred in one of the VV quadrants. The helium can be simulated in MELCOR 1. 8.6 Fusion as fluid and as Non-Condensable Gas (NCG) [16, 17]. In this analysis, helium is considered a NCG since the MELCOR working fluid is water (considered in the suppression pools). The main reason is the unavailability of MELCOR to simulate more working fluid, which leads to this simplification. The pool scrubbers are placed at 0.5 m from the bottom of each PSS wet tank in each model. The wet tanks are simulated for the preliminary analysis with 10 axial nodes, 1.0 m height each. The dry tanks are a 1000 m^3 single volume and 10 m height. In the dry tanks, the adopted PAR model is the Framatome FR1–150 recombiner, which has been taken as a reference from the analyses performed in [12,14].

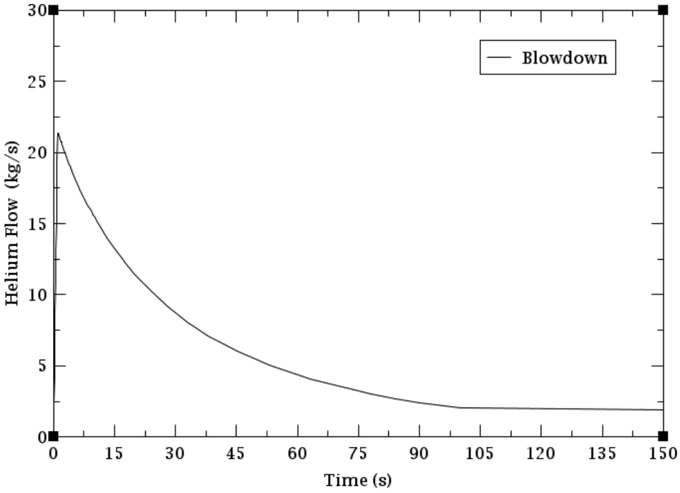

Fig. 2. Helium Blowdown [11].

The mobilized source term inventory involved in the transient was only the mass of tritium located in the VV, according to [18]. The total mass inventory is 2.673 kg of tritium [19]. The tritium mass was preliminary absorbed by permeability at high temperature in the first wall tungsten [20]. At initial of the accident, it is released from the dust constantly eroded by the first wall during the DEMO operation and directly by the tungsten coating [19,21,22], when it is exposed by the heating up due to the accident condition [20]. However, due to the lack of experimental data, it is considered to have a large uncertainty estimated around 25% (already included in the estimated tritium inventory) [23]. Contrary to what happens for the WCLL concept [9], no hydrogen is generated from the steam-tungsten chemical reaction since the blowdown inventory is helium gas.

The wet tanks and dry tanks' initial conditions are similar to those adopted in the analyses performed for the WCLL:

1. Wet tanks pressure: 45 kPa with 100% of relative humidity

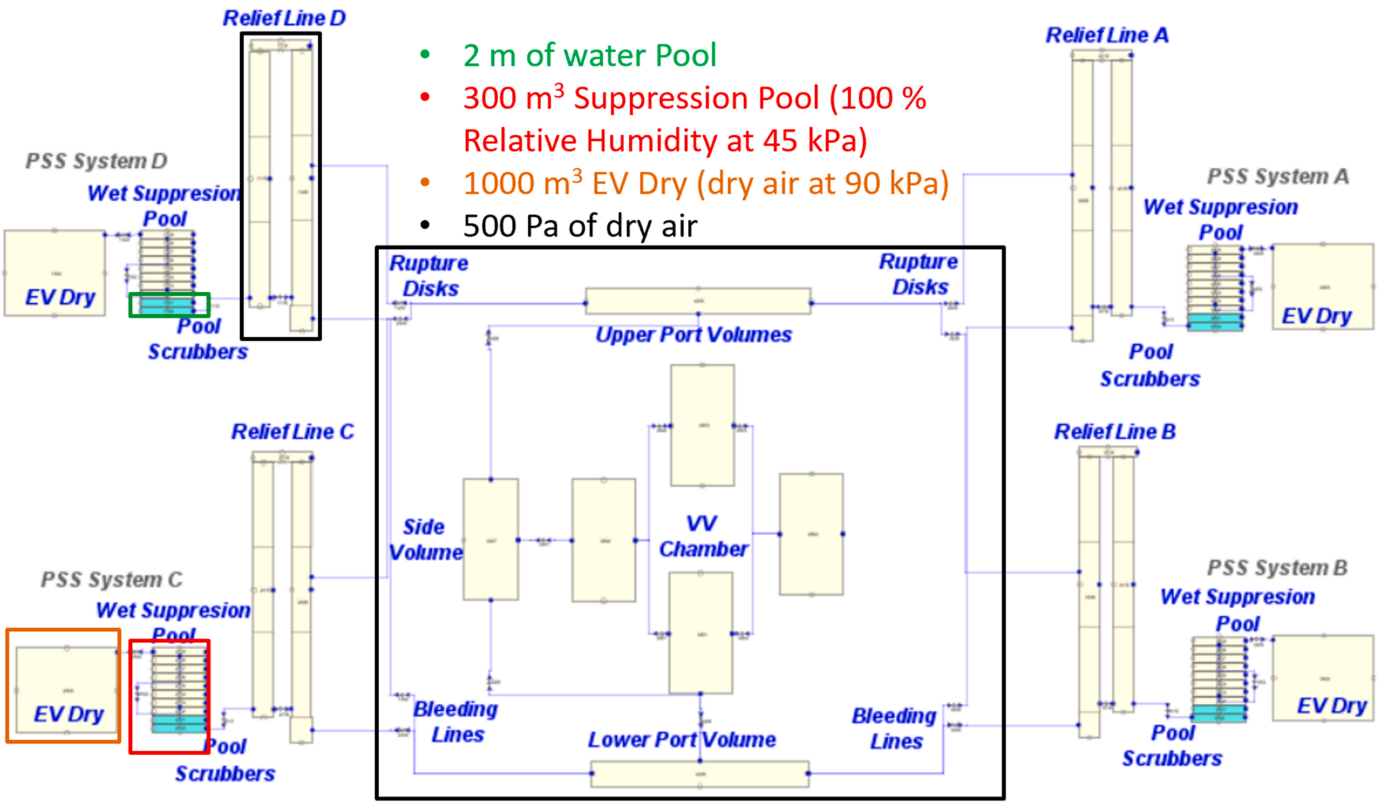

Fig. 1. VV and PSS MELCOR model for the preliminary analyses.

2 Dry EV tanks pressure: 90 kPa (to increase the O_2 quantity) in dry air condition
3 The temperature of the water and the atmosphere is considered 300 K.

The Bleed Lines (BL), with the function to address minor transient scenarios (such as small LOCA with minor damage to the First Wall and Divertor). The second group includes the Rupture Disks (RD), which contain the pressure peak in the case of large In Vessel LOCA. These two groups of lines are connected to the pool scrubbers to suppress the helium pressure and recombine the tritium into the PSS wet tanks. The last group is the RD, which connects the wet tanks to EV Tanks, where the PARs are located.

For the sensitivity analyses, the models were prepared to analyze only the mole fraction distribution as a function of wet tank volumes starting from 225 m^3 up to 375 m^3 and based on the water level from 0. m up to 3.5 m. The model is the same from a geometrical and boundary condition point of view except for the variation of the EV tanks non-activated to achieve the goal of studying the distribution of the tritium in the suppression tanks. Fig. 3 presents the modification adopted to the input deck.

In addition, the helium and the hydrogen molar weight are corrected in the tentative to simulate the hydrogen stratification as it should happen in the long-term accident management of a tritium blowdown in a helium flow. The adopted molar fractions are:

- $^3H_2$ Molar Weight 6.032×10^{-3} kg/mol
- ^4He Molar Weight 4.002×10^{-3} kg/mol.

Table 1 presents the parametric feature analyzed. For these analyses, the criterion of the Design Pressure in the VV, which should not exceed the 2.0 bar, is neglected. This criterion should be reconsidered when the EV is reintegrated and nodalized in the model.

The main criterion for using the PAR is the H_2 mole fraction: it should be > 0.5%, at least in PSS wet tanks, to possibly recombine the tritium in the PAR systems. Such a system will play an important role in scenarios that will be considered in the future.

Table 1
Parametrization adopted during the sensitivity analysis.

Water Level [m]	Initial Volume per Wet Tank [m^3]						
0.0	225	250	275	300	325	350	375
0.5	225	250	275	300	325	350	375
1.0	225	250	275	300	325	350	375
1.5	225	250	275	300	325	350	375
2.0	225	250	275	300	325	350	375
2.5	225	250	275	300	325	350	375
3.0	225	250	275	300	325	350	375
3.5	225	250	275	300	325	350	375

3. Analyses results

3.1. Preliminary results with the dry EV tanks and PAR system

As the first part of the work, a preliminary analysis was conducted to study the possibility of using the PAR system in the In-vessel LOCA in the case of the HCPB concept. The preliminary results underline that the PSS system is able to allocate the pressure peak (shown in Fig. 4) in the case of 4 PSS tanks with a wet tank of a volume of 300 m^3 and dry EV tanks of 1000 m^3 each.

In the case of hydrogen mole fraction, the analysis showed that the helium blowdown inerts the atmosphere reducing the hydrogen mole fraction below 4% and not reaching any flammability point (see Fig. 5). In addition, as shown in Fig. 5, the maximum molar fraction (around 0.275%) reached into the PAR system does not trigger the catalytic recombination (since the threshold value required is 0.5%).

3.2. Parametric analysis

The results of the sensitivity analyses are divided based on the water

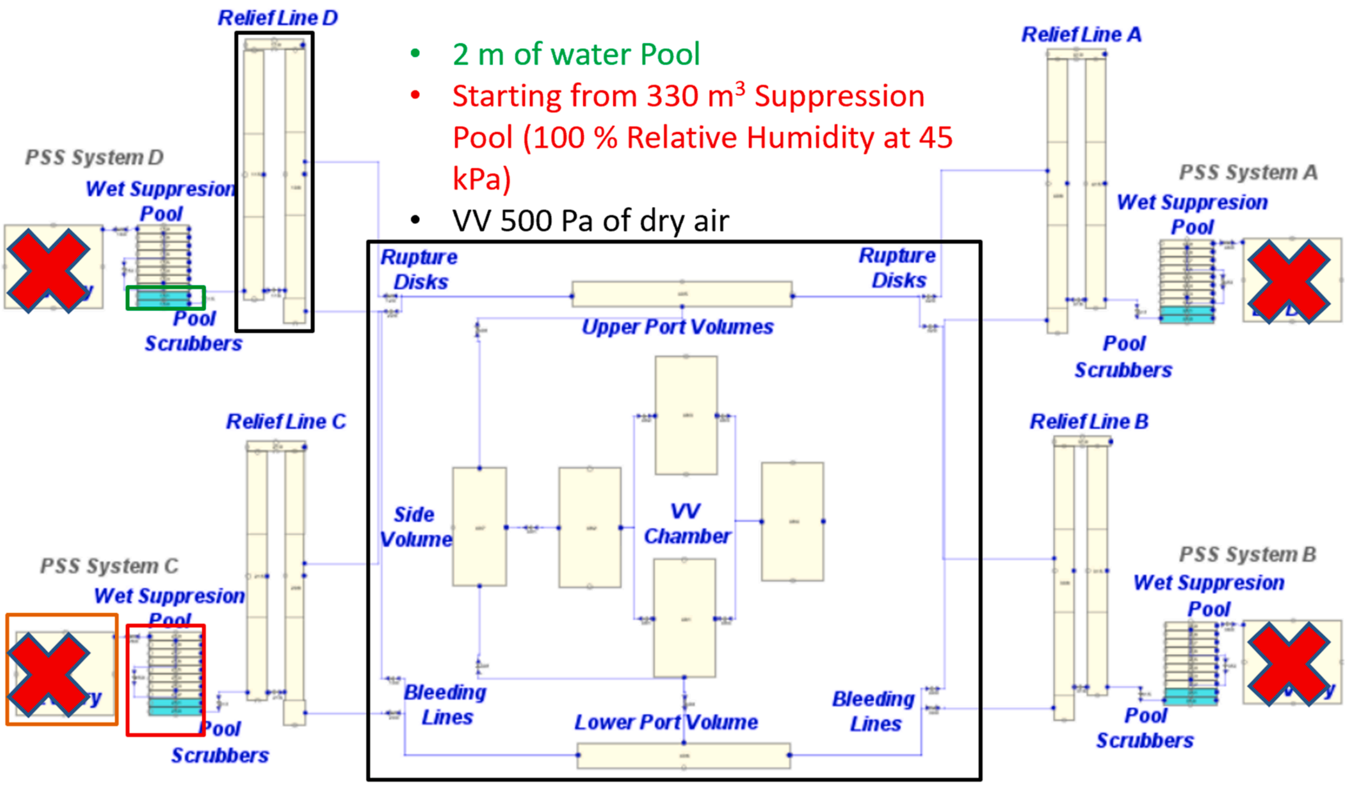

Fig. 3. VV and PSS MELCOR model for the sensitivity analyses.

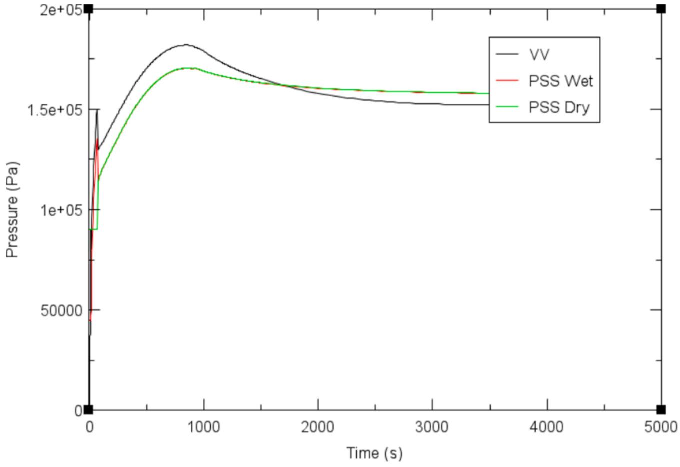

Fig. 4. Pressure in VV and PSS (corresponding to 300 m^3 initial pool volume).

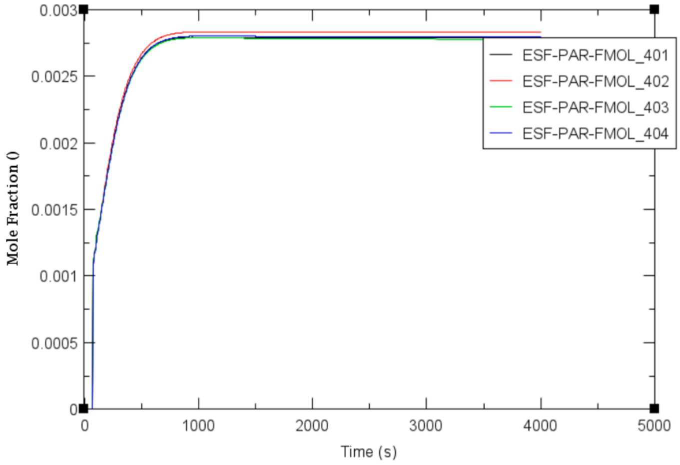

Fig. 5. Hydrogen mole fraction inside PSS EVs located in the PAR system.

pool level and the parametrized wet tank volume (see Table 2). As representative results, 3 pool water levels have been presented due to their importance. These suppression pool levels are:

- 0.0 m: empty suppression pool, where the absence of the suppression pool directly influences the concentration and the pressure wave without water pressure suppression mitigation (Fig. 6, Fig. 7, and Fig. 8).
- 2.0 m: selected weight where the influence of the water level has a limited impact on the VV pressure, and it significantly impacts the helium thermohydraulic (Fig. 9, Fig. 10, and Fig. 11).
- 3.5 m: is an upper band where the water level is choking the pressure in the VV (Fig. 12, Fig. 13, and Fig. 14).

In addition, for all these 3 pool levels, the 300 m^3 tank is chosen as the main observable for the axial hydrogen fraction distribution as a function of time. In these parametric analyses, where the dry EVs are maintained close, in each analyzed case, the pressure exceeds the design criterion of 2.0 bar. The pool water level decreases the PSS and VV pressures mainly when the water level is around 2.0 m, as shown in Fig. 9. In addition, the water level generally decreases the molar fraction maximum peak from 0.90% (Fig. 7) to 0.71% (Fig. 13). As shown in Fig. 8, Fig. 11, and Fig. 14, the maximum molar fraction peak in the atmosphere is reached in the first seconds and immediately above the water pool level. The reason is the obstruction generated by the pool water, which choked the hydrogen mole fraction. In general, such behavior is underlined in Table 2, except for some interesting fluctuation in molar fraction results when the water level is in the middle of the control volume. Such behavior is mainly assumed by the MELCOR approach when an oscillating level insists on two control volumes. The maximum value changes between the tank's volume (as shown in Table 2 at the pool level of 2.5 m).

Although these results are promising, reaching the concentration required to initiate the recombination in the PAR (Fig. 7, Fig. 10, and Fig. 13) when the dry EV is opened will not be easy. In particular, all results are below 1%, so they will probably not be effective for the catalytic reaction. These results, in any case, evidence that for the In-vessel LOCA, the HCPB concept can inert itself in short-term scenarios (Fig. 8, Fig. 11, and Fig. 14). The results can be investigated by introducing mitigative solutions for the long-term state. Along all scenarios, the higher molar fraction was reached with tanks of 225 m^3 and without a pool; however, this scenario will have serious limitations in the dust trapping and, eventually, other scenarios such as divertor LOCA, which a LOCA with water required a suppression system.

In addition, the water expanded the peak duration, while the increased tank volume decreased the time the concentration was above the 0.5% threshold (Fig. 10 and Fig. 13). The only exception was the case with 0.0 m (Fig. 7), where both peak and the time are larger in comparison to the rest of the analyses with the water pool.

Table 2
Summary of the main result: Hydrogen concentration measured above the water level (in light gray) and duration time with a concentration above 0.5% (in light blue).

4	Initial Volume per Wet Tank [m^3]						
	225	250	275	300	325	350	375
0.0	0.93%	0.92%	0.91%	0.90%	0.88%	0.87%	0.85%
	45.8 s	40.8 s	40.8 s	40.8 s	35.5 s	30.4 s	30.4 s
0.5	0.84%	0.86%	0.86%	0.84%	0.84%	0.83%	0.82%
	21.2 s	20.1 s	15.9 s	15.9 s	10.8 s	10.8 s	10.8s
1.0	0.86%	0.84%	0.83%	0.82%	0.81%	0.80%	0.79%
	29.6 s	22.8 s	21.2 s	17.3 s	15.5 s	14.1 s	13.3 s
1.5	0.90%	0.89%	0.88%	0.87%	0.86%	0.85%	0.84%
	24.1 s	24.0 s	24.0 s	18.9 s	13.8 s	13.8 s	13.7 s
2.0	0.80%	0.77%	0.76%	0.75%	0.74%	0.73%	0.72%
	31.4 s	26.3 s	26.2 s	26.0 s	21.0 s	20.8 s	20.7 s
2.5	0.80%	0.79%	0.78%	0.78%	0.77%	0.77%	0.77%
	31.3 s	31.1 s	26.0 s	25.9s	25.8 s	20.6 s	20.6 s
3.0	0.76%	0.74%	0.76%	0.74%	0.74%	0.71%	0.73%
	32.4 s	28.0 s	30.7 s	24.8 s	26.7 s	21.5 s	21.3 s
3.5	0.81%	0.82%	0.80%	0.81%	0.81%	0.80%	0.79%
	32.7 s	32.3 s	25.1 s	27.0 s	26.9 s	27.7 s	26.5 s

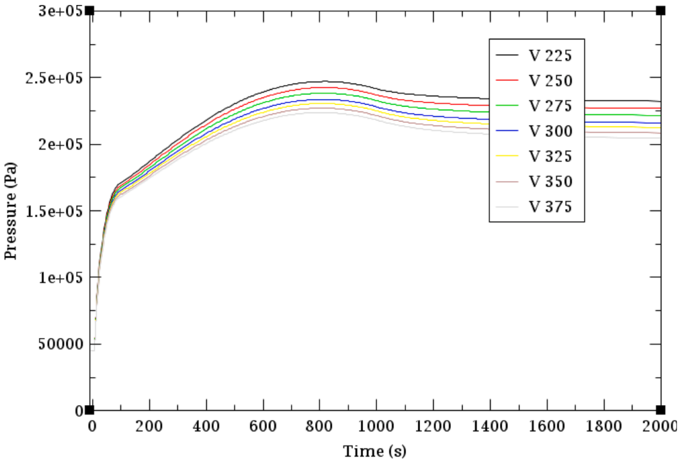

Fig. 6. Pressure in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 0.0 m.

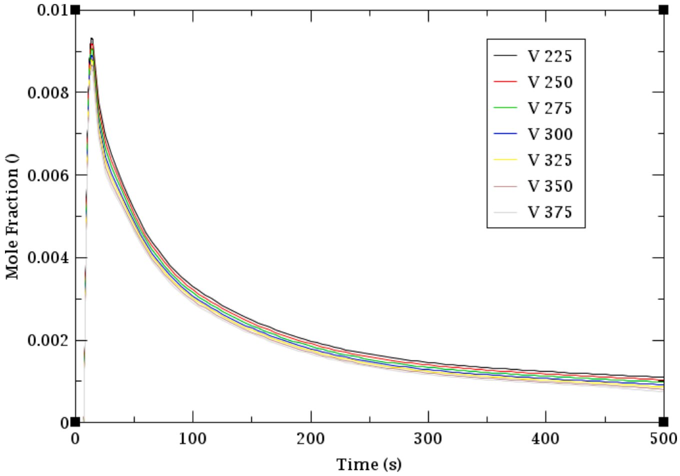

Fig. 7. Hydrogen mole fraction in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 0.0 m.

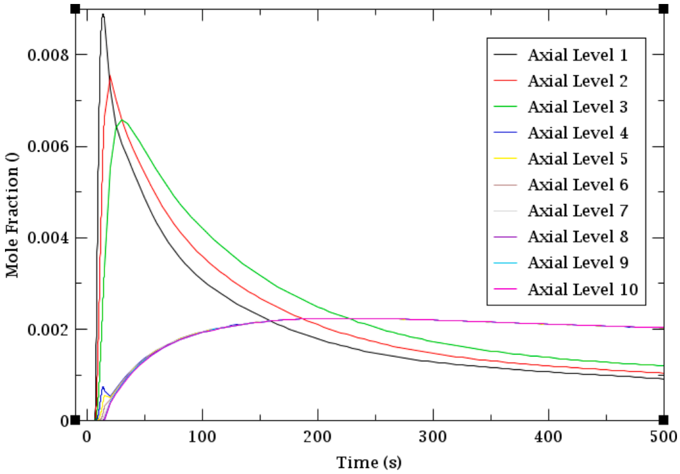

Fig. 8. Hydrogen mole fraction in the Wet tanks 300 m^3 and water level 0.0 m for each axial level.

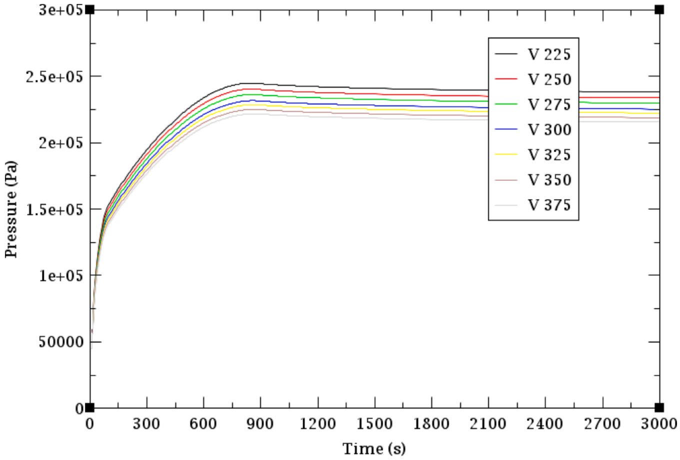

Fig. 9. Pressure in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 2.0 m.

In the last step of the current analysis, the molar weight of the Hydrogen was changed because the source term will be tritium. This boundary condition affects the long-term stratification, as shown in

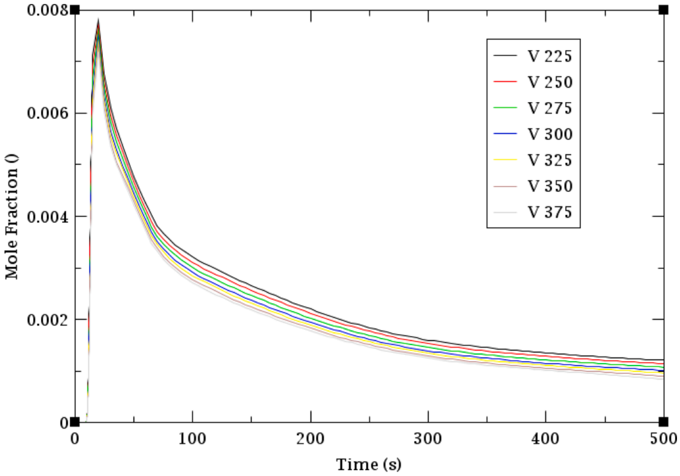

Fig. 10. Hydrogen mole fraction in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 2.0 m.

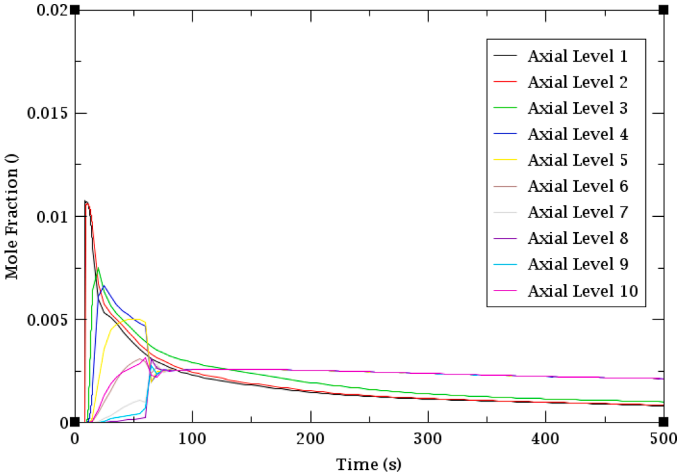

Fig. 11. Hydrogen mole fraction in the Wet tanks 300 m^3 and water level 2.0 m for each axial level.

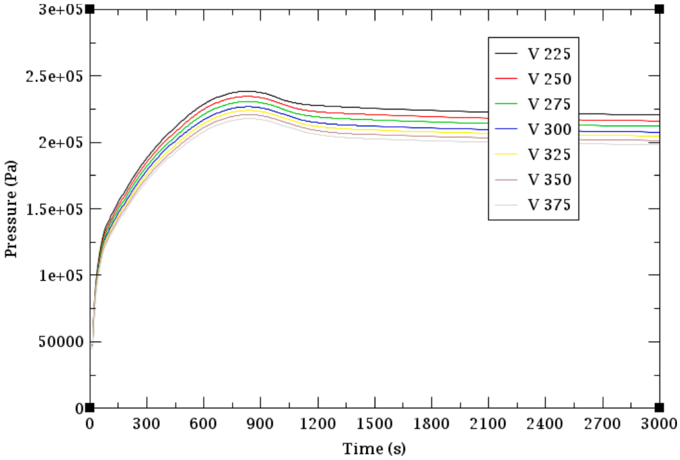

Fig. 12. Pressure in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 3.5 m.

Fig. 15. After one day of simulation, such an effect is negligible and does not reach the critical concentration (0.5%) that can trigger the PAR. This phenomenon can be influenced by additional hydraulic boundary

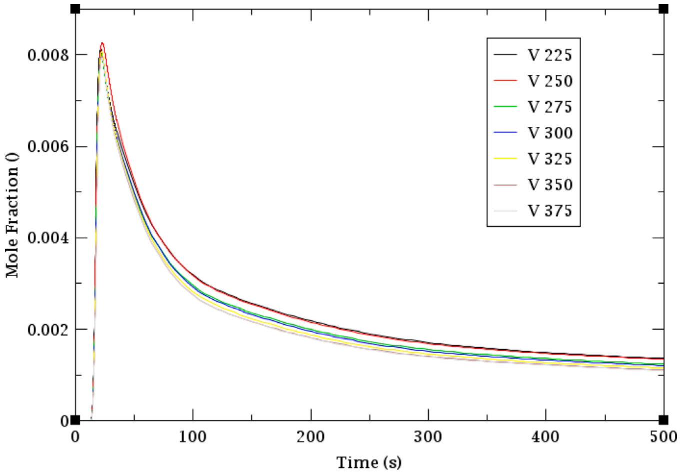

Fig. 13. Hydrogen mole fraction in the Wet tanks(from 225 up to 375 m^3 initial volume) for Water Level 3.5 m.

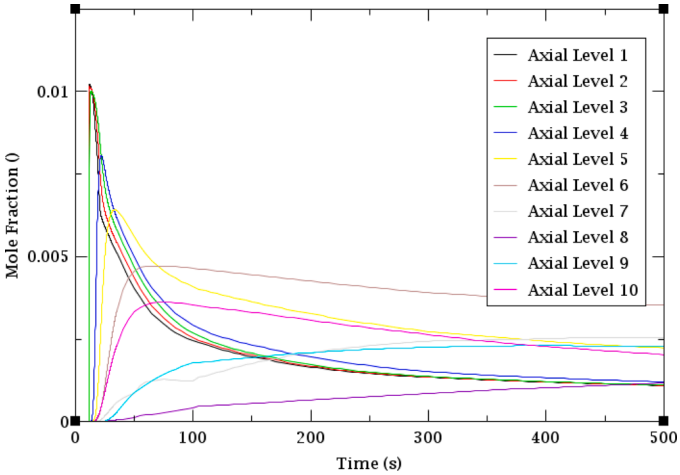

Fig. 14. Hydrogen mole fraction in the Wet tanks 300 m^3 and water level 3.5 m for each axial level.

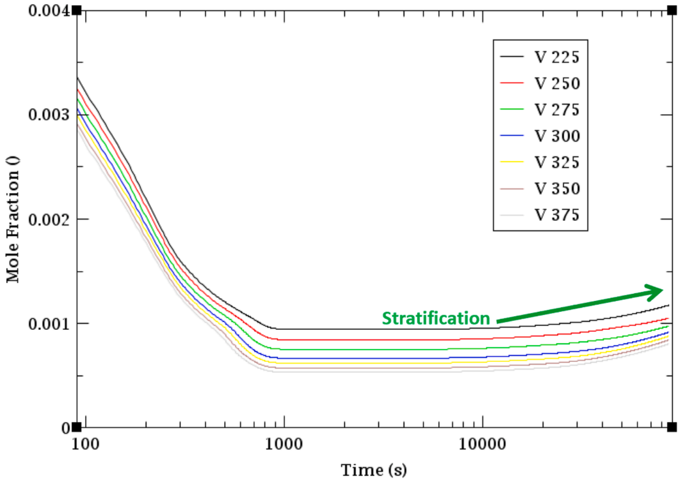

Fig. 15. Hydrogen mole fraction in the Wet tanks (from 225 up to 375 m^3 initial volume) for Water Level 2.0 long term stratifications.

conditions (such as heat losses), which can generate convective regimes. For this reason, it required Computational Fluid Dynamic (CFD) codes and methods to be deeply investigated.

Another interesting phenomenon underlined in the MELCOR, due to its specificities, is the presence of adiabatic compression and expansion. MELCOR evidenced an increase of the temperature in the VV during the LOCA occurrence (see Fig. 16). This also happened in the PSS wet tanks, where in the case of the presence of the water pool, this phenomenon is significantly mitigated (see Fig. 17). However, the results need to be assessed by different tools such as CFD as it was postulated by the hydrogen concentration.

As an additional remark, only some minor deflagrations were detected in the VV (see Fig. 18). These are mainly due to the parametric approach used in MELCOR to simulate deflagration. These deflagrations are initiated based on the molar fraction criterion, and their contribution to the overall hydrogen transport was negligible.

4. Summary and conclusion

The present simulation is based on the previous analyses done for the WCLL concept and applied to the HCPB one. Analogically to the WCLL concept, the hydrogen source is postulated by the presence of tritium, which consists of 2.673 kg in VV. The preliminary results demonstrate that Hydrogen is diluted inside the helium blowdown. Such results were also confirmed in the more detailed parametric analyses where the Hydrogen molar fraction was evaluated as a function of the PSS wet tank volumes and at different suppression pool heights.

In addition, in the case of the preliminary analyses, the PAR did not activate during the scenarios in the first 4000 s. These results, however, are mainly driven by the postulated parametric conditions, showing that it is possible to reach concentration for PAR activation.

The main parametric analyses also underlined that the molar fraction peak is reached in the first seconds after the postulated initiator event (In-vessel LOCA). Such results could last from 10 to 32 s depending on the water levels and wet tank volumes. Specific results will be addressed in the case of dry PSS tanks, which reach the highest values in terms of time and Hydrogen molar fraction. In all analyses, the BUR package was activated, and it simulated minor deflagration in the VV. Still, their effect on the pressure is negligible. This indicates that in the first seconds when the blowdown occurred, it is possible to reach a higher hydrogen molar fraction, leading to minor deflagration.

Future analyses will continue the investigation of the molar fraction and PAR recombination using a detailed dry EV nodalization. In addition, it will be interesting to study the PSS system's behavior in the divertor LOCA or other scenarios. Such analyses must also be assessed by different codes (such as CFD) and supported by experimental tests.

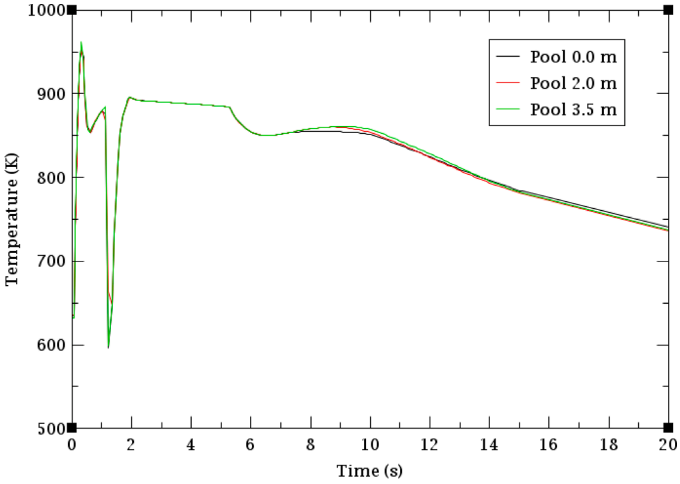

Fig. 16. VV Helium atmosphere temperature for initial pool volume of 300 m^3.

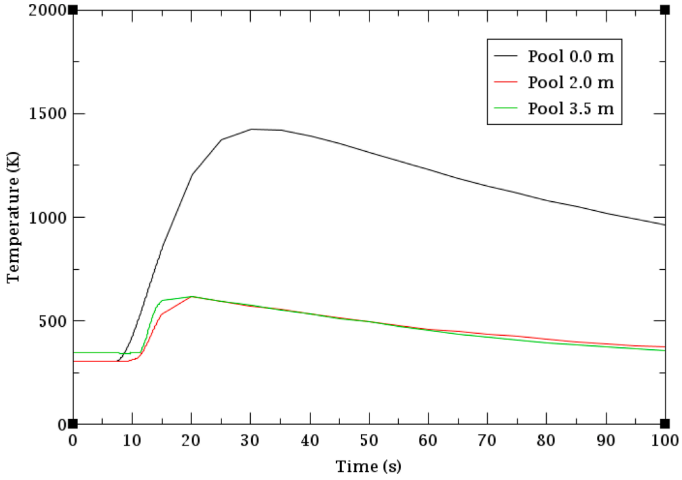

Fig. 17. Wet tank Helium atmosphere temperature for initial pool volume of 300 m^3.

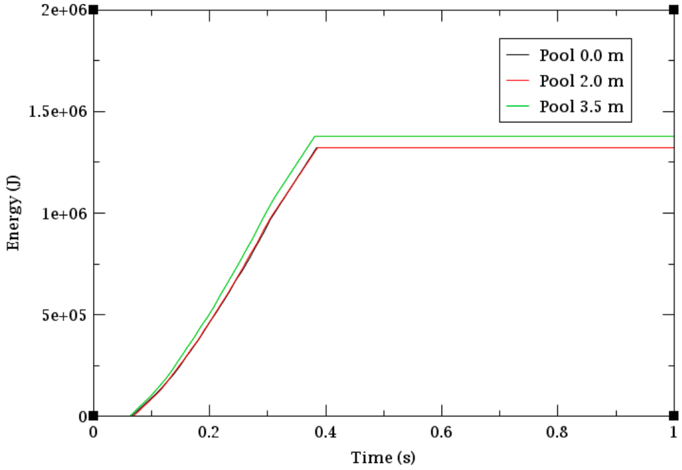

Fig. 18. Energy production from hydroven combustion with the residual oxigen.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] IAEA, STI/PUB/1710 978-92-0-107015-9, IAEA, Vienna, 2015.
[2] M. D'Onorio, A. Giampaolo, G. Caruso, F. Giannetti, Preliminary uncertainty quantification of the core degradation models in predicting the Fukushima Daiichi unit 3 severe accident, Nucl. Eng. Des. (382) (2021), 111383, https://doi.org/10.1016/j.nucengdes.2021.111383.
[3] M. D'Onorio, F. Giannetti, M.T. Porfiri, G. Caruso, Preliminary sensitivity analysis for an ex-vessel LOCA without plasma shutdown for the EU DEMO WCLL blanket concept, Fusion Eng. Des. 158 (2020), 111745, https://doi.org/10.1016/j.fusengdes.2020.111745. ISSN 0920-3796.
[4] M. D'Onorio, F. Giannetti, G. Caruso, M.T. Porfiri, In-box LOCA accident analysis for the European DEMO water-cooled reactor, Fusion Eng. Des. 146 (Part A) (2019) 732–735, https://doi.org/10.1016/j.fusengdes.2019.01.066. ISSN 0920-3796.
[5] D.N. Dongiovanni, M. D'Onorio, G. Caruso, T. Pinna, M.T. Porfiri, DEMO Divertor Cassette and Plasma facing Unit in Vessel Loss-of-Coolant Accident, Energies 15 (2022) 8879, https://doi.org/10.3390/en15238879.
[6] M. D'Onorio, F. Giannetti, M.T. Porfiri, G. Caruso, Preliminary safety analysis of an in-vessel LOCA for the EU-DEMO WCLL blanket concept, Fusion Eng. Des. 155 (2020), 111560, https://doi.org/10.1016/j.fusengdes.2020.111560.
[7] M. D'Onorio, G. Caruso, Pressure suppression system influence on vacuum vessel thermal-hydraulics and on source term mobilization during a multiple First Wall – Blanket pipe break, Fusion Eng. Des. 164 (2021), 112224, https://doi.org/10.1016/j.fusengdes.2020.112224.
[8] G. Caruso, F. Giannetti, Sizing of the Vacuum Vessel Pressure Suppression System of a Fusion Reactor Based on a Water-Cooled Blanket, for the Purpose of the Preconceptual Design, Sci. Tech. Nucl. Install. (2016) 1–11, https://doi.org/10.1155/2016/8719695.
[9] G. Mazzini M. D'Onorio, G. Caruso, Hydrogen explosion mitigation in DEMO vacuum vessel pressure suppression system using passive recombiners, Fusion Eng. Des. 171 (2021), 112713, https://doi.org/10.1016/j.fusengdes.2021.112713.
[10] M. D'Onorio, T. Glingler, G. Mazzini, M.T. Porfiri, G. Caruso, Passive Hydrogen Recombination during a Beyond Design Basis Accident in a Fusion DEMO Plant, Energies 16 (6) (2023) 2569, https://doi.org/10.3390/en16062569.
[11] Xue Zhou Jin, "Final report on selected accident analyses by KIT, in-vessel LOCA for the HCPB blanket concept", 31 December 2020: https://idm.euro-fusion.org/default.aspx?uid=2NX7B4.
[12] OECD Members, "International Standard Problem-49 on Hydrogen Combustion", Nuclear Safety NEA/CSNI/R(2011), 9 January 2012.
[13] OECD/NEA, NEA Thermal-hydraulics, Hydrogen, Aerosols and Iodine Project Phase 2 (THAI-2), August 2011 to July 2014, https://www.oecd-nea.org/jointproj/thai2.html.
[14] AREVA, "Passive Autocatalytic Recombiner: severe Accident-Qualified PAR for Combustible Gas Control", 2018, http://us.areva.com/home/liblocal/docs/solutions/literature/g-008-v1pb-2011-eng_par_reader.pdf.
[15] OECD/NEA, Status Report on Hydrogen Management and Related Computer Codes, NEA/CSNI/R(2014)8, 20-Jan-2015. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=NEA/CSNI/R(2014)8&docLanguage=En.
[16] R.O. Gauntt et al. "MELCOR Computer Code Manuals – Version 1.8.6", NUREG/CR-6119, Vol. 2, Rev. 3, September 2005.
[17] B.J. Merrill, P.W. Humrickhouse, Aerosol Resuspension Model For MELCOR For Fusion and Very High Temperature Reactor Applications, Idaho National Laboratory, January 2011. INL/EXT-10-19683.
[18] Guido Mazzini, Tadas Kaliatka, Maria Teresa Porfiri, Tritium and dust source term inventory evaluation issues in the European DEMO reactor concepts, Fusion Eng. Des. 146 (Part A) (2019) 510–513, https://doi.org/10.1016/j.fusengdes.2019.01.008.
[19] G. Mazzini, T. Kaliatka, M.T. Porfiri, Estimation of Tritium and Dust Source Term in European DEMOnstration Fusion Reactor During Accident Scenarios, ASME. ASME J. Nucl. Rad. Sci. 5 (3) (July 2019), 030916, https://doi.org/10.1115/1.4043379.
[20] C.H. Skinner, et al., Recent Advances on Hydrogen Retention in ITER'sPlasma-Facing Materials: beryllium, Carbon, and Tungsten, Fusion Sci. Tech. 54 (Nov. 2008).
[21] M.Z. Tokar, An assessment for the erosion rate of DEMO first wall, Nucl. Fusion 58 (2018), 016016.
[22] G. Federici, et al., Plasma-material interactions in current tokamaks and their implications for next step fusion reactors, Nucl. Fusion 41 (2001) 1967.
[23] S. Ciattaglia, Strategy and plan for in-vacuum vessel dust (and tritium retention) control in ITER. Status November 2011, Dust workshop, 3rd presentation - -2011-11-30 page 18.