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Analyses of vacuum vessel pressure suppression system during divertor LOCA for Helium cooled pebble bed DEMO

G. Mazzini [a,*], M. D'Onorio [b], D.N. Dongiovanni [c], J. Syblik [a,d]

[a] Research Centre Rez, Hlavní 130, 250 68, Husinec-Řež, Czech Republic
[b] Sapienza University of Rome, Department of Astronautical, Electrical and Energy Engineering, Corso Vittorio Emanuele II 244, 00186, Rome, Italy
[c] ENEA, CR. Frascati, FSN-TEN department, Via Enrico Fermi, 45, 00044, Frascati, Rome, Italy
[d] Department of Energy Engineering, Czech Technical University in Prague, Technicka 1902/4, 160 00, Prague, Czech Republic

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ABSTRACT

An important aspect under investigation for several years in the EU-DEMO reactor is the mitigation of hydrogen concentration - mainly tritium and deuterium - in the Vacuum Vessel (VV) and the surrounding volumes. This accumulation poses risks, including potential explosion hazards, which could damage confinement barriers. One of the possible solutions, applicable to both water and helium-cooled blanket concepts, involves the use of Passive Autocatalytic Recombines (PAR). These devices, representing a cross-cutting technology between fission and fusion facilities, are being considered for integration into the Vacuum Vessel Pressure Suppression System (VVPSS) and related systems.

This paper focuses on the hydrogen transport analysis, specifically the inVV tritium and deuterium inventory mobilization towards the VVPSS designed for - Helium-Cooled Pebble Bed (HCPB) concept for which a model was developed by means of MELCOR 1.8.6 for fusion applications. Previous work on the HCPB Loss of Coolant Accident (LOCA) analyses suggests that inert helium resulting from Helium coolant blowdown can significantly mitigate the risk of hydrogen deflagration. The paper explores a new scenario, the Divertor in-vessel LOCA, which may lead to increased hydrogen mass due to the water-metal reaction. The paper discusses the integration of PAR technology within the operational range of fusion devices, specifically focusing on its potential to recombine hydrogen within the Expansion Volumes.

1. Introduction

As already presented in several research activities, hydrogen production is a significant issue impacting nuclear safety in both fission and fusion reactor technologies. The European DEMOnstration Reactor (EU-DEMO) is no exception since hydrogen can be produced by steam-metal reaction or is located in the Vacuum Vessel (VV) from tritium and deuterium mobilization. The design of safety systems, such as the Vacuum Vessel Pressure Suppression System (VVPSS), aims to evaluate potential mitigation solutions based on different scenarios. Several studies have been conducted or are ongoing in both Water-Cooled Lithium Lead (WCLL) [1,2] and Helium Cooled Pebble Bed (HCPB), EU-DEMO [3–5]. In both concepts, as first mitigative approach, Passive Autocatalytic Recombiners (PARs) were placed in dry tanks in order to recombine the mass of hydrogen coming from the VV in order not to reach the deflagration concentration. While the WCLL is more sensible to the problem of the hydrogen production due to the larger amount of water contained in Primary Heat Transport System (PHTS) [6], allocate in both Breeding Blanket and Divertor, the HCPB should has less risk to reach this limit due to presence of helium as coolant.

Specific criteria were adopted, considering the design of the PSS and the PARs recombination phenomenon, in a sensitivity analysis involving volume distribution and water levels in suppression pools. The model developed using MELCOR 1.8.6 Fusion version [7,8] with water as the working fluid, is prepared in two variants. The first one is the reference from the presented in the Safety Data List (SDL) [9] and introduced in [5], while the second one is a variant coming from the previous sensitivity analyses [10], which demonstrates that there is a certain margin in the PSS optimization. The boundary conditions, geometries, and related safety data are taken from [5,9,11,12].

This paper aims to identify the margins of optimization of the VVPSS to be indicated in order to solve remaining issues. In particular, the

* Corresponding author.
E-mail address: guido.mazzini@cvrez.cz (G. Mazzini).

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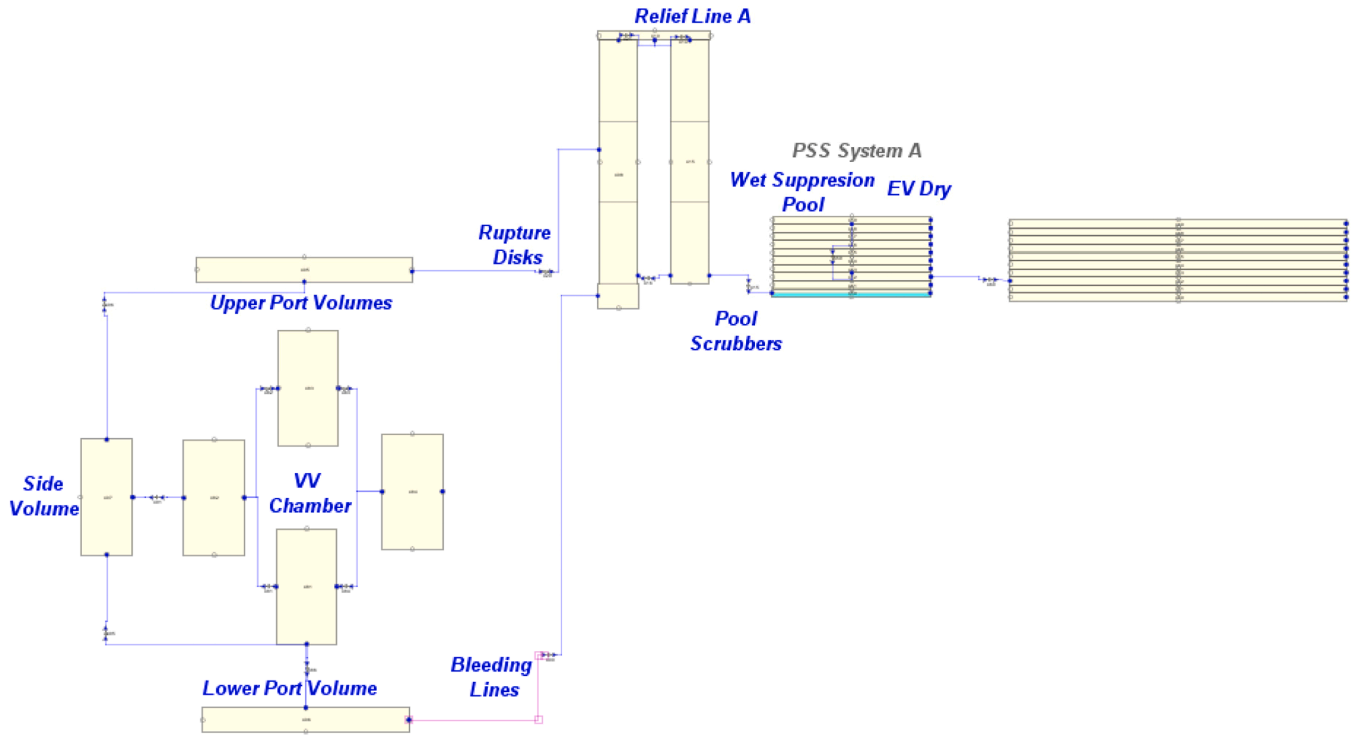

Fig. 1. MELCOR model of VV and PSS system for HCPB.

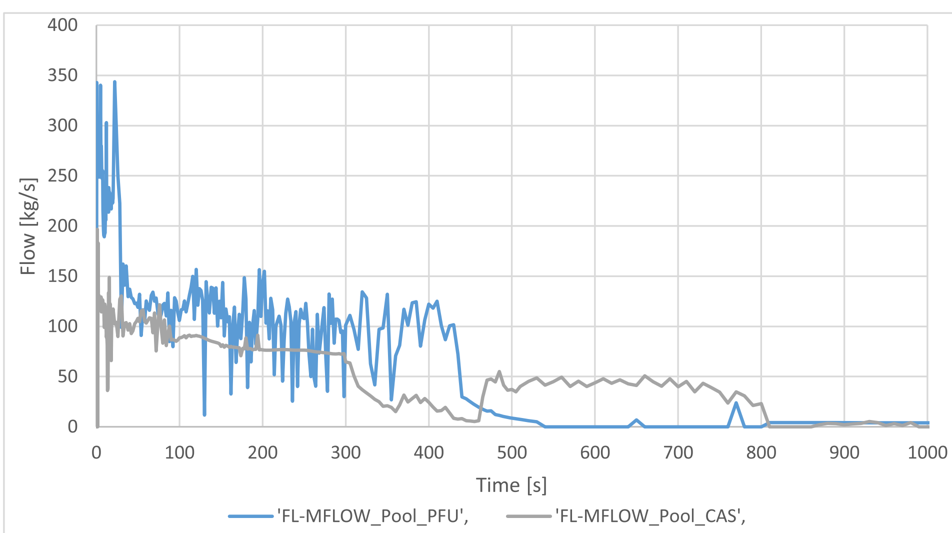

Fig. 2. Blowdown water mass flows from cassette and plasma facing unit [13].

position of the PARs and pressure criterion suggest future modifications to be adopted in the following activities. A key role is played by the postulated accident: the Divertor Loss of Coolant Accident (LOCA). Being the divertor units cooled by water, such an accident will generate hydrogen, which is going to be combined with the tritium and deuterium mass already presented in the VV.

2. Model description

As done from the previous activities [3,4], the model was developed with new initial and boundary conditions, such as the PARs position located in the 8 axial levels of the Expansion Volumes (EV). The nodalization is shown in Fig. 1. Two models reference and "Variant A" are developed in order to investigate the impact of the tank volume and suppression pool level on the hydrogen recombination. Both models have the same control volume pattern. In the model, the main components are simulated, including the VV, the upper and lower ports, the VV side volumes, and the piping from the VV to the PSS. For each one of these components, dedicated heat structures are added as needed to simulate pipings, floors, and walls (e.g., in the PSS wet tank axial ring 1). In particular, a simplified version of FW and Divertor heat structures are considered in the model in order to simulate parametrically their heat inertia and allowing the reaction with the tungsten. The Divertor and FW are considered has simple heat structures connected to the VV chamber for each quadrant, where the temperatures are imposed according to [13]

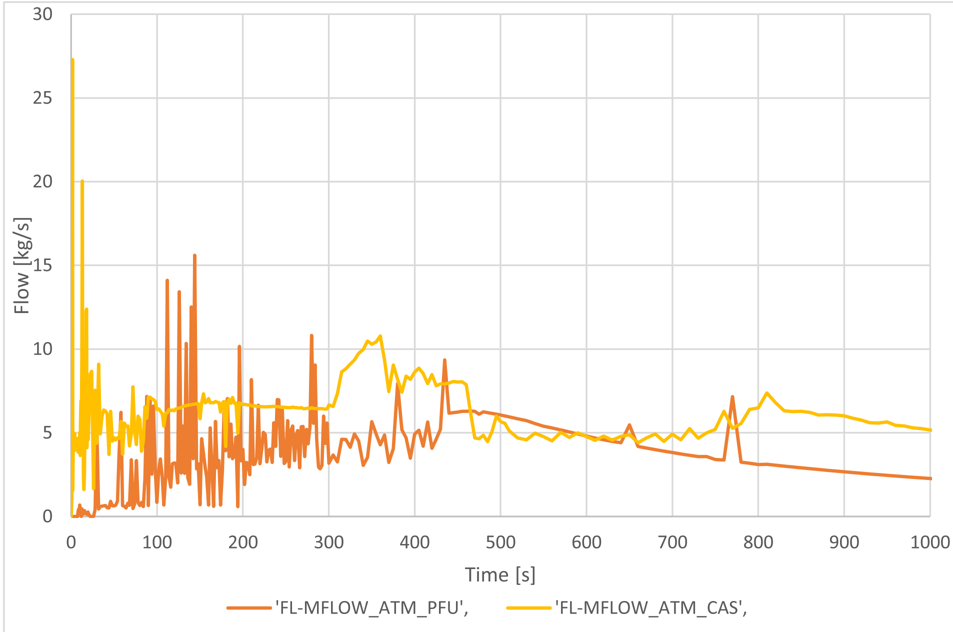

Fig. 3. Blowdown steam mass flows from cassette and plasma facing unit [13].

Table 1
Bleed lines and rupture disk main geometrical data [5,9].

4	Volume [m^3]	Pipe diameter [m]	1 Pipe section [m^2]	Pipe length [m]	Local loss coefficient in the path [-]	ΔP to open rupture disk or valve [kPa]
VVPSS RD	40.0	1.1280	1.0	40	3	90
VVPSS BL	2.0	0.2523	0.5	40	3	45
EV RD	40.0	1.1280	1.0	40	3	150

Table 2
Main geometrical data for the VV and PSS including initial conditions [3,4].

		Volume [m^3]	Pool Level [m]	Pressure [Pa]	Temperature [°C]	Humidity (%)	Atmosphere [-]
Both	**PC**	2964	-	500	300	0.0	He
	UP	1664	-	500	300	0.0	He
	LP	1630	-	500	300	0.0	He
Reference	**Wet tank**	3000	0.5	45000	20	65.0	Air
	EV	13500	-	45000	20	65.0	Air
Variant A	**Wet tank**	1200	2.0	45000	30	65.0	Air
	EV	4400	-	90000	30	0.0	Air

Another major modification in comparison to [3,4] was the splitting of EV into 10 axial levels, in a similar way as was done for the PSS wet tanks. The goal is to estimate locally the concentration of hydrogen in order to simulate the recombination.

The blowdown is extrapolated from a Divertor LOCA reported in [13], performed by the Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA) Frascati unit. The blowdown consisted of more than 3000 values, requiring a scripting procedure to reprocess the data and collapse them to around 90 points, as required by MELCOR 1.8.6. The results are presented in Fig. 2 and Fig. 3, where the cassette and Plasma Facing Unit blowdown are shown as water and steam sources. During this process, impulsive peaks were suppressed while maintaining the integral value unchanged to improve code stability. The scripting process was done using Python code.

As already introduce, the selected location is EV tanks at the 7th axial level, where a highest hydrogen concentration was reached.

The tritium and deuteron source term are equivalent to 2.673 kg each and is based on [14] according to the average values from the tritium source term estimation methodology. The mass inventory was highly used in EUROFusion consortium and it is considered as an activity limit, where cleaning actions are required to ensure safety [5,14,15].

Due to the Divertor LOCA and the presence of the simplified heat structures, the tungsten-steam reaction is simulated in the control volumes of the VV. The main geometrical data and initial/boundary conditions are reported in Tables 1 and 2. The difference between variants comes from the activity done in the previous phase of the EUROFusion project. The water level and volume of the tanks were optimized in order to find a compromise between the dust sedimentation and pressure/temperature peaks in the VV. The model was continuously updated in parallel with the “reference” one.

The standard Fisher model [7] is adjusted to simulate the PAR Framatome FR-150T [16,4]. According to its specifications, the limit to initiate recombination in the PAR is set at around 0.5 %. At the current stage of the model, the PARs are located in the EV at a pressure of 0.9 bar in dry conditions. Such a boundary condition was applied in order to take into account the minimum pressure set up in the THAI experiment [16].

The whole model is developed in MELCOR 1.8.6 Fusion version [7,8]. Computationally, MELCOR analyses were set down with a

Table 3
Events list.

Event	Time for Reference [s]	Time for "Variant A" [s]
Start of simulation	-10.0	-10.0
Divertor Blowdown	0.0	0.0
Opening of BLs	60.3	60.3
Opening of RDs	124.1	113.4
Start of PAR Reaction	N/A	235.0
End of the Sequence	4000.0	4000.0

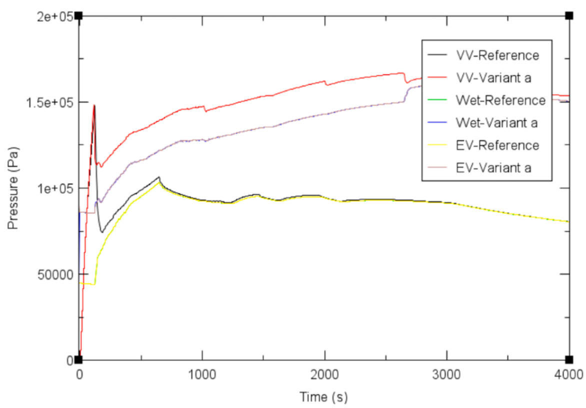

Fig. 4. Pressure comparison in VV, wet tank and EV.

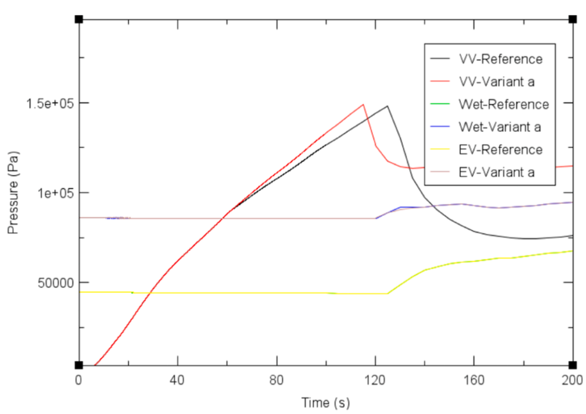

Fig. 5. Pressure comparison in VV, wet tank and EV (200 s).

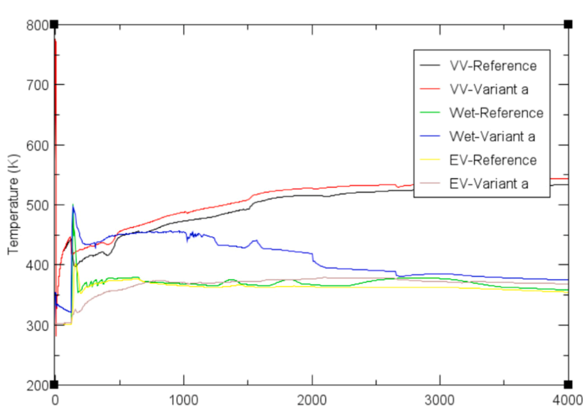

Fig. 6. Atmosphere temperature comparison in VV, wet tank and EV.

calculation time of 10^{-4} s as the maximum timestep, which was performed during the first 100 s, and a plotting frequency of 10^{-3} s. After 140 s, the timestep was increased to 10^{-1} and plotting frequency of 5 s. The calculations terminated at 4000 s [11], similar to what was performed in [11]; however, it could be extended depending on future activities.

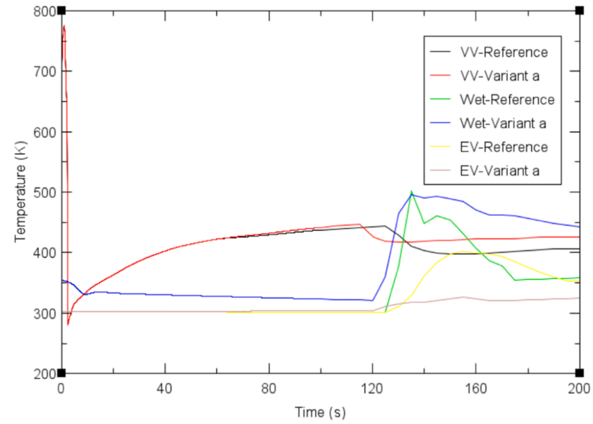

Fig. 7. Atmosphere temperature comparison in VV, wet tank and EV (200 s).

The wet tank and EV nodalization were divided into 10 axial levels and 11 flow paths, which are used to simulate a simplified circulation system in the tanks.

3. Results

As presented in [12], this analysis was conducted in order to study the possibility of using the PAR system in the case of a Divertor LOCA for the HCPB. Table 3 presents the main events which are faced by the VV and PSS systems. The main parameters are:

- Pressures: Figs. 4 and 5.
- Temperatures: Figss 6–9.
- Mass of Hydrogen from metal water reactions: Fig. 10
- Mole Fractions: Figs. 11 and 12.
- Recombined Hydrogen mass: Fig. 13.

As for the previous results, both solutions seem mitigating the pressure peaks (Figs. 4 and 5). In the reference calculation, the pressure (second peak around 106.4 kPa) is particularly reduced by the larger volumes, which lead to the release of the blowdown in the wet tanks and in the EVs. In the case of the results based on the parametric analysis from 2021, named "Variant A", the pressure (second peak around 164.9 kPa) is controlled by the condensation in the pool of the wet tanks. However, both concepts are below the design pressure of 200 kPa [5], though there are differences between these approaches. The difference in volumes between the reference and the "Variant A" cases leads to a delay in opening of around 10 seconds, as presented in Table 3. This difference is underlined in Fig. 5, where the first peak is narrowed by the opening of the rupture disks in the EV at 150 kPa. The second peak is achieved around 645 seconds for the reference case and 3000 seconds for the "Variant A" case, caused by the residual flow from the VV from the remaining steam and water mass coming from the cassettes and PF, as shown in Fig. 4. The pressures stabilize at 80.4 kPa for the reference and 153.5 kPa for the "Variant A" model.

In the case of the atmosphere temperature in the VV, it increased due to compression, as shown in Figs. 6 and 7, when the pressure is significantly lower than 50 kPa. This phenomenon is probably due to MELCOR's capability to consider the blowdown according to the steam table at such lower pressure regimes, which is simulated as compression and not expansion. This parametric approach is similar to what was highlighted with helium in previous years' activities [3,12,17]. However, in both cases, the peak is limited due to the adopted nodalization and the

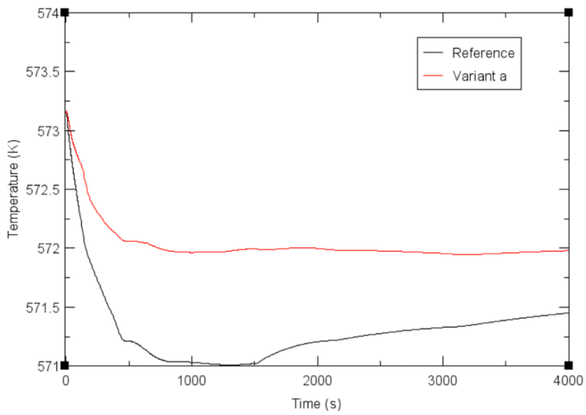

Fig. 8. Divertor average surface temperature.

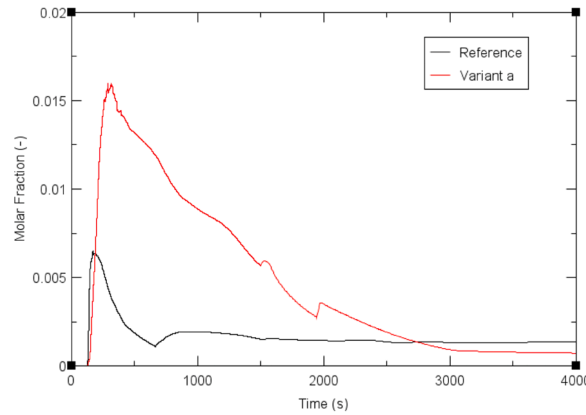

Fig. 11. Hydrogen mole fraction evaluated in EV.

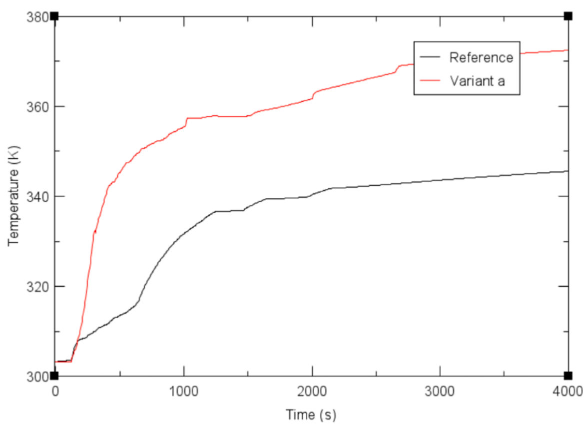

Fig. 9. Wet tanks pool temperature.

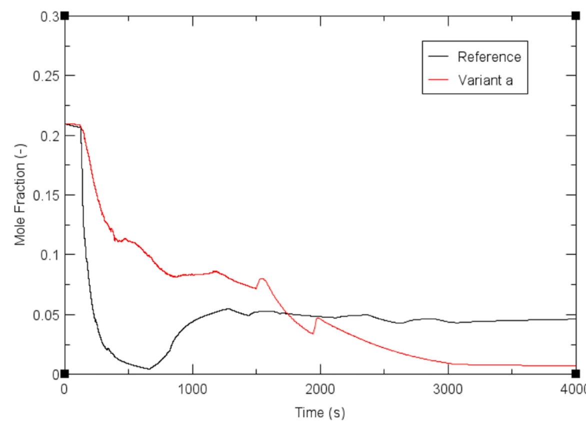

Fig. 12. O_2 mole fraction evaluated in EV.

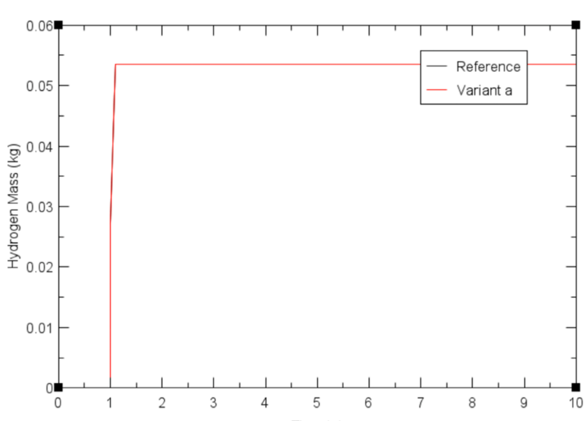

Fig. 10. Hydrogen production from tungsten water reactions.

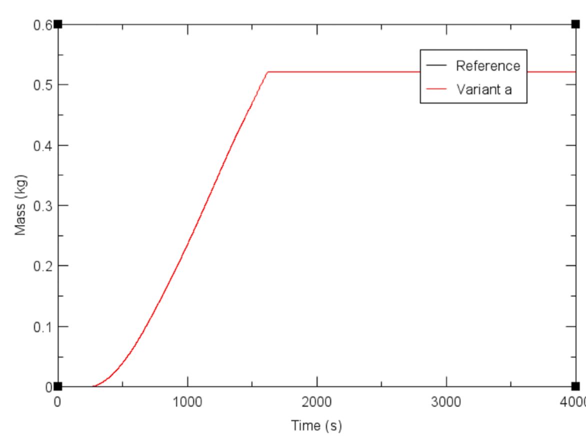

Fig. 13. Hydrogen recombined mass.

steam properties, particularly in comparison to the helium In-Vessel LOCA, as shown in Fig. 7. Both VV and PSS atmospheres stabilize their temperatures around 260.0 - 270.1 °C in the case of VV and 81.6 - 95.4 °C in the case of PSS. In any case, the blowdown expansion seems to cool down the divertor, as presented in Fig. 8. The expansion causes massive evaporation of the water into steam.

Regarding the condensation process, the pool temperature difference between the reference (increased up to 72.4 °C) and the “Variant A” (around 99.3 °C) highlights the phenomenon, as presented in Fig. 9. Indeed, the higher temperature in the case of the “Variant A” model underlines the potential of the suppression pool to condense the steam if the water level is increased compared to the nominal value. Such results also emphasize the impact of the condensation, which can be further illustrated by difference in maximum temperature mitigation between the reference model and the "Variant A" model.. The temperatures reach, in the case of the reference model, a maximum of 228.1 °C and 128.4 °C in wet tanks and EV (see Fig. 6), respectively. However, in the case of the “Variant A” model, the temperatures are 222.0°C and 101.3 °C for wet tanks and EVs, as shown in Fig. 6.

At the occurrence of the Divertor LOCA, there is a 53.6 g of hydrogen produced in VV due to H2O and W reaction in both cases. These results are underlined in Fig. 10. In the case of hydrogen mole fraction, the

Table 4
Summery of the main result.

	Pressure Peak -second [kPa]	Hydrogen Production [kg]	Mole Fraction in EV [-] at PAR	Maximum Temperature in VV [°C]	Maximum Temperature in Wet Tank [°C]	Maximum Temperature in EV [°C]	Quantity of Hydrogen recombined [kg]
Reference	106.4	0.0536	0.64 %	503.1	228.1	128.4	0.000
“Variant A”	164.9	0.0536	1.51 %	503.1	222.0	101.3	0.522

analyses show that the blowdown does not initiate the PAR reaction in the case of the reference model in the short-medium term. However, it seems that the concentration of hydrogen (see Fig. 11) and oxygen (see Fig. 12) are in the appropriate range. The results were plotted for EV at 7 m from the bottom, where it is supposed to allocate the tritium and the deuterium coming from the VV. Both models reach a value above the 0.5 % limit sufficient to initiate the recombination (Figs. 11 and 12), however only in the “Variant A” case model starts the catalytic recombination of PAR system. The recombined hydrogen mass inventory presented in Fig. 13 reached a value of 0.522 kg. Any hydrogen deflagration does not seem to be achieved in comparison of previous year results due to the new boundary condition of the VV and side volumes. However, these results are strongly influenced by the parametric approach used in MELCOR adopted for both nodalizations in order to simulate the deflagration. The deflagrations are initiated on molar fraction criterion presented in Fig. 11, the contribution on the overall hydrogen transport seems smaller than the concentration limit of 4 %. The maximum concentration detected are 0.64 % in the case of the reference and 1.51 % in the “Variant A” model. In addition, the reason of the absence of hydrogen recombining in the “reference case” seems caused by too low oxygen concentration reached after the 188 s due to the steam flow in the EV.

All the main results are summarized in Table 4.

4. Conclusions

The experience in the previous activities and in this one indicates that the risk of having a deflagration in the HCPB concept is lower in comparison to the WCLL. In particular as a follow-up activity, the model initially developed for the helium blowdown was modified by introducing new initial and boundary conditions to investigate the thermo-hydraulic and tritium mole concentration in the VV and PSS. The modifications included an inert atmosphere for the VV, a new position of PAR in EV, and the blowdown, which consists of the divertor LOCA.

Two variants of the model were built to analyse the hydrogen transport and the thermohydraulic behaviour of VV and PSS, characterized by the wet tank and the expansion volumes. The PSS design specifications were based on the main data available and the optimized system from previous years’ activities. The results indicated that both configurations can withstand the pressure peak caused by the blowdown. The major difference was that, compared to the helium blowdown, the results reached a mitigated stage in the case of the divertor blowdown. The tritium concentration reached a critical value of 0.5 % in the EV to activate the PAR. However, with the Fisher model, hydrogen recombination was achieved only in the case of the “Variant A” model. The total mass recombined was approximately 0.618 kg. This indicates that there were other criteria limiting the startup of PAR recombination. Future investigations can include an improved and detailed model to properly underline the PAR behaviour in the VV, particularly for the reference model.

Regarding the VV and PSS temperature, it was clearly indicated that optimizing the water level in the suppression pool of the wet tank is important. The results showed that the water level can be used to reduce the PSS volumes. Future work will be needed to continue the evaluation and optimization of the PSS design to improve the hydrogen mitigation system, including long-term management.

CRediT authorship contribution statement

G. Mazzini: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **M. D’Onorio:** Supervision, Investigation. **D.N. Dongiovanni:** Methodology, Formal analysis, Conceptualization. **J. Syblik:** Software, Methodology, Data curation.

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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Data availability

The data that has been used is confidential.

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