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Hydrogen Explosion Mitigation in DEMO Vacuum Vessel Pressure Suppression System using Passive Recombiners

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Abstract

An important issue for the Fusion Reactors is the hydrogen explosion hazard assessment. For this reason, in the Work Package of Safety Analyses and Environment (WPSAE) of the EUROFusion consortium, a task was established to identify the potential for hydrogen production in DEMO vessel in accident situations and to investigate the possible solutions which can prevent the risk of hydrogen and dust explosion. The hydrogen in the Vacuum Vessel (VV) can lead to combustion progressing in deflagration and detonation. Besides, the tungsten dust could enhance the effects of H_2 reaction as demonstrated by experiments, however, in this first set of accidents, only the H_2 generated by the chemical reaction is accounted for.

For these reasons, the solutions to avoid or limit the H_2 production and/or to control safely the risk of H_2 accumulation and explosion need to be screened starting from the solutions adopted in the fission technology, and later on, adapted and assessed in the Pressure Suppression System (PSS) foreseen in DEMO. One promising idea seems to install passive catalytic recombiners in the PSS.

The aim of this paper is firstly to set a range of operating parameters for the PAR functioning and intervention suitable in DEMO PSS configuration. Secondly to verify if the present criteria and parameters work efficiently in mitigating the H_2 accumulation a PSS in accidental conditions. To test the theoretical effectiveness of the PAR intervention, two reference accidents have been analyzed: an in-VV Loss Of Coolant Accident (LOCA) in the frame of the Design Basis Accident (DBA) and a Loss Of Flow Accident (LOFA) without active plasma shutdown in the context of the Beyond Design Basis Accidents (BDBA).

The results seem promising if the performances of the PAR will be confirmed in sub atmospheric and saturated conditions.

Keywords: Hydrogen, Deflagration. Safety. DEMO, passive autocatalytic recombiners

1. Introduction

The H_2 production, its accumulation and the consequent risk of explosion is among the critical issues both for fission and fusion nuclear plants. In fission, the H_2 generation is activated by the core material water reactions (e.g. with zirconium cladding, steel from supporting structures and boron carbide control rods). In fusion reactors, the H_2 sources are mainly related to the oxidation reactions between water/steam and plasma facing components (PFCs) or hot dust (W and Be) or liquid metal. In fission plants mitigative solutions have been adopted to reduce the consequences. Such experience was obtained addressing the few worldwide severe accidents, which were encountered in these years (in particular after Fukushima Daiichi accident [1]), and through some intensive experimental campaigns [2][3][4]. Some of those technical solutions can be cross-referred and applied to the fusion reactors, although the operating domain (i.e. pressure) is different and it needs to be investigated and verified. In particular, one technology used to address the H_2 explosion in the containment of the Pressurized Water Reactors (PWR) is the Passive Autocatalytic Recombiners (PAR) widely adopted in Europe [5].

The paper aim is firstly to screen the range of operating parameters for the PAR normally used in the fission NPPs and the PAR recombination capacity to analyse if they cope with the fusion needs. Secondly, to verify if the PAR model implemented in MELCOR 1.8.6 code for Fusion application [6][7] and its parameters work efficiently in mitigating the H_2 accumulation a PSS in accidental conditions. To test the theoretical effectiveness of the PAR intervention, two reference accidents have been analysed: an in-Vacuum Vessel (in-VV) Loss Of Coolant Accident (LOCA) in the frame of the Design Basis Accident (DBA) and a Loss Of Flow Accident (LOFA) without active plasma shutdown in the context of the Beyond Design Basis Accidents (BDBA).

2. PAR Recombination Capacity in Fission

In the PWR technology the strategy for H_2 ignition and recombination in post-accident states are based on several autocatalytic recombiners (Dual-PAR) function (recombining H_2 and CO during a deflagration also in presence of the fission product aerosols). In the VVER technology [5][8], some types of recombiners are used and placed according by the requirements (location of the main flows directions, H_2 integral and local concentrations). The PARs recombination capacity m_{H2} is calculated according to [8][9][10]:

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$$m_{H2} = N \cdot \eta \cdot (k_1 \cdot p + k_2) \cdot v \cdot tanh\big(v - min(vH_2)\big) \quad (1)$$

Where:
N - number of recombiners [-];
m_{H2} - recombination intensity [g/s];
η - recombination efficiency [-];
v - H_2 or oxygen concentration - [volume%];
p - pressure [bar];
k_1 - recombination empirical constant [g/(s·bar)];
k_2 - recombiner empirical constant [g/s];
$min(vH_2)$ [volume %]

The parameter $min(vH_2)$ is set up at about 0.5% and it is the H_2 percentage on volume oxygen. The recombiner starts to work from 2% by volume H_2 and above 50 °C. The variable η is the efficiency of the recombiner and can be determined by the conditions:

$$\eta = \begin{cases} 1.0 \Leftrightarrow \dfrac{VH2}{VO2} \leq 1 \\ 0.6 \Leftrightarrow \dfrac{VH2}{VO2} > 1 \end{cases}$$

The variable v is determined by the relationship:

$$V = \begin{cases} VH2 \Leftrightarrow \dfrac{VH2}{VO2} < 0.5 \\ VO2 \Leftrightarrow \dfrac{VH2}{VO2} \geq 0.5 \end{cases}$$

Several experimental programs were established to study the behaviour of the PARs under different conditions [2] [3] and [4]. In particular, THAI experimental program was one of the most comprehensive test series that were done using several different PAR manufactured worldwide (AREVA FR-380, NIS PAR and the AECL PAR). The program tested the PARs performance under several experimental regimes e.g. H_2 deflagration, different steam and oxygen concentrations, and exposed also to aerosol (a usual atmosphere for a severe accident in fission technology). Of course, some of the selected conditions are non-related with fusion technology where the number of different aerosols is limited depending on the structural material eroded during the normal operation or accident condition and there are different boundary conditions during the operation from the standard PWRs (e.g. pressure between 500 Pa and 45 kPa). For these reasons the possible solutions to avoid or limit the H_2 production and/or to control safely the risk of H_2 explosion need to be scrolled starting from the investigation of the solutions adopted in the fission technology, taking into account the different PFCs material and selecting the possible solutions suitable for the DEMO.

3. VV-VVPSS MELCOR Model

The proposed H_2 Mitigation System (HMS) in DEMO is a PARs installed in each tank of the VVPSS to prevent that H_2 concentrations increase leading to large scale H_2 deflagration or even detonations. Starting from [11], a tentative dimensioning and arrangement of the VVPSS is adopted in the study because the design is still on going. DEMO VV volume has been modelled with four control volumes simulating:

- plasma chamber (vol. 2466 m^3)
- upper port (vol. 1500 m^3)
- volume between the divertor and the VV structure (vol. 30 m^3) volume between the back of BB modules and VV structure (vol. 2400 m^3)

The VVPSS is connected with the VV by means of pipework's routing from the VV upper port area [12]. The preliminary VVPSS configuration is shown in Figure 1 and includes:

- 1 ST for small leakages
- 5 ST for DBA events
- 5 Rupture Disks (break setpoint 150 kPa) in order to take into account a sufficient safety margin from the Design Pressure of 200 kPa [13][14].
- 6 Bleed Lines to avoid the burst of the RD in case of small leakage (opening setpoint 90 kPa)

For small coolant leak handling, the bleed line connecting the VV to the suppression tank (tank A) will be opened when the VV pressure overcomes 90 kPa. Tank A has a volume of 300 m^3 filled with 30 m^3 of water. For large coolant leak, the rupture disks act when pressure in VV reaches 150 kPa opening a connection between the VV and 5 different suppression tanks. Each RDs tank has a volume of 500 m^3 filled with 300 m^3 of water. VVPSS tanks operating pressure is 9.5 kPa. The upper port (CV850) has been connected to the VVPSS tanks through 6 bleed lines (RPs) and 5 pipes with rupture disks (RDs).

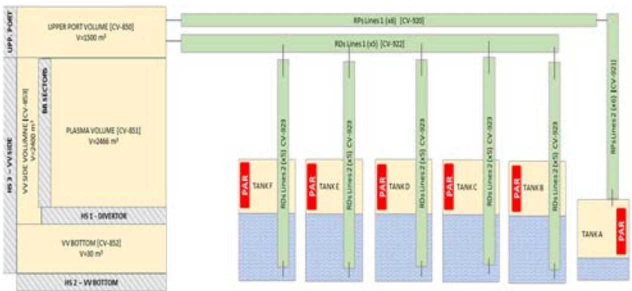

Figure 1 VV and PSS MELCOR model

In Table 1, the main parameters used by MELCOR 1.8.6 [6][7] to calculate the total gas flow rate through a PAR unit are summarized. From the PAR gas flow rate together with user provided PAR efficiencies, and the internally calculated H_2 mole fractions, the H_2 reaction rate is calculated. The adopted model used in these phase of the analyses is the MELCOR default model based on Fischer Correlation [15] as it is implemented in MELCOR code [6]. Normally those correlation are tested along the PARs in a rage between 90 kPa and 300 kPa in dry and humid conditions [2] [3]. The present application of the PAR in fusion field in such sence is still a pioner research area.

Table 1 Expected H_2 production in one year of DEMO full operation

Parameter	Description	Value
IPROPT	H_2 Recombiner flow model	Fischer (default)
IETAPR	H_2 Recombiner efficiency	Constant
EPAR	H_2 reaction efficiency	0.85
HPAR0	Minimum H_2 mole fraction start	0.02
HPARR	Minimum H_2 mole fraction stop	0.005
OPAR0	Minimum O_2 mole fraction start	0.03
OPARR	Minimum O_2 mole fraction stop	0.005

4. Analyses results for Postulated Scenarios

4.1 InVV-LOCA Scenario

This InVV-LOCA accident (DBA) sequence is characterized by a very low H_2 production. Chemical reactions between steam and tungsten hot surfaces within the vacuum vessel can produce about 1 g of H_2 due to the limited reached temperature on the PFC surfaces. However, it should be considered that the reaction between steam and tungsten dust deposited on the FW surface and on the divertor surface has not been considered in this simulation. Moreover, it is supposed that about 671.0 g of mobilizable tritium [16], present as source term in VV, can chemically react with the catalytic layer of the PARs.

The preliminary simulations have been performed assuming 150 kPa as set point for trigger of VVPSS-RDs. Such assumption is based on cocept to gather a certain safety margin from the 2 bar VV design criteria. Because all the RDs open at the same time the mass of H_2 is equally distributed in all the VVPSS suppression tanks and the minimum H_2 mole fraction is not reached for the PAR activation. For this reason, in order to reduce the volume available for H_2 migration, maximizing H_2 build-up into specific tanks, different RDs set points have been assumed (Table 2).

Table 2 VVPSS BLs and RDs pressure set point

VVPSS Suppression Tank	Pressure set-point [kPa]
Tank A	90
Tank B	150
Tank C	165
Tank D	175
Tank E	185
Tank F	190

The injection of steam inside the VVPSS causes an increase in pressure and temperature of VVPSS tanks and affects recombiner efficiency. Because there is no suppression of steam inside tank A (steam is directly injected in the tank atmosphere) high values of temperature and pressure are reached (Figure 2 and Figure 3). However, pressure remains between the operational limits of PAR (0.1 to 0.3 MPa according to [2]) for the entire accident sequence. Maximum temperature value in tank A is 607.95 K and decreases below 417.15 K (maximum operational temperature for PARs) about 69.5 s after the Postulate Initiating Event (PIE.

The results in Figure 4 show H_2 mass inside VVPSS Tank A and Tank B. The recombination process starts when H_2 mole fraction reaches 0.02 and stops after that the oxygen mole fraction drops to 0.005. The process of recombination is efficient, however, at the end of the accident sequence, only 36.5% of H_2 has been removed because there is not enough oxygen to sustain the catalytic reaction. The mass of oxygen available for the reaction is the fraction contained in bleed lines, rupture disks lines and STs atmosphere. To increase the inventory of H_2 removed the suppression tanks should be equipped with devices supplying oxygen sufficient to complete the reaction with H_2. Figure 4 shows the H_2 mass recombined by a PAR unit. Figure 5 shows the mole fraction of oxygen inside the VVPSS tanks. The main results indicating the main PARs time cut sets and their recombination capacity are summarized in Table 3.

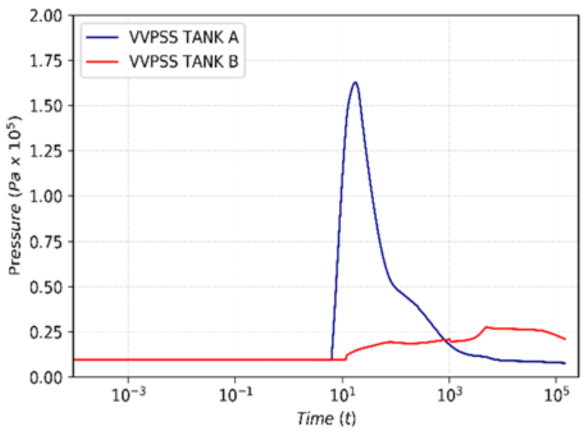

Figure 2 VVPSS Pressure (Tanks A and B)

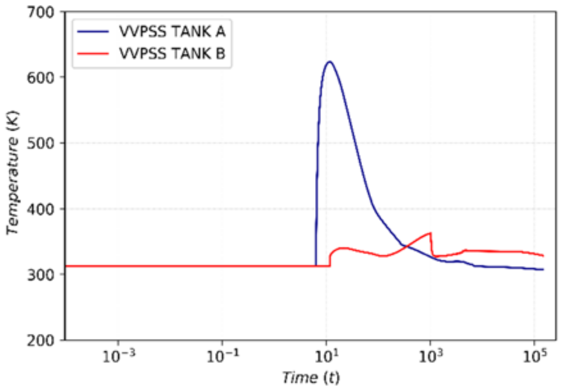

Figure 3 VVPSS temperature (Tanks A and B)

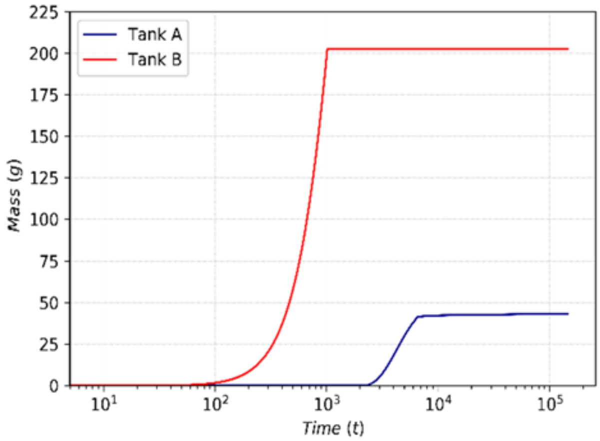

Figure 4 Mass of H_2 removed by PAR

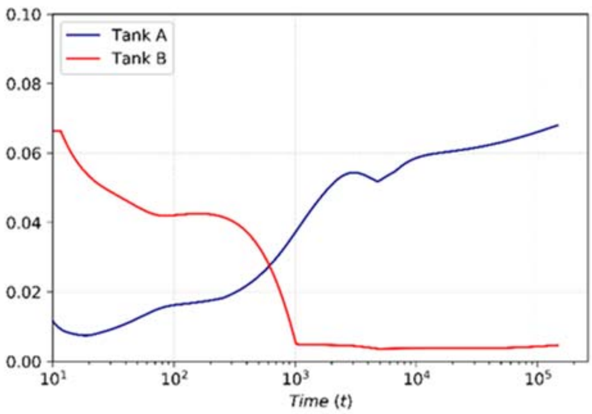

Figure 5 Oxygen mole fraction inside VVPSS

4.2 LOFA Scenario

This LOFA analysis is classified as BDBA due to the failure of the plasma shutdown system. The plasma burns continuously until the FW is overheated and fails causing an in-VV LOCA. The high temperatures reached by the plasma facing components cause a H_2 production higher than that obtained during an in-VV LOCA (DBA). All the five RDs connecting the VV to the VVPSS breaks when the pressure in the VV reaches a pressure peak of 150 kPa. The H_2 is equally distributed among the different tanks. The behaviour is the same in all the STs. For such a reason only the results for Tank B are shown in the figures below. However, they are representative of the other four suppression tanks.

As shown in Figure 6, the pressure has peak when the PHTS breakes due to the LOFA. The chemical reactions between steam and tungsten hot surfaces within the VV can produce about 300 g of H_2. As in the previous scenario, the reaction between steam and tungsten dust deposited on the FW surface and the divertor surface has not been considered in this simulation. Moreover, and as in the in-VV LOCA case, it is supposed that about 671.0 g of mobilizable tritium [12] in VV can chemically react with the catalytic layer of the PARs.

The injection of steam inside the VVPSS causes an increase in pressure and temperature of VVPSS tanks. It's important to take into account these values because they can affect recombiner operation. Because there is no suppression of steam inside tank A high values of temperature and pressure are reached (Figure 6 and Figure 7). However, pressure remains between the operational criteria of PAR (0.1 to 0.3 MPa according to [2]) for the entire accident sequence. The temperature peak in tank A is 645.7 K and decreases below 417.15 K (maximum operational temperature for PARs) about 322.5 s after the PIE.

The maximum value of 128 g of H_2 is reached in the Tank B. Because all the VVPSS suppression tanks are involved in the H_2 recombination process, the mass of oxygen available for the catalytic reaction is higher than that in the previous accident analysis (in-VV LOCA). The process of recombination is efficient; at the end of the accident sequence about 60% of H_2 has been removed by the PARs. The Figure 8 shows the H_2 mass recombined by a PAR unit. Figure 9 shows the mole fraction of oxygen inside the VVPSS tanks. The recombination process does not occur in Tank A, where the mole fraction of H_2 remains below 0.02 for the entire duration of the accident sequence. In other STs the recombination process starts when H_2 mole fraction reaches value of 0.02 (about 98 s) and stops after O_2 mole fraction drops to 0.005 (3981 s). The main results indicating the main PARs time cut sets and their recombination capacity are summarized in Table 3.

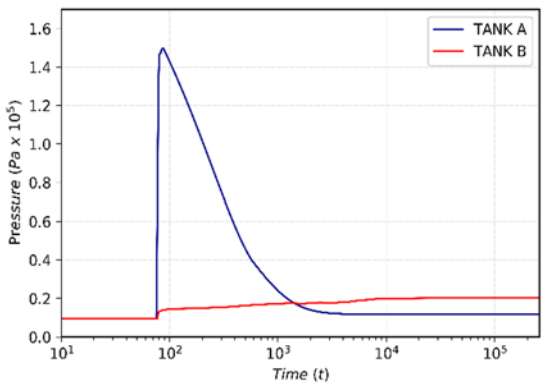

Figure 6 VVPSS Pressure

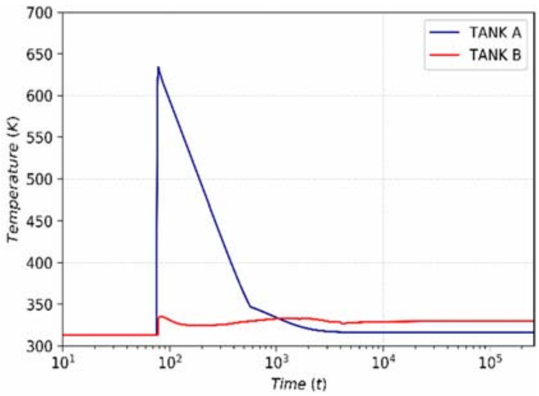

Figure 7 VVPSS temperature

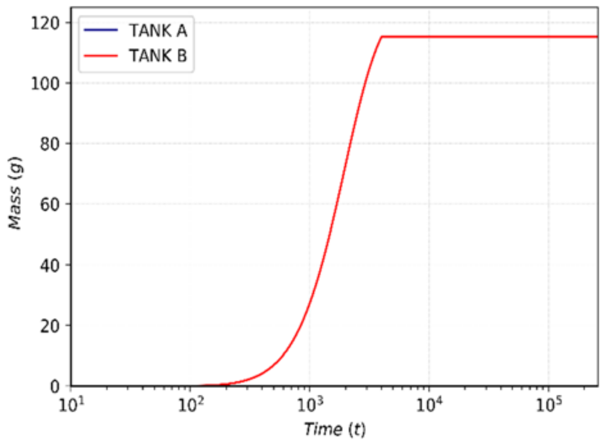

Figure 8 Mass of H_2 removed by PAR

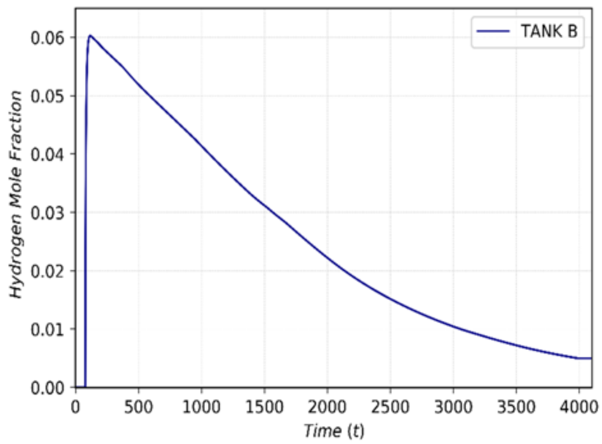

Figure 9 H_2 mole fraction inside VVPSS

Table 3 Summary of the Accident Results

Parameter	In-VV LOCA (DBA)		LOFA (BDBA)	
	Tank A	***Tank B***	***Tank A***	***Tank B to F***
Time at which PAR starts operating [s]	2160.0	24.8	-	97.9
Time at which PAR stops operating [s]	6623.0	1020	-	3981.0
Total H_2 mass removed by the PAR [g]	43.349	202.62	-	576.15
Residual H_2 mass in the tank after 72 h [g]	410.0	17	-	115.006

5. Summary and conclusions

A preliminary concept of HMS has been proposed with the aim to prevent the increase of H_2 concentrations to critical levels for H_2 deflagration or even detonations. It is based on the features used in the fission NPPs with particular attention on PARs. The operating data of existing PARs used in nuclear fission power plants, industrial plants, or experimental plants have to be evaluated before to be transferred in the DEMO context.

The HMS consists of passive PARs installed in each tank of the VVPSS, as shown in Figure 1. Two different accident sequences have been analysed to investigate H_2 mitigation systems' performance.

For the in-VV LOCA, in order to maximize the H_2 concentration inside the STs and reducing contamination issues, the H_2 is confined into a lower number of suppression tank, because the pressure set point of RDs line opening is different for any tank. In this case the HMS was able to remove only 36.5% of the mass H_2 inside the reactor because there is not enough oxygen to sustain the catalytic reaction. So, in this case, it will be necessary to equip the suppression tanks with devices acting as oxygen sources.

The second accident sequence was a LOFA. In this case, all the RDs are trigged at the same pressure setpoint, neglecting contaminations problems. The catalytic reaction occurs in all the five STs and at the end of the accident sequence, the HMS was able to remove about 60% of the mass H_2 inside the reactor.

However, those preliminary analyses show an interesting perspective on managing the H_2 deflagration issue, some future work is required to verify if the HMS concept works efficiently in subatmospheric conditions. In particular, a cost-benefit assessment shall address the opportunity of verifying some additional solutions. It is important to implement other PARs features in the MELCOR model that is tuned for fission plants.

Experimental campaigns to support the operation domain of fusion fusion devices should be beneficial.

Acknowledgments

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