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Pressure suppression system influence on vacuum vessel thermal-hydraulics and on source term mobilization during a multiple First Wall – Blanket pipe break

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Being the Vacuum Vessel Pressure Suppression System (VVPSS) one of the most important passive safety systems to be foreseen in DEMO plant, design and integration challenges have to be faced to ensure that best performance within safety requirements are always achieved. In this framework, parametric safety analyses have been performed to support VVPSS design activities; in particular to determine the minimum flow area required by the suppression system pipework to limit the vacuum vessel pressure below the limit imposed as a requirement by design.

The selected Postulated Initiating Event (PIE) is a double-ended guillotine break in the Primary Heat Transfer System (PHTS) feeding pipe of the Breeding Zone (BZ) during plasma activity. Coolant is discharged inside the VV upper port volume and an unmitigated disruption occurs, causing further breaks in the first wall (FW) cooling channels. Considering that limiters could be introduced in the future design of the EU DEMO reactor to prevent damages to plasma-facing components, the same parametric study has been performed considering limiters accident mitigation effects.

Because discharge flow area toward the suppression pool could also affect the source terms mobilization, the transport of radioactive products (e.g. tritium, tungsten dust and activated corrosion products) has been simulated with the fusion version of the MELCOR code (ver. 1.8.6).

Keywords: DEMO, Vacuum Vessel LOCA, Suppression System, Source Term, MELCOR

1. Introduction

The VV pressure suppression system is one of the most important safety passive systems to be foreseen in the DEMO plant, since it limits the allowable VV pressure in the event of in-vessel LOCA and confines radioactive sources in the system [1]. For this reason, it is classified as SIC-1 system [2] and its operation should be optimized, ensuring that the evolving system design will satisfy safety requirements and that it is optimized for the safety of personnel, public and environment [3][4][5].

A Functional Failure Modes and Effects Analysis (FFMEA), performed for all EU-DEMO key systems, led to the selection of 21 Postulated Initiating Events (PIEs) that envelope all identified failures [6]. In particular, in-vessel LOCA has been classified among the most representative events in terms of challenging conditions for plant safety, because it could cause substantial damage to the VV structure. In past activities, some in-vessel LOCA analyses have been conducted in this sense, choosing breaks in the FW channels [7][8] or in the divertor cassettes cooling system [9] as PIE.

In the present work, the selected postulated initiating event is a break in a BZ-PHTS feeding pipe during plasma activity. This PIE, rather than FW-PHTS LOCA, has been considered because of the larger inventory in the BZ-PHTS and because of the larger break flow area, which could cause severe overpressure conditions in the VV. Parametric analyses have been performed to determine the minimum flow area of VVPSS rupture disk pipes needed to keep the VV pressure below the design limit of 2 bar.

2. The WCLL EU DEMO reference design

The EU-DEMO reference design adopted for this LOCA analysis has 1923 MWth of fusion power. The WCLL breeding blanket concept, one of the candidate option for the future EU DEMO [10], consists of 16 sectors in the toroidal direction. Each sector includes 3 segments in the outboard blanket (OB) and 2 segments in the inboard (IB). The single segment is constituted of about 100 breeding cells distributed along the poloidal direction, following a Single Module Segment (SMS) approach. The reference breeding cell adopted for modelling purposes is the WCLL 2018 V0.6 Central OB equatorial cell, described in detail in [11]. The front part of the BZ module includes the First Wall, which is constituted by a 25 mm thickness of EUROFER and by 2 mm thickness of tungsten versus the plasma chamber. FW is integrated in the module and cooled by square channels with a dimension of 7 × 7 mm and pitch of 13.5 mm. The BZ cooling system is independent from the FW one. To minimize the risk of pipe rupture with consequent ingress of water into the breeding zone and violent chemical reactions occurring with the breeder [12], the BZ coolant pipe system consists of radial-toroidal Double Walled Tubes. Thermo-dynamic conditions of cooling water are 295–328 °C and 15.5 MPa.

Both FW and BZ blanket manifolds are connected to the PHTS through feeding pipes hosted in VV the upper port compartment. In the current design, the inlet/outlet BZ feeding pipes, object of the described accident, have an internal flow area of 0.02615 m2. The main PHTS components placed outside the VV are: the hot and cold distributor rings, the sector manifolds, the BZ Once-

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Through Steam Generators (OTSGs) and the FW Heat EXchangers (HEXs), pumps and pressurizers. A more comprehensive description of the PHTS design is contained in [13] and [14], including the description of out-of-vessel components. All these components are shown in Figure 1.

In the frame of EUROFusion Safety Analyses and Environment (SAE) project a new design of the VVPSS has been proposed for WCLL concept of the EU-DEMO. consists of six separate suppression tanks located in the containment basement, one of them is dedicated to handling the small leakages (Figure 2). The pipework consists mainly of six bleed lines connecting the VV to the small leakage tank, and five rupture disk lines one for each suppression tank. To avoid steam and radioactive flows inside neutral beam ports, pipework connecting the vacuum vessel to the suppression system has been attached to the upper port. Each suppression tank (ST) has a volume of 500 m^3 filled with 300 m^3 of water, while the tank for small leakages has a volume of 300 m^3 filled with 30 m^3 of water. Each tank is at 9.5 kPa during DEMO operation with subcooled water at 40 °C. VVPSS is equipped with rupture disks (RDs) and bleed valves that open when the pressure set point is reached. The pipework consists mainly of six Bleed Lines (BLs) (each line has a discharge area of 0.05 m^2) connecting the VV to the small leakage tank; and of five submerged RDs lines to allow steam condensation, one for each ST. The RDs lines flow area affects the VV pressure peak during in-vessel LOCA accident, and it is the aim of this work to provide a preliminary sizing of the RDs flow area. BLs are triggered by the defined VV pressure limit of 90 kPa, while RDs act when VV pressure is 150 kPa.

3. Accident description

Parametric accident analyses of an in-vacuum vessel LOCA have been performed to determine the minimum flow area of VVPSS rupture disk pipes needed to maintain VV pressure below 2 bar. Two different accident scenarios have been investigated:

- A “worst case” accident scenario involving the simultaneous failure of both BZ and FW PHTS;
- A “baseline case” scenario in which limiters are foreseen to adsorb the plasma energy deposited by an unmitigated plasma shutdown, preventing the failure of plasma-facing components and associated cooling system.

In both the considered scenarios the postulated initiating event is a double-ended guillotine break of the BZ feeding pipe located inside the upper port, for a total break area of 0.0523 m^2. The primary cooling system involves a large amount of energy due to the pressurized water coolant (15.5 MPa), therefore the pressurized steam spilled into the vacuum vessel may damage the VV structures causing a loss of confinement function.

An unmitigated plasma disruption occurs because of the presence of steam and other impurities at the plasma edges. If the disruption is faced by the limiters, no additional leaks occur. While, if limiters protection fails and the temperature of the plasma-facing components (PFCs) affected by the plasma disruption increases up to the limit temperature for the EUROFER wall failure (assumed to be 1000°C) further steam and water are discharged inside the plasma volume.

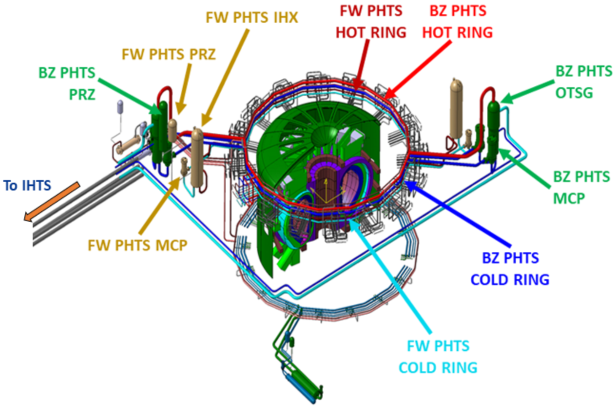

Figure 1 - DEMO WCLL system configuration [13]

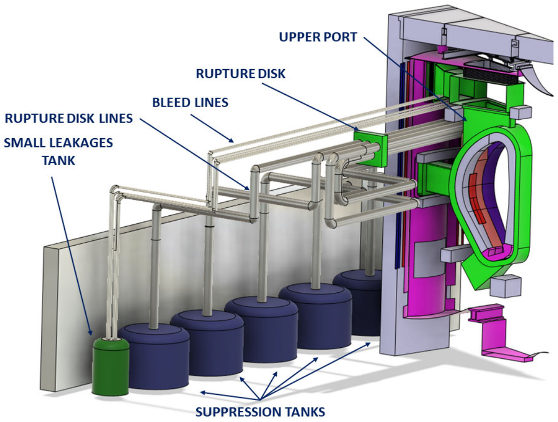

Figure 2 – 3D CAD scheme of EU DEMO VVPSS

The unmitigated disruption affects 2 different outboard segments one of which will be completely broken and the other partially broken, causing the break of 262 FW channels, for a total break area of 0.02568 m^2 [15].

Limiters could be foreseen in different areas of the DEMO first wall to prevent the plasma from touching the breeding blankets PFCs during all plasma transients such as ramp-up, vertical displacement event and loss of confinement [16]. DEMO limiters must withstand very high heat fluxes for such a reason their design follows the monobloc approach, similarly to the divertor. However, unlike the divertor, which has to withstand a high steady-state heat flux, the heat flux for the limiters can be extremely high, but at the same time, the duration of these loads is short [17].

4. MELCOR modelling

The fully integrated, engineering-level thermal hydraulics analysis code, MELCOR (v. 1.86) [18] with modifications for fusion reactor safety applications [19] has been used to evaluate accident consequences for the selected scenarios. MELCOR has been chosen because of its capability of consistently simulating coolant thermal-hydraulic behavior and radionuclide and aerosol

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transport in nuclear facilities and reactor cooling systems during severe accident scenarios.

4.1 PHTS Nodalization

The whole EU-DEMO BB has been modelled, as in [20], with the division in three different regions simulating respectively 1 sector, a group of 7 sectors (from sector 2 to sector 8) and a group of 8 sectors (from sector 9 to sector 16). All the PHTS main components have been modelled by using one-dimensional components, design data have been taken from a 3D CAD model in [14].

A schematic diagram of the MELCOR model used for this accident simulation is reported in Figure 3. It includes the FW and BB cooling loops, the blanket manifolds, the feeding pipes, the ex-vessel manifold and associated collector rings, the pressurizers, the heat exchangers system. Water enters and exits each sector through inlet and outlet feeding pipes connecting manifolds with ring distributors, which are connected to the steam generators through hot and cold legs.

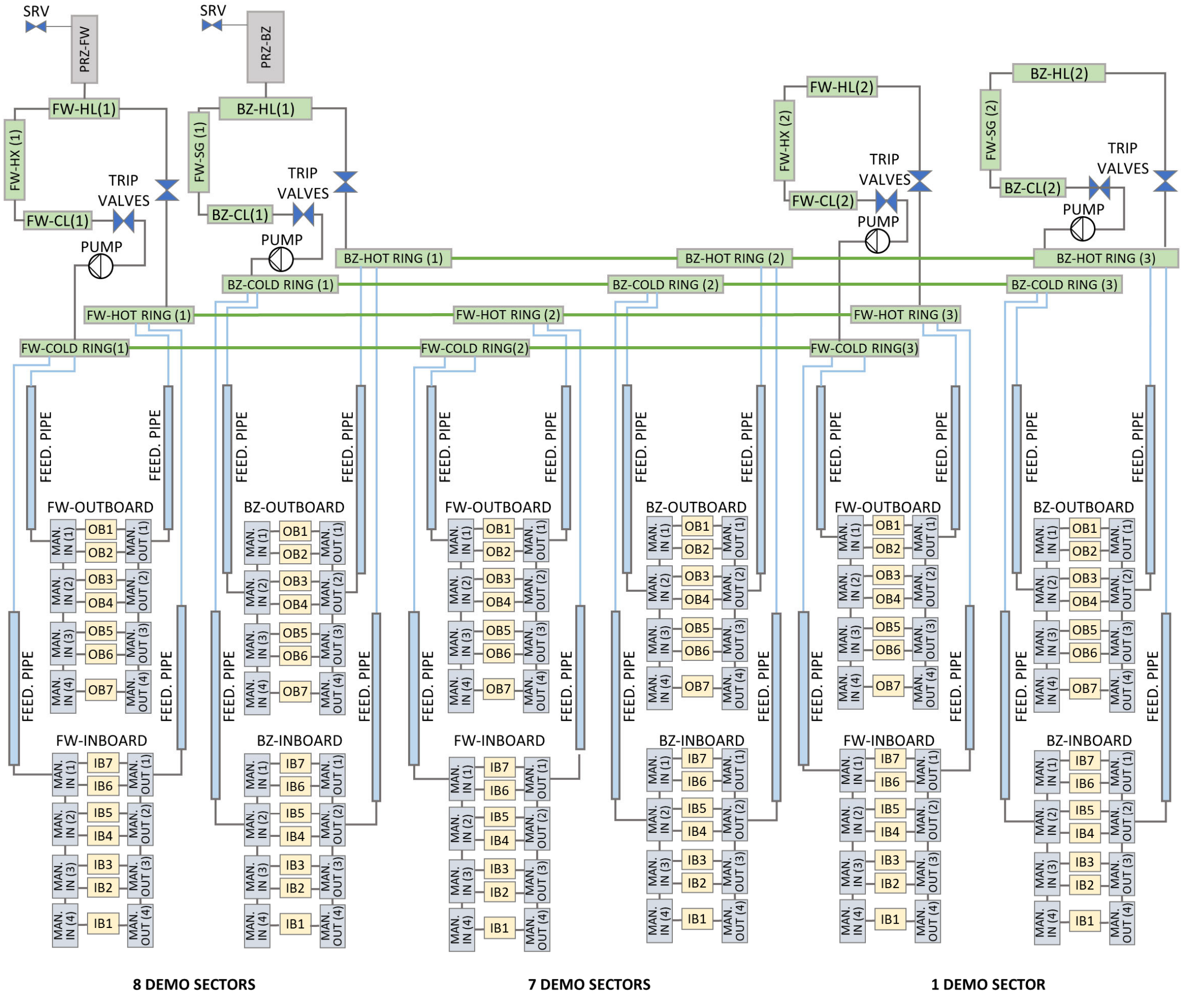

Figure 3 - Thermal hydraulic MELCOR nodalization scheme of the DEMO reactor [7]

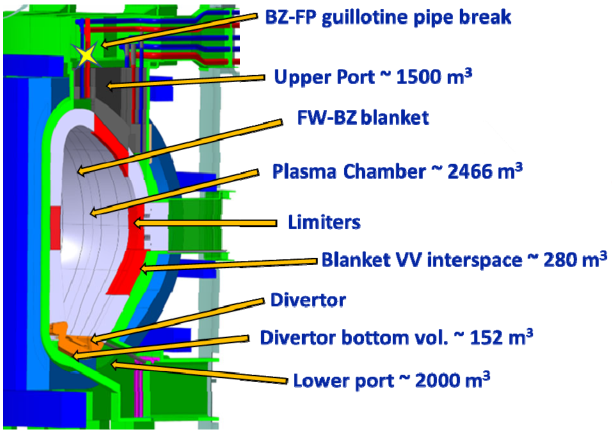

Figure 4 - EU DEMO baseline CAD model [16]

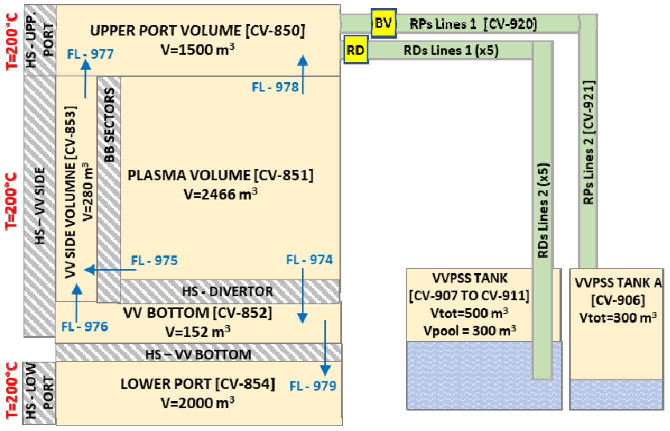

Figure 5 - MELCOR nodalization scheme of VV and VVPSS [7]

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Each sector has been modeled to investigate both inboard and outboard segments behavior during the accident sequences. FW and BZ manifolds distribute water to the modules. The overall segments have been poloidally divided in seven different volumes (OB1 to OB7 and IB1 to IB7). Blanket segments have been modelled by maintaining the design blanket material inventories and by preserving, as much as possible, the effective BB components design geometry.

Hot and cold leg of both PHTS are equipped with isolation valves, which begin to close when the pressure in the pressurizer is below 13.0 MPa. These valves are foreseen for limiting the amount of water entering the VV in case of LOCA.

4.2 VV and VVPSS nodalization

The total in-VV volume available for steam expansion in case of LOCA is about 6400 m3: 1500 m3 for the upper port volume, 2000 m3 for the lower port volume and 2900 m3 for the plasma chamber volume.

VV and VVPSS nodalization scheme is shown in Figure 5, together with the DEMO CAD model (Figure 4). To consider steam flow path from FW-PHTS to the VVPSS, the VV has been modeled with five control volume simulating the plasma chamber (CV851 of 2466 m3), the upper port (CV 850 of 1500 m3), the lower port (CV854 of 2000 m3), the volume interspace between the divertor and the VV structure (CV852 of 152 m3) and the interspace volume between the back-supporting structure (BSS) of BB modules and VV structure (CV853 of 280 m3). Connections paths and flow area between these volumes have been evaluated from EU-DEMO baseline CAD model in which all the components are at “room temperature”. Hence, the flow areas considered in this analysis are probably different than those at the operating conditions, during which the thermal expansion of the structures may lead to a different configuration of the steam path toward the VVPSS.

4.4 Source term modeling

In the performed safety analyses, the mobilized radioactive materials are activated dust and tritium (as tritiated water, HTO) from the VV, and HTO and activated corrosion products (ACP) from the failed FW/BL PHTS cooling loops. The total W-dust inventory in the VV is 694 kg (5 kg of dust are due to the plasma disruption) [21]. This mass has been input to the problem as 2.11 µm mass median diameter particle into the atmosphere phase of plasma volume (CV851) at the beginning of the problem. The mobilizable in-vessel tritium is 671.0 g. For radiological reasons tritium is assumed to be in the form of HTO after the coolant ingress within the VV. The tritium concentration in the primary cooling system is 0.015 g-T per cubic meter of water. The total amount of tritium in the form of HTO is 2.726 g-T in the FW-PHTS and 4.82 g-T in the BZ-PHTS. The quantity of ACP in a FW/BL PHTS loop is 10 kg. A mobilization fraction of 7% has been used for ACP [22].

5. Results of accident analysis

The parametric study includes 11 simulations performed by varying the rupture discs flow area from 1 m^2 (RD_1.0) to 2 m^2 (RD_2.0) for both “worst case” and “baseline case” accident scenarios.

5.1 Worst case scenario

PIE occurs at time t=0 s. The transient of water mass flow rate entering into the upper port from the feeding pipe rupture is shown in Figure 6. It is characterized by an initial rapid increase where the maximum of about 2975.6 kg/s is achieved, 0.6 s after the guillotine break. The total amount of water discharged in the VV from the BZ-PHTS is 116802.0 kg (Figure 7). The connection between the upper port and the plasma volume allows for the injection of steam inside the plasma volume.

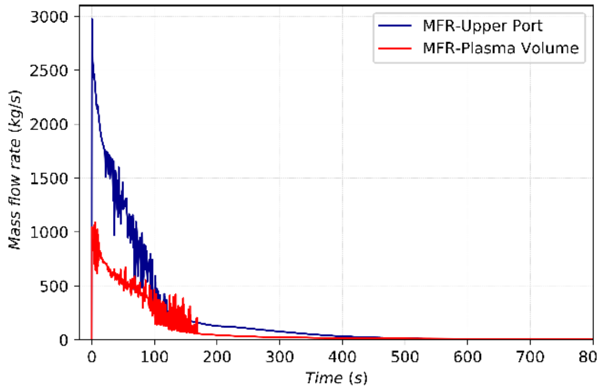

Figure 6 - MFR into upper port and plasma volume

The presence of steam impurities at the plasma edges causes an unplanned plasma termination with consequent deposition of plasma thermal and magnetic energy on plasma-facing components. As a result, FW temperature increases until the limit of 1000°C, causing the failure of 262 FW cooling channels. About 51 tons of additional water are discharged in the plasma volume (Figure 7).

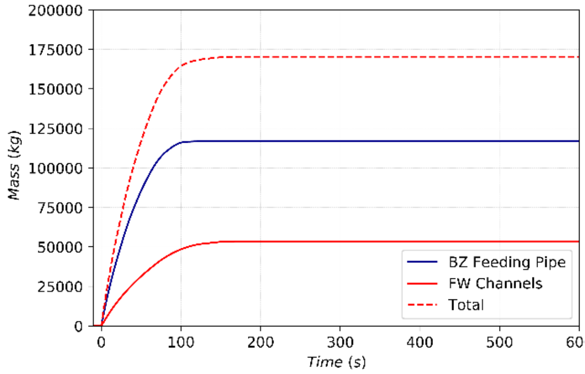

Figure 7 - Total mass discharged inside the VV

The mass flow rate into the plasma volume from failed FW channels is reported in Figure 6. The blowdown of the primary cooling system continues until the pressure in BZ and FW pressurizer reaches the set-point of 13.0 MPa for trip valve closure. This setpoint is reached at 7.4

s and 8.34 s for BZ and FW primary cooling system, respectively. The fully closed state is reached 10 s after the signal activation, when the pressure in the FW pressurizer is about 11.0 MPa and the pressure in the BZ pressurizer is 10.91 MPa.

These very large releases of water and steam lead to rapid pressurization of the upper port and the plasma volumes. The pressure peak reached in the VV volumes depends on the total flow area available for the discharge of steam in the VVPSS suppression tanks. In all the simulated cases the pressure in VV volumes increases very quickly and reaches the first pressure peak of 1.5 bar at about 1.958 s, when the rupture discs open a path between the upper port and the suppression tanks. The timing of this peak is slightly influenced by the discharge area. Once the disks have ruptured pressure inside the VV continue to increase, because the total mass entering the VVPSS is lower than the mass discharged into the VV (Figure 8). A second pressure peak is reached at around 9.0 s, which value and timing are reported in Table **1** for different cases.

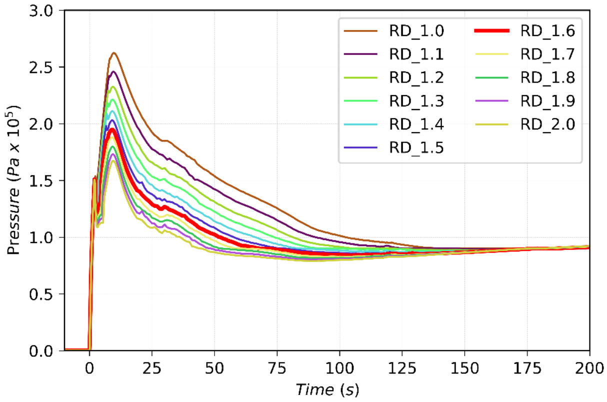

Figure 8 – Parametric results of VV pressure transient predicted by MELCOR for worst case scenario

Figure 9 to 10 show the total mass of radioactive materials in VVPSS volumes for different rupture disc line flow area. Transport of tungsten dust in VVPSS is strongly dependent on steam flow toward VVPPS pipework. Of the 694 kg of mobilizable tungsten dust, about 223.52 kg and 182.015 kg are confined in VVPSS suppression tanks, for case RD_2.0 and RD_1.0 respectively. After 32 h large part of the tungsten dust is suspended in the atmosphere and in the pool of VV volumes being the deposited mass around 3.0 kg for all the cases

Tritium mass follows a very similar behavior. In case of larger RD pipes, 0.2326 kg-T in the form of HTO are moved into VVPSS-STs while 0.446 kg-T remains in the VV volumes. In the opposite case (RD_2.0), 0.26 kg-T in the form of HTO are transported into the suppression tanks, and 0.411 kg are still in the VV after 32 h from the PIE.

The mobilization of ACPs inside the VVPSS tanks occurs together with the dry-up of the liquid phase inside the VV volumes, which occurs after around 1,000 s. ACPs are transferred from the liquid phase into the atmosphere of the volume by MELCOR and then mobilized toward the VVPSS-STs. 32 h after the PIE, of the initial 1.4 kg of ACP in DEMO, around 800 g remain confined in the PHTS, 575 g are suspended in the VV atmosphere and about 25 g are transferred into the suppression system tanks.

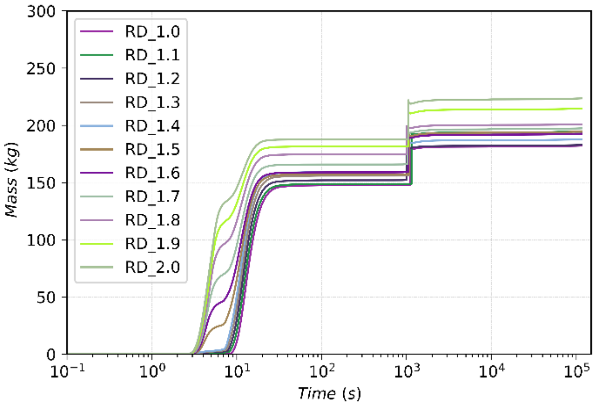

Figure 9 - Mass of W dust in VVPSS

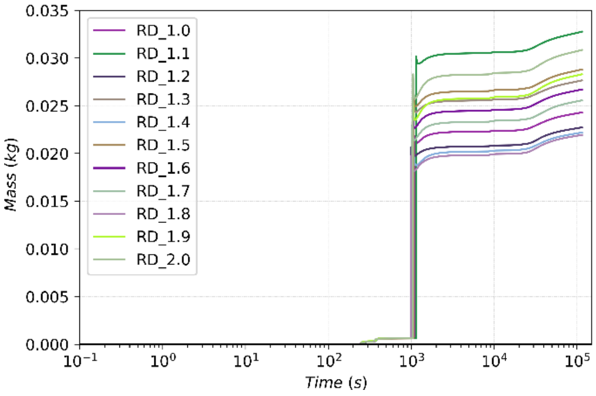

Figure 10 - Mass of ACP in VVPSS

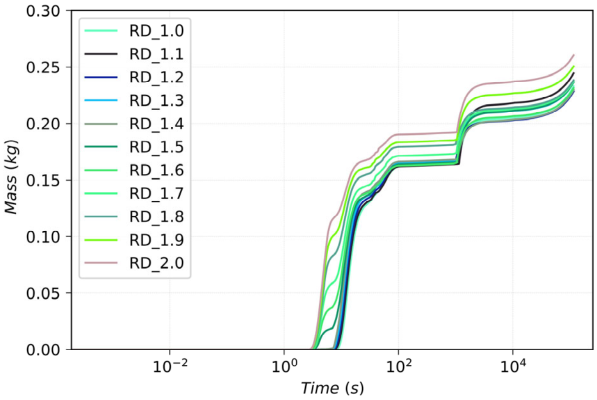

Figure 11 - Mass of tritium in the form of HTO in VVPSS

5.1 Base line case scenario

The PIE and its timing are the same as the worst case scenario. The presence of steam impurities at the plasma edges causes an unplanned plasma termination with consequent deposition of plasma thermal and magnetic energy and on limiters. During the disruption, a small portion of all the limiters will undergo a heat flux of 10 GW/m^2. The temperature of the tungsten layer of each limiter has been imposed as boundary condition through tabular function. It has been assumed equal to 3673 K for 100 ms (from plasma disruption), after that the W temperature is reduced to 423 K (limiters cooling water temperature) in 3s.

The 13 MPa pressure setpoint for the closure of BZ-PHTS trip valves is reached at 7.4 s. The fully closed state is reached 10 s after the signal activation, when the pressure in the BZ pressurizer is about 10.9 MPa.

Mass flow rate transient from the feeding pipe rupture in the upper port is characterized by an initial rapid increase where the maximum of about 2975.0 kg/s is achieved after around 0.7 s from the PIE. The total amount of water released from the BZ-PS into the VV is 117038 kg. Parametric results of the pressurization in the VV caused by this huge amount of water entering the upper port is shown in Figure 12.

Because of the limiters mitigative action, which prevent the break of FW channels, a 1.3 m^2 flow area is required for each RD line to withstand the VV imposed pressure limit of 2.0 bar. This result in a total area of 7.1 m^2. Results of the parametric study are summarized in Table **1**.

The total mass of tungsten dust, HTO and ACP mobilized into VVPSS is shown in Figure 13 to Figure 15.

The PIE occurs in the upper port, where the VVPSS pipework is connected, moreover in this case FW channels are protected by limiters. Thus any water release occurs directly into the chamber volume, where most of radioactive aerosol mass resides. This cause lower mobilization and transport phenomena in that volume. As a result, the maximum mass of tungsten dust transferred to the VVPPS is 198 kg for case RD_2.0 against the 223.52 kg obtained for the “worst case”. After 32 h of simulation, around 200 kg of tungsten dust are deposited on VV structure. Two orders of magnitude bigger than the previous case, to emphasize how particles gravitational settling is the dominant mechanism of aerosol mobilization in case of lack of high fluid flows.

Because of the lower mass of water released in the VV, after about 300 s there is no more liquid water in the upper port volume and ACP are moved to the gas phase and transferred to the VVPSS tanks. Of the 700 g of ACP in the BZ-PHTS at the steady-state only 4 g reach the suppression systems.

The faster evaporation of liquid water also causes a higher mobilization of tritium in the form of HTO that passes from the liquid to the gaseous form and is moved under the action of a pressure cascade toward the VVPSS.

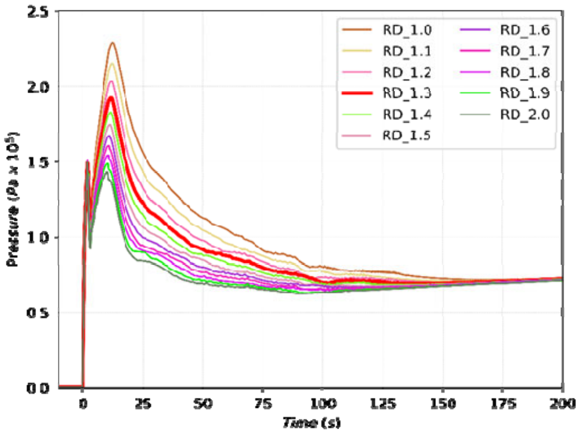

Figure 12 - Upper port pressure for different RD flow area

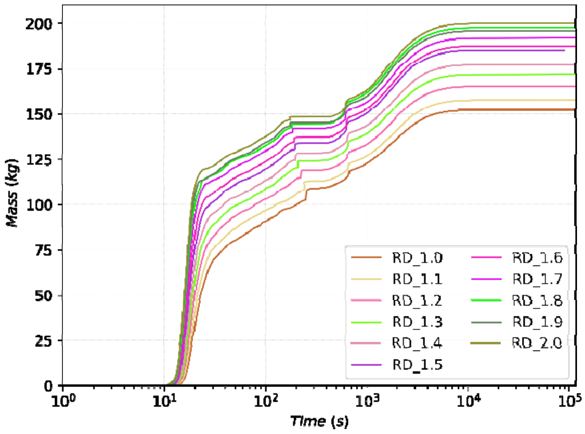

Figure 13 - Mass of W dust in VVPSS volumes

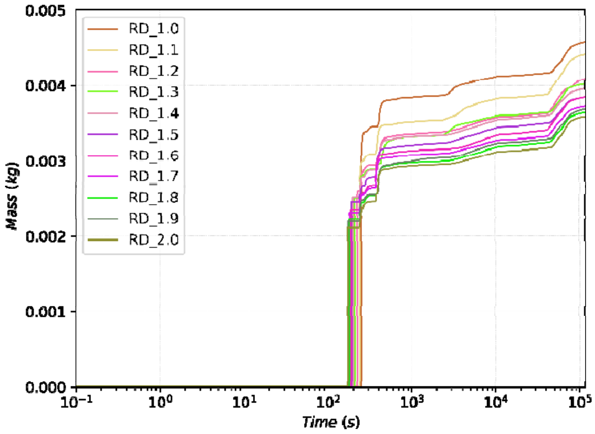

Figure 14 - Mass of ACP aerosol in VVPPS

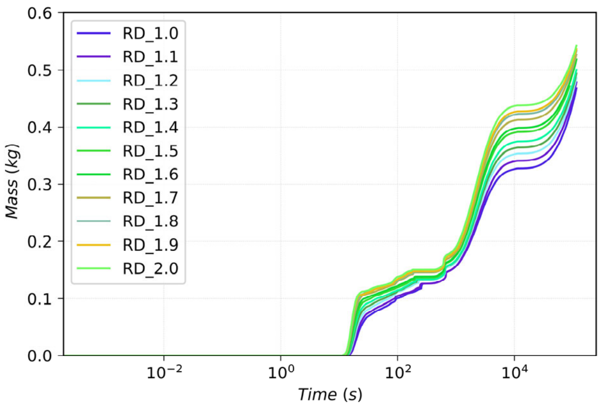

Figure 15 - Mass of tritium in the form of HTO in VVPSS

Table 1 – Summary table of VV pressurization results

Scenario	Total discharge flow area [m^2]	Base line scenario		Worst case scenario	
		Pressure peak [bar]	Time [s]	Pressure peak [bar]	Time [s]
RD_1.0	6×0.1 (BLs) + 5×1.0 (RDs) = 5.6	2.2703	12.500	2.5967	9.7028
RD_1.1	6×0.1 (BLs) + 5×1.1 (RDs) = 6.1	2.1337	12.307	2.4335	9.5054
RD_1.2	6×0.1 (BLs) + 5×1.2 (RDs) = 6.6	2.0155	12.108	2.3022	9.3008
RD_1.3	**6×0.1 (BLs) + 5×1.3 (RDs) = 7.1**	**1.9051**	**11.900**	2.1898	9.2028
RD_1.4	6×0.1 (BLs) + 5×1.4 (RDs) = 7.6	1.8120	11.703	2.0896	9.1030
RD_1.5	6×0.1 (BLs) + 5×1.5 (RDs) = 8.1	1.7312	11.404	2.0095	9.0003
RD_1.6	**6×0.1 (BLs) + 5×1.6 (RDs) = 8.6**	1.6563	11.209	**1.9291**	**9.0058**
RD_1.7	6×0.1 (BLs) + 5×1.7 (RDs) = 9.1	1.5892	10.904	1.8611	9.0089
RD_1.8	6×0.1 (BLs) + 5×1.8 (RDs) = 9.6	1.5269	10.700	1.78066	9.2080
RD_1.9	6×0.1 (BLs) + 5×1.9 (RDs) = 10.1	1.4798	2.1197	1.7139	9.3073
RD_2.0	6×0.1 (BLs) + 5×2.0 (RDs) = 10.6	1.4789	2.1095	1.6558	9.5079

6. Summary and conclusions

The aim of these two simulations, which events have been classified as DBA, was to define the needed flow area of VVPSS suppression pipework to limit the VV pressure below the limit imposed by safety requirements. In both cases, a pipe rupture was initiated by opening a connection between the BZ feeding pipe and the upper port volume. Water injection inside the plasma volume, in turn, causes an unmitigated plasma shutdown transient. In the case in which limiters can mitigate the effects of a plasma disruption, no further leaks are considered (“baseline” scenario). In the case in which limiters are not installed (“worst” scenario), the unmitigated plasma disruption causes an additional break of 262 FW channels. For each scenario, a parametric study considering different sections for the 5 RDs lines connecting the upper port to the VVPSS has been performed. Due to the difference in the operating pressure (0.1 kPa in the VV vs 15.5 MPa in the BZ-PHTS and in the FW-PHTS), after the tube rupture, water and steam enter the VV volume causing rapid pressurization. The results indicate that the pressure dynamics inside the VV and its peak value strongly depend on the capability of the relief pipes to discharge an adequate flow of steam into the ST. Large VV penetration are needed to stay below the limit of 0.2 MPa. For the “worst case” scenario, a total discharge area of 8.6 m^2 is required, while in the “baseline” case scenario at least 7.1 m^2.

Acknowledgments

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