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ASSESSMENT OF W7-X PLASMA VESSEL PRESSURISATION IN CASE OF LOCA TAKING INTO ACCOUNT IN-VESSEL COMPONENTS

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ABSTRACT

This paper presents the analysis of W7-X vacuum vessel response taking into account in-vessel components. A detailed analysis of the vacuum vessel response to the loss of coolant accident was performed using lumped-parameter codes COCOSYS and ASTEC. The performed analysis showed that the installed plasma vessel venting system prevents overpressure of PV in case of 40 mm diameter LOCA in “baking” mode. The performed analysis revealed differences in heat transfer modelling implemented in ASTEC and COCOSYS computer codes, which require further investigation to justify the correct approach for application to fusion facilities.

INTRODUCTION

Wendelstein 7-X (W7-X) is an experimental stellarator that is currently being built in Greifswald, Germany by the Max-Planck-Institut für Plasmaphysik (IPP) [1]. Loss of coolant accident (LOCA) is one of the design basis accidents to be investigated to show the safety of the facility. A rupture of one of the 40 mm inner diameter coolant pipes providing water for the divertor targets during the operation mode “baking” is considered the most severe accident in terms of the Plasma Vessel (PV) pressurization.

In case of LOCA inside the vacuum vessel, the water would be released to the plasma vessel venting system, which exists in the space between in-vessel components and the outer vessel. The steam generated in this space would enter the main volume of the vacuum vessel through the gaps between the in-vessel components, i.e., steam flow to main volume would be limited. In previous analyses [2], the existence of in-vessel components and limitation of flow area was not taken into account, and the assumption was made that the coolant is released to the main volume.

A detailed analysis of the cooling system and coolant discharge to the vacuum vessel using RELAP5 code is presented in [3].

Recently, IRSN (France) presented results of adaption of ASTEC computer code for fusion installations, where ASTEC validation against ICE P1 test is presented [4]. COCOSYS code developed by GRS mbH is a computer code for containment analysis [5]. Most of the models included in COCOSYS code are the same as in CPA module of ASTEC code, but some differences exist due to different requirements for these codes. Benchmarking of the results received with two codes provides more confidence in results and helps in identification of possible important differences in the modelling.

This paper presents the analysis of W7-X vacuum vessel response to LOCA taking into account the in-vessel components. Such investigation provides estimates if these components have influence on the general vacuum vessel response as well as the possible pressure differences acting on in-vessel components. A detailed analysis of the vacuum vessel response to the loss of coolant accident was performed using lumped-parameter codes COCOSYS and ASTEC. The performed analysis answered the questions set in the installed plasma vessel venting system during overpressure of PV in case of 40 mm diameter LOCA in “baking” mode. The performed analysis also revealed code differences, which require further investigation to justify the correct approach for application to fusion facilities.

DESCRIPTION OF W7-X PLASMA VESSEL

The plasma inside PV is retained and shaped into an appropriate form using magnetic field, which is induced by the magnet system. Vacuum in the space filled with plasma is maintained by PV. The PV has a rather sophisticated shape, largely similar to the geometry of the space occupied by plasma. The PV is made of a 17 mm metal shell covered by the thermal isolation. Inside the PV, in the space between the shell and the plasma, there are a number of different components known as components inside the PV like baffles, targets, walls, etc. (Fig. 1).

The plasma vessel of W7-X consists of 5 modules having the same configuration and volume. According to W7-X design description, plasma vessel could be considered in simplified geometry as torus with a major radius of 5.5 m and a minor radius of 1 m with a free volume of 108.5 m^3. PV is made of stainless steel with total weight of the torus walls of 95100 kg (32600 kg torus walls and 62500 kg torus ports). The total surface area of the walls is 708.1 m^2, which was calculated assuming that the average thickness is 17 mm, and the steel density is 7900 kg/m^3.

To protect the PV from overpressure two burst disks are installed: 1) one with opening pressure of 1.1 bar and 2) one with opening pressure of 1.2 bar. The diameter of both burst disks is 250 mm. Both burst disks are installed on the pipelines of 300 mm inner diameter that are connected to the main pipeline of 500 mm inner diameter. The exit of main pipeline is outside the building above the roof level.

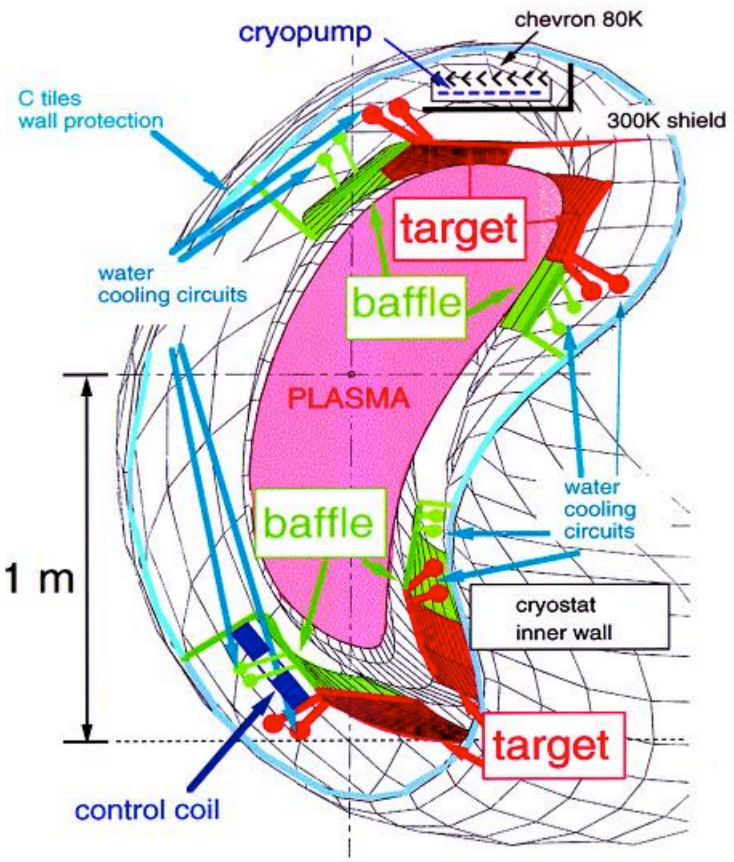


Fig. 1. Cross-section of the plasma vessel with a schematic illustration of the in-vessel components [6]

DESCRIPTION OF THE MODEL FOR COCOSYS AND ASTEC CODES

1. COCOSYS and ASTEC codes

Simulations of W7-X Plasma Vessel venting system results were performed using COCOSYS (version V2.4v3) and ASTEC (version V2.0r3p2) codes.

COCOSYS (Containment Code System) is a lumped-parameter program code designed for simulation of essential processes and states during severe accident propagation in the containment of light water reactor atmosphere, and it also covers the design basis accidents [5]. This software package is under development and validation by GRS mbH (Germany) scientists. COCOSYS is used for the identification of possible deficits in plant safety, qualification of the safety reserves of the entire system, assessment of damage-limiting or mitigating accident management measures.

ASTEC (Accident Source Term Evaluation Code) has a similar to COCOSYS code model CPA, dedicated to severe accident phenomena in containment of light water reactors investigation. This code created in cooperation between IRSN (France) and GRS mbH (Germany) was validated by making simulations at different experimental facilities (the Phebus containment, the KAEVER vessel, the Battelle Model Containment, the LACE facility and the VVER-1000 NPP containment, etc.) [7]. As it was mentioned, recently IRSN (France) presented results of adaption of ASTEC computer code for fusion installations [4]; consequently, these codes could be used to simulate possible accidents in the fusion facilities.

2. Description of nodalization scheme

The nodalisation scheme of W7-X Plasma Vessel venting system is shown in Fig. 2. Red lines show junctions between the nodes for gas flow, and blue arrows indicate the flow of water, which comes through the ruptured pipe or could be formed due to steam condensation on the structures.

Each of 5 modules is modelled separately since only the main volume of PV has full area connection. The outer spaces do not have connection between modules; thus, in case of LOCA, the water is released in the volume close to port (PV-O); then it is partially converted to steam, which flows though the gaps to the main volume (PV-C), and then it is distributed to the other modules as well as other spaces behind the in-vessel components (PV-T, PV-I, and PV-B). The water from the node PV-O flows to the PV-C, and then it could flow downwards to PV-B or if the water level rises high enough – to the nodes PV-C of the connected modules.

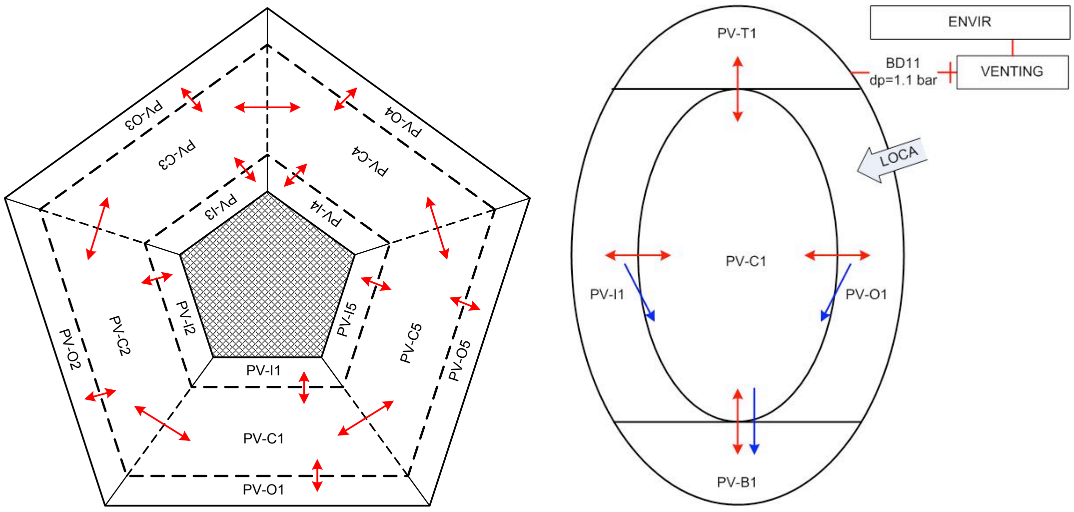
The structures of the plasma vessel were assumed to be at temperature of 150 °C. The free convection, forced convection, condensation and wall to gas radiation heat transfer models were considered in the analysis. The structures simulating the in-vessel components are also considered in the analysis. They separate the inner and outer volumes, and the heat transfer is considered.

When the burst disk opens, the steam flows to the venting system, which has piping in the torus hall and other compartments at room temperature. The heat transfer in these pipes is considered as well enabling steam to condense in these pipes. In the developed models, it is assumed that the temperature of torus hall is 20 °C.

Since COCOSYS code cannot simulate deep vacuum conditions, it is assumed that the initial pressure inside the plasma vessel is 1000 Pa, which is the lowest possible pressure in the code.

The models for COCOSYS and ASTEC codes are the same; however, some differences exist inside the codes for modelling of gas flows and heat transfer to the structures.

The analysis of the venting system was performed for the loss of coolant accident scenario, which assumes a rupture of 40 mm diameter pipe in the operation mode "Baking". The coolant release rate and the specific enthalpy of the released coolant were calculated using RELAP5 code [3] and are shown in Fig. 3. The cooling water temperature is 160°C and the pressure is 10 bar [3]. After pipe rupture, the maximal flow rate through the break into the plasma vessel reaches ~28 kg/s, but after this peak, it gradually decreases. This decrease is related to closure of the automatic valves in the baking circuit. After 25 s, the release rate to the plasma vessel is ~5 kg/s, and after 80 s, it is <2 kg/s. The specific enthalpy of the released coolant changes with the time; at first only water is released, but after ~75 s, the superheated steam appears.



(a) (b)

Fig. 2. Nodalisation scheme of W7-X Plasma Vessel (a) top view; (b) cross-section view

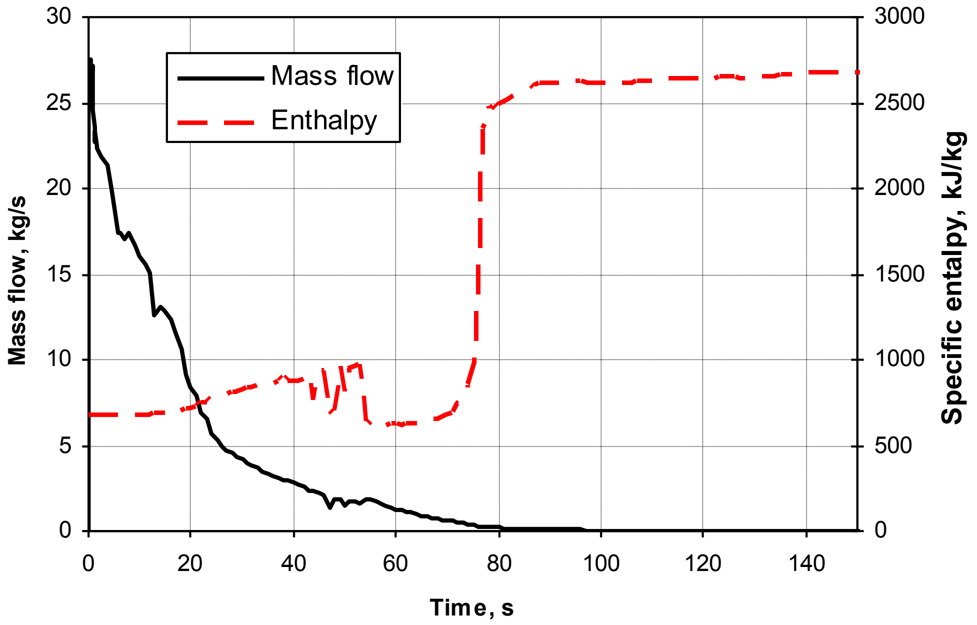
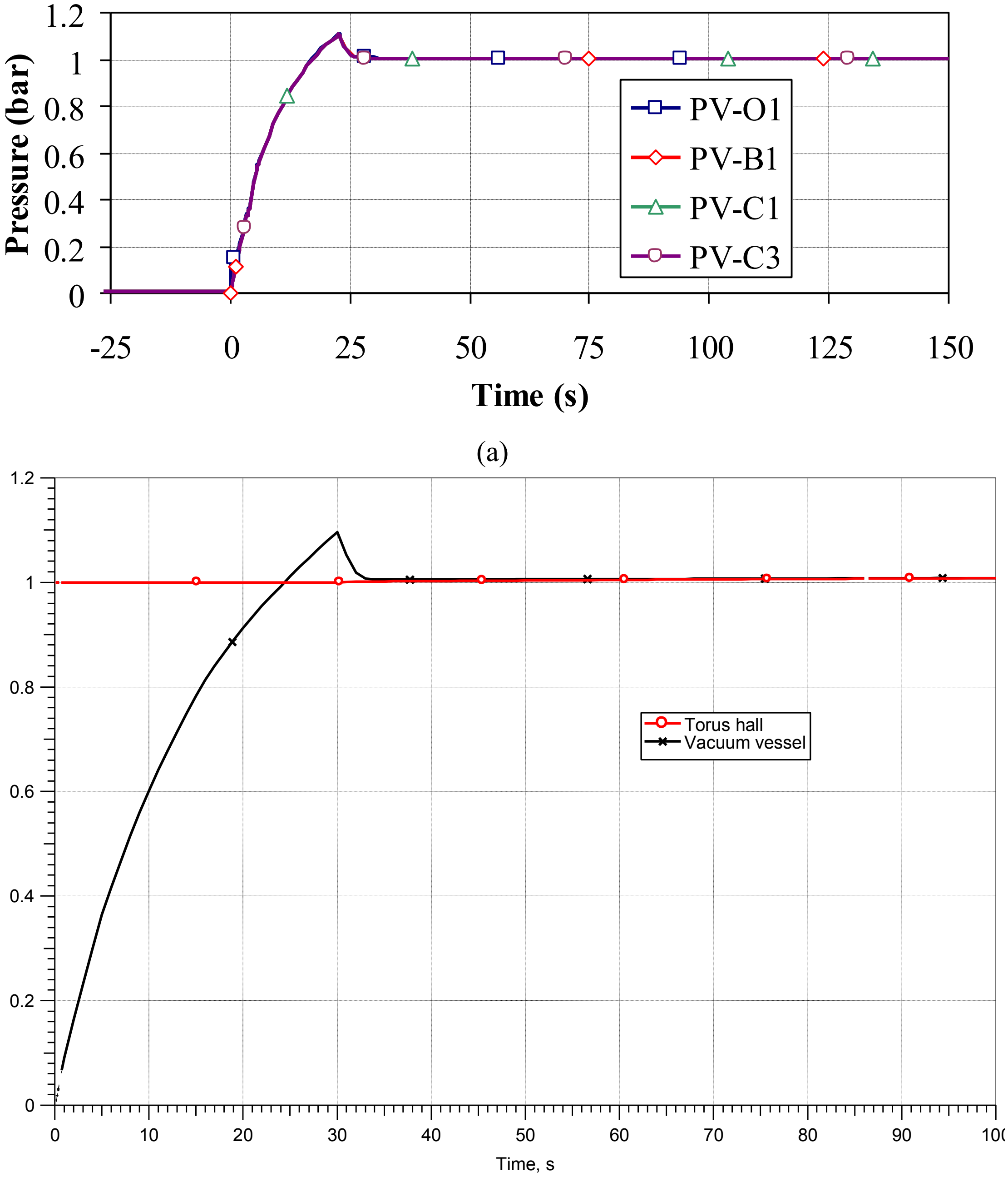


Fig. 3. Coolant release rate and specific enthalpy to plasma vessel received from RELAP5 code analysis [3]

RESULTS OF THE ANALYSIS

This section presents the results of the base case scenario calculated using COCOSYS code, which assumes normal operation of all the systems and equipment. Fig. 4(a) presents how the pressure in the nodes PV-O1, PV-B1, PV-C1 and PV-C3 changes during the accident. After the pipe rupture, the pressure in nodes increases till it reaches 1.1 bar, which is a set-point for the 1st burst disk opening (after 23 s). After burst disk opening, the steam is discharged to the piping of venting system, and the pressure in PV starts decreasing. Nevertheless, the pressure in PV stays slightly above the atmospheric due to vaporization of water in PV, which appears due to contact between water and hot structures. The maximal pressure peak is ~1.105 bar, which means that the diameter of the installed burst disk is sufficient to prevent further pressure increase.



(a)

(b)

Fig. 4. (a) Pressure in PV-O1, PV-B1, PV-C1, PV-C3 nodes; (b) Pressure evolutions inside the vacuum vessel and torus hall during the accident. Results from earlier performed analyses **[**2**].**

The main objective of the developed model was to check the influence of the in-vessel components on the results. As it is shown in Fig. 4(a)**,** the global behaviour of pressure is similar and it complies with earlier performed analyses without separate evaluation of in-vessel components Fig. 4(b) [2]. However, in the initial phase of the accident, there is a pressure difference between rupture node (PV-O1) and the connected node (PV-C1) **(**Fig. 5**)**. Pressure difference between these nodes is ~0.11 bar, i.e., such pressure difference is acting on the in-vessel components pushing them to the central part of PV. This pressure peak is short-term, and within ~8 s, the pressure difference becomes negligible. The pressure differences between PV-C1 and other nodes are negligible during the entire analysed period.

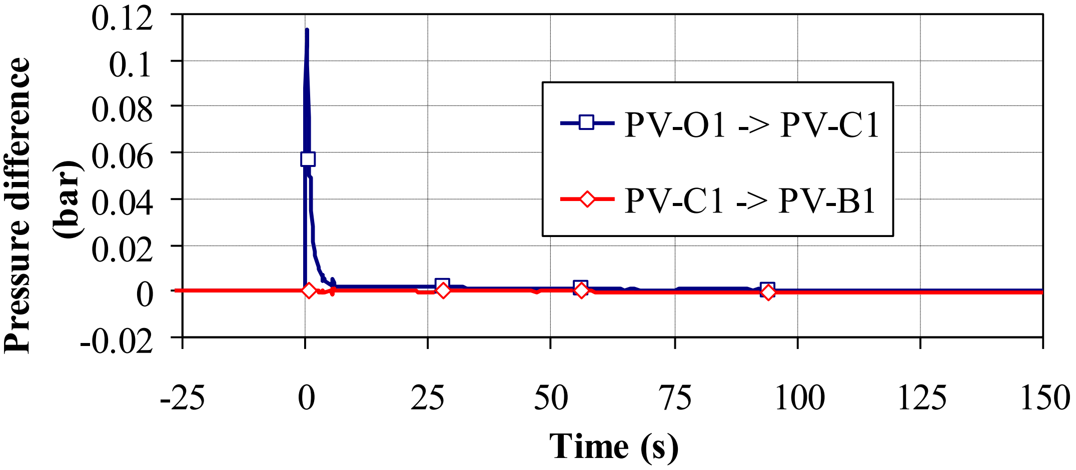


Fig. 5. Pressure difference between PV-O1 and PV-C1, PV-C1 and PV-B1 nodes

The calculated gas temperatures in the representative nodes are shown in Fig. 6. As it was described before, the initial temperatures in PV are assumed to be 150°C. Due to release of water, the temperature in PV-O1 and PV-C1 decreases down to ~115-120 °C. The gas temperature drop in the first seconds after accident is related with assumptions in the lumped parameter codes that the water cannot exist in superheated gas; it has to be evaporated to saturated conditions or deposited to the sump. Therefore, the initial temperature drop corresponds to saturation temperature at sub atmospheric pressure. While in PV-B1 and PV-C3, temperature spike up to ~194°C is observed, which is related to continuous pressure increase inside the zone. Initially, pressure in PV-O1, PV-C1, PV-B1 and PV-C3 is equal and rises from 0 to 1.1 bar (see Fig. 4**)** and steam enthalpy varies 2700–2900 kJ/kg. Later, gas temperatures are determined by the heat transfer to the structures. This node faces surfaces of the in-vessel components and does not face the main mass of steel structures of PV. The gas temperature in PV-O1 gradually increases to ~135 °C due to energy accumulated in hot external steel structures. After the initial peek, the gas temperature in another module (PV-C3) comes down to initial value of 150 °C, and the temperature in PV-B1 gradually decreases to ~110 °C at the end of calculations. This temperature decrease is determined by the water pool in the node. The water mass distribution is shown in Fig. 7. As it was expected in the beginning of the analysis, the water released in PV-O1 flows to PV-C1 and then to the lowest part of the vessel simulated by PV-B1. After 80 s, the coolant release to PV is not significant (Fig. 3); therefore, after this time, the water mass distribution almost does not change. After this time, the water mass depends only on the heat transfer from the hot structures, which cause evaporation, but this process is slow and is not observed in the given figures due to scale. The total accumulated water mass in PV-B1 node is 368 kg.

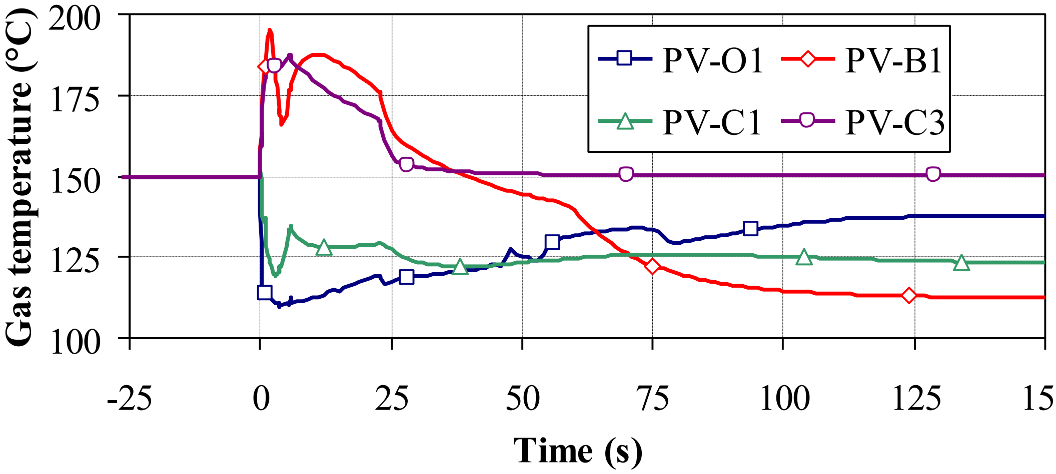


Fig. 6. Temperature in PV-O1, PV-B1, PV-C1 and PV-C3 nodes

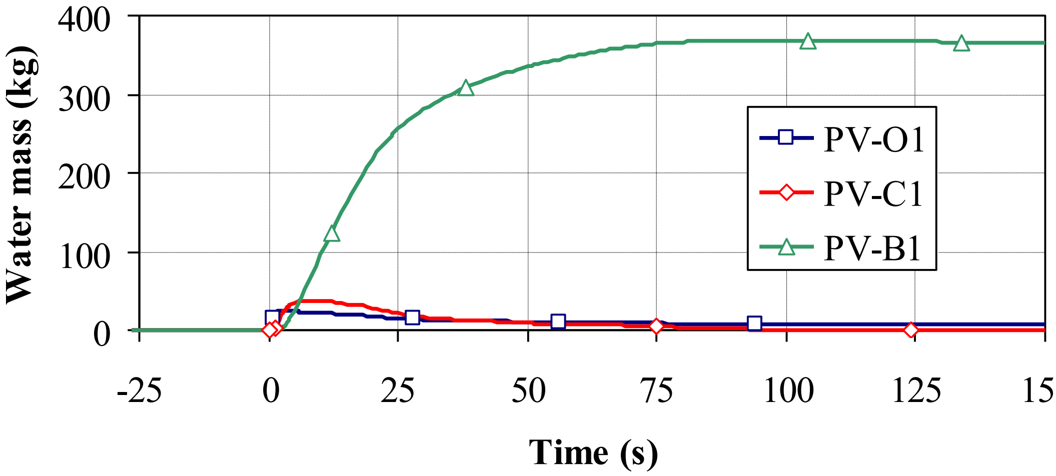


Fig. 7. Water mass in PV-O1, PV-C1 and PV-B1 nodes

Fig. 8 presents water temperature in PV-B1 node during an accident. The temperature of water released to Plasma Vessel is 160 °C, but it decreases to the temperature of PV structures (150 °C) due to heat exchange with them. When the water pool appears in in PV-B1 node its temperature is complies with temperature of water flowing along the PV structures (150 °C) but then it sharply decreases to saturation temperature at given pressure (Fig. 4).

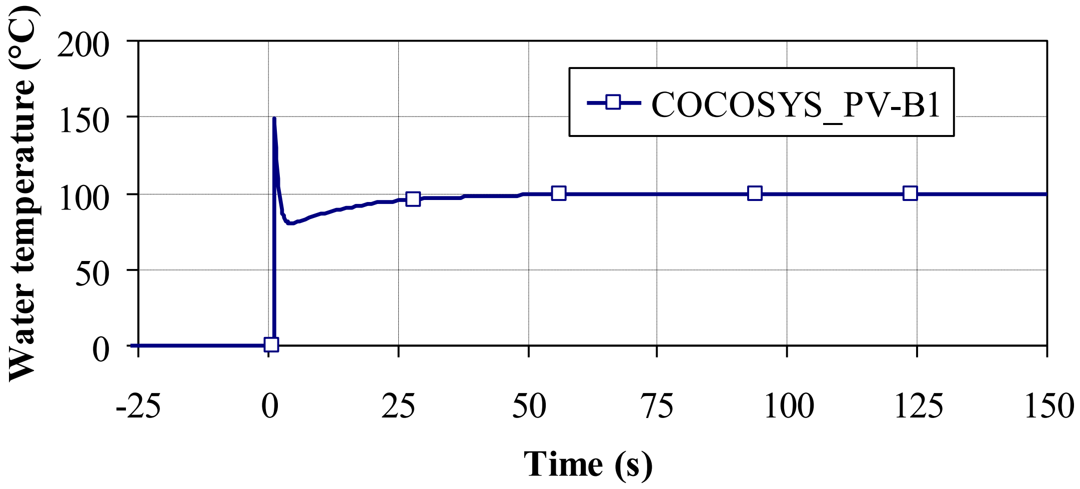


Fig. 8. Water temperature in PV-B1 node

To assess the reliability of the obtained results, benchmark calculations were performed using computer code ASTEC. Comparison of calculated pressure in PV-C nodes using COCOSYS and ASTEC codes is shown in Fig. 9**.** The calculated peak pressures are the same; however, a difference in timing to the peak pressure is observed. ASTEC code shows that the burst disk opens after 19 s, while in COCOSYS results, the burst disk opens 4 s later (after 23 s). After 25 s, the results of the two are almost identical. The reasons for such difference could be differences in the heat transfer modelling.

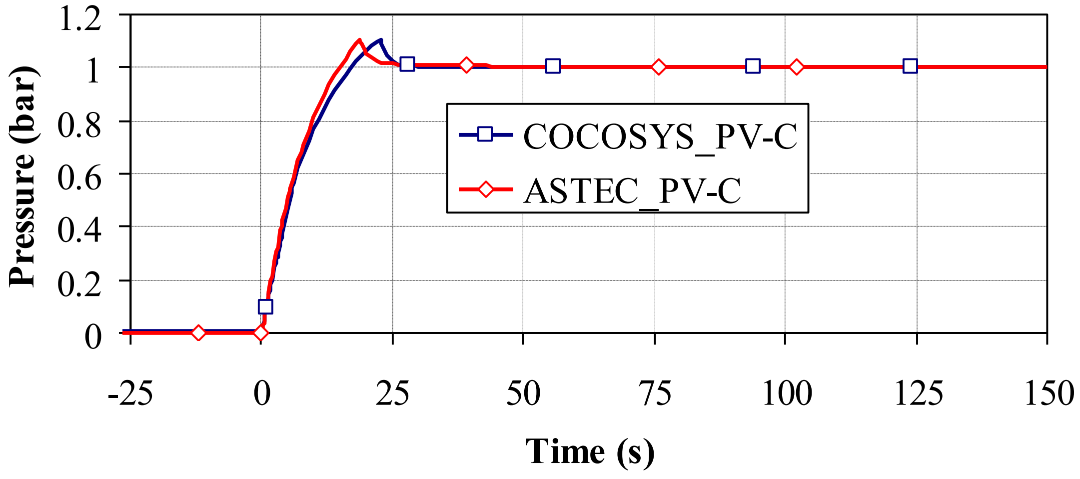


Fig. 9. Pressure in PV-C nodes (COCOSYS and ASTEC results)

Fig. 10 presents comparison of calculated gas temperature in PV-B1 node. The codes show different behavior of the gas temperature – COCOSYS shows initial peak of 194 °C and later gradual decrease down to ~115 °C, while ASTEC shows initial peak of almost the same level, but then the temperature goes down to ~100 °C rather quickly. This result clearly shows that differences in ASTEC and COCOSYS heat transfer modelling exist, but are not publicly documented and could not be explained in detail.

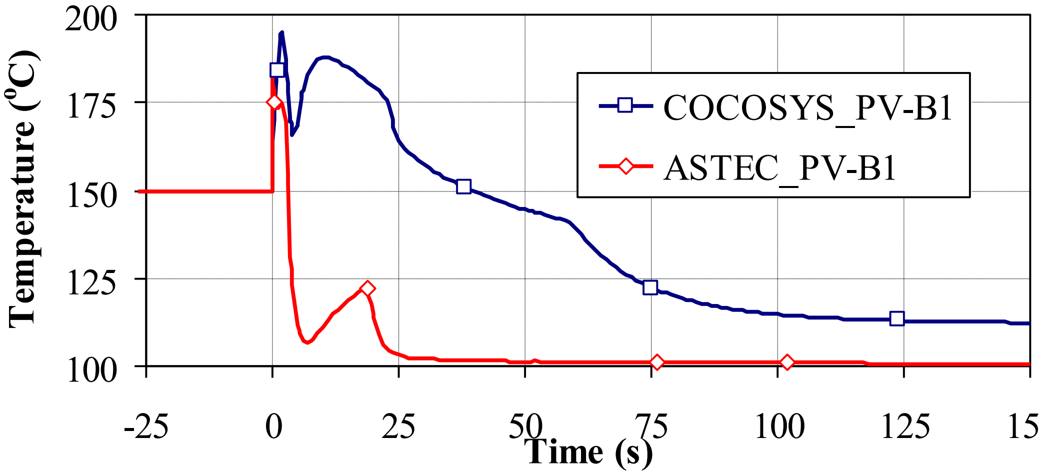


Fig. 10. Gas temperatures in PV-B1 node (COCOSYS and ASTEC results)

Fig. 11 presents comparison of calculated water mass in PV-B1 and PV-C1 nodes using ASTEC and COCOSYS computer codes. The water mass in PV-C1 node is the same. However, there is a difference in the water mass in PV-B1, the node where the water is accumulated. This result shows that in COCOSYS case, less water evaporates due to heat transfer to structures, and this result explains the difference in timing until burst disk opening (Fig. 9), i.e., a more intensive evaporation of water predicted by ASTEC code leads to faster pressurization of PV and faster opening of the burst disk.

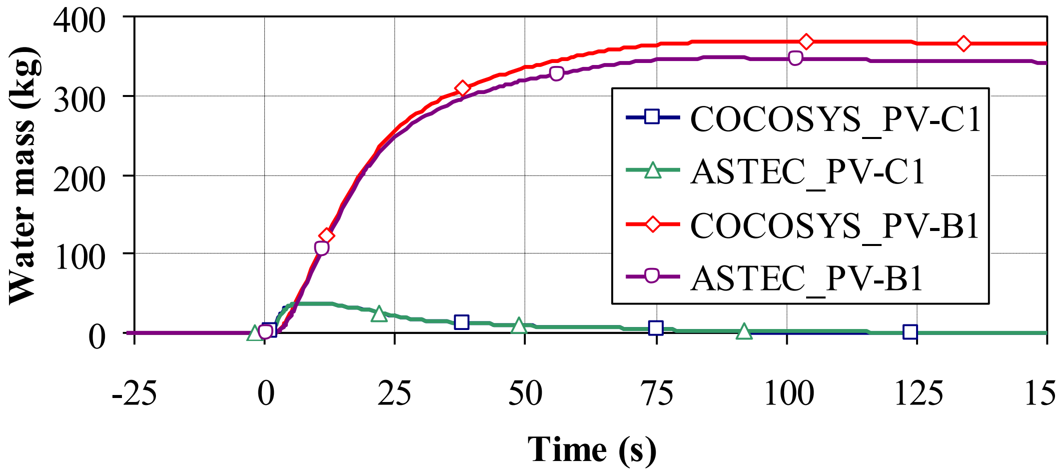


Fig. 11. Water mass in PV-B1 and PV-C1 nodes (COCOSYS and ASTEC results)

In the modelling, steam condensation or water evaporation are calculated not only on the structures, but on the water surface as well. The same heat transfer models are used for heat transfer to structures and on water surface. Fig. 12 presents comparison of calculated condensation/evaporation rate in PV-B1 node on water surface. In case of negative values, the water evaporates, and in case of positive values, the steam is condensed on the water surface. It is clearly seen that differences in the heat transfer modelling give different evaporation rates. COCOSYS code shows no evaporation and even some condensation in the period 5-55 s, while ASTEC shows water evaporation occurring right after the water appears in the node.

Further investigation and validation of the heat transfer modelling in both codes is needed to define which model is correct and should be used for safety analysis of fusion facilities.

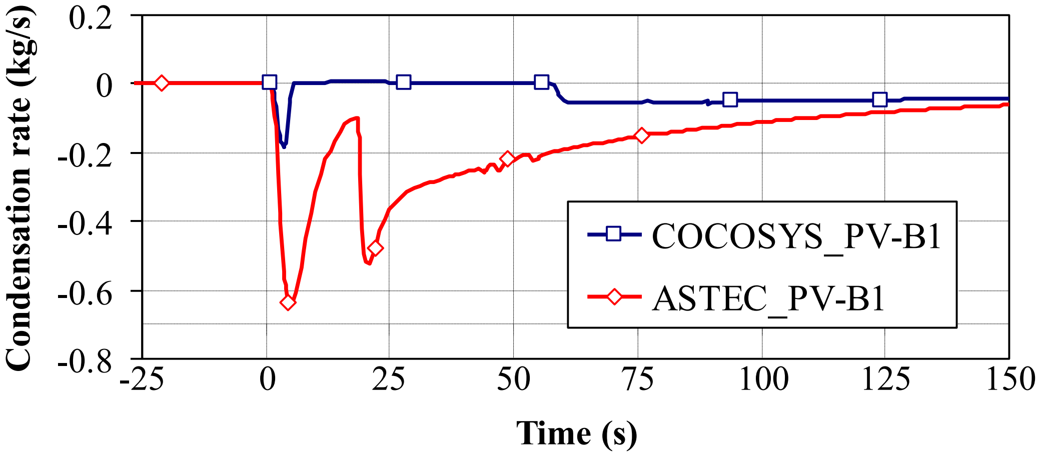


Fig. 12. Condensation/evaporation rate in PV-B1 node (COCOSYS and ASTEC results)

CONCLUSIONS

The analysis of 40 mm pipe rupture inside the Plasma Vessel was performed using COCOSYS and ASTEC codes in order to estimate whether the installed burst disks and venting system are capable to remove the accident-generated steam from the Plasma Vessel during W7-X operation in “baking” mode. The results of the analysis confirmed that the venting system is capable of preventing overpressure of the Plasma Vessel.

Taking into account the in-vessel components, a short-term pressure difference in the analysis is observed; however, that does not affect the global response of the facility and maximum pressure in the pressure vessel.

Differences in time until opening the burst disk observed in ASTEC and COCOSYS results are caused by differences in heat transfer modelling. Further investigation and validation of the heat transfer modelling in both codes is needed to define, which heat transfer model is correct and should be used for safety analysis of fusion facilities.

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