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Research Article

Thermal-Hydraulic Assessment of W7-X Plasma Vessel Venting System in Case of 40 mm In-Vessel LOCA

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This paper presents assessment of the capacity of W7-X venting system in response to in-vessel LOCA, rupture of 40 mm diameter pipe during operation mode "baking." The integral analysis of the coolant release from the cooling system, pressurisation of PV, and response of the venting system is performed using RELAP5 code. The same coolant release rate was introduced to the COCOSYS code, which is a lumped-parameter code developed for analysis of processes in containment of the light water reactors and the detailed analysis of the plasma vessel and the venting system is performed. Different options of coolant release modeling available in COCOSYS are compared to define the base case model, which is further used for assessment of the other parameters, that is, the failure of one burst disk, the temperature in the environment, and the pressure losses in the piping of venting system. The performed analysis identified the best option for coolant release modeling and showed that the capacity of the W7-X venting system is enough to prevent overpressure of the plasma vessel in the case of in-vessel LOCA.

1. Introduction

Wendelstein 7-X (W7-X) is a superconducting stellarator, the construction of which was recently completed in Greifswald, Germany, by Max-Planck-Institut für Plasmaphysik (IPP). The status of the W7-X project implementation is described in [1].

The loss of coolant accident (LOCA) is one of the design basis accidents to be investigated to show the safety of the facility. The accident scenarios for coolant release to the plasma vessel (PV) and to the outer vessel are shortly described in [2]. Rupture of one of the 40 mm inner diameter coolant pipes providing water for the divertor targets during the "no plasma" operation mode "baking" is considered to be the most severe accident in terms of PV pressurisation. To protect PV from overpressure, the venting system is installed.

In case of LOCA inside a vacuum vessel, the water would be released to PV, where it will be converted to steam due to flash evaporation and secondary evaporation that appears due to heat transfer from the hot structures. Analysis of the coolant discharge to PV was performed using computer code RELAP5 and is presented in [3]. The detailed description of the analysis of the divertor cooling system and the results of LOCA analysis is given in [4], where different closing times of the valves installed on the cooling system were investigated. Also the paper presented the results of analysis assuming rupture of the cooling system pipes of the lower or upper divertors.

This paper presents detailed assessment of the capacity of the W7-X venting system using computer code COCOSYS. COCOSYS is a lumped-parameter code developed by GRS mbH (Germany) for modeling all important phenomena occurring during both design basis and beyond design basis accidents in the light water reactor containment [5]. The received results are compared with the results of earlier performed analysis using computer code RELAP5 [3]. Benchmarking of the results received with two independent computer codes provides more confidence in the results and helps in the identification of possible important differences in modelling.

The performed analysis identified the best option for coolant release modeling and showed that the capacity of the W7-X venting system is enough to prevent overpressure of the plasma vessel in the case of in-vessel LOCA.

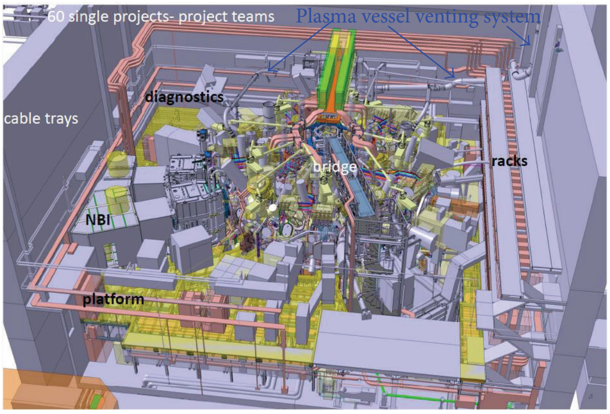

Figure 1: CAD view of venting system connected to PV [6].

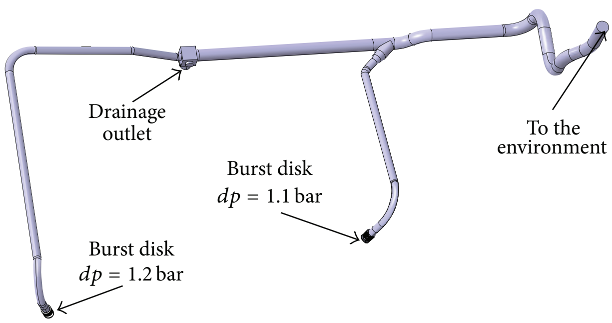

Figure 2: Layout of piping of W7-X plasma vessel venting system.

2. Description of W7-X Plasma Vessel Venting System

To protect PV from overpressure, the venting system is installed. The CAD view of W7-X in the torus hall together with the piping of the venting system connected to PV is shown in Figure 1. A more detailed layout of piping the venting system is shown in Figure 2. There are two burst disks installed: (1) one opens at pressure of 1.1 bar and (2) another opens at 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 main part of the piping is located in the torus hall, and it is not thermally insulated. The exit of the main pipeline is outside the building above the roof level.

In case of in-vessel LOCA, the burst disk opens and the steam through the piping of the venting system is directed outside the building. The steam would be condensing on the colder surfaces of the piping; therefore, the piping is designed with inclination, which ensures that water flows to the drainage outlet.

3. Description of the Model for COCOSYS

The nodalisation scheme of PV venting system for COCOSYS code is presented in Figure 3. The volume of each node and the associated areas of the structures connected to the nodes are presented as well. The red lines show junctions between the nodes for atmospheric flow, and the blue arrows indicate the flow of water, which appears due to steam condensation. Node LEIT1 represents the shorter line with the burst disk of 1.1-bar opening pressure. Node LEIT2 represents the longer line with burst disk of 1.2-bar opening pressure. Also, this node includes a part of the main line with the drainage outlet. Both nodes LEIT1 and LEIT2 are connected to node GABEL, which represents the "fork" of the connected pipes. The rest part of the main pipeline inside the building is represented by the node HAUPT. In the model, it is assumed that a certain part of the pipe would be located outside the building, and this part is represented by node CHIMNEY. The volume of the nodes was calculated from the drawings provided by W7-X team.

It is assumed that the turbine hall (node THALL) and the piping of the venting system are filled with air at temperature of 20°C and with the relative humidity of 60%. It is assumed that initially (before the accident) the plasma vessel (node PV) is filled with helium gas at temperature of 150°C and the relative humidity of 0% (dry gas).

In COCOSYS code the atmospheric and water flows are simulated separately; therefore, separate junctions have to be defined. The burst disks are simulated by a special junction type, which considers that after reaching the defined set point the junction opens and stays open until the end of the analysis. The other atmospheric junctions are always open. The associated flow loss coefficients were estimated taking into account the friction loss and the local pressure losses due to the changing flow direction and diameter. In the model, it is assumed that the water starts flowing from one node to another when the water film thickness on the inner surface of the pipe reaches 1 mm.

The piping is made of 1 mm thick stainless steel. The heat transfer area of the piping was calculated from the drawings provided by W7-X team. It is assumed that heat exchange on both surfaces could occur due to convection, condensation, and wall to gas radiation.

The outer surface of structure associated with this node faces the outside environment, which could have different temperature from that inside the building. For the base case analysis it was assumed that the temperature in the outside environment is also 20°C.

The structures of the plasma vessel were assumed to be hot with temperature of 150°C. Such temperature is constant during all calculation time. Since COCOSYS code cannot simulate deep vacuum conditions, it is assumed that the initial absolute pressure inside plasma vessel is 1000 Pa, which is the lowest possible pressure possible in the code.

The analysis of the venting system was performed for the loss of coolant accident scenario, which assumes 40 mm diameter pipe rupture in the operation mode "baking." During this operation mode, the inner surfaces in the plasma vessel are cleaned from impurities, and plasma vessel is prepared for plasma ignition. The coolant release rate and the specific enthalpy of the released coolant were calculated using RELAP5 code and are shown in Figure 4 [4]. After the pipe rupture, the maximal flow rate through to PV reaches ~28 kg/s, but after this peak it gradually decreases. This

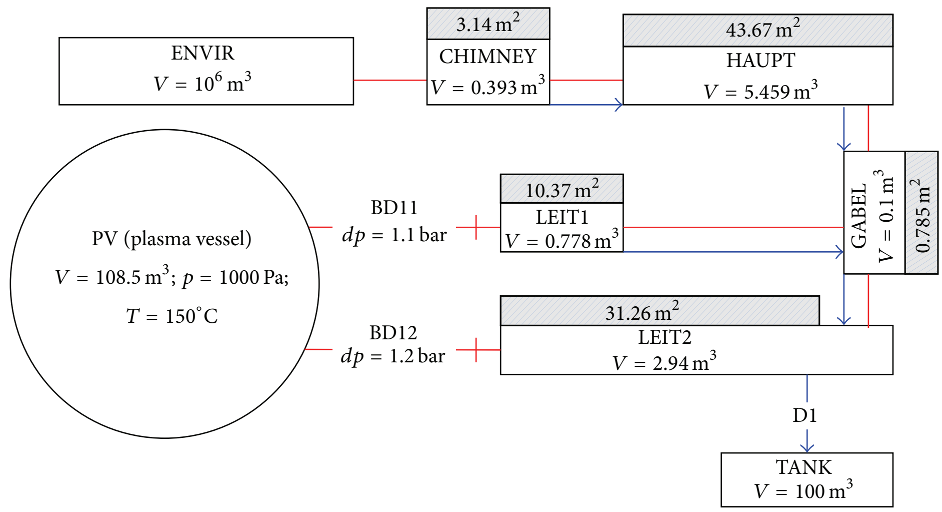

FIGURE 3: Nodalisation scheme of W7-X venting system for COCOSYS.

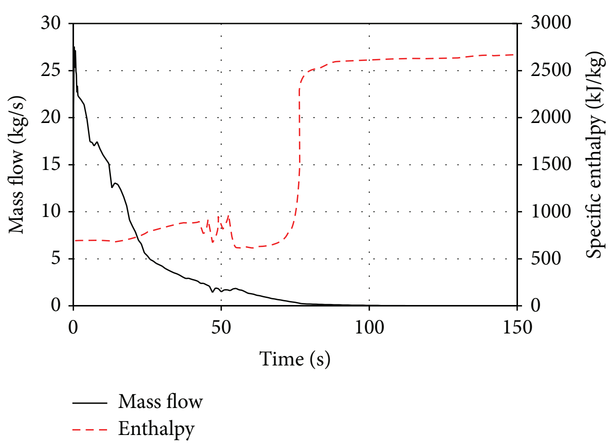

FIGURE 4: Coolant release rate and specific enthalpy to plasma vessel received from RELAP5 code analysis [4].

decrease is related to the closure of the automatic valves in the "baking" circuit. After 25 s, the release rate to PV 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.

4. Results of Analysis

To investigate the piping of venting system in case of LOCA during "baking" mode, the following variants were investigated:

(1) influence of coolant release modeling options;

(2) the base case scenario when all relevant systems operate as expected;

(3) failure of burst disk opening at 1.1 bar;

(4) temperature of outside environment 0°C;

(5) influence of pressure losses inside venting system.

Further, all of these investigated variants will be described in detail.

4.1. Influence of Coolant Release Modeling Options. COCOSYS code includes several options for the definition of the coolant release from the ruptured pipe to the compartments or to the plasma vessel in the case of considered accident scenario for W7-X. This section presents the results of assessment of these options. In COCOSYS, the coolant injection is defined as the mass flow rate and the specific enthalpy associated with it. The required information is taken from RELAP5 analysis [4]. From the specific enthalpy of released coolant and pressure in PV, the computer code COCOSYS calculates the separation of the released coolant to the water and steam fractions. In COCOSYS, there are several options to be chosen by the code user; for example, (1) the main fraction of released coolant is steam, which is released to gas phase. In this case, the released coolant is set to saturated steam at a given pressure in the node, and the remaining part is deposited to the sump. (2) The main fraction of released coolant is water, which is released to gas phase. In this case, the heat transfer between the water and gas is calculated first, and then the remaining water is deposited to the sump. (3) The main fraction of the released coolant is water, which is released to the sump. In this case, the injected energy at first is consumed to heat up the sump, and then the heat exchange between the gas and water occurs via the water surface. (4) The coolant is released to gas phase via spray (i.e., as droplets) and could be directed to the wall. In such case, at first, the heat transfer between the discharged water droplets and the gas is calculated. Later, these droplets impact the wall, forming the water film which could be partially evaporated and the remaining part could run down the structures to the sump. The heat transfer between the walls and the water film is calculated along the way. The latest option could be representative of the jet impact phenomenon.

The four coolant release options described in the previous paragraph were compared with the results received using RELAP5 code, which was used to calculate the coolant release to plasma vessel and further enhanced to include PV and the venting system. RELAP5 solves mass and energy balance

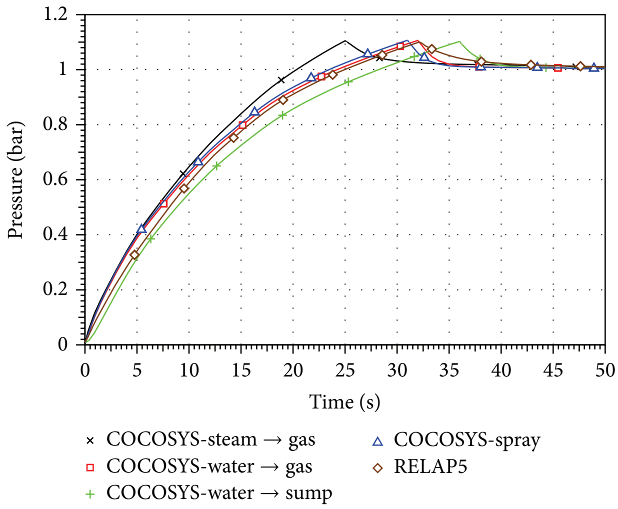

FIGURE 5: Coolant release options: pressure in the PV.

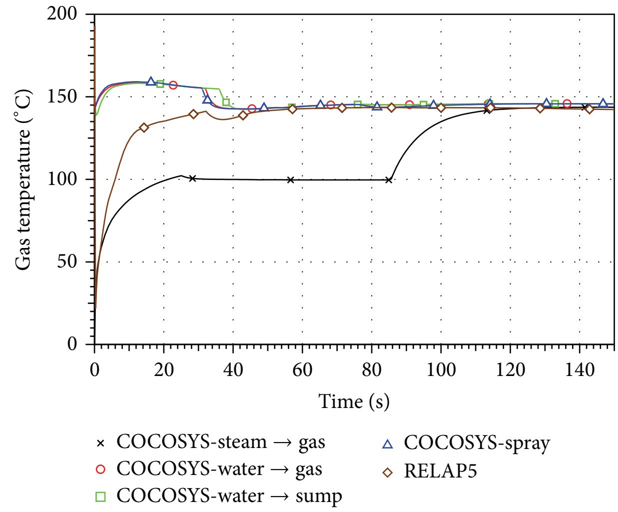

FIGURE 6: Coolant release options: gas temperature in PV.

equations for each phase (water and steam) separately; that is, the water and steam could have different temperatures, and thermal equilibrium between the phases is not required.

Figure 5 shows that depending on the selection of coolant release option, the pressure peak in PV is reached between 25 s and 37 s. The pressure peak in all cases is ~1.11 bar when the burst disk opens, and the pressure decreases down to atmospheric and remains at such level until the end of the calculations. Thus, the selection of the coolant release option does not change the pressure peak but impacts the peak pressure timing.

The fastest pressurisation of PV is observed if the main fraction of released coolant is assumed to be steam; that is, the energy of the released steam is used for pressurisation, and the remaining water is deposited to the sump. Taking into account the fact that in case of LOCA in W7-X the major part of coolant would be released as water, this option is too conservative; thus, it is not realistic and should not be used unless as limiting case.

Another limiting case of considered coolant release options is assuming that the main release fraction is water, which is released to the sump. In this case, the peak pressure and opening of the burst disk are observed after 37 s. The reason is that in this case the evaporation of water is calculated only through the water surface, which is much slower process compared with immediate evaporation if release is assumed as steam or the water is released to the gas phase. The water in the sump is heated by the hot structures on the bottom of PV and caused further evaporation. This option is another limiting case, which is not realistic since the coolant in case of LOCA in W7-X will always be to the gas phase. Such injection option in the computer code should be used only if the rupture place is located under the water layer, which in some specific cases could happen during the course of the accident.

The other two coolant release options and results of RELAP5 calculations show the peak pressure at ~31-32 s, which is very close and seems to be most realistic. RELAP5 code always calculates mass and energy balances of water and steam separately; thus, after the coolant release to PV, the steam contributes to pressurisation of PV, and water is deposited to the sump. In COCOSYS, assuming that the water is released to the gas phase, the immediate water evaporation is assumed and the remaining water is deposited to the sump, which gives secondary evaporation through the water surface. There is another special feature of COCOSYS code that the coolant could be released to PV through the spray system and direct all or a part of it onto the surface of walls. In the performed calculations, it was assumed that the spray droplets of 5 mm diameter after flying 0.1 m in gas phase hit the surface of the vertical wall of 1 m^2 area. Interaction of water with hot wall causes secondary evaporation and the rest part of the water flows down the wall to the sump, which also gives a secondary evaporation of released water. Taking into account the limited space for coolant release to PV, such assumption seems to be the most realistic.

Figure 6 shows the calculated gas temperature in PV for all the considered coolant release options. The figure clearly shows that assuming the main coolant release fraction as steam leads to saturated conditions in PV until ~85 s. The gas temperature drop in the first seconds of the accident appears in all calculations, and it is related to 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 subatmospheric pressure. In case if coolant release is assumed as steam after ~85 s, the gas temperature starts increasing, which shows transition from saturated to superheated steam conditions in PV. This transition is caused by increasing specific enthalpy of the released coolant; that is, more steam is discharged from the cooling circuit to PV (see Figure 4). In case of all the other assumed coolant release options, transition to superheated atmosphere is observed much earlier. In the longer term, all the calculated variants lead to the same gas temperature ~140°C, which is determined by the heat transfer from the hot PV walls.

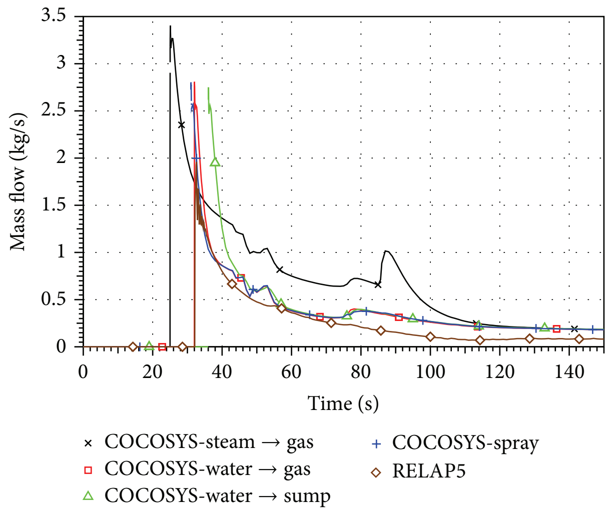

Figure 7: Coolant release options: flow rate through the burst disk.

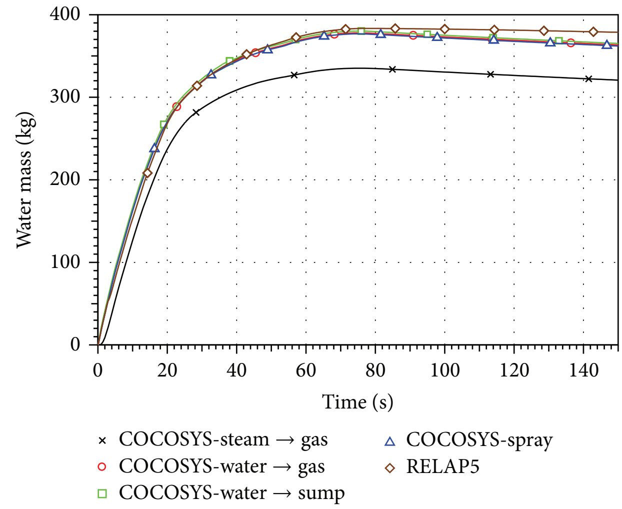

Figure 8: Coolant release options: water mass in PV.

Figure 7 presents comparison of the calculated steam flow through the ruptured burst disk. The largest peak of the steam flow is calculated with COCOSYS assuming that the coolant is released as steam to the gas phase. The peak value of almost 3.5 kg/s is reached right after the rupture of the burst disk. After that the flow rate decreases following changes of the coolant release from the cooling system. The influence of the enthalpy of the released coolant is observed for the case of steam release to the gas phase. Using this option, the flow rate through the burst disk is the largest compared to other calculated variants. The mass flow through the burst disk calculated with RELAP5 is the lowest of all calculated variants, peak value ~2 kg/s, while COCOSYS gives ~2.7 kg/s. Several peaks of mass flow through the burst disk are observed, and most clearly they are seen when the injection is assumed to be steam. These peaks are caused by the changes of the properties of coolant released through the ruptured pipe (Figure 4). Even though the coolant mass flow through the ruptured pipe decreases gradually to the end of calculations, the specific enthalpy plays a major role giving some short term peaks of the energy flow, which is calculated as the mass flow multiplied by the specific enthalpy.

Figure 8 shows the water mass inside PV. The water mass in PV increases ~70 s and later starts slow decrease, which indicates evaporation of water from the sump due to heat exchange with hot structures of PV. As it could be expected from the previous results, the lowest mass of water is received in case if coolant release is assumed as steam, which leads to more steam discharged through the burst disk and venting system to the environment and consequently less mass of water remains in PV. In general, there is good agreement between RELAP5 and COCOSYS results (except assumption of injection as steam), but RELAP5 shows less evaporation in the longer term.

The performed analysis using different injection options showed that except two limiting cases (injection as steam or injection as water to sump) the other COCOSYS variants and RELAP5 give similar results. Therefore, further assessment of PV venting system capacity is performed with COCOSYS code assuming that coolant release to PV is modelled using spray injection model.

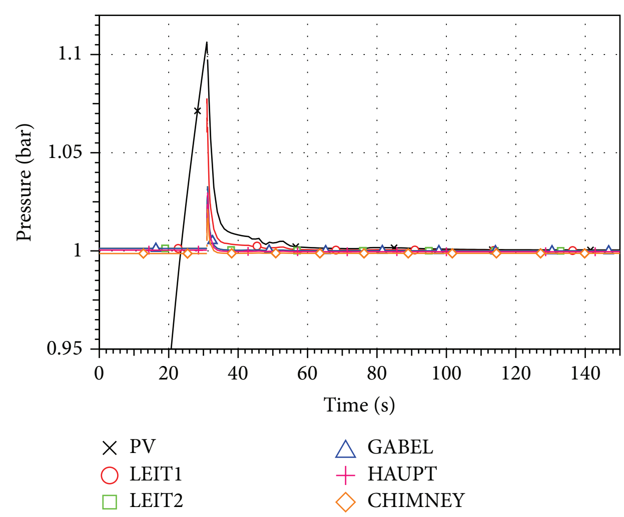

Figure 9: Base case scenario: pressure in the nodes.

4.2. The Base Case Scenario. This section presents the results of the base case scenario, which assumes normal operation of all the systems and equipment in case of 40 mm in-vessel LOCA of W7-X. As it is described in the previous section, the coolant release is modeled as water droplets impacting the PV wall. Figure 9 shows that after the pipe rupture, the pressure in PV starts increasing and in ~31 s reaches 1.1 bar, which is a set point for the 1st burst disk opening. After the burst disk opens, the steam is discharged to the venting system, and the pressure in PV starts decreasing. This result shows that the diameter of the installed burst disk is sufficient to prevent overpressure in PV. Nevertheless, the pressure in PV stays slightly above atmospheric due to evaporation of the water in PV caused by heat transfer from the hot structures. Before the accident, the pressure in the piping of venting system is atmospheric, and when the burst disk opens the pressure

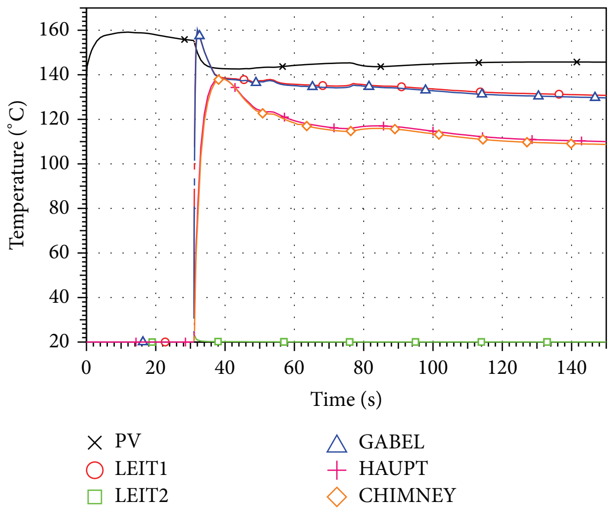

FIGURE 10: Base case scenario: gas temperature in the nodes.

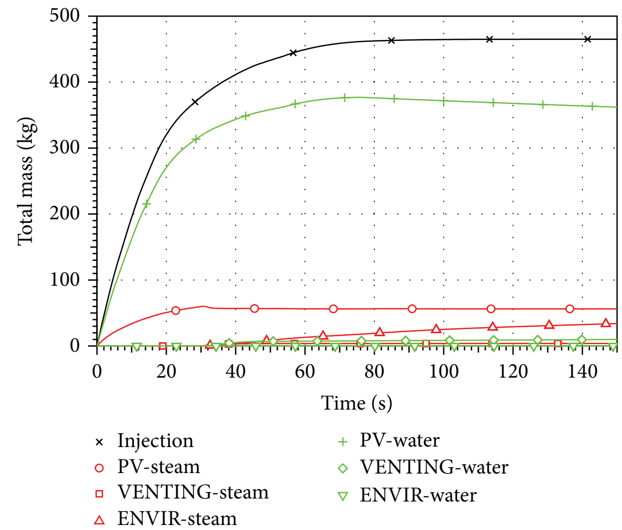

FIGURE 11: Base case scenario: the mass balance.

spike is observed. The highest pressure peak is observed in LEIT1; that is, piping part connected to PV and peaks are smaller going further from PV.

Figure 10 shows the gas temperature in the nodes. After the pipe rupture, the gas temperature in PV is in the range 140–160°C, which is mostly determined by the hot structures of PV. The initial temperature of the piping of venting system is assumed 20°C and stays constant until the burst disk opens. After that, the gas temperature increases along the flow path. The gas temperature in the node LEIT2 does not change since the second burst disk remains intact, and no steam enters this part of the venting system. In this part of piping, there is only a small and short term temperature peak right after burst disk opening caused by gas compression.

Figure 11 shows the mass balance in case of 40 mm in-vessel LOCA in W7-X. The total mass of water released to PV from the cooling system as calculated using RELAP5 is ~466 kg. Most of it deposits and remains in the lower part of PV. The maximum mass of water (375 kg) is observed at ~75 s, and then it starts decreasing slowly, which shows that sump evaporation starts dominating. At the end of the analysed period, the mass of water in PV is ~363.4 kg. The mass of steam in PV is ~56.2 kg, which gives the total mass of steam, and water in PV is 419.6 kg, which is ~90% of the total coolant released from the cooling system. At the end of the analysed period, the mass of water in the venting system (combined all piping length) is ~10 kg and the mass of steam is ~3.8 kg. The mass of water in the venting system is slowly rising due to condensation of steam on the inner surfaces of the pipes, while the mass of steam is constant due to continuous inflow from PV, where the water evaporates from the sump. The steam is continuously released to the environment and at the end of analysed process it is ~32.8 kg, which is ~7% of the total mass released to PV.

4.3. Failure of Opening of Burst Disk at 1.1 Bar. In order to investigate the reliability of the venting system, it was decided to perform analysis assuming that the first burst disk

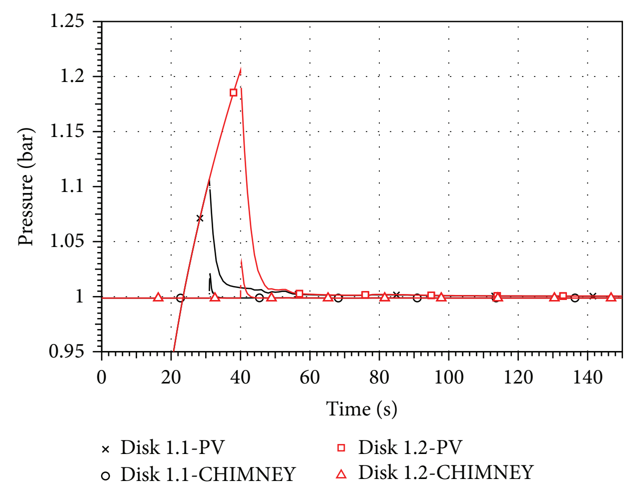

FIGURE 12: Failure of opening of burst disk at 1.1 bar: pressure in the nodes.

with opening set point 1.1 bar fails to open. The results of performed analysis are presented in Figures 12–14.

Figure 12 compares the base case scenario with the scenario (curves "Disk 1.1_. . . .") with failed one burst disk (curves "Disk 1.2_. . . ."). One could see that if the first burst disk fails, then the maximal pressure in PV increases to ~1.22 bar. After that, the pressure in PV decreases down, and after ~50 s the pressure behavior is the same as that in the base case scenario. The maximal pressure in the last node of the venting system piping (node CHIMNEY) reaches 1.1 bar. The performed analysis shows that the diameter of the burst disk is enough to prevent the further rise of the pressure in the plasma vessel.

Figure 13 presents the mass flow rate through the burst disks in case of both accident scenarios. One could see that in case of scenario with failed to open burst disk the first burst disk stays closed while the second opens later after ~32 s, and the flow rate through this burst disk is higher. This difference is caused by the larger pressure differences in the piping. After the peak of flow rate decreases and after ~50 s, it becomes the same as in the base case scenario.

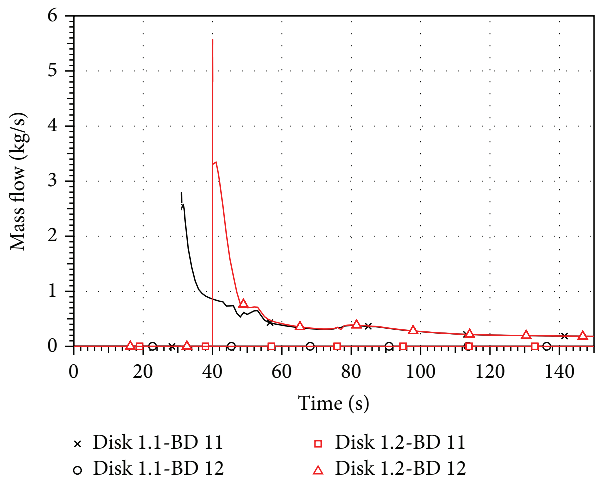

FIGURE 13: Failure of opening of burst disk at 1.1 bar: flow rate through the burst disks.

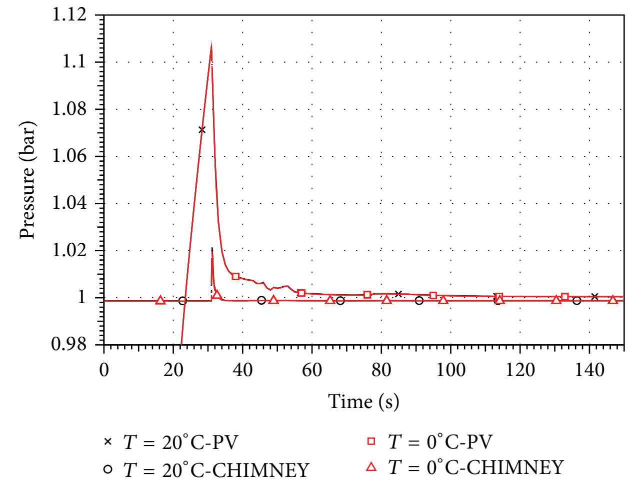

FIGURE 15: Temperature of outside environment 0°C: pressure in the nodes.

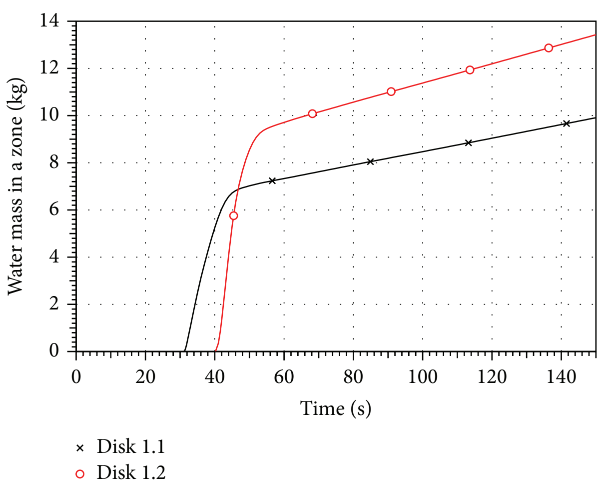

FIGURE 14: Failure of opening of burst disk at 1.1 bar: total water mass in piping.

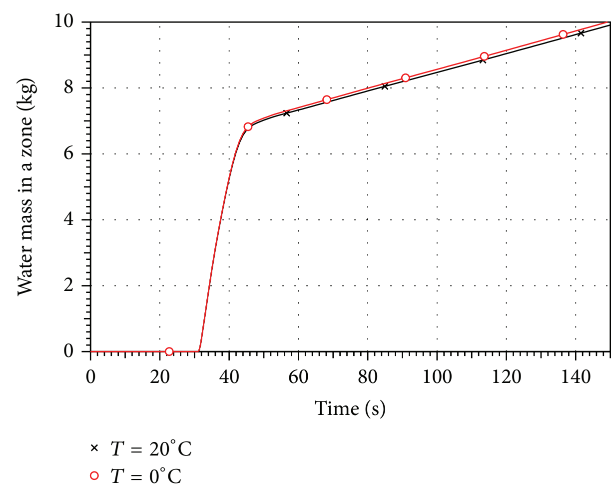

FIGURE 16: Temperature of outside environment 0°C: total water mass in piping.

Figure 14 presents the total amount of water in the piping of venting system. This parameter was received summing up the water mass in each node. It is clearly seen that, in case of failed to open burst disk scenario, the steam starts condensing in the piping later, but more steam is condensed due to larger heat transfer area (the longer branch of piping is opened). In base case scenario at the end of analysed accident period the total mass of water in the piping is ~15.5 kg, while in case of failed to open burst disk scenario it is ~18 kg.

4.4. Temperature of Outside Environment 0°C. Taking into account the fact that some part of the venting system piping is located outside the building, it was decided to perform analysis assuming that the temperature in environment is 0°C; that is, accident happens in the colder period of the year. Such assumption was considered important taking into account the fact that there could be stronger steam condensation on the cold pipes, which could cause higher friction and higher pressure losses in the venting system which could consequently lead to higher pressure in PV. It should be noted that 0°C is the lowest temperature that could be assumed for analysis using computer code COCOSYS.

Figure 15 shows that no noticeable pressure difference is observed compared with the base case scenario; that is, the disk of 1.1bar opening set point opens as designed. Figure 16 compares the total water mass in the piping. There is slight difference, more steam is condensed assuming the colder temperature in the environment, but the difference is not significant due to small length of the pipe outside the building (assumed to be 2 m length in environment).

4.5. Influence of Pressure Losses Inside the Venting System Pipes. The most uncertain parameter is the pressure losses in the piping of venting system. These loses appear due to roughness of inner surface of the pipes and local losses on different pipe fittings, for example, bends, branches, and

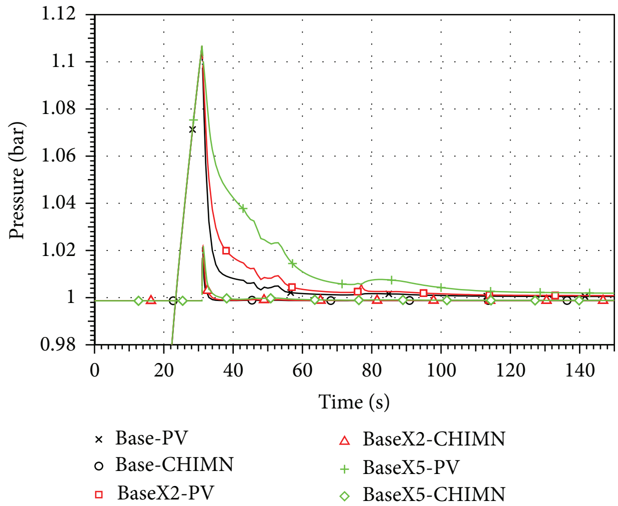

FIGURE 17: Pressure losses: comparison of pressure in PV and CHIMNEY.

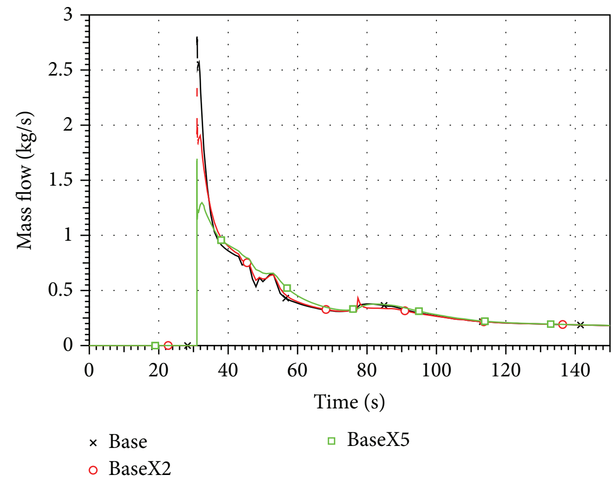

FIGURE 18: Pressure losses: comparison of flow rates through the burst disk.

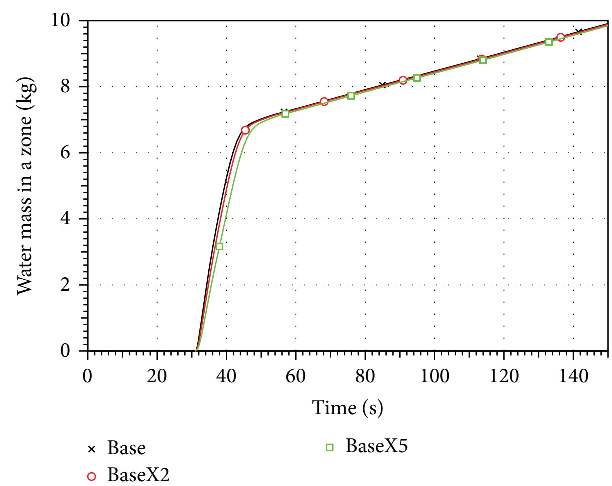

FIGURE 19: Pressure losses: comparison of total water mass in the piping of venting system.

expansions. There is number of different fittings in the W7-X plasma vessel venting system, and they were taken into account to develop the base case model; nevertheless, some uncertainty exists, and, in the course of accident, steam would be condensing on the inner surface of the piping, which could increase the resistance to flow as well. Therefore, it was decided to investigate the influence of this parameter on the accident progression. Two additional runs of the code were performed: (1) assuming that all pressure loss coefficients for junctions between nodes are 2 times higher and (2) assuming that all pressure loss coefficients for junctions between nodes are 5 times higher. The performed analysis is compared with the base case scenario. This analysis also covers impact of the condensed water film on the inner surface of piping, because the water film could enhance the friction losses.

Figure 17 shows that there is only minor influence of pressure loss coefficient on the maximal pressure peak in PV. The influence of the pressure losses is observed in pressure behavior in longer term after the first peak. One could see that the larger the pressure losses are the slower the pressure decrease is observed, but, in all cases after 120 s, the pressure in PV is close to atmospheric.

The difference is observed in mass flow through the ruptured disk as well (Figure 18). As it was expected, the larger the pressure losses are assumed, the less the maximal mass flow through the opened burst disk is observed. The slower change of the flow causes that during periods 40–70 s and 90–110 s the flow rate through the opened disk is even larger than in the case of base case scenario.

Figure 19 shows that less water mass is in the piping when larger pressure losses are assumed. The reason is that less steam enters the piping and more stays in the plasma vessel, but the difference is not significant.

5. Conclusions

The analysis of 40 mm pipe rupture inside the plasma vessel during operation mode “baking” was performed using COCOSYS code in order to estimate if the installed venting system is capable of preventing overpressure of the plasma vessel. The received results were compared with the results of RELAP5 code.

Comparison between COCOSYS and RELAP5 results helped to identify the best option for modeling of the coolant release to PV using COCOSYS. It is suggested that coolant release to PV is modeled as water droplets impacting the hot walls of PV.

The results of performed analysis showed the following:

(i) If the burst disks open as designed the maximal pressure in PV is 1.11 bar. Design of the venting system ensures prevention of PV overpressure.

(ii) If the first burst disk fails to open then the maximal pressure in PV is 1.22 bar. Design of the venting system ensures prevention of PV overpressure.

(iii) The temperature of the outside environment does not have a significant influence on the results due to short length of the pipe located outside the building.

(iv) The pressure losses in the venting system pipes have only minor influence on maximal pressure in PV, but it influences the depressurisation rate; that is, the larger the pressure losses are the slower the change in pressure is observed.

Highlights

(i) In-vessel LOCA in W7-X was simulated using lumped-parameter code COCOSYS.

(ii) Coolant release options available in COCOSYS are compared to select the best approach for detailed analysis.

(iii) The capacity of the W7-X plasma vessel venting system is assessed for several modeling assumptions.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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