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Analysis of Ingress of Coolant Accident to the Vacuum Vessel of the W7-X Fusion Experimental Facility

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Abstract — *An event of water coolant ingress into the vacuum vessel (VV) is one of the most important events leading to severe consequences in nuclear fusion reactors. The ingress of coolant to the VV could appear due to coolant pipe rupture of in-vessel components. Any damage of in-vessel components could lead to water ingress and may lead to pressure increase and possible damage of the VV. Therefore, it is important to understand thermohydraulic processes in the VV during the ingress of coolant event (ICE) to prevent overpressurization of the VV. This technical note updates the developed Wendelstein 7-X (W7-X) model in accordance with the experience gained from the modeling of ICE experiments. Calculation results using the updated model are compared with the results obtained using an older model and the results of other researchers. The calculation results of the updated W7-X model show a much smaller pressure increase rate in the VV compared to the old model. In order to find the maximal area of partial break, which increases pressure in the VV but does not reach burst disk activation pressure (no steam release from the VV to the environment), the best-estimate approach is provided. The results of the analysis reveal that partial break using the updated W7-X model could be much bigger than what was considered before.*

Keywords — *Wendelstein 7-X, RELAP5, ingress of coolant event.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Wendelstein 7-X (W7-X), completed in October 2015 in Germany,^{1,2} is at the moment the largest stellarator-type fusion device in the world. The vacuum vessel (VV) of this fusion facility is assembled shaped as a ring (torus) with a diameter of about 12 m. The whole volume of the VV is 108 m³. The in-vessel components consist of the divertor units, baffles, panels and heat shields, control coils, cryopumps, port protection and special port liners, and a complex system of cooling water supply lines as well as different diagnostics. The cooling system of the in-vessel components of the W7-X facility consists of two coolant circuits: the main cooling circuit (MCC) and the so-called “baking” circuit. The MCC is used for cooling of the in-vessel components

during normal operation of W7-X. Before plasma operation, the in-vessel components must be heated up in order to “clean” the surfaces by thermal desorption and the subsequent pumping out of the released volatile molecules. The baking circuit is mainly used for this purpose. During operation of W7-X in the baking mode, the heat, necessary for the heating of in-vessel components, is generated in the electrical heater. The MCC and baking circuits have their individual pumps for water circulation.

As with all energy-generating devices, nuclear fusion devices must be safe for humans and the surrounding environment. Safety assessment of these devices is based on the identification and analysis of hazards (nuclear and conventional). The nuclear hazards are related to radioactive source terms, which for fusion devices are generated due to

1. neutrons produced during the burn phase
2. activated material of the plasma-facing components

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3. active corrosion production in the cooling circuits
4. activated dust produced by plasma-wall interaction in the VV
5. availability of a small amount of tritium in the VV.

The bigger part of radioactive materials is concentrated in the VV of the fusion device. The VV is the barrier to prevent the release of radioactive materials into the environment. The analyses presented in this technical note are related to the period of investigation when the radiological dose is not a concern. However, issues related to water ingress in the VV of W7-X should be investigated. Water ingress into the VV of the W7-X device is dangerous for two reasons (excepting the increase of radiological dose): damage of the VV and cost of the ruptured disk. The VV is designed for vacuum conditions, and any rupture of in-vessel component cooling system pipes will lead to ingress of water in the VV. According to the designers of the device, some components (for example, ports) may lose their integrity when the pressure in the VV exceeds 50 kPa above the atmospheric pressure.³ In order to avoid such undesirable consequences, the pressure increase protection system (PIPS), which protects the VV from a possible pressure increase, is designed. This system consists of two burst disks, venting pipelines, and a draining tank. The most important components, burst disks, connect the VV to the chimney and environment through the venting pipelines. The opening pressure of the first burst disk is 110 kPa, while the opening pressure of the second burst disk is 120 kPa (the absolute pressure). The burst disks are made very precisely, and specific production technology for them is costly.

The main goal of this technical note is to investigate the possible consequences of water ingress into the VV of the W7-X experimental device. In order to achieve this goal, thermohydraulic models of the in-vessel components' cooling system, the VV, and the system for emergency steam discharge were developed using the RELAP5 code, and water leak into the VV was analyzed. However, water ingress into the VV is a specific phenomenon, not met in analysis of loss-of-coolant accidents in fission devices, for which the RELAP5 code is designed. So, the computer code and developed models needed to be validated. For validation of the RELAP5 code, experiments related to an ingress of coolant event (ICE) were analyzed. Experience and modeling recommendations gained from the modeling of the ICE experiments were

used in order to update the W7-X model. Using the updated model of the W7-X VV, we carried out the analysis in order to investigate the possible consequences of water ingress. In the first part of this technical note, the guillotine 40-mm-diameter cooling system pipe break was analyzed. The second part of the technical note consists of the application of the best-estimate approach for determination of the maximal allowed area of a partial break.

The results of the presented studies are used to define protection measures and instructions to operators in order to ensure safe operation of the W7-X fusion experimental device.

II. MODELING OF ICE EXPERIMENTS USING RELAP5 CODE

In order to investigate the processes in the VV, special experimental facilities were developed in the Japan Atomic Energy Research Institute (now Japan Atomic Energy Agency). The first ICE experiment was executed in 1996 (Ref. 4). Nowadays, there are a few experimental investigations of water injection in the low-pressure (vacuum) vessel. There are two significant groups of those investigations. In the first group, the initial temperature of injected water and the VV walls is low (at room temperature).⁵ In the second group, the walls of the VV are heated, or a special hot steel structure is installed inside the VV imitating hot in-vessel components.⁶ The first group mimics fusion devices that are in a shutdown situation (cooling circuit is circulating, vacuum conditions in the VV are maintained, but there is no plasma operation). After injection of cooling water at the volume of the initial vacuum conditions, the water evaporates very fast (a flashing effect, which is driven by excess sensible energy in the coolant), and the pressure inside the VV increases up to the saturation pressure, corresponding to the VV walls and coolant water temperature. The second group of experiments mimics fusion devices in baking modes. After the break of the in-vessel component cooling system, pipe water is injected into the VV. Pressure in the VV will increase due to a flashing effect (injection of high-pressure coolant) and by boiling of the coolant on the hot surfaces of the in-vessel components. Water boiling caused by contact with the hot surface is dominant in this group of the experiments. We selected the experiment in Ref. 5 as representative of the first group of ICE events. We selected the experiment illustrated in Ref. 7 for the second group of ICE events.

A detailed description of the ICE experimental facility model is presented in Ref. 8, which demonstrates that the

RELAP5 code could be used for the analysis of the processes in the VV of a nuclear fusion reactor during ICE. Comparison of calculation results and experimental data⁵ shows that a higher-pressure increase was achieved in the calculations when it was assumed initially to fill the VV with noncondensable gases, compared with the case when a water-steam mixture was initially assumed inside the VV. The comparison of the calculated results by RELAP5 (the VV filled with noncondensable gases and water-steam mixture) and experimental data is presented in Fig. 1.

The minimal possible pressure in RELAP5 is 700 Pa. Taking into account this limitation of RELAP5, modeling of ICE experiments is performed assuming the initial pressure in the VV to be equal to 700 Pa. But, in the real experiment, water starts to be injected into the VV at a lower initial pressure, and after a few seconds, the pressure increases, and when 700-Pa pressure is reached, at that moment the VV already is filled with a water-steam mixture because of the flashing effect of the injected water. The main conclusion of these results is that realistic initial conditions of the VV must be considered in the developed RELAP5 program code model in order to model the pressure increase in the VV. If the initial pressure in the VV is less than 700 Pa, the steam inside the VV must be assumed. Otherwise, if the initial pressure in the VV is more than 700 Pa, noncondensing gas must be assumed in the model. This conclusion is especially important for cases when the injected water flow rate in the VV is small.

The experiment presented in the literature⁷ was chosen as representative of the second group of ICE experiments. In this experiment water is injected into the VV with heated in-vessel components. For the analysis of the ICE facility, two models of RELAP5 were developed.^{8,9}

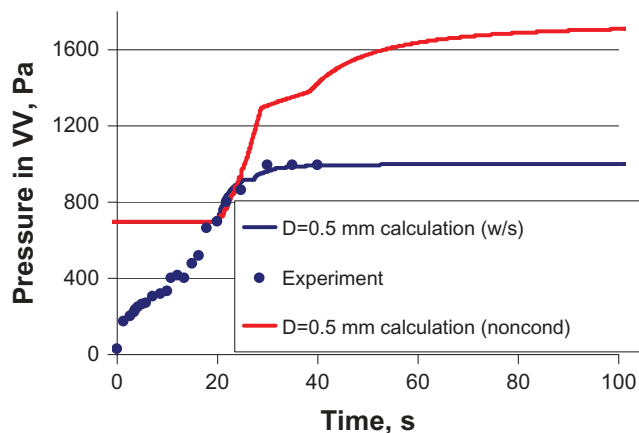


Fig. 1. Comparison of pressure increase in VV calculated by RELAP5 and experimental data. Walls of VV are not heated.

Both models consist of two hydrodynamic components (pipes). In the first ICE facility model, the interaction between the water jet and heated block is simulated using a small vertical pipe element. The second model for the same purpose uses a horizontal pipe. The comparison of the calculated and measured pressure in the VV of the ICE experiment⁶ showed that calculation results using the model with a vertical component is closer to the experimental data (Fig. 2). More detailed information about the RELAP5 models developed, assumptions used, and calculation results received are presented in Refs. 8 and 9. However, the main conclusion is that in the case of loss of coolant in a hot VV event, counter-current flow of water and steam in the vertical direction and stratification of steam should be evaluated for modeling the VV of nuclear fusion devices.

III. W7-X MODEL IMPROVEMENTS TAKING INTO ACCOUNT THE RESULTS OF ICE BENCHMARK

Since 2010 the Lithuanian Energy Institute has simulated processes in the VV of the W7-X experimental facility in the case of water ingress.¹⁰ Initially, a simple model of the VV of W7-X was developed.² The complicated three-dimensional geometry of the VV volume in the W7-X stellarator in the first (old) model developed was simplified to the geometry of a horizontal cylindrical pipe. The ends of the cylinder are open and joined together, simulating a closed circle of torus geometry (Fig. 3a). The whole volume (108 m³) of the VV was modeled using one pipe element. The inner surface area (707.5 m²) and wall thickness (0.019 m) of the vessel structures in the model correspond to the available design data.^{11,12}

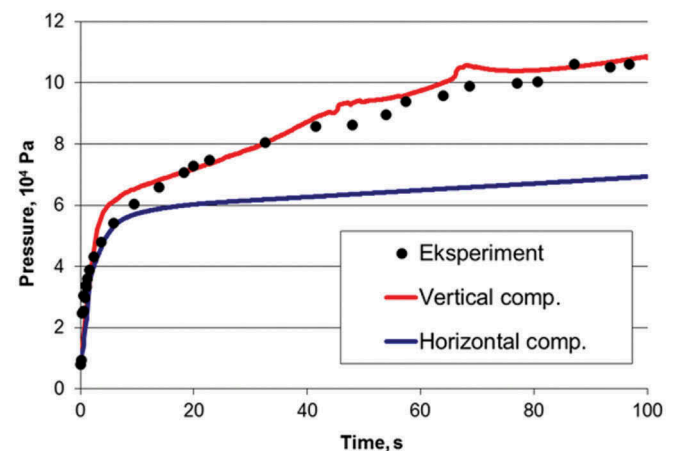


Fig. 2. Comparison of pressure increase in VV calculated by RELAP5 and experimental data.^{8,9} Walls of VV are heated.

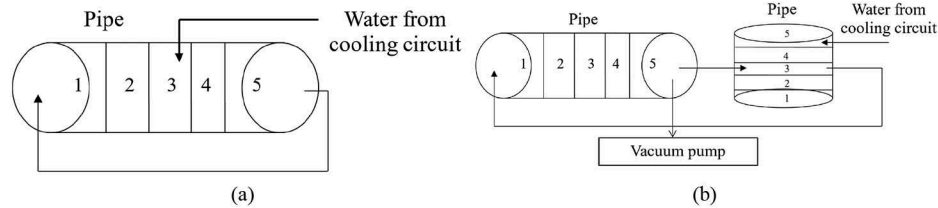


Fig. 3. Model of VV for RELAP5 code: (a) old model and (b) updated model.

According to the results of the ICE experiment modeling, presented in Sec. II, it was decided that counter-current flow of water and steam in the vertical direction and stratification of steam should be evaluated for the modeling of the VV, whereas the old W7-X VV model² had to be updated. A vertical pipe was connected to the horizontal pipe (Fig. 3b). The volume of the vertical pipe is 1/10 of the entire volume of the VV, and 9/10 of the volume belongs to the horizontal pipe. The vertical and horizontal pipes have five inner nodes. The last node of the horizontal pipe is connected to the third node of the vertical pipe. Also, the third node of the vertical pipe is connected to the beginning of the horizontal pipe. These connections were carried out in order to simulate the closed circle of torus geometry. In this technical note the pipe break of the upper in-vessel component is assumed. In this case water from the cooling circuit of the in-vessel components is injected into the upper node of the vertical pipe. The water discharged through the break in the top of the vertical pipe component partially evaporates, while the remaining part of the water flows down through this pipe. The remaining water is collected in the lowest node of the vertical pipe. In the vertical pipe the steam that is produced flows through the third node to the horizontal pipe component. The updated model of the VV is connected to the vacuum pump, which is modeled as the time-dependent volume. Specific conditions are required to activate the connection to the vacuum pump. More about this option is found in Sec. IV.B.

IV. ANALYSIS OF COOLANT INGRESS INTO THE VV ACCIDENT

This section presents the calculation results of the RELAP5 code. The comparison of the calculation results using the old and updated models is presented in this section. As is mentioned in Sec. I, the calculations were provided for two accident scenarios: a guillotine 40-mm-diameter pipe break of the in-vessel component cooling system (Sec. IV.A) and partial (1-mm²) break (Sec. IV.B).

IV.A. Guillotine 40-mm-Diameter Cooling System Pipe Break

In terms of VV pressurization, a break of the 40-mm-internal diameter coolant pipe that provides water for the in-vessel components during the baking regime of facility operation is considered to be the most severe accident. It was assumed that the guillotine pipe break occurs in the cooling system of the upper in-vessel component. Other calculation assumptions are the following:

1. At time moment $t = 0$ s, the double-ended guillotine break occurs. The break area develops from 0% up to 200% of the pipe cross-flow area within 0.01 s.
2. To reduce the discharge of water from the broken pipe to the VV, automatic valves are installed on the inlet of the cooling system. It is assumed that the signal for automatic valve actuation is generated when pressure in the VV reaches 2000 Pa. Delay between parameters reaches the set point, and signal generation is 0.5 s. Delay between the signal generation and start of valve actuation is 1 s. Full closure time of the automatic valve on the target module inlets is 5 s.
3. Another measure to reduce the discharge of water to the VV in the case of pipe rupture is automatic trip of the pump in the baking circuit. It was assumed that the signal for the automatic pump trip is the same as for the automatic valve trip, i.e., when the pressure in the VV reaches 2000 Pa. The delay between reaching of the set point by the parameter and pump trip is 1 s.

After the water discharge into the the VV, the pressure starts to increase there. When the opening pressure of the burst disk is reached, this disk will open, and water steam from the VV will enter the venting piping of the PIPS and through it will flow outside the building. The surface of the venting pipe walls is colder than the steam released through the burst disk. The steam would condense on the colder surfaces of the venting piping. Therefore, a draining tank is installed at the lowest point of the venting piping. More

information about assumptions, technical data, and calculation results using the old model of the VV may be found in Refs. 2 and 13.

However, the initial analysis presented in Refs. 2 and 13 does not evaluate the findings from ICE benchmarks. The comparison of the calculation results using the old and updated models of the VV is presented in Fig. 4. Using the updated model of the VV, RELAP5 calculates that the burst disk activation pressure is reached sooner with the updated model than the old model. Using the old model the burst disk is opened ~ 34 s after the beginning of the break. Using the updated model a burst disk is opened 3 s earlier. In the old model the injected water was spread along the horizontal pipe, while in the updated model of the VV, the discharge of water from the ruptured pipe in the cooling system of the in-vessel components is simulated as the injection of water into the vertical pipe (Fig. 3b). The injected water evaporates because of the flashing effect and contact with the hot surface. In the vertical pipe the injected water due to gravity forces flows down and collects at the bottom of the pipe. The water and hot structure contact surface area is higher in the updated model. Also, in the updated model the water-steam counter-current flow is modeled. This leads to faster boiling and faster pressure increase in the VV.

The calculation results using the updated VV model are in better agreement with other researchers who calculated the same accident scenario. Using the MELCOR code, Topilski calculated that a burst disk occurs only 13 s after the break.¹¹ Reference 14 reports that using the ASTEC code, a burst disk opens ~ 22 s after the break and using the COCOSYS code it opens 2 s later than with ASTEC. Comparing these results, it is clear that when the RELAP5 code is used, the VV pressurization process is slower.

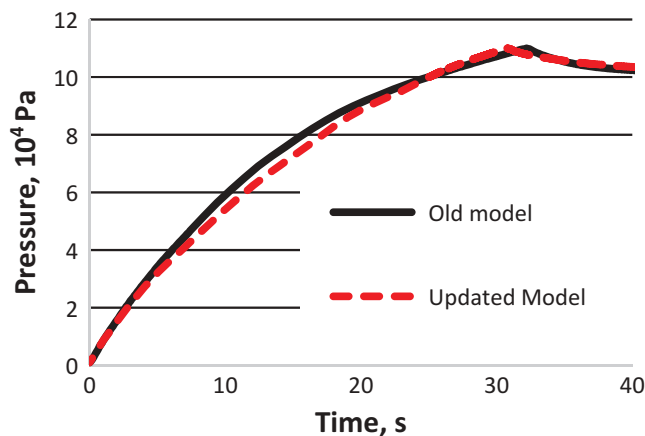


Fig. 4. Comparison of calculation results of old and updated models.

IV.B. Partial 1-mm² Break of Cooling System Pipe

In the W7-X facility, a vacuum pump is used to achieve vacuum conditions in the VV. This pump can also be used to ensure the vacuum conditions in case of a small break in the cooling system of the in-vessel component. The working of this vacuum pump consists of a four-stage, dry compressing rotary piston pump UniDry50S and roots pump Okta250. A detailed description of this vacuum pump can be found in Ref. 15. The maximal flow rate of the vacuum pump installed in the W7-X facility is 240 m³/h, but the flow rate depends on the suction pressure (pressure in a VV). The main characteristic curve (volumetric flow rate versus pressure) of the pump is presented in Fig. 5. The relative volumetric flow in the vacuum pump decreases when the pressure in the VV increases higher than 20 Pa. The mass flow rate of the gases through the pump also depends on the air-steam-mixture density inside the VV. With decreasing pressure in the VV, the air-steam-mixture density also decreases, and the mass flow rate through the pump decreases.

A partial break of the cooling system was performed using the updated RELAP5 model, presented in Fig. 3b. As mentioned in Sec. II, because of RELAP5 limitations regarding modeling of the system at the lowest possible pressure, the initial availability of steam inside the VV was assumed as the initial condition (the same assumptions are used in Sec. V.A). In the older model of the VV, the presence of noncondensable gases was chosen initially.

In the case of a partial break (1-mm² break area) of the cooling system of the in-vessel components, water is discharged into the VV with a flow rate of ~ 0.028 kg/s.

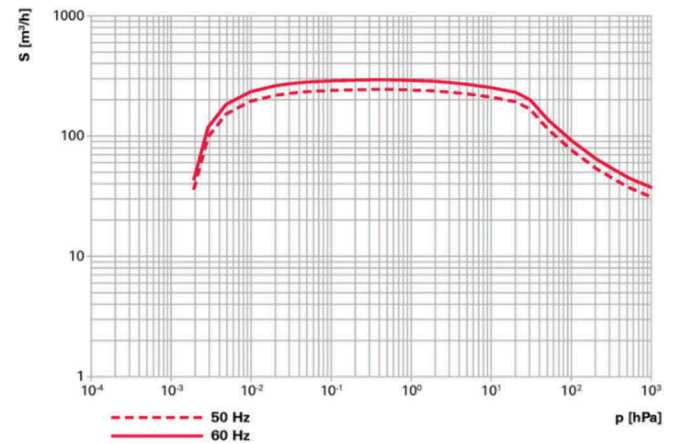


Fig. 5. Relative volumetric flow dependence on pressure in VV.

Pressure in the vessel starts to increase, and after 2-kPa pressure in the VV is reached, the signal is given to stop the circulation pump, to close the automatic valves on the inlet of the cooling system, and to start the vacuum pump. When the automatic valves are closed, the flow rate of the water-steam mixture through the break decreases to 8×10^{-4} kg/s. The water discharge from the lower components into the VV is only due to pressure difference. At the beginning of the break, the density of the air-steam mixture in the VV is low. Because of water discharge, the pressure in the VV increases, and the density in the VV also increases. The density of the water-steam mixture directly affects the mass flow rate through the vacuum pump. The increase of pressure in the VV decreases the volumetric efficiency of the vacuum pump, but the increased density in the volume leads to an increase of the mass flow rate through the pump (Fig. 5). The density of the air-steam mixture in the VV at 1-kPa pressure is ~ 100 times lower than the density at the maximum allowed pressure in the VV (120 kPa). When the mass flow rate through the vacuum pump becomes higher than the mass flow through the break, the pressure in the VV starts to decrease. The calculation results using the older model of the VV and noncondensable gases inside are presented in detail in Ref. 16.

The partial break (1-mm² break area) was modeled using the updated model of the VV and compared with the calculation results of the old model and noncondensable gases inside the VV (Ref. 16) (Fig. 6). Comparison of the calculation results shows that when using the updated model and steam as the initial conditions, the pressure inside the VV rises much more slowly than when using the old model and noncondensable gases as the initial conditions of the VV. The peak pressure inside the VV is also much lower when using the updated model. The calculation results using the updated model show one sharp pressure peak. This peak is associated with the correlations used in RELAP5 and the changes of the flow regime. The water through the broken pipe is discharged into the upper part of the vertical pipe of the updated RELAP5 model (Fig. 3b). Water evaporates because of the flashing effect and contact with hot surfaces of the VV. However, because of gravity, some part of the water will go to the bottom of the vertical pipe (in the same way as presented in Sec. IV.A). Because of the good contact with the hot surface of the VV, the water continuously evaporates (in the RELAP5 model this heat transfer between the steam-water mixture inside the VV and the walls is modeled using the annular mist flow regime). Later (at the time moment $t = 7300$ s), when

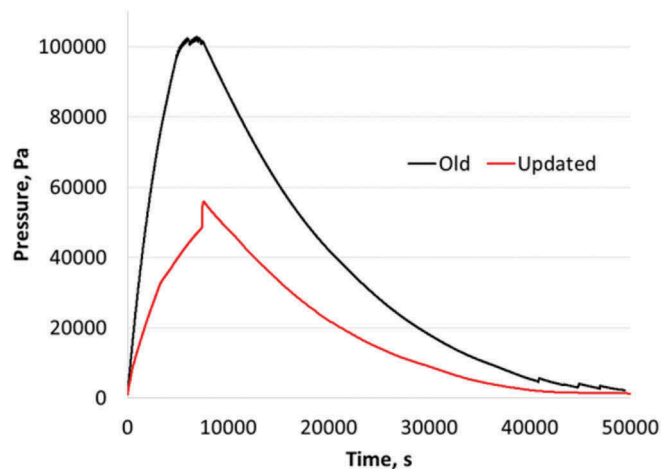


Fig. 6. Pressure in VV in the case of partial break of 1 mm². The comparison of old and updated model.

the quantity of the water in the lower node of the vertical pipe becomes very low, the coolant flow regime in the RELAP5 calculation is changed to the “mist post-CHF” (void fraction lower than 0.001). At this moment the heat transfer coefficient shortly increases ~ 90 times, and the evaporation rate also increases. This could explain the pressure peak observed in the calculation results using the updated model at the time moment from 7320 to 7600 s.

V. APPLICATION OF BEST-ESTIMATE APPROACH FOR DETERMINATION OF MAXIMAL ALLOWED AREA OF PARTIAL BREAK

The calculation results using the updated RELAP5 model clearly show that the PIPS system could withstand a bigger area of the partial break of the in-vessel component cooling system (see Fig. 6). In order to find the maximal area of an in-vessel component cooling system break that will not cause a burst disk to open, the best-estimate approach has been used. The best-estimate approach consists of using the RELAP5 best-estimate computer code¹⁷ and the uncertainty and sensitivity analysis provided for the calculation results. For the uncertainty and sensitivity analysis of the RELAP5 calculation results, the GRS (Germany) methodology¹⁸ based on the Software System for Uncertainty and Sensitivity Analysis (SUSA) tool¹⁹ has been performed. The results of the uncertainty analysis are presented in Sec. V.A. The sensitivity analysis is presented in Sec. V.B. In Sec. V.C the maximal partial break is presented, which was calculated according to the the results of the uncertainty and sensitivity analysis.

V.A. Uncertainty Analysis

The GRS methodology is based on systematic identification of relevant physical processes and on probabilistic quantification of the uncertainty of corresponding parameters. The uncertainty of the investigated parameters is described by their ranges and subjective probability distributions. Based on this knowledge, random uncertain parameter value vectors are generated by Monte Carlo methods. The main advantage of the GRS methodology is that the minimum number of calculations that are performed using codes is independent of the number of parameters to be investigated. The number of code runs depends only on the desired probability content and confidence level. The relationship between these parameters is described by the Wilks formula.²⁰ In the case of finding the minimal area of the partial break of the in-vessel components, the pressure peak inside the VV is the most important parameter. Thus, uncertainty analysis was performed using a one-sided (maximal

pressure inside the VV) tolerance limit with 0.95 probability and 0.95 confidence. Based on the Wilks formula, in order to perform a one-sided tolerance limit with the 95% probability content and 95% confidence level, 59 calculations are needed. The first step of the best-estimate methodology is to select parameters that have uncertainties. For those parameters it is necessary to identify a deviation range and a deviation distribution type. The uncertain parameters for the analysis of the W7-X device and 2-mm² partial break of the cooling pipe are presented in Table I. In total, 13 uncertain parameters were chosen. These parameters are the initial and boundary conditions in the cooling system of the in-vessel components, VV, PIPS, and vacuum pump of the W7-X device. These parameters were chosen because they mostly effect the calculation results in the case of a partial break of the in-vessel cooling system.

Deviation ranges for the geometrical parameters and the initial and boundary conditions were chosen according to experience and possible measurement errors.

TABLE I
Uncertain Parameters for W7-X Partial Break Analysis

Number	Uncertainty Parameter	Basic Value	Probability Distribution and Range	Range	
				Minimal Value	Maximal Value
Cooling System					
1	Initial pressure in cooling system (Pa)	1.15×10^6	Normal ($\pm 3\%$)	1.155×10^6	1.185×10^6
2	Initial temperature in cooling system (K)	433.15	Normal ($\pm 3\%$)	420.15	446.15
3	Signal actuation (stop circulation pump, close automatic valves) (Pa)	2000	Uniform ($\pm 3\%$)	1940	2060
4	Closure time of automatic valves (s)	5	Normal ($\pm 3\%$)	4.85	5.15
5	Pump rated flow (kg/s)	44.6	Uniform ($\pm 3\%$)	43.262	45.938
6	Pump stop signal delay	1	Uniform	0.5	1.5
7	Valve closure signal delay	1.5	Uniform	1	2
Vacuum Vessel					
8	Initial pressure in VV (Pa)	1000	Normal ($\pm 20\%$)	800	1200
9	Temperature in VV and in-vessel components (K)	423.15	Uniform ($\pm 3\%$)	410.45	435.84
Pressure Increase Protection System					
10	Temperature in the torus hall (K)	293.15	Uniform ($\pm 5\%$)	278.5	307.8
Vacuum Pump					
11	Vacuum pump actuation pressure (Pa)	2000	Uniform ($\pm 10\%$)	1800	2200
12	Vacuum pump efficiency dependence from the pressure	According to Fig. 5	Uniform ($\pm 3\%$)	0.97	1.03
13	Maximal flow rate of vacuum pump (m ³ /h)	240	Normal ($\pm 3\%$)	232.8	247.2

It was assumed that the flow rate through the pumps and the pressure and temperature in the cooling system could vary in the interval $\pm 3\%$. The same interval was used for the temperature inside the VV and in-vessel components. Such a range of mentioned input parameters was accepted according to the experience of safety analysis calculations of the Ignalina nuclear power plant. The actuation signal and automatic valve closure time could vary in the interval $\pm 3\%$. Delay of the “stop” signal could vary in the interval 0.5 to 1.5 s, and the delay signal of the automatic valve closure could vary in the interval 1 to 2 s. These uncertainty variations were discussed during the meeting of the W7-X development team.²¹ The initial pressure inside the VV has the highest assumed variation ($\pm 20\%$). It was decided to have large range of pressure variation in order to determine the influence of the initial pressure related to the RELAP5 low-system-pressure limitation. The temperature in the torus hall is usually room temperature. During normal operation the equipment is heated, and the temperature in the room could increase. However, an air-cooling system is used in the W7-X facility to control the temperature in the torus hall. In order to simulate a larger variation of temperature inside the torus hall, it was decided to have $\pm 5\%$ deviation from 293.15 K. The vacuum pump is started when the pressure in the VV starts to increase. The set-point actuation pressure is 2 kPa. However, the vacuum pump is not part of the active safety systems, and automatic start-up of the vacuum pump is not available. This pump could be switched on manually. Thus, to simulate this manual actuation, it was decided to have a higher uncertainty range ($\pm 10\%$) for the vacuum pump actuation set point of pressure in the calculations. The uncertainty range for all the investigated parameters and for the minimal and maximal parameter values are presented in Table I.

When uncertain parameters are defined, it is necessary to set distribution functions of parameter variation. Laws of normal and uniform distribution were used to evaluate the potential margins of all parameters. Normal distribution function is used for those parameters for which the basic value is more probable (for example, initial pressure and temperature in the cooling system). Uniform distribution function is used for those parameters for which the basic value is considered for the modeling (for example, signal delay of pump trip, temperature in the torus hall). For the uncertainty analysis, it was assumed that the parameters (Table I), which may impact the calculation uncertainty, are independent.

SUSA program tool 59 generated collections of uncertain parameter data. For each collection the input file for the

RELAP5 program code was composed, and calculations were provided. The results of 59 calculations are presented in Fig. 7, which shows that the pressure increase inside the VV is sharp and the calculation results did not change significantly. However, the calculated maximal values of pressure vary between $\sim 61\,500$ and $\sim 63\,800$ Pa. When the pressure in the VV starts to decrease, the calculation results of the 59 calculations vary somewhat more (Fig. 7).

V.B. Sensitivity Analysis

Sensitivity analysis of a 2-mm² partial break of a cooling pipe of in-vessel components is presented in this section. To perform the sensitivity analysis of the calculation results (pressure inside the VV), the pressure behavior curves were divided into two time intervals (Fig. 7). The two intervals were selected because of different processes and different influences of the analyzed parameters in those intervals:

1. fast pressure increase due to water flashing and contact with hot surfaces of in-vessel components
2. slow decrease of pressure in the VV because of activation of vacuum pump and reduced flow rate of water discharge to the VV (automatic valves on the inlet of the cooling system are closed).

In order to provide a sensitivity analysis for the calculation results, it was decided to have three analyzing points (Fig. 7): one point for the pressure increase part and two for the pressure decrease part. The calculation results of the sensitivity analysis for those three points are presented in Figs. 8, 9, and 10. It was decided to not analyze the parameters that influence the calculation results lower than 0.2.

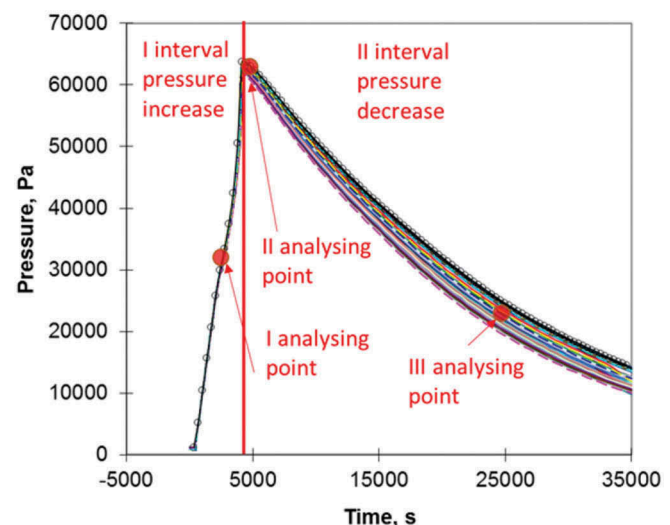


Fig. 7. Results of 59 calculation results.

In the first time interval of the calculations, the pressure in the VV starts to increase because of water flashing and water evaporation due to contact with the hot surfaces of the in-vessel components. It was decided to analyze the influence of the parameters at the time moment 3100 s from the start of the calculations, i.e., the first analyzing point (Fig. 7). The parameters that have the biggest influence are presented in Fig. 8. As is shown in Fig. 8, the highest influence on the calculation results at the fast pressure increase period has characteristics of the vacuum pump (maximal flow rate and efficiency dependence from the pressure). However, in this first time interval of the calculation, the initial pressure in the VV and signal actuation (time of closing the automatic valves and starting the vacuum pump) also have considerable influence.

The second time interval of the calculations is when the pressure in the VV starts to decrease. This pressure decrease is due to reduction of the discharged water flow rate (automatic valves are closed) and flow rate increase through the vacuum pump (change of the volumetric density inside the VV). It was decided to analyze the influence of the parameters at time moment $t = 5000$ s (the second analyzing point) (Fig. 7). The parameters that

have the biggest influence are presented in Fig. 9. In this time interval of the calculations, the characteristics of the vacuum pump have a big influence, but the initial temperature inside the torus hall has the highest influence. These results reflect the influence of the heat transfer process from the walls of the VV and in-vessel components to the torus hall. The temperature of the torus hall affects the temperature inside the VV despite the fact that the heat transfer coefficient is low ($\sim 8 \text{ W/m}^2\cdot\text{K}$). The third analyzing point was chosen at the time moment $t = 25\,000$ s (Fig. 7). At this point the pressure in the VV continually decreases. The reasons for this are the same as described above. The parameters that have the biggest influence are presented in Fig. 10. The influences of the parameters to the results are very similar as it was observed in the second analyzing point (Fig. 9). However, the tendencies reveal which vacuum pump characteristics become more important and that the initial temperature of the torus hall is less important.

For reliability of the performed sensitivity analysis, the value of the coefficient of determination R^2 is very important. In statistics, R^2 is used in the context of statistical models, the main purpose of which is the

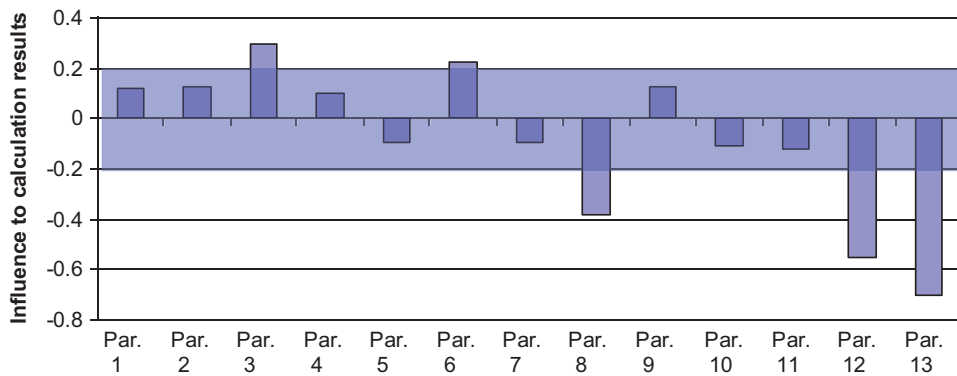


Fig. 8. First analyzing point. Pressure increase in VV. Influence of parameters.

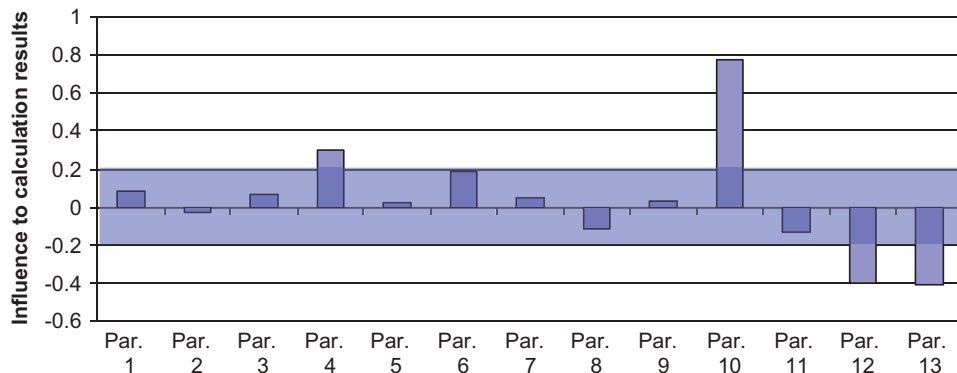


Fig. 9. Second analyzing point. Pressure decrease in VV. Influence of parameters.

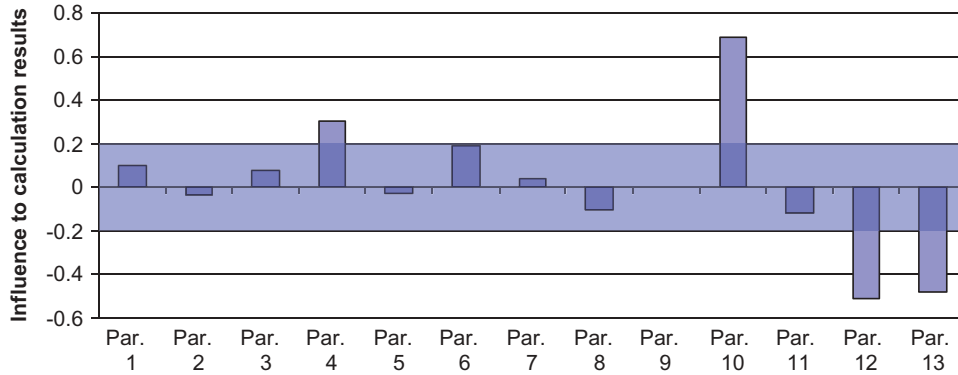


Fig. 10. Third analyzing point. Pressure continually decreases. Influence of parameters.

prediction of future outcomes on the basis of other related information. R^2 is calculated by the following equation²²:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2},$$

where

\hat{y}_i = estimation of variables y_i (where $i = 1, \dots, n$) calculated from the regression equation

\bar{y}_i = mean of variables y_i

n = sample size (in our case is equal to the number of the sets generated for model parameters).

The numerator of the equation reflects the scattering of the values of variables y_i around the regression line. The denominator reflects the scattering of the values of variables y_i around its mean. For example, if $R^2 = 0.85$, it means that 85% of the total variation of y can be explained by the linear relation (as described by the regression equation). The other 15% of the total variation of y remains unexplained. From the practice, in order to have reliable results of uncertainty and sensitivity, the value of the determination coefficient must be higher than 0.6. If the R^2 value is less, then the results of the sensitivity analysis may be incorrect because of too many unexplained y variations.

The determination coefficient of this sensitivity and uncertainty analysis is presented in Fig. 11. The determination coefficient is low (~0.5) within the first interval of calculation, when the water injection in the VV starts. However, the determination coefficient increases during pressure increase in the VV (more than 0.8). Later (within the second interval of calculation), as is presented in Fig. 11, the value of the determination coefficient is

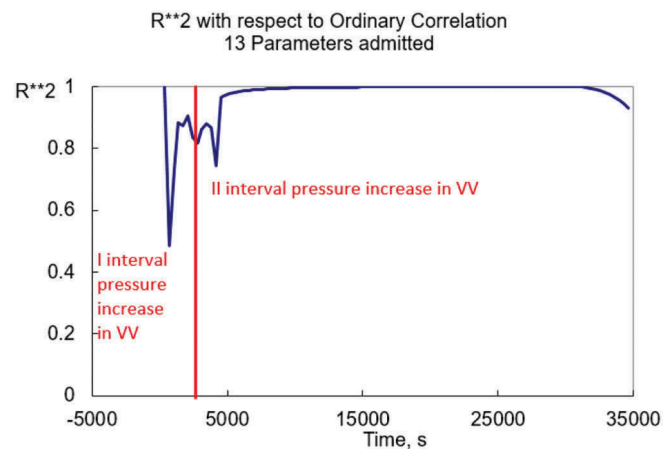


Fig. 11. Determination coefficient of the sensitivity analysis.

close to 1 at the time when pressure in the VV starts to continuously decrease.

V.C. Determination of Maximal Allowed Area of Partial Break

In this section the maximal area of the partial break, which could be compensated by a vacuum pump, is determined. For this analysis the maximal values of the pressure increase inside the VV are the most important. So, it is enough to analyze only the first interval of the calculations. According to the results of the sensitivity analysis, presented in Fig. 8, the minimal or maximal values of parameters that have the highest influence on the calculation results (pressure increase inside the VV) were investigated. The values of these parameters are presented in Table I and are indicated by italicized numbers. For other parameters that have an influence on the calculation results lower than 0.2, the basic values (presented in Table I) were considered. Using these values the

calculation that calculates the maximal pressure increase inside the VV was provided. In order to determine the maximal possible value of the break area, a few calculations were performed. In each calculation, the area of the break of the cooling system pipe was increased. Figure 12 presents the behavior of pressure inside the VV, when the area of the pipe partial break is 19, 22, and 23 mm². The burst disk opening pressure is 110 kPa. The results of the performed calculations showed that the maximal break area could be 22 mm². However, opening of the burst disk could also have uncertainties. The burst disk for the W7-X facility is fabricated very precisely, especially taking into account the actuation pressure. Thus, it was decided that the maximum uncertainty (lower limit) of the burst disk activation pressure could be -3%. If this burst disk opening uncertainty is considered, then the maximal area of the break could be 19 mm².

VI. SUMMARY AND CONCLUSIONS

In order to study the processes that occur in the cooling systems of in-vessel components and the VVs of nuclear fusion devices, the best-estimate code RELAP5 was selected, and numerical models were developed. For validation of the models that represent the processes in the VV, experimental data obtained at the ICE experimental facility were used. The studies of the ICE experimental facility lead to the following main conclusions:

1. Realistic initial conditions of the VV must be considered in the RELAP5 program code model that is developed in order to model the pressure increase in the VV. If the initial pressure in the VV is less than 700 Pa, the steam inside the VV must be assumed. Otherwise, if

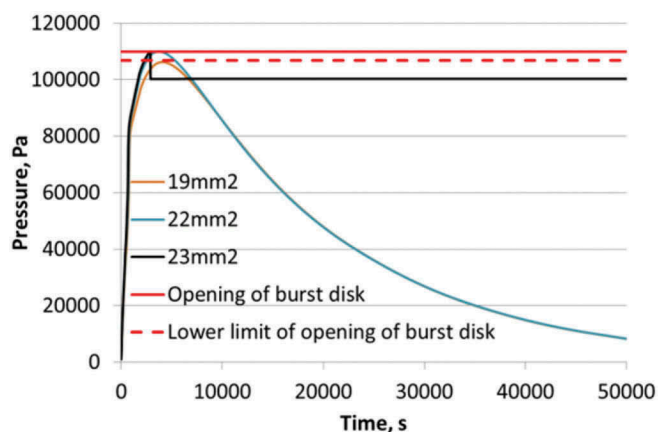


Fig. 12. Calculation of maximal break area.

the initial pressure in the VV is more than 700 Pa, non-condensing gas must be assumed in the model.

2. Counter-current flow of water and steam in the vertical direction and stratification of steam should be evaluated for modeling of the VVs of nuclear fusion devices in the case of a loss-of-coolant event.

Using the experience gained from the modeling of ICE experiments, the numerical model of the W7-X experimental device was updated, and possible consequences of water ingress were investigated, with the following main results:

1. Calculation results using the updated VV model are in better agreement with those of other authors in the case of guillotine 40-mm-diameter cooling system pipe break analysis.

2. The peak pressure inside the VV is much lower using the updated W7-X VV model than using the older model in the case of the partial 1-mm² break of the cooling system pipe.

The best-estimate approach was applied for the updated VV model in order to determine the maximal allowed area of a partial break. Uncertainty analysis (95% probability and 95% confidence level) of a 2-mm² partial break of the cooling pipe inside the VV showed that calculated maximal pressure inside the VV does not reach burst disk opening pressure. Sensitivity analysis showed that the influence of the parameters to the calculation results varies during time intervals because of the different processes in the VV. In the first time interval of the calculations, the pressure in the VV increased because of water flashing and water evaporation due to contact with the hot surfaces of in-vessel components. In this time interval the biggest influences on the calculation results were characteristics of the vacuum pump (maximal flow rate and efficiency dependence from the pressure), initial pressure in the VV, and signal actuation time. The second time interval of the calculations is when the pressure in the VV starts to decrease because of reduction of the discharged water flow rate and flow rate increase through the vacuum pump. In this time interval of the calculations, the characteristics of the vacuum pump have a big influence, but the initial temperature inside the torus hall has the most influence.

According to the results of the sensitivity analysis, an input deck that would calculate the maximal values of the pressure increase inside the VV was developed. The results of the performed calculations showed that the maximal break area could be 22 mm². However, if burst disk opening uncertainty is considered, then the maximal area of the break could be 19 mm².

The results of these studies are used to define protection measures and instructions to operators in order to ensure safe operation of the W7-X fusion experimental device.

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