EUROFUSION WPSAE-PR(16) 16324

T Kaliatka et al.

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Preprint of Paper to be submitted for publication in
Fusion Science and Technology

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ANALYSIS OF INGRESS OF COOLANT ACCIDENT IN 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 is one of the most important events challenging safety barriers in nuclear fusion reactors. The ingress of coolant into the vacuum vessel could appear due to rupture of coolant pipe in-vessel components. Any damage of in-vessel components could lead to water ingress and may lead to a pressure increase and possible damage of the vacuum vessel. Therefore, it is important to understand thermo-hydraulic processes in vacuum vessel during the ingress of coolant events to prevent the over pressurization of VV.

There are few experimental investigations performed of ingress of coolant events. The comparisons of calculation results and experimental data showed that with some limitations the RELAP5 code could be used for the analysis of the thermal hydraulic processes in the vacuum vessel during ingress of coolant event. This conclusion confirms that the RELAP5 code could be used for the analysis of accidents in Wendelstein 7-X experimental fusion facility.

In this article the modification, according the experience gained from the modelling of the ICE experiments, of early developed W7-X model is presented. Two accident scenarios were analysed in this article. First scenario is a guillotine 40 mm pipe break accident. Calculation results were compared with the results received using the older model and results of other researchers, who investigated the same accident. The second scenario is a partial break of the pipe in cooling system of in-vessel components. Calculation results of a 1 mm^2 area partial break using old and updated Wendelstein 7-X models are provided. The updated Wendelstein 7-X model showed much smaller pressure increase rate in vacuum vessel comparing to the old model. In order to find the maximal area of a partial break, which causes a pressure increase in the vacuum vessel, but does not lead to the burst disc activation (no steam release from vacuum vessel to the environment), the uncertainty and sensitivity analysis of calculation

results is used. The results of the analysis using the updated Wendelstein 7-X model showed that a partial break area, which does not lead release of steam from vacuum vessel to the environment, could be much larger than it was considered before.

INTRODUCTION

Fusion reactors could be one of the alternatives to the energy produced in fission reactors which, as history shows, have safety issues. However, in order to achieve efficient use of energy from the fusion reaction, a number of fusion physics and engineering issues still need to be solved. The key issue among them is how to maintain a stable high temperature (more than 10^8 K), of the plasma in the vacuum vessel for a long time. This is one of the main causes why mankind among many experimental devices do not have an operating commercial fusion device in the world yet. The European Union has 16 experimental devices which are used for fusion experiments. Two experimental devices which are based on magnetic confinement method are in commissioning recently. The most important nuclear fusion devices and the projects in the European Union are tokamak type ASDEX Upgrade, JET, ITER, DEMO and stellarator type Wendelstein 7 X.

Wendelstein 7-X, which, lately completed in Germany [1, 2], is at the moment the largest stellarator-type fusion device in the world, which does not produce energy, but is used for investigations of its suitability of this type for a power station. With discharges lasting up to 30 minutes, it should demonstrate its significant property, its ability to operate continuously. The plasma is generated in the Vacuum Vessel (VV). VV is assembled in form of a ring-shaped (torus) with a diameter of about 12 metres. VV confines the plasma heated to 100 million degrees. The geometry shape of the vessel is matched to the twisting plasma ring. The whole volume of vacuum vessel is about 108 m^3. The in-vessel components consist of divertor units, baffles, panels and heat shields, control coils, cryo-pumps, port protection and special port liners, and the complex system of cooling water supply lines as well different diagnostics [3, 4]. The cooling system of in-vessel components in 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. Both MCC and “baking” circuits are connected together and supply water to the same in-vessel components. Water inside the “baking” circuit is heated using electrical heater in order to heat up the in-vessel components during “baking” operation. MCC and “baking” circuits have their individual pumps for the water circulation. During “baking” operation mode the water mass flow rate is lower than it is required for the cooling of the in-vessel components during normal operation.

Safety is the number one priority for all nuclear energy generating devices. The safety assessment of fusion devices are based on the identification and analysis of the hazards. The radiation hazards are related to the radioactive source terms. In the W7-X fusion device the neutrons are produced during fusion operation; activated materials on the plasma facing components, activated corrosion products in the cooling circuits, activated dust produced by plasma-wall interaction in the VV and small amount of the tritium inside VV are the main radioactive source terms in the fusion device. The greatest part of the radioactive materials is concentrated inside the VV. Thus, VV is acting as a barrier, which prevents environment from the release of radioactive materials.

The analyses, presented in this paper, are related to the period of investigation, when the radiological dose is not a concern. However, issues, related to the water ingress in vacuum vessel of W7-X should be investigated. The water ingress into VV of W7-X device is an issue due to three reasons: (1) damage of VV, (2) cost of rupture disc and (3) loss of device operation time. The VV is designed for the vacuum conditions, and any rupture of in-vessel components cooling system pipes, leads to ingress of water in the VV. This process may lead to sharp pressure increase and possible damage of VV and its component, in particular the multilayer bellows of the large ports might be affected. According the designers of device, some components (for example ports) may lose their integrity when the pressure in vacuum vessel exceeds 50 kPa above the atmospheric pressure [5]. In order to avoid such undesirable consequences, the Pressure Increase Protection System, which protects vacuum vessel from a possible pressure increase, is designed. This system consists of two burst disks, venting pipe lines and draining tank. The most important components are the burst disks, which connect the VV with the chimney and environment through the venting pipelines. The opening pressure of these disks are different – the first burst disk opens at 110 kPa pressure in VV, while the opening pressure of the second burst disk is 120 kPa (absolute pressure). The burst disks are made very precisely and specific production technology makes it costly.

The main goal of this article – to investigate the possible consequences of water ingress into VV of W7-X experimental device. In order to achieve this goal the thermo-hydraulic analysis has been performed using RELAP5 code. To perform the analysis RELAP5 model was developed. However, the water ingress into VV is a specific phenomenon, not met in the analysis of loss of coolant accidents in nuclear fission reactors, for which the RELAP5 code is designed. This requires to perform validation of computer code and developed models. For the validation of RELAP5 code, the experiments related to the Ingress of Coolant Event (ICE) were analysed. Experience and modelling recommendations gained from the modelling of ICE experiments was used in order to update the W7-X model. Using updated model of W7-X vacuum vessel, the analysis was carried out in order to investigate the possible consequences of water ingress. In the first part of the article, the guillotine 40 mm diameter cooling system pipe break was analysed. Second part of the article consists of the application of best estimate approach for determination of maximal allowed area of partial break.

1. Modelling of ICE experiments using RELAP5 code

In order to investigate the processes in the vacuum vessel, in the Japan Atomic Energy Research Institute (now Japan Atomic Energy Agency) a special experimental facility was developed. The first Ingress of Coolant Event (ICE) experiment was provided in 1996 [6]. Nowadays there are documented few experimental investigations of water injection in the low pressure (vacuum) vessel. These experimental investigations could be divided into two groups. In the first group initial temperature of injected water and VV walls is low (at room temperature) [7]. In the second group the walls of VV are heated or special hot steel structure are installed inside VV, imitating hot in-vessel components [8]. The first group imitates fusion devices which are in "shut down" situation (cooling circuit is circulating, vacuum conditions in VV is maintained, but no plasma operation). After injection of cooling water in the volume at initial vacuum conditions, the water is evaporating very fast (flashing effect, which is driven by the excess sensible energy in the coolant) and the pressure inside the vacuum vessel increases to the saturation pressure, corresponding to the temperature of the coolant water. In the case if the water injection rate is very small, in some experiments the water temperature at the nozzle of injection is sharply decreasing down to freezing of water, what leads to the termination of water injection. The second group of the experiments imitates fusion devices in "baking" modes. Before plasma operation, in-vessel components of vacuum vessel 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" operation mode is mainly used for this purpose. After the break of the cooling system pipe of in-vessel components the water is injected in the VV. Pressurization of VV will be due the vaporization of the ingresses coolant by flashing and by boiling of the coolant on the hot surfaces of the in-vessel components. Boiling cause by the contact of the hot surface is the dominant in this group of the experiments.

The model of vacuum vessel of ICE experimental facility is presented in the article [9]. In this article it was demonstrated that the RELAP5 code could be used for the analysis of the processes in the VV of nuclear fusion reactors during ICE. In this article the calculation results are compared with the measurements of the two ICE experiments. As the representative – for the first group of the ICE experiment was selected in the literature [7] described experiment, from the second group of ICE events – the experiment, illustrated in literature [10] was selected.

Due to RELAP5 limitation, the initial pressure in VV during the modelling cannot be lower as ~1kPa. The assumptions were made, that before the water injection VV is filled by non-condensable gas or by water steam at initial pressure 700 Pa. The comparison of the calculation results with the measurements, performed during experiment [7] showed that in the case if VV was initially filled with non-condensable gases, the higher pressure increase had been achieved in RELAP5 calculations, comparing with the case when in VV the water steam was assumed initially. The comparison of calculated results by RELAP5 (VV filed with non-condensable gases and water steam) and experimental data is presented in Figure 1.

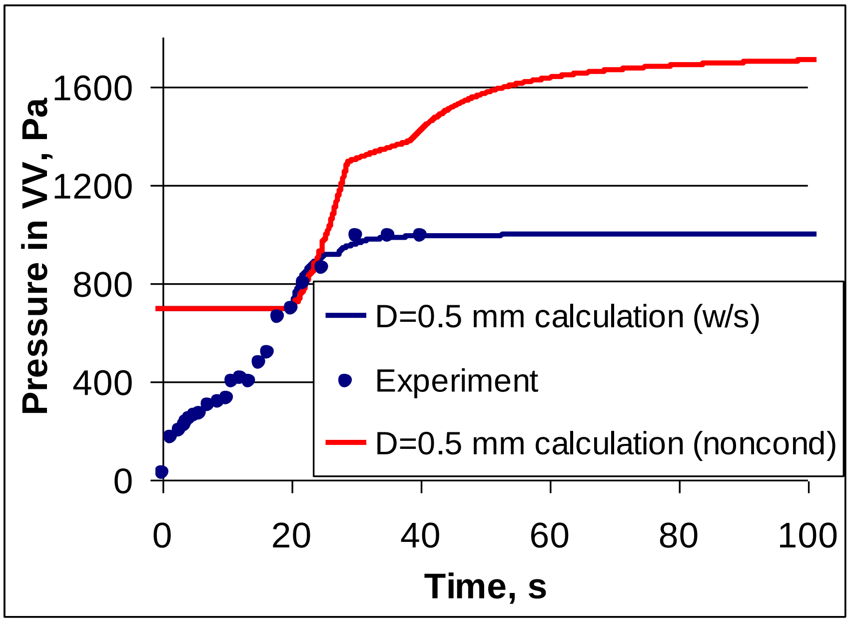


Figure 1. Comparison of pressure increase in VV calculated by RELAP5 and experimental data. Walls of VV is not heated.

The initial pressure in VV before the water injection in experiment [7] was 30 Pa, what is considerable lower the minimal pressure due to RELAP5 limitation 700 Pa. In real experiment, when 700 Pa pressure is reached after a few seconds and at that moment VV already is filled with water steam - air mixture (very low content of air), because of the flashing effect of injected water.

The main conclusion of these results is that realistic initial conditions of the vacuum vessel must be considered in the developed RELAP5 program code model in order to model the pressure increase in vacuum vessel. If the initial pressure in vacuum vessel is less than 700 Pa, the steam inside the vacuum vessel must be assumed. Otherwise, if the initial pressure in vacuum vessel is more than 700 Pa - non-condensing gas (high content of air) must be assumed in the model. This conclusion especially important for the cases when the injected water flow rate in VV is small.

The experiment presented in literature [10] was chosen as the representative of the second group of ICE experiments. In this experiment water is injected in VV with heated in-vessel components. For the analysis of ICE facility two models of RELAP5 were developed [9, 11]. Both models consist of two hydrodynamic components (pipes). In the first ICE facility model, in order to simulate the heated block presented in the experiment and the interaction between the water jet and heated block, the small vertical pipe was used. The second model for the same purpose uses horizontal pipe. The comparison of calculated and measured pressure in the VV of ICE experiment [10] showed that the calculation results using model with vertical component are closer to experimental data (Figure 2). More detail information on the developed RELAP5 models, used assumptions, received calculation results are presented in [9, 11]. However, the main conclusion is that counter current flow of water and steam in the vertical direction and stratification of steam should be evaluated for the modelling of the VV of nuclear fusion devices in the case of loss of coolant event.

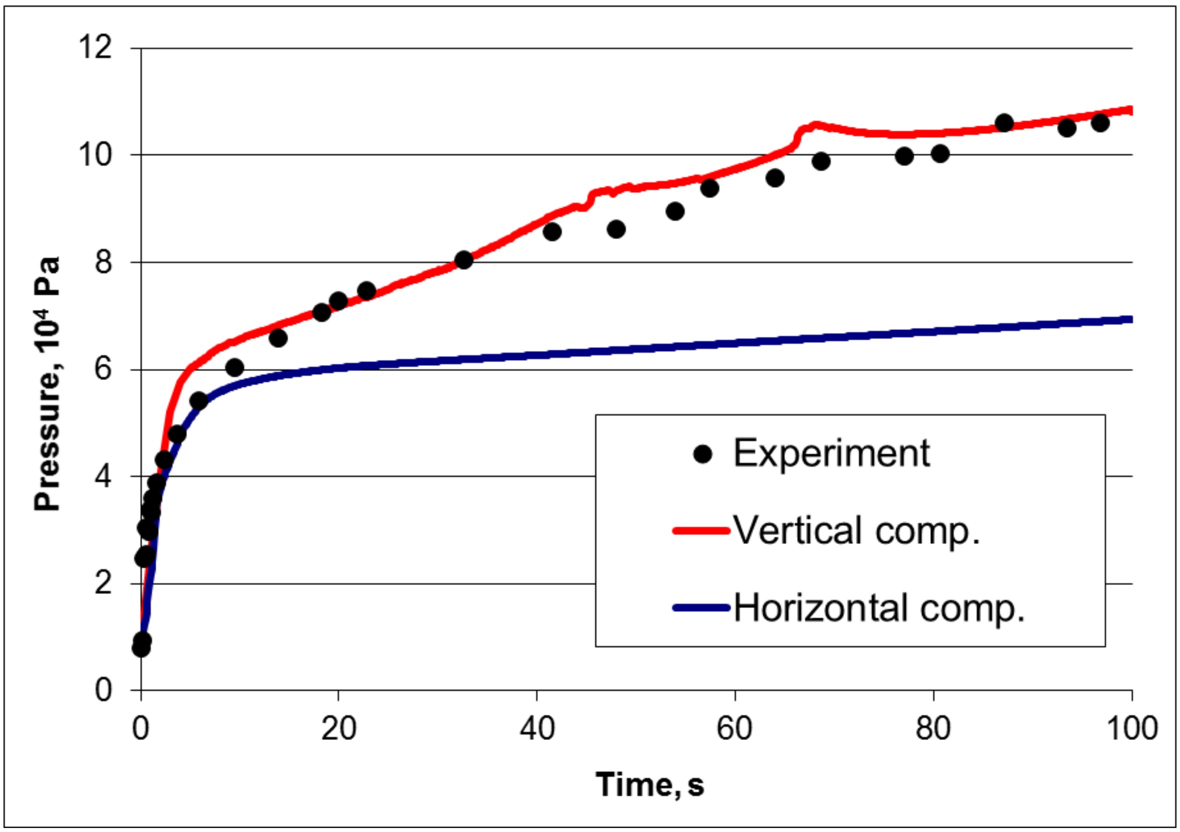


Figure 2. Comparison of pressure increase in VV calculated by RELAP5 and experimental data [9, 11]. Walls of VV is heated.

2. W7-X model improvements, taking into account results of ICE benchmark

In Lithuanian Energy Institute the attempts to simulate the processes in the vacuum vessel of W7-X experimental facility in the case of water ingress were performed starting 2010 [12]. Initially the simple model of the vacuum vessel of W7-X was developed [13]. The complicated three-dimensional geometry of the VV volume in the W7-X stellarator in the first developed (old) model was simplified to the geometry of horizontal cylindrical pipe. Ends of the cylinder are open and joined together, simulating closed circle of torus geometry (Figure 3 *a)*). Whole volume (108 m^3) of the VV was modelled using one pipe element "199." The inner surface area (707.5 m^2) and wall thickness (0.019 m) of vessels structures in the model correspond to the available design data [4, 14].

According to the results of the modelling of ICE experiment facility it was decided that counter current flow of water and steam in the vertical direction and stratification of steam should be evaluated in the water injection area for the modelling of the VV. According to the received conclusions, the old W7-X model [13] of vacuum vessel have been updated. Vertical pipe (pipe 196) have been connected to the horizontal pipe (Figure 3 b*)*). Volume of vertical pipe is 1/10 of all volume of VV and 9/10 of volume belongs to the horizontal pipe. Vertical and horizontal pipes have 5 inner nodes each. The last node of the horizontal pipe is connected to the 3rd node of the vertical pipe. Also the third node of vertical pipe is connected to the begging of the horizontal pipe. These connections were done in order to simulate the closed circle of torus geometry. In this article the pipe break of upper in-vessel component is assumed. In this case water from the cooling circuit of in-vessel components is injected in upper node of vertical pipe "196". At the top of vertical pipe injected water is evaporating and flowing down through the pipe. Water is collected in the lowest node of pipe "196". In vertical pipe produced steam is flowing through the third node to the horizontal pipe. Updated model of the vacuum vessel have connection (TDJ 119) to the vacuum pump which is modelled as the time dependent volume "399". The connection to the vacuum pump is activated when specific conditions are required. More about this option is described in section 3.2.

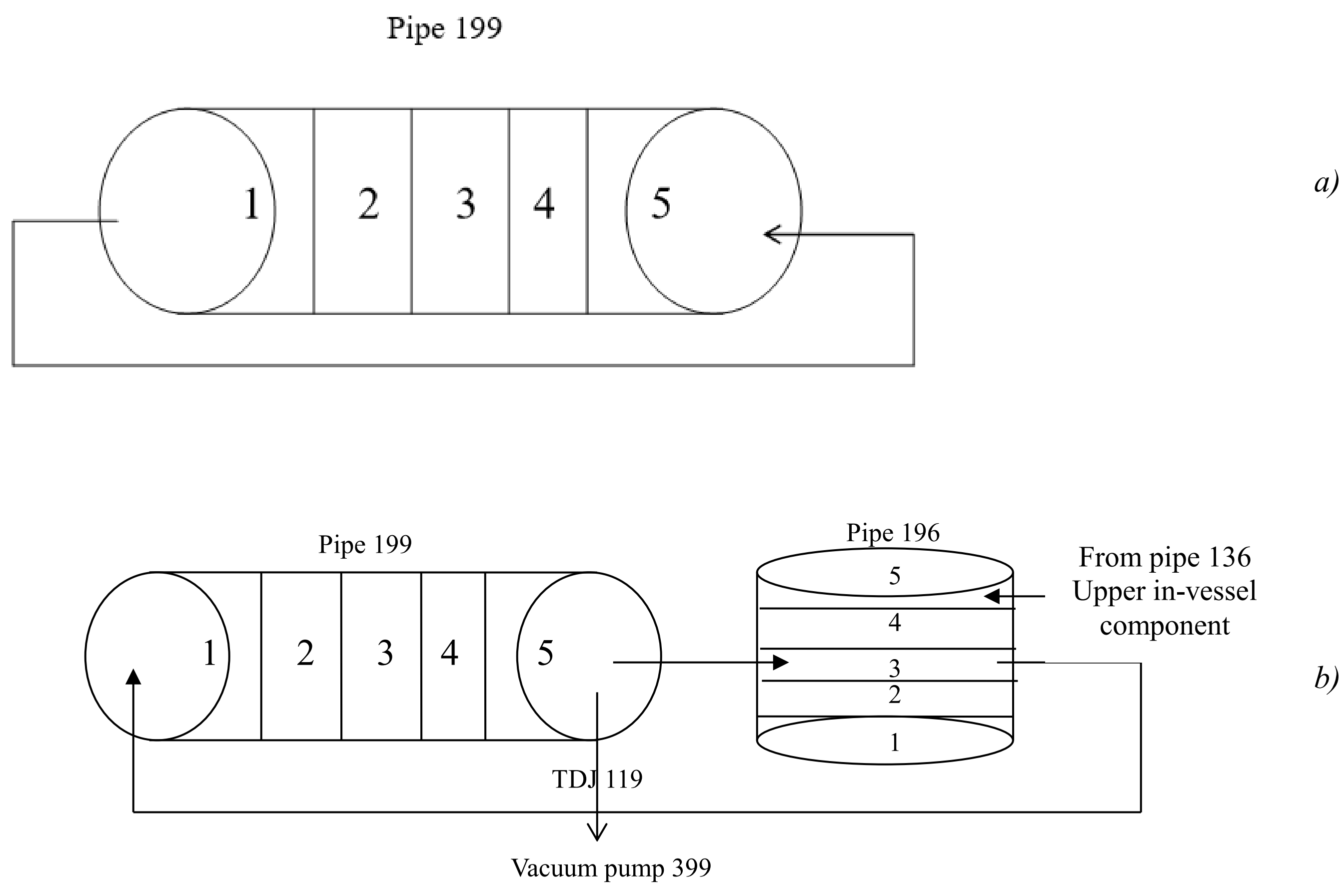


Figure 3. Model of vacuum vessel for RELAP5 code: a) old model, b) updated model

3. Analysis of coolant ingress to the vacuum vessel accident

This section presents the calculation results of the RELAP5 code. Comparison of received calculation results using old and updated model are presented in this section. As it was mention in the introduction, the calculations have been provided for two accident scenarios:

- Guillotine 40 mm diameter pipe break of in-vessel components cooling system (Section 3.1), and
- Partial (1 mm^2) break (Section 3.2).

3.1 Guillotine 40 mm diameter cooling system pipe break

Break of the 40 mm inner diameter coolant pipe providing water for the in-vessel components during the “baking” regime of the facility operation is considered to be the most severe accident in terms of the VV pressurization. It was assumed that the guillotine pipe break occurs in cooling system of upper in-vessel component. Other calculation assumptions are used:

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

More information about assumptions, technical data and calculation results using the old model of vacuum vessel could be found in [13, 15].

As it was already mentioned, to prevent the possible damage of VV due to overpressure, in W7-X device the Pressure Increase Protection System with two burst disks, connecting VV with the venting pipe lines is designed. Both burst disks are installed on the pipelines of 0.3 m inner diameter that are connected to the main venting pipeline of 0.5 m inner diameter. The exit of main venting pipeline is outside the building above the roof level. In the case of LOCA, water ingress in the VV and pressure starts to increase in the VV. Then opening pressure of the burst disk would be reached, disk will be opened and water steam from VV would enter in to the venting piping and through it will be discharged outside the building. The surface of venting pipe walls is colder than the steam released through the burst disk. The steam would be condensing on the colder surfaces of the venting piping. Therefore, at the lowest point of venting piping the draining tank is installed. To evaluate the capability of this Pressure Increase Protection System the thermal hydraulic analysis was performed. However, initially analysis, presented in [13, 15], was performed not evaluating the findings from ICE benchmarks. The comparison of calculation results received using old and updated model of vacuum vessel is presented in

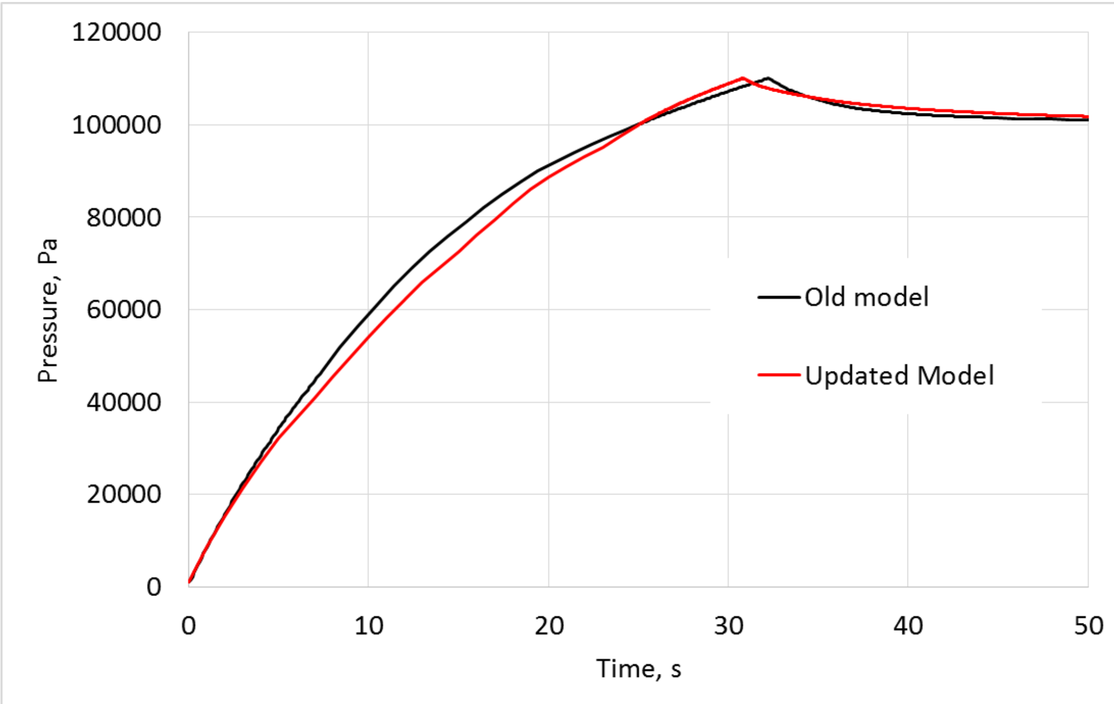


Figure 4. Using the updated model of vacuum vessel, RELAP5 calculates that the burst disc activation pressure is reached sooner than using the old model. Using the old model the burst disk is opened ~34 s after the beginning of the break. Using the updated model burst disk is opened 3 s earlier [16]. In the old model injected water was spread along horizontal pipe, while in the new model of vacuum vessel, the discharge of water from the ruptured pipe in the cooling system of in-vessel components is simulated as the injection of water in the vertical pipe (Figure 3 *b)*). The injected water evaporates due to flashing effect and contact with hot surface. In the vertical pipe injected water due to gravity forces are flowing down and collecting at the bottom of the pipe. Water and hot structure contact surface area is higher in the updated model. Also in new model the water-steam counter current flow is modelled. This leads to the faster process of water boiling and the faster pressure increase in vacuum vessel.

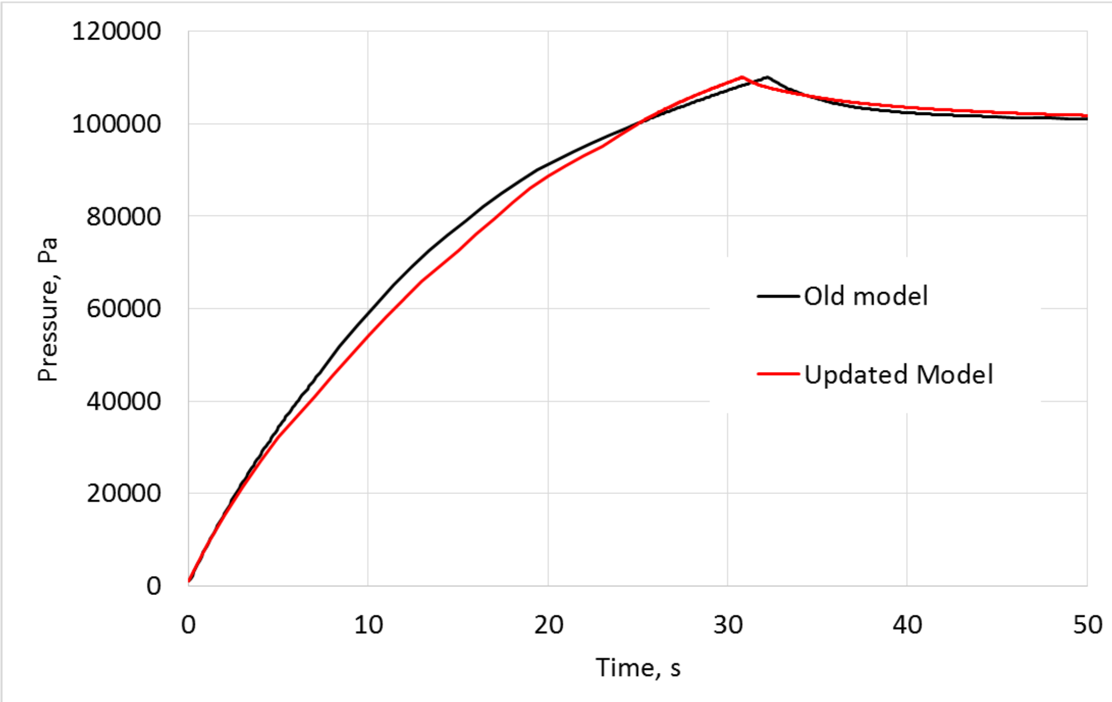


Figure 4. Comparison of calculation results of old and updated models

Achieved calculation results using updated VV model is in better agreement with other authors calculated the same accident scenario. L. Topilski using MELCOR code calculated that opening of burst disc occurs only 13 s after the break [4]. In publication [17] it is presented that using ASTEC code burst disc opening is observed ~22 s after the break and after 24 s using COCOSYS. Comparing this results it is clear that vacuum vessel pressurization process is still observed slower using RELAP5 code.

3.2 Partial 1 mm^2 break of cooling system pipe

In the W7-X facility, in order to achieve vacuum conditions in the VV, a vacuum pump is used. This pump can also be used to ensure the vacuum conditions in case of small break in the cooling system of the in-vessel component. The working of this vacuum pump consists of four-stage, dry compressing rotary piston pump UniDry50S and roots pump Okta250. Detail description of this vacuum pump could be find in [18]. The maximal flow rate of vacuum pump installed in the W7-X facility is 240 m^3/h, but the flow rate depends on the suction pressure (pressure in a vacuum vessel). The main characteristic curve (volumetric flow rate versus pressure) of the pump is presented in Figure 5. Relative volumetric flow in vacuum pump decreases when the pressure in VV increases higher than 20 Pa. But the mass flow rate of the gasses through the pump depends on the air-steam mixture density inside the vacuum vessel. With decreasing pressure in VV, air-steam mixture density also decreases, and the mass flow rate through the pump decreases.

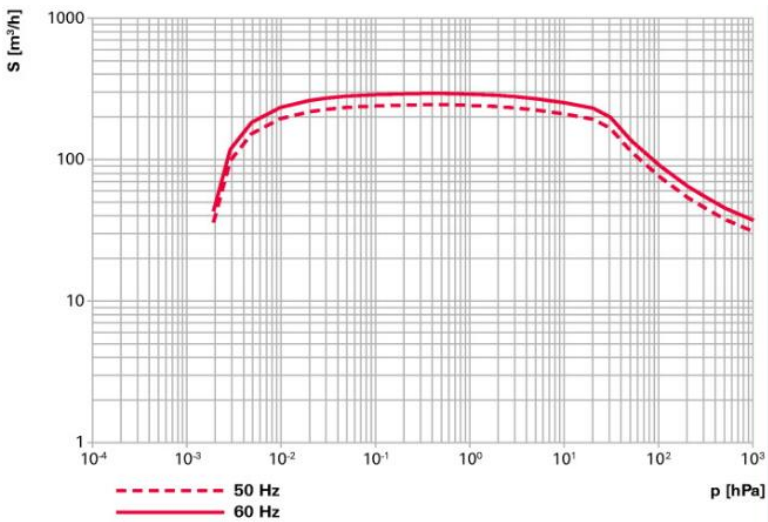


Figure 5. Relative volumetric flow dependence on pressure in vacuum vessel.

The partial break of cooling system was performed using the updated RELAP5 model, presented in Figure 3 *b)*. In this model the initial availability of steam inside the vacuum vessel was assumed as initial condition. This assumption was done according the experience of the modelling of ICE experiments (see Section 1) – the same assumptions were used in section 3.1. In the older model of vacuum vessel the presence of non-condensable gases were chosen initially.

In the case of partial break of the cooling system of in vessel components with 1 mm^2 area of break opening, water is discharged into the VV with the 0.028 kg/s flow rate. Pressure in the vessel starts increasing and after reaching 2 kPa pressure in the VV, the signal to stop circulation pump, to close automatic valves on the inlet of cooling system and to start the vacuum pump is given. When the automatic valves are closed, the flow rate of water-steam mixture through the break decreases down to 8 10^{-4} kg/s. The water discharge from the lower components into the vacuum vessel is only due to pressure difference. At the beginning of the break, density of the air-steam mixture in the vacuum vessel is low. Cause of water discharge pressure in VV is increasing and density in VV increases as well. The density of water-steam mixture directly affects the mass flow rate through the vacuum pump. Increase of pressure in the VV decreases the volumetric efficiency of the vacuum pump, but increased density in the volume leads to the increase of mass flow rate through the pump (Figure 5). The density of air-steam mixture in VV at 1 kPa pressure is ~ 100 times lower than the density at the maximum allowed pressure in 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. Calculation results using the older model of vacuum vessel and non-condensable gases inside is presented in details in article [19].

The partial break (1 mm^2 area) was modelled using updated model of VV and compared with the calculation results, received using old model and assumption regarding non-condensable gases inside VV [19] (Figure 6). Comparison of calculation results shows that using updated model and steam as initial conditions, the pressure inside VV is rising much slower than using the old model and non-condensable gases as initial conditions of VV. The peak pressure inside VV is also much lower using updated model, then old model. Calculation results using the updated model showed one sharp pressure peak. This peak is associated to the used correlations in the RELAP5 and changes of flow regime. The water through broken pipe is discharged in the upper part of the vertical pipe of updated RELAP5 model (see Figure 3 *b)*). Water evaporates because of the flashing effect and contact with hot surfaces. However some part of water, because of gravity will go down to the bottom of vertical pipe. Due to the good contact with hot surface of VV, the water continuously evaporating (in the RELAP5 model this heat transfer between stem-water mixture inside VV and the walls is modelled using – annular mist flow regime). Later (at the time moment t = 7300 s), when the quantity of the water in the lower node of vertical pipe becomes very low, the coolant flow regime in RELAP5 calculation is changed to the "mist post-CHF" (void fraction lower than 0.001). At this moment heat transfer coefficient shortly increases ~ 90 times; evaporation rate also increases. This could explain the pressure peak observed in the calculation results using the updated model at time moment form 7320s to 7600s.

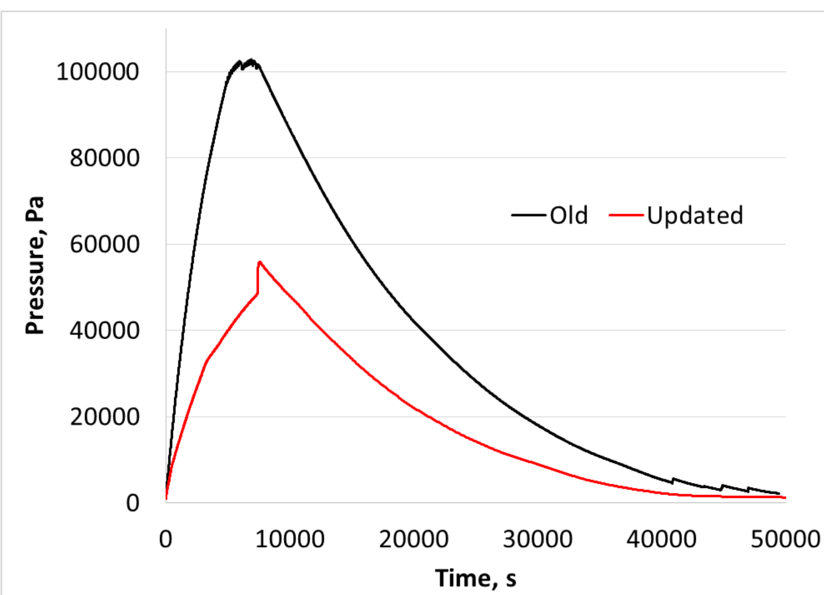


Figure 6. Pressure in vacuum vessel in the case of partial break of 1 mm^2. Comparison of old and updated model.

4. Application of Best Estimate approach for determination of maximal allowed area of partial break

Comparing the results of new and old calculations, presented in Figure 6, it is clear that according updated model the system could withstand to bigger area of the partial break in the in-vessel component cooling system. In order to find the maximal area of in-vessel component cooling system break, which will not cause opening of burst disc, the best estimate approach was used. Best estimate approach consists of the best estimate computer code and uncertainty and sensitivity analysis provided for the calculation results. RELAP5 [20] is the best estimate code. For the uncertainty and sensitivity analysis of RELAP5 calculation results the GRS (Germany) methodology [21] based on the SUSA (Software System for Uncertainty and Sensitivity Analysis) tool [22] were performed. The results of provided uncertainty analysis are presented in section 5.1. Sensitivity analysis is presented in section 5.2. In section 5.3 the maximal partial break is presented, which was calculated according to the results of provided uncertainty and sensitivity analysis.

4.1 Uncertainty analysis

The GRS methodology is based on a systematic identification of relevant physical processes and on a 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 values vectors are generated by Monte-Carlo methods. The main advantage of the GRS methodology is that the minimum number of calculations performed using codes is independent from the number of parameters to be investigated. Number of code runs depends only from the desired probability content and confidence level. The relationship between these parameters is described by Wilks' formula [23]. In the case of the finding the minimal area of the partial break of in-vessel components the pressure peak inside VV is the most important parameter. Thus uncertainty analysis was performed using a one-side (only one parameter - maximal pressure inside VV) tolerance limit with 0.95 of probability and 0.95 confidences. 59 calculations should be performed for one-sided tolerance limit with the 95% probability content and 95% of confidence level. The first step of the best estimate methodology is to select parameters which leads to the uncertainties of calculation results. For those parameters it is need to identify deviation range and deviation distribution type. Uncertain parameters for the analysis of W7-X device, 2 mm^2 partial break of cooling pipe, is presented in Table 1. 13 uncertain parameters were chosen in total. These parameters are initial and boundary conditions in cooling system of in-vessel components, vacuum vessel, pressure increase protection system and vacuum pump of W7-X device. These parameters have been chosen, because they mostly effect the calculation results in the case of the partial break of in-vessel cooling system.

Deviation ranges for geometrical parameters, initial and boundary conditions were chosen according to the experience and possible measurements errors. An assumption was made that flow rate through pumps, pressure and temperature in the cooling system could wary in interval ±3%. The same interval have been used also for temperature inside VV and in-vessel components. Such range of mentioned input parameters was accepted according to experience of safety analysis calculations of Ignalina NPP. Actuation signal and automatic valve closure time could wary also in the interval ±3%. Delay of the "stop" signal could wary in the interval 0.5 – 1.5 s and delay signal of automatic valve closure could wary in the interval 1 – 2 s. These uncertainty variations was discussed during the meeting with the W7-X development team. Initial pressure inside VV has highest assumed variation (±20%). As it was already mention RELAP5 has the limitation - the minimal possible pressure is 700 Pa. It was decided to have big range of pressure variation in order to indicate the influence of the of initial pressure limitation. The temperature in the torus hall is usually room temperature. During the normal operation the equipment is heat-upped and temperature in the room could increase. However, the air cooling system to control the temperature in the torus hall is used in W7-X facility. In order to simulate bigger variation of the temperature inside the torus hall, it was decided to have ±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 a part of the active safety systems the start-up and automatic of vacuum pump is not available. This pump could be switched on manually. Thus, to simulate this manual actuation, it was decided to have higher uncertainty range (±10%) for the vacuum pump actuation set-point of pressure in the calculations. The uncertainty range for all investigated parameters as well as minimal and maximal parameter values are presented in Table 1.

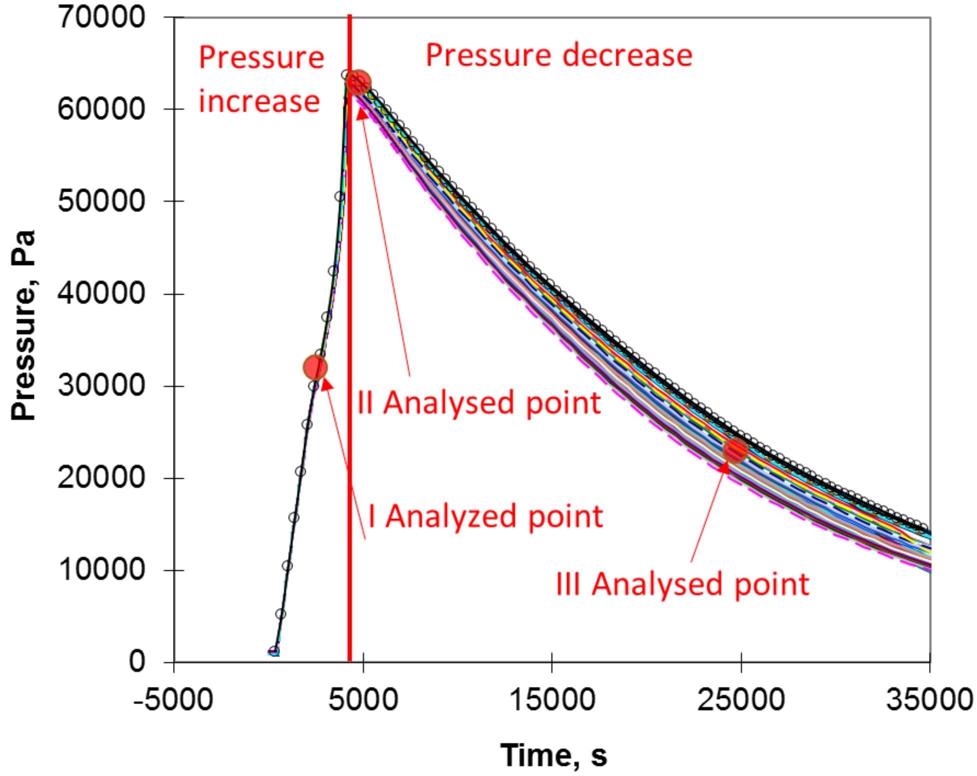
Table 1. Uncertain parameters for W7-X partial break analysis:

#	**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 ± 3%	$1.155 \cdot 10^6$	$1.1845 \cdot 10^6$
2	Initial temperature in cooling system, K	433.15	Normal ± 3%	420.15	446.15
3	Signal actuation, Pa (to stop circulation pump, to close automatic valves)	2000	Uniform ± 3%	1940	2060
4	Closure time of automatic valves, s	5	Normal ± 3%	4.85	5.15 +3%
5	Pump rated flow, kg/s	44.6	Uniform ± 3%	43.262	45.938 +3%

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 ± 20%	800	1200
9	Temperature in VV and in-vessel comp., K	423.15	Uniform ± 3%	410.45	435.84
			Pressure increase protection system		
10	Temperature in the torus hall, K	293.15	Uniform ± 5%	278.5	307.8
			Vacuum pump		
11	VP actuation pressure, Pa	2000	Uniform ± 10%	1800	2200
12	VP efficiency dependence from the pressure, -	According to Figure 5	Uniform ± 3%	0.97	1.03
13	Maximal flow rate of VP, m^3/h	240	Normal ± 3%	232.8	247.2

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 which basic value is more probable (for example: initial pressure and temperature in cooling system). Uniform distribution function is used for those parameters which basic value is considered for the modelling (for example: signal delay of pump trip, temperature in the torus hall). For the uncertainty analysis it was assumed that the parameters (Table 1), which may impact the uncertainty of calculation result, are independent.

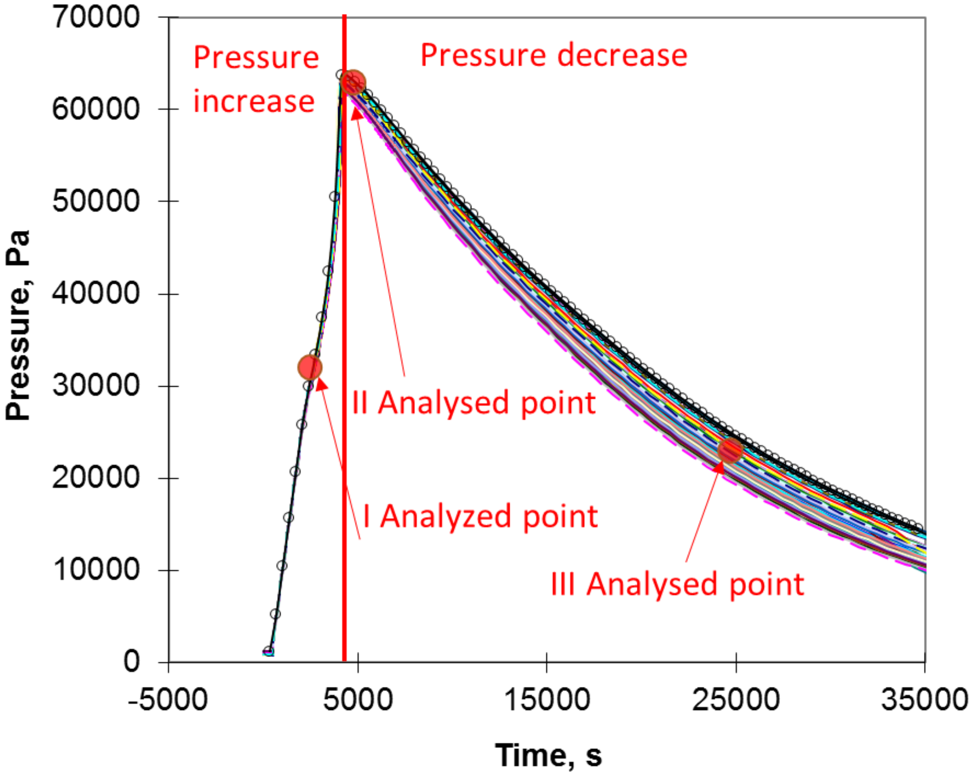
Using SUSA program tool 59 collections of uncertain parameters data had been generated. For each collection the input file for RELAP5 program code was composed and calculations were provided. The results of 59



calculations are presented in

Figure 7. As it is presented in the figure, the pressure increase inside the VV is sharp and calculation results did not change very much. However, the calculated maximal values of pressure varies between ~61500 Pa to ~63800 Pa. When the pressure in VV starts to decrease the calculation results of 59 calculations varies a little bit more. The upper tolerance limit (with 95% probability content and 95% of confidence level) is also presented in

the same figure. Using SUSA program tool calculated upper tolerance limit is on the top of the all calculated



values (

Figure 7).

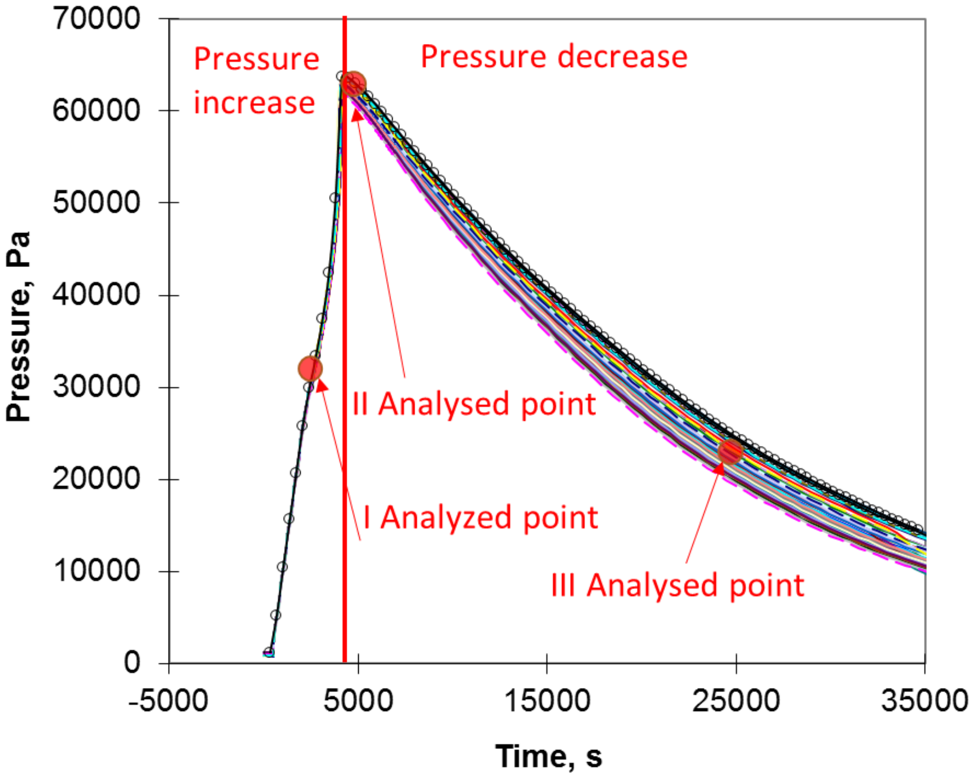
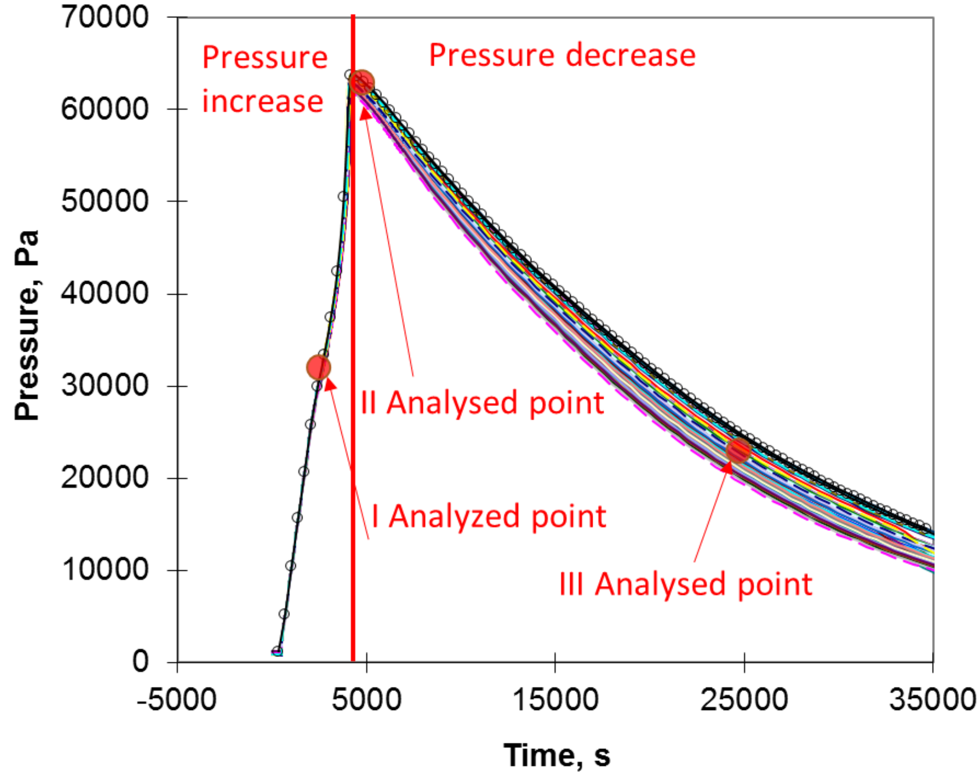


Figure 7. Results of 59 calculations and upper tolerance limit (black, dotted line)

4.2 Sensitivity analysis

Sensitivity analysis of 2 mm^2 partial break of cooling pipe of in-vessel components is presented in this section. To perform the sensitivity analysis of calculation results (pressure inside VV) the pressure behaviour curves were



divided into two time intervals (

Figure 7). The two intervals were selected because of different processes and different mechanism of influence of analysed 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 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 sensitivity analysis for calculation results it was decided to have 3 analysing points (

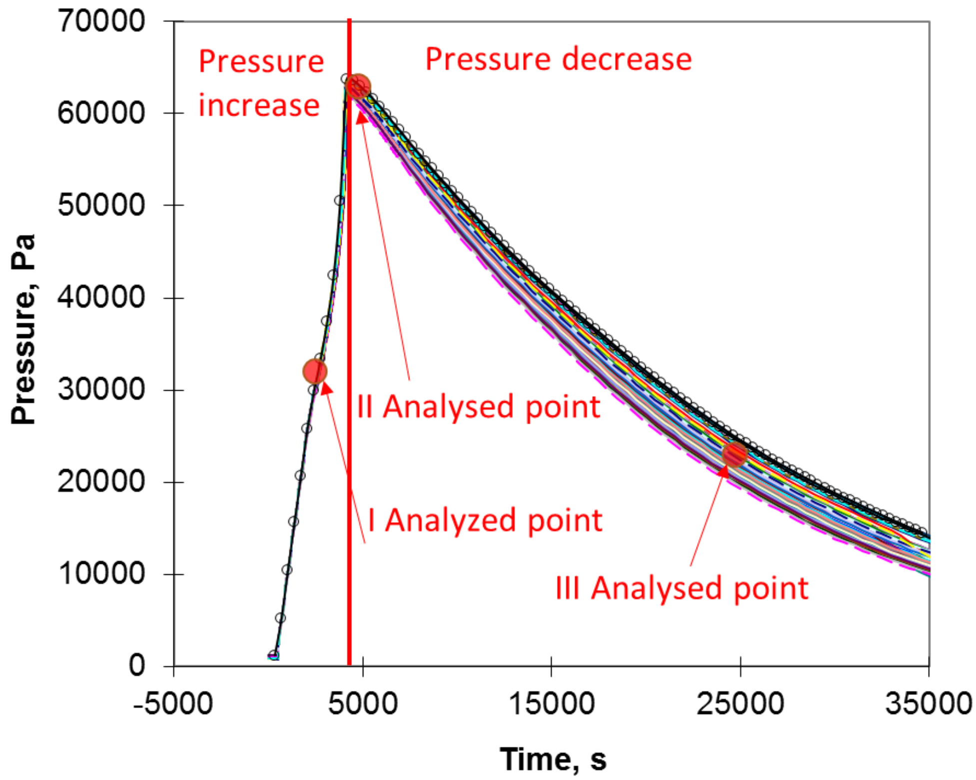
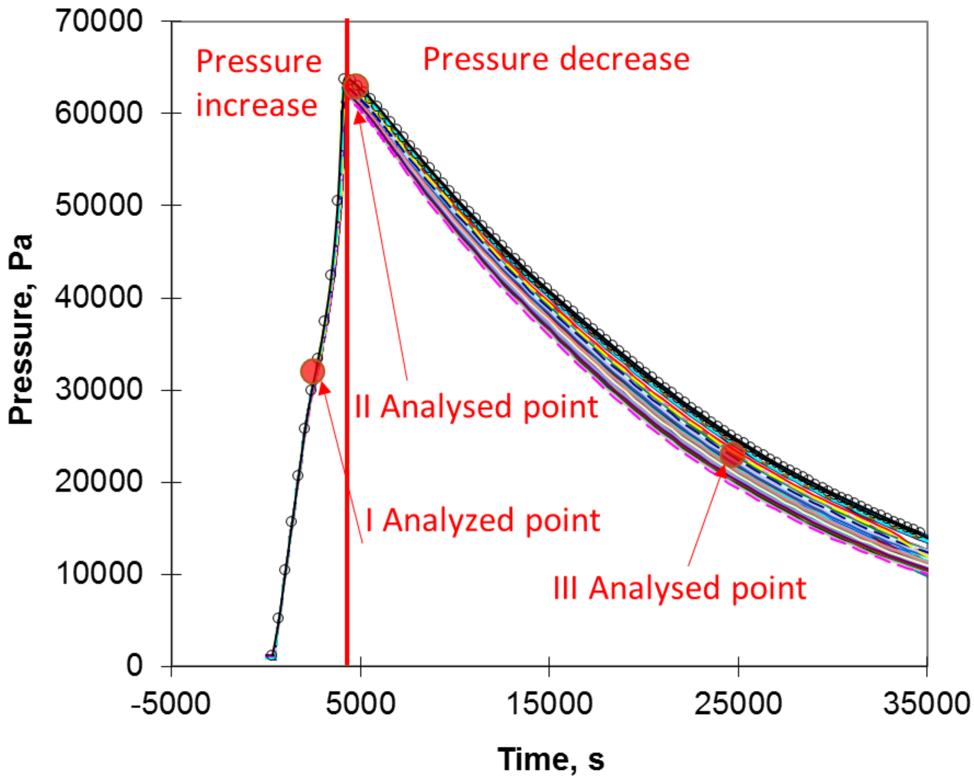


Figure 7). One point for the pressure increase part and two for the pressure decrease part. The first analysing point represents the pressure increase in VV, second – beginning of pressure decrease and third - continually pressure decrease in VV. Calculation results of the sensitivity analysis in those 3 points are presented in Figure 8 - Figure 10. It was decided to not analyse the parameters which influence the calculation results lower than 0.2.

In the first time interval of the calculations the pressure in the vacuum vessel is starting to increase due to water flashing and water evaporation due to the contact with hot surfaces of in-vessel components. It was decided to analyse the influence of parameters at the time moment 3100 s from the start of calculations - first analysing



point (

Figure 7). The parameters that have the biggest influence are presented in Figure 8. As it is shown in the figure, the highest influence on the calculation results at the fast pressure increase period has the characteristics of vacuum pump (maximal flow rate and efficiency dependence from the pressure – parameter No. 13). Likewise, in this first time interval of the calculation the initial pressure in VV (parameter No. 8) and signal actuation (time of the closing automatic valves and start the vacuum pump - parameter No. 3) have also considerable influence.

The second time interval of the calculations is when the pressure in VV starts to decrease. This pressure decrease is due to reduction of 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 analyse the influence of parameters at the time moment t=5000 s (second analysing point) (

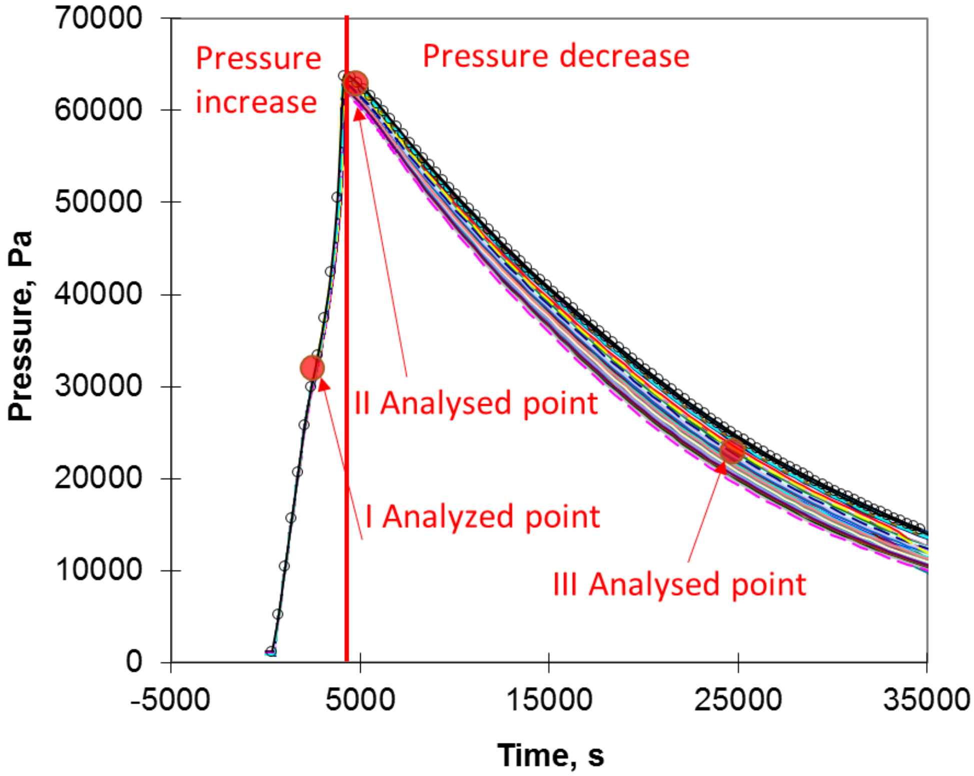


Figure 7). The parameters that have the biggest influence are presented in Figure 9. In this time interval of the calculations characteristics of vacuum pump have significant influence (parameters No. 12 and 13), but initial temperature inside the torus hall have the highest influence (parameter No. 10). This results reveal the influence of heat transfer process from the walls of the VV and in-vessel components to the torus hall. Temperature of the torus hall affect the temperature inside the VV despite the fact that heat transfer coefficient is low (~8 W/m^2K).

the third analysing point was chosen at the time moment t=25000 s (

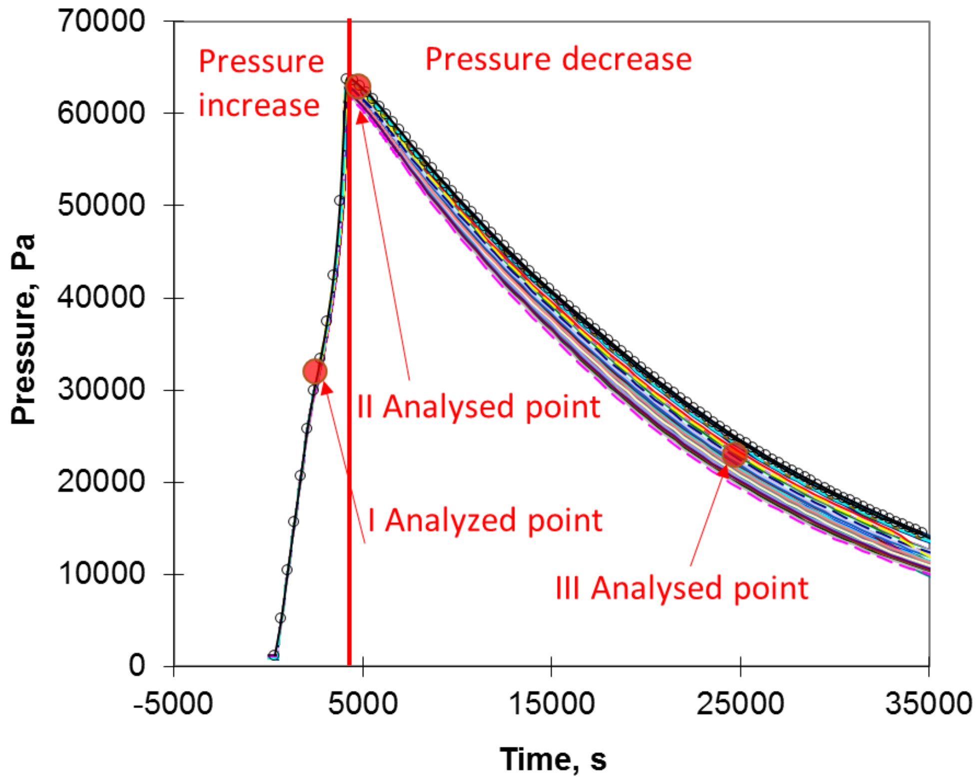


Figure 7). At this point the pressure in VV continually decreases. The reasons for this are the same as described above. The parameters that have the biggest influence are presented in Figure 10. The influence of the parameters are very similar, however the tendencies show that vacuum pump characteristics become more important and the initial temperature of the torus hall is less important.

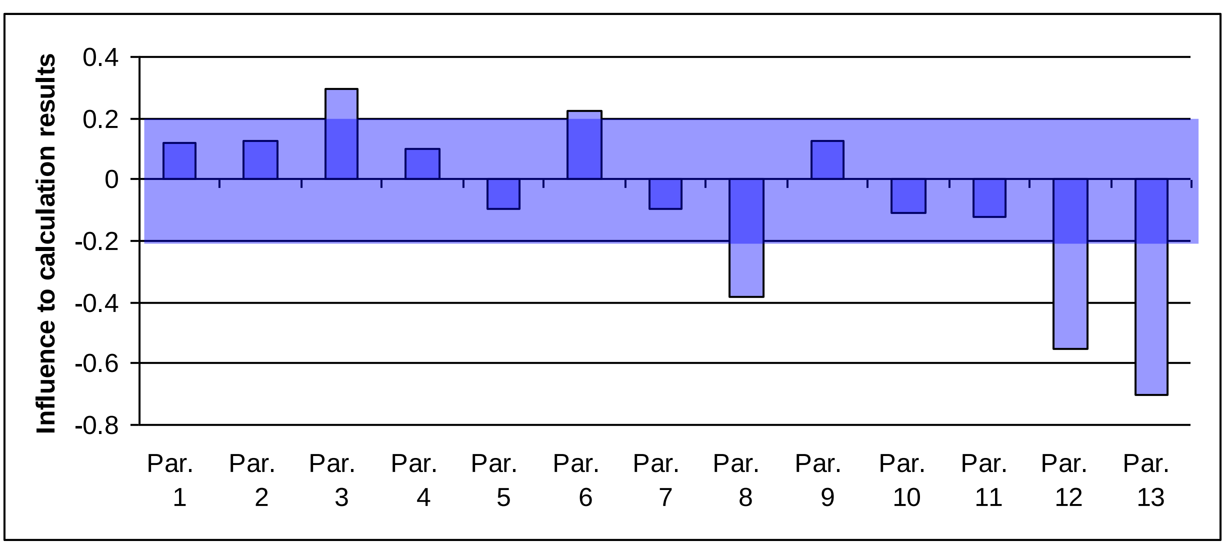


Figure 8. First analysing point. Pressure increase in VV. Influence of parameters.

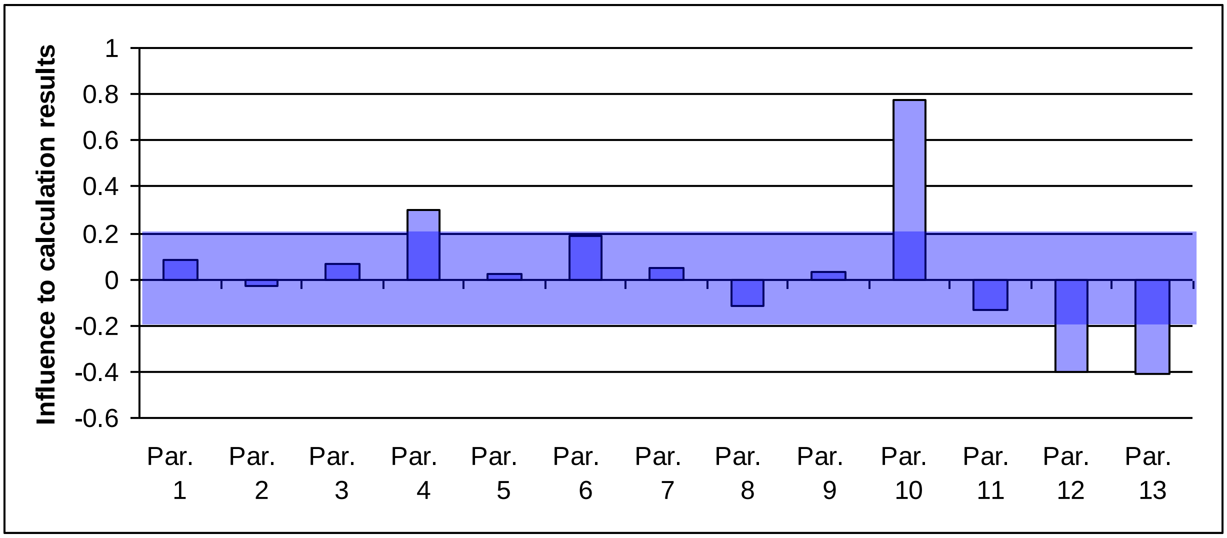


Figure 9. Second analysing point. Pressure decrease in VV. Influence of parameters.

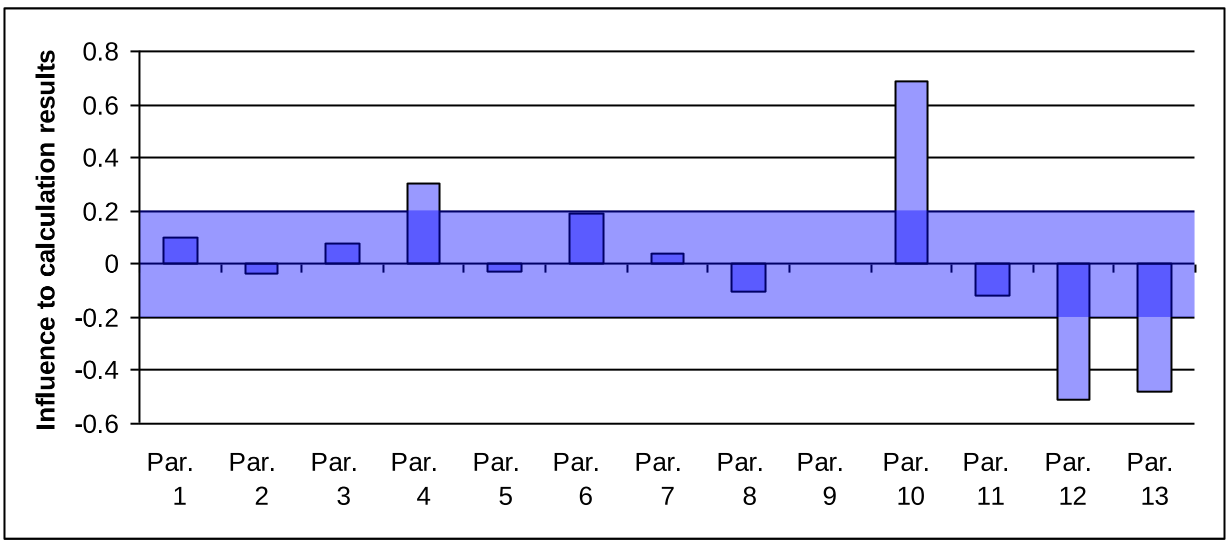


Figure 10. Third analysing point. Pressure continually decreases. Influence of parameters.

For the reliability of performed sensitivity analysis the value of coefficient of determination R^2 is very important. In statistics, the R^2 is used in the context of statistical models, which main purpose is the prediction of future outcomes on the basis of other related information. R^2 is calculated by this equation [24]:

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

where $\hat{y}_i$ is the estimation of variables y_i (where i = 1,…, n) calculated from the regression equation, $\bar{y}_i$ is the mean of the variables y_i, n is the 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 determination coefficient must be higher than 0.6. If R^2 value is less, then the results of sensitivity analysis may be incorrect, because of too many unexplained y variations.

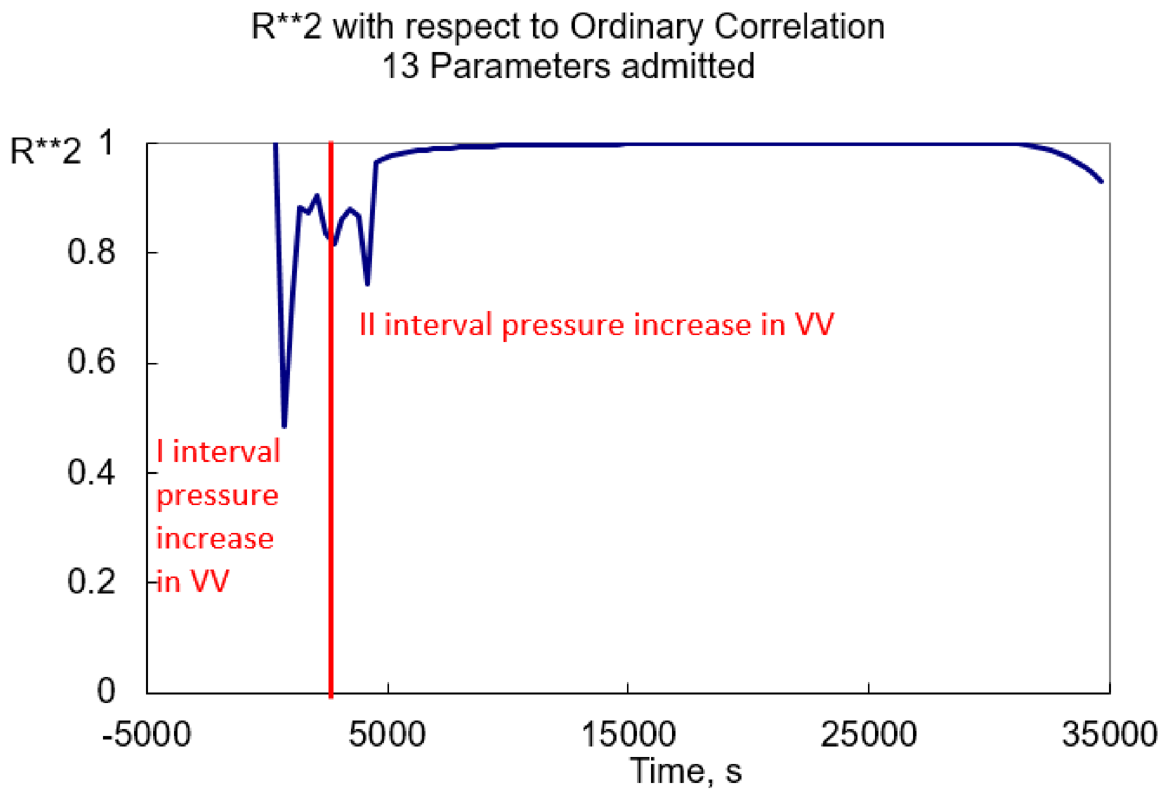


Figure 11. Determination coefficient of the sensitivity analysis.

The determination coefficient of this sensitivity and uncertainty analysis is presented in Figure 11. Determination coefficient is low (~0.5) within the first interval of calculation, when the water injection in VV starts. However, determination coefficient increases, during pressure increase in the VV (more than 0.8). Latter, (within the second interval of calculation) as it is presented in the figure, value of determination coefficient is close to 1 at the time when pressure in the vacuum vessel starts to continuously decrease.

4.3 Determination of Maximal allowed area of partial break

In this section the maximal area of the partial break, which could be compensated by vacuum pump is determined. For this analysis the maximal values of the pressure increase inside the VV is the most important. So it is enough to analyse only first interval of the calculations. According to the results of sensitivity analysis presented in Figure 8, the minimal or maximal values of parameters which have the highest influence to the calculation results (pressure increase inside the VV) were investigated. Values of these parameters are presented in Table 1 and indicated as grey cells. For other parameters, which influence the calculation results lower than 0.2, the basic values (presented in Table 1) were considered. Using these parameters values the input deck, which will calculate the maximal values of the pressure increase inside the VV, was developed. In order to determine the maximal possible value of break area, some calculations were performed. In each calculation, the area of the break of the cooling system pipe was increased. The behaviour of pressure inside the VV when the area of the pipe partial break area are 19, 22 and 23 mm^2 are presented in Figure 12. Burst disc opening pressure 110 kPa is declared. The results of performed calculations showed that the maximal break area, when the pressure in VV does not exceed 110 kPa, could be 22 mm^2. However, opening of the burst disc could also have uncertainties. Burst disc for W7-X facility is fabricated very precisely, especially taking into the account actuation pressure. Thus, it was decided that the maximum uncertainty (lower limit) of the burst disc activation pressure could be -3%. If this burst disc opening uncertainty is considered, then the maximal area of the break could be 19 mm^2.

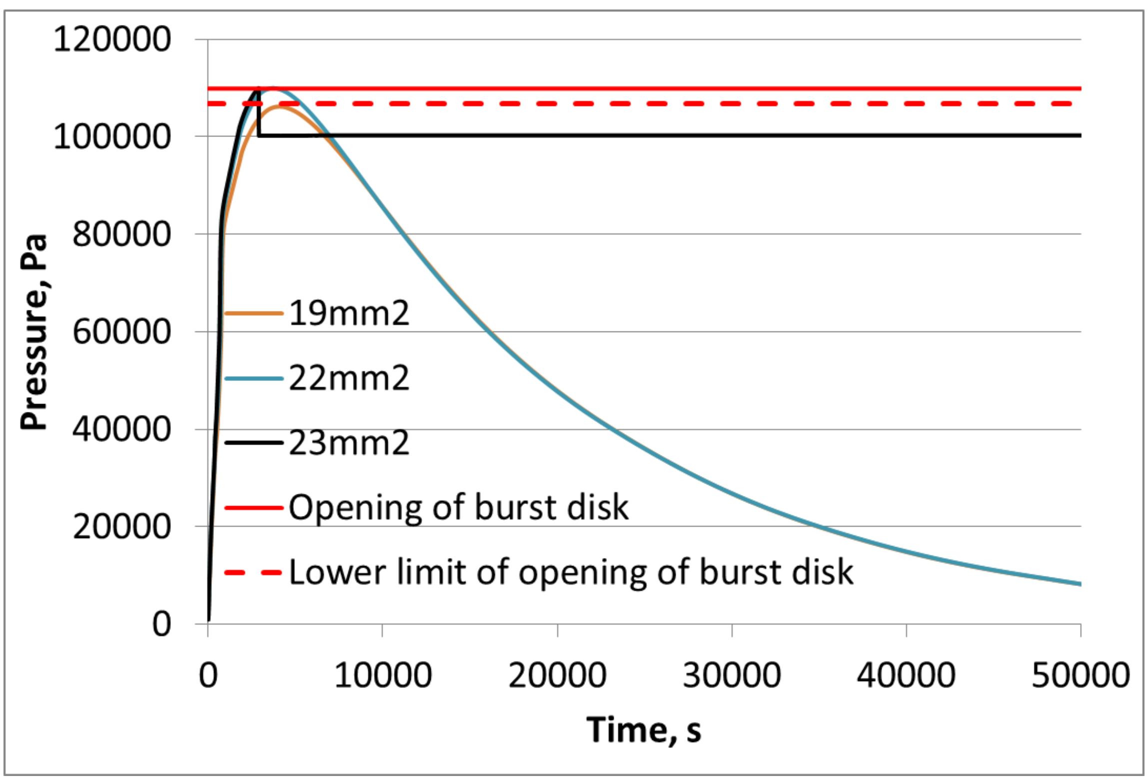


Figure 12. Calculation of maximal break area.

Summary and conclusions

In order to study the processes that occur in cooling systems of in-vessel components and vacuum vessels of nuclear fusion devices, the best estimate code RELAP5 was selected and numerical models were developed. For the validation of the models experimental data received from Ingress of Coolant Event experimental facility were used. The studies of the Ingress of Coolant Event experimental facility leads to the following main conclusions, which allow to use standard RELAP5 code:

- Because of RELAP5 limitation, the initial pressure in vacuum vessel model cannot be lower than 700 Pa. If the initial pressure in the experiment in the vacuum vessel is less than 700 Pa, the water steam inside the vacuum vessel model must be considered in the initial condition. Otherwise, if the initial pressure in real vacuum vessel is more than 700 Pa - non-condensed gas must be assumed in the model.
- Counter current flow of water and steam in the vertical direction and stratification of steam should be evaluated for the modelling of the vacuum vessels of nuclear fusion devices in the case of loss of coolant event.

Using the experience gained from the modelling of Ingress of Coolant Event experiments, the numerical model of W7 X experimental device was updated and possible consequences of water ingress were investigated.

- Calculation results using updated VV model is in better agreement with other authors in the case of guillotine 40 mm diameter cooling system pipe break analysis.
- The peak pressure inside VV is much lower using the updated W7-X vacuum vessel model than the value obtained by means of the old model in the case of the partial 1 mm^2 break of cooling system pipe.

The best estimate approach was applied for the updated VV model in order to determine the maximal allowed area of partial break. The results of pressure in VV calculations were divided in two time intervals taking into account the accruing phenomena in VV. In the first time interval, the pressure in the vacuum vessel increases due to water flashing and water evaporation due to the contact with hot surfaces of in-vessel components. In this time interval, the following factors have the biggest influence on the calculation results: characteristics of vacuum pump, initial pressure in VV and signal for circulation pumps stop and automatic valves closure. The second time interval of the calculations is when the pressure in VV starts to decrease due to the reduction of discharged water and flow rate increase through the vacuum pump. In this time interval the initial temperature inside the torus hall and characteristics of vacuum pump have the biggest influence on the calculation results. According to the results of sensitivity analysis, the values of input parameters, which enable to calculate the maximal values of the pressure increase inside the VV, were developed. The results of performed calculations showed that the maximal break area, at which the steam is not discharged from VV to the environment, could be 22 mm^2. However, if burst disc opening uncertainty is considered, then the maximal area of the break could be 19 mm^2.

The results of LOCA 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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ACKNOWLEDGEMENT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014 - 2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.