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ANALYSIS OF PRESSURIZED THERMAL SHOCKS FOR INLET NOZZLE OF VVER REACTOR PRESSURE VESSEL

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ABSTRACT

Rector pressure vessel (RPV) is a key component of all pressurised water reactor (PWR) or water-cooled water-moderated energy reactor (VVER) nuclear power plants (NPPs). Assuring its integrity is therefore of high importance. The RPV can undergo severe loading during potential events of type of pressurised thermal shock (PTS), possibly occurring in the NPP. PTS is characterised by rapid cool-down of the reactor coolant and (usually) by high pressure. Conventionally, PTS analyses are performed for the most embrittled part of RPV close to the reactor core. Additionally to this location, assessment of the RPV inlet nozzle should be performed, as this location is most loaded. Stress concentrator appears in the bottom part of the nozzle ("nozzle corner"), and, moreover, this region is the coldest one in the RPV.

Due to complicated mixing of cold water injected into the main circulating piping cold leg by the emergency core cooling system (ECCS) with the coolant flowing in the cold leg, computational fluid dynamics (CFD) type code FLUENT was used for detailed thermal hydraulic mixing calculations. Results from mixing calculations were transferred to finite element model of RPV with crack postulated in the nozzle corner and temperature and stress fields were calculated by SYSTUS code. Finally, the fracture mechanic assessment was performed and the maximum allowable critical temperature of brittleness was established. Description of methodology, models and examples of results for PTS assessment of inlet nozzle for both VVER 440 and VVER 1000 RPVs will be presented in the paper.

INTRODUCTION

For the assessment of pressurised thermal shock for the region of RPV inlet nozzle, sequence of different types of analyses was performed. The sequence started with system thermal hydraulic calculations by RELAP5 code modelling the whole reactor, primary circuit, secondary circuit, emergency core cooling systems and some auxiliary systems (not discussed in this paper). The results from system thermal hydraulic calculations served as input data for detailed computational fluid dynamics (CFD) analyses of mixing in cold legs of main circulating piping and in the reactor downcomer. These simulations were performed by the commercial CFD code Ansys FLUENT 13. Results from the FLUENT calculations (temperatures of inner surface of RPV wall) were used as boundary conditions for determining of the temperature field in the RPV wall by FEM code SYSTUS. The resulting temperature fields (together with mechanical load due to coolant pressure - determined by results of RELAP5 analyses) served as loads for mechanical problem, solved again by SYSTUS FEM code. For the final fracture mechanics assessment , the SYSTUS code postprocerssing module was used to establish the fracture mechanics parameter energy release rate G.

COMPUTATIONAL FLUID DYNAMICS CALCULATIONS

Models for CFD program FLUENT

Models of VVER-440 and VVER-1000 reactors for CFD simulation of PTS transients were created in the Ansys Gambit code environment. Computational grid for the VVER-440 case is shown in Figure 1.

Computational domain contains flow channels and solid walls of the following zones: cold legs of all 6 circulating loops, reactor downcomer and lower plenum. Models of cold legs with ECCS injections include loop seal and a simplified reactor coolant pump (RCP). Models of cold legs without ECCS injections begin at the RCP outlet. Downcomer model includes 2 ECCS injections, 3 flow separators next to the ECCS injection nozzles and 8 spacers. Perforated elliptical bottom of core barrel is modelled with porous medium.

Solution domain inlets are placed at the exits from steam generators (for cold legs with ECCS injection), at the exits from RCPs (cold legs without ECCS injection) and at the ECCS injections nozzles. Solution domain outlet is placed on the lower horizontal perforated plate inside the core barrel. Transient boundary conditions for all inlets and for outlet are taken from the RELAP5 calculation. Turbulence of the coolant is modelled by the realizable k-epsilon model. Computational domain is split into 1,400,000 fluid cells and 695,000 solid cells. Cells in boundary layers are refined, wall-adjacent fluid cells are 1 mm thin.

Figure 1. CFD model of part of the VVER-440 RPV and primary circuit.

Computational grid for the VVER-1000 case is shown in Figure 2. It is created in the same way as the VVER-440 model. Computational domain is split into 1,250,000 fluid cells and 535,000 solid cells.

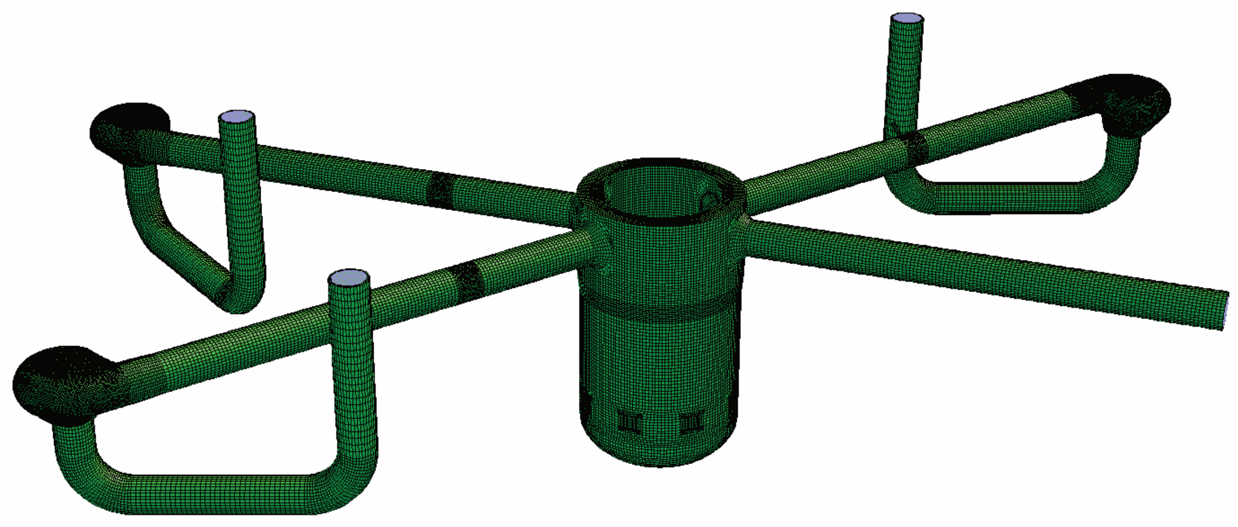

Figure 2. CFD model of part of the VVER-1000 RPV and primary circuit.

Examples of Results

Nine PTS-relevant scenarios were simulated in FLUENT code using the models described in the previous section. The calculations were run on Linux cluster using 16-32 cores. Each calculation took 3-4 weeks to be completed. Results from one VVER-440 scenario and from one VVER-1000 scenario are briefly described in this section.

Figures 3 and 4 present results from simulation of the LOCA H30z scenario in VVER-440 reactor. In this scenario, there is a leak of the equivalent diameter 30 mm from the hot leg and reactor is at hot zero power. All three high pressure ECCS injections (on loops 2, 3 and 5) are in operation.

Figure 3 displays temporal evolution of maximum and minimum temperatures of wetted surfaces in the RPV inlet nozzle 3 and on the RPV weld 5/6 in the downcomer. The weld 5/6 is located next to the reactor core, 3.735 m below axes of the cold legs. Note the large temperature difference in the RPV inlet nozzle which is caused by thermal stratification in the uppermost part of the downcomer (see Figure 4). This temperature difference rapidly decreases after flow reversal in the loop 3 at approx. 2300 s. Temperature of water injected from the ECCS into the cold leg 3 decreases from 55 °C to 20 °C at approx. 2600 s when all water from the heated tank is spent. This causes the decrease of minimum temperature in the RPV inlet nozzle. ECCS injection into the cold leg 3 stops at about 2900 s and the minimum temperature in the RPV inlet nozzle increases. All ECCS injections are stopped at about 3100 s.

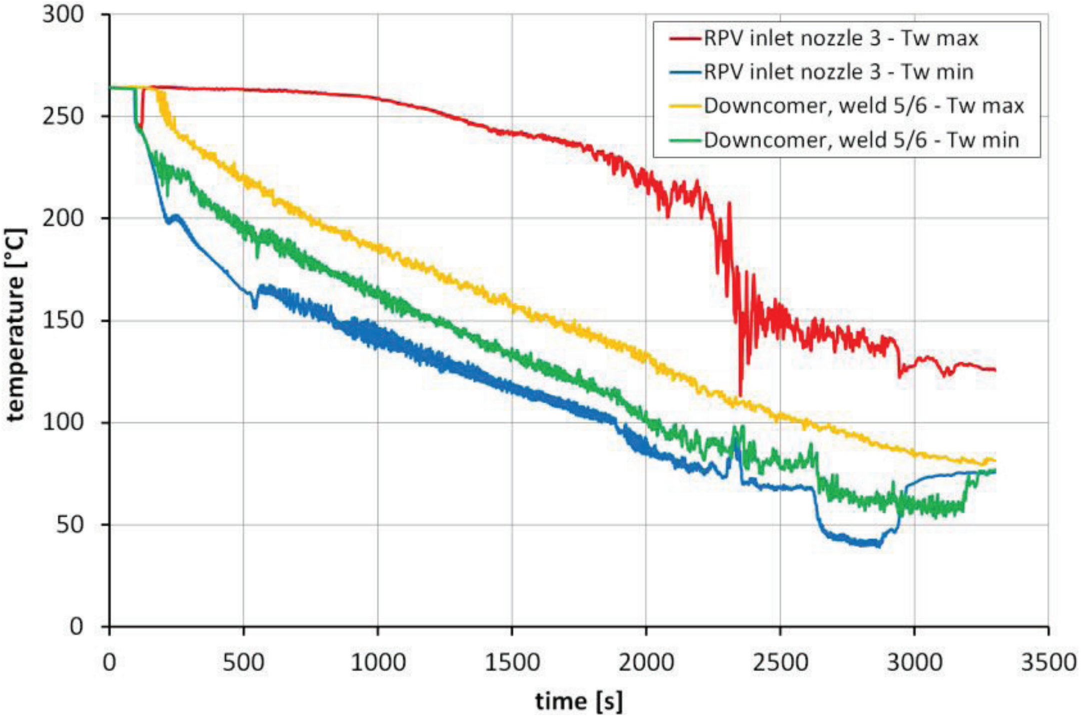

Figure 3. VVER-440, LOCA H30z scenario. Temperature of the wetted surface calculated by FLUENT: maximum and minimum temperature in the RPV inlet nozzle 3 and on the RPV weld 5/6.

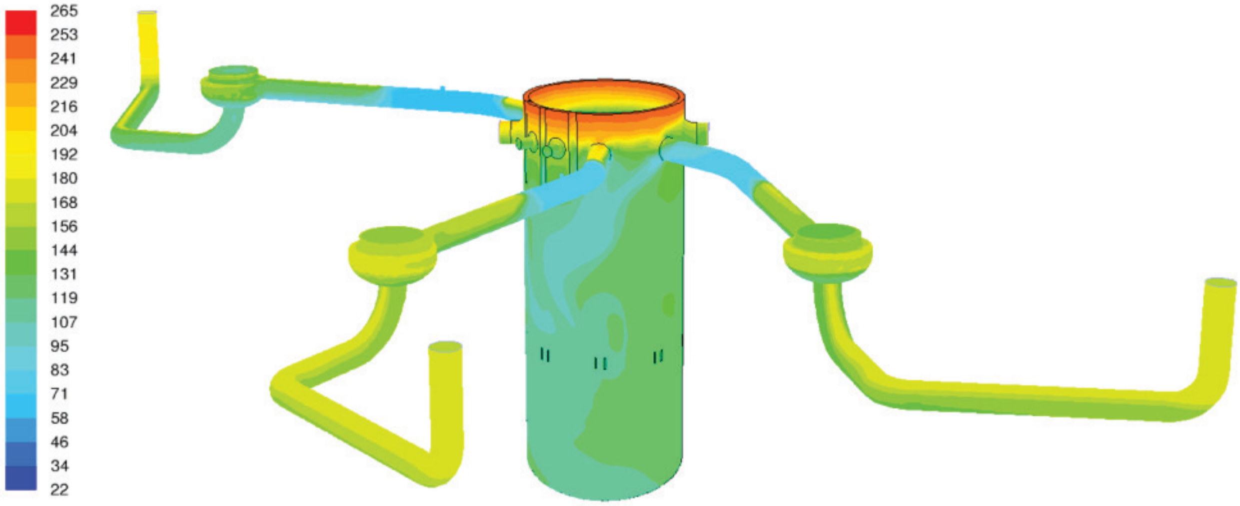

Figure 4. VVER-440, LOCA H30z scenario. Distribution of the temperature [°C] of the wetted surface calculated by FLUENT, time 2000 s.

Figures 5 and 6 present results from simulation of the PRISE 3SGT scenario in VVER-1000 reactor. In this scenario, full rupture of 3 tubes in steam generator No.1 occurs. Only one high pressure ECCS injection is in operation - on cold leg 1. Initial reactor power is at 1% of its nominal power. At 0 s, there is a loss of offsite power.

Figure 5 displays temporal evolution of maximum and minimum temperatures of wetted surfaces in the RPV inlet nozzle 1 and on the RPV weld 4 in the downcomer. The weld 4 is located next to the reactor core, 2.2 m below axes of the cold legs. At about 5200 s, mass flow rate from RCP in cold leg 1 increases. At 5500 s, flow in cold leg 1 reverses. Hot water from the uppermost part of the downcomer enters the RPV inlet nozzle. This results in increase of temperatures in the RPV inlet nozzle and also on the RPV weld 4.

Figure 5 also presents a comparison of temperatures on RPV weld 4 calculated with FLUENT code and corresponding temperatures in RELAP5 code. Temperature outside of the cold plume is very similar in both codes. On the other hand, minimum surface temperature on RPV weld 4 in FLUENT code is lower than in RELAP5 code because computational grid in the system code RELAP5 is too coarse to capture the cold plume. That is why CFD code is necessary for simulation of mixing during PTS transients. Cold plume in CFD simulation can be seen in Figure 6.

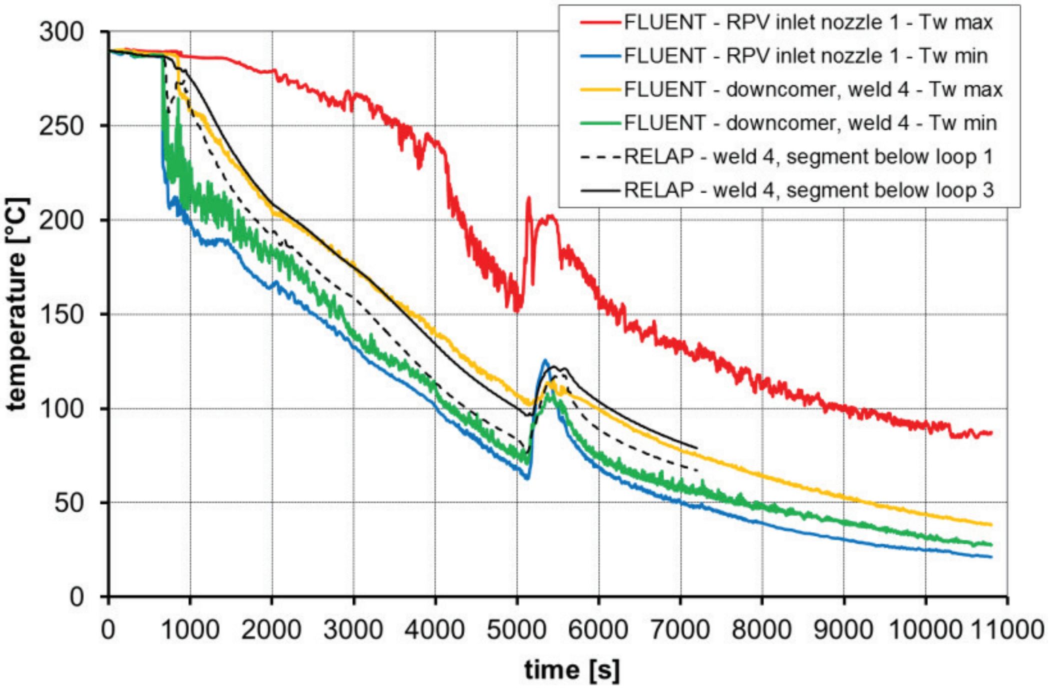

Figure 5. VVER-1000, PRISE 3SGT scenario. Calculated temperatures of wetted surfaces: maximum and minimum temperature in the RPV inlet nozzle 1 and on the RPV weld 4. Temperatures on weld 4 are compared with corresponding temperatures calculated by RELAP5 code.

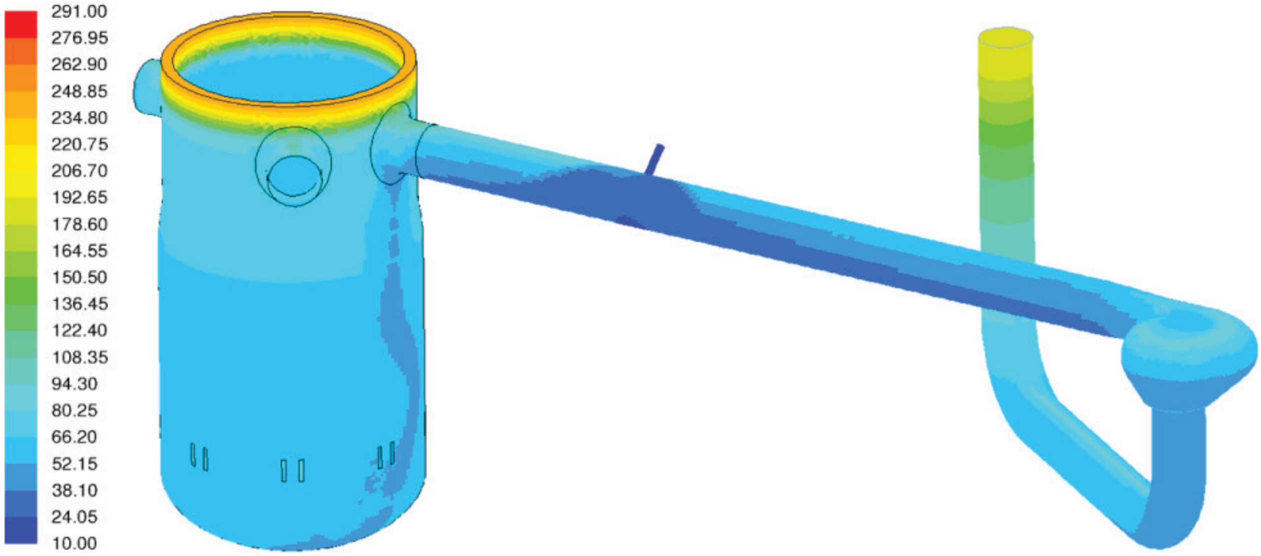

Figure 6. VVER-1000, PRISE 3SGT scenario. Distribution of the temperature [°C] of the wetted surface calculated by FLUENT, time 8000 s. Only cold leg of loop 1 is included in the simulation.

TEMPERATURE AND STRESS FIELDS CALCULATIONS

Set of finite element models was created for the purpose of temperature and stress fields calculations. The mesh generator ANSA was used for creation of the meshes. Isoparametric 20-node hexahedrons and 15-node pentahedrons were used. The vertical section of RPV from the flange to the cylindrical part including 2 layers of main circulating pipes (MCP) nozzles (top layer - outlet, bottom layer - inlet) was modelled. Symmetrical 1/4 of the RPV circumference was modelled. Due to different layout of VVER 440 and VVER 1000 MCPs, different number of nozzles in one layer was modelled, namely one full and one (symmetrical) half nozzle for VVER 440 (which is 6 loop NPP) and one full nozzle for VVER 1000 (which is 4 loop NPP). Postulated cracks were included into the meshes. The postulated cracks were located in the inlet (i.e. lower) nozzle in its bottom part ("nozzle corner", or "6 o'clock position"), where is significant stress concentrator due to the pressure load and also the coldest position due to cold plume in the bottom part of the MCP (caused by ECCS injection). The crack was postulated in accordance with the applied standard VERLIFE (2008) as semielliptical, underclad (partially penetrating 1 mm into the cladding), with depth $a = 22$ mm + 1 mm (VVER 440) or $a = 20$ mm + 1 mm (VVER 1000) and with two different aspect ratios $a/c = 0{,}3$ and $a/c = 0{,}7$. Examples of FEM meshes are presented in Figures 7 - 10.

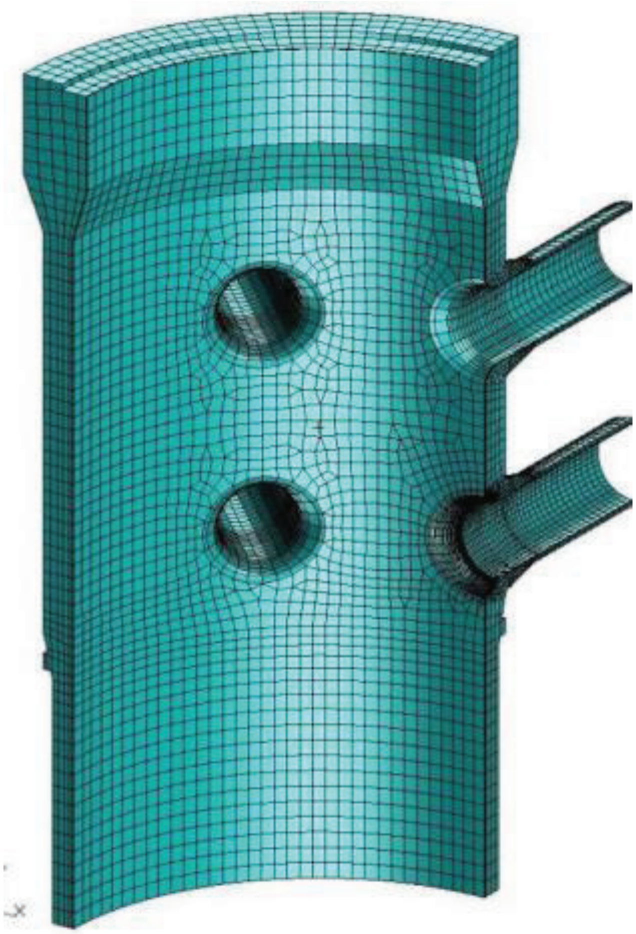

Fig. 7 FEM mesh of VVER 440 RPV

Fig. 8 FEM mesh of VVER 1000 RPV

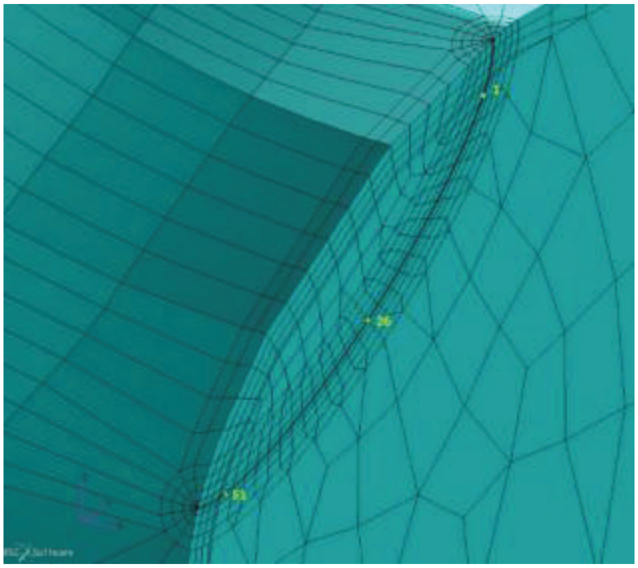

Fig. 9. FEM mesh, VVER 440 RPV, *a/c* = 0,3, detail

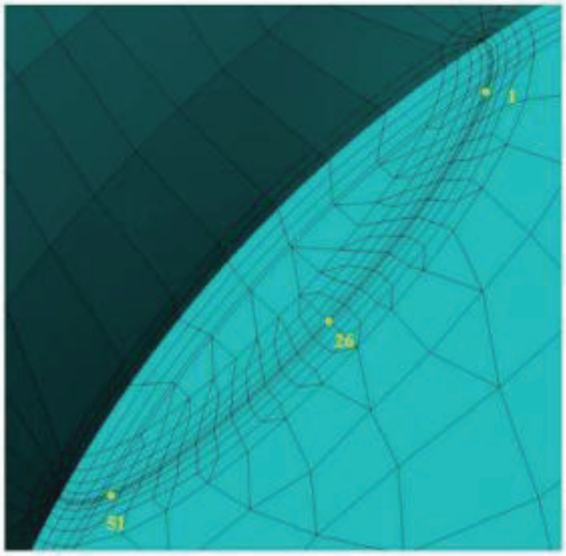

Fig. 10 FEM mesh, VVER1000 RPV, *a/c* = 0,3, detail

The heat transfer and mechanical problems were solved by FEM code SYSTUS. Specific software tool was developed for transferring data (inner surface temperatures of RPV wall) from the CFD code FLUENT results to SYSTUS FEM code model (using interpolations). The heat transfer problem was solved as transient nonlinear (thermal-physical properties dependent on temperature) with 1st type boundary condition on inner surface (prescribed temperature of the surface) and zero heat transfer at symmetry planes and at outer surface. The mechanical problem was solved as transient elastic-plastic loaded by nonuniform temperature fields (calculated in the previous step) and by inner pressure. Examples of resulting temperature and stress fields for model of RPV VVER 1000 are given in Figures 11 - 12.

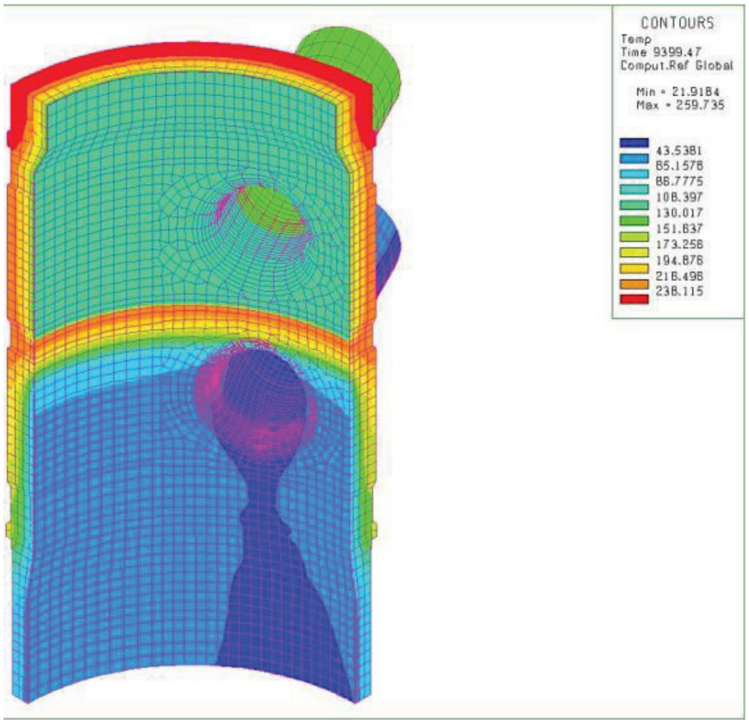

Figure 11. VVER 1000, PRISE 3SGT, temperature field in time 9400 s.

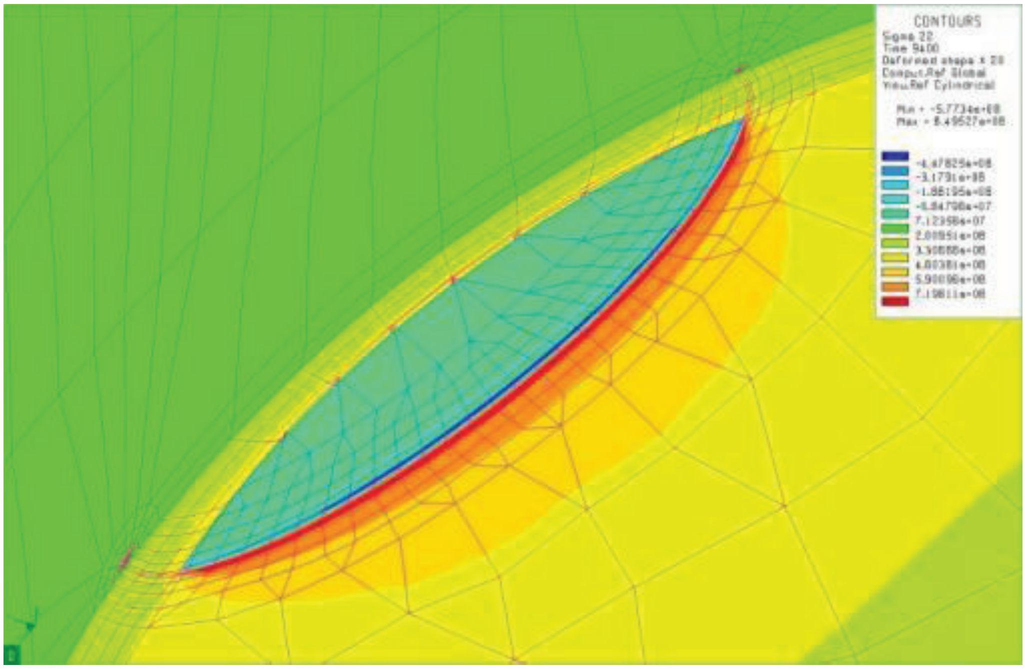

Figure 12. VVER 1000, PRISE 3SGT, stress field in crack region in time 9400 s (crack opening stress).

FRACTURE MECHANICS ASSESSMENT

Using the postprocessor of SYSTUS code, the energy release rate G was calculated for all nodes in the semielliptical part of crack front lying in the RPV base material. The energy release rate G was then converted to stress intensity factor K_I. For the final fracture mechanics assessment the following condition was used

$$K_I \leq [K_{IC}]_3 \tag{1}$$

where the allowable value of stress intensity factor $[K_{IC}]_3$ is given by the formula from the VERLIFE (2008) standard

$$[K_{IC}]_3 = \min\{26 + 36 \cdot \exp[0{,}02 \cdot (T - T_k)]; 200\} \ \mathrm{MPa \cdot m^{1/2}} \tag{2}$$

where T is temperature and T_k is the critical temperature of brittleness.
From the equality reached in the condition (1), the maximum allowable critical temperature of brittleness T_k^a was established for all nodes on the crack front, and the minimum of them was taken as the final T_k^a value. In some cases the less conservative warm prestressing approach (WPS) was used. In this case, the condition (1) was assessed only until 90% of the latest local maximum value of K_I. Resulting diagrams of dependence of K_I and $[K_{IC}]_3$ on temperature are presented for selected example of PTS scenarios in Figures 13 - 14.

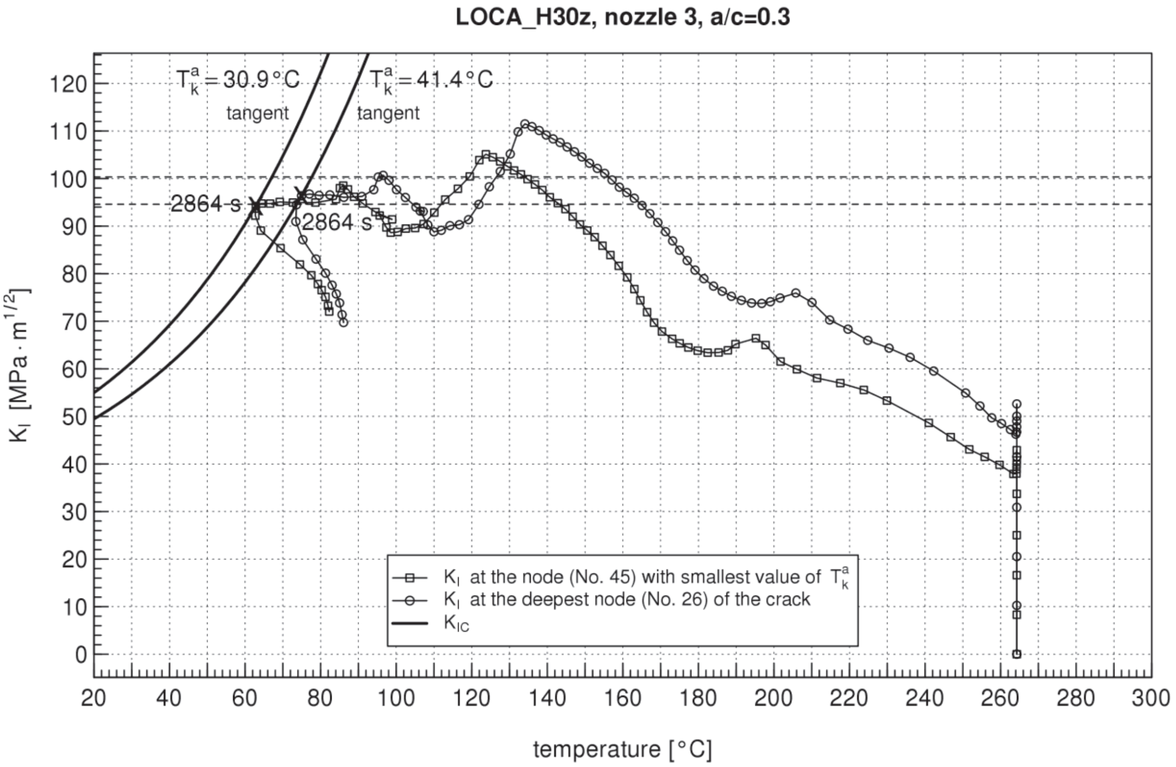

Figure 13. VVER 440, LOCA H30z, crack a/c = 0,3, dependency of K_I and $[K_{IC}]_3$ on temperature

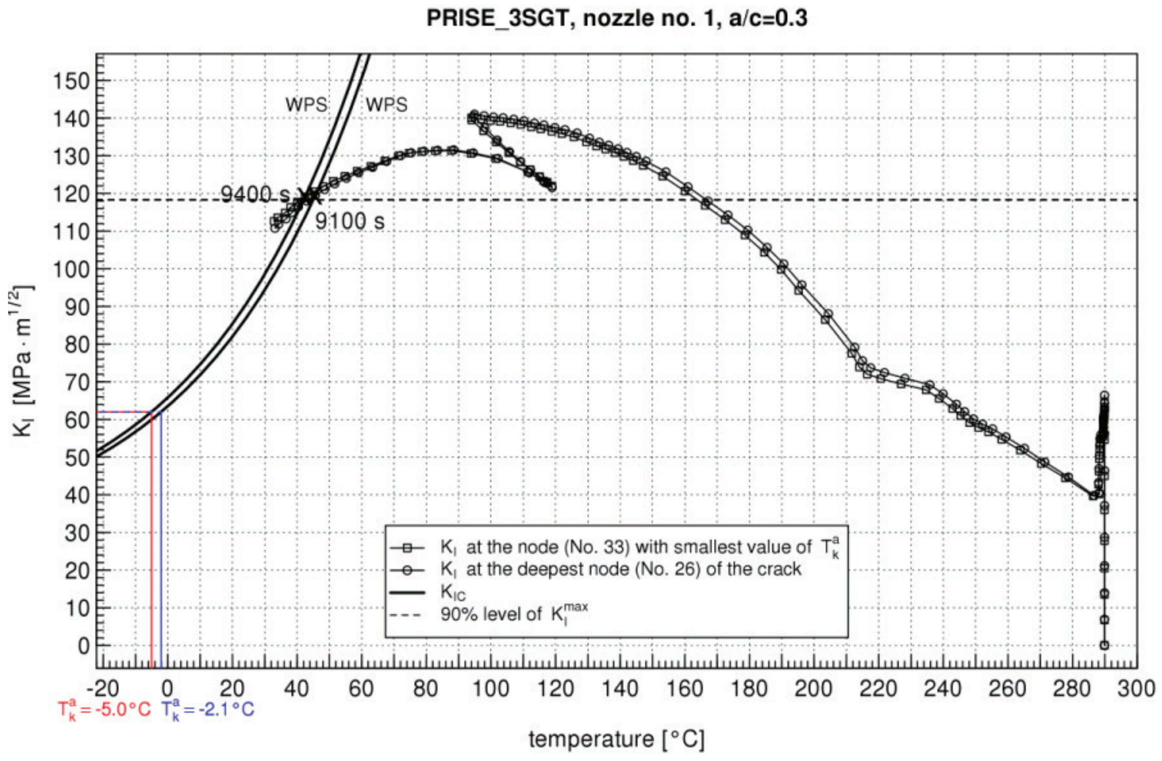

Figure 14. VVER 1000, PRISE 3SGT, crack a/c = 0,3, dependency of K_I and $[K_{IC}]_3$ on temperature

CONCLUSION

The RPV can undergo severe loading during potential events of type of pressurised thermal shock (PTS), possibly occurring in the NPP. Additionally to the commonly assessed RPV beltline zone (which is highly embrittled), PTS assessment of the RPV inlet nozzle was performed, as this location is most loaded. Detailed thermal hydraulic mixing analyses were performed by CFD code FLUENT. The CFD model contained the MCP cold legs, the reactor downcomer and bottom part of the RPV up to inlet to reactor core. Subsequently, temperature and stress fields were calculated by FEM code SYSTUS. The final fracture mechanics assessment was performed for cracks postulated in the "nozzle corner" by comparing the stress intensity factor with its allowable value. Maximum allowable critical temperature of brittleness was finally established. This value has to be larger than the current (or predicted for the RPV end-of-life) value of the critical temperature of brittleness. Examples of results for selected PTS transients for both VVER 440 and VVER 1000 RPVs were given.

REFERENCES

Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs “VERLIFE”, (2008). 6th Framework Programme of EU, Project COVERS, Contract N° 12727 (FI60), report COVERS-WP4-D4.10