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

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ABSTRACT

Reactor pressure vessel (RPV) is a key component of PWR and VVER nuclear power plants (NPPs), assuring its integrity is therefore of high importance. Pressurized thermal shock (PTS) is potentially the most dangerous emergency event for the RPV. PTS is characterized by a rapid cool-down of the reactor coolant usually accompanied with high pressure. Resistance of RPV against brittle fracture shall therefore be assessed for PTS regimes.

Usually, PTS analyses are performed for the most embrittled part of RPV near the reactor core (beltline zone). In addition, assessment of the RPV inlet nozzle is often performed, as this location belongs to the most loaded ones. The paper describes PTS assessment of another VVER RPV zone – the emergency core cooling system (ECCS) nozzle. As with the RPV inlet nozzle, there is a significant stress concentrator in the ECCS nozzle. Moreover, if the ECCS injection starts, the nozzle is loaded by practically instantaneous temperature drop. To prevent the thermal shock, the ECCS nozzle is equipped with a thermal sleeve, but its real effect in favour of PTS mitigation was not assessed in detail before. Moreover, due to presence of the thermal sleeve, it is impossible to perform the ultrasonic non-destructive testing (NDT) of the nozzle from the inner RPV surface, in consequence of which a large crack in the nozzle has to be postulated.

Large-break Loss-of-Coolant-Accident (LB LOCA) and medium-break LOCA events are the only PTS regimes leading to the ECCS injection through the ECCS nozzle, either from accumulator tanks or from low pressure ECCS. System thermal-hydraulic (TH) calculations of several LB LOCA events were performed using RELAP5 code. As the gap between the ECCS nozzle and its thermal sleeve cannot be modelled by RELAP5 code, a simplified approach was applied for modelling of the heat transfer through the gap.

Results from system TH calculations were transferred to the 3D finite element model of RPV with a crack postulated in the ECCS nozzle. The postulated crack was located in the bottom part of the nozzle. The depth of the crack was postulated as one quarter of the nominal wall thickness. The crack was postulated as a surface-breaking crack due to absence of NDT. Temperature and stress fields in the RPV were calculated by SYSTUS code.

Using the postprocessor of the SYSTUS code, the energy release rate G was calculated for all nodes in the semi-elliptical part of the crack front lying in the RPV base material. The energy release is then converted to stress intensity factor K_I. Finally, the maximum allowable critical temperature of brittleness T_k^a was established based on comparison of the stress intensity factor K_I with its allowable value $[K_{IC}]_3$ using formula taken from the standard. Warm prestressing approach (WPS) was also considered in the assessment.

The description of both the methodology and models, as well as examples of the results for the PTS assessment of the ECCS nozzle for VVER 440 RPVs are presented in the paper.

INTRODUCTION

Reactor pressure vessels of both VVER 440 and VVER 1000 reactors are equipped with specific ECCS nozzles for injecting the boric acid solution directly into the RPV. The nozzles serve for injection of the passive ECCS, i.e., from accumulator-tanks. There are four accumulator tanks, two of them inject during the emergency event the boric acid solution into the region above the reactor core (using the ECCS nozzles in upper nozzle ring of RPV) and two of them inject below the reactor core (using the ECCS nozzles in lower nozzle ring of RPV). The RPV ECCS nozzles are also connected to the low pressure ECCS. The layout of ECCS nozzles in VVER 440 and VVER 1000 is different, in VVER 440 the 2 nozzles are close to each other, while in VVER 1000 they are located on the opposite side of the RPV circumference. As the passive and low pressure ECCSs are operating only in the case of large-break (or medium-break) Loss-of-Coolant-Accident events, when the pressure in the RPV is relatively low, only for these PTS regimes the integrity of ECCS nozzle needs to be assessed.

For the PTS assessment of the region of RPV ECCS nozzle, a sequence of different types of analyses was performed. The sequence started with system thermal hydraulic calculations by RELAP5 code. Results from the RELAP5 calculations (temperatures of the inner surface of the RPV wall) were used as boundary conditions for determination of the temperature field in the RPV wall by the 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 a mechanical problem, solved again by SYSTUS FEM code.

For the final fracture mechanics assessment, the SYSTUS code postprocessing module was used to establish the fracture mechanics parameter energy release rate G. The analyses were performed for both VVER 440 and VVER 1000 RPVs, but the paper is focussed only on VVER 440.

THERMAL HYDRAULIC ANALYSES

The system TH analyses were performed for LOCAs with equivalent diameter of the leak 2x500 mm and 200 mm. The system TH codes RELAP5/MOD3.3 and RELAP5-3D were used. The whole reactor, primary circuit, secondary circuit, emergency core cooling systems and some auxiliary systems were modelled. There is no temperature stratification in the ECCS piping (including the RPV ECCS nozzle) during the injection, therefore there is no need for specific thermal hydraulic mixing analysis. Moreover, during the assessed LB LOCA events, two-phase flow occurs in the reactor downcomer, which practically cannot be analysed by current commercial CFD codes.

Time variation of pressure in RPV for three analysed transients in VVER 440 are shown in Figure 1. Time variation of coolant temperature in lower ECCS nozzle and time variation of RPV wall temperature in downcomer in the vicinity of one lower ECCS nozzle are shown in Figures 2 and 3, respectively. It can be seen that inside the nozzle the temperature drops abruptly (practically in one step), while in its vicinity in the reactor downcomer the drop is smaller and temporarily interrupted.

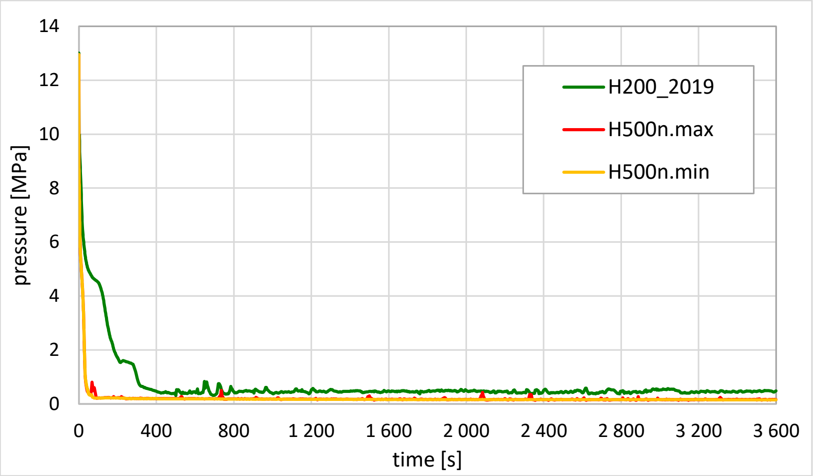

Figure 1. Time variation of pressure in VVER 440 reactor downcomer (3 variants of LOCA).

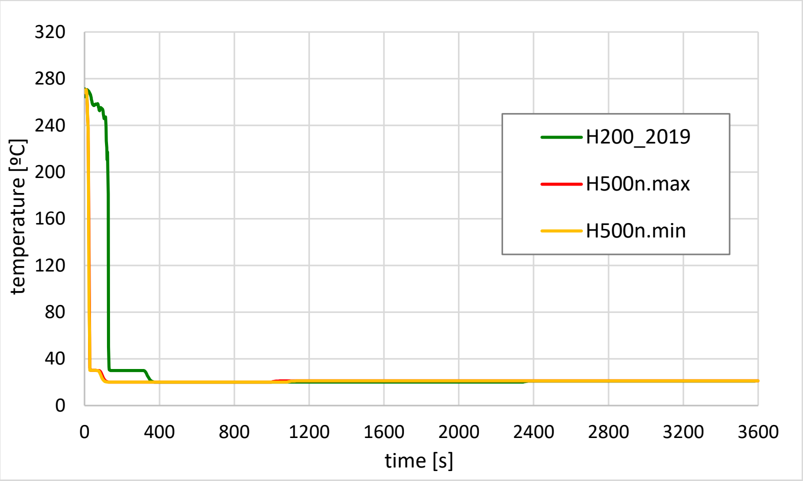

Figure 2. Time variation of coolant temperature in VVER 440 lower ECCS nozzle (3 variants of LOCA).

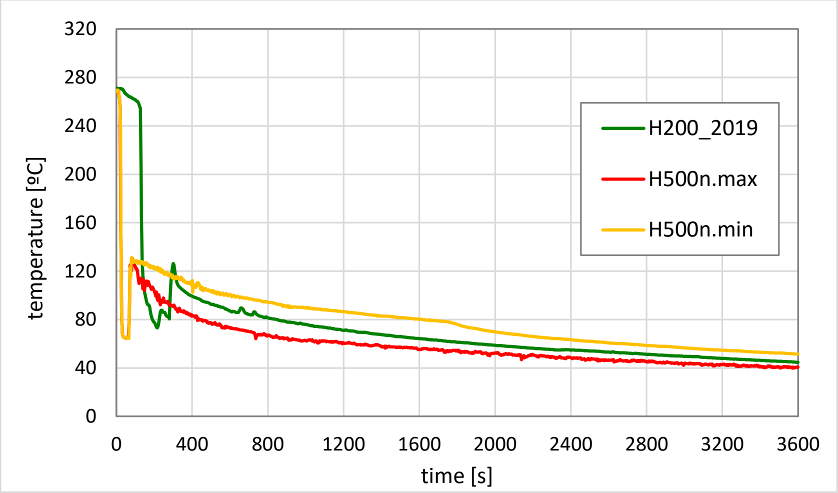

Figure 3. Time variation of wall temperature in the vicinity of lower ECCS nozzle (3 variants of LOCA).

TEMPERATURE AND STRESS FIELDS CALCULATIONS

FEM model

Two finite element models were created for the purpose of temperature and stress fields calculation. 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 two layers of nozzles (main circulating pipes (MCP) nozzles, as well as ECCS nozzles) was modelled. Symmetrical quarter of the RPV circumference was modelled, including one full and one (symmetrical) half of MCP nozzle and one ECCS nozzle in each layer. Postulated crack was included into each mesh. The postulated crack was located in the lower ECCS nozzle in one case and in the upper ECCS nozzle in the other case. The crack was modelled in the bottom part of the nozzle ("nozzle corner", or "six o'clock position"), where there is a significant stress concentrator due to the pressure load. The crack was postulated in accordance with the applied standard NTD AME (2020). Due to the presence of the thermal sleeve in the ECCS nozzle, it is impossible to use the ultrasonic non-destructive testing of the nozzle from the inner RPV surface, and thus large surface breaking crack has to be postulated in the nozzle. The crack was postulated as semi-elliptical with the depth equal to one quarter of the nominal wall thickness of the nozzle ring, i.e. a = 54.75 mm, and with aspect ratio a/c = 0.3.

The sketch of VVER 440 ECCS nozzle with the postulated cracks is seen in Figure 4. The full FEM mesh is presented in Figure 5. Detail of the FEM mesh in the nozzle region including the crack and the gap filled by water is presented in Figure 6.

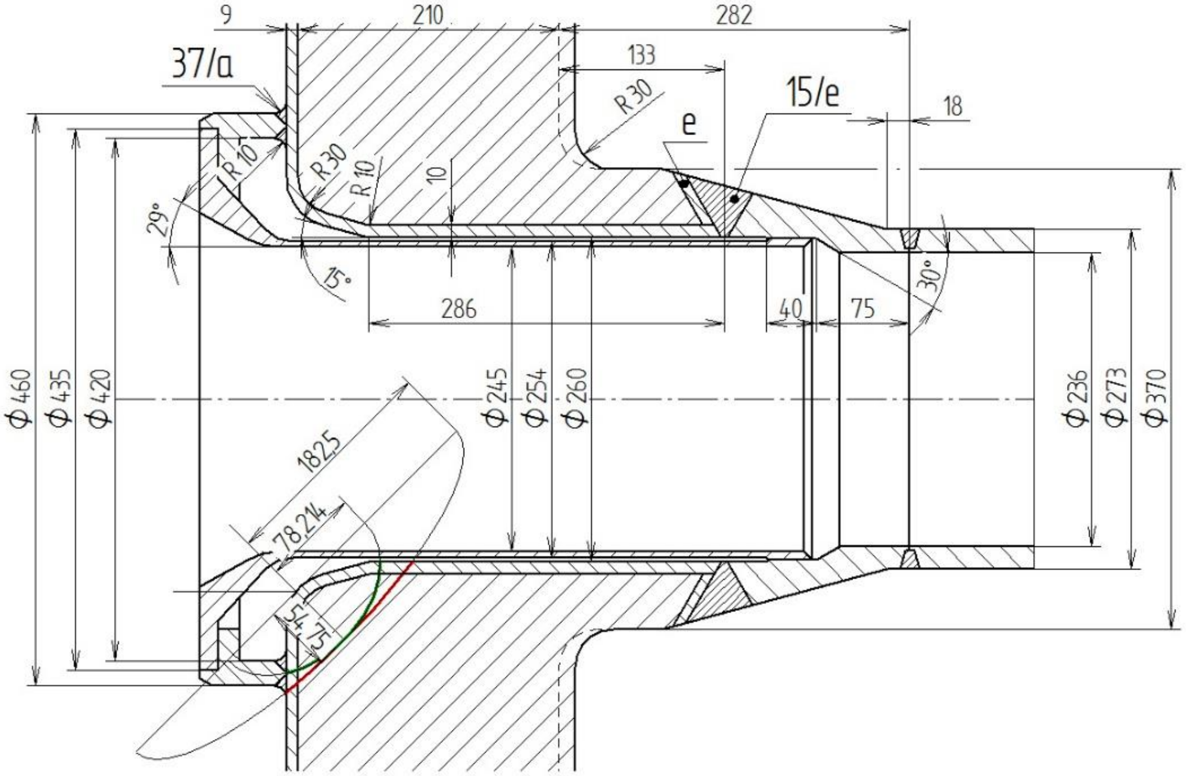

Figure 4. Sketch of VVER 440 ECCS nozzle with thermal sleeve and with postulated cracks

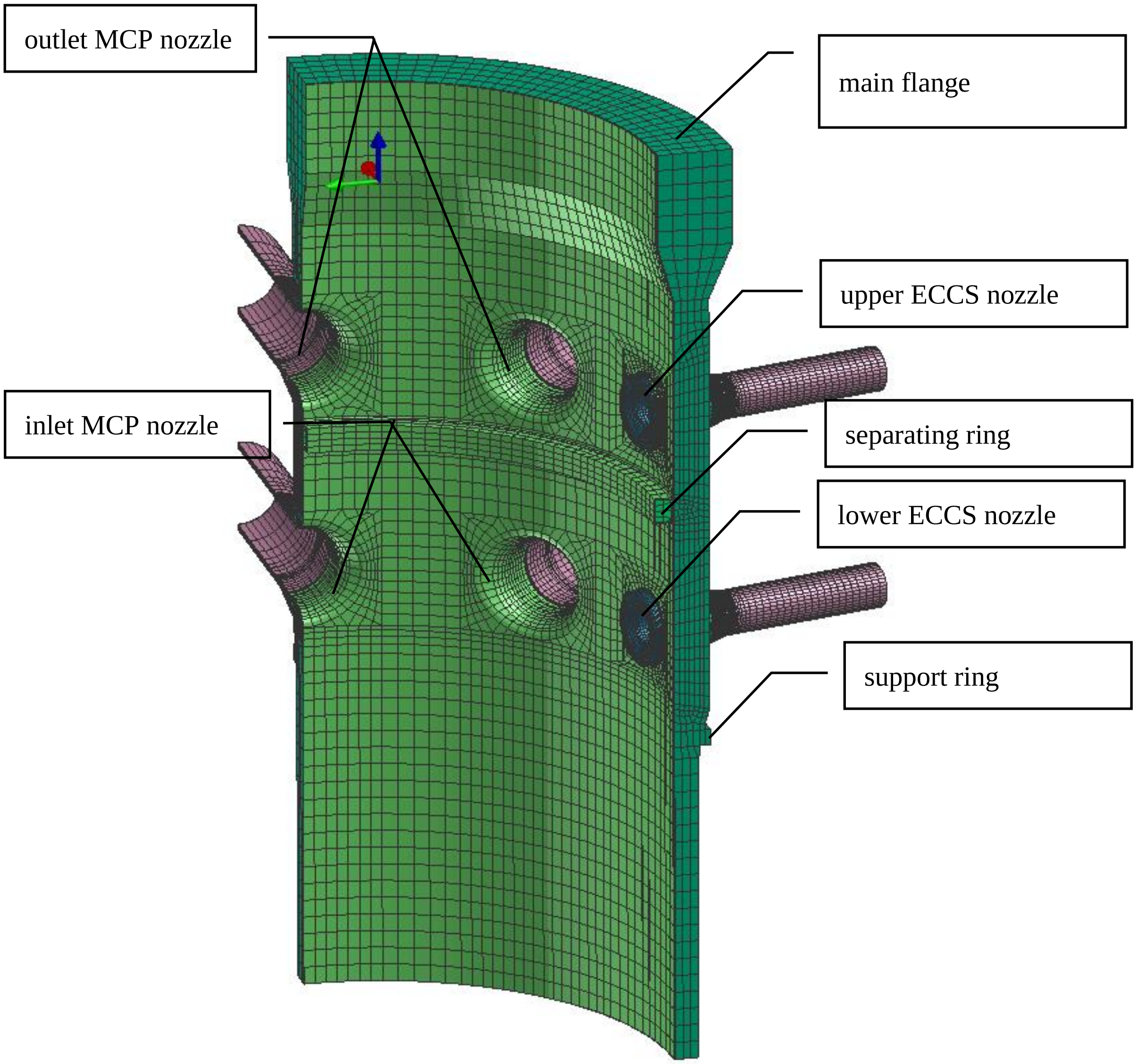

Figure 5. FEM mesh (full model)

Heat transfer problem

The heat transfer and mechanical problems were solved by the code SYSTUS. The heat transfer problem was solved as a nonlinear transient problem (thermal-physical properties dependent on temperature) with third type boundary condition on the inner surface (prescribed time-dependent coolant temperature and heat transfer coefficient) and zero heat transfer on the symmetry planes and on the outer surface. The heat transfer through the water gap between the thermal sleeve and the cladded inner RPV surface is modelled in a simplified way without directly modelling the convective heat transfer and phase change phenomena in the gap. The gap can be divided into three regions (denoted by A, B and C) which are shown in the Figure 6.

A – large volume between the thermal sleeve and inner surface of the nozzle (cross section 55 x 80 mm), connected with inner volume of the RPV nozzle by four holes,

B – cylindrical gap between the thermal sleeve and inner surface of the nozzle (thickness 3 mm),

C – narrow cylindrical gap between the thermal sleeve and inner surface of the nozzle (thickness 0.1 mm, during the transient it is enlarged till 0,3 mm due to rapid cooling and shrinking of the thermal sleeve in comparison to the ECCS nozzle).

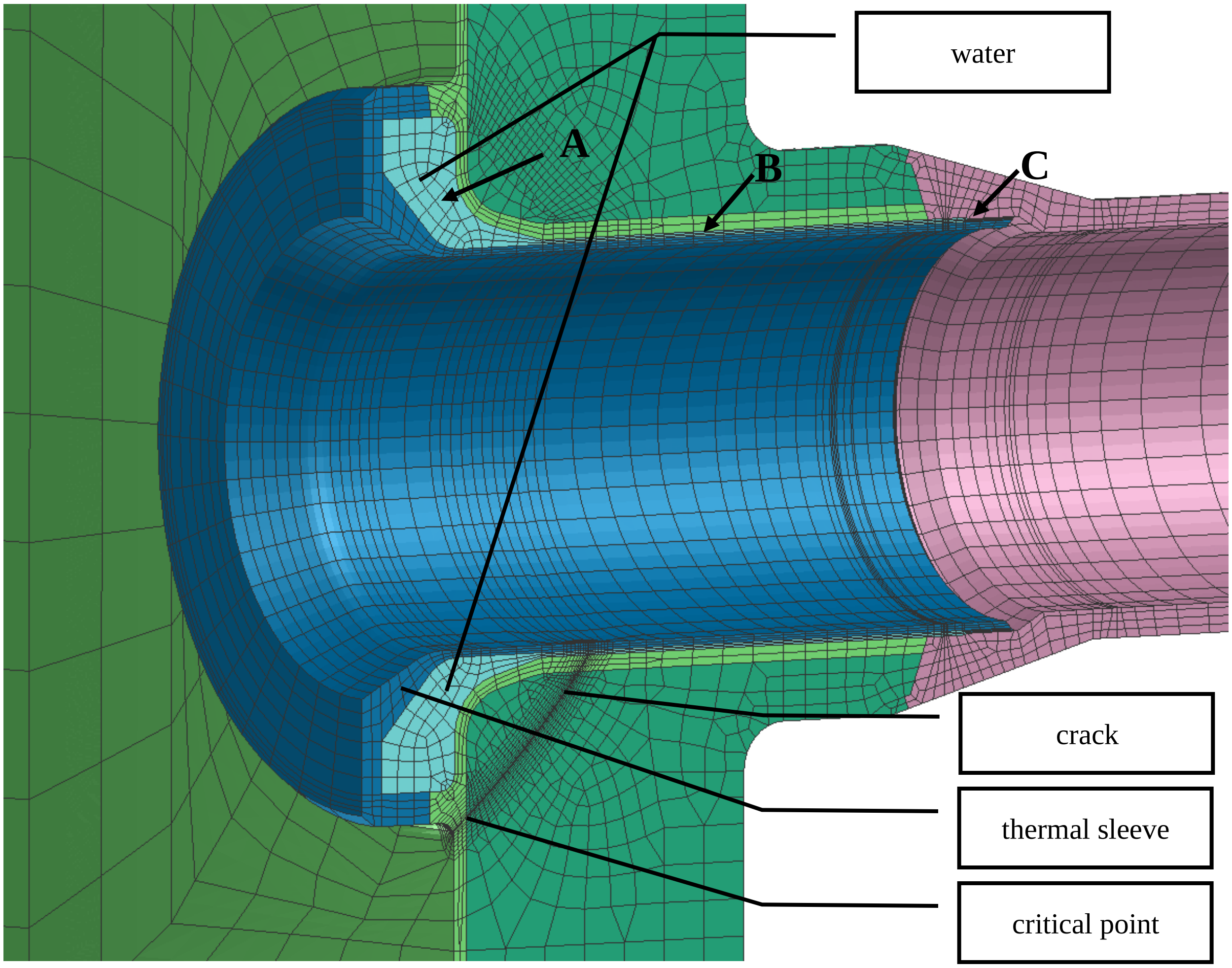

Figure 6. FEM mesh with crack in ECCS nozzle with regions of the gap between the thermal sleeve and the nozzle

Due to geometrical configuration of the gap and complicated thermal hydraulic behaviour of water inside it during LB LOCA (temporary occurrence of steam and its subsequent condensation etc.), detailed TH analysis is out of the scope of current TH codes. For the assessment we neglected the occurrence of the steam in the gap, and for simplicity we considered only liquid water during the whole event. This approach is conservative from the point of view of the assessment of the thermal shock. The TH behaviour of the three regions of the gap was included in the model in a simplified way as follows:

A – strong natural circulation of water is expected in this region due to cooling from the inner volume of the nozzle (through the thin thermal sleeve) and heating from the RPV wall. The volume is modelled by finite elements (entering only the thermal problem, not the mechanical one). The thermal conductivity of the finite elements (representing water in this volume) was artificially increased to model the natural circulation. The thermal contact between steel and water elements was modelled using high value of heat transfer coefficient.

B – stagnant water is expected in this region, which was modelled again by finite elements, but with thermal conductivity of the elements corresponding to real thermal conductivity of water. Thermal contact between steel and water elements was modelled with high value of heat transfer coefficient.

C – direct thermal contact of thermal sleeve and ECCS nozzle was modelled. Heat transfer coefficient was selected to correspond to the gap of 0.3 mm thickness filled by stagnant liquid water considering its real thermal conductivity.

Examples of resulting temperature fields are given in Figures 7 and 8.

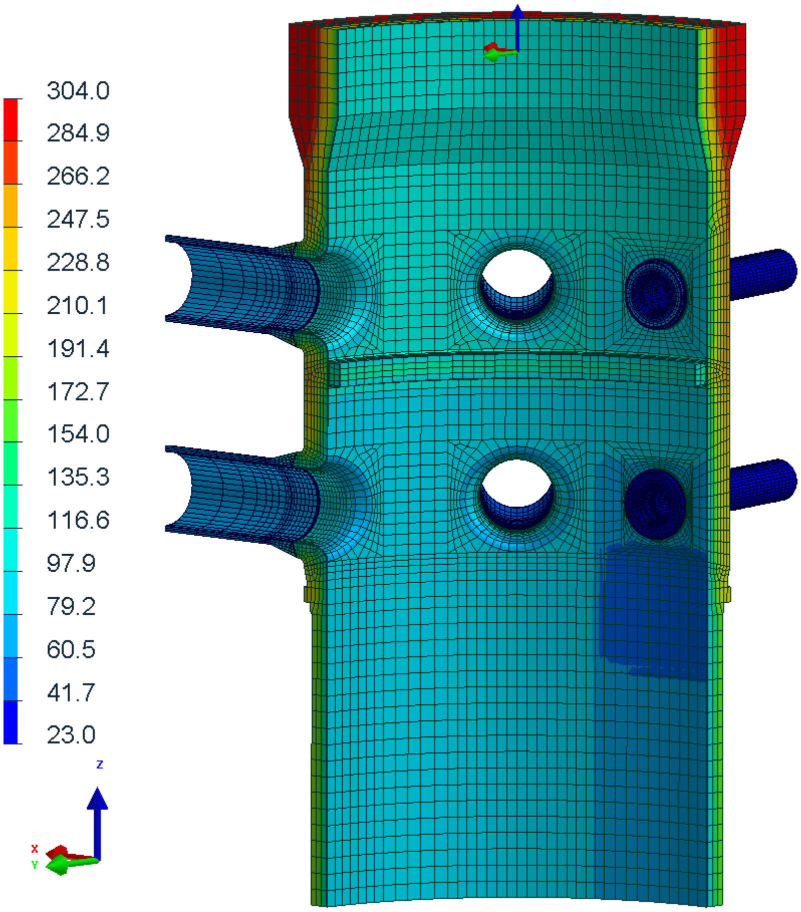

Figure 7. Scenario H500n.max, temperature (in °C) field in time 1150 s, full model.

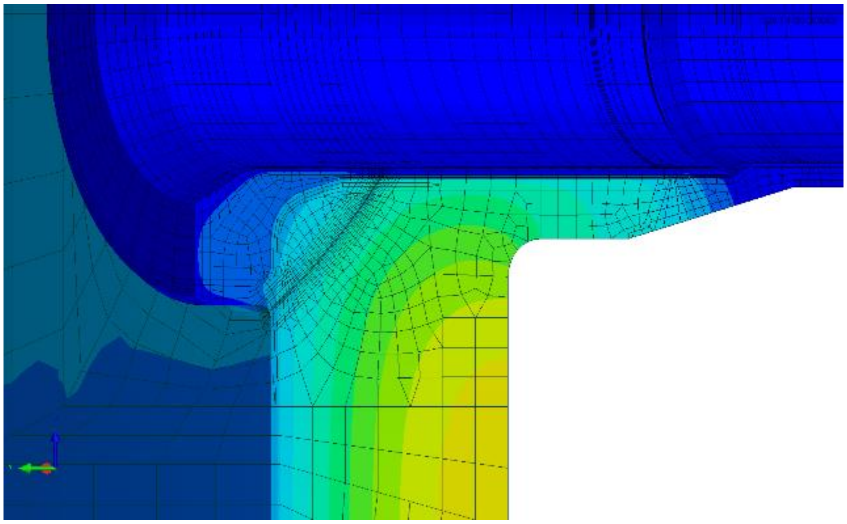

Figure 8. Scenario H500n.max, temperature field in time 1150 s, detail in the ECCS nozzle region (the same scale in °C as in Figure 7 is used).

Mechanical problem

The mechanical problem was solved as a transient quasistatic elastic-plastic problem. The model was loaded by nonuniform temperature fields and inner pressure. Examples of resulting stress fields are given in Figures 9 - 10.

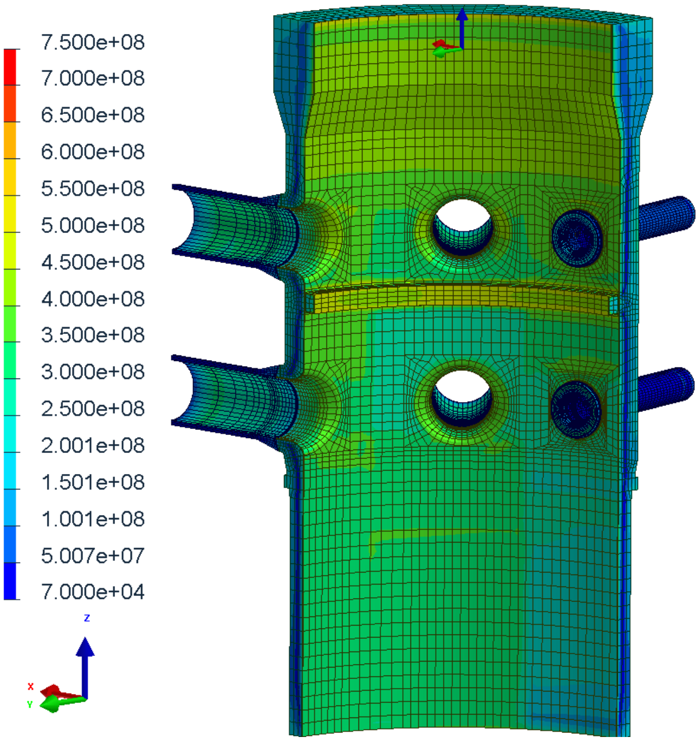

Figure 9. Scenario H500n.max, von Mises stress (in Pa) field in time 1150 s, full model

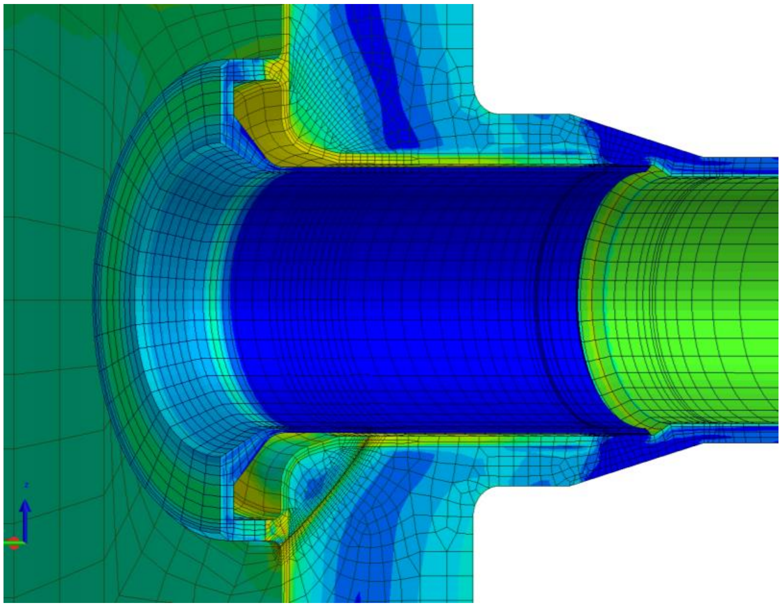

Figure 10. Scenario H500n.max, von Mises stress field in time 1150 s, detail in ECCS nozzle region (the same scale in Pa as in Figure 9 is used).

FRACTURE MECHANICS ASSESSMENT

The fracture mechanics assessment was performed in accordance with the Czech standard NTD AME (2020). Using the postprocessor of SYSTUS code, the energy release rate G was calculated for all nodes in the semi-elliptical part of the crack front lying in the RPV base material. The energy release rate G was then converted to stress intensity factor K_I.

The allowable value of stress intensity factor $[K_{IC}]_3$ is given by the formula from NTD AME (2020) standard

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

where T is temperature and T_k is the critical temperature of brittleness.

For the final fracture mechanics assessment, the stress intensity factor K_I was compared with its allowable value $[K_{IC}]_3$. The warm prestressing (WPS) approach in accordance with NTD AME (2020) was used. In simple terms, it means that the part of transient, where K_I was below 90% of its global maximum, was not considered for the final assessment. Finally, the maximum allowable critical temperature of brittleness T_k^a was established for all nodes on the crack front, and the minimum of these values was taken as the final T_k^a value. The dependency of K_I and $[K_{IC}]_3$ on temperature for the scenario H500n.max is presented in Figure 11. The critical point on the crack front was found to be the near-interface point (just below the cladding) close to the RPV inner surface (see Figure 6). It has to be noted that this point is not protected by the thermal sleeve, due to very large size of the postulated crack. Nevertheless, the resulting maximum allowable critical temperature of brittleness T_k^a was higher than the predicted value of T_k for the RPV end-of-life, which means that the safe operation was guaranteed.

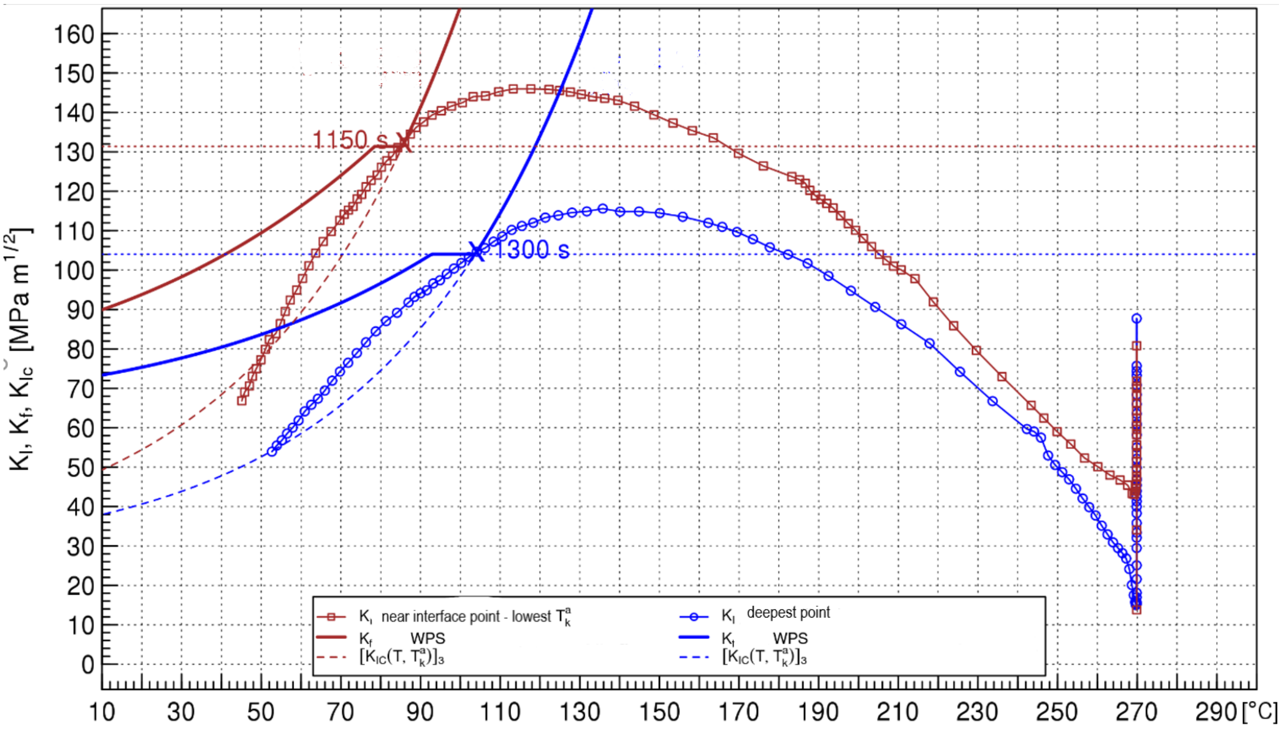

Figure 11. Scenario H500n.max, crack in lower ECCS nozzle, a/c = 0,3, dependency of K_I and $[K_{IC}]_3$ on temperature

CONCLUSION

ECCS nozzle is a specific part of RPV from the point of view of the brittle fracture assessment. Although there is negligible neutron fluence and only rather limited thermal embrittlement, the region can undergo a very severe loading due to a potential LB LOCA event leading to a pressurized thermal shock. The impossibility of ultrasonic testing from the inner surface (due to presence of thermal sleeve) led to postulation of a large crack in the ECCS nozzle region. These factors contributed to the necessity of detailed brittle fracture assessment of the ECCS nozzle.

System thermal hydraulic analyses were performed by the RELAP5 code. Subsequently, temperature and stress fields were calculated by the FEM code SYSTUS. The final fracture mechanics assessment was performed for crack 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 was found higher than the current (or predicted for the RPV end-of-life) value of the critical temperature of brittleness. It means that the resistance against brittle fracture was assured and safe RPV operation was guaranteed. Examples of results for a selected PTS transient were given.

NOMENCLATURE

ECCS	emergency core cooling system
FEM	finite element method
LB LOCA	large-break loss-of-coolant-accident
NDT	non-destructive testing
NPP	nuclear power plant
PTS	pressurised thermal shock
PWR	pressurised water reactor
RPV	reactor pressure vessel
TH	thermal hydraulic
VVER	water-cooled water-moderated reactor
WPS	warm prestressing

a	[mm]	crack depth
c	[mm]	crack half length
K_I	[MPa.m$^{1/2}$]	stress intensity factor
$[K_{IC}]_3$	[MPa.m$^{1/2}$]	allowable value of stress intensity factor
G	[J.m^{-2}]	energy release rate
T	[°C]	temperature
T_k	[°C]	critical temperature of brittleness
T_k^a	[°C]	maximum allowable critical temperature of brittleness

REFERENCES

Normative Technical Documentation of Association of Mechanical Engineers (NTD AME). (2020), Section IV - Lifetime Assessment of Components and Piping in VVER NPPs.