CENTERED BENCHMARK ON STRUCTURAL ASSESSMENT WITHIN APAL PROJECT – RESULTS AND CONCLUSIONS

Bernadett Spisák[1], Ralf Tiete[2], Vladislav Pistora[3], Peter Dillström[4], Szabolcs Szávai[5], Oriol Costa-Garrido[6], Diego F. Mora[7], Polina Baranova[8], Sebastien Blasset[9], Miroslav Pošta[10], Katarína Šišková[10], Yaroslav Dubyk[11], Piotr Darnowski[12], Piotr Mazgaj[12], Oleksii Shugailo[13], Volodymyr Diemienkov[13]

[1] Expert, Bay Zoltán Nonprofit Ltd. for Applied Research, Miskolc, Hungary (bernadett.spisak@bayzoltan.hu)
[2] Senior Expert, Framatome GmbH, Erlangen, Germany (ralf.tiete@framatome.com)
[3] Senior Expert, ÚJV Řež, a. s, Řež, Czech Republic (vladislav.pistora@ujv.cz)
[4] Senior Expert, Kiwa Technical Consulting AB, Solna, Sweden (peter.dillstrom@kiwa.com)
[5] Senior Expert, Bay Zoltán Nonprofit Ltd. for Applied Research, Miskolc, Hungary
[6] Research Associate, Jožef Stefan Institute, Slovenia
[7] Research Scientist, Paul Scherrer Institute, Laboratory of Nuclear Materials, Switzerland
[8] Engineer, Framatome GmbH, Erlangen, Germany
[9] Senior Expert, Framatome GmbH, Erlangen, Germany
[10] UJV Řež, a.s., Czech Republic
[11] Head of the department, IPP-Centre
[12] Warsaw University of Technology (WUT), Warsaw, Poland
[13] Senior Experts of State scientific and technical centre for nuclear and radiation safety (SSTC), Kyiv, Ukraine

INTRODUCTION

Many nuclear power plants in the EU are currently in the second half of their designed lifetime, therefore life extension is an important consideration for EU countries seeking to continue nuclear power generation in the long term. Modern methods and developments are needed to demonstrate the safe operation of existing nuclear power plants undergoing long term operation (LTO) upgrades. One of the most limiting safety assessments for LTO is the analysis of the integrity of the reactor pressure vessel (RPV) under pressurized thermal shock (PTS) to prevent severe accident events. PTS analysis is a multidisciplinary work consisting of interdependent thermal-hydraulic (TH), structural and fracture mechanics analyses.

This paper presents the structural calculations carried out as part of the Advanced Pressurized thermal shock Analysis for Long term operation (APAL) project to determine stresses and temperatures in the RPV wall for a selected ICAS transient (reference case), as well as for selected LTO developments and uncertainties in the TH data. 1D, 2D and 3D calculations were carried out for the determination of the stress and temperature distributions in the RPV wall for the subsequent fracture-mechanics assessment. In case of the 1D and 2D simulations the thermal-hydraulic data was simplified, however for the 3D analyses the location and time-dependent temperature and heat transfer coefficient values were applied.

BASIC SETTINGS

The investigated reactor was a four-loop, 1300 MWe pressurized water reactor (PWR) of the type built by Siemens/KWU, such as the PWR at Grafenrheinfeld. A general description is given in the report of Nuclear Energy Agency (1999). In the near-core region, the proposed four-loop reactor pressure vessel (RPV) has an internal diameter of 4870 mm in the downcomer, a wall thickness of 243 mm in the base/weld material and a 6 mm cladding thickness.

The base material is ferritic steel 22NiMoCr37, and the austenitic cladding is X5CrNiNb19-9. For the simulations the linear-elastic material model was considered. The density of the base/weld metal and the cladding was set as 7800 kg/m^3. Furthermore, the relevant temperature-dependent material properties of the RPV are presented in Table 1, where the reference temperature of the mean (secant) thermal expansion coefficient (α) is denoted by T_m, T is the temperature, E is the Young's modulus, λ refers to the thermal conductivity and the heat capacity is noted with C_p. The Poission's ratio is 0.3, and the reference temperature of the stress-free state is 291°C.

Depending on the software used, 1D, 2D and/or 3D finite element model was created, and an example of the 1D finite element (FE) model is shown in Figure 1. The FAVOR code (nodalization with 1 element for cladding, 7 elements for base metal), in-house and commercial software with different meshing were used. For the round-robin, thermal-hydraulic (TH) data were obtained with the RELAP5 code, which provided time-dependent values of pressure, fluid temperature and heat transfer coefficient (HTC), while the calculations of base case, LTO improvements and TH uncertainties were also done with ATHLET, TRACE (system TH analysis), ECC-MIX and KWU-MIX (mixing TH analysis) (Kral et al., 2023). The boundary conditions introduced below were similarly used for every input TH data.

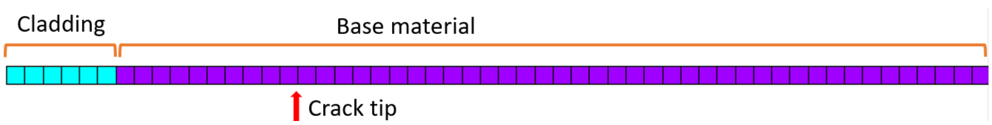

Figure 1. Example of FE model for 1D simulation.

Table 1: Material properties of the base metal and the austenitic cladding

	22NiMoCr37					X5CrNiNb19-9				
T [°C]	20 (T_m)	100	200	300	350	20 (T_m)	100	200	300	400
E [GPa]	206	199	190	181	172	200	194	186	179	172
λ [W/(m·K)]	44.4	44.4	43.2	41.8	39.4	16	16	17	17	18
C_p [J/(g·K)]	0.45	0.49	0.52	0.56	0.61	0.5	0.5	0.54	0.54	0.59
α [10^{-6}/K]	10.3	11.1	12.1	12.9	13.5	15	16	17	19	21

The TH data were simplified for the 1D and 2D finite element simulations due to geometric limitations, and the so-called 0V/1V/2V cases were generated. Table 2 contains the RELAP5 data cases with their explanations, where the term "ambient" means the position of outside of plume.

The elevation and azimuth values in the RPV give the position in the downcomer where the TH data will be obtained from for the structural analysis. Therefore, the 0V/1V/2V cases mean the following. In case of the 0V simulation, the TH inputs were averaged in the whole geometry and are time-dependent. The 1V simulations mean that at a given elevation (2638 mm or 1130 mm) the TH input data are averaged along the circumference and are time-dependent. Finally, for the 2V simulations the TH inputs were from a specific position of the downcomer.

In 1D and 2D simulations, the liquid temperature and the HTC were applied on the inside of the RPV model, while the outside surface was adiabatic. The mechanical boundary conditions include the inner pressure at the cladding wet surface, 0 MPa at the outer surface, an end-cap pressure for axial stress applied to end cross-section of RPV model and fixed at the other side of the RPV.

The 3D simulations were performed with several commercial FE software (MSC.Marc, ABAQUS, ANSYS Mechanical). The most important boundary conditions used in the 3D simulations are introduced in Figure 2. Temperatures of the fluid layer which is in contact with the RPV wall and related heat transfer coefficients were applied as time and location-dependent properties on the inner surface of the RPV. CL1-

CL4 indicate the cold legs. Inside these nozzles the heat flux was uniformly applied. The internal pressure was uniformly distributed over the inner surface of the RPV, and the geometry was fixed.

Table 2: RELAP5 TH data variations (no local mixing, i.e. no validated plume)

Abbreviations	Description of the Case	Evaluation of RELAP5 data	
		Elevation (height)	Azimuth (circumference)
Case 1	0V – average	average	average
Case 2	1V – core weld (CW)	2638 mm	average
Case 3	2V – core weld/cold plume	2638 mm	202.5°
Case 4	2V – core weld/ambient	2638 mm	337.5°
Case 5	1V – flange weld (FW)	1130 mm*	Average
Case 6	2V – flange weld/cold plume	1130 mm*	202.5°
Case 7	2V – flange weld/ambient	1130 mm*	337.5°

* the flange weld elevation is 1350 mm, however, the RELAP5 nodalisation has only evaluated 1130mm

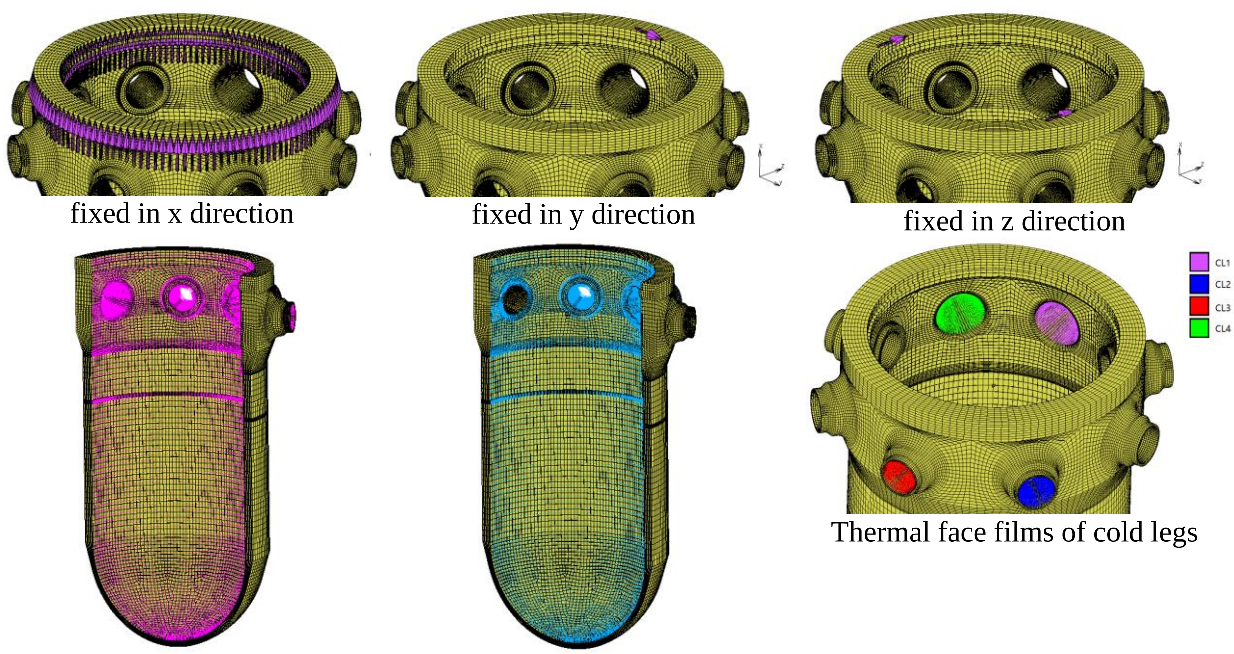

Figure 2. Boundary conditions of 3D simulations.

ROUND ROBIN INVESTIGATION OF THE 7 CASES

In total, twelve partners participated in the Round Robin task. Three parameters were evaluated: temperature, circumferential stress and axial stress. The first aim was to compare the TH averaging effects and select the appropriate TH data for flange and core welds. The seven cases (Table 2) were therefore compared where the values were generated from the averaging of the results of all the partners. The most interesting location (introduced in the work of Blasset et al. (2024)) important for further analysis within

APAL project, is the crack tip, i.e. 16 mm from the wet surface. Therefore, Figure 3. shows the temperature and circumferential stress distribution as a function of time for the 7 cases.

The comparisons show that lower temperature-values are observed in Case 3 (core weld, cold plume position) and Case 6 (flange weld, cold plume position). The fully averaged and azimuth averaged versions (Case 1, Case 2 and Case 5) overestimate the temperature values. The difference between Case 3 (at flange weld position Case 6) and Case 4 (at flange weld position Case 7) is the circumferential position, where the TH data are taken from. Case 3 and Case 6 show higher stress values and give the most conservative results therefore they were chosen for future investigations.

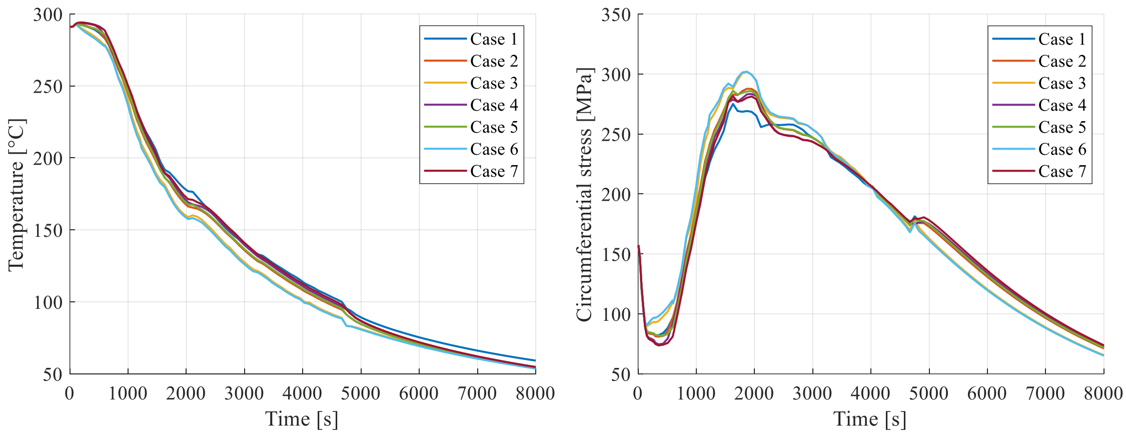

Figure 3. Comparison of temperature and circumferential stress profiles at the crack tip for the 7 Cases.

Comparison of partners' results for temperatures, circumferential and axial stresses as a function of time showed good agreement, the differences between the partners' results were less than 5% compared to compared to the results shown in Figure 3.

RESULTS OF SENSITIVITY STUDIES

Several sensitivity studies were carried out. First, the effect of the RPV location where the data is taken from was investigated. Here beside the base case version (core weld inside plume) the following locations were selected: flange weld inside plume, outside of plume and at the nozzle corner. The core weld is placed at the high of 2638 mm where the thickness of the reactor pressure vessel wall is already uniform. The flange weld is located at 1350 mm which is already very close to the nozzle area, therefore here 50-100 MPa stress increase was observed (Figure 4), which was much higher in case of the nozzle corner.

The temperatures at the core weld below the nozzles where the ECC water is injected and the plume is formed, are lower than the temperatures below other nozzles (outside plume) during most of the transient. As expected, this yields higher stresses in the two plume locations than in the other locations, which means that calculations at the locations of outside plume do not give conservative results.

The thickness of the cladding can vary during RPV manufacturing, so 1D simulations were performed where the cladding thickness was varied between 4 and 8 mm and were compared to the base case where the cladding thickness was 6 mm. The results indicated that the cladding thickness does not have a large effect on the stress results, however, it should be noted that it has a more significant effect when evaluating underclad cracking.

The effect of mesh refinement was investigated in the case of 3D simulations. The results showed that the usage of uncoupled heat-transfer (HT) and mechanical (MC) analyses with quadratic elements is suggested.

Comparing 1D, 2D and 3D simulations was essential to see how much simplification was possible. For this purpose, the position of the core weld (CW) and the position of the flange weld (FW) were examined. As it is described in Table 3, the 1D simulation used the TH data from Case 3 for core weld and Case 6 for flange weld. The results were compared with those from the 2D (uniform) and 3D (uniform and non-uniform) simulations. In the 2D and 3D Case 3 (CW) and Case 6 (FW) data, the loads were uniformly applied at the RPV inner surface.

Table 3: Description of 1D, 2D and 3D models for core weld and flange weld

Cases	Description		
	FEA model	Core weld	Flange weld
1D Case 3/Case 6	1D	2638 mm, 202.5°	1130 mm, 202.5°
2D Case 3/Case 6	2D	2638 mm, 202.5°	1130 mm, 202.5°
3D Case 3/Case 6	3D	2638 mm, 202.5° (uniform)	1130 mm, 202.5° (uniform)
3D non-uniform	3D	non-uniform (without local mixing analysis)	

Based on the comparison of the results, it can be concluded that in case of the core weld, the introduced four calculation types were in good agreement, therefore in this case the simplification of the geometry has no large effect on the results. A 3D non-uniform analysis remains necessary for the analysis of TH loading with individual or merging plumes (necessitating local mixing TH-analysis).

In case of the flange weld the resulting stress distributions as a function of time are shown in Figure 4. Some deviations can be noticed in the temperature fields in the 1D simulation compared to the other three versions which started from around 2000 s and at 6000 s the largest deviation reached up to 20°C. In the 1D results, this can be explained as a consequence of non-considering the conical part of the RPV in the vicinity of flange weld, where the transition to the thicker nozzle region is present. It "contains" more heat in the initial state of PTS resulting in the temperature deviation. Within 1D simulations this effect cannot be modelled. Therefore, it was concluded that in the presented form the 1D Case 6 simulation cannot be used for the flange weld as it underestimates the stress values compared to the 3D non-uniform results.

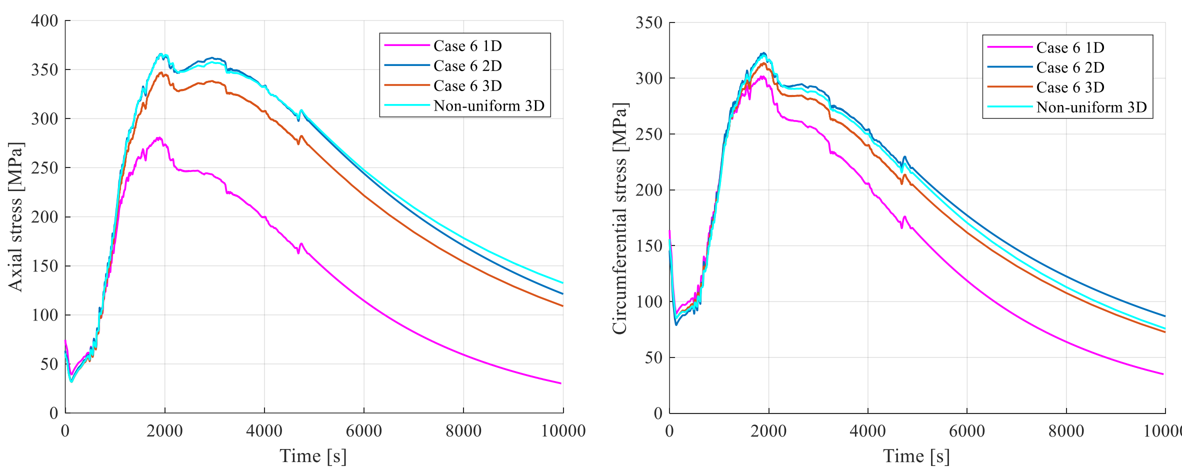

Figure 4. Comparison of hoop and axial stress profiles as a function of time at the flange weld.

The 2D axisymmetric finite element simulation gives better results than 1D simulation for flange weld region, because it takes into account to some extent the influence of the conical part of the RPV and the nozzle region of the RPV. However, the effect of the nozzles can only be modelled in a simplified way using reduced Young's modulus, thermal capacity, and density. Also, the heat exchange area (wet surface) is not properly modelled, resulting in inaccurate temperatures in the nozzle region. It must be noted, the consideration of real 3D TH boundary condition (TH-mixing) is increasing this deficit therefore 3D SA shall be performed in case of non-uniform TH boundary loading.

EFFECT OF DIFFERENT THERMAL HYDRAULIC CODES

The comparison was made with the base case 3D non-uniform simulation versions of the partners, where three types of TH data were used: RELAP, KWU-MIX and TRACE. The comparisons of temperature and stress histories at the crack tip are shown in Figure 5. Large differences in the obtained temperatures can be seen, which resulted from the use of different TH data. In case of the KWU-MIX data, the cold plume was also considered (existence validated from experimental test results), therefore the data are taken from azimuthal position of 180°, where the coldest wall temperatures are occurring in case of the core weld (2638 mm), and the main difference in temperature between the KWU-MIX and RELAP TH data results is due to the usage of mixing code. In the other TH data the circumferential angle was 202.5°.

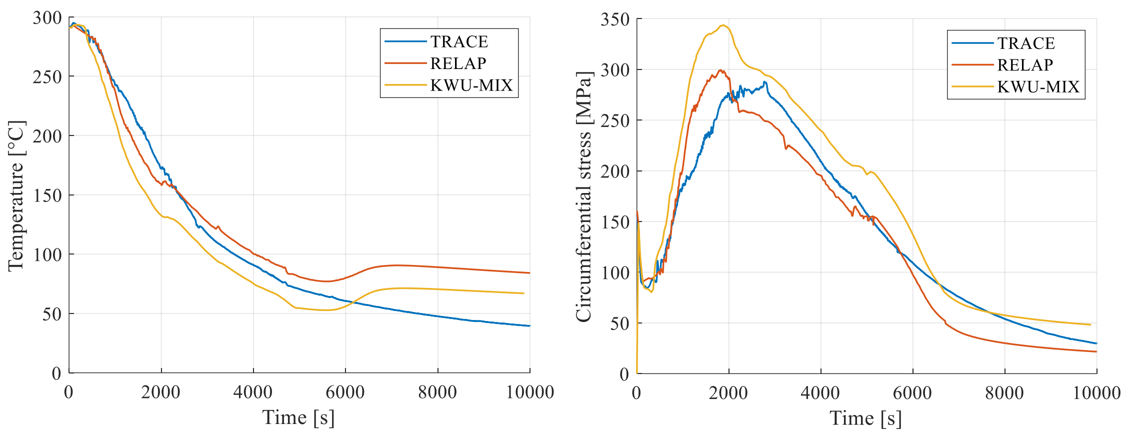

Figure 5. Comparison of temperature and stress profiles of different TH calculation methods at the crack tip.

The plume effect on axial stresses is even more pronounced at increasing elevation (FW, nozzle) demonstrating that system analysis TH code only are not able to reproduce the plume effect correctly compared to local-mixing analysis. Furthermore, simplified SA (1D, 2D) is not able to reflect correctly/safely the complex 3D temperature distribution and therefore the stress profiles.

EFFECTS OF LONG-TERM OPERATION IMPROVEMENTS ON THE TEMPERATURE AND STRESS FIELDS

Nine types of long-term operation improvements and human actions were simulated, the meaning of which and the used abbreviations are presented below:

- LTO 1 was simulated by increasing the water temperature in the high-pressure safety injection (HPSI) tanks from the reference value of 15 °C to the LTO value of 45 °C.
- LTO 2 was simulated by increasing the water temperature in accumulators (ACCs) from the reference value of 20 °C to 50°C.
- LTO 3 was simulated by increasing the water temperature in the low-pressure safety injection tanks from the reference value of 15 °C to 45 °C.
- LTO 4 was simulated by scaling the pressure of the HPSI pump curve down to 75% of the reference value.
- LTO 5 was simulated via scaling the flow capacity of the HPSI pump curve down to 75%.
- LTO 6 was simulated by switching off 1 of 2 HPSI pumps at 1800 s after the initiation of the break.

- LTO 7 was modelled by decreasing the initial pressure opening setpoint in the ACCs from the nominal value of 2.6 MPa to 2 MPa.
- LTO 8 was simulated by increasing the cooldown of the secondary side from 100 K/h to 200 K/h.
- LTO 9 the results from the system analysis performed with RELAP5, were repeated with the addition of a time for ACC isolation at 500 s.

As already mentioned, the thermal-hydraulic simulations were performed with different system codes and mixing codes, namely ATHLET, RELAP5, TRACE, KWU-MIX and ECC-MIX. For every action 1D and 3D simulations were created, where the TH data were generated the same way as in Case 3 (Table 2).

Figure 6 and 7 shows the temperature and circumferential stress curves as a function of time for the base case and the LTO calculations. Figure 8 shows the axial stress curves, indicating the proper consideration of mixing leads to an increase of the axial stresses compared to axial stress considering system code only. In order to see the actual impact of different LTO improvements and to eliminate the effect of the TH calculation method, the RELAP5, the TRACE and KWU-mix TH data were compared separately. As it can be seen from the diagrams LTO 1, LTO 4, LTO 5, LTO 6 and LTO 8 had some influence on the curves.

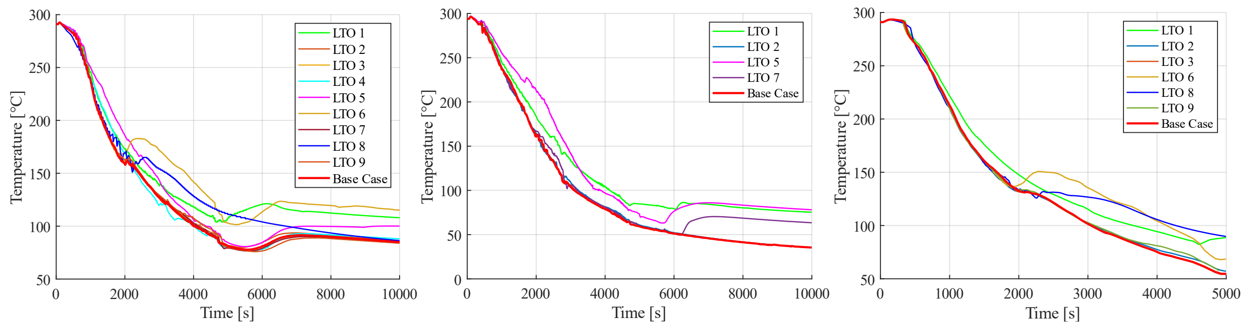

Figure 6. Comparison of temperature profiles for the LTO cases at the crack tip with RELAP5 (left), TRACE (middle) and KWU-mix (right) TH data.

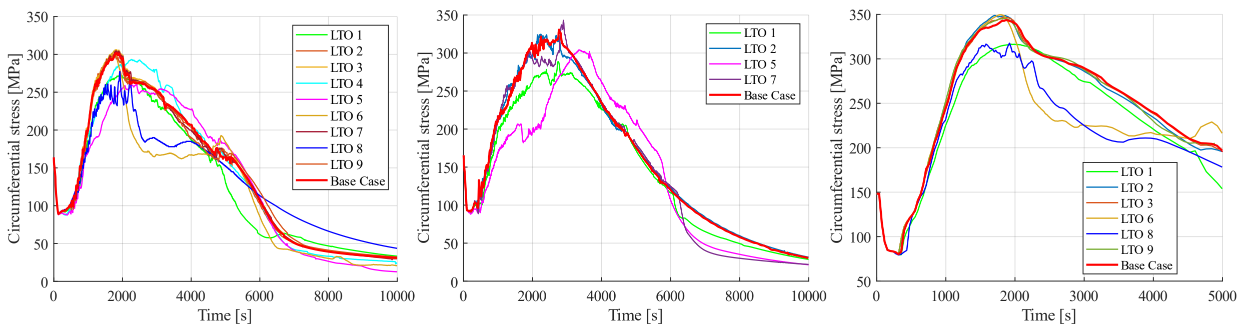

Figure 7. Comparison of circumferential stress profiles for the LTO cases at the crack tip with RELAP5 (left), TRACE (middle) and KWU-mix (right) TH data.

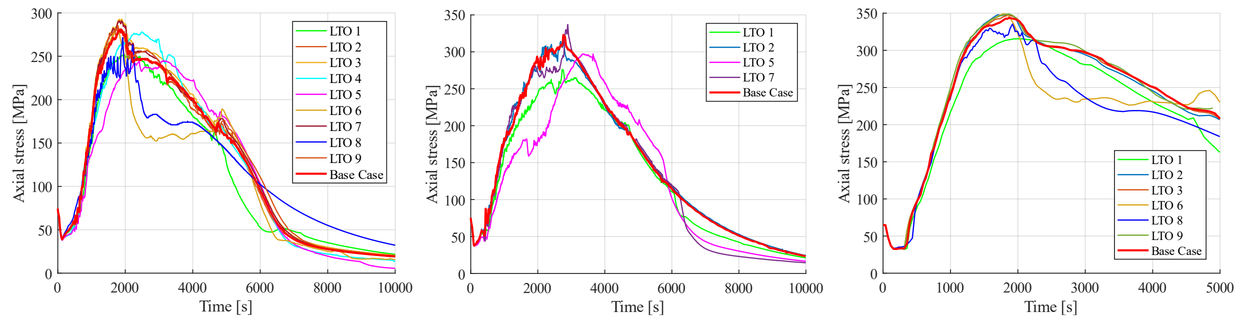

Figure 8. Comparison of axial stress profiles for the LTO cases at the crack tip with RELAP5 (left), TRACE (middle) and KWU-mix (right) TH data.

Table 4 summarizes the evaluation of impact of LTO improvements and human factors on the temperatures and stresses. It should be noted that the evaluation was made based on the results of the temperature and stress field at the crack tip location (16 mm from the wet surface), therefore the final assessment of the effect of different LTO improvements are introduced in Pištora et al. (2024), which contains the deterministic fracture-mechanic assessment. It should be also noted that the evaluation of impact of LTO improvement is valid for the assessed PTS regime and can be different for other regimes.

Table 4: Evaluation of impact of LTO improvements on the temperature and stress field

	LTO 1	LTO 2	LTO 3	LTO 4	LTO 5	LTO 6	LTO 7	LTO 8	LTO 9
Impact	Beneficial	None	None	Small	Beneficial	Unclear	Small	Unclear	None

UNCERTAINTIES IN TH DATA ANALYSIS FOR WILKS

Besides the model uncertainties connected with computer code and plant uncertainties covering initial and boundary conditions and parameters of nuclear power plant (NPP) systems, the work carried out also focused on uncertainties connected with human factors. Therefore, the uncertainty analyses of small break loss of coolant accident (SBLOCA) in 1300 MWe PWR were performed. Several system thermal-hydraulic codes (RELAP5, ATHLET, TRACE) and one regional mixing calculation code (KWU-MIX) were applied to the sets of 59, 93 and 130 sampled calculations obtained with Wilks method to yield 95%/95% one-sided tolerance bound. As an example, the results of stress and temperature calculations based on RELAP5 TH calculation with 93 samples are presented. The following variants were analyzed:

- Best Estimate: This is the reference best-estimate calculation. This scenario was intended to represent the best estimate values of the input TH parameters.
- Base Case: The scenario was prepared according to the ICAS T2 transient.
- Wilks samples: The Wilks data set was calculated using DAKOTA code with uncertain parameters (statistical distributions) to generate the random TH data.
- Conservative Case: This scenario was intended to represent conservative values of the input TH parameters leading to the most stringent transient for the structure that can be obtained within the uncertainty of the input parameters. The values of the input parameters were found using sensitivity analyses and engineering judgement in the same way as for a “conventional” deterministic PTS analysis.

The stress and temperature calculations with the Wilks-93 data set were performed with weld residual stress (WRS) and without cold-plume correction. From the TH data set, the values of liquid temperature, HTC and pressure were used for FEA. In order to provide a reasonable and useful way to handle WRS in RPV assessments, several standards and codes solutions for WRS profiles in welds and claddings were checked. The WRS in the base material was given according to the German KTA 3201.2

(2017) standard, which states that a constant value of 56 MPa in the longitudinal direction of the weld is considered if no other value can be determined. Equation (1) was used for axial WRS.

$$\sigma_R(x, s) = 56 \cdot \cos\left(2\pi \cdot \frac{x}{s}\right) \quad (1)$$

where σ_R is the weld residual stress in MPa, x is the current coordinate along the path through the wall and s is the wall thickness without cladding.

For residual stresses in the cladding, it is common practice to consider the operating temperature as a stress-free temperature for the cladding in the finite element analysis if no detailed information is available. Therefore, the stresses due to different thermal expansion coefficients of base and clad material lead to a conservative stress generation during thermal transients. Based on this, axial and circumferential WRS in the cladding was assumed to be zero.

The finite element simulations results at 16 mm inside the RPV wall for the circumferential and axial stresses as a function of crack tip temperature are summarized in Figure 9.

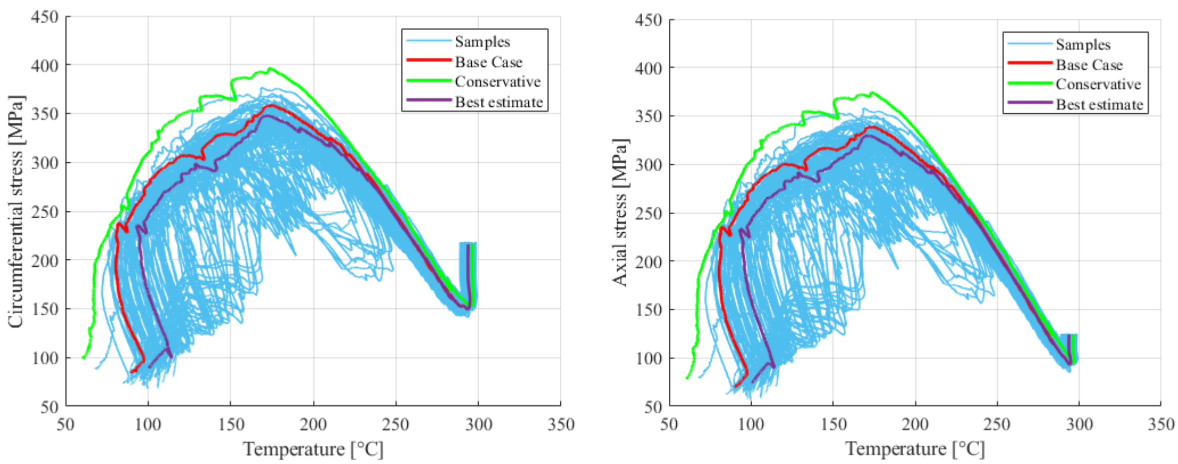

Figure 10. Circumferential and axial stresses at the crack tip as a function of crack tip temperature for Wilks-93 with WRS.

The introduced structural results in terms of temperature and stress distributions as a function of time and at specific locations in the RPV wall can be seen as "interim" results that were dealt with further in deterministic margin assessments, which are introduced in the work of Pištora et al. (2024).

CONCLUSIONS

In this paper, structural assessments for the base case (SBLOCA with 50 cm^2 break in HL and with loss of offsite power) and for selected LTO improvements and operator actions were performed with different analysis methods.

As a first step a round-robin task was generated to determine how the TH data can be used in 1D finite element simulations. 7 cases were chosen where the TH data were averaged or, in some cases, taken from an exact location, thus leading to 0V, 1V and 2V TH data. The agreement of resulting temperatures and stresses among partners was good. It was also concluded that the 2V TH data version (TH data from a given location e.g., at core weld under the cold plume) gives the most conservative results. Any averaging of TH data leads to non-conservative solution.

In the case of the flange weld the effect of the geometry had to be checked as the position of this weld is close to the nozzle region with thicker wall. The results showed that in this case the 1D finite element simulations with 2V TH data do not deliver the correct results as compared to the 2D or 3D simulations, and they underestimate the stress fields. Due to this reason, it is recommended that future work is dedicated to generate new formulae to determine the stress values in the flange weld with consideration of this geometrical effect.

Several sensitivity cases were analysed and some conclusions were made based on the stress distributions. The results at different locations showed that the stresses depend highly on the studied position. As expected, the out of plume position resulted in lower stress values, while the flange weld and nozzle corner positions generated higher stresses. Besides the locations, the thickness of the cladding, the mesh and the time step were also varied, which showed lower impact on the temperature and stress results.

The LTO improvements were investigated with 1D and 3D finite element simulations. The structural assessment calculations were done for 9 LTO cases, 3 of them being operator actions (LTO6, LTO8 and LTO9). Some of the cases had impact on the temperature and stress field. It should be noted that the evaluation based on the results of the temperature and stress field at the crack tip location is still limited.

Finally, the temperature and stress field results of Wilks calculations were also introduced. These can be seen as “interim” results that were dealt with in deterministic margin assessments by Pištora et al. (2024).

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