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EVALUATION OF THE DETERMINISTIC BENCHMARK FOR THE ADVANCED PRESSURIZED THERMAL SHOCK ANALYSIS FOR LONG TERM OPERATION (APAL) PROJECT

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ABSTRACT

The APAL project (Advanced PTS analyses for long term operation) has been launched in October 2020 within the EU's HORIZON 2020 and with a duration of four years. The main objectives of APAL are developing advanced probabilistic pressurized thermal shock (PTS) assessment methods, quantifying safety margins for long term operation (LTO) improvements and developing best-practice guidance. This paper presents the work and conclusions drawn within the baseline deterministic benchmark (task 3.3 of work package WP3) of the APAL project.

The deterministic benchmark consists of structural and fracture mechanics (FM) analyses to quantify the safety margins related to LTO improvements and uncertainties in thermos-hydraulic (TH) analysis. The benchmark was defined based on existing plant data and state-of-the-art research results. It consists of two parts: calculations based on provided temperature and stress distributions, and calculations based on several TH calculations and individual structural and FM methods. Each of the two parts is divided into the subtasks of first calculation of stress intensity factors (SIF), then determination of maximum allowable adjusted reference temperature (max. allow. ART) considering crack initiation or reactor pressure vessel (RPV).

The analysed crack geometries are semi-elliptical through-clad cracks (TCC) and under-clad cracks (UCC) in cylindrical components, both in axial and circumferential direction. The subtasks were completed by thirteen APAL partners. In this paper a detailed comparison of the results for the baseline benchmark is given. The differences in the results and the reasons for them were analysed in detail. Through this process, ambiguities in the application of the solutions and formulas were identified. Discussing the implementation of the formulas and revising the results by each partner remedied the discrepancies. The findings and experiences from the benchmark were turned into a best practice guideline to be provided within the sub-sequent tasks and next WP. The most important insights are described in this paper.

BENCHMARK DEFINITION

The baseline deterministic benchmark consists of structural and fracture mechanics (FM) analyses to identify critical steps within the defined benchmark and to give recommendations for methods and tools to be used in the following benchmark cases. The benchmark was defined based on existing plant data and state-of-the-art research results. It consists of two parts: calculations based on provided temperature and stress distributions, and calculations based on several TH calculations and individual structural and FM methods. Each of the two parts is divided into the subtasks of first calculation of SIF, then determination of max. allowable adjusted reference temperature (ART) considering crack initiation or RPV failure by non-arresting crack growth.

The analysed crack geometries are semi-elliptical through-clad cracks (TCC) and under-clad cracks (UCC) in cylindrical components, both in axial and circumferential direction. The geometry is shown in Figure 1. The dimensions of the postulated crack are a = 10 mm, 2c = 60 mm, and r = 6 mm, the latter being the stainless-steel cladding thickness. The reference K_I solution is by Marie and Chapuliot (2008) for TCC and UCC (elastic solution) and for the UCC plastic correction Marie and Nédelec (2007) should be applied. Some partners used the FAVOR solution for TCC instead.

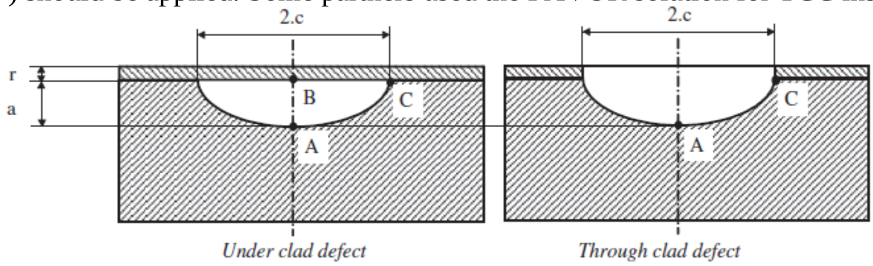

Figure 1. Geometry of postulated UCC and TCC (Marie and Chapuliot, 2008)

The examined location in the reactor pressure vessel (RPV) is at the core weld below the cold leg (CW-CL), i.e., 2638 mm elevation (height) and 202.5° azimuth (circumference). Residual stresses (RS) in the RPV beltline welds were considered with a cosine shape for circumferential cracks and a constant shape for axial cracks with a maximum of 56 MPa. Some partners used the FAVOR residual stress profile instead, which have a slightly different shape and maximum value of 45 MPa at the inner RPV surface.

For the second subtask, the determination of max. allowable ART considering only crack initiation, both the tangent approach and several warm pre-stressing (WPS) approaches were assessed. For the fracture toughness curves both the RT_{NDT} concept according to ASME XI Appendix A and the master curve (T_0) concept according to the 5% master curve approach were used (lower bound curves). Concerning WPS application, the tangent approach (i.e. no WPS) and the simple WPS-max approach were analysed. The tangent point is the point in which the equality $K_I = K_{IC}$ is reached:

$$max.all.ART = \sup\{ART: \forall t\; K_I(t) \leq K_{Jc}(ART, T(t))\} \quad (1)$$

The simple WPS-max approach considers no crack initiation after the global maximum SIF in the transient. The tasks of the FM benchmark performance are described in more detail in Blasset et al (2024).

BENCHMARK RESULTS WITH GIVEN METHODOLOGY AND INPUT

In the first subtask of the benchmark thirteen partners of the APAL project calculated K_I values implementing the reference solution for given transients of temperature and stresses. The transient load for the benchmark part 1 is given as a temperature and stress distribution through the wall thickness over time. The basis and a detailed description of the transient loads are given in the benchmark definition, see Blasset et al. (2024).

Thirteen of the APAL partners were involved in this part of the benchmark: Bay Zoltán, Framatome, GRS, IPP, IRSN, JSI, Kiwa, OCI, PSI, SSTC, Tecnatom, UJV and WUT. The results are presented anonymously, i.e., every partner is denoted by a number (P1 to P13). After a revision of the results good agreement between the participating partners could be observed (relative deviation < 5%), see Figure 2 for TCC. For UCC the same good agreement could be achieved.

For the results that are comparable in terms of input data and method used the overall scatter in K_I is in a range of ± 5% in most parts of the transient. Some oscillations and other deviations are observed and can be associated with the different implementations of the same method. In summary, within part 1 of the benchmark a common understanding of the tasks and the methods was established.

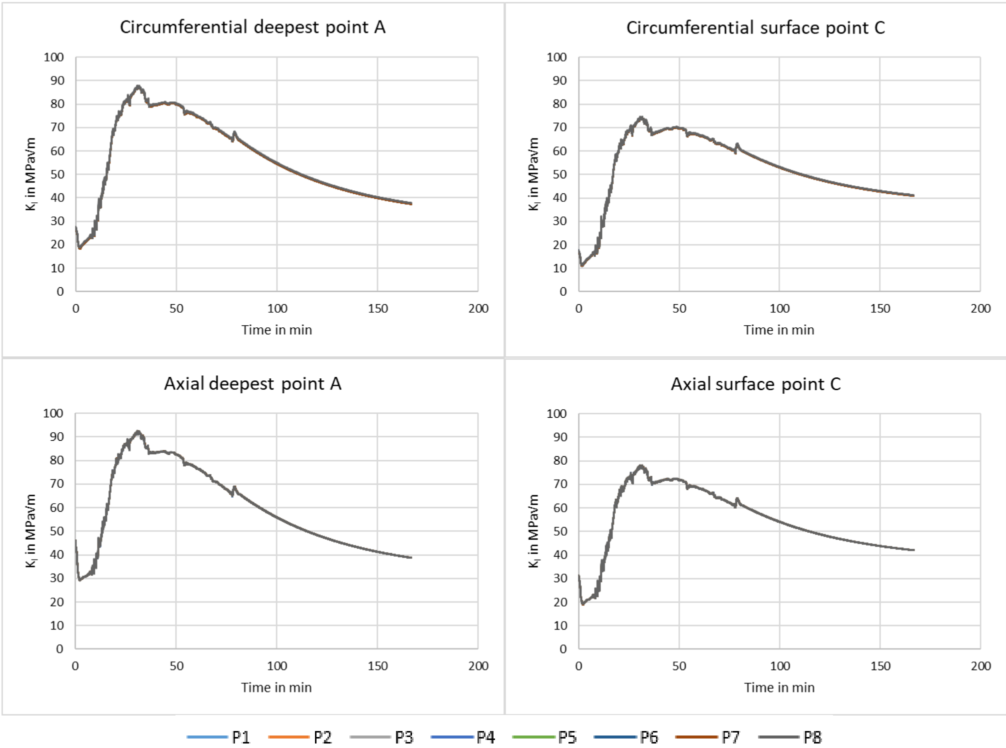

Figure 2. Results for SIF for TCC with CEA method

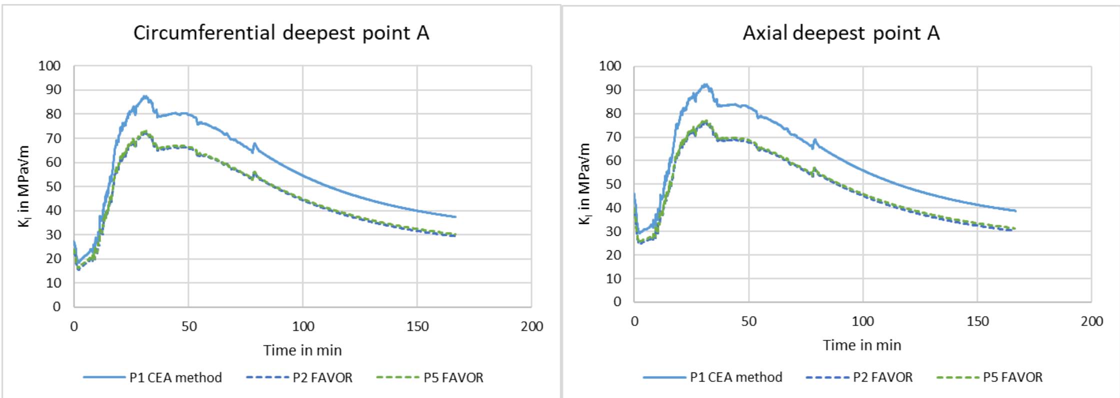

Figure 3. Results for SIF for TCC, comparison of CEA and FAVOR method

A second task of the benchmark part 1 was a comparison of the CEA method (Marie, Chapuliot (2008)) and the FAVOR method (Williams et al. (2016)) for SIF calculation, see Figure 3. This is relevant for the further benchmarks in WP3 (LTOs and margin assessment) and WP4 (probabilistic benchmark), where several partners will use FAVOR for the calculations.

The FAVOR results are different compared to the CEA method since FAVOR uses equations for SIF calculations, which are different from the CEA equations. Within FAVOR, the truncated stress distribution is approximated with a third order polynomial. K_I values are calculated for each of the individual terms and then added to obtain the total K_I value. Also, FAVOR can consider TCC with length to total depth (2c/(a+r)) ratios equal to 2, 6 and 10. The SIF results for the APAL TCC ratio of 3.75 (= 60/(6+10)) are obtained by linear interpolation of the values computed by FAVOR. A clear source of the discrepancy for FAVOR-TCC2 SIF results is thus the linear interpolation for length-to-total-depth ratios of 2 and 6 at the required value of 3.75.

The second subtask of the benchmark consists of the calculation of maximum allowable adjusted reference temperature (max. allow. ART) where the SIF distribution as well as the temperature at each crack tip were provided. Please note that these values are different than the results presented before. For the assessment both the limit condition for the tangent approach and the simplified WPS-max approach were used. The results presented in Figure 4 and Table 1 are in the following units if not stated differently: K_{IC} in MPa√m, max. allow. ART in °C and time of initiation in minutes. The value of K_{IC} corresponds to the time of initiation.

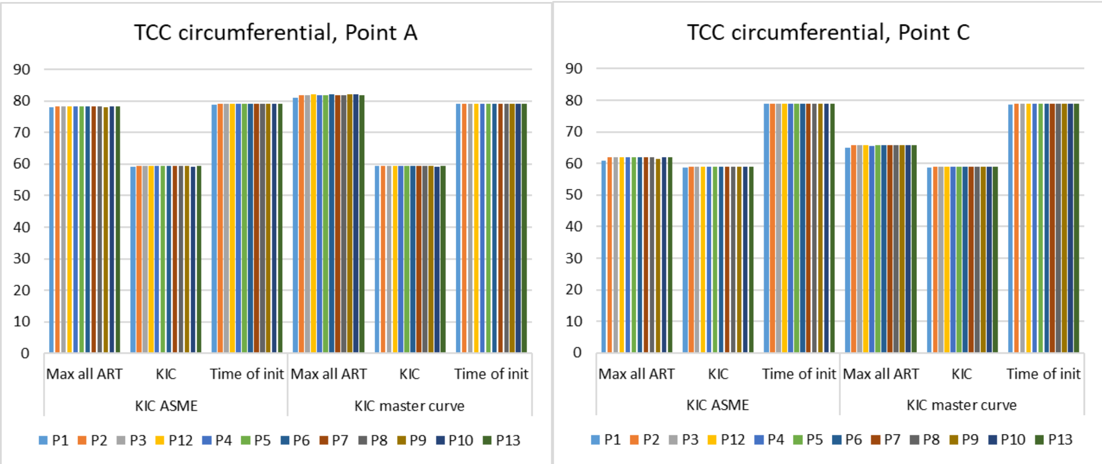

Figure 4. Results for max. allowable ART – circumferential oriented TCC with tangent approach applying RT_{NDT} and master curve concepts

The results agree well between the partners, see Figure 4 for circumferential oriented TCC. The results for the other cases are summarised in Table 1 for the tangent approach and Table 2 for the simple WPS-max. approach, the results are the same for each partner. The results for the master curve concept are without size correction. The difference between the results for the two approaches is quite large, about 40°C. The difference between the ASME and the master curve concepts is small, 4°C for the tangent approach and only 1°C for the simple WPS-max. approach. For UCC there is only a limit on the max. allow. ART for point A, in point C there is no initiation.

Table 1: Results for max. allowable ART – tangent approach

	K_{IC} ASME			K_{IC} master curve		
	Max. allow. ART [°C]	K_{IC} [MPa√m]	Time of init [min]	Max. allow. ART [°C]	K_{IC} [MPa√m]	Time of init [min]
TCC circ. point A	78	59.3	79.1	81	59.3	79.1
TCC circ. point C	61	58.9	78.8	65	58.9	78.8
TCC axial point A	77	60.3	79.1	80	60.3	79.1
TCC axial point C	60	59.7	78.8	64	59.7	78.8
UCC circ. point A	127	40.4	79.2	124	40.4	79.2
UCC circ. point C	-	-	-	-	-	-
UCC axial point A	116	42.2	79.2	118	42.2	79.2
UCC axial point C	-	-	-	-	-	-

Table 2: Results for max. allowable ART – simple WPS-max. approach

	K_{IC} ASME			K_{IC} master curve		
	Max. allow. ART [°C]	K_{IC} [MPa√m]	Time of init [min]	Max. allow. ART [°C]	K_{IC} [MPa√m]	Time of init [min]
TCC circ. point A	138	79.2	31.6	135	79.2	31.6
TCC circ. point C	122	70.5	30.6	122	70.5	30.6
TCC axial point A	138	83.9	30.7	133	83.9	30.7
TCC axial point C	119	74.1	30.6	118	74.1	30.6
UCC circ. point A	164	54.6	30.7	169	54.6	30.7
UCC circ. point C	-	-	-	-	-	-
UCC axial point A	159	58.6	30.7	163	58.6	30.7
UCC axial point C	-	-	-	-	-	-

The results presented in Table 1 and 2 confirm that the tangent approach delivers the lowest results for max. allow. ART, whereas the simple WPS-max delivers the highest results. It can be concluded, that within part 1 of the benchmark the FM calculation chain up to the determination of the max. allow. ART could be verified. As a final step in the round-robin, a non-mandatory task with crack arrest calculations was performed. A good agreement between the participants was achieved, with the same results of crack initiation and arrest for TCC circumferential, axial TCC has a non-arrest behaviour.

BENCHMARK WITH INDIVIDUAL METHODOLOGY AND INPUT

For part 2 of the benchmark only the TH transient description (input for TH calculations) is given as starting point for the calculation chain. Other relevant data (crack type, size, orientation, own SIF solution) remain the same. In this case TH transient results come from outputs of different codes (system code or system code + mixing code). Ten of the APAL partners were involved in this part of the benchmark: Bay Zoltán, Framatome, IPP, JSI, Kiwa, PSI, SSTC, Tecnatom, UJV and WUT. The results are presented anonymously, i.e., every partner is denoted by a number (P1 to P10). The settings and the results of the structural assessment are given in detail in Spisák et al. (2024). The investigated location is the core weld cold leg location, i.e., below the injection nozzle or in the merging plume area (mixing case). Please note that for P6 the inside cold plume (IP) and inside merging plumes (IMP) results are taken from a slightly different position, IP is at 202.5° and IMP is taken from 180°.

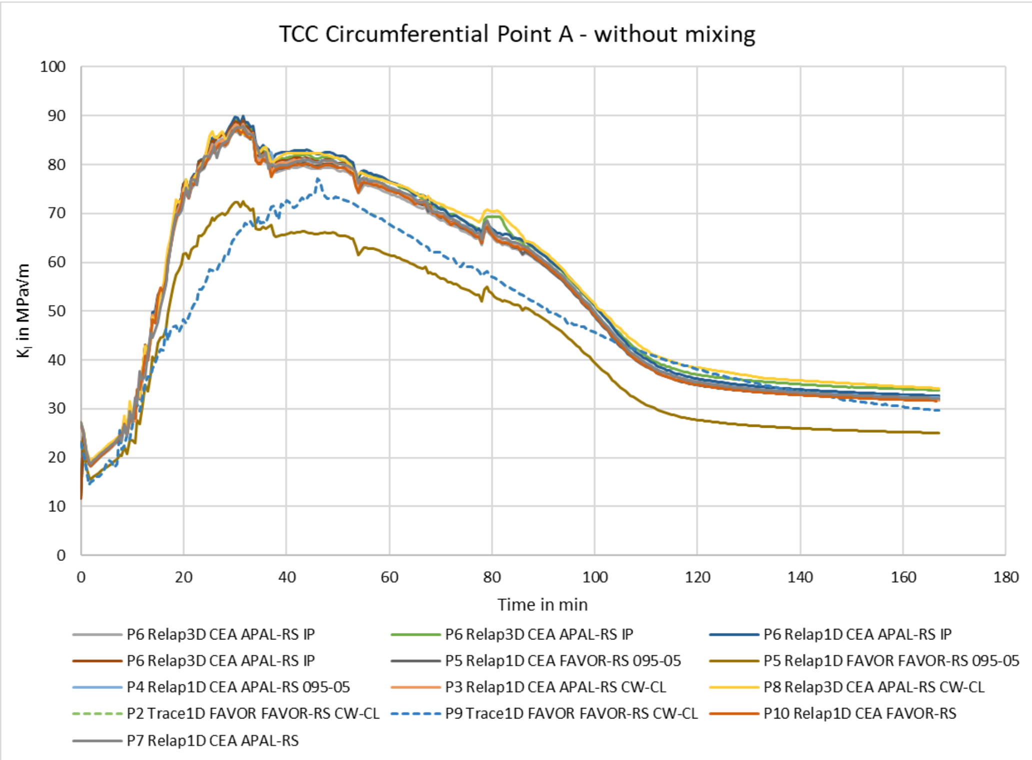

Figure 5. Results for SIF for TCC circumferential point A – without TH mixing

In Figure 5 the results for TCC circumferential point A (deepest point) are shown. The notation CEA/FAVOR corresponds to the SIF solution used, FAVOR-RS/APAL-RS denotes the residual stress profile used. The only results that differ from the others are the ones calculated with FAVOR and/or Trace TH-data. The difference of about 20 MPa√m at the maximum SIF value for the FAVOR results was already seen in the benchmark part 1, it is due to the required interpolation for the crack size defined in the APAL benchmark. The difference between stresses based on Relap and Trace TH codes was already observed in work package 3.1 (Spisák et al. (2024)), the corresponding plot is shown in Figure 6. The results “P6 Relap1D CEA APAL-RS IP” and “P10 Relap1D CEA FAVOR-RS” in Figure 5 differ only in the type of residual stresses used. The results for FAVOR-RS are slightly lower than for

APAL-RS. For the 1D and 3D structural analysis there is no trend in the difference of the two groups of results.

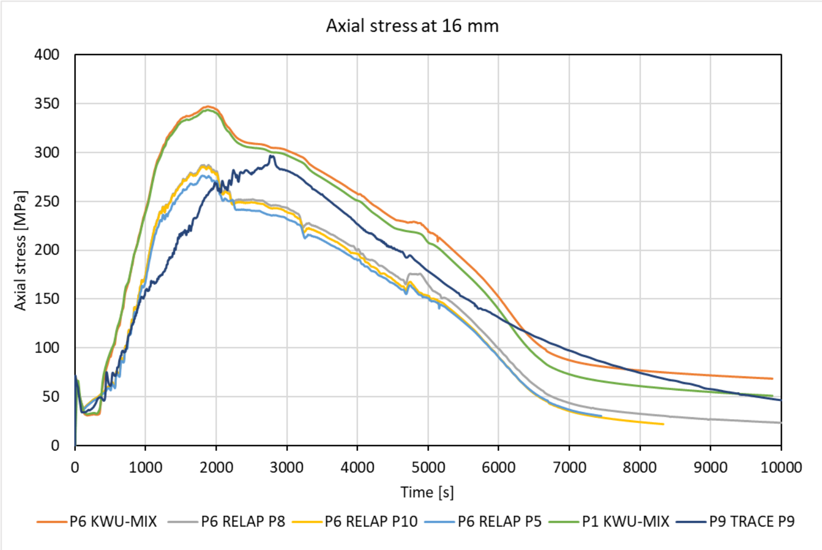

Figure 6. Comparison of stresses based on different TH codes

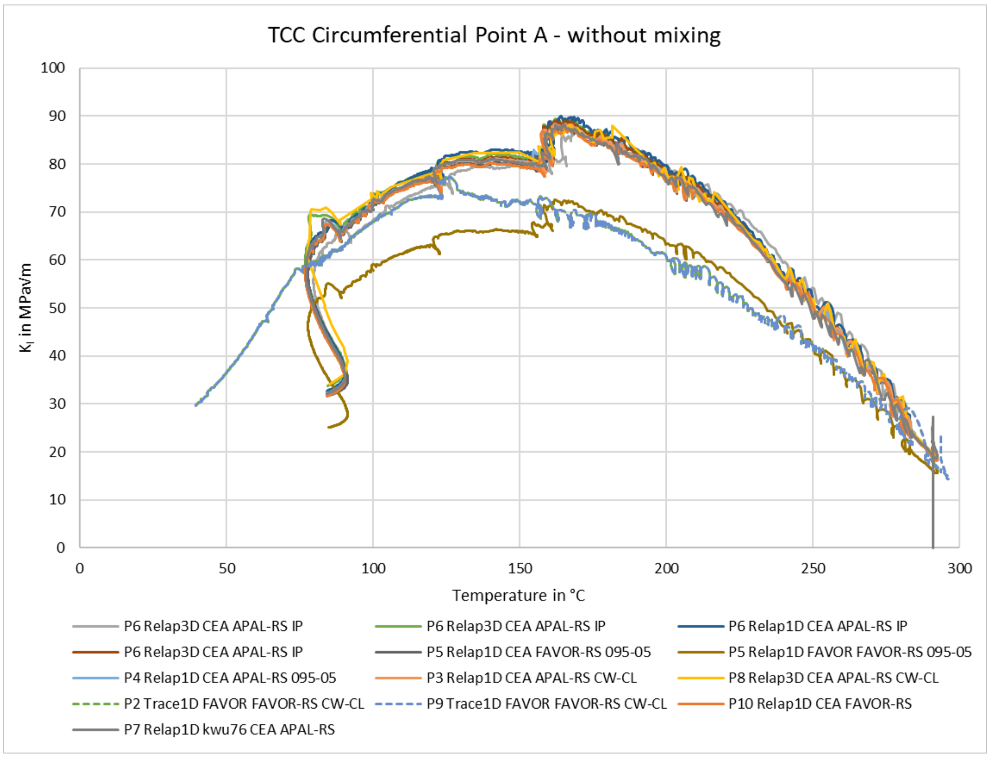

Figure 7. Results for SIF for TCC circumferential point A plotted over temperature – without TH mixing

For the determination of the max. allow. ART not only the K_I curve over time but also over crack-tip temperature is to be considered. The latter are plotted in Figure 7 to help understand the results for the max. allow. ART.

The results for K_I with consideration of TH mixing are shown in Figure 8, plotted over time and over temperature. The results with TH mixing are higher than the results that do not consider mixing. This could be expected, since at the examined location at the cold leg mixing has great significance for the stresses. The different shape of the ECC-Mix based stresses was already observed in the structural assessment (Spisák et al. (2024)). The difference between the two ECC-Mix results is due to the different SIF method used, i.e., FAVOR and CEA.

The results for point C show lower values but have the same tendencies as for point A. For point C there are no FAVOR results. For the axial crack, the same observations and explanations as for the circumferential crack are valid, but with slightly higher values.

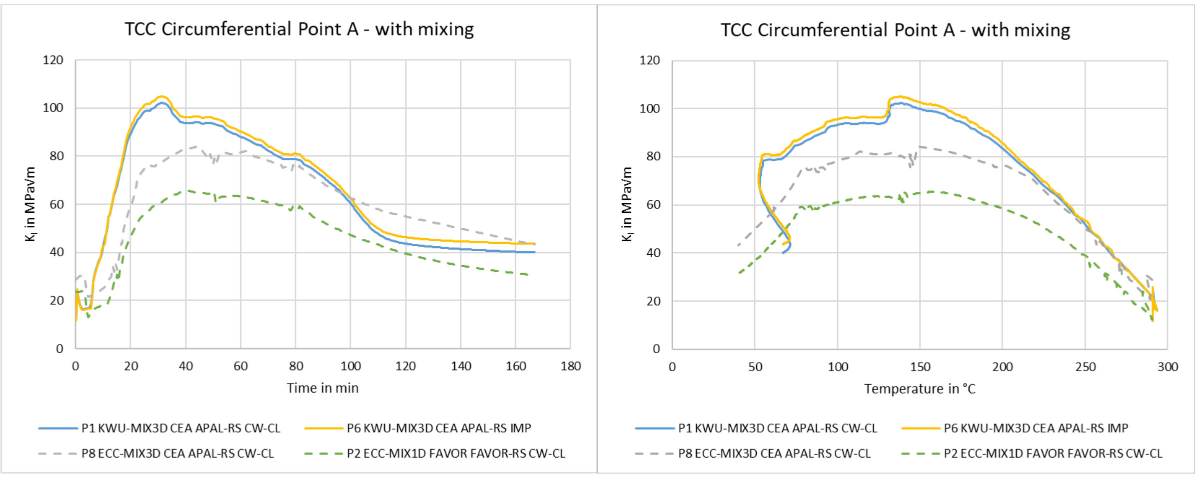

Figure 8. Results for SIF for TCC circumferential point A over time and over temperature – with TH mixing, inside merging plumes

The results for the tangent approach with the ASME and master curve concepts are shown in Figure 9. The results match the K_I results from Figure 7 well when looking at the K_I value at the time of initiation. For example, the result for max. allow. ART with FAVOR is about 15-20 °C higher than with the CEA method. However, the combination of using Trace for the structural assessment and the FAVOR approach for the FM does not make a large difference compared to the Relap and CEA approach. The reason for this is that at the relevant temperature of 75 to 80°C the Trace and Relap results for K_I over temperature are quite close together, see Figure 7. The results for max. allow. ART with consideration of TH mixing are shown in Figure 10. In general the results are lower than without mixing, the difference is large for the KWU-MIX results and smaller for the ECC-MIX results.

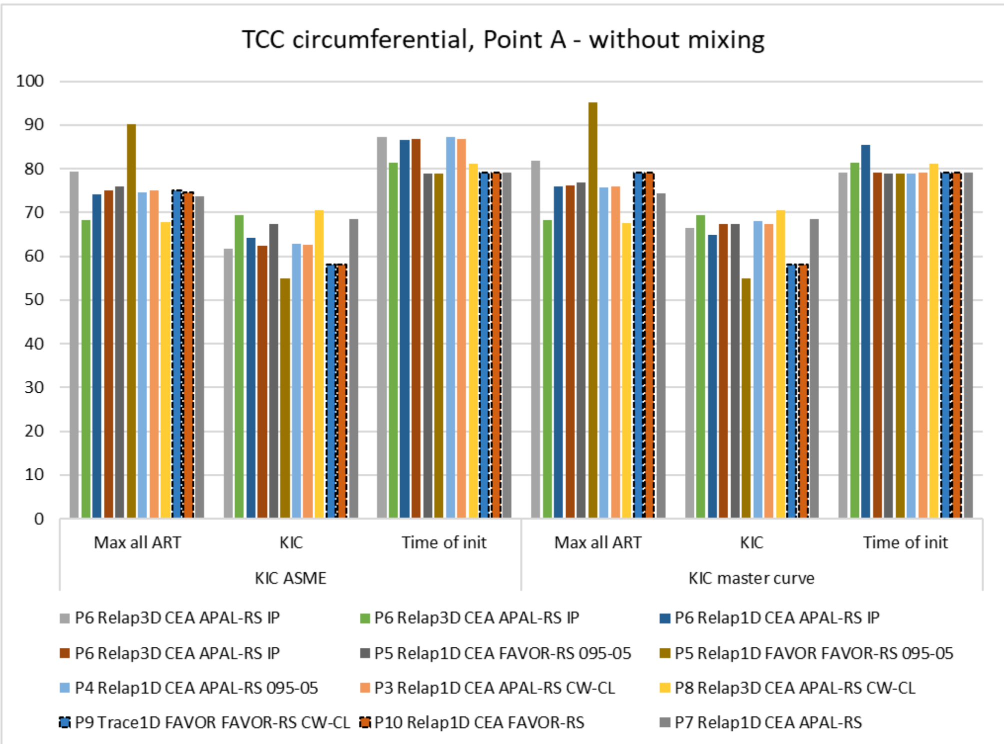

Figure 9. Results for max. allow. ART for TCC circumferential point A – tangent approach, without TH mixing

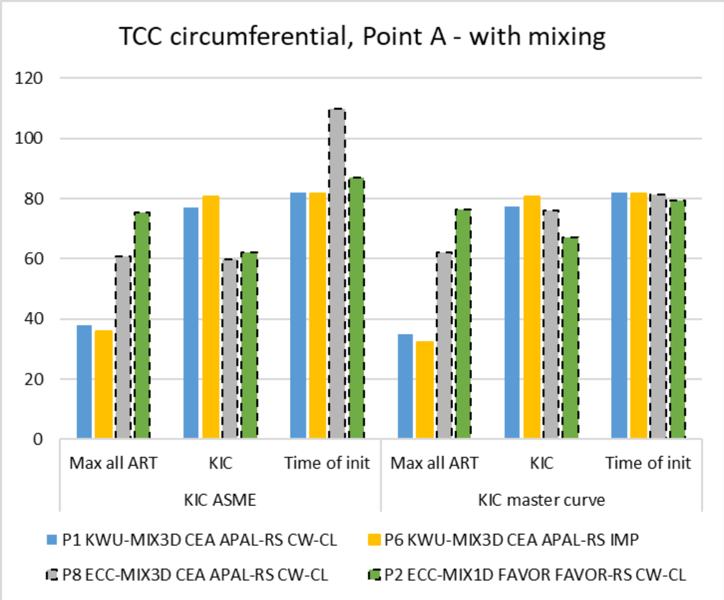

Figure 10. Results for max. allow. ART for TCC circumferential point A – tangent approach, with TH mixing

The results for CW-A outside cold plume (azimuth 337.5°) are shown in Figure 11 and are slightly lower than the results inside plume without TH mixing, but much lower than for the case considering TH mixing (see Figure 8). This could be expected, since at the location outside plume the influence of the TH mixing is small, therefore the results with and without mixing are quite similar. The small difference between the P1 and P5 Relap results was examined in detail to fully understand the deviations. Comparisons were performed and concluded that the input pressures and temperature are quite similar. Also, the use of either APAL or FAVOR residual stresses does not make noticeable difference for the K_I results. It was concluded that the differences in the stress intensity factor values result from differences in the structural assessment, see Spisák et al. (2024). The FAVOR results are again lower than the results for the CEA method. The results for max. allow. ART in Figure 12 match the K_I results.

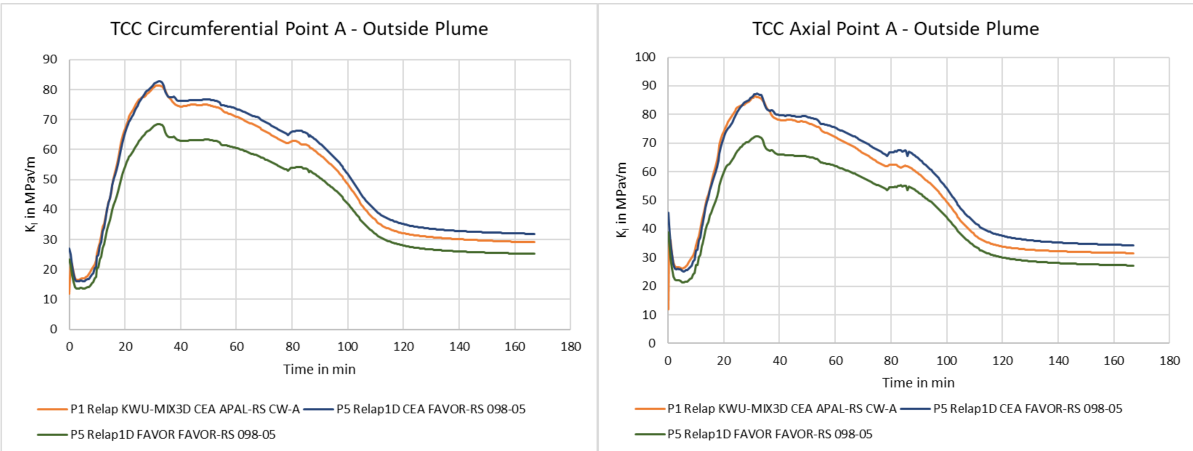

Figure 11. Results for SIF for TCC circumferential point A – outside plume location

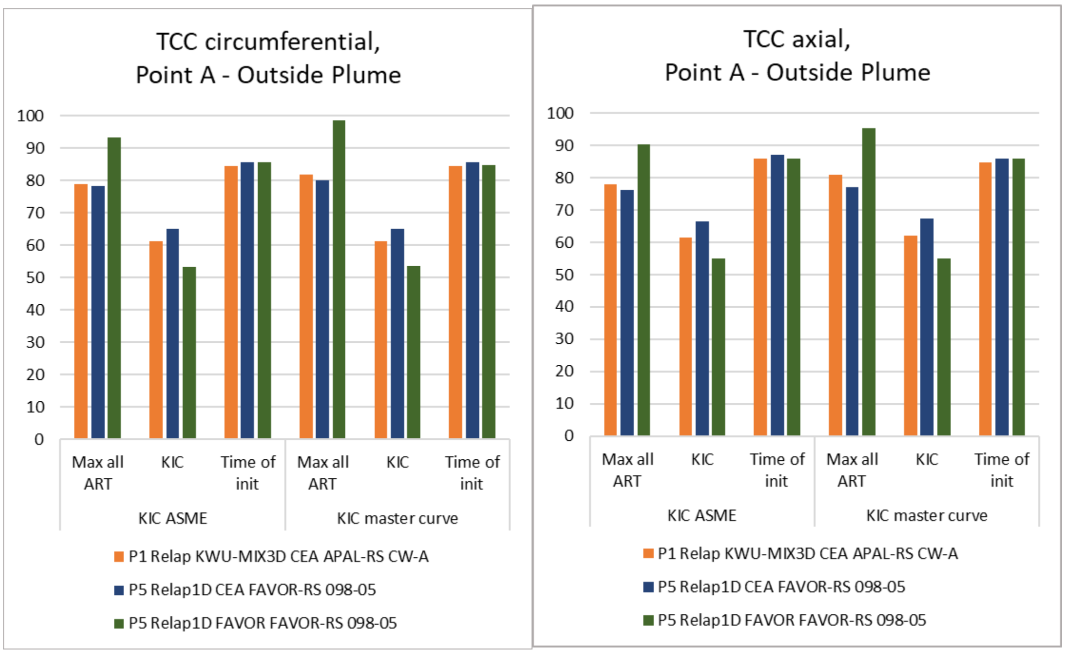

Figure 12. Results for max. allow. ART for TCC circumferential point A – tangent approach, outside plume location

The results for UCC circumferential point A are shown in Figure 13. There are no FAVOR results, since there is no option to consider UCC in FAVOR. The scatter of the results without TH mixing for UCC (Figure 13) is larger than for TCC, where the results without TH mixing were closer together (Figure 5). As for TCC, the results with TH mixing are much larger than the results that do not consider TH mixing. The curve with ECC-Mix data is again different from the others.

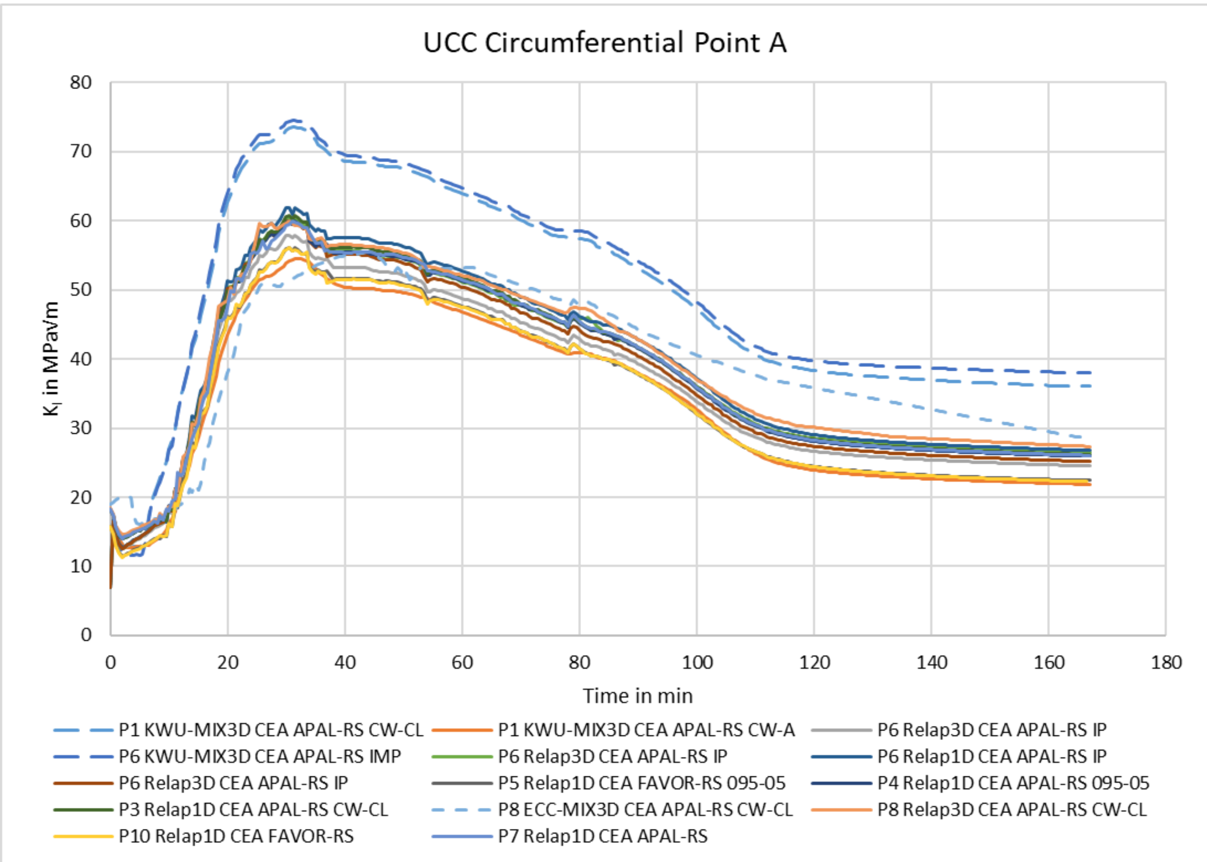

Figure 13. Results for SIF for UCC circumferential point A

CONCLUSION

Within the work package 3.3 of the APAL project extensive calculations for the PTS analysis were performed by each participating partner. This includes SIF calculation, max. allow. ART calculation, and crack arrest calculation. In this paper an extract of the produced results was compared and discussed.

Within part 1 of the benchmark a common understanding of the whole assessment was established since all partners performed the calculation with the same input data and method. The results for the benchmark part 2 show that the choice of TH code, structural analysis, K_I formula and consideration of TH mixing can have a considerable influence on the obtained K_I results and on the max. allow. ART results. This influence is highly dependent on the location, crack orientation, and transient considered. The FAVOR calculation of K_I leads to a lower K_I of up to 20 MPa√m compared to the CEA method for TCC. A part of that difference is probably caused by the required interpolation of crack depth/crack length ratios in FAVOR. The consideration of TH mixing is less relevant in the locations outside of the cold plume. For the locations below cold plume TH mixing can play an influential role, the difference is large for circumferential crack and not so large for the axial crack.

The difference between the calculation of maximum allowable adjusted reference temperature (max. allow. ART) ASME and the master curve approach is small for the tangent approach and negligible for the simple WPS-max. approach. In general, TCC are more dangerous compared to UCC even if a plastic correction formula is applied, the scatter of the results without TH mixing for UCC is larger than for TCC.

ACKNOWLEDGEMENT

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