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DETERMINISTIC ASSESSMENT OF LTO IMPROVEMENTS WITHIN APAL PROJECT

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ABSTRACT

The assessment of the reactor pressure vessel (RPV) resistance against fast fracture during pressurized thermal shock (PTS) accidents is essential for the long-term operation (LTO) of nuclear power plants (NPPs). Several "LTO improvements" (both NPP parameter improvements and operator actions) focused on mitigating PTS conditions were analysed within the APAL project. APAL (Advanced PTS Analysis for LTO) project was funded by the EU within the HORIZON 2020 program.

The impact of the selected LTO improvements on the RPV integrity during PTS events was investigated based on a Loss-of-Coolant Accident (LOCA) transient scenario arisen from a 50 cm^2 break in a 4-loop NPP of German Konvoi design. The LTO improvements that have a potential impact on PTS analysis results were identified in APAL Work-package 1 (WP1), and the appropriate advanced thermal-hydraulic (TH) analyses were performed within WP2. Based on the results obtained from these analyses, nine LTO were selected for further deterministic structural and fracture-mechanics PTS analyses within WP3. Some examples of the results are presented in this paper.

INTRODUCTION

One of the most limiting safety assessments for long-term operation (LTO) of nuclear power plants (NPPs) is the reactor pressure vessel (RPV) integrity assessment for pressurized thermal shock (PTS). PTS is characterized by rapid cooling of the downcomer and internal RPV surface, which leads to high thermal stresses in RPV wall, accompanied in some cases by high coolant pressure in the RPV. If a flaw existed in an embrittled RPV and PTS occurred, the flaw could initiate fast fracture, which would challenge the integrity of the RPV. Thus, PTS evaluation is important to support the LTO.

PTS assessment is a multidisciplinary task, covering such processes as selection of transients to be assessed, performing the sequence of thermal-hydraulic (TH) analyses (both system TH analyses of the whole NPP and detailed analyses of mixing in the reactor downcomer and in the cold legs with safety injection), structural analyses (STA) and fracture-mechanics analyses (FMA).

In the EU, PTS analyses are currently based on deterministic assessments with conservative input data (both TH and STA+FMA).

One of the main objectives of the APAL project (Advanced PTS Analysis for LTO) was to determine the impact of selected LTO improvements (i.e., such improvements of NPP parameters or operator actions that can help mitigate the PTS conditions) on PTS analysis results. This impact was investigated based on Loss-of-Coolant Accident (LOCA) transient scenario arisen from a 50 cm^2 break in a 4-loop NPP of German Konvoi design. The analysed PTS transient was based on transient T2 from the OECD NEA ICAS project, see OECD NEA (1999).

Nine LTO improvements that could have a potential impact on PTS analysis results were identified in APAL Work-package 1 (WP1), and the appropriate advanced TH analyses were performed within WP2. Based on the results obtained from these analyses, the subsequent deterministic PTS analyses were performed within APAL WP3. Their selected results are presented in this paper.

The quantification of safety margins in terms of risk of RPV failure during PTS based on advanced probabilistic methods was also significant part of APAL project, but it is not described in this paper.

APAL PROJECT – OVERVIEW

The international project APAL (Advanced PTS Analysis for LTO) was performed from October 2020 till September 2024. The project was funded by the EU within HORIZON 2020 program under the Grant agreement number 945253. The APAL project involved 14 partners from 11 EU countries (including Ukraine) plus 2 international partners (USA, Japan) with in-kind contributions. The main objectives of the APAL project were developing advanced probabilistic PTS assessment methods, quantifying safety margins for LTO improvements, and developing best-practice guidance.

The work within APAL was divided into six technical work packages (WPs):

WP1 (LTO improvements relevant for PTS analysis) consisted of an extensive literature review and collection of experience to identify the state of the art of LTO improvements with an impact on the results of PTS analysis. One task was dedicated to further potential LTO improvements (due to adjustment of NPP parameters, including operator actions) relevant to PTS analysis. Nine such improvements were defined, which are discussed in this paper. WP1 results are gathered in the report by Cueto-Felgueroso et al. (2021) publicly available on the APAL project web page.

In WP2 (entitled Improved TH analysis), several TH analyses were performed for the selected LOCA 50 cm^2 transient scenario, including the analyses for nine LTO improvements with boundary conditions changed compared to the “base case” (BC); these TH analyses were the basis for the performed STA+FMA, as described in this paper. The system and mixing TH codes used by the APAL partners in the simulations were RELAP5, ATHLET, TRACE, KWU MIX, GRS-MIX and ECC-MIX. Results of WP2 are gathered in the document by Kral et al. (2023).

The objective of WP3 (entitled Deterministic margin assessment) was to determine the impact of LTO improvements and uncertainties in TH data on PTS analysis by deterministic structural and fracture mechanics assessment. Margins (in terms of maximum allowable reference temperature) related to selected LTO improvements were quantified to evaluate their benefit for PTS analysis. The benefit quantification was performed by comparing the results for the case with LTO improvement to the results for the base case (without LTO improvements). These results are described in the subsequent chapters of this paper. A comprehensive overview of all results reached in WP3 is given in Tiete et al. (2024).

The objective of WP4 (entitled Probabilistic margin assessment) was to determine the impact of LTO improvements and uncertainties in thermal hydraulic data on PTS analysis by performing a probabilistic assessment. The assessment allows for the quantification of safety margins in terms of the risk of brittle fracture initiation or RPV failure. Probabilistic PTS analyses are not discussed in this paper. A comprehensive overview of the results achieved in WP4 is given in Shipsha et al. (2024).

The main output of APAL was prepared within WP5 (Definition of best practices for advanced PTS analysis), see Cueto-Felgueroso et al. (2024). The best-practice guidance was formulated considering improved methodologies and recommendations for the assessment of LTO improvements. It describes the advanced methods assessed in the project (both deterministic and probabilistic).

The overall presentation of APAL project was given in SMiRT 27 conference by Pištora (2024) together with 7 detailed presentations on different APAL results within the special session „European Horizon 2020 APAL project results“.

SHORT DESCRIPTION OF THE LTO IMPROVEMENTS AND RESULTS OF TH ANALYSES

Nine LTO improvements were defined in WP1, see Cueto-Felgueroso et al. (2021), as listed in Tab. 1.

Table 1: List of LTO improvements selected for deterministic PTS analyses

No.	LTO improvement description	Simulated change
1	Heating of water in the high-pressure safety injection (HPSI) tanks	Heated from 15 °C to 45 °C
2	Heating of water in the accumulators (ACCs)	Heated from 20 °C to 50 °C
3	Heating of water in the low-pressure safety injection (LPSI) tanks	Heated from 15 °C to 45 °C
4	Decreasing the HPSI head	Decreased down to 75%
5	Decreasing the HPSI capacity	Decreased down to 75 %
6	Reduction of HPSI flow (operator action)	Reduced at 1800 s to one pump
7	Decreasing of ACCs pressure	Decreased from 26 bar to 20 bar
8	Change of cool down rate (operator action)	Changed from 100 K/h to 200 K/h
9	Isolation of ACCs (operator action)	ACC isolated at 500 s

TH analyses of the base case (i.e., without considering any LTO improvement) as well as of the nine LTO improvements were performed in WP2, see Kral et al. (2023). The TH analyses were split among all partners involved in WP2. Some partners performed only system TH analyses (using RELAP5, ATHLET or TRACE code), while other partners continued with mixing TH analyses (using KWU MIX, GRS-MIX or ECC-MIX code). In Figs. 1 and 2, the main TH results for LTO improvements No. 1 and 6 (compared to the base case) are shown. The main outputs of TH analyses, which serve as input data for subsequent structural analyses, are inner pressure, coolant temperature and heat transfer coefficient (not shown here) in reactor downcomer. The results shown in this paper are in most cases limited to LTO improvements No. 1 and 6, which were finally found among the most beneficial from the PTS point of view.

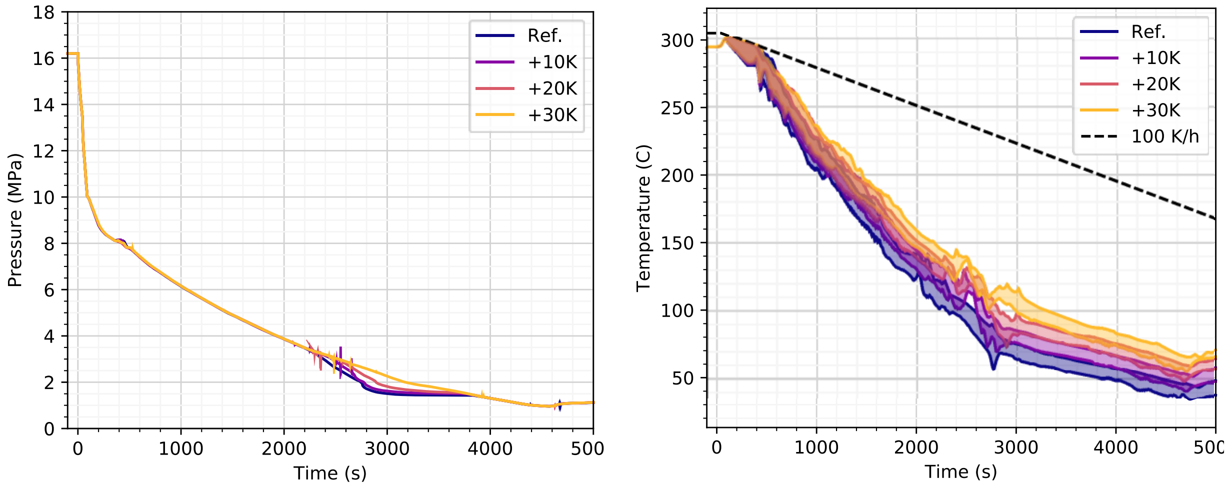


Figure 1. LTO improvement No. 1 (heating of water in the HPSI tanks). TRACE results. Time variation of pressure (left) and coolant temperature range (minimum to maximum) (right) in the downcomer at 2.638 m below the cold nozzle (core weld position). 3 variants of heating of HPSI tanks considered.

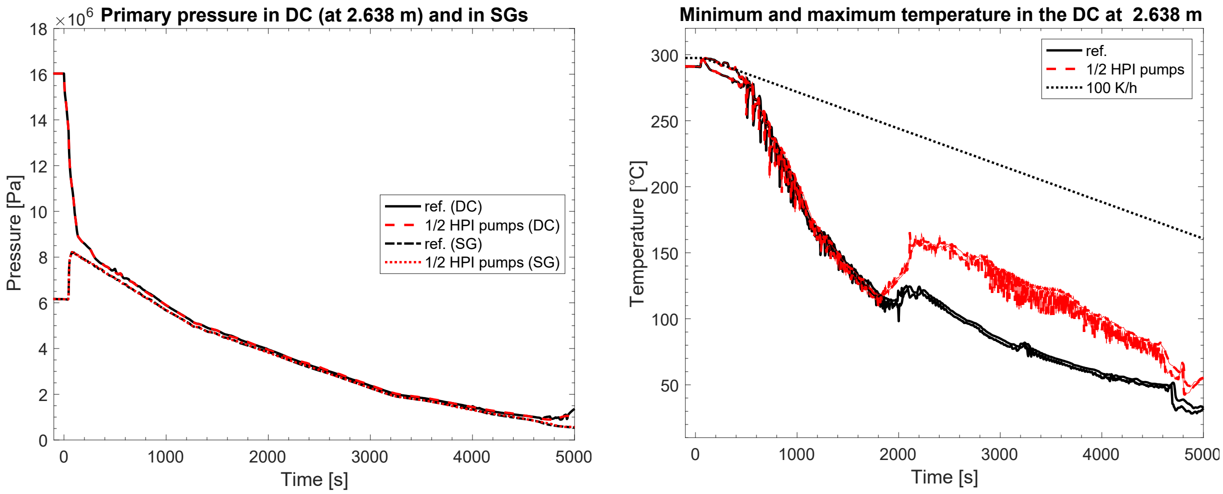


Figure 2. LTO improvement No. 6 (reduction of HPSI flow - operator action). RELAP5 results. Time variation of pressure (left) and coolant temperature range (minimum to maximum) (right) in the downcomer at 2.638 m below the cold nozzle (core weld position).

STRUCTURAL ANALYSES RELATED TO LTO IMPROVEMENTS

Within Task 3.1 of APAL WP3, a large number of structural analyses (i.e., calculations of temperature and stress fields in the RPV wall) was performed. Different partners involved in WP3 used different finite element (FE) codes and models as well as different input TH data (preferably from their own TH analyses, but in some cases from other partners). Both 1D and 3D FE models were used within the analyses. Unified RPV geometry and material properties were prescribed within the benchmark definition. Results of the benchmark are available in Tiete R. et al. (2024). Presentation of this task was given in Spisák B. et al. (2024). Examples of results for LTO improvements No. 1 and 6 are shown in Figs. 3 and 4.

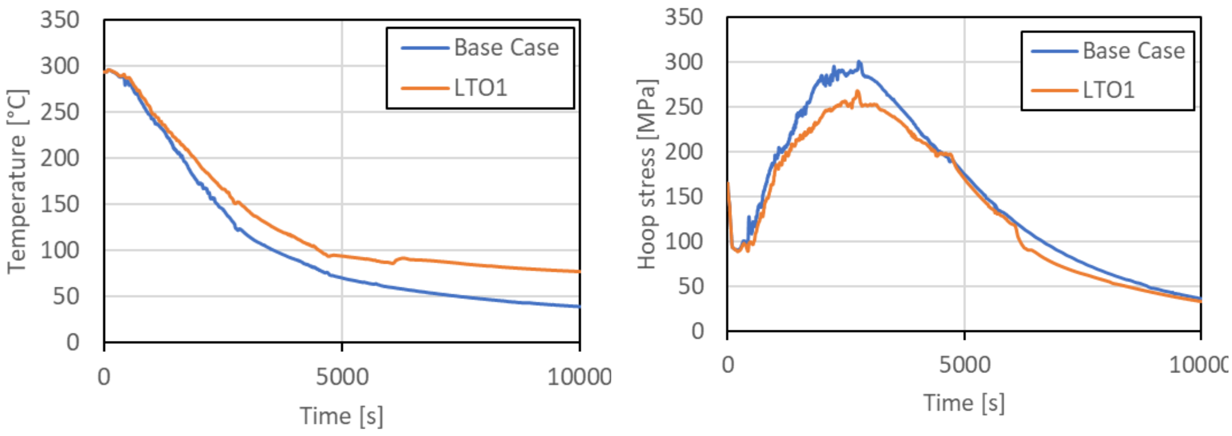


Figure 3. LTO improvement No. 1 (heating of water in the HPSI tanks). Time variation of temperature (left) and hoop stress (right) at 16 mm of RPV wall thickness (deepest point of the postulated crack). Based on TRACE results.

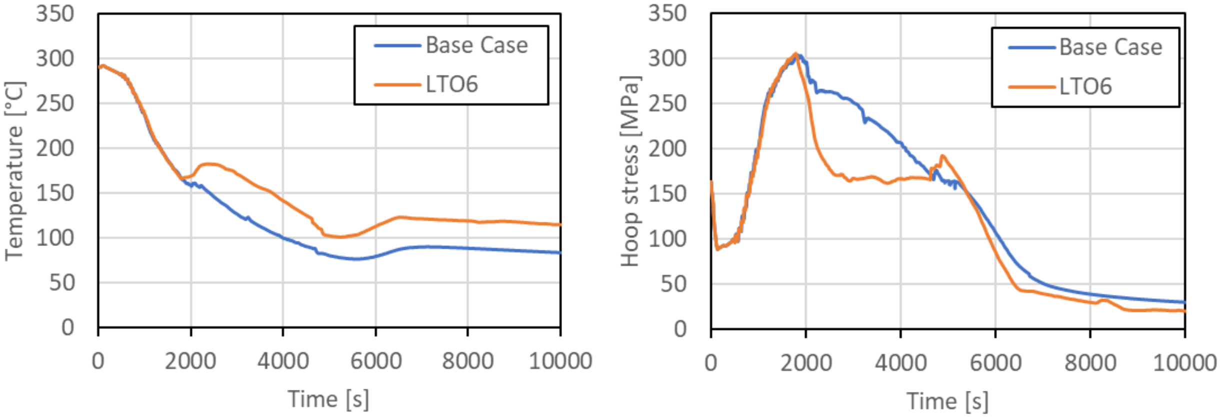


Figure 4. LTO improvement No. 6 (reduction of HPSI flow - operator action). Time variation of temperature (left) and hoop stress (right) at 16 mm of RPV wall thickness. Based on RELAP5 results.

SAFETY MARGINS RELATED TO LTO IMPROVEMENTS

Overview of APAL Task 3.4

The goal of Task 3.4 of APAL WP3 (which is the main subject of this paper) was to determine the benefit (margin) of the individual LTO improvements with respect to the "base case" scenario (i.e., scenario without any LTO improvement). The margin was determined in terms of the maximum allowable adjusted reference temperature (max. all. ART).

In task 3.4, the following work was performed:

- Fracture-mechanics calculations to determine the stress intensity factors K_I in specified points of the postulated crack for the examined LTO improvements.
- Evaluation of max. all. ART (RT_{NDT}^a or T_0^a) for the examined LTO improvements using both tangent approach and warm-prestressing (WPS) approach.
- Comparison of max. all. ART values for the examined LTO improvements with the corresponding value for the base case.
- Evaluation of margins in RPV integrity due to individual LTO improvements.

Definition of the benchmark

Definition of the fracture-mechanics benchmark is given in Tiete R. et al. (2024) and briefly also in Blasset S., Tiete R. (2024).

For the benchmark, the semi-elliptical crack was postulated, both through-clad crack (TCC) and under-clad crack (UCC), see Fig. 5. Some partners analysed also embedded cracks using FAVOR code (not shown in this paper). Both axial and circumferential orientation of the crack was investigated. The dimensions of the postulated crack are $a = 10$ mm, $2c = 60$ mm, and $r = 6$ mm (a is the crack depth, c is its half-length, r is austenitic cladding thickness). The assessment was performed for the deepest point A and the corner point C (near interface point in the ferritic material) on the crack front of the TCC and UCC. Crack location was prescribed below the cold plume at the elevation of the core weld (2638 mm below the nozzle centreline). The fracture toughness curve K_{IC} based on RT_{NDT} reference temperature corresponding to 5% lower bound was prescribed. Two basic approaches to PTS assessment were applied: tangent approach, where the condition $K_I \leq K_{IC}$ must be fulfilled throughout the whole PTS transient, and max WPS approach (as an alternative name "simple WPS approach" is used), where the condition $K_I \leq K_{IC}$ must be fulfilled only until the global maximum of K_I is reached. Residual stresses (RS) in the weld and in the cladding were also prescribed.

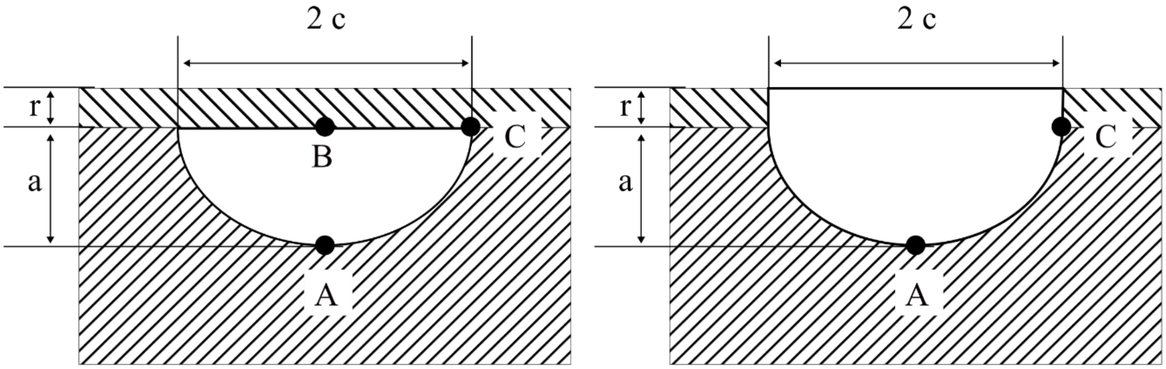
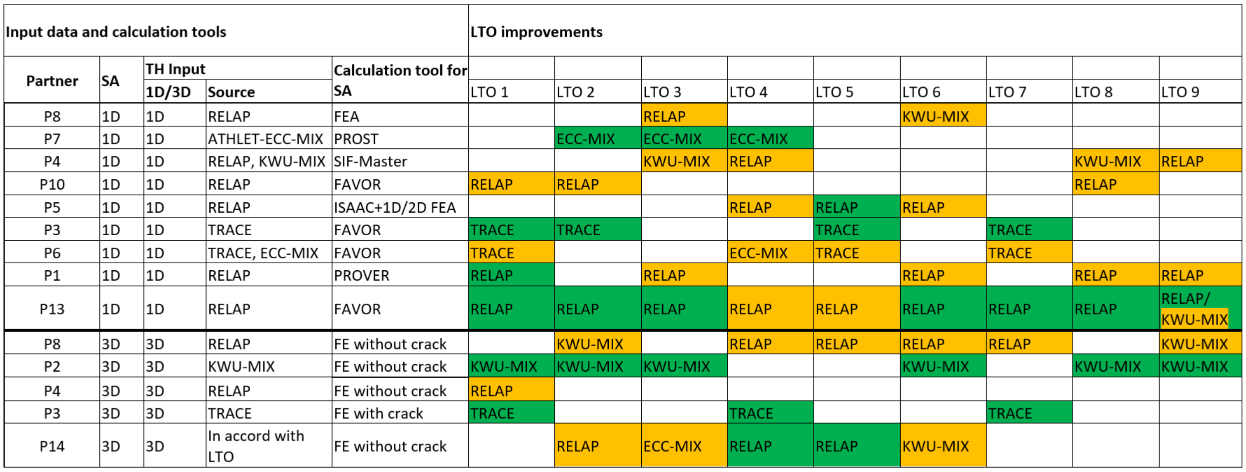


Figure 5. Postulated cracks

Some non-mandatory tasks were also defined and analysed by some partners, e.g., calculation of max. all. ART based on 5% fracture-toughness curve associated with Master curve reference temperature T_0, calculation of max. all. ART based on median fracture-toughness curves (based on RT_{NDT} or T_0), crack arrest analysis (for the base case only), other (national) WPS approaches, crack postulated in other RPV position, etc. The non-mandatory tasks are not presented in this paper.

The split of the LTO improvements analyses among 11 APAL partners involved in Task 3.4 (including indication of the calculation tools used and TH input data source) is shown in Tab. 2. Green colour in the table means that partner's own TH code was used, while yellow colour means that partner used another partner's TH data. Apart from the LTO improvements, all partners were obliged to analyse the base case. Some results of the deterministic benchmark for the base case are presented in Angermeier K.et al (2024).

Table 2. Distribution of LTO improvements task among partners



Input data and calculation tools					**LTO improvements**								
Partner	**SA**	**TH Input**		**Calculation tool for SA**									
		1D/3D	**Source**		LTO 1	LTO 2	LTO 3	LTO 4	LTO 5	LTO 6	LTO 7	LTO 8	LTO 9
P8	1D	1D	RELAP	FEA			RELAP			KWU-MIX			
P7	1D	1D	ATHLET-ECC-MIX	PROST		ECC-MIX	ECC-MIX	ECC-MIX					
P4	1D	1D	RELAP, KWU-MIX	SIF-Master			KWU-MIX	RELAP				KWU-MIX	RELAP
P10	1D	1D	RELAP	FAVOR	RELAP	RELAP						RELAP	
P5	1D	1D	RELAP	ISAAC+1D/2D FEA				RELAP	RELAP	RELAP			
P3	1D	1D	TRACE	FAVOR	TRACE	TRACE			TRACE		TRACE		
P6	1D	1D	TRACE, ECC-MIX	FAVOR	TRACE			ECC-MIX	TRACE		TRACE		
P1	1D	1D	RELAP	PROVER	RELAP		RELAP			RELAP		RELAP	RELAP
P13	1D	1D	RELAP	FAVOR	RELAP	RELAP	RELAP	RELAP	RELAP	RELAP	RELAP	RELAP	RELAP/ KWU-MIX
P8	3D	3D	RELAP	FE without crack		KWU-MIX		RELAP	RELAP	RELAP	RELAP		KWU-MIX
P2	3D	3D	KWU-MIX	FE without crack	KWU-MIX	KWU-MIX	KWU-MIX			KWU-MIX		KWU-MIX	KWU-MIX
P4	3D	3D	RELAP	FE without crack	RELAP								
P3	3D	3D	TRACE	FE with crack	TRACE			TRACE			TRACE		
P14	3D	3D	In accord with LTO	FE without crack		RELAP	ECC-MIX	RELAP	RELAP	KWU-MIX			

Results of fracture-mechanics calculations

In this subsection, selected results of the APAL Task 3.4 for TCC are presented. The results are presented in such form that for each LTO improvement, the following comparative figures were constructed:

- K_I vs. T curves (where T means temperature of the crack point assessed) were compared between the partners. For calculations of K_I values, either engineering methods or results from 3D FE calculations with crack included in the mesh were used.

- Values of max. all. ART for LTO and BC, as well as values of LTO margin were compared between the partners using bar plots. In these plots, LTO margin means the following difference: max. all. ART for LTO – max. all. ART for BC.

The comparison was performed separately for each crack configuration (TCC/UCC, axial/circumferential, point A/point C) and for each approach (tangent/WPS-max), but due to lack of space not all cases are shown in this paper.

The basic information about K_I vs. T curves regarding the effect of crack orientation and effect of point position on the crack front can be seen in Fig. 6. It is seen that the difference between axial and circumferential crack for the analysed case is negligible. In the deepest point of the crack (A) the stress intensity factor is higher than in the near interface point C; however, the temperature in point C at the corresponding time is lower than in point A.

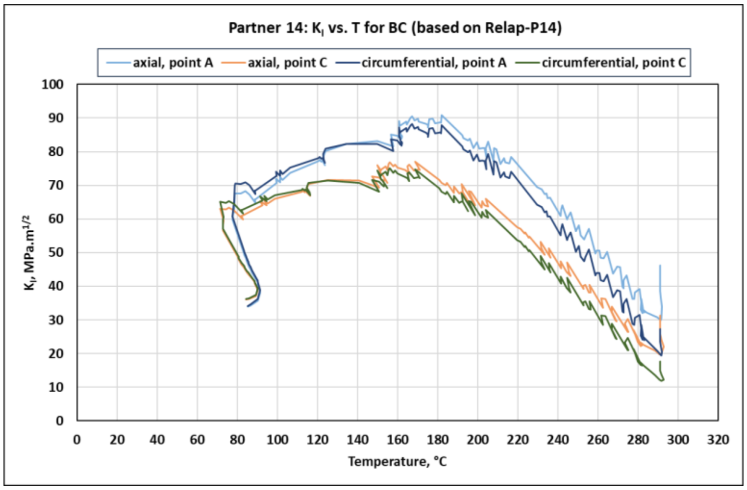


Figure 6. K_I vs. T curves for one partner, for base case, based on RELAP5, for TCC, 4 configurations (axial/circumferential, point A/point C).

Examples of results (K_I vs. T curves) for LTO improvements No. 1 and 6 compared with the base case, for axial TCC, deepest point A, for TH analyses without mixing, are shown in Fig. 7. The values of max. all. ART for BC, LTO improvements No. 1 and 6 and Delta max. all. ART (“margin”) for axial TCC in point A, using tangent approach are shown in Fig. 8 using bar plots. The analogous plot for max WPS approach is shown in Fig. 9. It can be concluded from figure 8 that there are big differences among partners concerning max. all. ART for BC or LTO improvement, namely between Partner 2 and other partners. The reason is obvious – using KWU-MIX code for TH mixing calculations by Partner 2 gives a more pronounced cold plume and thus more conservative results. It should be noted that these results are more realistic than directly using results of system TH calculations as input data for STA and FMA. Despite the differences in max. all. ART for BC and for LTO improvements, the margins (or LTO benefits) expressed as the difference between the max. all. ART for LTO improvement and for BC compare well. The benefit of LTO improvement No. 1 is in the range 20 ºC – 30 ºC and the benefit of LTO improvement No. 6 is in the range 10 ºC – 20 ºC. When using max WPS approach, the max. all. ART values are generally much higher than for the tangent approach (which was expected), but the benefits of LTO improvements are smaller.

In Fig. 10, the K_I vs. T curves for seven LTO improvements (separately for the most influential and for the least influential ones) together with the curves for BC are presented. The curves are based on analyses of one APAL partner to be comparable (to exclude user or model effect).

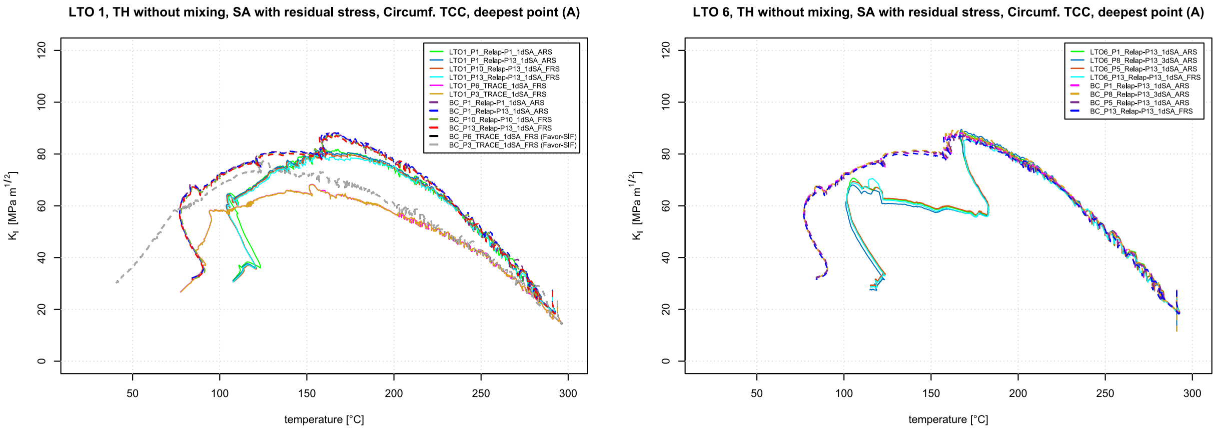


Figure 7. K_I vs. T curves for the base case and LTO improvement No. 1 (left) and 6 (right), for axial TCC, in point A. (FRS=Favor RS, ARS=APAL RS)

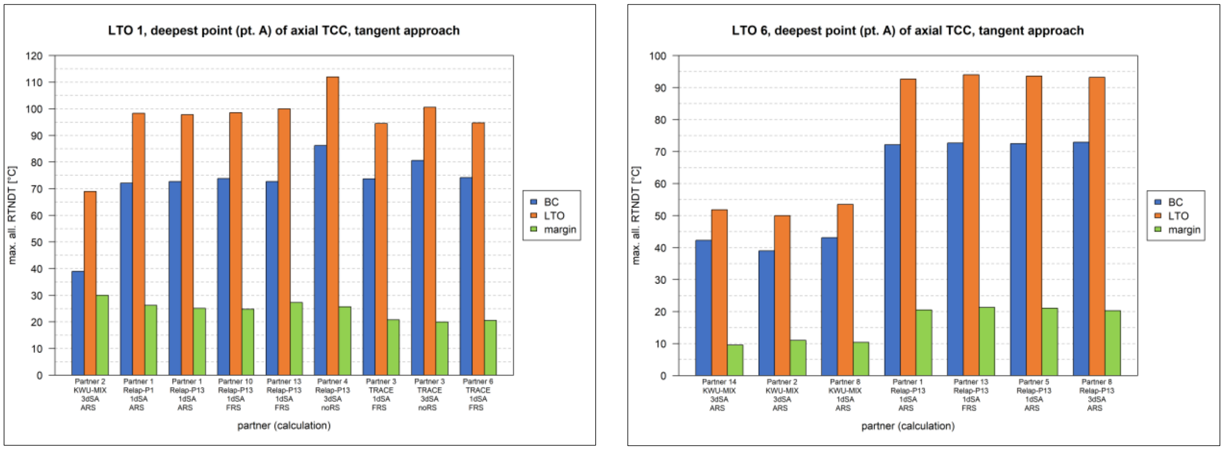


Figure 8. Values of max. all. ART for BC, LTO improvement No. 1 (left) and 6 (right) and LTO margin for different partners, models and TH input data. Results for axial TCC in point A, tangent approach.

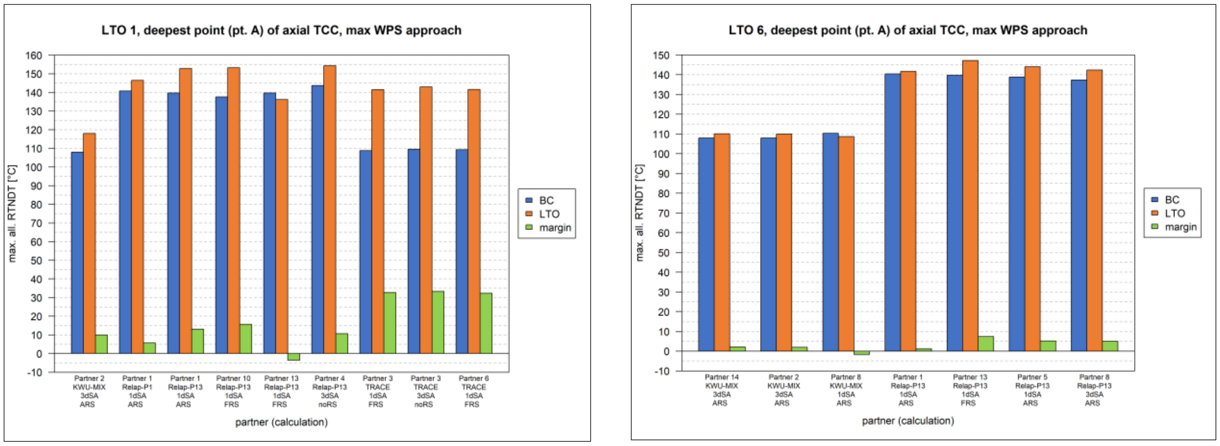


Figure 9. Values of max. all. ART for BC, LTO improvement No. 1 (left) and 6 (right) and LTO margin for different partners, models and TH input data. Results for axial TCC in point A, max WPS approach.

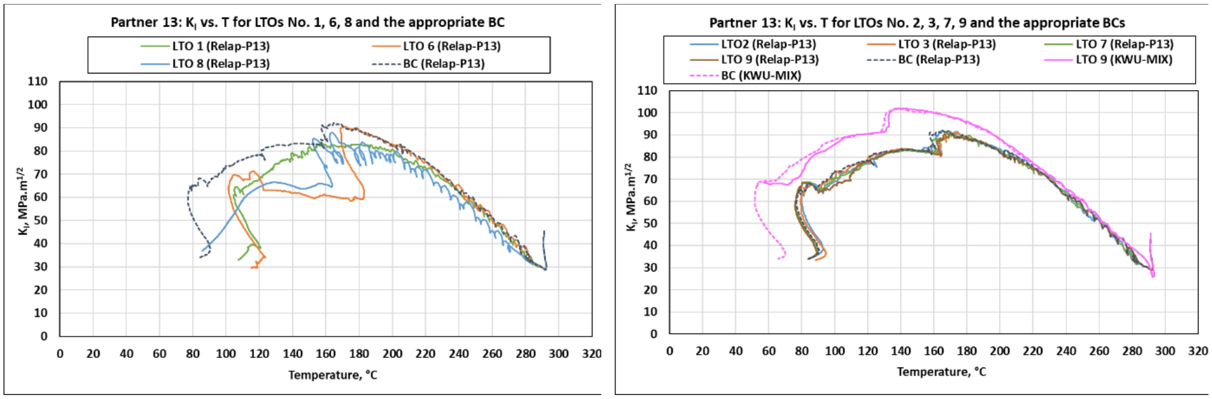


Figure 10. K_I vs. T curves for the base case and most influential (left) or least influential (right) LTO improvement, for axial TCC, in point A

The resulting plots summarize the margins (benefits) for all LTO improvements together. These graphs were constructed for each of the crack configurations (TCC/UCC/embedded, axial/circumferential, point A/point C) but, due to lack of space, only the results for axial crack in point A for both applied approaches (tangent/max WPS) are presented in Fig. 11. The TH code used for generation of input TH data is also indicated in the graphs.

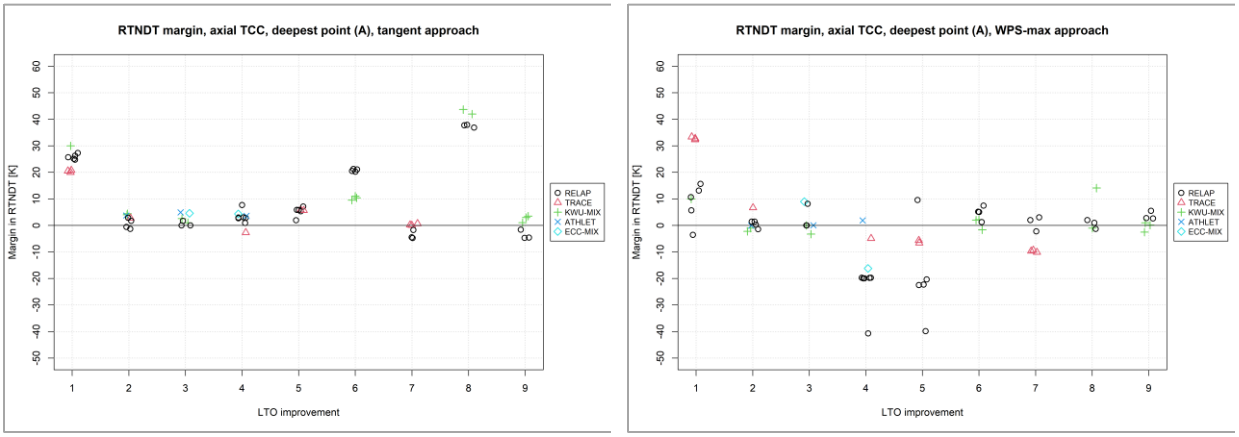


Figure 11. Comparison of LTO margins for all LTO improvements, tangent approach (left) and max WPS approach (right), for axial TCC, in point A

For results related to the tangent approach, the following conclusions may be drawn:

- the largest margins (i.e., the most beneficial effect on max. all. ART) are obtained for LTO 1 (Heating of water in the HPSI tanks), LTO 6 (Reduction of HPSI flow – operator action) and LTO 8 (Change of cool down rate – operator action),
- insignificant effect (in average zero effect, or even small negative effect) is obtained for all other LTOs, i.e., LTOs No. 2, 3, 4, 5, 7, 9,
- from the other results (not presented in this paper), it could be concluded that there was no significant qualitative difference between figures related to different crack orientations (axial/circumferential) and points on the crack front (A/C).

For results related to the max WPS approach, the following conclusions may be drawn:

- The scatter of LTO margins for individual LTO improvements is relatively large (significantly larger than in case of tangent approach).
- There is a positive effect of LTO 1, while LTO 4 and LTO 5 exhibit negative margins (worsening effect on max. all. ART).
- The large scatter in the data for individual LTO improvements witnesses in favour of the fact that the max WPS approach is very sensitive to the shape of K_I vs. T curve, which in turn is very sensitive to both the TH code used and the transient parameters selected. Consequently, the max. all. ART calculated based on max WPS approach is not a stable quantity with respect to various aspects associated with both TH analysis and structural and/or fracture-mechanics analysis.

CONCLUSION

The EU-funded APAL (Advanced PTS Analysis for LTO) project investigated, among many other tasks, the impact of selected LTO improvements on RPV integrity during PTS events. The analyses were performed for the LOCA 50 cm^2 PTS transient. The LTO improvement benefit was determined in terms of an increase of the maximum allowable adjusted reference temperature (max. all. ART) compared to the “base case”.

The LTO improvement No. 1 (heating of water in the high-pressure safety injection tanks), LTO improvement No. 6 (reduction of high-pressure safety injection flow – operator action) and LTO improvement No. 8 (change of cool down rate – operator action) were found to be the most influential for the tangent approach. Only LTO No. 1 exhibited some benefit if WPS-max approach was applied, while other LTO improvements exhibited none or worsening effect.

ACKNOWLEDGEMENT

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