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COMPREHENSIVE ANALYSIS OF THE WPS EFFECT PERFORMED FOR THE PURPOSES OF RPV LONG-TERM OPERATION

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ABSTRACT

Within the EU HORIZON 2020 APAL (Advanced PTS Analysis for LTO) project the comprehensive analysis of the warm pre-stress (WPS) effect was performed. The WPS effect was studied from two points of view: First, WPS experimental background was examined in terms of determining the predictive capability of the WPS models. The second one is computational analysis of the impact of application of WPS models/approaches on the RPV brittle fracture margin for the most representative PTS transients.

Performed analysis of the predictive capabilities of the examined WPS models showed that application of modified Wallin, Chell&Haigh and ACE models leads to conservative predictions in respect to experimental data and, consequently, also in respect to RPV brittle fracture assessment.

The values of the maximum allowable transition temperature were calculated using different approaches: without considering WPS effect, then different approaches with considering WPS effect such as the US, Ukrainian, Russian and Czech national WPS approaches, and also using different WPS models, and using the IAEA recommendations. It is shown that almost all WPS approaches, except Ukrainian and Russian ones (for some PTS), lead to decreasing of conservatism in RPV safety assessment. The authors recommend using the physically relevant WPS approaches, based on the modified Wallin or ACE models.

INTRODUCTION

Reactor pressure vessel (RPV) is the most important component of the nuclear power plant (NPP). Its replacement is considered as almost impossible for many technical and economic reasons. Demonstration of the RPV integrity is a necessary condition for safe operation of NPP throughout its project life and long-term operation (LTO) as well. It is well known that RPV service life assessment is based on brittle fracture (BF) margin calculation for pressurized thermal shock (PTS) scenarios.

Estimation of the RPV integrity under PTS conditions consists in the postulation (or generation – for probabilistic calculations) of flaws at critical locations. This requires thermal analyses, temperature and stress field calculations and fracture mechanics calculations as well. The crack initiation criterion, all along the crack front of the ferritic material, is based on the following criterion

$$K_I(T) \leq K_{IC}(T). \quad (1)$$

Where K_I – stress intensity factor (SIF); T – temperature; K_{IC} – fracture toughness (FT).

Since the general shape of the FT curve is expressed as exponential function indexed by ductile to brittle transition temperature T_{DBTT}, associated with the RPV material degradation, the RPV BF criterion in nuclear industry is generally formulated as BF temperature margin

$$T_{ka} - T_{DBTT} \geq 0. \tag{2}$$

While doing so, two methods for T_{ka} (i.e. maximum allowable transition temperature) determination could be used, classic "tangent point" (TP) method and warm pre-stressing (WPS) approach, if the latter is applicable. The main advantage of applying WPS approach for T_{ka} determination is increase of the brittle fracture temperature margin of the RPV and consequently – prolongation of RPV lifetime.

The WPS effect nature consists in material FT increasing. If we consider a structure with a crack-like defect, which is loaded in tension at a temperature corresponding to the ductile region of the material and subsequently unloaded either completely or partially. The structure is then cooled to the brittle region of the material and, when reloaded, fracture occurs at a higher load than what is expected (origin FT).

The WPS effect has been studied experimentally for several decades, see, for example, Loss et al. (1977), Pokrovsky et al. (1995), Smith et al. (2004), D.Moinereau and G.Bezdikian (2008), Lauerova et al. (2009), and also on theoretical basis, see, for example, Chell (1980), Curry (1981), Chell and Haigh (1986), Wallin (2003), Marie et al. (2016). In result of such investigations several WPS models were developed with their subsequent implementation into national standards for RPV integrity assessment. The practice of utilizing the beneficial WPS effect in RPV assessments have been adopted in some European countries, USA and Japan, as can be seen e.g. from IAEA TECDOC-1627 (2010).

The inclusion of WPS effect in RPV assessment can reduce over-conservatism (in comparison with the TP method) and enables more accurate evaluations of the safety margins against limiting conditions, which may occur at PTS events. However, the inclusion of WPS effect in PTS analyses is currently not uniform across the different countries, nor is the position of national regulators regarding its acceptance.

Thus, it is obvious that using different WPS models, we obtain different values of the predicted fracture toughness after reloading, and, simultaneously, application of different national WPS approaches leads to different values of the RPV safety margin. So, the main aim of the current work is as follows:

- analysis of the WPS experimental background, as provided by APAL partners as well as literature data, in terms of determining the predictive capability of the modern WPS models such as Chell and Haigh, Wallin, modified Wallin and ACE (Areva-CEA-EdF) models;
- analysis of the impact of the application of WPS models/approaches to the RPV brittle fracture margin for real PTS.

The results of this paper are based on the APAL Task 1.2 Report: "State-of-the-art for warm pre-stress" (publication restricted). Information about APAL can be seen on the site: https://apal-project.eu/.

ANALYSIS OF THE WPS MODELS IN TERMS OF THEIR PREDICTIVE CAPABILITY

Introduction to the WPS phenomenon

The WPS effect can be attributed to four main mechanisms, which have earlier been studied thoroughly by Bolinder et al. (2019). These mechanisms can be expected to have different impacts, depending on the load path and pre-load level. All the mechanisms are related to the level of applied load and straining during the pre-load in the ductile regime. The four main mechanisms contributing to WPS are as follows:

- introduction of a beneficial compressive residual stress field in front of the crack tip, due to local plastic deformation from the preloading and unloading;

– change of yield properties due to lowering of temperature;
– deactivation of cleavage initiation sites by pre-straining;
– blunting of the crack tip.

The effects of WPS can be divided (see Chell (1980)) into three cases according to the relative sizes of the plastic zones formed during each loading step. Case 1 is the condition where the plastic zone S_1 due to step 1 (pre-load at higher temperature) is greater than that due to step 2 (unload) which in turn exceeds that resulting from step 3 (re-load at lower temperature), i.e., $S_1 > S_2 > S_3$. Case 2 corresponds to $S_1 > S_3 > S_2$ and here the effects of WPS step 2 are wiped out, so that the final solution is indistinguishable from that obtained by omitting step 2 and following step 1 immediately on cooling by step 3. Case 3 occurs when $S_1 > S_2 > S_3$ and the effects of WPS are totally removed during load step 3. The result is indistinguishable from when the structure is loaded directly to the operating load at lower temperature. The important feature of Case 1 is the fact that K_F (enhanced FT at re-load, after WPS) may be lower than level of K_{WPS} (global maximum of SIF trajectory), but still higher than FT of virgin material. From point of view of parameters of WPS cycle, Case 1 occurs at more significant unloading (e.g., total unloading) and lower temperatures at re-load, at otherwise sufficiently high levels of the pre-load. For more details see Chell (1980).

Brief description of the modern WPS models

In order to perform the analysis, the four engineering WPS models are considered: Wallin, modified Wallin, ACE and Chell & Haigh. These models were selected since they divide the WPS phenomenon into physically-relevant cases (Case 1, Case 2 and Case 3) and their applicability has been proved by numerous WPS experiments. Hereinafter, these models are referred to as "physically-relevant" models. The formulas for fracture toughness predictions, denoted by K_F, are presented in Table 1, for three different WPS models, namely Kim Wallin, modified Kim Wallin, and ACE models.

Table 1: Characterisation of the WPS models.

Kim Wallin model, see Wallin, K. (2003)			
Case 1	$K_{WPS} - K_2 \geq K_{IC}$	$K_F = 0{,}15 \cdot K_{IC} + \sqrt{K_{IC} \cdot (K_{WPS} - K_2)} + K_2$	(3)
Case 2	$0{,}85 \cdot K_{IC} < K_{WPS} < K_2 + K_{IC}$	$K_F = 0{,}15 \cdot K_{IC} + K_{WPS}$	
Case 3	$K_{WPS} < 0{,}85 \cdot K_{IC}$	$K_F = K_{IC}$	
modified Kim Wallin model, see Lauerova et al. (2009)			
Case 1	$K_{WPS} - K_2 \geq K_{IC}$	$K_F = \sqrt{K_{IC} \cdot (K_{WPS} - K_2)} + K_2$	(4)
Case 2	$K_{IC} < K_{WPS} < K_2 + K_{IC}$	$K_F = K_{WPS}$	
Case 3	$K_{WPS} < K_{IC}$	$K_F = K_{IC}$	
Areva-CEA-EdF model (ACE model), see Marie et al. (2016)			
$K_F = max \begin{cases} K_{IC} \\ min \begin{cases} K_2 + K_{WPS}/2. \\ K_{WPS} \end{cases} \end{cases}$			(5)

Kim Wallin model is used in the UK. Modified Kim Wallin model was proposed by UJV based on the analysis of large number of experimental data, see Lauerova et al. (2009), and it differs from Wallin model by removing the member $0{,}15 \cdot K_{IC}$ from the formulae (3) for Case 1 and Case 2, which enhances conservativeness of the Wallin model to a sufficient level. For Chell & Haigh model, see Chell, and Haigh (1986), prediction for Case 1 is the following:

$$K_F = K_2 + 0.2 \cdot (K_{WPS} - K_2) + 0.87 \cdot K_{IC}. \tag{6}$$

Regarding the formula (6), note that it holds if the following inequality is valid

$$K_F - K_2 \leq (1 + G)\,(K_{WPS} - K_2)/2. \tag{7}$$

Where K_2 – local minimum of SIF trajectory, G is ratio of the flow stresses

$$G = \sigma_{flow}^{T_F} / \sigma_{flow}^{Twps}, \qquad \sigma_{flow} = \left(\sigma_{yield} + \sigma_{ultimate}\right)/2. \tag{8}$$

Since the original reference does not provide any guideline for the case when the inequality (7) does not hold, we take, in this case, conservatively:

$$K_F = max(K_{IC}; K_2). \tag{9}$$

Experimental background

In the Czech Republic, a large experimental programme was performed in 2006 – 2008 within a research project focussed on WPS; this project was funded by the Czech Regulatory Body. WPS tests were performed on non-irradiated, artificially aged and irradiated (in research reactor) materials. Base materials of WWER-440 and WWER-1000 RPVs were tested. Both Charpy size SENB specimens and 1T C(T) specimens were used for testing. The total number of specimens was about 600. Different WPS-type tests like LCF, LUCF, LPUCF, LTUF, LPTUF were performed (LUCF: Load → Unload → Cool → Fracture; LPUCF: Load → Partial Unload → Cool → Fracture; LTUF: Load → Transient Unload → Fracture; LPTUF:Load → Partial Transient Unload → Fracture, LCF: Load → Cool → Fracture, as shown in Fig. 1). Various test conditions (temperature and load at preloading and temperature at fracture) were used. Results of the project were used for preparation of the requirements for the WPS approach application in RPV integrity assessment; these requirements were then implemented in "Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs – VERLIFE", which was later converted to the Czech standard NTD AME for WWER components and piping lifetime assessment. Some experimental results are presented in Refs. Lauerova et al. (2009) and in Chapuliot et all (2010).

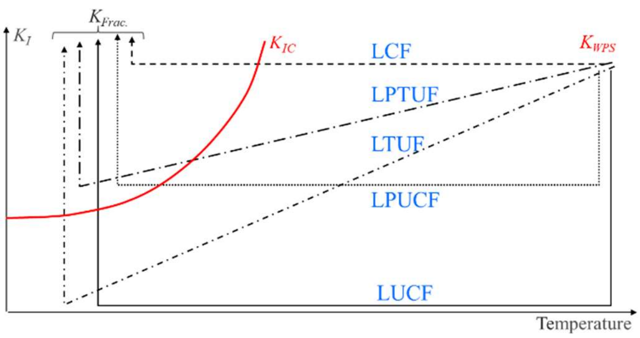

Figure 1. Types of WPS regimes.

In Ukraine, the experimental studies of the WPS effect were performed at the end of the 80's – beginning of the 90's of the last century in G.S. Pysarenko Institute for Problems of Strength of the NAS of Ukraine. The results of these works were summarized in the Pokrovsky's et al (1995) article. The base and weld metals of WWER 440 and WWER-1000 RPVs in artificially aged state were tested. The effect of WPS on FT characteristics has been most extensively studied on 25 mm and 50 mm thick specimens of WWER-440 RPV materials. Specimens of 150 mm thickness were tested after the 1T and 2T specimen test results had been analysed in order to confirm the most important conclusions obtained from the performed analysis and also to obtain the best experimentally substantiated data that could be applied to real structures. Available data (in numerical form) were taken in Yasniy's work (1998). The 1T and 2T specimens were made from two WWER-440 RPV forgings and one weldment (in total 19 specimens were tested).

Predicted values of fracture toughness and their analysis

Based on the Ukrainian and Czech experimental WPS data, the calculation of predictions of FT values using the considered WPS models was performed. The results are presented in Fig. 2 and Fig. 3, respectively. In these figures as well as in the calculations, the FT values K_{IC} were taken as 5% confidence level values (determined using Master Curve method for Ukrainian data and using 3-parametric Weibull distributions of the corresponding Czech experimental data for the virgin material of the elastic parts of K_{JC}). Also, the K_{WPS} values and experimental K_F values shown in these figures are elastic parts of the FT.

The 5% confidence level of FT was selected, since such predictions (for 5%, as in Ukraine and Russia) or "simple" lower envelope of the experimental data (such as NTD AME's curve or US adjusted K_{IC} curve, which are close to the 5% curves) are used in PTS evaluations, and we need that these predictions (5%) be conservative, i.e. experimental data should be "higher" than predictions for 5% level of fracture probability. If it is the case, the WPS model is considered conservative and may be used in PTS assessments.

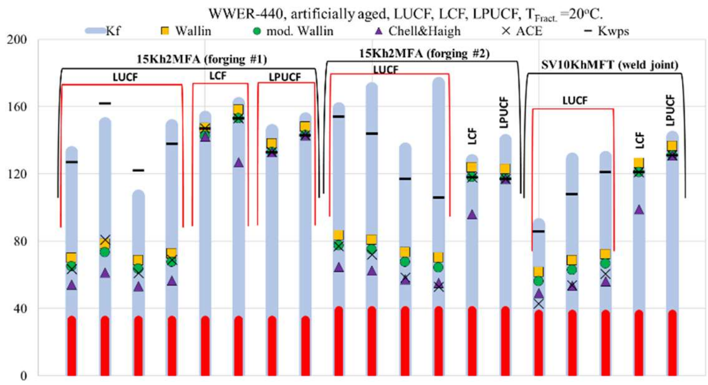

Figure 2. Ukrainian WPS experimental data and predicted values of material FT after WPS.

Summarised comparison between the predicted values of the material fracture toughness at re-load (after pre-stressing) and Czech experimental results, provided by ÚJV Řež, are presented in Table 2 (predictions performed with using $K_{IC,5\%}$). The first cell of the "WPS model" column indicates number of cases when the predicted values using the respective model are not conservative relatively to the experimentally obtained values, i.e. when $K_F^{experimental} < K_F^{predicted}$, the second cell shows this result in % relatively to the total number of experiments tested in the respective group. Note, that such predictions performed for Ukrainian WPS data, resulted to the only one case when $K_F^{experimental} < K_F^{predicted}$ (it is Wallin model prediction for SV10XMFT weld joint as can be seen on Fig. 2).

Comparing the predictions (calculated based on $K_{IC,5\%}$) with experimental data, it can be seen that application of modified Wallin, Chell-Haigh and ACE models leads to conservative results (experimental data are higher than predictions). The predictions by Wallin model are slightly less conservative in respect to experimental data, and therefore application of this model in PTS assessments could lead to overestimation of the RPV BF margin. Thus, application of ACE, modified Wallin and Chell-Haigh models may be considered preferable from point of view of their usage in both deterministic and probabilistic RPV brittle fracture assessments. Application of Wallin model could be considered for probabilistic applications.

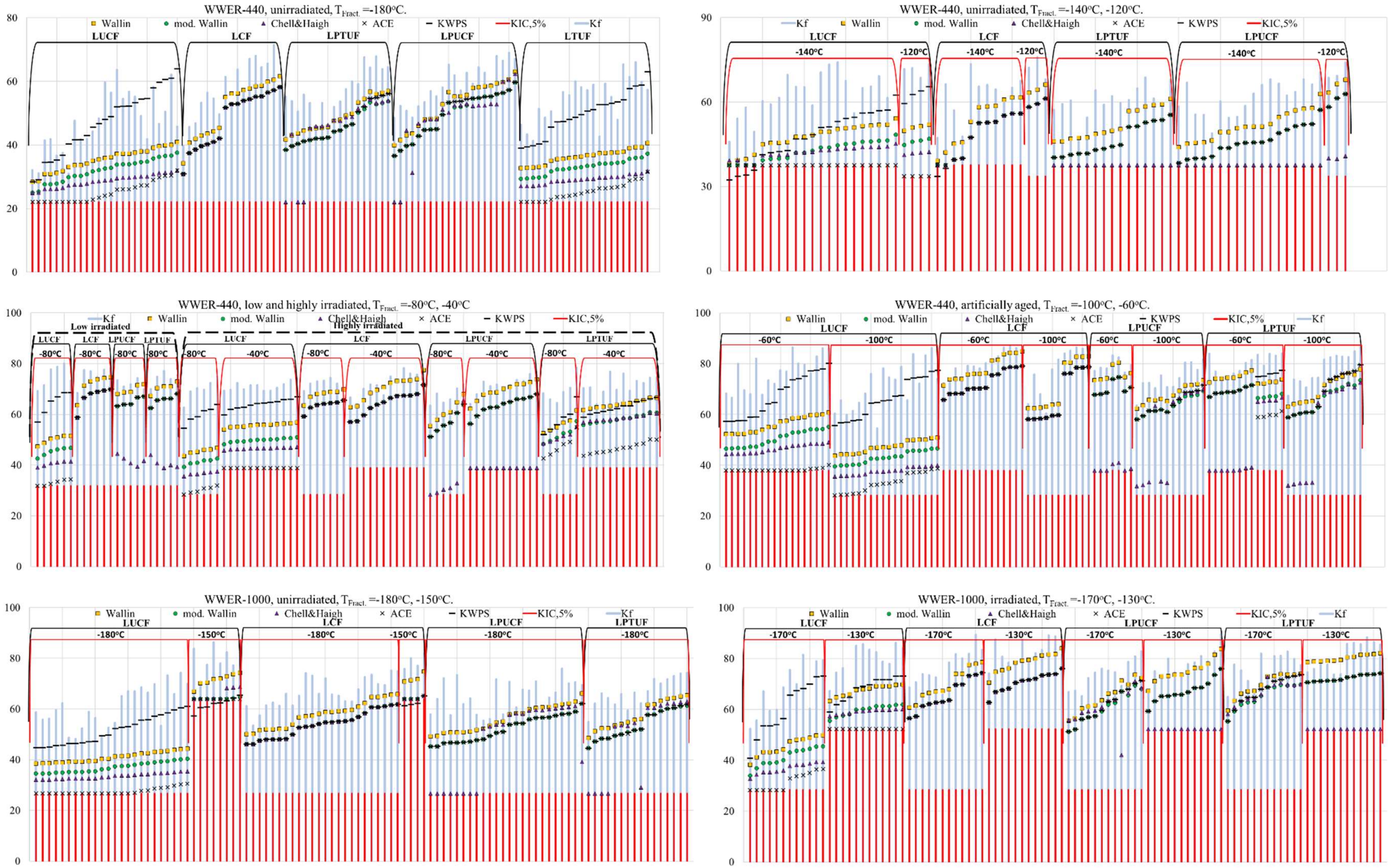

Figure 3. Czech WPS experimental data and predicted values of material FT after WPS (WWER-440 RPV low irradiated material – accumulated neutron fluence is from 211÷253×10^{22} to neutron/m^2, mean value = 233,4×10^{22} neutron/m^2; WWER-440 RPV highly irradiated material – accumulated neutron fluence is from 277×10^{22} neutron/m^2 to 310×10^{22} neutron/m^2, mean value - 298,8×10^{22} neutron/m^2).

Table 2: Number of cases when the predicted values of the material fracture toughness after pre-stressing overestimate the Czech experimental data.

WPS loading mode	Wallin		mod. Wallin		Chell-Haigh		ACE		Wallin		mod. Wallin		Chell-Haigh		ACE	
	WWER-440, unirradiated								WWER-440, low irradiated							
LCF	4	12.9	1	3.23	0	0	1	3.23	0	0	0	0	0	0	0	0
LUCF	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LPTUF	1	3.03	0	0	1	3.03	0	0	0	0	0	0	0	0	0	0
LPUCF	0	0	0	0	0	0	0	0	1	16.7	0	0	0	0	0	0
LTUF	0	0	0	0	0	0	0	0	–	–	–	–	–	–	–	–
	WWER-440, highly irradiated								WWER-440, artificially aged							
LCF	4	21.1	0	0	0	0	0	0	2	8	0	0	0	0	0	0
LUCF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LPTUF	0	0	0	0	0	0	0	0	1	3.85	0	0	0	0	0	0
LPUCF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WWER-1000, unirradiated								WWER-1000, irradiated							
LCF	0	0	0	0	0	0	0	0	2	8.33	0	0	0	0	0	0
LUCF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LPTUF	0	0	0	0	0	0	0	0	5	20.8	0	0	0	0	0	0
LPUCF	1	4.17	1	4.17	1	4.17	1	4.17	4	16.7	0	0	0	0	0	0

IMPACT OF WPS APPLICATION ON THE DETERMINATION OF RPV BRITTLE FRACTURE MARGIN IN PTS EVALUATIONS

In order to determine the influence of different WPS models (or WPS procedures) application on determination of RPV brittle fracture margin in PTS evaluations, seven model PTS transients were selected: Regime 1 "Loss of Coolant Accident with break equivalent diameter 200 mm in hot leg"; Regime 2 "Small Break Loss of Coolant Accident (SBLOCA) with break equivalent diameter 32 mm in cold leg"; Regime 3 "False Pressurizes safe valve opening with maximum configuration of the ECCS, followed by closing after 2570 s in the "hot shutdown" state and operator actions to turn off the TQ14-34D01 pumps"; Regime 4 "SG's 3 tubes rupture with the maximum configuration of the ECCS in the "hot shutdown" state"; Regime 5 "Primary leakage Dn 32 with maximum ECCS configuration (hot shutdown state)"; Regime 6 "ECCS HPIS pipeline rupture Dn 125 with minimum ECCS configuration (power operating state)" Regime 7 "Inadvertent opening of fast acting reducing valve for steam discharge into the condenser with minimum ECCS configuration (hot shutdown state)". The first regime is representative for WWER-440 Units, the other six – for WWER-1000. The K_I vs T curves relevant for the considered regimes (except Regime 3) together with K_{IC} curves touching these SIF curves (TP approach) are presented in Fig. 4.

The results of RPV brittle fracture margin assessment for considered model transients with using eleven WPS models and/or national standards and the TP method, are presented in Table 3. Description of the WPS national standards/rules is presented in paper Zarazovskii et al. (2022). Examples of the T_{ka} determination for Regime 3 using Wallin model and NTD AME (2020) procedure, are shown in Fig. 5 (i.e. FT curve, modified due to WPS model application, touching the SIF curve). It can be seen from Table 3 that WPS application according to the IAEA Guidelines (1997) and (2008) can give benefit for monotonically decreasing loading path transients, which has limited practical benefit. In general, almost all WPS approaches, except Ukrainian and Russian for some cases, lead to the reasonable decreasing of conservativeness in the RPV safety assessment.

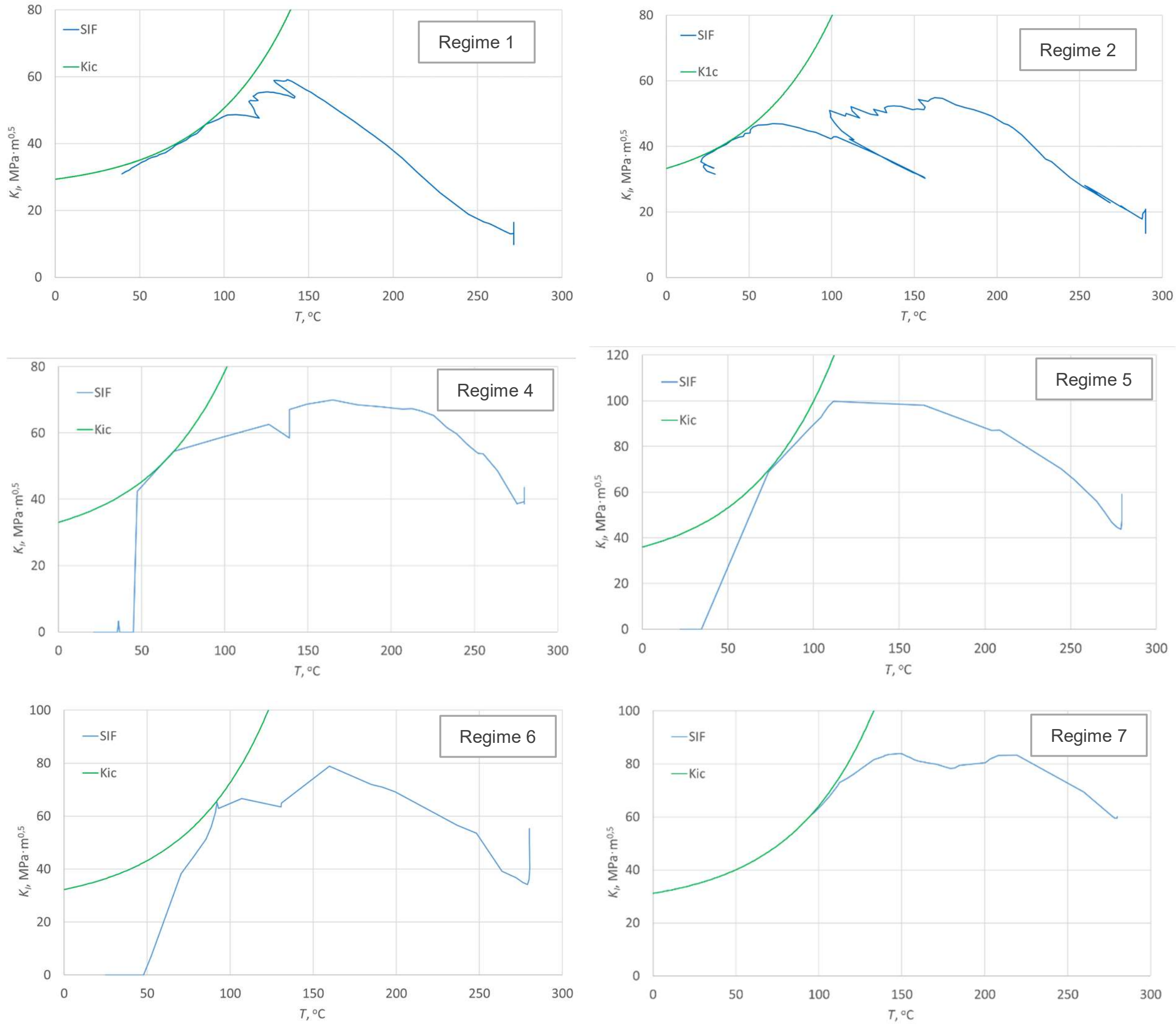

Figure 4. Loading path for Regime 1, Regime 2, and Regimes 4 – 7.

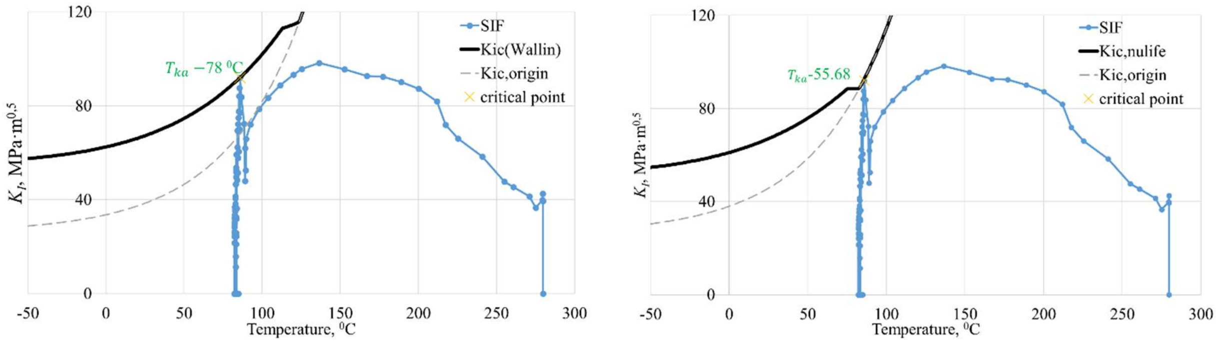

Figure 5. Plot of the T_{ka} determination for Regime 3 according to Wallin and NTD AME models.

Table 3: Variation of the T_{ka} for considered transients depending on the WPS model or standard applied.

Regime	TP	k=0.8[1]	k=0.9[2]	VERLIFE-2008[3]	Ukrainian	Russian[4]	USA		ACE	Wallin	mod. Wallin	NTD AME 2020
							baseline model, K_{max} estimated	all local maximums estimated				
1	119.1	119.1	119.1	119.1	119.1	120.6	141.5	129.98	141.5	141.5	141.5	129.4
2	80.5	80.5	80.5	80.5	80.5	107.6	173.5	91.33	173.5	173.5	173.5	116.9
3	55.7	55.7	55.7	55.7	55.7	49.1	96.7	55.7	55.7	78.0	60.4	55.7
4	80.8	80.8	80.8	80.8	83.6	109.8	154.6	125.5	80.8	139.0	108.2	95.6
5	57.5	71.1	73.36	73.36	67.84	60.44	69.69	69.69	64.38	75.5	75.5	71.5
6	83.3	83.3	83.34	83.34	83.34	83.23	125.32	83.34	87.61	127.4	104.4	94.8
7	97.3	98.9	104.3	104.34	101.54	97.27	124.99	124.99	124.99	125.0	125.0	104.3

Yellow cells indicate that WPS approach is inapplicable according to the corresponding rules.

CONCLUSIONS

Application of modified Wallin, Chell-Haigh and ACE models leads to conservative results (experimental data are higher than predictions). The predictions by Wallin model are slightly less conservative in respect to experimental data, and therefore application of this model in PTS assessments could lead to overestimation of the RPV brittle fracture margin. Modification of Wallin model proposed by UJV (removing the member $0{,}15 \cdot K_{IC}$) enhances conservativeness of Wallin model to a sufficient level.

Thus, application of ACE, modified Wallin and Chell-Haigh models may be considered more preferable from point of view of their usage in both deterministic and probabilistic RPV brittle fracture assessments. Application of Wallin model could be considered for probabilistic applications.

In general, almost all considered WPS approaches/standards, except Ukrainian and Russian ones for some cases, lead to reasonable decreasing of conservativeness in the RPV safety assessment. It is seen that Ukrainian WPS approach is not applicable almost for any of the representative transients (due to its excessive conservativeness). Therefore, it doesn't provide any practical benefit. Consequently, it is recommended that this approach should be examined more carefully, taking into account the nature of WPS experimental data, or should be harmonized with some of the physically relevant models.

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[1] This approach is taken according to the chapter 8.3 of IAEA recommendation for WWER reactors (1997), according to which WPS is applicable for those transients which are characterized by continuously decreasing loading path after reaching K_{wps}. In this case T_{ka} is defined using tangent point method within range $K_I = [0.8 \cdot K_{WPS}; K_{WPS}]$.

[2] This approach is taken according to the latest IAEA recommendation for WWER reactors (2008), similar to the previous one, but for range $K_I = [0.9 \cdot K_{WPS}; K_{WPS}]$.

[3] According to the VERLIFE-2008 in the case with reloading (when the loading path of temperature is not monotonically decreasing), T_{ka} can be determined using the most conservative value from all 90% of local maxima of SIF.

[4] Gray cells indicate the case when application of the Russian approach results in decreasing the RPV brittle fracture margin in comparison to classic TP approach (it is due to the fact, that according to Russian brittle fracture criterion, SIF is multiplied by safety factor 1.1). This statement is true if we compare the Russian approach with the classic TP approach, but it is not true if we compare Russian approach with the "Russian TP approach" where the safety factor of 1.1 is also applied.

This paper is dedicated to the memory of our dear co-author, professor Petro Yasniy, who passed away in 2021 while all the results of this paper were obtained, and abstract was prepared. The authors would like to express their thanks to Prof. Yasniy for kindly providing the experimental data, their support and analysis.

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