Warm Pre-stressing Tests for WWER Materials

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1 ABSTRACT

Warm pre-stressing (WPS) effect can be described as follows: after loading of a specimen or component containing a crack at relatively high temperature (warm pre-stressing), the specimen (component) can withstand higher loading at low temperature than corresponds to original (virgin) fracture toughness prediction for the low temperature. A large national project funded by the Czech regulatory body (State Office for Nuclear Safety) was established to validate the WPS effect for WWER reactor pressure vessel (RPV) materials. The aim of the project was validation of WPS effect for WWER RPV materials in as-received, artificially aged and irradiated states. The final aim was improving (reducing the conservatism) of the WPS approach in the procedure for RPV integrity assessment included in Unified Procedure VERLIFE.

The following regimes were tested:

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.

The tests were performed for different levels of K_I at pre-stressing and for different temperatures at pre-stressing and at final fracture. About 600 specimens were tested. The experimental results were statistically treated and compared with predictive models. Results for 15Kh2MFA material for initial state and the proposed new procedure are discussed in detail in the paper.

2 INTRODUCTION

The warm pre-stressing effect is a well-known phenomenon that may be successfully exploited at reactor pressure vessel integrity assessment against fast (brittle) fracture for events of pressurized thermal shock (PTS) type. The PTS event is characterised by fast cooldown of RPV inner surface, while the inner pressure (usually) remains high. This phenomenon is basically associated with the following experimental result: A cleavage fracture toughness enhancement at low temperature is observed, if a specimen (or component) is pre-loaded at a substantially higher temperature. The effect of warm pre-stressing is sometimes described by the words: There is no fracture if the stress intensity factor decreases (or is held constant) while the crack tip temperature decreases, even if the (virgin) material fracture toughness is exceeded.

When applying this phenomenon to a ferritic steel of reactor pressure vessel, the pre-stressing is considered usually at temperatures above the ductile-brittle transition temperature while the (potential) fracture itself is considered at lower temperatures. This is associated with time evolution of PTS events, when usually the maximum load due to thermal stresses is reached at the intermediate phase of the event, when the RPV temperature is relatively high (for WWER usually within the range from 100 °C to 170 °C), but the critical (from the point of view of fast fracture) phase is reached at lower temperature (for WWER usually within the range from 30 °C to 120 °C) but also at lower load.

The WPS effect was quantitatively described in detail in papers by Chell (1980, 1981, 1986), and later by Wallin (2003). In these papers the predictions of enhanced fracture toughness values obtained after warm pre-stressing are provided; the appropriate theories including the predictions are referred to in this paper as Chell and Wallin predictive models, respectively.

Recently, the project SMILE funded by EU 5th EURATOM Framework programme was conducted (see Moinereau (2008)) with large number of experimental results. Several predictive models were validated. The project was focused on western PWR RPV materials.

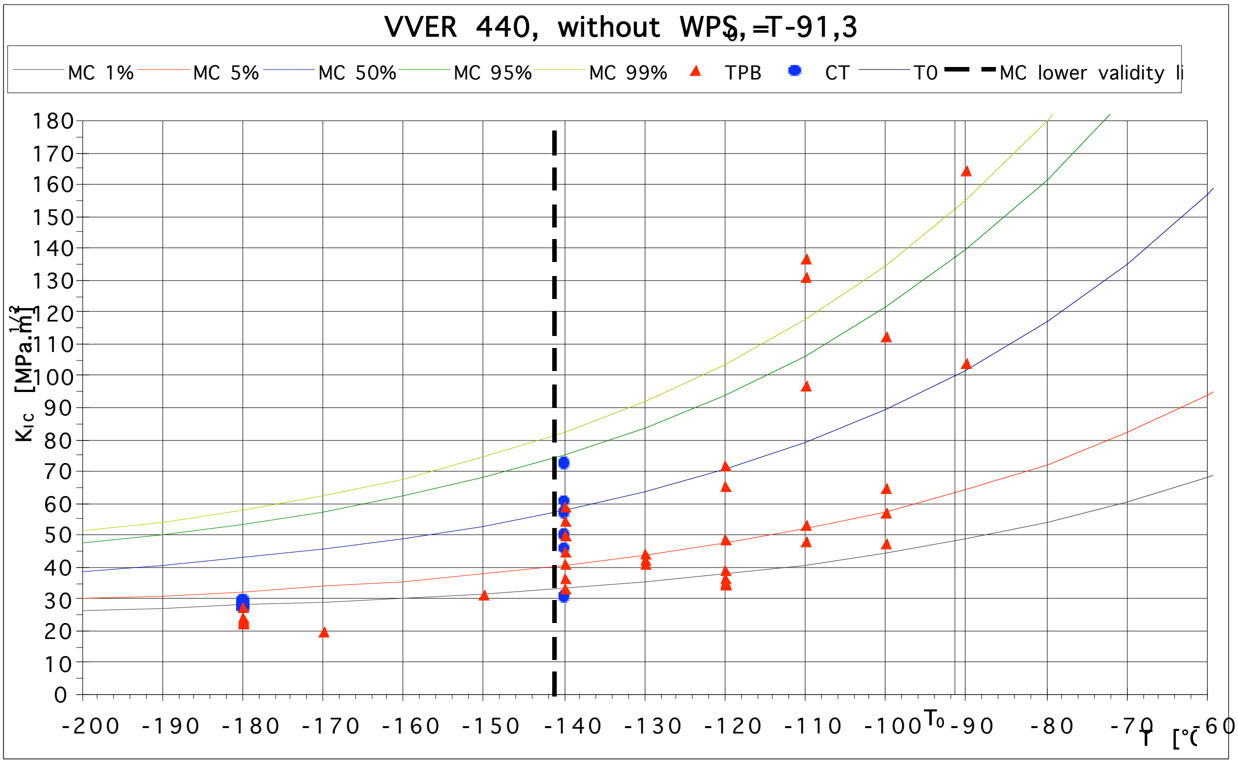
Lack o experimental validation of WPS effect and the appropriate predictive models for WWER RPV materials was one of reasons for establishing a national WPS research project in the Czech Republic. The project was held during years 2006 – 2008 in NRI Rez, plc., supported by the Czech Regulatory Body, the State Office for Nuclear Safety. Warm pre-stressing tests on small (Charpy size) and 1T CT specimens were performed. Within this programme, specimens made of WWER 440 and WWER 1000 reactor pressure vessel materials in different conditions were tested: in as-received, thermal treated (artificially aged) and irradiated conditions, the last two conditions simulating the end of life of RPV. In the presented paper, only the results of experiments performed for WWER 440 RPV material 15Kh2MFA in as-received condition are attached. Total number of specimens tested within the project was about 600. The Chell and Wallin models were validated for WWER RPV materials based on the experimental results.

3 TESTS FOR MATERIAL 15Kh2MFA IN AS-RECEIVED CONDITION

3.1 Fracture tests without WPS

For the tests, material 15Kh2MFA taken from decommissioned (not operated) WWER 440 was used. First of all, tensile properties of the tested material were measured within the temperature range -180 °C to room temperature. These properties are necessary for applying Chell predictive model. Subsequently the Master Curve reference temperature T_0 was established using pre-cracked Charpy specimens, and also CT specimens. Totally 52 specimens in “virgin state” (i.e. without pre-stressing) was tested in large temperature range. The resulting value T_0 = -91.3 °C was obtained using multi-temperature approach. The results of fracture tests without pre-stressing are seen in Fig. 1.

Figure 1. Fracture tests results – without WPS



To demonstrate significant benefit of WPS, very low temperatures T_F in comparison to T_0 for final fracture were chosen, namely temperatures -180°C, -140 °C and -120 °C. As the Master Curve theory is valid only within the range T_0 ± 50 °C and the proposed fracture temperatures lye outside or close to the limits, it was decided to perform sufficient number of tests (without WPS) directly at these proposed temperatures. The fracture toughness statistical distribution (Weibull distribution) was then established directly from these tests, separately for each proposed fracture temperature, instead using the general distribution according to Master Curve theory. It is seen from Fig. 1 that the results for low temperature (mainly for -180 °C) lie below the range predicted by Master Curve.

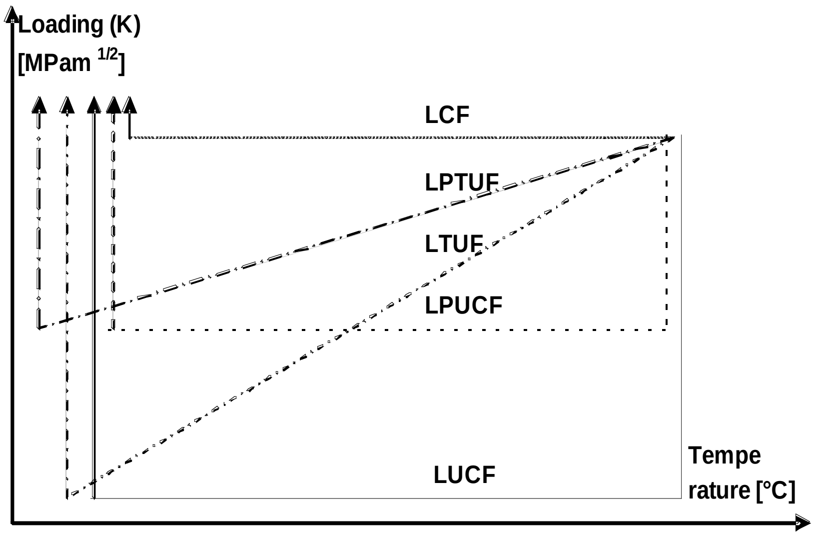
3.2 Determination of WPS test conditions

The following WPS regimes were tested (see Fig. 2):

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.

Figure 2. Scheme of WPS regimes tested

In Tables 1 and 2 is presented the overview of performed WPS tests on Charpy size three-point-bending (TPB) and 1T CT specimens, respectively. The following denotation is used:



T_{WPS} – temperature at pre-stressing
T_U – temperature at unloading
T_F – temperature at fracture
K_{IWPS} – stress intensity factor at pre-stressing
K_{IU} – stress intensity factor at unloading
K_{IF} – stress intensity factor at fracture

The aim was to perform the tests for different regimes, different temperatures at fracture T_F and different levels of pre-stressing K_{IWPS}. The temperature of prestressing T_{WPS} (which does not influence significantly the WPS effect) was chosen high enough to prevent "premature" fracture at pre-stressing. For the evaluation it would be useful to have sets of specimens with one value of K_{IWPS}, but due to some relatively small scatter in crack depth of the specimens (caused by their fabrication using fatigue pre-cracking of the notch), even for unique force at pre-stressing, there is some scatter in K_{IWPS} values. The scatter is larger for TPB Charpy size specimens. Moreover, for TPB specimens, in contrary to CT specimens, it was not possible to obtain high values of K_{IWPS} (more than about 60 MPa.m$^{1/2}$) due to large plastification of the specimens. As within the subsequent stages of the project (not described in detail in this paper) the specimens irradiated in research reactor were tested, focussing on Charpy size specimens was necessary. The CT specimens could be tested only in as-received state.

Table 1. Overview of WPS tests performed on Charpy size TPB specimens (10 mm thickness)

C	T_{WPS}	K_{IWPS}	K_{IU}	T_F	Number of spec.
	[°C]	[MPa.m$^{1/2}$]	[MPa.m$^{1/2}$]	[°C]	

LUCF	-80, 24	28 - 64	0	-180	25
LUCF	-80	32 - 62	0	-140	21
LUCF	-80	59 - 66	0	-120	4
LPUCF	-80	37 - 60	20 – 53	-180	21
LPUCF	-80	38 - 57	20 – 30	-140	18
LPUCF	-80	58 - 63	40 – 41	-120	3
LCF	-80, 24	31 - 58	31 – 58	-180	17
LCF	-80, 24	34 - 56	34 - 56	-140	11
LCF	-80, 24	58 - 61	58 - 61	-120	3
LTUF	-80, 24	39 - 63	0	-180	22
LPTUF	-80, 24	38 - 56	20 - 30	-180	18
LPTUF	-80	40 - 55	21 - 29	-140	15
Totally					178

Table 2. Overview of WPS tests performed 1T CT specimens (25 mm thickness)

Regime	T_{WPS}	K_{IWPS}	K_{IU}	T_F	Number of spec.
	[ºC]	[MPa.m$^{1/2}$]	[MPa.m$^{1/2}$]	[ºC]	
LUCF	-80, 22	60 - 64	0	-180	6
LUCF	22	96 - 100	0	-180	5
LUCF	22	101 - 104	0	-140	5
LCF	-80, 22	58 - 62	58 - 62	-180	5
LCF	22	100 - 102	100 - 102	-180	7
LCF	22	100 - 102	100 - 102	-140	6
LPTUF	-80, 22	60 - 64	30 - 31	-180	6
LPTUF	22	99 - 103	50 - 51	-180	6
LPTUF	22	102 - 104	51 - 52	-140	2
Totally					48

4 ASSESSMENT OF THE TESTS RESULTS – VALIDATION OF THE PREDICTIVE MODELS

4.1 Chell model

The results of evaluation the experimental data using Chell predictive model, see Chell (1980, 1981, 1986), were published in detail by Lauerova et al. (2009) at ASME PVP 2009 conference. One example of the evaluation for LUCF regime for TPB specimens is seen in Fig. 3. In this figure, the fracture predictions by Chell model are plotted, using light and dark blue-green columns (the dark blue-green column means prediction of fracture with probability of fracture in range 5% - 50%, while the light blue-green column means prediction of fracture with probability of fracture in range 50% - 95%). In these figures, there are also represented the following quantities: warm pre-stressing K_{IWPS}-values (blue “minus signs”), temperatures of fracture (text in the figure), virgin 5% and 95% K_{IC} values (brown and green lines), and experimental data (red triangles). All plotted values (virgin K_{IC}, K_{IWPS}, K_{IF}) are elastic parts of fracture toughness values or of stress intensity factor values. All these values were determined based on procedures usually used for determination of fracture toughness, i.e. using experimental load vs. displacement curves and applying the formulas of the appropriate standard. Within this approach, values of K_{IF} were determined as if there were no pre-stressing history of the specimen, which means, in particular, that the plastic part of K_{IWPS} has been “forgotten”.

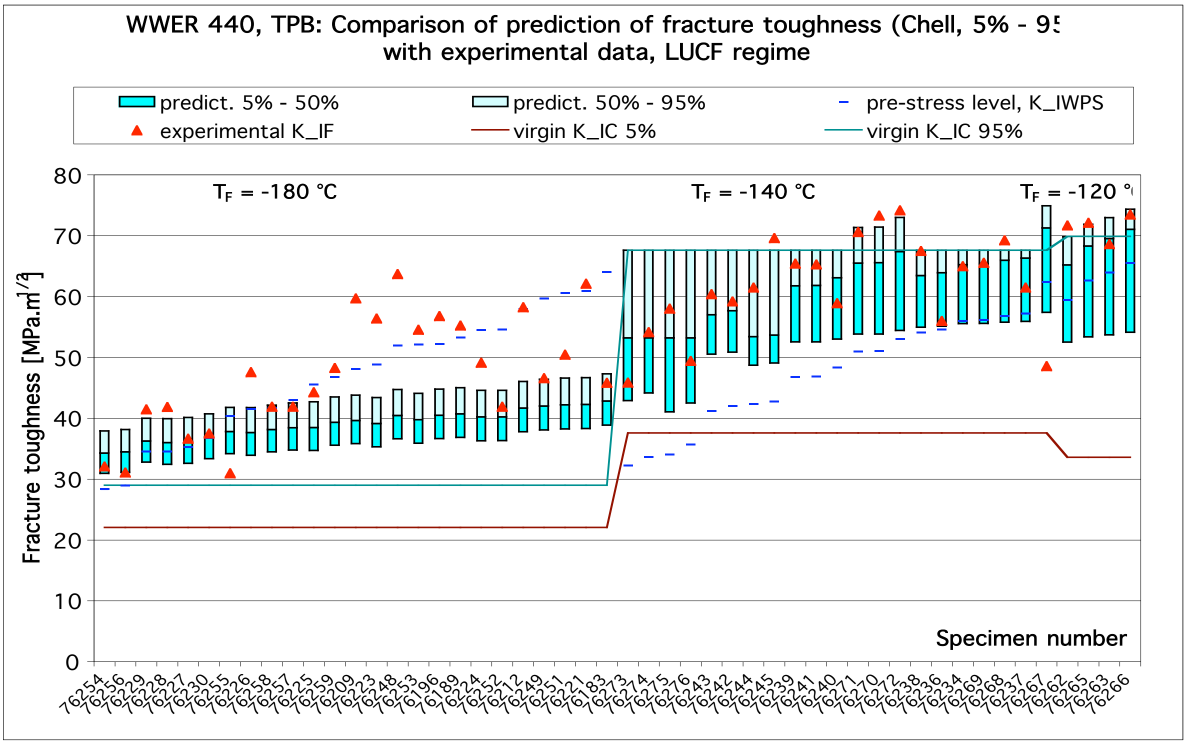


Figure 3. Results of evaluation of experimental data for LUCF regime using Chell model.

Comparing the experimental data with virgin K_{IC} values in Fig. 3, the WPS effect is clearly visible: the experimental data are either significantly above (5% - 95%) interval of the virgin K_{IC} values (this is the case of temperature of fracture T_F = -180 °C) or are distributed mainly in the upper part of this interval (for T_F = -140 °C and T_F = -120 °C). Comparing the experimental data with Chell predictions in Fig. 3, we see that in majority of cases the experimental data lie either within the (5% - 95%) columns or above them, only in 3 of 50 cases they lie below these columns. The percentage portion of experimental data lying below the columns corresponds roughly to 5%. We see that for some tests (mainly for T_F = -180 °C) the predictions (and in some cases also the fracture data of the specimens) lie below the pre-stress level K_{IWPS}. These tests belong to so called "Case 1", see the details below. It is in contrary with sometimes-applied "maximum" approach to WPS for PTS assessment, according to which after reaching global maximum of K_I, no fracture can occur even during non-monotonous unloading. This "maximum" approach is according to our opinion non-correct. (To apply correctly the "maximum" approach to a particular PTS event, it should be demonstrated that Case 1 is not applicable for the PTS event in question.)

4.2 Wallin model

Wallin model, described in Wallin (2003), is based on statistical evaluation of large set of WPS tests, mainly of PWR RPV steels. This model is much simpler than Chell model and is described as follows:

Case 1 occurs, when the following inequality (1) is fulfilled

$$K_{IWPS} - K_{IU} \geq K_{IC} \quad (1)$$

In this case, the predicted value K_{IF} is determined according to the following formula:

$$K_{IF} = 0{,}15\, K_{IC} + \sqrt{K_{IC} \cdot (K_{IWPS} - K_{IU})} + K_{IU} \quad (2)$$

Case 2 occurs, when the inequality (1) is not fulfilled. In this case K_{IF} is determined according to the following formula:

$$K_{IF} = 0{,}15\, K_{IC} + K_{IWPS} \quad (3)$$

If, however, in this case the following inequality is fulfilled:

$$K_{IF} \leq K_{IC} \quad (4)$$

Case 3 occurs and the predicted fracture toughness after WPS remains at its original value, i.e.

$$K_{IF} = K_{IC} \,. \qquad (5)$$

In the above-presented formulae, the K_{IC} value means the fracture toughness in virgin state (without WPS). The Wallin model should be valid also in statistical way, i.e. when the fracture toughness value K_{IC} represents some probability level of fracture, the relevant K_{IF} value should represent the same probability fracture after WPS. This means, that the model correctly transforms the virgin fracture toughness distribution function to fracture toughness distribution function after WPS.

4.3 Validation of Wallin model on test results

It was proved within the tests evaluation that the predictions according to Chell and Wallin model differ only little. Due to this fact, presentation of results in the way similar to Fig. 3 would not bring significant new information. As Wallin model is much simpler than the Chell one, a different way of presentation of results can be used for Wallin model, which would be very difficult for Chell model.

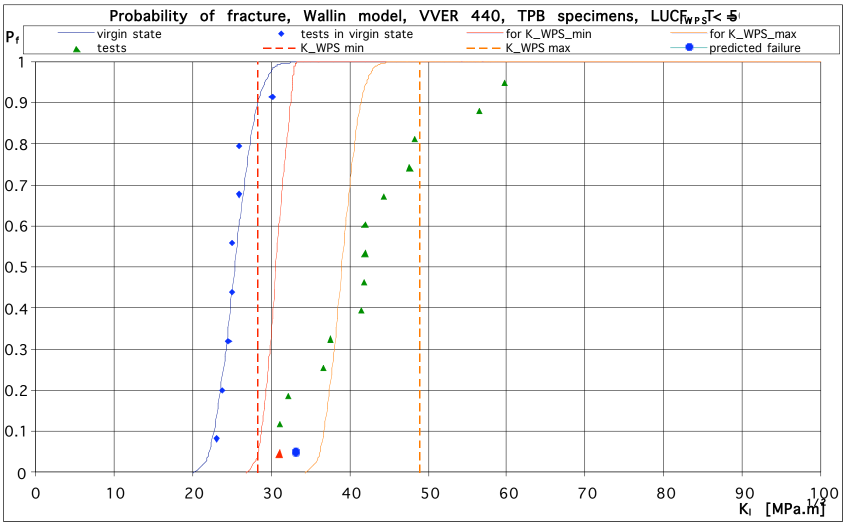
In the following figures the group of specimens for specific regime, specific T_F and ”similar” K_{IWPS} are assessed. The distribution functions of probabilities of fracture in virgin state (based on statistical treatment of tests without WPS, see Chap. 3.1) and after pre-stressing based on Wallin model are drawn in the figures as dependencies of cumulative probability of fracture on applied stress intensity factor K_I. As there is not one value of K_{IWPS}, as was discussed above, the distribution functions of probabilities of fracture after WPS are drawn for minimum and maximum K_{IWPS} values within the assessed group of specimens. Moreover, the minimum and maximum K_{IWPS} values are also drawn in the figures.

Within each group, the specimens are ordered according to magnitude of K_{IF}. For each specimen, the empirical probability of fracture is determined based on the following formula:

$$P_f = (i-0.3)/(n+0.4) \quad , \qquad (6)$$

where i is the sequence number of the specimen within the (ordered) group, n is number of specimens in the group. The empirical probabilities are drawn in dependency on K_{IF} for all specimens (using triangle symbols). If these points lie on the right hand side from the distribution function for the maximum K_{IWPS}, the predictive model is surely conservative. Due to relatively large variability of K_{IWPS} and, consequently, wide band between the distribution functions for minimum and maximum K_{IWPS}, also some points lying between these two distribution functions are conservative. For this reason, all these points were individually checked and when they lie on the right hand side form the prediction, they are marked by green colour. In the opposite case, they are marked by red colour and the appropriate prediction of fracture by Wallin model is marked by blue circle. Finally, the number of data points lying on the left hand side from the prediction was assessed, as presented in Table 3 and 4. Due to relatively large variability of K_{IWPS} the groups indicated in Table 1 were further divided to subgroups with similar K_{IWPS} values. Only some examples of large number of results are presented in the following figures 4 -7.

Figure 4. LUCF regime, results of evaluation of experimental data for using Wallin model



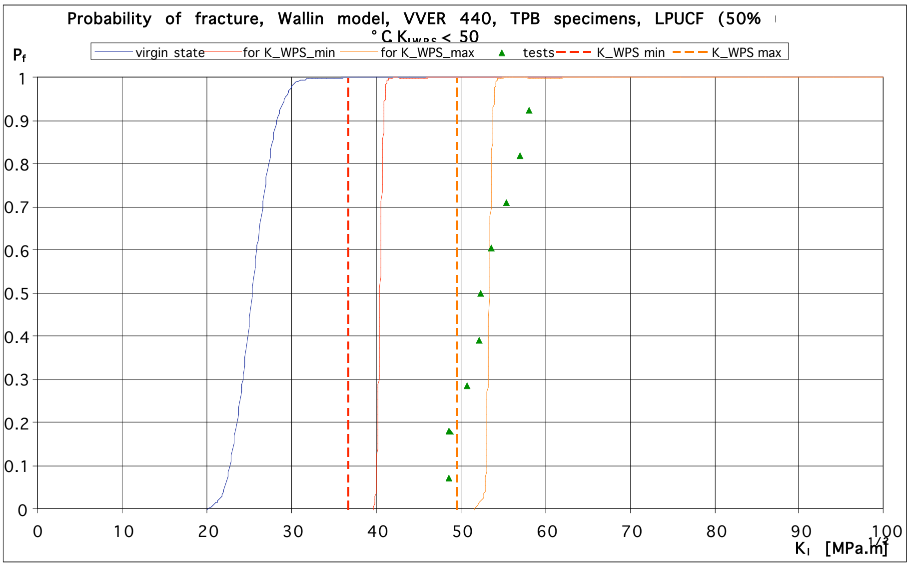


Figure 5. LPUCF regime, results of evaluation of experimental data for using Wallin model

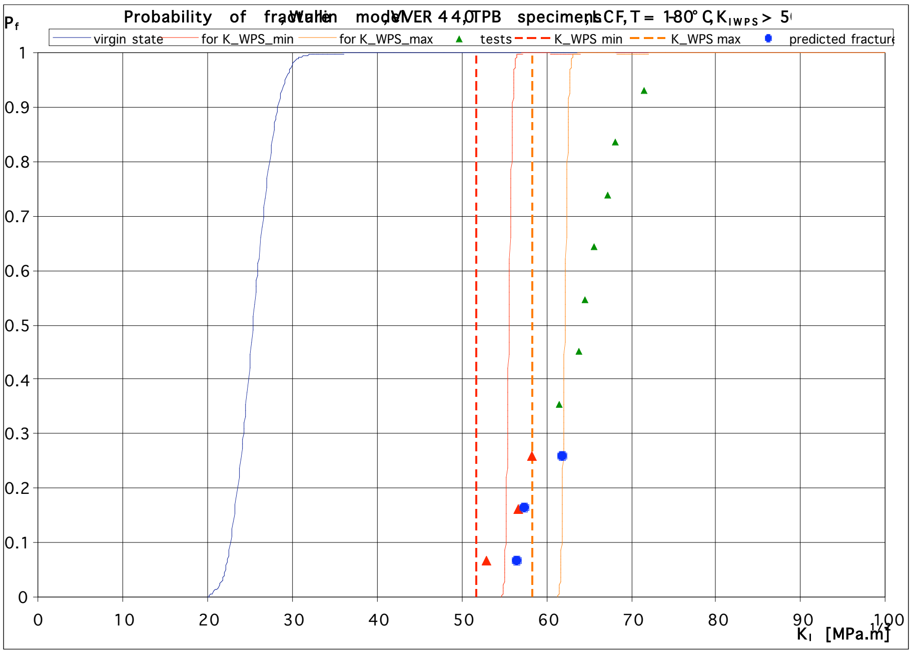


Figure 6. LCF regime, results of evaluation of experimental data for using Wallin model

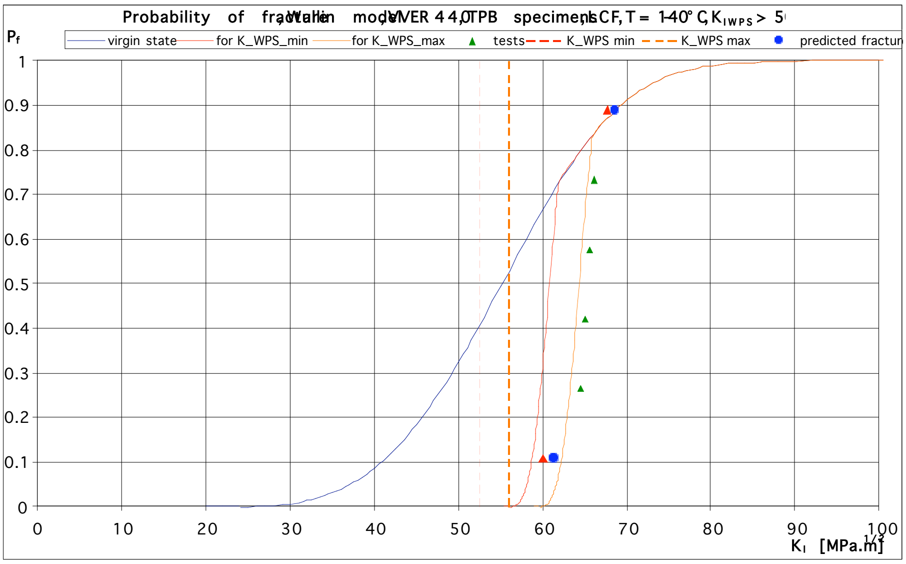


Figure 7. LCF regime, results of evaluation of experimental data for using Wallin model

Table 3. TPB specimens, Wallin model, numbers of specimens lying on the left side from the distribution function, prediction of fracture (Remark: Numbers for -120 °C are relevant to comparison with Wallin predictions developed for distribution function based on only elastic part of K_I in virgin state)

Regime	T_F = -180 °C			T_F = -140 °C			T_F = -120 °C		
	Number of spec.	Number on left	% on left	Number of spec.	Number on left	% on left	Number of spec.	Number on left	% on left
LUCF	25	1	4	21	3	14	4	0	0
LPUCF	21	0	0	18	2	11	3	0	0
LCF	17	3	18	11	3	27	3	0	0
LTUF	22	0	0	0	-	-	0	-	-
LPTUF	18	1	6	15	3	20	0	-	-
Totally	103	5	5	65	11	17	10	0	0

Table 4. CT specimens, Wallin model, number of specimens lying on the left side from the distribution function, prediction of fracture

Regime	T_F = -180 °C			T_F = -140 °C		
	Number of spec.	Number on left	% on left	Number of spec.	Number on left	% on left
LUCF	11	1	9	5	1	20
LCF	12	0	0	6	0	0
LPTUF	12	0	0	2	0	0
Totally	35	1	3	13	1	8

It has to be noted that if the Wallin model exactly described the WPS effect (without any additional conservatisms), approximately 1/2 of the specimens would lie on the left side from the distribution function, similarly as it is for the virgin state (see Fig. 4).

For LCF regime (always Case 2 or Case 3), it was observed that the Wallin prediction is rather realistic than conservative and for the purpose of RPV integrity assessment no increase of K_{IF} above K_{IWPS} should be supposed.

5 PROPOSAL FOR IMPROVING THE WPS APPROACH IN THE PROCEDURE FOR RPV INTEGRITY ASSESSMENT

In the Czech Republic, the Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs VERLIFE (2008) is used for RPV integrity evaluation. In the current version of this standard, a WPS effect is already included, but only for case of monotonous unloading. In this case, the 90% of K_{Imax} (maximum value of stress intensity factor during PTS) may be taken for determination of maximum allowable temperature of brittleness.

The WPS experiments described in the presented paper enable application of WPS effect also in case of non-monotonous unloading. In the same manner as in the current version, 90% of K_{Imax} shall be taken for determination of maximum allowable temperature of brittleness, but it can be applied also in the situation of non monotonous unloading after reaching K_{Imax}. Additional assessment of Case 1 is required by the proposed procedure, i.e. stress intensity factor K_I after reaching K_{Imax} has to be smaller than K_{IF} predicted by the formula (2) (in dependency on the unloading K_{IU}).

6 CONCLUSION

Large set warm pre-stressing tests were performed on both TPB and CT specimens. WWER 440 reactor pressure vessel base material 15Kh2MFA was tested in as-received, aged and irradiated states for different WPS regimes, temperatures and loads at pre-stressing and temperatures at fracture. The test results were compared to predictions according to Chell and Wallin models with the following conclusions:

- For most of the tests the resulting values K_{IF} were above the predicted values according to both models. The number of tests where K_{IF} was below prediction corresponds to the appropriate probability of fracture, for which the prediction was done. Both Chell and Wallin predictive models are conservative for the assessed material.
- The only exception is regime LCF, where more specimens than corresponding to the applied statistics fractured below the predicted value. The predictive models are slightly non-conservative for this regime. In the proposed new procedure for WPS this problem will be solved by not considering any increase of fracture toughness above the K_{IWPS} value, and, moreover, by using only 90% of K_{Imax} for the assessment.
- There was not observed any significant difference between the predictions obtained by the two used models. For most cases the Wallin model was slightly more conservative and it is much simpler for application.
- Wallin model (with the above mentioned modification) was taken as the basis for the proposed new procedure for RPV integrity assessment with application of WPS effect.

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Symbols

T_{WPS}	temperature at pre-stressing	°C
T_U	temperature at unloading	°C
T_F	temperature at fracture	°C
T_0	Master Curve reference temperature	°C
K_I	stress intensity factor	$MPa.m^{1/2}$
K_{IC}	fracture toughness	$MPa.m^{1/2}$
i	sequence number of the specimen within the group	1
n	number of specimens in the group	1
K_{IWPS}	stress intensity factor at pre-stressing	$MPa.m^{1/2}$
K_{IU}	stress intensity factor at unloading	$MPa.m^{1/2}$
K_{IF}	stress intensity factor at fracture	$MPa.m^{1/2}$
K_{Imax}	maximum value of stress intensity factor during PTS	$MPa.m^{1/2}$
P_f	probability of fracture	1

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