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STATE-OF-THE-ART OF WPS IN RPV PTS ANALYSIS

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ABSTRACT

The APAL (Advanced Pressurized Thermal Shock (PTS) Analysis for Long-Term Operation (LTO)) project was launched in October 2020 for four years with funding from the European Union's HORIZON 2020 program.

Within APAL, an extensive literature review was performed and experience with defining the state-of-the-art of the Warm Pre-Stress (WPS) effect, which has an impact on the reactor pressure vessel (RPV) brittle fracture margin in both deterministic and probabilistic terms, was collected. To gather the worldwide experience of the WPS approaches and models, a comprehensive questionnaire was developed followed by each APAL partner response. It mainly focused on the following aspects: collection of existing WPS approaches and models implemented in standards and rules for RPV brittle fracture assessment; identification of the WPS issues; collection and analysis of the existing experimental data.

The work presents a short description of the existing WPS national approaches and models along with standards or rules for RPV brittle fracture assessment under PTS events. Attention is focused on the applicability of WPS and its restrictions for constraint effect and crack arrest.

The second part of this work is devoted to the identification of the open issues connected to the practical WPS application in RPV integrity assessment together with the APAL partners' views on this topic. The following problems are discussed:

- *Overall view regarding including WPS in the RPV PTS assessment (applicability, benefit in practical applications);*
- *thermal-hydraulic aspects of a WPS approach (WPS benefits depending on the transient history);*
- *WPS and probabilistic RPV brittle fracture assessment (applicability);*
- *WPS and ductile fracture (applicability);*
- *WPS and residual stress (RS), (treatment of RS in regard to WPS effect).*

The last part is dedicated to the analysis of experimental data for defining the WPS benefit. For this purpose, the Czech and Ukrainian experimental data (WWER materials), and the SMILE's project data (heat-treated 17MoV8-4mod steel and 18MND5 steel) were analysed. The WPS effect on fracture toughness (FT) was evaluated using the ratio of enhanced FT K_{Frac} (at re-load, after WPS) to FT of virgin material K_{IC} (without pre-load), as obtained from the experimental data. It was shown, that relatively to the $K_{IC,50\%}$ and $K_{IC,95\%}$, the WPS effect led to an

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increase of FT in 97.6% and 80.9% of cases respectively, which quantifies and confirms the benefit of WPS.

This work describes worldwide experience and best practice of the WPS and its application for the RPV integrity assessment. The paper's conclusions are also focused on the recommendations for dealing with WPS issues.

Keywords: reactor pressure vessel, fracture toughness, warm pre-stress, pressurized thermal shock.

NOMENCLATURE

K_I, K_J	stress intensity factor (SIF)
K_{IC}	fracture toughness (FT)
K_{Frac}	enhanced FT at re-load, after WPS
T_{frac}	temperature at K_{Frac}
K_{WPS} or K_{max}	global maximum of SIF trajectory
K_{reload}	local maximum of SIF path after K_{WPS}
T_{reload}	temperature at K_{reload}
K_2 or K_{min}	local minimum of SIF trajectory
K_{Ia}	crack arrest toughness
T_{DBTT}	ductile to brittle transition temperature
T_k	critical temperature of brittleness
T_{ka}	maximum allowable transition temperature

1. INTRODUCTION

According to the IAEA (International Atomic Energy Agency) data [1], most of the Reactor Pressure Vessels (RPV) are currently over 30 years of operation, which makes their lifetime extension and Long Term Operation (LTO) important aspects for the European countries, US and Japan. The RPV integrity is a necessary condition for safe operation of Nuclear Power Plant (NPP) throughout the project life and LTO as well. For Pressurised Water Rectors (PWR) and Water-Water Energetic Reactors (WWER) type RPVs, their service life assessment is based on deterministic and/or probabilistic brittle strength calculation for Pressurized Thermal Shock (PTS) scenarios. The goal of the assessment is to demonstrate the safety margin against RPV brittle fracture.

As a rule, demonstration 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.

The crack initiation criterion, along the front of a postulated or existed (generated) crack front of the ferritic material, with (or without) a safety factor, is based on the following relation:

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

Since the general shape of the FT curve is expressed as exponential function indexed by T_{DBTT}, (in countries using WWER type reactors the critical temperature of brittleness T_k is used), the RPV brittle fracture criterion in nuclear industry is generally formulated as brittle fracture temperature margin

$$T_{ka} - T_{DBTT} \geq 0 \quad (2)$$

While doing so, the two methods for T_{ka} determination could be used – classic "tangent point" (TP) method (i.e. T_{ka} is defined as such value of T_{DBTT} (considered as a parameter in (1)) for which in (1) the equality occurs, and warm pre-stress (WPS) approach, if the latter one is applicable by national standards.

To explain the WPS effect let us consider a structure with a crack like defect. The structure is loaded in tension at a temperature corresponding to the ductile upper shelf region of the material and subsequently unloaded either completely or partially. The structure is then cooled to the brittle region of the material FT transition curve and, when reloaded, fracture occurs at a higher load than what is expected, as shown in Fig. 1 (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).

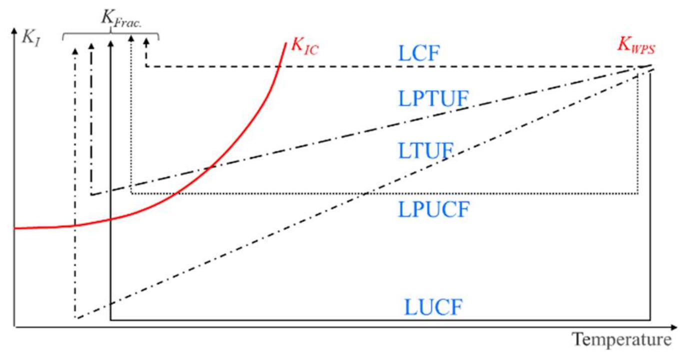

FIGURE 1: TYPES OF WPS REGIMES

The effects of WPS can be divided (according to [14]) into three cases according to the relative sizes of the plastic zones formed during each loading step. Case 1 is the situation 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., $S_1 > S_2 > S_3$, where S_i is the plastic zone calculated for state i due to load step i). 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 $S_3 > S_1 > S_2$ 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_{Frac} at re-load may be lower than level of K_{WPS}, but still higher than fracture toughness 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 [14].

The main advantages of inclusion WPS effect in RPV integrity assessment are that it can reduce over-conservatism of the TP method and enable more accurate evaluations of the safety margins against brittle fracture, which may occur at PTS events.

Current level of WPS practice is such that RPV integrity assurance is not an issue for the design lifetime. However, for LTO of existing PWRs and WWERs, the modern advanced methods and improvements could be needed.

To comprehend WPS more deeply, a state-of-the art review has been performed within the APAL project, dedicated to gathering world-wide WPS experience, studying and analysing it, and producing a detailed overview of this worldwide experience. For this purpose, firstly a questionnaire "State-of-the-art of warm pre-stress approach applied in the PTS" was prepared, discussed, and distributed among the partners for their response.

Based on the partners' responses, the open issues associated with the practical WPS application in RPV integrity assessment were identified, discussed and presented in this paper, together with the APAL partners' views on this topic.

Finally, based on the available experimental data (the Czech and Ukrainian experimental data and the SMILE's [17] project data) the analysis of WPS benefit was performed.

In fact, the results of this paper are fully based on the APAL Task 1.2 Report: "State-of-the-art for warm pre-stress" [38].

2. OVERALL POINT OF VIEW CONCERNING WPS CONSIDERATION

This chapter contains description based on the partners' responses (see following abbreviations: UJV – ÚJV Řež; Framatome GmbH – FRA-G; Paul Scherrer Institute – PSI; IPP-CENTRE – IPP; Kiwa Technical Consulting – KIWA; Tech – TECNATOM, BZN – Bay Zoltán Nonprofit Ltd for Applied Research; JSI – Jozef Stefan Institute; IRSN – Radioprotection and Nuclear Safety Institute; LUT – LUT University, Lappeenranta; JAEA – Japan Atomic Energy Agency; OCI – Oakridge Consulting International, Inc.; SSTC – State Scientific and Technical Center for Nuclear and Radiation Safety) related to the WPS model/approach or standard, limitation of the WPS applicability, connection with the other PTS topics etc.

WPS standard/model description

For the assessment of a PTS scenario, the applied WPS method is usually specified in the corresponding national standard (or rules, document etc.) which is accepted by the regulatory body.

The comparison of WPS rules is shown in Table 1. The main differences between standards consist in the following aspects: possibility of WPS application for monotonical unloading (i.e. for cases without reloading after global K_{max}, as shown in Fig. 3 (before T_{Frac})) or non-monotonical (i.e. when reloading occurs – see Fig. 1 and Fig. 2), consideration of Case 1 in WPS approach, application of different WPS models for Case 1 and application of additional safety margins.

Among the partners only Sweden, Slovenia, France and Finland have not yet implemented the WPS approach into the RPV PTS assessment rules.

The Swedish Radiation Authority do allow the use of WPS in a case-to-case basis. In Slovenia, due to PTS criterion satisfying for 60 years of operation, there is no practical reason for using a WPS rule. In Finland, WPS is not applied quantitatively for PTS analyses.

In France, the WPS-ACE «AREVA-CEA-EDF» criteria [2] have been proposed which has already been introduced in the RSE-M code but it is not yet approved by the French authority. It means that it has a provisory status. The status may change after a position from the French nuclear authority.

TABLE 1: COMPARISON OF APPROACHES TO WPS APPLICATION IN PARTNERS' COUNTRIES

Country	Czech Rep.	Germany	Switzerland	Ukraine	Hungary	France	Japan	Spain	Slovenia	USA	Russia
Partner	UJV	FRA-G	PSI	IPP, SSTC	BZN	IRSN	JAEA	Tecn	JSI	OCI	
Standard	NTD AME [4]	KTA [3]		PM-T.0.03.415--16 [6]	HAEA guide is used [7]	RCC-M /RSE-M	JEAC/JEAG [8], [9]	US Federal Register, Title 10 CFR 50.61a [10][4]			RD EO 0606-2005 [13]
WPS for monotonical	+	+		+	+	+ / +	+ / +	+			+
WPS for non-monotonical	+	+		+	+[1]	- / +	+ / +	+			+
Case 1	+	+		–	+	- / +	+ / +	–			–
WPS model for Case 1	modified Wallin	Chell, other allowed		–	–	-/ACE	+ / ACE	–			–
Safety factor[2]	0,9	1		0,9	0,9	1	1	1			0.9[3]
Additional condition	–	–		$T_{reload}< T_{WPS}$ $K_{reload}<0,9K_{WPS}$	$K_{reload}<0,9\ K_{WPS}$	–	–	Necessary conditions for a flaw to initiate: $K_{applied} > K_{Ic(\min)}$ $dK_{applied}/d\tau > 0$ $K_{\text{applied}}(\tau) \geq \alpha \cdot \max\limits_{0\leq t\leq\tau} K_{\text{applied}}(t)$			–

(1) Always the latest monotonic part of the K_I(T) to be considered. (2) Larger value is less conservative. (3) Before application of the safety factor 0.9 for WPS the PTS loading path (SIF) must be multiplied by 1.1. (4) NUREG-1806 [12] is cited by reference in 10 CFR Part 50.61a [10] and USNRC RG 1.230 [11]; NUREG-1806 provides specific USNRC guidance on plant-specific analysis using a PFM model that incorporates WPS effects.
+ or – means that aspect is considered or is not considered in the standard.

The only rule in Switzerland is that safety analyses have to be performed according to the state-of-the-art. The German KTA rules [3] which contain WPS, are accepted by the Swiss Federal Nuclear Safety Inspectorate (ENSI).

USA, Spain, and Slovenia use the US Nuclear Regulatory Commission (US NRC) rules for RPV integrity assessment which include WPS application.

In Germany and Switzerland, the KTA WPS rules [3] are specified in the national standards. Czech Republic, Ukraine, Hungary, France and Japan have their own domestic rules.

In what follows, some of the WPS models are described in more detail, this is the case of the WPS model applied in the Czech Republic (modified Wallin model), in Germany (KTA approach), in France (ACE model) or in the USA (WPS model implemented in FAVOR code).

In the Czech Republic, the WPS approach is implemented in standard [4] and is based on Wallin model [5] (but without the $0.15 \cdot K_{IC}$ term), complemented with an additional safety factor 0,9 applied to the pre-load level. It may be described as follows:

If $K_{IC} \leq 0{,}9K_{max} - K_2$

then $K_{Frac} = \sqrt{K_{IC}(0{,}9K_{max} - K_2)} + K_2$ (Case 1) (3)

If $K_{IC} < 0{,}9K_{max} < K_{IC} + K_2$ then $K_{Frac} = 0{,}9K_{max}$ (Case 2)

If $K_{IC} \geq 0{,}9K_{max}$ then $K_{Farc} = K_{IC}$ (Case 3)

where K_2 is the "unloading" value, i.e. $K_2 = K_{min}$ as far as condition for Case 1 (with $K_2 = K_{min}$) is being fulfilled, and if this condition stops being fulfilled, then $K_2 = 0{,}9K_{max}$ (Case 2 occurs). K_{FRAC} means here the predicted value of FT (at re-load).

The KTA's WPS approach [3] is divided in the effect on the loading side (crack tip loading) and the effect on the material side. "Upon warm pre-stressing of the crack front and in the case of a monotonously decreasing stress intensity factor (specimen cooling under sustained load), i.e. at $dK/dt \leq 0$, crack initiation is to be excluded". This statement holds even if the load reaches the material's fracture toughness during unloading and cooling.

The KTA also allows taking the increase of the apparent fracture toughness into account to exclude crack initiation in case of a sudden increase of the stress intensity factor (reloading at lower temperature). In such cases, it is advised to determine the apparent fracture toughness K_{Frac} after a warm pre-loading that is also depending on the unloading before the rise of the stress intensity factor. The following model describes the approach:

Fig. 2 shows a principle sketch to show the determination of the fracture toughness K_{Frac} upon WPS for the complete unloading range of a fictitious transient. The approach described within the KTA is basically the approach proposed in 1980 by G.G. Chell [14]. German R&D results were used to verify its application. It is important to note that besides the described approach the KTA also allows using other models to determine the FT upon WPS. In this context it refers to the method used in the British Standard BS 7910 [15] as an example.

Description of the Ukrainian WPS method is presented in PVP-2020 paper [18]. It is included into the PM-T.0.03.415-16 standard [6] which was developed based on the recommendations of IAEA-EBP-WWER-08/Rev.1 [16] for WWER type reactors and based on the results of international project SMILE [17].

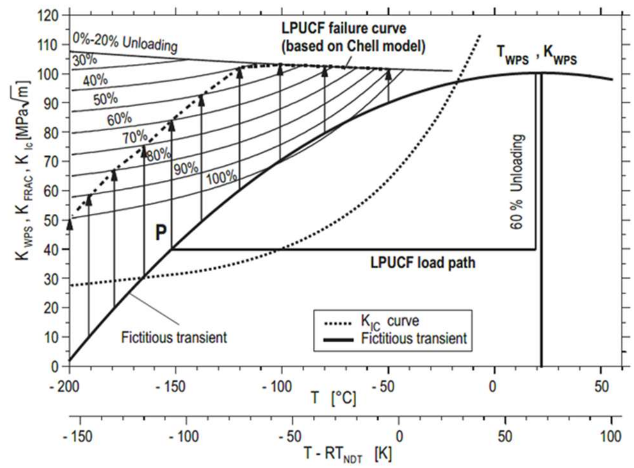

FIGURE 2: PRINCIPLE SKETCH TO SHOW THE DETERMINATION OF THE FRACTURE TOUGHNESS K_{Frac} UPON WARM PRE-STRESSING ACCORDING TO KTA [3]

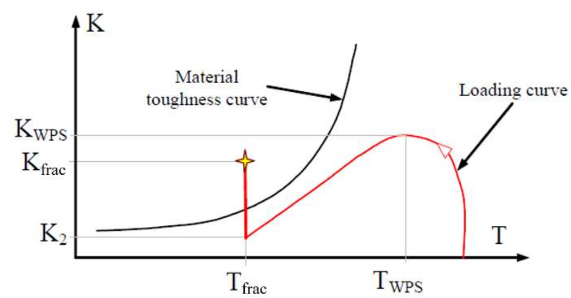

FIGURE 3: ILLUSTRATION OF THE PROCEDURE FOR WPS APPROACH APPLICATION ACCORDING TO ACE MODEL

In Hungary, the effect of WPS can be taken into account for transients in which the RPV is not re-pressurized. When using WPS approach, the latest monotonic part of the $K_I(T)$ curve should be considered and the 90% value of the latest local maximum point on the $K_I(T)$ curve, just before the reloading, is used instead of the value of K_{IC} at the given time of reloading.

Regarding the WPS criterion in France, the ACE model methodology is used (see Fig. 3). The predicted value of fracture toughness in cold conditions is given by the formula:

$$K_{Frac} = max \begin{cases} K_{IC}; \\ min \begin{cases} K_2 + K_{WPS}/2; \\ K_{WPS}, \end{cases} \end{cases} \quad (4)$$

with: K_{IC} value given by the toughness curve (RCC-M code ZG 6000); t_{max} is the time at maximum K_J between 0 and t, T is the crack tip temperature at t.

In Japan, for deterministic evaluation prescribed in JEAC4206-2016 [8] crack initiation cannot occur during dK/dt<0, here K and t mean the SIF and time, respectively. On the other hand, French ACE model is prescribed in JEAG4640-2018 [9] for probabilistic calculations of Japanese RPVs. This model was validated by comparison with experimental results using Japanese RPV steels and it was shown to rationally and conservatively evaluate the WPS effect [32], and as such it is considered a recommended method for evaluating Japanese RPVs.

In the US, WPS is applied in safety assessments of United States commercial nuclear RPVs. RPVs are regulated by the US NRC rules [10], [11], [12] which are implemented in the FAVOR v16.1 code [19]. The randomness of K_{IC} is based on a Weibull distribution and the probability for crack initiation at certain K_I is:

$$P(K_{IC} \leq K_I) = \begin{cases} 0 & K_I \leq a_K \\ 1 - \exp\left(-\left[\frac{K_I - a_K}{b_K}\right]^{c_K}\right) & K_I > a_K \end{cases} \tag{5}$$

where: $a_K = 21.27 + 9.18\exp(0.041[T - RT_{NDT}])$,
$b_K = 17.16 + 55.10\exp(0.014[T - RT_{NDT}])$,
$c_K = 4$.

In FAVOR v16.1, the necessary conditions for a crack not to be in the state of WPS (i.e., eligible for initiation) are:

i. applied-$K_I(t)$ > $K_{IC(min)}$
ii. dK_I/dt > 0
iii. applied-$K_I(t)$ >= α·$K_{I(max)}(t)$

$K_{IC(min)}$ in (i) is the minimum K_{IC} from the Weibull distribution, i.e., a_K defined in Eq. (5). In (iii), $K_{I(max)}(t)$ is the maximum K_I reached during the stress intensity factor history up to time t and alpha is a factor dependent on the chosen WPS model. In the probabilistic module of FAVOR v16.1, there are 4 WPS models available:

i. without WPS
ii. baseline model: $\alpha = 1$
iii. conservative model: $\alpha = 0$
iv. best-estimate model: alpha = random parameter, sampled from a log-logistic distribution

An α =1 picked from the log-logistic distribution in the best-estimate model is associated with about 5% cumulative probability, i.e., there is a 95% probability that the flaw still remains in WPS state as compared to the baseline model. Moreover, α =1.3 represents approximately a 95% cumulative probability of the log-logistic distribution implemented in FAVOR best-estimate model.

Note, that above is the brief description of the USNRC WPS approach, for more details see refs. [10], [11], [12] and [19].

It should also be noted that despite the fact that Russian side is not represented in APAL, their WPS rules are also considered (original standard [13] is in Russian, English description of Russian WPS rules is presented in the paper [18]).

WPS Applicability

As far as WPS applicability is concerned, three topics were considered:

- application of the WPS to irradiated zones of RPV;
- WPS and constraint effect (shallow crack effect and/or biaxial loading effect);
- WPS and crack arrest.

Regarding the aspect of applicability, two questions were asked: “Is WPS applicable for irradiated materials?” and “Is there any limitation on the ductility or embrittlement?”. The answer was received that in all participating countries WPS is applicable for irradiated materials. However, in Germany, KTA [3] specifies an embrittlement level and in Switzerland, ENSI approves level of both embrittlement and ductility.

At present, constraint effect (shallow crack effect and/or biaxial loading effect) is not included to any national standard in terms of interaction with the WPS (except Russian [13], where FT curve to be modified for the shallow crack with no restriction for WPS). However, it should be noted that some investigations related to the study of the WPS effect at biaxial loading were performed within the NESC VII project, which included large-scale cruciform specimens [33] and [34]. The main result of this project is that WPS effect takes place at biaxial loading and experimental results confirmed the applicability of considered WPS models (Chell, Chell & Haigh, Wallin and ACE) to predict the WPS effect in case of biaxial loading with an acceptable level of accuracy. So, biaxial loading does not restrict the WPS effect.

Crack arrest is not considered by the majority of APAL participants in their PTS assessments. The participants from Switzerland and Japan state that WPS effect is only applicable for crack initiation. In addition, WPS effect is not considered in crack arrest evaluation by Japan Atomic Energy Agency (JAEA). Participants, from Germany USA and Spain (and also JSI, if a PTS assessment would be in the future performed in Slovenia following USNRC rules), state that WPS effect and crack arrest can be applied simultaneously. Additionally, FRA-G recommends that future experimental work shall be directed to assess whether the static K_{Ia} concept is valid or not under WPS.

The outcome is that the whole spectrum of possible answers is covered by the APAL participants. Thus, a recommendation would be to analyse the possible benefits in terms of margin assessment, based on considering the WPS effect in re-initiation events after crack arrest, both in the deterministic and probabilistic PTS analyses to be performed within APAL [38].

WPS experimental background

Usually, implementation of the WPS effect into national standards and the decision on which approach to use are based on experimental investigations that have been carried out. Experiments that are explicitly investigating the WPS effect or experiments that consider the WPS effect besides other effects have been carried out for over 50 years. Tests have been performed from large scale specimens down to small 10x10 Single Edged Notch Bending (SENB) specimen, on base and weld metals in unirradiated, artificially aged and irradiated conditions. Table 2 provides an overview of the reported national efforts to implement a suitable WPS approach into the respective national standards.

Besides these reported projects, several other projects have been conducted to investigate WPS effect with a lot of published data. Summarizing all these available data and making their access easier could further improve the research of the WPS effect and its understanding.

In the Czech Republic the 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 tested. The total number of specimens was about 600. Different WPS-type tests like LCF, LUCF, LPUCF, LTUF, LPTUF were performed. 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 implementation in "Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs – VERLIFE", which was later converted to Czech standard NTD AME [4]. Some experimental results are presented in [20] and [21]. Currently, a large project funded by ČEZ Company (owner of the Czech NPPs) is running, in frame of which the WPS tests are being performed with the goal to support application of WPS approach in PTS evaluations in accord with the NTD AME standard. Within this project, surveillance specimens irradiated (to various levels of fluence) directly in WWER-440 and WWER-1000 reactors are tested. Both base and weld materials are tested. Approximately 1600 specimens have been tested to date.

In Germany, a large experimental program (>100 specimens) was performed that covered different loading cycles (LCF – LUCF), different specimen sizes (1T C(T) up to 235mm C(T)), different materials with properties ranging from beginning of life to beyond end-of-life (see Refs. [22] – [27]). Currently, a project funded by the German ministry for economic affairs and energy is running to demonstrate the WPS effect for different unirradiated and irradiated base and weld materials.

Experimental work has been performed in [28] (experimental program to identify underlying mechanism behind the WPS effect, in total 63 experiments) and is ongoing in a joint research project with organizations from Sweden and Finland. These two projects are intended to give the authorities enough knowledge to better judge the applicability of the WPS effect.

US WPS model is based on the experimental results of an extensive European Commission funded investigation of WPS

TABLE 2: SUMMARISED INFORMATION REGARDING WPS EXPERIMENTAL DATA

Participant	National test program	Materials	Conditions	Type of specimen	WPS regime	Number of tests	Info
UJV	YES	different VVER base materials	unirradiated, artificially aged and irradiated / different temperatures and pre-load levels	Charpy sized SENB, 1T C(T)	LCF, LUCF, LPUCF, LTUF, LPTUF	~600	Currently ongoing project with ~ 1600 specimens from surveillance programs
FRA-G	YES	different base materials	begin of life - beyond end of life (artificially aged)	1T C(T) up to 235mm C(T)	LCF, LPUCF, LUCF, LCUF, LTUF	> 100	Currently ongoing project with unirradiated and irradiated materials
PSI	NO	n.i.	n.i.	n.i.	n.i.	n.i.	—
IPP	NO*	WWER-440 RPV: two forgings and one weld. WWER-1000 one forging and one weld	artificially aged for end of life	1T C(T) 2T C(T) SENB T=150mm	LCF, LUCF, LPUCF	19 15	WPS used according to the IAEA guidelines with taking into account literature experimental data and conclusions of SMILE
KIWA	YES	18MND5	Test temperature -150 C	3 point bending W=50 mm, a/W=0.5	LUCF LU(HT)CF	63	—
Tecn.	NO	n.i.	n.i.	n.i.	n.i.	n.i.	WPS model by NRC used, based on results from HSST program
BZN	NO	n.i.	n.i.	n.i.	n.i.	n.i.	—
JSI	NO	n.i.	n.i.	n.i.	n.i.	n.i.	WPS model by NRC used, based on results from HSST program
IRSN	YES	n.i.	n.i.	n.i.	n.i.	n.i.	—
JAEA	YES	A533B Cl.1 steel	unirradiated /different temperatures and pre-load levels	1T C(T), 0.4T C(T)	LTTUF, LTPTUF, LUCF	66	Additional tests on the other conditions are ongoing.
OCI	YES	n.i.	n.i.	n.i.	n.i.	n.i.	WPS model by NRC used, based on results from HSST program

n.i. = no information provided; *The data of WPS research, performed in G.S. Pisarenko Institute for Problems of Strength (Kyiv, Ukraine), is presented by IPP, there was no national test WPS program in Ukraine; XT or x mm C(T) – X inches thick or x mm thick compact tension FT specimen.

called SMILE [17]. A study of WPS conditions (e.g., LCF, LUCF, LTUF, etc.) was performed using three nuclear pressure vessel grade ferritic steels. Data from a total of 86 experiments were reported and summarized in Table 15 of [19].

French ACE model is based on the WPS experiments [29].

At the end of the last century the WPS project was conducted in Ukraine, which included 1500mm thick specimens made from artificially aged WWER-440 and WWER-1000 materials, but the results alone did not lead to the WPS implementation in Ukraine. Some of the results are presented in [30] and [31].

3. WPS ISSUES

This section contains the issues associated with the practical WPS application in RPV integrity assessment as well as issues associated with the partners' opinions on this topic and recommendations for further works within APAL project.

Overall opinion concerning the most sophisticated WPS model

Almost all participants support application of some of the specific WPS models, like Chell, Wallin, modified Wallin or ACE. This fact implicitly means that WPS can be applied also for non-monotonical unloading during PTS. This becomes more important for currently performed PTS analyses which are based on more realistic representations of the transients (mixing analyses performed by computational fluid dynamics codes), including consideration of operator's actions (which can lead to re-pressurization of the primary system or to switch off/switch on of Emergency Core Cooling Systems). In these cases, the time dependent stress intensity factor curve after reaching its maximum exhibits at least small fluctuations or even large unloadings and reloadings. Applicability of WPS for non-monotonical unloading seems necessary in this context.

On the other hand, when WPS is applied to non-monotonical unloading, consideration of Case 1 criterion is necessary, since Case 1 curve depends on level of unloading and under certain conditions the Case 1 curve may represent limiting condition of the WPS effect. Application of WPS effect has to assure conservatism of the RPV integrity assessment. Some methodologies currently in use in participating countries do not consider Case 1, but its relevancy was proven by many WPS tests, when final fracture occurs below K_{WPS}. All the above mentioned WPS models consider Case 1. Chell model was found to be rather complicated for practical application. Wallin model was not found to be sufficiently conservative for some types of WPS tests, e.g., for LCF tests. Both modified Wallin and ACE models are simple for use and sufficiently conservative. Advantage of ACE model is its independence of K_{IC} value, but this model is slightly more conservative than modified Wallin model.

The partners using FAVOR code for probabilistic PTS assessment consider the WPS model used within this code as relevant. Some APAL partners recommend using local approach of fracture mechanics as most physically relevant, but they acknowledge its difficulty for practical use.

WPS and ductile fracture

Exceeding the ductile upper shelf limit (as shown in Fig. 4) is not allowed by majority of standards. Nevertheless, question whether WPS takes places in conditions of preload approaching or slightly exceeding this limit is of interest.

The WPS mechanisms are related to the level of applied load and strain during the pre-load in the ductile regime. In case of ductile fracture all mechanisms (voids development, plastic deformation etc.) are part of the crack development and these degradation mechanisms are more intensive at higher temperature. That is why the ductile fracture occurs at slightly lower load at higher temperature.

It is also a well-known fact that ductile tearing and cleavage are two competing fracture mechanisms. The ductile tearing mechanism can affect the development of the brittle fracture. The main driving fracture mechanism when exceeding the upper shelf of FT curve is ductile tearing, and cleavage and micro crack initiation are not relevant.

As a result of APAL partners discussion, it was concluded that the WPS effect is not recommended for taking into consideration in case of loading path (K_{max} or K_{WPS}) exceeding the upper shelf of FT curve (e.g. 200 MPa·m$^{0.5}$).

However, it is an open issue since there is no harmonized practice. Therefore, in order to avoid further obscurity, some research is required, and a common position of the APAL partners should be established for application of the WPS concept if pre-load exceeds or approaches the FT upper shelf curve, both on the theoretical and experimental basis.

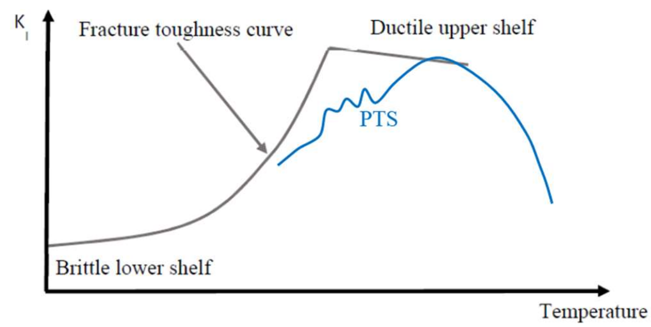

FIGURE 4: PTS APPROACHING TO DUCTILE UPPER SHELF AND TO BRITTLE FRACTURE REGION OF FT CURVE

WPS and probabilistic brittle fracture assessment of RPV

Regarding this open issue two questions were considered, which alongside with results are summarised in the Table 3.

Thermal Hydraulic (TH) aspects of WPS approach

Although the WPS approach can bring benefits to the RPV structural integrity assessment, requirements for TH analyses in case of WPS application are not clearly defined yet. This leads to varied application of WPS in PTS analyses in different countries. Mentioned variation potentially can impact the TH transient selection for PTS analysis and affect the results of structural integrity assessment of the RPV. Therefore, analysis of applied approaches and development of recommendations (unified approach) for the TH analyses with respect to WPS

TABLE 3: BRIEF SUMMARY OF WPS IMPLEMENTATION TO PROBABILISTIC INTEGRITY ASSESSMENT OF RPV

UJV	FRA-G	PSI	IPP, SSTC	KIWA	Tecn.	BZN	JSI	IRSN	LUT	JAEA	OCI
Is WPS applicable in probabilistic assessment according to your national standard?											
no	yes	yes	no	yes	yes	–	yes	no	yes	yes	yes
Probabilistic nature of the WPS model?											
no	–	yes	–	no	yes	–	yes	–	yes	–	yes

application is an important aspect of the RPV structural integrity assessment for LTO. Therefore, APAL partners were asked to give their opinion regarding the following questions:

- Do we need to perform variant TH calculations for one and the same transient to obtain different K_{max} and K_{min} values with subsequently obtaining the most conservative T_{ka}?
- Is it necessary to change the approach to conservative selection of PTS scenarios and input parameters for TH analyses, if WPS approach is applied?

Feedback of APAL partners showed the absence of a unified methodology not only for WPS approach, but also for TH aspects of its application.

In the Czech Republic, Ukraine and Spain conservative TH calculations should be performed for their further application in structural analyses. At the same time Czech requirements foreseen that the TH analyses should be conservative in relation to K_{min} determination, which does not necessarily correspond to the conservative K_{max} values. Such approach may require performing variant TH calculations.

German regulations do not require performing of conservative TH calculations. Preference is given to variant analyses (several transients need to be investigated), which should demonstrate that leading transient provides lowest T_{ka}. Similar position is demonstrated by Finland (LUT), which indicated the need to perform TH analyses with varying parameters in case of WPS application.

France, Switzerland, Sweden and Slovenia indicated the reasonability to perform sensitivity study or variant calculations in case of WPS approach application.

Applied in Japan WPS approach is based on the conservative methodology and does not require variant TH calculations or uncertainties evaluation.

In the USA, the WPS approach is linked with a probabilistic fracture mechanic computer program. It is assumed that for the severe PTS transients, that dominate risk for RPV, there is a small difference between the conditional probabilities of crack initiation and of through-wall cracking frequency predicted by the different WPS models. Thus, changing the approach for the TH analysis or the variant TH calculations are not foreseen.

The current TH analyses are focused on most severe cooling at the beginning of PTS, which will enhance preloading (WPS), but unloading phase may not be considered in TH analyses conservatively enough from the point of view of WPS.

Only KTA (based on Chell model), Czech NTD AME (based on modified Wallin model) and French RSE-M (based on ACE model) standards consider unloading in WPS application for PTS assessment. Most approaches do not consider "Case 1" at all and use only K_{WPS} (i.e., maximum approach).

4. ANALYSIS OF THE WPS EXPERIMENTAL DATA

In order to define quantitatively a WPS benefit, the available experimental data, gathered by APAL partners, were analyzed. For this purpose, UJV (with kind permission of the Czech Regulatory Body) and IPP provided Czech and Ukrainian data correspondingly (see Table 2 of current paper and section "*WPS experimental background*"). In addition, the experimental data of international project SMILE [17] were also considered.

WPS effect on FT is evaluated in terms of the ratio of enhanced fracture toughness $K_{Fracture}$ (at re-load, after WPS) to fracture toughness of virgin material K_{IC} (without pre-load), as obtained from the experimental data as K_{Frac}/K_{IC}.

Since FT is of stochastic nature, for evaluation of the WPS effect (as objectively as possible) the value of K_{IC} relevant to 50% and 95% confidence levels of FT was selected.

Some results of this evaluation relatively to $K_{IC,50\%}$ for Czech WPS experimental data (only two irradiated materials are selected for this paper) are presented in Figs. 5 and 6, while Fig. 7 contains Ukrainian results.

In summary we obtained that:

- relatively to the $K_{IC,50\%}$ the WPS effect led to increase of fracture toughness in 579 cases from 593 experiments that is equal 97.6%;
- relatively to the $K_{IC,95\%}$ the WPS effect led to increase of fracture toughness in 480 cases from 593 experiments that is equal 80,9%.

This conclusion is based on increased material FT after WPS compared to the 50% and 95% FT confidence levels of virgin material (material to which WPS was not applied).

When we performed the above evaluation of the effect of WPS separately for irradiated or aged specimens and separately for unirradiated specimens, we obtained the following quantitative evaluation of the WPS effect:

- relatively to the $K_{IC,50\%}$, the WPS effect for irradiated or aged specimens led to increase of fracture toughness in 314 from 315 cases (99,7%) while for unirradiated specimens the WPS effect led to increase of fracture toughness in 265 from 278 cases (95,3%)
- relatively to the $K_{IC,95\%}$, the WPS effect for irradiated or aged specimens led to increase of fracture toughness in 271 from 315 cases (86,0%) while for unirradiated specimens the WPS effect led to increase of fracture toughness in 209 from 278 cases (78,9%).

This result witnesses in favor of the fact that beneficial WPS effect takes place for irradiated materials in the same manner as for the unirradiated ones.

Additional, material FT increasing compared to the level of the pre-stressing at elevated temperature was also assessed (i.e., the K_{Frac}/K_{IC} ratio) for Czech and Ukrainian WPS data and for international project SMILE data as well. We obtained that in 4.6% cases $K_{Fract} \leq K_{WPS}$. Thus, approximately in 95% cases pre-stressing leads to material FT increasing to values higher, than the pre-stressing level.

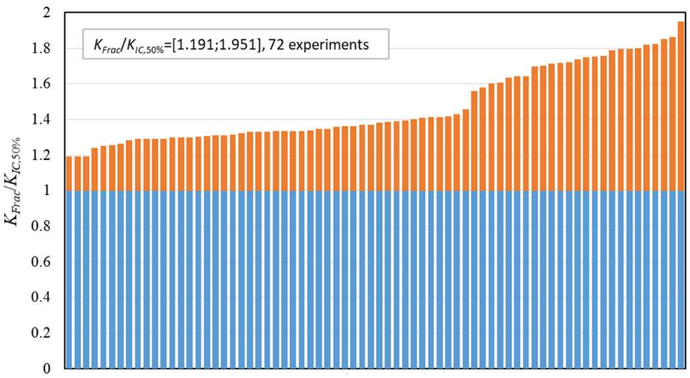

FIGURE 5: EVALUATION OF WPS EFFECT. CZECH PROJECT WPS DATA RELATED TO THE WWER-440 RPV IRRADIATED MATERIAL (neutron fluence is from 277×10^{22} neutr./m^2 to 310×10^{22} neutr./m^2).

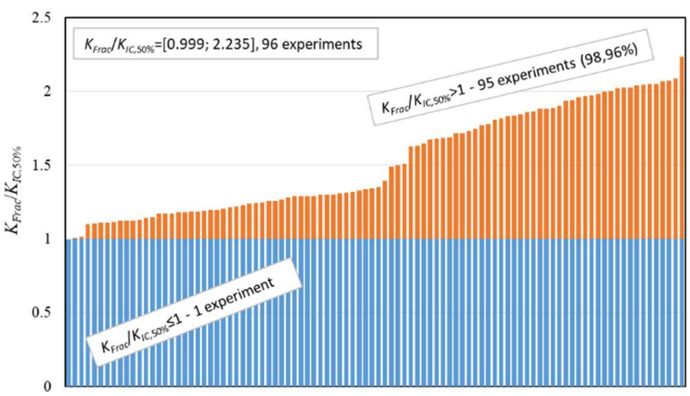

FIGURE 6: EVALUATION OF WPS EFFECT. CZECH PROJECT WPS DATA RELATED TO THE WWER-1000 RPV IRRADIATED MATERIAL.

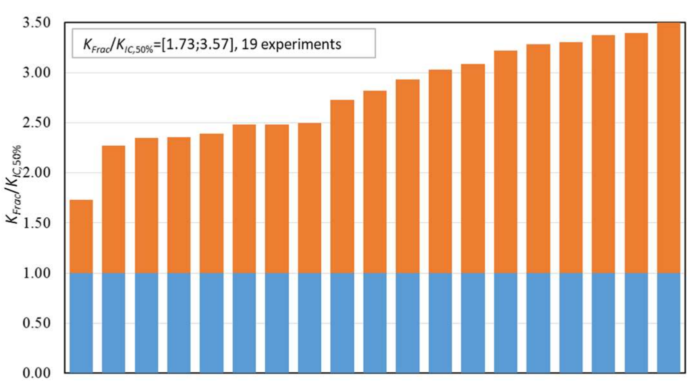

FIGURE 7: EVALUATION OF WPS EFFECT. UKRAINIAN WPS DATA [31] RELATED TO THE WWER-1000 RPV UNIRRADIATED MATERIALS.

5. CONCLUSIONS

Based on the APAL partners' opinions it is evident that the WPS effect is an important subject. Furthermore, most partners have the opinion that the WPS effect is a relevant and, in some cases, required effect to be considered in PTS assessments especially when considering LTO. Some open questions or issues regarding the WPS effect have also been identified and summarised:

The possible non-conservative estimation of the WPS effect when the most severe load is estimated within the TH analysis. The reasoning behind this is that the magnitude of the WPS effect is directly connected with the magnitude of the pre-load. A higher pre-load gives a larger WPS effect. Hence, overpredicting the pre-load would lead to over predicting the WPS effect leading to a possible nonconservative result.

The possibility that important information from the transient is lost when an envelope of the results of the TH analyses is used. The level of margin to fracture given by the WPS effect during the cooling phase of the PTS transient is not known with certainty. Therefore, it is important to know if there exist load disturbances during the transient. If there exist load disturbances during the cooling phase the criteria of monotonic decreasing load could be violated. These transients could possibly be analysed with local probabilistic models such as Beremin [35] or Kroon and Faleskog [36].

The majority of the published experimental results demonstrating the WPS effect are on non-irradiated material where low temperatures are used to mimic the effect of the irradiation on the fracture toughness curve. There exist some published experimental results regarding the WPS effect on irradiated materials, e.g. [37]. But as one partner points out, all these experiments have been conducted on material that has not been irradiated in loaded condition. It is suggested that material from decommissioned RPV could be used to determine if this fact could be of importance. This investigation would also increase the available experimental data on irradiated material.

How to treat residual stresses in regard to the WPS effect in the analyses is not fully examined. There is very little published work on this subject. There is ongoing work that suggests that a prior high residual stress field can slightly affect the WPS-effect in both positive and negative sense. Further experimental and numerical research in this field is recommended.

Interaction between constraint and the WPS effect is also suggested as a topic that could need more studies. The majority of the performed WPS experiments have been conducted on standard high constraint specimens. A situation with low constraint (shallow crack) would lead to a larger plastic zone during the pre-load. This larger plastic zone in front of the crack tip could, due to the mechanisms behind the WPS effect, possibly also lead to a larger WPS effect.

The last unresolved issue is how to deal with WPS effect in case that the pre-load exceeds or approaches the FT upper shelf curve. Therefore, in order to avoid further obscurity, some research is required both on the theoretical and experimental basis.

Within further APAL works, a recommendation was given to analyse the possible WPS benefits in terms of margin assessment, based on considering the WPS effect in re-initiation events after crack arrest, both in the deterministic and probabilistic PTS analyses.

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Also, the work was built upon national approaches, standards, and existing knowledge from Euratom projects (ATLAS+, SMILE and NESC VII), NUGENIA and SNETP activities and projects (DEFI-PROSAFE) and at the same time fully utilizing the completed and ongoing national programs in this field. Knowledge and recommendations of the APAL Advisory Board and interested end-users were also considered.

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