Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division II

NESC VII project : a European project for application of WPS in RPV assessment including biaxial loading

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ABSTRACT

The Reactor Pressure Vessel (RPV) is an essential component liable to limit the lifetime of PWR plants. The assessment of defects in RPV subjected to PTS transients made at an European level do not take necessary into account the effect of load history (warm pre-stress WPS) on the resistance of RPV material regarding the risk of brittle failure. Numerous experimental, analytical and numerical results are available, which confirm the beneficial effect of warm pre-stress on RPV steels with an effective significant increase of the material resistance regarding the risk of brittle failure.

NESC VII, a new project dealing with WPS, launched in 2008 with the participation of numerous international organizations (involving R&D, Utilities and Manufacturers, Technical supports, Regulatory), will be finished in 2013. Based on experimental, analytical and numerical tasks, the project is focused on topics generally not covered by past experience on WPS : biaxiality of loading on small and large-scale specimens, effect of irradiation, modeling (including analytical and numerical models) … Among these tasks, new original WPS experiments have been conducted on small and large scale specimens to study the influence of biaxial loading on WPS effect, using a fully representative RPV steel. All WPS experiments have been interpreted with a wide panel of methods, including analytical, engineering and numerical analyses. A description of NESC VII project is presented in this paper including a preliminary synthesis of the available experimental, analytical and numerical results.

INTRODUCTION

The Reactor Pressure Vessel (RPV) is an essential component liable to limit the lifetime duration of PWR plants. The assessment of defects in RPV subjected to PTS transients made at an European level do not take necessary into account the effect of load history (warm pre-stress WPS) on the resistance of RPV material regarding the risk of brittle failure. Numerous experimental, analytical and numerical results are available, old and more recent, which confirm the beneficial effect of warm pre-stress on RPV steels, with an effective significant increase of the material resistance regarding the risk of brittle failure. For example, the European R&D program SMILE has been successfully conducted between 2002 and 2005 [1]. The objective of SMILE project was to give sufficient elements to demonstrate, to model and to validate the WPS effect in a RPV integrity assessment.

In addition to SMILE, a new project - NESC VII - dealing with WPS has been launched in 2008 with the participation of numerous international organizations (involving R&D, Technical supports, Utilities, Manufacturers and Regulatory)[2][3]. Based on experimental, analytical and numerical tasks, the project is focused on topics generally not covered by past experience on WPS :

- biaxial loading on medium and large-scale specimens
- influence and effect of irradiation
- applicability to intergranular fracture
- modeling (including analytical and numerical models) …

Among these tasks, new original WPS experiments involving biaxial loading are conducted on small, medium and large scale specimens to study the influence of biaxial loading on WPS effect, using a fully representative RPV steel (18MND5 steel similar to A533B steel).

A full description of NESC VII project is presented in this paper including a preliminary synthesis of the available experimental, analytical and numerical results.

THE WARM PRE-STRESS CONCEPT IN RPV ASSESSMENT

Material fracture toughness K_{Ic} (or K_{Jc}) is usually determined through monotonic loading at a constant temperature on standard compact tension (CT) specimens. Thus, based on high constraint geometry like CT specimens, conservative values of fracture toughness are obtained to be used in a classical RPV integrity assessment based on the comparison between the K_{Ic} (or K_{Jc}) material fracture toughness and the stress intensity factor K_J (or K_I) which characterizes the damage on the component. In practice, loading in a RPV assessment is more complex (e.g. pressurized thermal shock transient PTS), involving non monotonic loading on a large range of temperature.

The warm pre-stress (WPS) in RPV integrity assessment is well known on the resistance of ferritic steels regarding the risk of brittle failure. A cooling PTS type transient generally involves several steps, as depicted on Figure 1 :

- an initial preloading at 'high' temperature T_1 with an increasing of stress intensity factor K
- a decreasing of K in a second step with decreasing temperature, between temperatures T_1 and T_2
- a possible final reloading at the lower temperature T_2

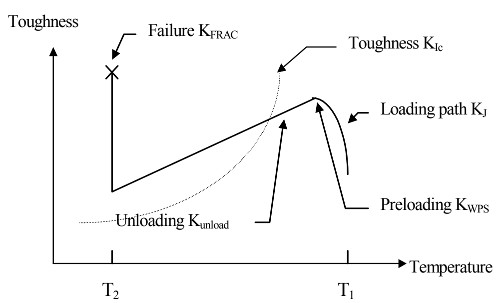

Figure 1. Warm pre-stress principle.

The consequences of the WPS effect, due to the load history, can be shortly summarized as follows :

- brittle fracture initiation is not possible during the unloading phase of K (also if the loading K remains constant), even if the load path K_J – T intersects the K_{Ic} material fracture toughness lower bound curve (the 'conservative principle')
- in case of an additional reloading at lower temperature (T_2), the brittle failure initiation would be obtained with additional margins, compared to the original material fracture toughness obtained on a 'virgin' material

This effect is widely described in literature, e.g. [4][5][[6]. It is generally attributed to several factors, such as a compressive residual stress zone ahead of the crack tip, crack tip blunting, and strain hardening. In some countries (e.g. France), the structural integrity assessment of a RPV subjected to PTS transient doesn't account the potential beneficial effect of the load history ('warm pre-stress WPS') on the vessel resistance regarding the risk of brittle failure, at least the 'conservative principle'. In order to justify the introduction of this concept in French RPV assessment and French Regulatory Code RSEM, significant R&D actions have been conducted by EDF, in collaboration with several organizations, to demonstrate, model and validate the beneficial WPS effect on materials fully representative of RPV steels, e.g. [7][8][9].

NESC VII PROJECT

Purpose and expected results

A new project – NESC VII – has been launched in 2008 with the participation of numerous international organizations, involving R&D and Technical supports, Utilities, Manufacturers and Regulatory. Based on experimental, analytical and numerical tasks, the project NESC VII is focused on topics generally not covered by past experience on WPS [2][3] :

- biaxial loading on small, medium and large-scale specimens
- influence and effect of irradiation
- applicability to intergranular fracture
- modeling (including analytical and numerical models) …

Among these tasks, some new original WPS experiments are conducted on cracked specimens (including disks and bend bar cruciform specimens) to investigate the influence of a biaxial loading on WPS effect – more representative of a real PTS transient – using a fully representative RPV plate steel (18MND5 steel similar to A533 B steel).

This project must contribute to harmonize the different approaches in main Codes and Standards regarding the inclusion of the warm pre-stress in a RPV structural integrity assessment. Some recommendations and guidelines will be proposed with this goal. Main expected NESC VII results can be thus summarized :

- a description of state of art on WPS
- a compilation of available WPS data in conditions including biaxial loading, irradiation, intergranular failure …
- a more deeper experimental demonstration of WPS effect in RPV assessment, more particularly in conditions not covered by past experience : biaxial loading, irradiation …
- an evaluation and validation of analytical and numerical WPS models in complex situations (biaxial loading) more representative of real PTS transients, through benchmark and analyses of NESC VII WPS experiments
- some final guidelines and recommendations for Regulatory Codes

Organization of the project

17 international partners are associated to NESC VII project, on the basis of in-kind contributions, including :

- R&D : EDF (F), CEA (F), ORNL (USA), BZN (H), University of Bristol (UK), AEKI (H), ENEA (I), SCK-CEN (B), UJV (CZ), MPA (D)
- Utilities & Technical support : TWI (UK), AMEC (UK), IWM (D)
- Manufacturers : AREVA (F), AREVA GmbH (D)
- Safety & Regulatory : Inspecta (S), IRSN (F)

NESC VII project is organized in 6 work packages :

- *WP0 : Management and Coordination*

The objective of the work package, managed by EDF, is to provide overall management and coordination of the project. Regular meetings (~ 2 / year) are organized to facilitate ongoing interaction between participants during the course of the project.

- *WP1 : WPS experiments*

This work package, managed by CEA, includes all experimental aspects of the project :

- design of specimens and experimental devices
- manufacturing of specimens

- instrumentation
- material characterization
- experiments on large scale and medium cracked mock-ups
- final expertise of specimens

The material selected for the project is the French RPV plate steel 18MND5 (similar to A533B steel)(200 mm thick) with the chemical composition given in Table 1 :

Table 1: Chemical composition of the 18MND5 material.

C	Mn	Si	Ni	Cr	Mo	Cu	S	P	Al	V
0.19	1.5	0.23	0.66	0.17	0.08	0.084	<0.001	0.004	0.011	0.004

The WPS experiments are conducted on medium and large scale cracked specimens, including :

- bend bar cruciform specimens designed and tested by CEA
- PTS-D cracked disks designed and tested by SCK-CEN
- conventional fracture mechanics specimens tested by TWI (CT, SENB ..)

All specimens are fatigue pre-cracked before final WPS experiments. The fracture surfaces are observed after failure of specimens to identify mode of fracture and location of initiation sites. A full characterization of the 18MND5 steel is made, including fracture toughness measurements on deeped cracked (CT) and on shallow cracked (SENB) specimens.

- *WP2 : Analyses of experiments*

The work package, managed by AREVA NP, is in charge of :

- definition of experimental conditions for WPS experiments
- design of specimens
- interpretation of experiments by a large panel of engineering models and numerical analyses
- final synthesis of analyses to evaluate the capability of the models to account WPS effect in case of complex loadings

- *WP3 : Effects of irradiation and intergranular fracture on WPS*

The objective of the work package, managed by UJV, is to collect available WPS data and evaluate the capability of simplified models to predict WPS effect on the resistance of materials, including :

- unirradiated and irradiated materials
- materials sensitive to intergranular fracture

- *WP4 : Fundamental aspects*

The work package, managed by University of Bristol, must contribute to a better understanding of WPS effect on brittle fracture resistance of materials submitted to non monotonic loading :

- influence of residual stress ahead of the crack tip
- crack tip blunting during the preloading
- role of 'active plasticity' in WPS modeling…

- *WP5 : Synthesis*

The final synthesis of the project is prepared in this work package (end 2013) managed by EDF.

STATUS OF THE PROJECT AND PRELIMINARY SYNTHESIS

The NESC VII project has been launched in June 2008, and is expected to be finished in 2013. A significant progress is now noticed with achievement of main experimental tasks (including material characterization and WPS experiments) and analyses. A lot of information and details can be found in specific presentations [10][11][12][13][14][15], summarized in this paper.

Material fracture toughness characterization

The material selected for the project is the French RPV 200 mm thick plate steel 18MND5 (similar to A533B steel), with an RT_{NDT} = -32 °C. The material fracture toughness characterization - based on EDF, CEA and TWI contributions - is now achieved, including T_0 evaluation based on deep and shallow cracked specimens (CT, SENB). The effect of orientation of specimens (comparison between L-T and L-S orientations) has also been investigated, showing no significant effect on T_0 (3° C shift). The effect of constraint is more significant with a ΔT_0 shift ~ 30 °C. Main results are gathered in the following Table 2 and an illustration of fracture toughness properties is given on Figure 2 (based on a/W = 0.5) :

Table 2 : T_0 evaluation for 18MND5 steel.

CEA data (T_0)		**TWI data (T_0)**	
L-S orientation, ¼ thickness		L-S orientation, ¼ thickness	
a/W = 0.5	a/W = 0.1	a/W = 0.5	a/W = 0.1
-98 °C		-96 °C	-128 °C
L-T orientation, ¼ thickness			
-95 °C	-132 °C		

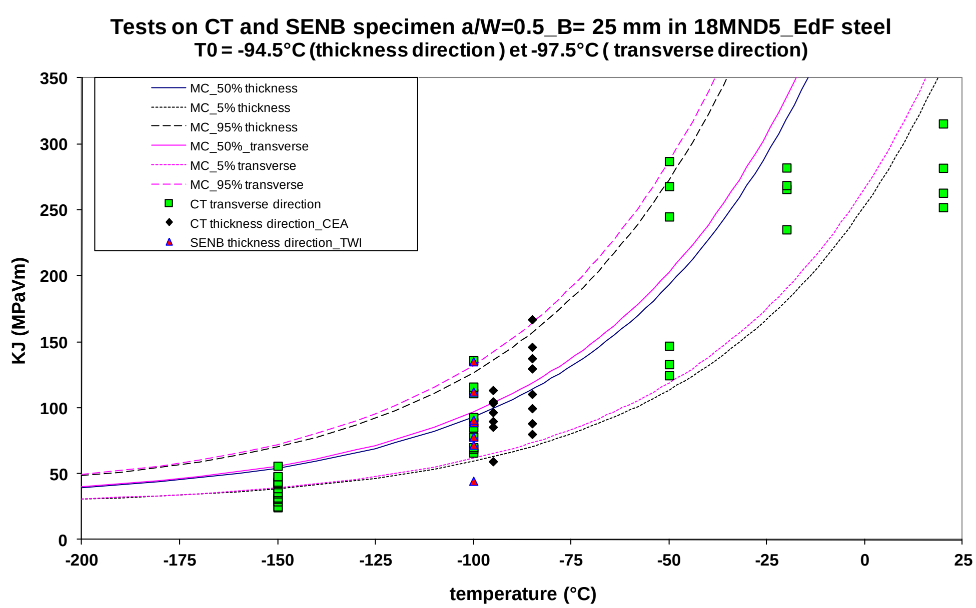

Figure 2. 18MND5 fracture toughness.

WPS experiments under biaxial loading

WPS experiments under biaxial loading are also achieved. After initial design and manufacturing of the specimens, the WPS experiments have been conducted with full success on 3 types of specimens :

- 6 WPS bend bar cruciform specimens containing a shallow ½ elliptical fatigue surface flaw (a ~ 12 mm, 2c ~ 36 mm) tested by CEA, with different loading paths (LCF and LCTF cycles), including a feasibility test
- 16 PTS-D cracked disks containing a ½ elliptical fatigue surface flaw (a ~ 12 mm, 2c ~ 45 mm) tested by SCK-CEN, with different loading paths (LCF, LUCF and LCTF cycles)
- some more conventional WPS experiments by TWI on SENB specimens

Based on these experiments, the beneficial effect of WPS regarding the cleavage fracture resistance of the material is fully confirmed for a biaxial loading, whatever experimental conditions (level of preloading, loading path, specimens …) :

- the 'conservative principle' is again verified, no fracture occurs during the cooling phase although K_J curve crossing the K_{Ic} fracture toughness curve, with constant K_J (LCF cycle) or decreasing K_J (LCTF)
- an increase of the fracture resistance of the material (K_{FRAC}) is observed in case of a final reloading at low temperature, compared to the initial material fracture toughness

These experiments, with their main characteristics, are illustrated on Figures 3, 4, 5 and 6 (CEA experiments) and on Figures 7, 8 and 9 (SCK-CEN disks) :

Figure 3. CEA WPS cruciform specimen (with a view of typical flaw after fracture).

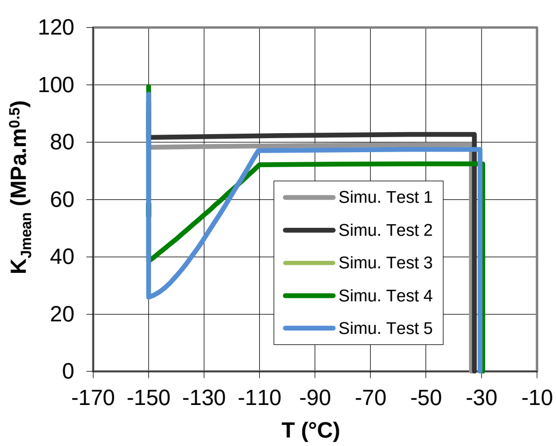

Figure 4. Illustration of LCF and LCTF loading paths applied on CEA WPS cruciform specimens.

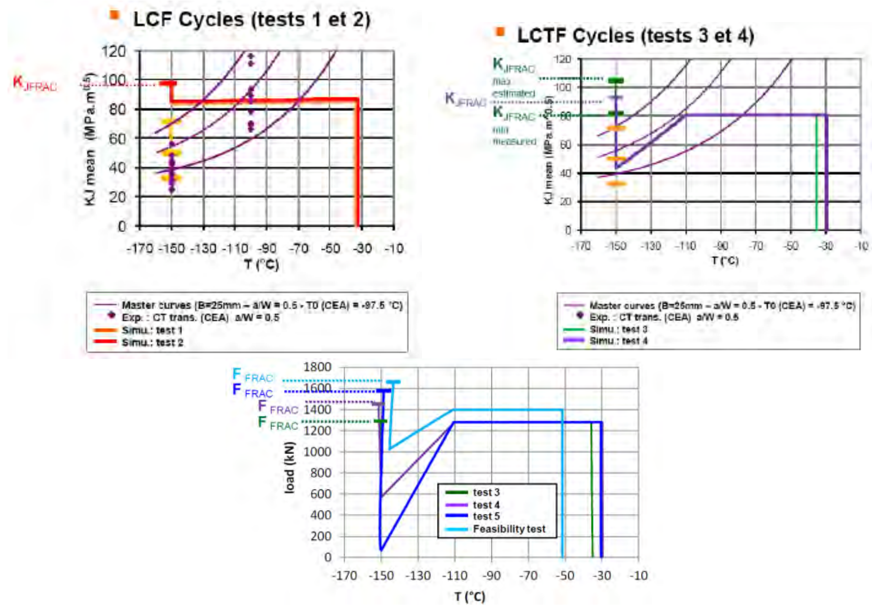

Figure 5 : Demonstration of WPS effect on CEA cruciform specimens (LCF & LCTF tests).

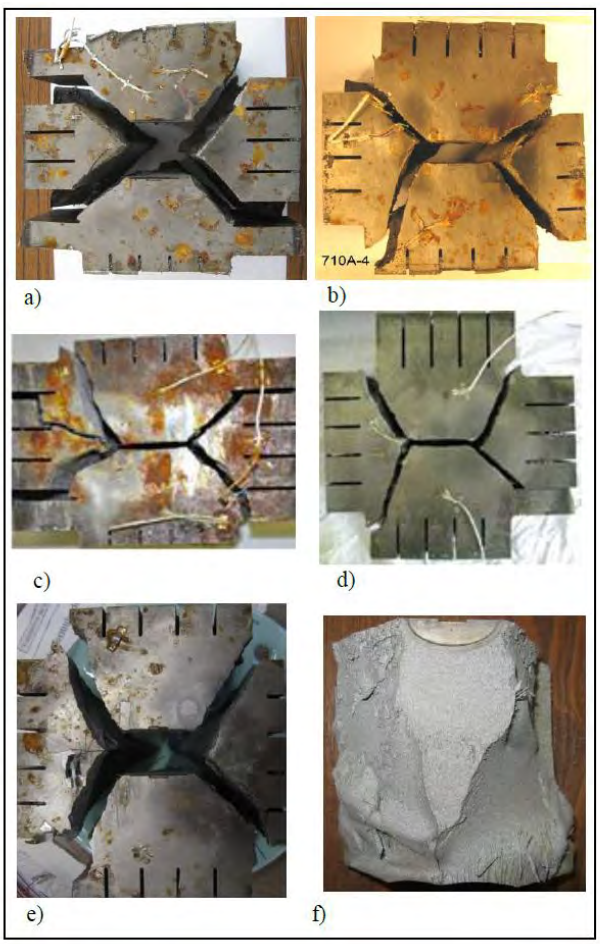

Figure 6. CEA fractured specimens of LCF and LCTF tests.

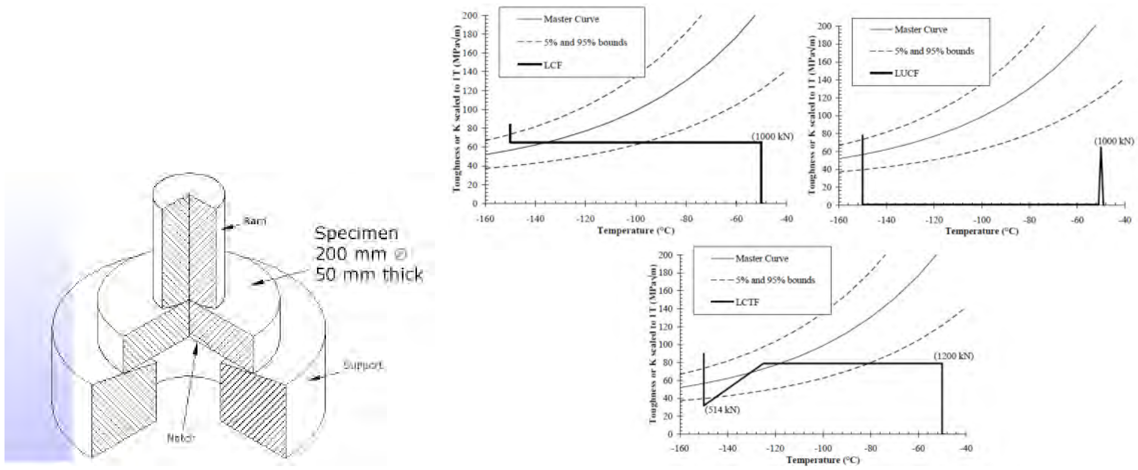

Figure 7. SCK-CEN WPS experiments on PTS-D disks. WPS cycles applied on specimens.

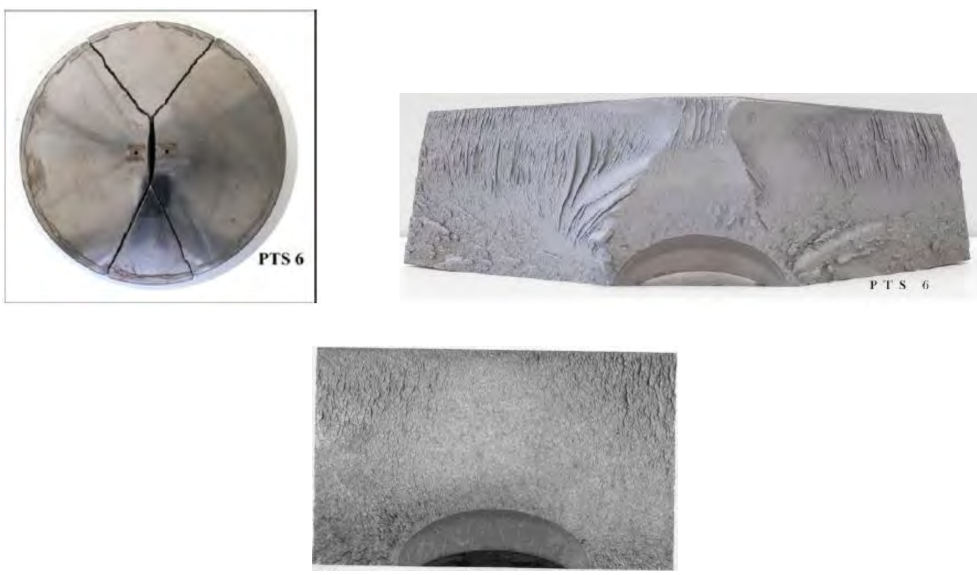

Figure 8. View of PTS-D specimen after fracture.

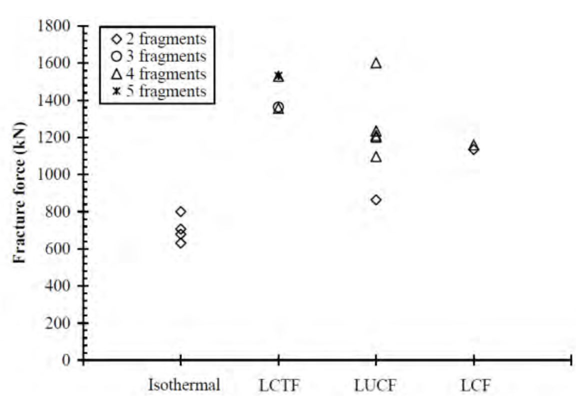

Figure 9. Effect of WPS on fracture resistance (PTS-D specimen).

The fractographic examinations of the fracture surfaces, made on all specimens, generally confirm a typical cleavage fracture aspect (transgranular). However, some cases of intergranular fracture have been observed on a limited number of PTS-D specimens, without specific consequence on the WPS behavior of these specimens (Figure 10).

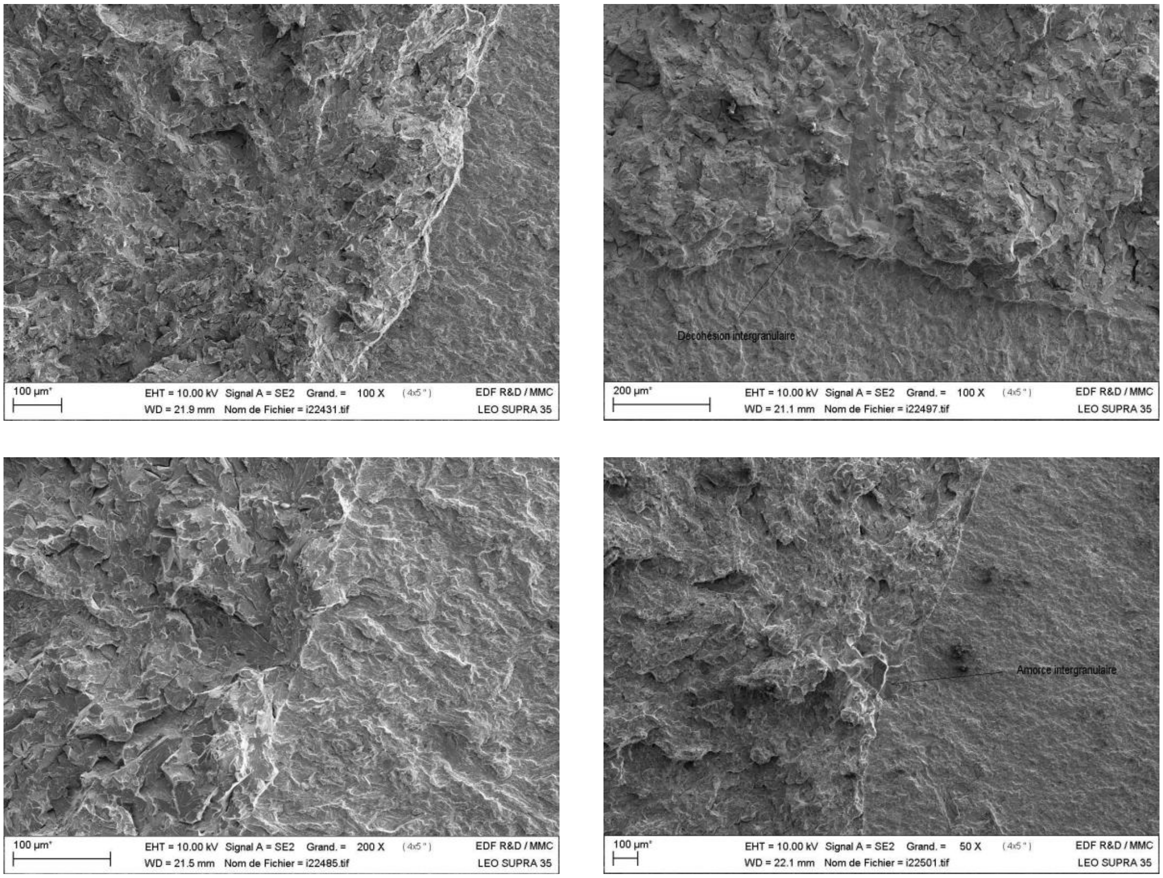

Figure 10. Examples of fracture surfaces on PTS-D disks : transgranular (left) and intergranular (right).

More detailed information on the experimental aspect of the program are available in papers [3][10][11][12][13][14][15].

Analyses of WPS experiments

In a first step, 3D FE computations of the specimens have been conducted within the project to contribute to design of specimens (e.g. selection of flaws size) and definition of WPS experimental conditions (e.g. level of preloading K_{WPS}, failure probability of specimens during experiments) to reach final objectives. Some examples of mesh are shown on Figure 11.

Following this 'design stage', detailed analyses of all WPS experiments (CEA cruciform specimens and SCK-CEN PTS-D disks) have been conducted by almost all partners of the project. This work is based on use of both engineering models and more refined approaches generally derived from local approach to cleavage fracture.

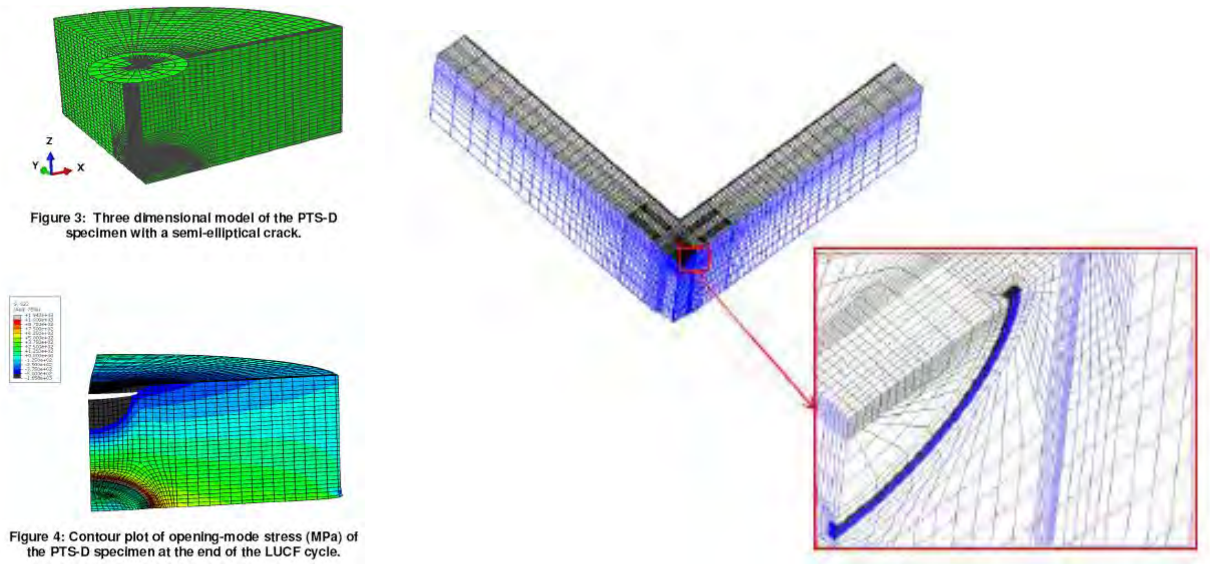

Figure 11. Examples of mesh of WPS specimens (PTS-D disk and cruciform specimen).

- Engineering models

The predicted fracture of the specimens, K_{FRAC} , is evaluated using four engineering models :

- *Chell model [4]*
- *Chell & Haigh model [5]*

$$K_{FRAC} = K_2 + 0.2\ \Delta K_U + 0.87\ K_{MAT}$$

- *Wallin model [16]*

$$K_{FRAC} = K_2 + (K_{MAT}\ .\ \Delta K_U)^{0.5} + 0.15\ K_{MAT}$$

- *New WPS criterion ACE proposed in France [17]*

$$K_{JC-WPS}(t) = \max\left[K_{IC}(T); \min\{K_{WPS}; K_2 + K_{WPS}/2\}\right]$$

- Refined models

More refined models based on elastic-plastic analyses, and generally derived from the local approach to cleavage fracture, are used to evaluate the failure probability of the specimens during the loading :

- *Beremin model [18] and its extension to non monotonic loading [19]*

$$P_f(\sigma_W) = 1 - \exp\left(-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right)$$

$$P_r = 1 - e^{\left(-\int_V \left[\max_{\{u<t,\ \dot{p}(u)>0\}} \left(\frac{\sigma_I(u)}{\sigma_u(\theta(u))}\right)\right]^m \frac{dV}{V_0}\right)}$$

- *IWM incremental model [20]*

$$\Delta p = \frac{\Delta\varepsilon_{pl}}{\Delta\varepsilon_{pl0}} \exp\left(-\frac{\varepsilon_{pl}}{\varepsilon_{pl0}}\right)\left(\frac{\sigma_I}{\sigma_u}\right)^m$$

- *Bordet model [21][22] and modified Bordet model [23]*

More information on the models and analyses are available in referenced papers. The corresponding synthesis of the computations is in progress and nearly achieved (~ May 2013). These analyses confirm the applicability of models to predict WPS in case of a complex biaxial loading with an acceptable level of accuracy. A relatively good agreement is also observed between FE computations. These observations are illustrated on the following Figures 12, 13 and 14 (Load – CMOD, K_J – Temperature).

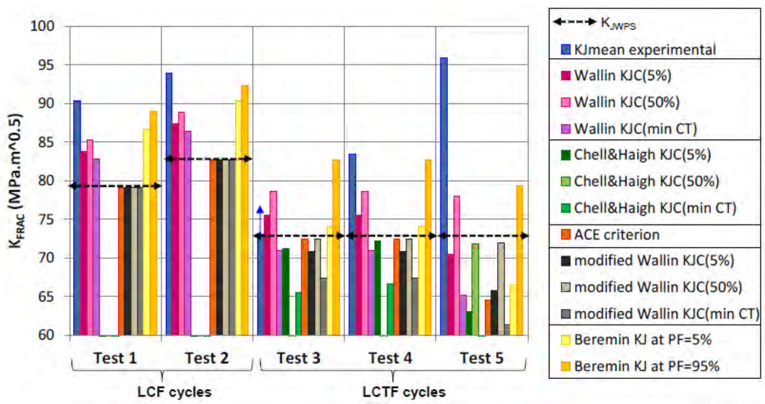

Figure 12. CEA interpretation of WPS cruciform specimens.

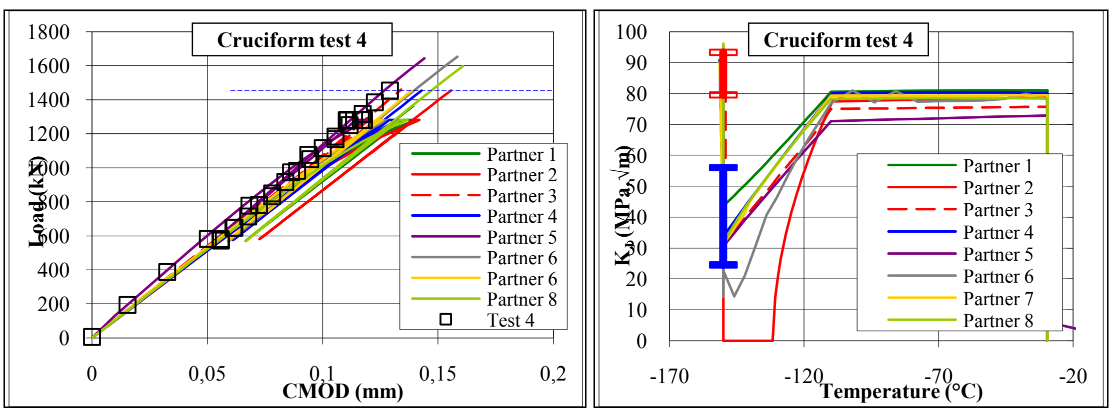

Figure 13. Finite element analyses of WPS cruciform specimens (test LCTF 4).

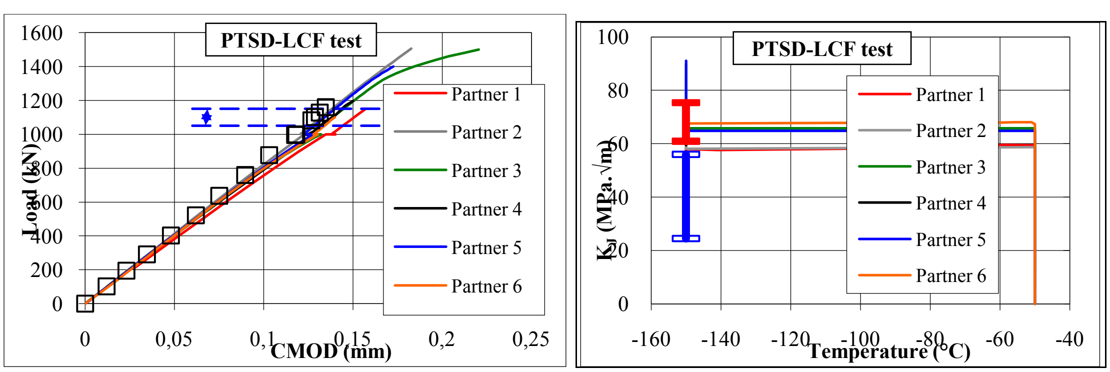

Figure 14. Finite element analyses of PTS-D specimens (LCF cycle).

Evaluation of engineering WPS models to NESC VII WPS database

A specific WPS database has been constituted to confirm the WPS effect on irradiated materials and then allow an evaluation of WPS engineering models and their capability to predict WPS effect on the fracture resistance of the considered materials. Several set of data have been gathered :

- An extensive WPS data set provided by UJV on WWER material (as received, heat-treated and irradiated material) [24]
- Some AREVA GmbH WPS fracture toughness data measured on irradiated RPV weld material [25]
- Some recent EDF WPS fracture toughness data obtained on two highly irradiated RPV steels coming from French RPV surveillance program [26]
- Some IWM WPS fracture toughness data measured on irradiated RPV weld material

Although the corresponding synthesis report is not yet available (~ May 2013), the WPS effect has been confirmed on these irradiated materials. The applicability of WPS engineering models has been verified on this set of data, for all engineering approaches. It is illustrated on the Figure 15 on EDF data (ACE and Wallin-NRI models)

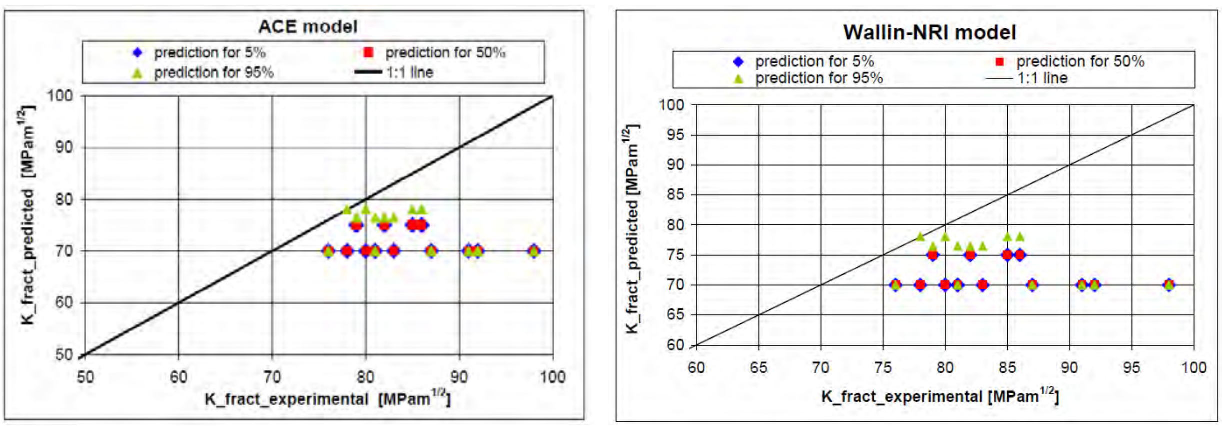

Figure 15. Example of application of WPS simplified models on EDF irradiated data.

CONCLUSION

NESC VII – a European project dealing with WPS based on in-kind contributions – has been launched in 2008 with a wide international participation (17 partners). Based on experimental, analytical and numerical work, the project is focused on topics not covered by past experience and knowledge on WPS : biaxial loading, effect of irradiation, applicability to different modes of failure, modeling …

Among these tasks, some new original WPS experiments – by CEA, SCK-CEN and TWI - have been conducted on medium and large scale specimens to evaluate the influence of a biaxial loading (more representative of a real PTS transient) on WPS effect using a fully representative RPV plate steel (18MND5). These WPS experiments are achieved and all results confirm the effect of WPS in case of a biaxial loading, whatever the specimens and the experimental conditions.

Other significant tasks are nearly achieved including the refined analyses of the WPS experiments, and the evaluation of the capability of simplified WPS models to predict WPS effect using a specific collection of WPS data (involving as-received, thermal aged or irradiated materials). Although the corresponding synthesis reports are not yet available, the present results confirm the applicability of models to predict WPS in case of biaxial loading with an acceptable level of accuracy.

Started at mid 2008, the NESC VII project will be closed at end 2013 with a final report synthesis.

ACKNOWLEDGMENTS

The authors thank all partners of NESC VII for their participation and significant contribution to the project. They also thank H. Churier-Bossennec (EDF SEPTEN) and C. Pagès (EDF UNIE) for their technical and financial support. A particular thank to organizations which have sponsored the WPS experiments : TWI, UJV, SCK-CEN and GDFSUEZ, EDF UNIE and IRSN.

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