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SMILE: A EUROPEAN R&D PROGRAM FOR THE INCLUSION OF WARM PRE-STRESS IN RPV ASSESSMENT

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ABSTRACT

The reactor pressure vessel (RPV) is an essential component liable to limit the lifetime duration of nuclear PWR power plants. The assessment of defects in RPV subjected to PTS transients made at an European level not always account the beneficial effect of load history (warm pre-stress WPS) on material resistance regarding the risk of brittle failure. A 3-year European Research & Development program (SMILE) started in January 2002 as part of the 5th Framework Program (FP) of the European Atomic Energy Community (EURATOM).

The SMILE project ('Structural Margin Improvements in aged-embrittled RPV with Load history Effects') is one of a 'cluster' of 5th FP projects in the area of Plant Life Management. It aims to give sufficient elements to model and to validate the beneficial WPS effect in a RPV integrity assessment. Finally, this project aims to harmonize the different approaches in European Codes and Standards regarding the inclusion of WPS effect in RPV integrity assessment.

Within the framework of the project, an important experimental work has been conducted including WPS type experiments on CT specimens, and one PTS type transient experiment on a large component. The experimental results on CT specimens confirm the beneficial effect of warm pre-stress, with a significant increase of the material resistance regarding the risk of brittle failure. The WPS type experiment on the cylinder has been successfully conducted, with a final brittle failure during reloading.

The present paper describes the aims and objectives of SMILE project. The status of the project progress is also presented including main available results.

Keywords: Warm pre-stress, RPV, fracture mechanics, brittle failure

1. INTRODUCTION

The integrity of the reactor pressure vessel (RPV) of nuclear power plants (NPP) is essential to its safe operation. A hypothetical rupture of the vessel has the potential to cause a massive loss of coolant, overheating of the reactor core, and a subsequent major release of radioactivity to the environment. As part of the assurance of structural integrity, the RPV structural integrity analyses - based on fracture mechanics - consider the behavior of defects under normal and abnormal loading conditions to assess safety margins and component lifetimes as materials become degraded by irradiation and (or) thermal ageing. These analyses compare load and resistance

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terms to demonstrate that the crack driving force does not exceed the vessel material fracture toughness during all the transient, whatever the loading path (loading part and decreasing part of the transient). In some Western countries (such as France), the assessment of a RPV subjected to PTS transients doesn't take into account the potential beneficial effect of the load history ('warm pre-stress WPS') on the vessel resistance regarding the risk of brittle failure. Such approach has then some major consequences :

- a potentially over-conservative assessment of the margins associated with the loading to which the component (RPV) is subjected
- a potential economic penalty due to under-estimation of the component safe lifetime

A 3-year European Research & Development project (SMILE) started in January 2002 as part of the 5th Framework Programme of the European Atomic Energy Community (EURATOM).

SMILE '**S**tructural **M**argin **I**mprovements in aged-embrittled RPV with **L**oad history **E**ffects' is one of a 'cluster' projects in the area of Plant Life Management. It aims to demonstrate on specimens (small and large scales), to model and to validate the beneficial effect of the warm pre-stress in a RPV assessment. Finally, this project aims to harmonize the different approaches to lay the basis for European codes and standards regarding the inclusion of the WPS effect in a RPV assessment.

The present paper describes the main aims and objectives of SMILE project, gives details of its various work-packages, and shows its interactions with European network NESC (Network for Evaluating Steel Components) [1] and other European projects. Finally, the status of the project progress is shortly described.

2. PARTICIPANTS

The participants (11 partners) in SMILE, with the various contributions of these participants, are shown in Table 1. For main participants, participation is on the basis of a Shared-Cost Action, managed by EDF on behalf of the European Commission by DG RTD. In the case of Oak Ridge National Laboratory (ORNL) and IWM Freiburg, participation is on the basis of in-kind contributions.

This consortium has a very significant European nature (10 European partners covering different aspects of the nuclear energy field, 4 countries) and also includes a specially invited partner from USA (ORNL). The expertise of the members is both interdisciplinary and complementary in many fields. It includes three utilities (EDF, British Energy and E.ON), one RPV manufacturer (Framatome-ANP & Framatome-ANP Gmbh, the largest European RPV manufacturer), three research organizations (CEA, SERCO and MPA), one European research laboratory (JRC Petten, Institute of Energy), one safety authority (BCCN) and one US National Laboratory (ORNL with the sponsor of the US NRC).

Except the French Safety Authority, all the participants – including ORNL - are members of NESC network [1] and JRC Petten acts as Operating Agent for this network. Through NESC, all participants have an extensive experience of working together.

3. PURPOSE OF PROJECT AND EXPECTED RESULTS

The aim of this project is to show and better understand the effect of warm pre-stress (WPS) in a RPV integrity assessment, and to define and establish some recommendations and guidelines for a pre-codification in main European codes and standards.

The beneficial effect of the load history ('warm pre-stress') on the vessel resistance regarding the risk of brittle failure can be summarized as follows (Fig. 1) :

- Brittle failure is impossible during the unloading of the vessel (decrease of the stress intensity factor K_J versus temperature T, even if the loading path K_J – T intersects the material fracture toughness curve)
- In case of a final reloading of the vessel at lower temperature, the brittle failure would be obtained with beneficial and substantial margins compared to material fracture toughness obtained on a 'virgin' material

All elements necessary to propose a methodology to account WPS effect in a RPV assessment are gathered or obtained. This is done through experimental works on conventional fracture mechanics specimens (such as CT specimens) and a 'large-scale' component (cracked cylinder submitted to a PTS type transient) leading to a deep understanding of metallurgical and mechanical phenomena, and through numerical works and development (or improvement) of analytical and numerical models. The results obtained during this project will permit a more precise prediction of a possible brittle failure in a RPV submitted to a severe overcooling transient.

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Finally, this project aims to harmonize the different approaches in main European Codes and Standards regarding the inclusion of the warm pre-stress in a RPV assessment. Some recommendations and guidelines will be proposed with this goal.

The expected results of SMILE project can be summarized as follows :

- a description of the state of art regarding the warm pre-stress in RPV assessment, including modeling
- a more deeper demonstration and understanding of the warm pre-stress effect through experimental works on CT specimens and a 'large-scale' WPS experiment on a cracked cylinder
- a validation of analytical and numerical models through benchmarks and analyses of WPS experiments
- some applications to real European reactor pressure vessels
- an establishment of recommendations concerning the use and application of warm pre-stress in real industrial cases
- a final draft giving guidelines and recommendations for design and regulatory Codes

Additional informations concerning SMILE can also be found in paper [19].

4. DESCRIPTION OF WORK-PACKAGES

The SMILE project is organized in 6 work packages (Table 2), in harmony with European NESC [1] and VOCALIST [2][3] projects.

4.1 WP1 : Coordination and project management

The purpose of the work package, managed by EDF, is to provide overall coordination and management of the project. Some regular meetings are organized to facilitate ongoing interaction between participants during the course of the project.

4.2 WP2 : Calibration tests

Prior to this project, preliminary investigations on the WPS effect by means of CT specimens (CT25, CT50, CT100 and CT235) have been investigated at MPA Stuttgart with different materials [4].

SMILE project aims to demonstrate by WPS type experiments performed in laboratories on conventional CT fracture mechanics specimens (1T, 2T and 4T CT specimens) the beneficial effect of warm pre-stress on the material resistance regarding the risk of brittle failure. These tests are performed by MPA Stuttgart and EDF on two specific materials :

- WPS3 steel (17 MoV 8 4 mod.), which is a material degraded by special heat treatment, to be representative of an end of life RPV material (high RT_{NDT}, low upper shelf for ductile tearing)
- 18MND5 RPV steel (forging material similar to A508 Cl.3 ferritic steel) fully representative of a RPV steel at beginning of life

In order to perform the interpretation of the experiments (including analytical and numerical models), a full characterization of each material is included.

4.3 WP3 : Assessment of models

In a first step, the tools and models (including analytical, engineering and numerical models) to be used in the interpretation of WPS type experiments are identified, selected and described.

In a second step, these models are applied to analyze the WPS type experiments (on fracture mechanics CT specimens and on a 'large-scale' WPS experiment) conducted in this project. Some 'benchmark' checks between partners and tools are also being performed on selected experiments. Consistency of predictions between partners and a good correlation with experimental results are necessary conditions for validation of the models.

4.4 WP4 : Validation test

A WPS type experiment is performed by MPA Stuttgart on a 'large scale' structure (cracked cylinder submitted to a WPS representative loading). The experiment is intended to demonstrate the warm pre-stress effect under conditions very close to realistic PTS loading conditions. The material of the cylinder is the degraded – by special heat treatment - WPS3 steel (17 MoV 8 4 mod.) previously described in WP3. The vessel, containing an internal circumferential pre-fatigue crack, is submitted to combined thermal & mechanical loading (mechanical tensile pre-loading, thermal transient and cooling, final tensile reloading of the cylinder up to failure). The objectives can be summarized as follows :

- apply a pronounced preloading in the upper shelf region without inducing ductile tearing initiation

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- apply a thermal transient to the cylinder, excluding brittle failure initiation during the transient
- obtain a final brittle failure at lower temperature clearly above the critical toughness of the virgin material

After the test, the specimen is carefully examined (fractographies, identification of brittle failure initiation sites …) and the post-test analyses performed using the models previously selected in WP3.

4.5 WP5 : Cases studies

Using the tools and models previously tested and validated, two additional applications of WPS assessment methods are checked on a real vessel submitted to a severe SBLOCA overcooling transient (Small break LOCA). The selected vessel is a German PWR RPV. Two types of flaws are taken into account : a semi-elliptical surface crack and a shallow semi-elliptical subclad flaw.

4.6 WP6 : Programme evaluation, synthesis and recommendations

The synthesis of the project will be made and guidelines proposed for a pre inclusion of 'warm pre-stress' in main European design and regulatory codes. From a scientific and technical point of view, the key points of SMILE project are the following :

- **A good understanding of fundamental mechanisms :** all elements necessary for an in-depth understanding of the origin of the beneficial effect of WPS are being obtained and validated in the WP2 ('Calibration tests') and WP3 ('Assessment of models') work packages
- **A demonstration** in WP4 ('Validation test') **of the warm pre-stress effect under conditions very close to realistic PTS loading scenarios.** It is a key point regarding the problem of transferability of data from small scale specimens to structures for defect assessment on LWR components [5]
- **An assessment of appropriate models** in WP3 ('Assessment of models') including a critical review of already existing models. Both global (e.g. Curry or Chell models) and local models (e.g. Beremin model, Margolin model, Energy approach …)[6][7][8][9][10][11] are investigated. Moreover, some already existing ideas concerning adjustments of cleavage models will be developed to take into account complex and non-monotonic loading
- **A demonstration of the capabilities of models** (analytical and more refined models) to account WPS effect on the material resistance regarding the risk of brittle failure, both on conventional fracture mechanics specimens and large scale real components (WP2, WP3, WP4 & WP5)

The elaboration of a synthesis and recommendations at the end of the project regarding the inclusion of WPS in main European design and regulatory guides

5. INTERACTIONS BETWEEN SMILE AND OTHER EUROPEAN PROJECTS

Almost all of the SMILE partners are members of the NESC network, operated by the Institute of Energy of the European Commission's Joint Research Centre, Petten (The Netherlands) [1]. Through NESC, main of the participants have extensive experience of working together on the various Tasks Groups set up as part of NESC-I, NESC-II & NESC-IV large-scale fracture experiments.

Related 5th Framework project in the EURATOM 'ageing cluster' is VOCALIST [2][3], which is concerned by 'constraint effect', also associated project of NESC. A mutual exchange of information and ideas between **SMILE** and **VOCALIST** is therefore actively encouraged and facilitated by the NESC link. These exchanges are more particularly focused on some key points such as materials characterization, use of Master curve approach [12][13], constraint effect in fracture mechanics specimens and structures [14][15], transferability of materials properties from conventional specimens to structures [5], local approach to fracture.

6. STATUS OF THE PROJECT

Started in January 2002, significant progress of the project has been made and numerous results are now available. All experimental tasks are fully completed and the last interpretations of experiments are in progress. The synthesis of the project, including some recommendations regarding WPS inclusion in RPV assessment, will be prepared during summer 2005.

6.1 WP2 : Calibration tests

A significant work has been already conducted regarding the mechanical and metallurgical characterizations of both materials WPS3 (German 17 MoV 8 4 mod. steel) and 18MND5 (French RPV steel) involved in the project. Fracture toughness properties of both materials are now available, based on the use of the Master curve approach

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and the experimental determination of temperature T_0 [12][13]. The fracture toughness curve of WPS3 material – based on the use of conventional deep cracked 1T CT specimens (a/W ≈ 0.5) - is given for example on Fig. 2 (T_0 ≈ 140 °C).
Fractographic examinations have been also made, confirming the transgranular fracture mode of the specimens on both materials.
Following these conventional characterizations, the identification of specific parameters required by analytical and numerical models has been conducted and is now achieved.
In parallel, the expected beneficial effect of warm pre-stress on the material resistance regarding the risk of brittle failure has been studied, using classical WPS type experiments performed in laboratories on conventional deep cracked conventional CT fracture mechanics specimens (1T, 2T and 4T CT specimens). These experiments have been conducted on both materials (WPS3 and 18 MND5 steels) with several classical WPS loading paths (K_J – T) cycles : LCF (Load, Cooling and Fracture), LUCF (Load, Unloading, Cooling and Fracture) ... All the experimental results confirm the beneficial effect of warm pre-stress, with a significant increase of the material resistance regarding the risk of brittle failure. A synthesis of all WPS experimental results is presented on Fig. 3 (18 MND5 steel) and 4 (WPS3 steel).

6.2 WP3 : Assessment of models

This work package has been engaged in a survey and a selection of analytical and numerical models for interpreting and analyzing the WPS type experiments :

- Analytical and engineering models in consideration are Chell model, Chell & Haigh model, Wallin model
- Numerical models under consideration include Beremin model [6][7] and some recent evolutions of this model [8][9], Margolin model [10], Energy Approach [11]

The selected models are applied to the interpretation of the WPS type experiments conducted within the framework of this project. The corresponding synthesis is in progress, but all available predictions are in good agreement with experimental results, still conservative with a sufficient level of accuracy.

6.3 WP4 : Validation test

In order to demonstrate the WPS effect on a 'representative' component under thermal shock conditions (PTS), a model vessel in the form of a cylinder containing a circumferential shallow crack has been tested by MPA Stuttgart under combined mechanical and thermal loading. Full information about this experiment can be found in papers [16][17].
The material used for the validation test is the WPS3 steel (17 MoV 8 4 mod. steel). In order to simulate an irradiated end of life RPV material, it was artificially degraded by special heat treatment. The wall thickness of the cylinder is 40 mm and the inside diameter 80 mm (Fig. 5). The characterization of material properties has been fully achieved, including the evaluation of the fracture toughness behaviour by applying the Master curve approach (T_0 ≈ 140 °C), using CT specimens (Fig. 2).
The experiment was conducted as follow, and also described on Fig. 5 :

1/ Pronounced pre-loading in the upper shelf region of fracture toughness without ductile tearing initiation
2/ Thermal shock by internal cooling of the specimen
3/ No fracture is expected during cooling phase, although crossing of fracture toughness K_{Ic} and stress intensity factor K_J (decreasing K_J) curves
4/ Final tensile reloading at room temperature up to final failure (expected brittle failure)

The initial crack was induced by spark eroding and fatigue cracking with internal pressure. The fatigue cracking was stopped at an averaged crack depth of 14.3 mm (13.5 mm ≤ a ≤ 15.5 mm). All the experimental conditions (Pressure, temperature, initial tensile load, crack depth …) were previously defined during the design of the experiment, particularly to achieve the initial objectives.
Prior to this experiment, the experimental program contains also some WPS type experiments performed on conventional deep cracked CT fracture mechanics specimens, useful for the analysis of the validation test. Moreover all the experimental data obtained on the CT specimens have confirmed the beneficial effect of warm pre-stress, with a significant increase of the material fracture toughness regarding the risk of brittle failure initiation (Fig. 4).
The experiment has been conducted by MPA Stuttgart on January 2004, with full success. Due to a technical problem the internal pressure during the experiment was only 3.5 MPa instead of 5 MPa (but without any influence on the test). The cylinder was first loaded at 2.1 MN at 290°C, then the load was kept constant during

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the whole cooling phase. No failure event occurred during the cooling crossing the fracture toughness curve in the transition region. Finally the reloading up to fracture was carried out at 37 °C with a loading rate of 2 MN/min. The failure of the cylinder was obtained during the final tensile re-loading of the cylinder, with a very significant high level of loading (5.3 MN)(Fig. 5, 7)[16][17].

The destructive examination of the cylinder after the test was made by JRC Petten, MPA Stuttgart and CEA , including particularly the refined examination of the fracture surfaces. These examinations show a brittle failure of the cylinder at the end of the test, as expected (Fig. 6)[16][17].

The interpretation of the WPS experiment on the cracked cylinder is nearly finished, involving a large panel of analyses :

- Engineering methods and models account for WPS, such as Chell, Chell & Haigh, Wallin …
- Global approaches based on the evaluation of the stress intensity factor (elastic K_I or elastic-plastic K_J) and the comparison with the K_{Ic} fracture toughness of the material
- Local approach of cleavage fracture based on Beremin model
- Energy approach

The final synthesis of these analyses is in progress. However, using EDF results [18], Fig. 7 and the following table clearly shows very significant margins between K_{Ic} fracture toughness values and the elastic-plastic stress intensity factor K_J at the cylinder failure (K_{FRAC}), with a higher resistance of the cylinder regarding the risk of brittle failure due to initial preloading (K_{WPS}) at higher temperature :

	K_{FRAC}	K_{WPS}	K_{FRAC}/K_{WPS}	K_{FRAC}/K_{Ic}
Failure of cylinder	84 MPa.m$^{0.5}$	78 MPa.m$^{0.5}$	1.08	1.62

Some more details about these analyses can be found in papers [18][20]. As mentioned, the final synthesis is in progress and will be soon available, including also the application of analytical and engineering methods.

The beneficial effect of warm pre-stress is clearly underlined through this experiment on a ‘large-scale component’, thus confirming previous experimental results on CT specimens on same material with various experimental conditions.

6.4 WP5 : Cases studies

This task, started at end 2004, is in progress. The analyses include engineering models (Chell, Haigh …) and numerical models based on local approach to fracture.

7. CONCLUSION

A brief overview of SMILE project progress (‘Structural Margin Improvement in aged-embrittled RPV with Load history Effects’) is presented in this paper. This project aims to give sufficient and important elements to experimentally demonstrate on specimens (on small and large scales), to model and to validate the beneficial effect of the warm pre-stress (WPS) in a RPV integrity assessment, particularly regarding the vessel resistance towards the risk of brittle failure during a severe PTS transient.

A significant progress of the project can be mentioned, concerning both experimental and numerical tasks. All the experimental results have been obtained, through CT specimens and a cracked cylinder, and confirm the beneficial effect of WPS, leading to a significant increase of the material fracture toughness resistance regarding brittle failure. Although some analyses are still in progress, a lot of numerical results are already available, showing a good agreement with experimental results, with a sufficient level of accuracy.

The final synthesis of the project will be prepared during 2005, when all results will be available, including also some recommendations regarding the use of WPS in RPV assessment.

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Table 1 - Participants in SMILE project

Reference	Participant	Tasks
P1	**Electricité de France (EDF)** *France*	. Leader of WP1, WP6 . Contributor to WP 2, 3, 4, 5
P2	**SERCO Assurance (SERCO)** *United Kingdom*	. Leader of WP2 . Contributor to WP 3, 5, 6
P3	**Commissariat à l’Energie Atomique (CEA)** *France*	. Leader of WP3 . Contributor to WP 4, 5, 6
P4	**Bureau de Contrôle des Chaudières Nucléaires (BCCN)** *France*	. Contributor to WP 2, 3, 6
P5	**MPA Stuttgart (MPA)** *Germany*	. Leader of WP4 . Contributor to WP 2, 6
P6	**British Energy (BE)** *United Kingdom*	. Contributor to WP 2, 6
P7	**FRAMATOME-ANP (FRA)** *France*	. Contributor to WP 3, 4, 5, 6
P8	**FRAMATOME-ANP GmbH** *Germany*	. Leader of WP5 . Contributor to WP 3, 4, 6
P9	**JRC-IAM Petten (JRC)** *The Netherlands*	. Contributor to WP 4, 6
P10	**E.ON KernKraft (E.ON)** *Germany*	. Contributor to WP 2, 3, 4, 5, 6
P11	**Oak Ridge National Laboratory (ORNL)** *USA*	. Contributor to WP 3, 4, 5, 6

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Table 2 - Description of SMILE work-packages

WP	Tasks	WP Leader
WP1	**Co-ordination and Management**	EDF
WP2	**Calibration tests** **WP2.1** Characterization of the degraded material **WP2.2** Confirmation of the WPS effect on degraded material (WPS3) **WP2.3** Calibration of WPS models on undegraded material (18MND5) **WP2.4** Load history effect on ductile tearing	SERCO
WP3	**Assessment of models** **WP3.1** Selection of models **WP3.2** Validation of models against existing data (WPS3 & 18MND5)	CEA
WP4	**Validation test** **WP4.1** Test specification and design of test **WP4.2** Validation test **WP4.3** Fractography **WP4.4** Interpretation of validation test	MPA
WP5	**Cases studies** **WP5.1** Development of cases studies specifications **WP5.2** Application to a RPV subclad flaw with an actual PTS transient **WP5.3** Application to a RPV through clad surface crack with an actual PTS transient	FRAMATOME -ANP GmbH
WP6	**Programme evaluation, synthesis and recommendations** **WP6.1** Guidelines for Codes & Standards **WP6.2** Conclusions and recommendations	EDF

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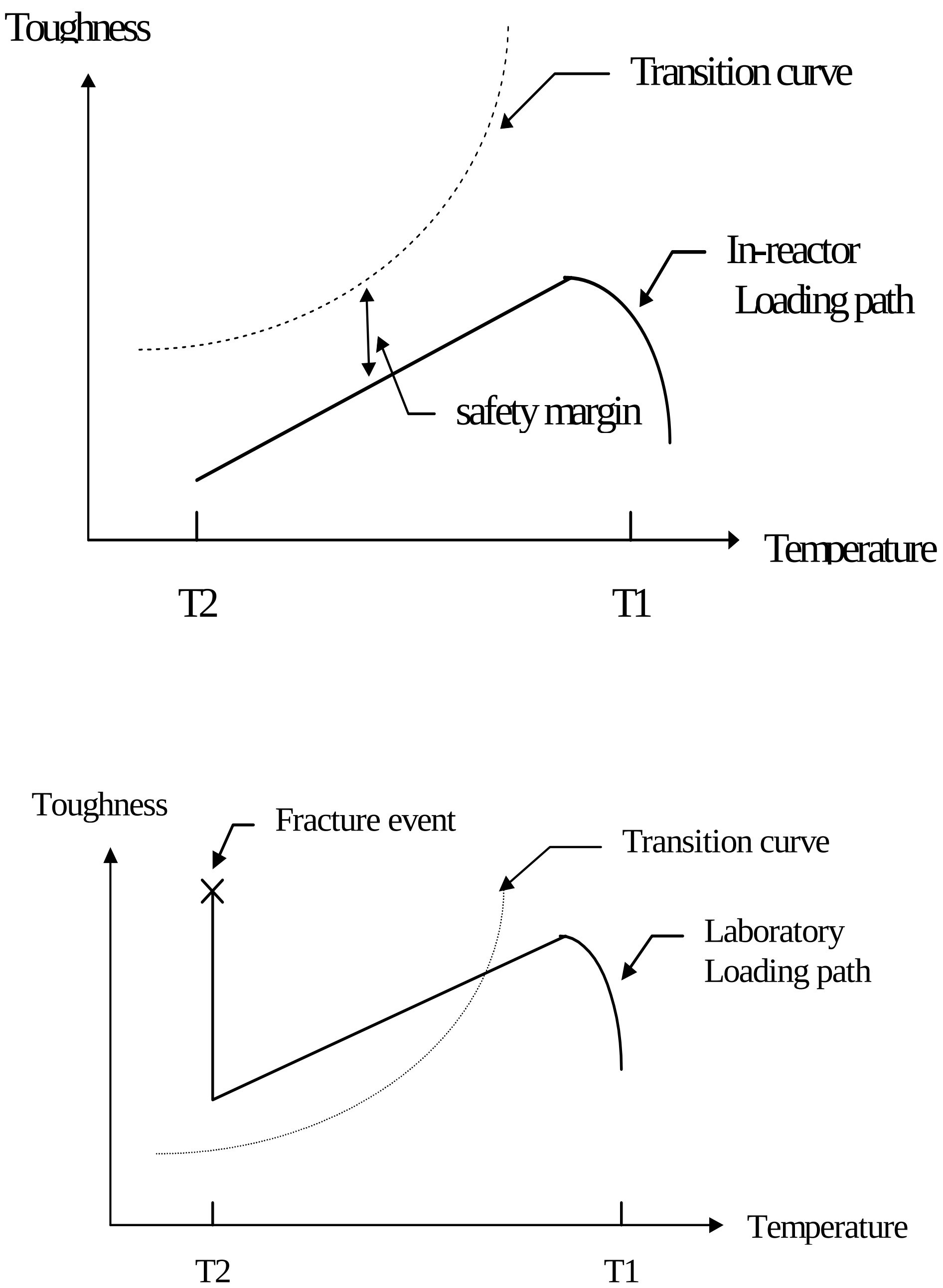

Fig. 1 - Schematic of warm pre-stress in RPV assessment

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SMILE (17 MoV 8 4 mod)

Masterkurve nach VTT

Fraunhofer Institut Werkstoffmechanik

Standard Masterkurve				VTT
Kmin	a	b	c	T_o
20	31,0	77	0,019	**140,0**
		Iteration:		-0,0037

%	D_1	D_2
50	30,04	70,26
95	34,47	101,30
5	25,23	36,64

Proben Nr.	Typ	B	T 癈	K MPa√m	$T-T_o$ 癈	K^*_{25} MPa√m	δ^*	Σ1	Σ2
KT1_01	C(T)	19,6	100	54,8	**-40**	**52,7**	**1**	0,0099	0,00234
KT1_02	C(T)	19,6	100	83,0	**-40**	**79,3**	**1**	0,0099	0,02516
KT1_03	C(T)	19,6	150	127,7	**10**	**121,3**	**1**	0,0116	0,01043
KT1_04	C(T)	19,6	150	103,3	**10**	**98,4**	**1**	0,0116	0,00373
KT1_05	C(T)	19,6	130	62,1	**-10**	**59,6**	**1**	0,0111	0,00088
KT1_06	C(T)	19,6	130	94,8	**-10**	**90,4**	**1**	0,0111	0,00874
KT1_07	C(T)	19,6	130	51,0	**-10**	**49,2**	**1**	0,0111	0,00026
KT1_08	C(T)	19,6	130	94,6	**-10**	**90,2**	**1**	0,0111	0,00865
KT1_09	C(T)	19,6	130	97,6	**-10**	**93,0**	**1**	0,0111	0,01012
KT1_10	C(T)	19,6	130	91,0	**-10**	**86,8**	**1**	0,0111	0,00709
KT1_11	C(T)	19,6	130	90,3	**-10**	**86,2**	**1**	0,0111	0,00682
KT1_12	C(T)	19,6	130	90,4	**-10**	**86,2**	**1**	0,0111	0,00686
KT1_13	C(T)	19,6	200	163,8	**60**	**155,3**	**1**	0,0124	0,00104
KT1_14	C(T)	19,6	200	140,8	**60**	**133,7**	**1**	0,0124	0,00052
MPA	C(T)	25	22	38,2	**-118**	**38,2**	**1**	0,0055	0,00449
MPA	C(T)	25	22	39,2	**-118**	**39,2**	**1**	0,0055	0,00556
MPA	C(T)	25	60	56,3	**-80**	**56,3**	**1**	0,0079	0,02270
MPA	C(T)	25	100	54,9	**-40**	**54,9**	**1**	0,0099	0,00302
MPA	C(T)	25	100	64,0	**-40**	**64,0**	**1**	0,0099	0,00763
CEA	C(T)	20	22	36,4	**-118**	**36,4**	**1**	0,0055	0,00296
CEA	C(T)	20	22,1	38,3	**-117,9**	**38,3**	**1**	0,0055	0,00458
CEA	C(T)	20	22,6	42,7	**-117,4**	**42,7**	**1**	0,0056	0,01073
CEA	C(T)	20	22,1	48,3	**-117,9**	**48,3**	**1**	0,0055	0,02619
CEA	C(T)	20	22	54,5	**-118**	**52,6**	**2**	0,0055	0,04638
Σ								0,2231	0,2269

* $\delta = 0$ $K_{Jc} = (E^* Rp^* bo/30)^{0.5}$

$\delta = 1$ g黚tiger K_{Jc}-Wert nach ASTM E1921

$\delta = 2$ g黚tiger K_{Ic}-Wert nach ASTM E399

$\delta = 3$ Z錼bruchinitiierung K_J

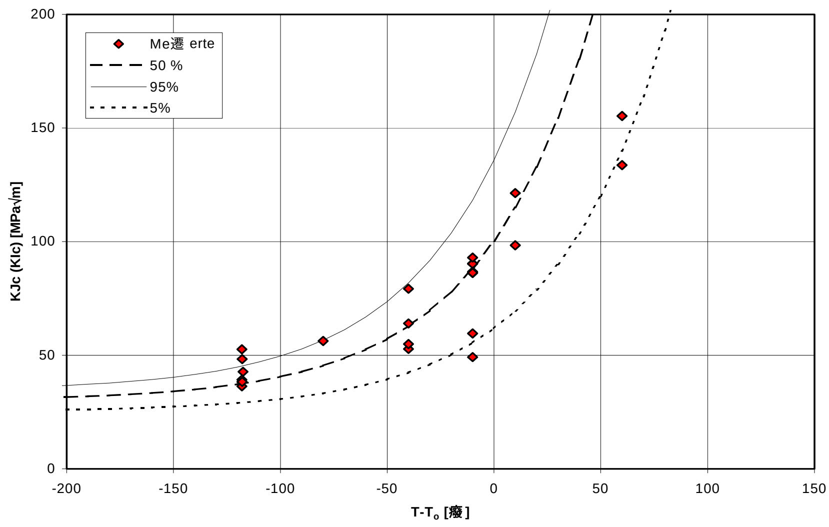

Fig. 2 – WPS3 (17 MoV 8 4 mod.) fracture toughness using Master curve

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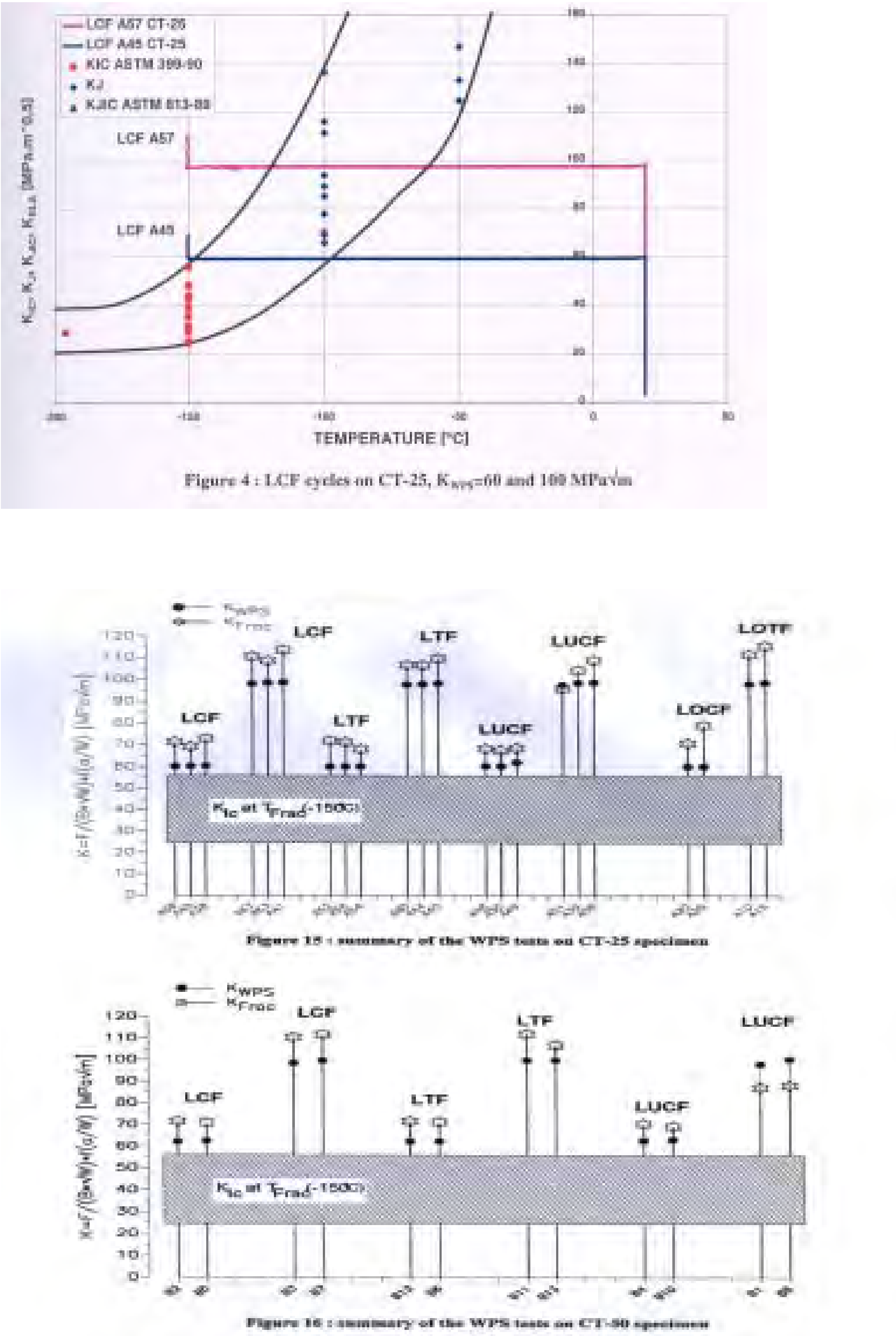

Fig. 3 - WPS experiments on CT specimens on French A508 Cl3 RPV steel

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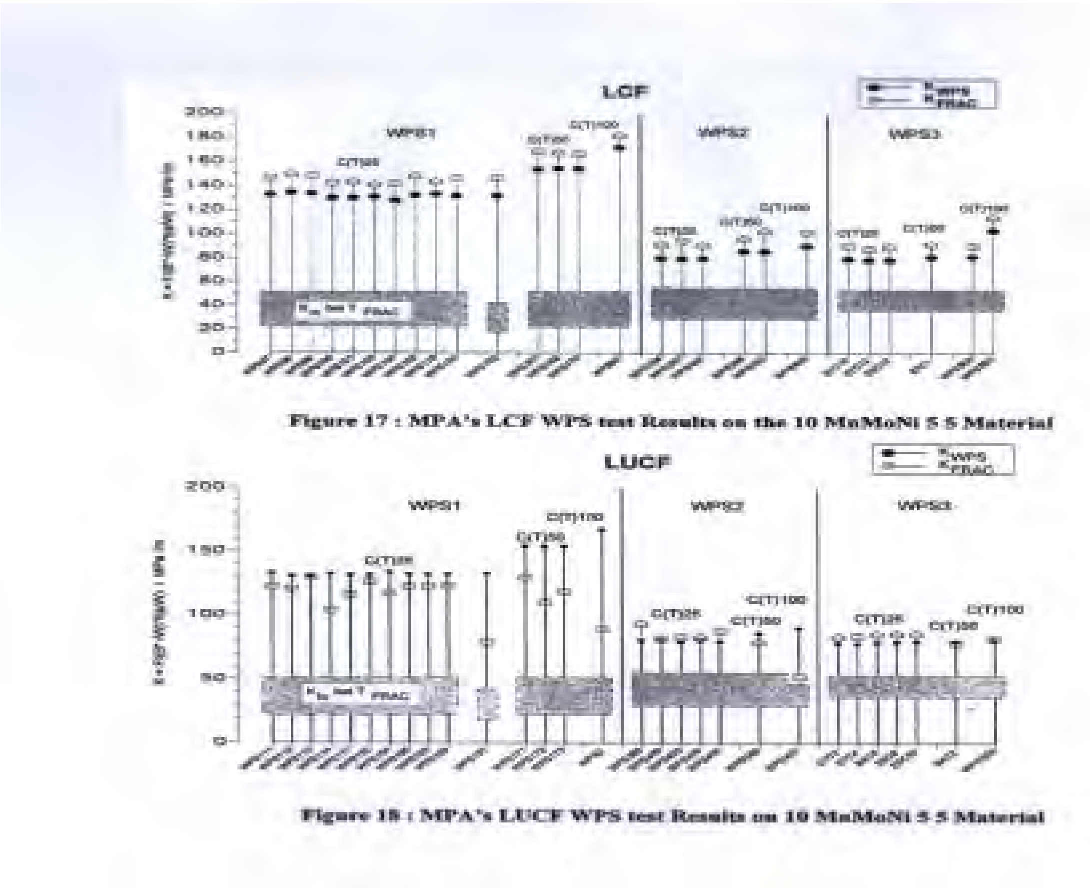

Fig. 4 - WPS experiments on CT specimens on German WPS3 (17 MoV 8 4 mod.) steel

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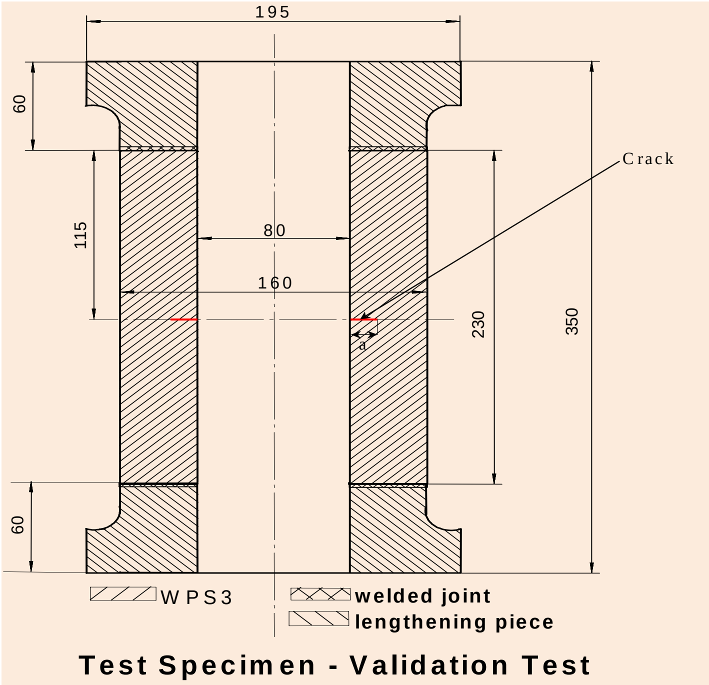

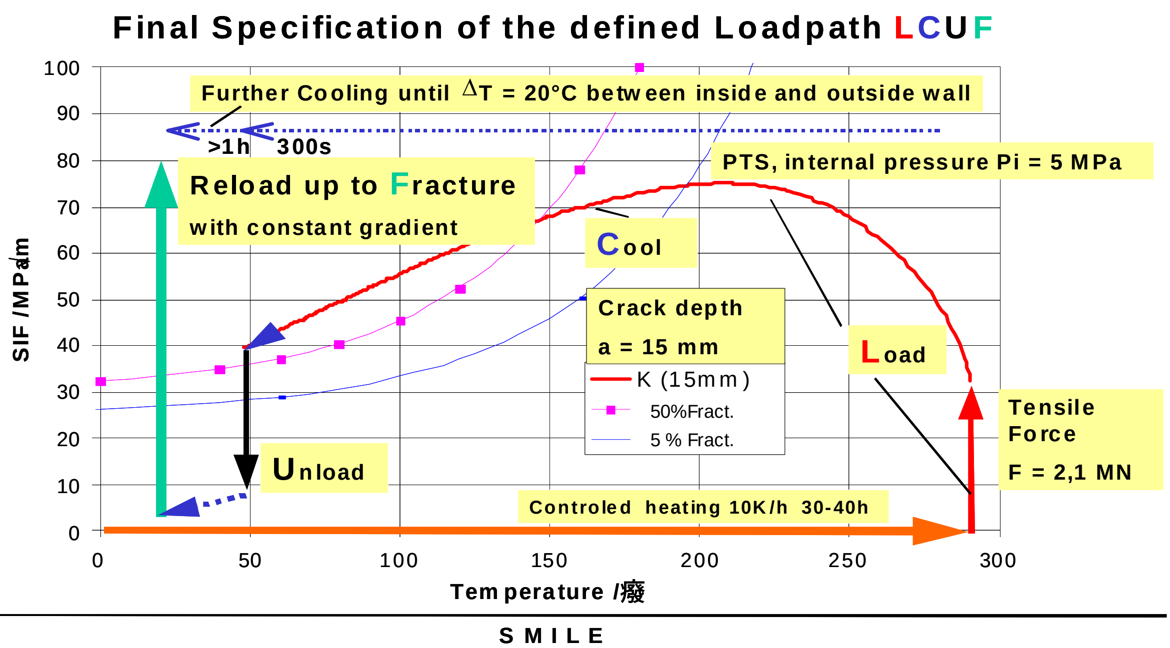

Fig. 5 - Schematic of WP4 'large scale' cracked cylinder experiment (17 MoV 8 4 mod.)

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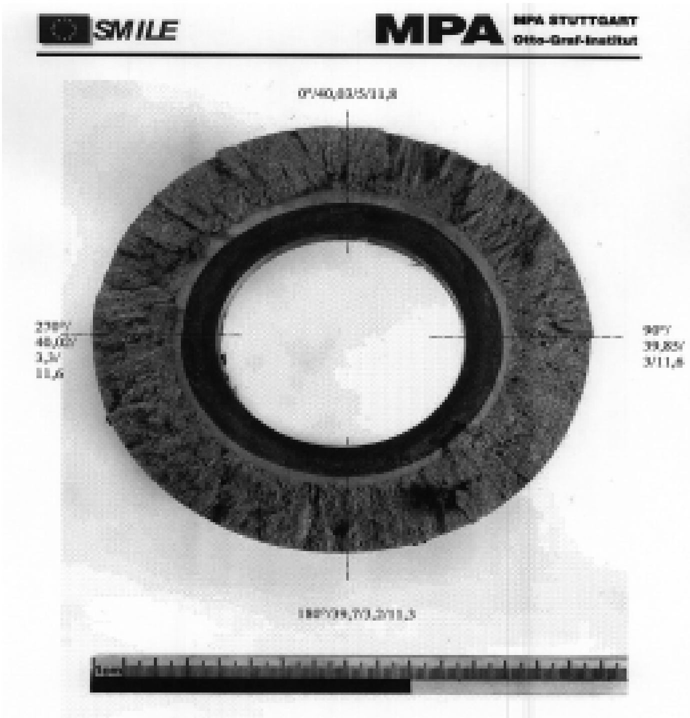

Fig. 6 - Brittle failure of the WP4 cylinder during final reloading

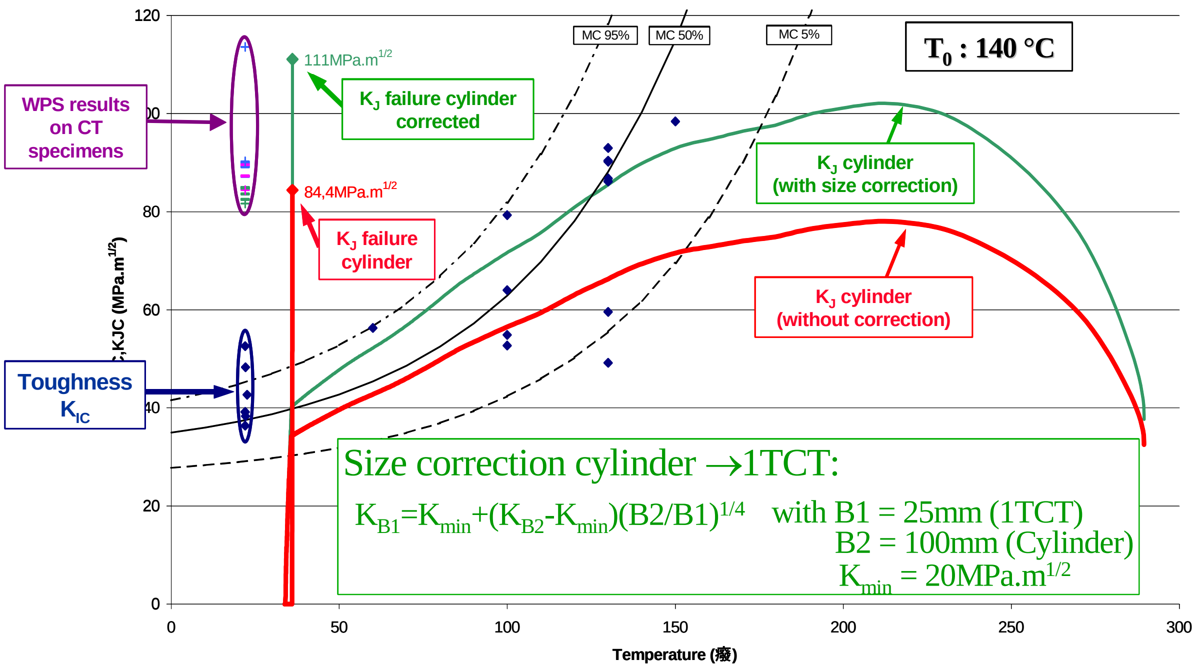

Fig. 7 - Interpretation of WP4 cylinder experiment

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