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CONSIDERATION OF SPECIAL EFFECTS FOR THE APPLICATION OF AN OPTIMIZED FRACTURE MECHANICS APPROACH FOR THE RPV SAFETY ASSESSMENT (CAMERA)

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ABSTRACT

A comprehensive fracture mechanics test program called CAMERA was carried out for seven RPV base and weld materials in unirradiated and irradiated conditions. The objective was to establish an application-oriented completion of the fracture mechanics approach for the RPV safety assessment over the entire relevant temperature range up to operating temperature. For this purpose, fracture toughness tests in the ductile-brittle transition region with and without warm pre-stress (WPS), and in the ductile region (upper shelf) were performed in order to complete the fracture toughness curves of the material concerned. The test program was completed by various analytical and numerical calculations and microstructural analyses. The benefit of the WPS effect was confirmed for both the material (higher apparent fracture toughness values) and the load path (no initiation after maximum loading). By fracture toughness tests in the ductile regime the fracture toughness curve could be completed up to the operating temperature and the T_0 based criterion temperature T_{US} beyond no brittle fracture occurs was determined and successfully verified. Based on the results obtained by the Master Curve, WPS and crack resistance tests it was demonstrated how to integrate the criterion temperature T_{US} in the fracture toughness- temperature diagram including the loading transient to an application window for the RPV safety assessment that is based on T_0 only. For three out of nineteen data sets the homogeneity screening procedure described in ASTM E1921 did indicate a macroscopically inhomogeneous material for that a generally conservative reference temperature T_{0IN} was calculated that is on average 11 K higher than the reference temperature T_0. A higher susceptibility of weld materials for macroscopic material inhomogeneity compared to base materials was found. The suitability of the applied SE(B) and C(T) specimens for the specific fracture mechanics tests (WPS and/or crack resistance in ductile region) was proven. Micromechanical Local Approach damage models (Bordet and Gurson) were successfully applied for test design and prediction of fracture toughness. The overall results reveal even so some open gaps remaining for future work that are addressed as well.

INTRODUCTION

The safety assessment procedure for reactor pressure vessels (RPV) applicable in Germany is stipulated in the KTA set of regulations. This worldwide applied evaluation concept is based on a deterministic approach comprising fracture mechanical calculations and the comparison of loading curves with the materials resistance in terms of fracture toughness. For the determination of the material's resistance according to the present KTA set of regulations, two fundamental concepts exist: the indirect RT_{NDT} concept and the direct Master Curve concept based on fracture mechanics tests. In the preceding research programs CARISMA, Hein et al. (2010) and CARINA, Hein et al. (2014) the application of the Master Curve approach was confirmed successfully for German RPV materials in the brittle and brittle-ductile material region for a fluence range exceeding the long term operation of German plants. With respect to the RPV proof of safety during plant operation, in particular at integrity assessments for Pressurized Thermal Shock (PTS) and at elaboration of p-T curves, further relevant issues arose in terms of the use of suitable fracture toughness curves for components and of the quantification of safety margins for the irradiated material state, in particular:

- the validity of fracture toughness curve and Master Curve respectively in the irradiated state at higher test temperatures (ductile material region),
- the verification of the WPS (warm pre-stress) effect in the irradiated state for representative load paths and materials,
- the impact of material inhomogeneities on the fracture toughness (e.g. segregations, hydrogen flakes, and different microstructure by manufacturing effects, heat treatment).

The CAMERA research program aims among others at clarifying these issues on the basis of further examinations of irradiated and non-irradiated RPV materials and was completed in 2020. The program targeted an application-oriented completion of the fracture mechanics approach for the RPV safety assessment over the entire relevant temperature range up to operation temperature to ensure particularly the safe long term operation of NPPs. For this purpose, fracture toughness tests in the ductile-brittle transition region with and without WPS, and in the ductile region (upper shelf) were performed in order to complete the fracture toughness curves of the material concerned. The test program was completed by various analytical and numerical calculations and microstructural analyses.

MATERIALS AND TEST MATRIX

The experimental test matrix consists of six mainly original RPV materials and one segregated respectively hydrogen flakes containing material that are most suitable for the planned studies, for reasons of their representativeness for European light water reactors (LWR) and the already available material property data. RPV materials with optimized chemical composition as well as materials with higher susceptibility for irradiation embrittlement caused by higher contents of nickel and copper are included in the test matrix. In total four base materials (BM) and three weld materials (WM) were selected for the material examinations, see Table 1. The CAMERA materials were studied in both unirradiated and irradiated conditions. The irradiated materials were pre-irradiated in several large-capacity capsules in the test nuclear power plant Kahl (VAK) at temperatures between 280 °C and 290 °C in the frame of several dedicated irradiation programs in the 1980s. The VAK reactor, a small experimental boiling water reactor operated by German utility RWE with an electrical output of approx. 15 MW, was active until 1985. Between 1975 and 1985 it was also used by Siemens/KWU as an irradiation plant for various research and irradiation surveillance programs. The neutron spectrum of the VAK reactor was comparable to that of other PWRs of Siemens/KWU.

For the different fracture mechanics tests the following specimen types were used:

- SE(B) 10x10 and C(T) 10 for the determination of reference temperature T_0
- SE(B) 10x10, C(T) 10 and C(T) 20 for the WPS tests

– SE(B) 10x10, SE(B) 20x20, C(T) 10, C(T) 12.5, C(T) 20, C(T) 25 and C(T) 50 for the upper shelf tests in the ductile region

Table 1: Materials of the CAMERA test matrix.

Material code	Type	Material	Cu [%]	P [%]	Ni [%]	Material features	Fluence*) [n/cm²] (E> 1 MeV)
P147	**BM**	22NiMoCr3-7 (manufacture by JSW)	0.05	0.007	0.84	low Cu / Ni / P	0 1,03E+19 1,17E+19 1,21E+19 3,41E+19
P142	**BM**	20MnMoNi5-5 (manufacture by JSW)	0.06	0.009	0.8	low Cu / Ni / P	0 3,27E+19
P7	**BM**	22NiMoCr3-7 (manufacture by Klöckner)	0.12	0.015	0.97	low Cu / Ni / P	0 3,73E+19 4,26E+19
KS02	**BM**	22NiMoCr3-7 (with segregations and flakes, from FKS program)	0.10	0.008	1.29	segregations, hydrogen flakes	0 2,3E+19
P141	**WM**	S3NiMo1/OP 41 TT (manufacture by GHH)	0.03	0.019	1.01	low Cu / Ni / P	0 8,82E+18 9,00E+18
P16	**WM**	S3NiMo3/OP 41 TT (manufacture by Uddcomb)	0.08	0.012	1.69	high Ni	0 7,34E+18 4,60E+19
P370	**WM**	NiCrMo1 UP/LW320, LW 330 (modified manufacture) generic examinations	0.22	0.015	1.11	high Cu	0 2,25E+19

*) estimated neutron fluences referring to available source material

WPS EFFECTS

The pre-loading of a ferritic cracked component at increased temperature, usually in the upper shelf region, yields to an increase of fracture toughness if loaded again at lower temperatures (transition / lower shelf region). This effect is commonly known as WPS effect. The principal scheme of a WPS loading transient is shown in Figure 1 explaining the basics. Following a high temperature pre-stress up to the WPS stress intensity factor at highest pre-loading in the ductile region K_{WPS}, the material is cooled down and re-stressed loaded in the brittle/ductile transition range at a lower temperature T_f with fracture if the stress intensity exceeds the WPS altered fracture toughness K_f. This procedure increases the measured fracture toughness in comparison to a case without pre-stress. It is credited that for transients with a strictly monotonously decreasing stress intensity over time after reaching the maximum load path, a crack initiation of the crack postulated for the calculation can be excluded if the crack tip has previously undergone warm pre-stress in the course of the currently considered transient. It is important to note that the WPS affects the materials fracture toughness in an indirect way because it alters the stress field around the crack resulting in an apparent (effective) increase of fracture toughness. The LCF (Load – Cool – Fracture) and LUCF (Load – Unload – Cool – Fracture, with complete unloading) paths represent the two bounding load paths. The LCF path yields to the highest benefit (regarding fracture toughness) and the lowest scatter of the test results, whereas the LUCF path yields to the lowest benefit and the highest scatter of the test results.

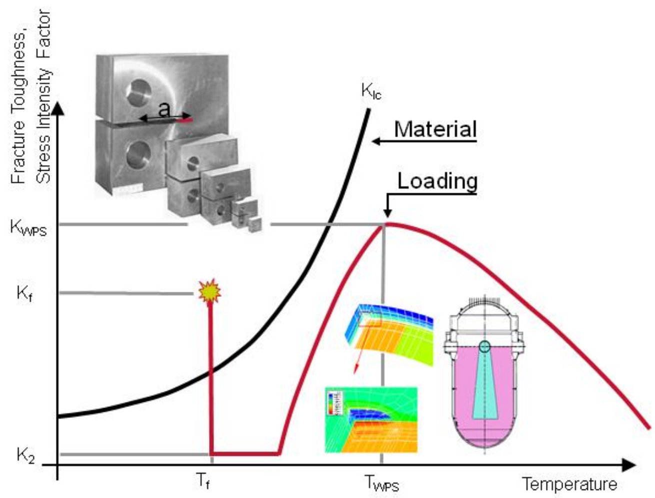

Figure 1: Scheme of a WPS loading transient.

According to the theory, it is assumed that the WPS effect is also valid for irradiated base and weld materials. However, the experimental data for irradiated German RPV steels are sparse. Therefore, various load paths including LTF (Load – Transient – Fracture) were applied to the test matrix to investigate the WPS phenomenon for the CAMERA materials by fracture toughness tests consisting of three phases. The first phase is the so called loading phase applying the pre-loading to the specimen at elevated temperatures. During the second phase the temperature is decreased down to the target temperature. Simultaneously the loading at the crack tip is also decreased in case of LUCF scenarios or kept constant in case of LCF scenarios. The last phase is basically an isothermal fracture toughness test in accordance with test standard ASTM E1921. It is initiated after reaching the target temperature and target crack tip loading in phase two.

For all investigated irradiated materials a significant increase of the apparent fracture toughness was observed as a result of the WPS effect and no specimen did fail while cooling and simultaneous constant unloading or sustained loading during the test as exemplary shown in Figure 2. This confirms the regulations in the safety standard KTA 3201.2 (2017) where is written that upon warm pre-stressing of the crack front and in the case of a monotonously decreasing stress intensity factor (specimen cooling under sustained load, crack initiation is to be excluded.

The test results for both simplified LUCF and LCF conditions showed a good agreement with the predictions of the WPS modified Master Curve for moderate unloading with a trend to underpredict for the case of complete unloading (see Figure 2). For LTF condition the increase of the apparent fracture toughness was the highest compared to simplified LUCF and LCF conditions. The parameters of these simplified load paths have been designed based on the crack tip loading history of a potential PTS event which has been altered to account for each material's transition temperature. In addition to the simplified WPS test a complete and detailed crack tip loading history of a potential PTS event was applied to one material as well also demonstrating a significant increase of the apparent fracture toughness.

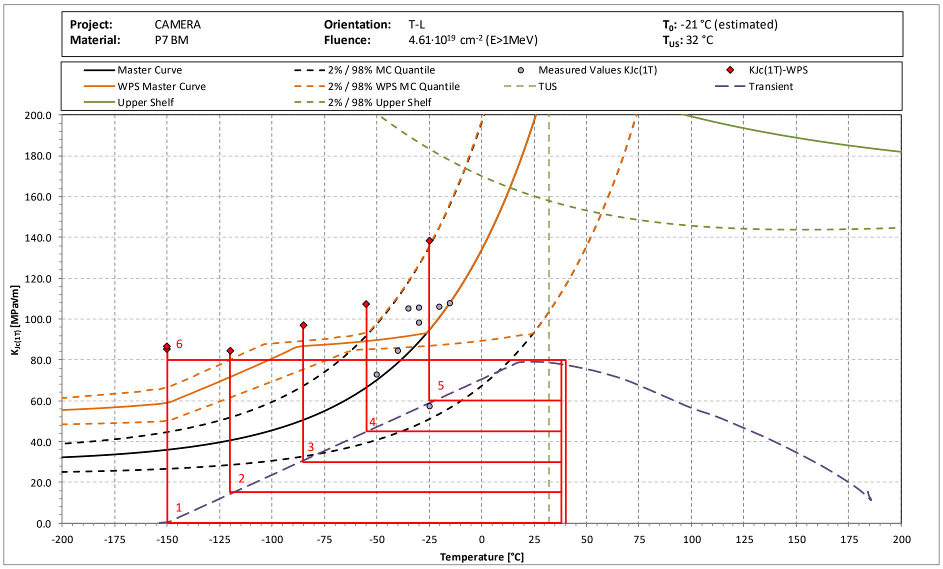

Figure 2: WPS design and results, P7 BM, neutron fluence $4.61{\cdot}10^{19}$ cm^{-2} (E > 1 MeV), SE(B) 10x10.

Regarding the provision of lower bound results, all base metal specimens but one could be covered by the WPS altered 5 % Master Curve, whereas for the weld metal specimens all but four were covered. Based on the database available the predictive capability of the Wallin model, Wallin (2011) was found to be an appropriate approach (Figure 3). Besides this the Local Approach Bordet model was applied as an appropriate tool to predict WPS tests as well.

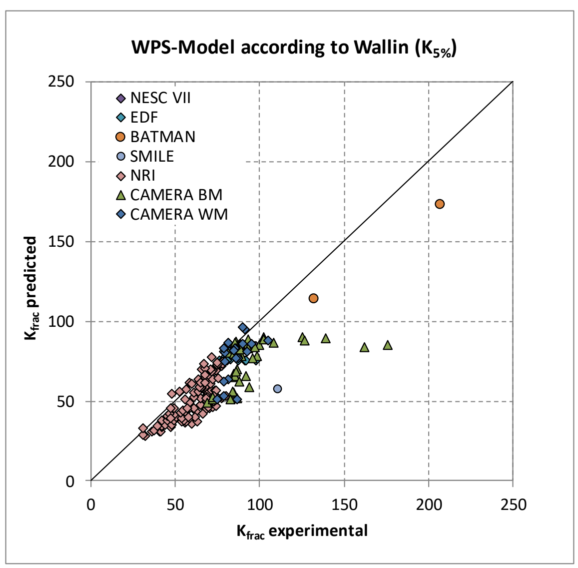

Figure 3: Predictive capability of Wallin model against experimental data, Wallin (2011).

A quantification of the WPS effect in terms of RPV safety assessment can be made by the increase of the margin between fracture toughness of the material and the stress intensity from the load. This margin depends also on the material, neutron fluence and the stress intensity from the load of any transient. Based on the results obtained up to some 10 MPa $m^{0.5}$ can be estimated as additional margin by taking into account the WPS effect on the apparent fracture toughness as exemplary shown in Figure 2.

FRACTURE TOUGHNESS IN THE UPPER SHELF

Fracture toughness tests were performed in the ductile region according to ASTM E1820 to determine the crack resistance curves J-R and crack initiation toughness $J_{0.2BL}$ and K_{Jc}, respectively. Different specimen types, SE(B) 10x10, SE(B) 20x20, C(T) 10, C(T) 12,5, C(T) 20, C(T) 25 and C(T) 50, were tested in different irradiation states to investigate the impact of specimen size and neutron fluence on the material behaviour in the transition region and in the upper shelf of fracture toughness. The upper shelf tests were used to complete the fracture toughness curve at higher temperatures and to validate prediction formulas. Based on the obtained results it is concluded that the used specimen types have a good applicability for fracture toughness testing in the ductile region even if for all specimen types crack instabilities like crack jumps and unstable crack growth, and exceeding of limits of J were observed sometimes.

Generally, a decrease of upper shelf with increasing neutron irradiation and at significant higher temperature (up to operating temperature) was observed independently of the specimen types used as shown in Figure 4.

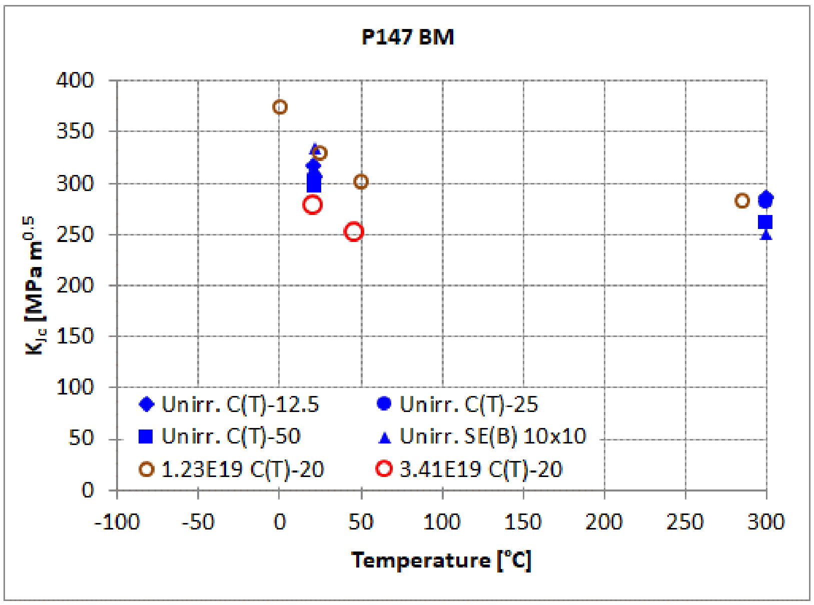

Figure 4: Ductile crack initiation toughness for material P147 BM - unirradiated and irradiated conditions.

In particular for irradiated materials with a high T_0 the ductile crack initiation values can be significantly below the formerly accepted value of 220 MPa $m^{0.5}$ (145-160 MPa $m^{0.5}$ for irradiated high Ni or high Cu welds), see Figure 5 showing the test results for a high Ni weld material.

For the upper shelf range, in addition to the Master Curve approach by Wallin, the “ductile crack initiation toughness J_{Ic}” model developed by Kirk et al (2011) can be linked with the reference temperature T_0 (Master Curve) via a criterion temperature T_{US} (intersection of Master Curve with upper shelf curve. According to Kirk et al (2011) this relationship can be described by Equation (1).

$$T_{US} = 48.8 + 0.799\, T_0 \quad (1)$$

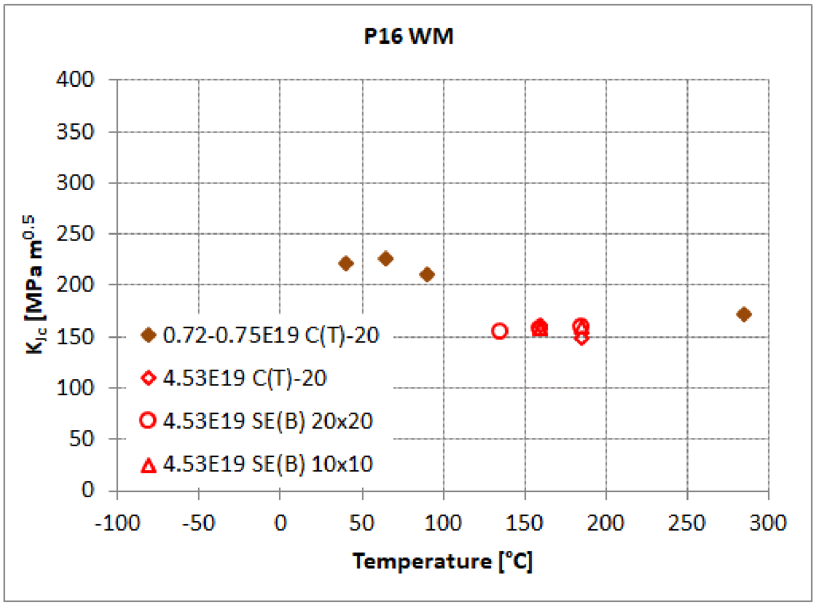

Figure 5: Ductile crack initiation toughness for material P16 WM - irradiated conditions.

The obtained test data are in good agreement with the scatter band from Kirk´s upper shelf model, Kirk et al (2011) for temperatures from the transition range up to 285 °C (RPV operation temperature) as shown in Figure 6 for the irradiated high Ni weld metal P16 WM. Regarding the onset of the upper shelf there is no clear trend within the investigated temperature ranges. Local instabilities based on the welding beads seem to promote crack jumps in this material that was confirmed by SEM investigations.

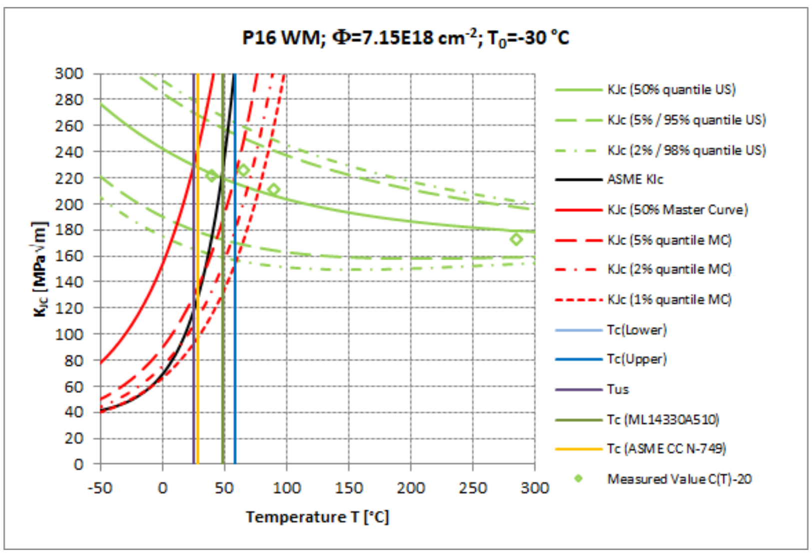

Figure 6: J-R test results and upper shelf predictions for irradiated material P16 WM, neutron fluence $7.15 \cdot 10^{18}$ cm^{-2} (E > 1 MeV).

ASTM E1921 HOMOGENEITY SCREENING CRITERION

With regard to the representativeness of a macroscopically homogeneous material for T_0 determination according to ASTM E1921 (edition 2018 and beyond) the application of the homogeneity screening procedure in section 10.6 of ASTM E1921-19b resulted in inhomogeneity for three out of nineteen data sets (9 BM, 10 WM), see Table 2. In case of macroscopically inhomogeneous material it was observed that a generally conservative reference temperature T_{0IN} determined by simplified method described in Appendix X5 of ASTM E1921-19b which may be used instead of T_0, is in average 11 K higher than the reference temperature T_0. A higher susceptibility of weld materials for macroscopic material inhomogeneity was found since all three inhomogeneity cases were from weld metals. It is assumed that this inhomogeneity is associated with the weld bead structure of the weld.

Table 2: Application of the homogeneity screening procedure in ASTM E1921-19b for materials examined in CAMERA.

	Fluence (E> 1 MeV) in cm^{-2}	**Previous evaluation**		**Evaluation according to ASTM E1921-19b**		
		Project	T_0 (°C)	T_0 (°C)	Homogeneous (section 10.6)	T_{0iN} (°C)
P147 BM	0,00E+00	CARISMA	-112	-112,2	yes	
	7,78E+18	CARISMA	-90	-90,1	yes	
	1,06E+19	CARISMA	-95	-94,5	yes	
	4,00E+19	CARISMA	-78	-77,7	yes	
P142 BM	0,00E+00	CARINA	-60,5	-60,3	yes	
	4,53E+19	CARINA	-3	-3,1	yes	
P7 BM	0,00E+00	CARISMA	-88	-88,2	yes	
	4,45E+19	CARISMA	-22	-21,6	yes	
KS02 BM	2,34E+19	CAMERA	18	18,1	yes	
P141 WM	0,00E+00	CARISMA	-25	-25,6	yes	
	9,79E+18	CARISMA	-26	-26,2	yes	
	9,79E+18	CAMERA	-14	-14,2	no	-3,0
	3,97E+19	LONGLIFE	30	30,1	yes	
P16 WM	0,00E+00	CARISMA	-86,1	-86	no	-74,9
	8,36E+18	CARISMA	-36	-35,6	yes	
	5,43E+19	CARINA	120	120	no	130,6
P370 WM	0,00E+00	CARISMA	-38	-37,9	yes	
	2,25E+19	CARISMA	102	101,8	yes	
	2,12E+19	CARISMA	103	103,2	yes	

APPLICATION OF MICROMECHANICAL LOCAL APPROACH DAMAGE MODELS

Micromechanical Local Approach damage models were successfully applied by means of Finite Element (FE) analyses for test design and prediction of fracture toughness. Whereas the design of load paths for the WPS tests was supported by the simulation of damage mechanisms in the brittle-ductile transition range by application of the Bordet model, Bordet (2005), for the upper shelf tests the damage mechanisms were simulated in the ductile regime by the Gurson model, Gurson (1979). Among other the calibration of the material parameters for the Gurson model was performed with a suitable specimen followed by application of the calibrated material model to the structure of interest, i.e. to another specimen or component. This was successfully done for example for the highly irradiated P16 WM material where the uppers shelf results of a C(T) 20 specimen tested at 160 °C were used for the calibration. The results of the calibration analysis were then used for the prediction of crack growth in a SE(B) 20x20 specimen tested at 160 °C. The comparison of the simulation with the experimental results shows in general a good agreement in terms of crack initiation, propagation rate and final crack shape at the end of the test.

COMPLETE FRACTURE TOUGHNESS-TEMPERATURE DIAGRAM

Based on the results obtained by the Master Curve, WPS and crack resistance tests it was demonstrated how to integrate the criterion temperature T_{US} in the fracture toughness- temperature diagram including the loading transient to an application window for the RPV safety assessment that is based on T_0 only for use in RPV safety assessment. This is given in the diagram in Figure 7 showing

- the assumed loading transient,
- the Master Curve,
- the WPS Master Curve,
- the K_{Frac} data from the WPS tests,
- the 50 % median K_{Jc} curve from the T_{US} approach, and
- the K_{Jc} data from the J-R tests.

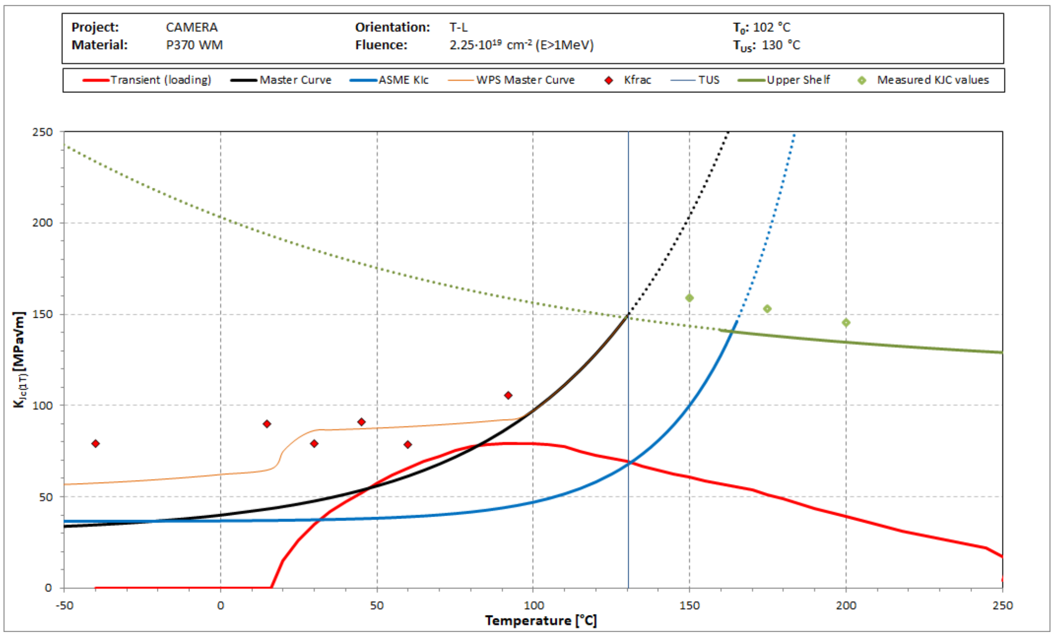

Figure 7: Application window of a master curve based fracture toughness curve for the material P370 WM (Cu=0.22 %), neutron fluence $2.23 \cdot 10^{19}$ cm^{-2} (E > 1 MeV).

CONCLUSIONS

In summary, the obtained fracture toughness and microstructural data complement the existing database of the well characterised RPV materials investigated in preceding research projects. Moreover, the up to date available database is well suited for the validation of models for the prediction of fracture toughness, and for the RPV safety assessment and quantification of safety margins. The benefit of the WPS effect was confirmed for both the material (higher apparent fracture toughness values) and the load path (no initiation after maximum pre-loading) in particular for the irradiated condition with various load and temperature parameters. The upper shelf of the fracture toughness was determined in the ductile tearing regime by means of crack resistance tests according to ASTM E1820 to obtain the J-R curve. In this way the fracture toughness curve could be completed up to the operating temperature and the T_0 based criterion temperature T_{US} beyond no brittle fracture occurs was determined and successfully verified. The prediction of the T_0 based Kirk model for the upper shelf was in good agreement with the experimental data obtained. The results indicate that in particular for irradiated materials with a high T_0 the ductile crack initiation values can be significantly below the formerly accepted value of 220 MPa $m^{0.5}$. Based on the results obtained by the Master Curve, WPS and crack resistance tests it was demonstrated how to integrate the criterion temperature T_{US} in the fracture toughness-temperature diagram including the loading transient to an application window that is based on T_0 only. This application window can be used for RPV safety assessment to reveal inherent safety margins. The application of the homogeneity screening procedure described in ASTM E1921 resulted in a macroscopically inhomogeneous material for a few data sets for that a generally conservative reference temperature T_{0IN} was calculated that is in average 11 K higher than the reference temperature T_0. A higher susceptibility of weld materials for macroscopic material inhomogeneity compared to base materials was found, however this has to be confirmed by more data. The micromechanical Local Approach damage models (Bordet and Gurson) were successfully applied for test design and prediction of fracture toughness and their verification was further advanced. The overall results reveal also some open gaps remaining for future work which are essentially:

- consideration of HAZ data in the database regarding long term operation conditions,
- quantification of constraint effects in particular for high irradiated materials to get best estimate safety margins in RPV safety assessments.,
- extended evaluation of data sets to quantify the impact of the ASTM E-1921 screening criterion for RPV safety assessment.

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