

## FINAL SUMMARY REPORT

**CONTRACT N°:** FIKS-CT-2000-00048

**PROJECT N°:** --

**ACRONYM:** CASTOC

**TITLE:** Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components under Transient Light Water Reactor Operating Conditions

**PROJECT CO-ORDINATOR :** Staatliche Materialprüfungsanstalt (MPA)  
Universität Stuttgart, D

**PARTNERS:** Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), ES

Nuclear Research Institute (NRI), CZ

Paul Scherrer Institut (PSI), CH

Framatome ANP GmbH (F ANP), D

Technical Research Centre of Finland (VTT), FIN

**PROJECT START DATE:** 01.09.2000      **DURATION:** 36 Months

**Date of issue of this report:** 19.01.2004

**CASTOC R008**

Project funded by the European Community under the 5<sup>th</sup> Framework Programme (1998-2002)

The information in this document is provided as it is and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability.

**Crack Growth Behaviour of Low Alloy Steels  
for Pressure Boundary Components under  
Transient Light Water Reactor Operating Conditions  
(CASTOC)**

**Project funded by the European Community under the 5<sup>th</sup> Framework Programme (1998-2002)**

**Contract N<sup>o</sup>: FIKS-CT-2000-00048**

**Co-ordinator: Staatliche Materialprüfungsanstalt (MPA)  
Universität Stuttgart**

**Partners: Centro de Investigaciones Energéticas, Medioambientales y  
Tecnológicas (CIEMAT), ES  
Nuclear Research Institute (NRI), CZ  
Paul Scherrer Institut (PSI), CH  
Framatome ANP GmbH (F ANP), D  
Technical Research Centre of Finland (VTT), FIN**

**Authors**

Jürgen Föhl, MPA  
Thomas Weissenberg, MPA  
Dolores Gómez-Briceño, CIEMAT  
Jesús Lapeña, CIEMAT  
Miroslava Ernestová, NRI  
Miroslav Žamboch, NRI  
Hans-Peter Seifert, PSI  
Stefan Ritter, PSI  
Armin Roth, F ANP  
Bastian Devrient, F ANP  
Ulla Ehrnstén, VTT



**Table of content**

- 1 Summary ..... 1**
- 2 General background..... 2**
- 3 Structure of the project..... 3**
- 4 Materials..... 4**
- 5 Environment ..... 5**
- 6 Experimental simulation of EAC ..... 7**
  - 6.1 Time effect..... 8
  - 6.2 Water conditions..... 8
  - 6.3 Flow rate and water volume ..... 8
  - 6.4 Radiolysis ..... 9
  - 6.5 Crack geometry ..... 9
  - 6.6 Stress state ..... 9
  - 6.7 General conditions..... 11
- 7 Conclusions from the project ..... 12**
  - 7.1 Reproducibility of test results..... 12
  - 7.2 Results from cyclic loading and load transients ..... 13
    - 7.2.1 Effect of material ..... 13
    - 7.2.2 Effect of oxygen ..... 15
    - 7.2.3 Effect of temperature ..... 15
    - 7.2.4 Effect of load transients and frequency ..... 16
    - 7.2.5 Effect of stress state..... 18
    - 7.2.6 Effect of sulphate..... 19
    - 7.2.7 Effect of chloride..... 20
  - 7.3 Results from static loading ..... 22
    - 7.3.1 Effect of material ..... 23
    - 7.3.2 Effect of environment..... 24
    - 7.3.3 General conclusions from static load tests ..... 25
- 8 Consequences for practical application..... 26**
- 9 References ..... 28**



## 1 Summary

The CASTOC project addresses environmentally assisted cracking (EAC) phenomena in low alloy steels used for pressure boundary components in both Western type boiling water reactors (BWR) and Russian type pressurised water reactors (VVER). It comprises the four work packages (WP):

- inter-laboratory comparison test (WP1)
- EAC behaviour under static load (WP2)
- EAC behaviour under cyclic load and load transients (WP3)
- evaluation of the results with regard to their relevance for components in practice (WP4)

The use of sophisticated test facilities and measurement techniques for the on-line detection of crack advances have provided a more detailed understanding of the mechanisms of environmentally assisted cracking and provided quantitative data of crack growth rates as a function of loading events and time, respectively. The effect of several major parameters controlling EAC was investigated with particular emphasis on the transferability of the results to components in service. The obtained crack growth rate data were reflected on literature data and on commonly applied prediction curves as presented in the appropriate Code.

At relevant stress intensity factors it could be shown that immediate cessation of growing cracks occurs after changing from cyclic to static load in high purity oxygenated BWR water and oxygen-free VVER water corresponding to steady state operation conditions.

Susceptibility to environmentally assisted cracking under static load was observed for a heat affected zone material in oxygenated high purity water and also in base materials during a chloride transient representing BWR water condition below Action Level 1 of the EPRI Water Chemistry Guidelines according to the electrical conductivity of the water but in the range of Action Level 2 according to the content of chlorides. Time based crack growth was also observed in one Russian type base material in oxygenated VVER water and in one Western type base material in oxygenated high purity BWR water at stress intensity factors above the limit for linear elastic fracture mechanics.

There is evidence that the prediction curves of the ASME Boiler and Pressure Vessel Code Section XI, Appendix A are not conservative for some relevant cases with regard to crack growth rates under cyclic load even in oxygenated high purity BWR water.

The CASTOC results have provided an important contribution to the understanding of crack growth behaviour on the one hand as a function of time and on the other hand as a consequence of the number and height of loading events. This is an important key for the evaluation of transient events, which may occur in a plant during service.

## 2 General background

Ageing of pressure boundary components is one of the main factors controlling the lifetime of nuclear power plants. Environmentally assisted cracking (EAC) under certain circumstances can be one of the major ageing mechanisms of low alloy steels in high temperature water. The project "Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components under Transient Light Water Reactor Operating Conditions", (CASTOC), was performed within the 5<sup>th</sup> EU framework programme - under contract no. FIKS-CT-2000-00048 and addressed the problem of EAC of Western and Eastern type steels used for pressure boundary components [1], [2].

The available data concerning EAC of low alloy steels in high temperature water under constant static load has revealed major discrepancies in crack growth rates under nominal similar conditions. These discrepancies have been primarily attributed to insufficient control of relevant experimental parameters and incomplete reporting of necessary information rather than to real scatter in material behaviour.

Based on these discrepancies an international Round Robin Programme has been organised between European laboratories [3]. However, since the tests performed with low alloy steel in high temperature water under purely static load did not reveal significant amounts of crack advance, the international acceptance of the results was limited. The main criticism was that even incubation times for the development of stable crack growth under static load could be greater than the duration of the experiment and therefore "zero" crack growth is not a sufficient evidence to confirm resistance to EAC under these conditions [4]. It was therefore suggested by international experts, that crack growth due to EAC should be initiated under conditions, where susceptibility to EAC is known to exist, e.g. under cyclic load at very low frequencies [5].

Most of the existing crack growth data to date was related to steady state operating conditions. Only few data is available with respect to controlled transient conditions (chemistry, loading).

The objectives of the CASTOC project were the generation of reliable crack growth data considering the following parameters:

- variations of material
  - \* different base materials
  - \* the heat affected zone of a joint weld
  - \* weld metal
  - \* specimens clad with austenitic stainless steel
- effect of chemical conditions of the water environment and transients in water chemistry
  - \* sulphate
  - \* chloride
  - \* oxygen
  - \* pressurised water reactor primary water for VVER
  - \* temperature

- effect of mechanical transients
  - \* transition from cyclic load to static load
  - \* hold time effects during cyclic load
- effect of stress state in the specimen
  - \* specimen geometry (surface cracked specimens, C(T) specimens)
  - \* specimen size (C(T)25 and C(T)50)

The results of the project should in particular be assessed with respect to quality, reliability and its application to plant concerns and possible Code implementation. This comprises a comparison of the data from the CASTOC project with data from literature and Codes and to give indications where the results may be considered in plant life management strategies.

### **3 Structure of the project**

WP1, in which all partners participated, was an inter-laboratory comparison test to be performed under nominally equal conditions with the aim to demonstrate the variation in test results and to verify the general applicability of laboratory test data [6]. With regard to long-term behaviour under static load the test was started with a cyclic phase in which continuous crack growth should occur under environmentally assisted conditions to overcome the issue of an assumed incubation phase for crack initiation under static load.

WP2 was focussed on the effect of chemical transients and temperature under constant static loading conditions [7]. The objective of this work package was to study predominantly the effect of static load following a period of cyclic load or mechanical transients to obtain cracks that are actively growing due to an environmentally assisted mechanism. The water conditions were chosen according to normal water chemistry (NWC) during steady state operation of boiling water reactors (BWR) and to the specifications of the EPRI Water Chemistry Guidelines [8] for Action Levels 1, 2 and even 3. For comparison, the normal primary water chemistry of Eastern type pressurised water reactors (VVER) and VVER conditions with increased oxygen content also were applied. The parameters of the load transients were mainly rise time and hold time at maximum load. In addition, tests were performed with specimens of different size and crack geometry, respectively, to achieve different stress/strain conditions at the crack tip and thus to assess the influence of linear-elastic and elastic-plastic loading conditions.

The aim of WP3 was to investigate crack growth under cyclic load and under well-defined load transients (periodical partial unloading, PPU) [9].

The activities in WP4 addressed in a joint action of all participating partners for evaluation of all the results with regard to applicability to practice [10]. One of the major aspects was to compare the results of this project with international laboratory experience and data used in plant life management to assess, e.g. time intervals for repeated in-service inspections and to give recommendation for the implementation of the results into plant life management strategies and into Codes.

With regard to the specific situation in Europe, the materials and water environment conditions were chosen to address both the concerns of BWR and VVER, respectively.

## 4 Materials

The main objective of the project was to investigate environmentally assisted cracking of low alloy steels used for the pressure retaining components of the primary coolant. For this purpose, materials were selected from semi-finished products representing different types of steels and different qualities.

- **Material A, base material**

Seamless forged ring of German type 20MnMoNi5-5 RPV steel (final wall thickness 300 mm), equivalent to ASME SA 508 Grade 3, Cl. 1

The selected heat is the so called "lower bound material" from a former German reactor materials research programme, i.e. a controlled heat designated "KS12" that conservatively covers the German reactor pressure vessel (RPV) steel 20MnMoNi5-5 with respect to chemical composition and Charpy-V- notch toughness.

The material state (regarding chemical composition) is characterised by enhanced phosphorus, sulphur, molybdenum and copper content compared with the specification. MnS-clusters are present in this heat, but similar may be present in real plant material as well, since segregation phenomena are not unusual for that kind of large size ingots.

- **Material A, weld metal**

S 3 NiMo 1/OP 41 TT (wire/flux), fabricated as circumferential weld using narrow gap welding according to nuclear grade quality with optimized wire and flux relevant to welding techniques, which were used for RPVs of Western plants

- **Material B, base material**

Seamless forged vessel shell of German type 22NiMoCr3-7 RPV steel (final wall thickness 250 mm), equivalent to ASME SA 508 Grade 2, Cl. 1, taken from a reactor pressure vessel fabricated for a nuclear power plant in Germany ("Biblis C"), however, which finally has not been built

This is a relevant material from a real (commercial) RPV. Note: The austenitic stainless steel cladding and its heat affected zone is relevant as well, but it is not directly a concern of this project.

- **Material C, base material**

Forged plate of Russian type 15Kh2MFA RPV steel for use in VVER reactors with enhanced sulphur content (thickness of the plate 140 mm), fabricated according to nuclear grade quality

- **Material D, base material**

Forged plate of Russian type 15Kh2NMFA RPV steel for use in VVER (thickness of the plate 320 mm), fabricated according to nuclear grade quality

Materials A and B are typical for Western type reactor pressure vessels whereas materials C and D represent VVER reactor pressure vessel materials. Significant differences exist in the chemical composition of the Western and the VVER type materials. The VVER types of steel have in particular high chromium and in case of the 15Kh2MFA (C) also a high vanadium content, see Table I. The nickel content is low in the 15Kh2MFA steel but high in the

15Kh2NMFA (D). In contrary, the Western type steels have little chromium, elevated nickel and in particular a high manganese content.

All base materials have a fine-grained bainitic microstructure. In case of material A, a high variation in the local sulphur content was observed ranging from 0.003 to 0.053 wt.%. Furthermore, portions of intergranular fracture were found on fracture surfaces produced under cyclic load in air giving indications for grain boundary segregations, which could be identified by Auger Electron Spectroscopy. This analysis revealed an enhanced content of phosphorus, molybdenum and manganese at the grain boundaries.

**Table I:** Chemical composition (major elements) and strength properties of the investigated materials.

Material	Chemical Composition [wt.%]							$\sigma_{YS}$ (RT) [MPa]	$\sigma_{ULT}$ (RT) [MPa]
	C	Mn	Cr	Ni	P	S	V		
<b>A (base)</b>	0.25	1.54	0.18	0.62	0.014	0.015	0.024	512	663
<b>A (weld)</b>	0.07	1.15	0.10	1.04	0.014	0.005	0.010	496	572
<b>B (base)</b>	0.22	0.91	0.42	0.88	0.008	0.007	0.007	444	594
<b>C (base)</b>	0.15	0.40	2.78	0.30	0.013	0.015	0.29	545	651
<b>D (base)</b>	0.14	0.45	2.15	1.23	0.009	0.007	0.008	570	674

$\sigma_{YS}$  = yield strength

$\sigma_{ULT}$  = ultimate tensile strength

RT = Room Temperature

base = base material

The specimens were predominantly taken from the 1/4 T to the 3/4 T position (T = thickness of the plate/forging) which corresponds to requirements according to the acceptance testing procedure.

One fracture mechanics specimen C(T)25 of material A was investigated with the crack located in the heat affected zone (HAZ) of the circumferential weld. The hardness determined on a metallographically prepared section near the location where the specimen was taken reached values of about 340 HV 0.1.

To investigate the situation as resulting from a postulated surface crack penetrating the austenitic stainless steel cladding, one specimen was prepared from the vessel shell of material B that was clad by a double layer strip cladding using Nb-stabilised austenitic stainless steel X2CrNiNb24-12 for the first layer and X2CrNiNb21-10 for the second layer. The component was heat treated after cladding. The crack front of this specimen is located in the austenitic cladding, in the HAZ of the cladding and in the ferritic base material. The hardness of the HAZ of the cladding was determined on a metallographically prepared section to about 300 HV 0.1.

## 5 Environment

The properties of the water environment like temperature, flow velocity and the chemical composition have a big influence on all corrosion processes including environmentally assisted cracking in structural materials. They also affect e.g. the activity build-up (dose rate increase) in nuclear power plant circuits. The specific electric conductivity, the content of oxidants (e.g. oxygen) and the pH depend on the chemical composition of the water and de-

scribe the aggressiveness of the environment. It has to be taken into account that the water conductivity itself is not responsible for the aggressiveness, but the water impurities like chlorides and sulphates, which cause higher conductivity values. In this context, water chemistry parameters like conductivity, oxygen concentration and pH value act as indicators for a deviation from the specified operational conditions of a coolant circuit. For steady state operation the main parameters of the water are specified in the EPRI Water Chemistry Guidelines, see Ref. [8]. Deviations from the normal operating conditions are grouped into different Action Levels, see Table II, and requires adequate measures as outlined in the definitions of the Action Levels, see Table III. Similar conditions for BWR operation are specified in the German "VGB-Richtlinie", see Ref. [11].

**Table II:** EPRI water chemistry guideline recommendations for the reactor water for BWR power operation (for NWC conditions).

Control Parameter	Unit	Median Value	Action Levels		
			1	2	3
conductivity	μS/cm	~ 0.11	> 0.30	> 1.0	> 5.0
chloride	μg/kg	~ 1	> 5	> 20	> 100
sulphate	μg/kg	~ 1	> 5	> 20	> 100

**Table III:** Definitions of Action Levels according to EPRI guidelines.

Parameter	Definition
Action Level 1	The Action Level 1 value of a parameter represents the level above which data or engineering judgement indicates that long-term system reliability may be threatened, thereby warranting an improvement of operating practices.
Action Level 2	The Action Level 2 value of a parameter represents the level, above which data or engineering judgement indicates that significant degradation of the system may occur in the short term, thereby warranting a prompt correction of the abnormal condition.
Action Level 3	The Action Level 3 value of a parameter represents the level above which data or engineering judgement indicate that it is inadvisable to continue to operate the plant.

Boiling water reactors are open systems in relation to the mass flow of the coolant. In order to avoid the accumulation of dissolved substances, the use of non-volatile chemicals for water chemistry adjustment is normally not possible. For this reason, most BWRs are operated with high purity water, which contains radiolysis products like oxygen, hydrogen peroxide and hydrogen. Normally, the BWR coolant contains 100 to 400 μg/kg dissolved oxygen and this is referred to as normal water chemistry (NWC). In some BWRs hydrogen gas is dosed into the feed water in order to reduce the total amount of oxidants to low levels and thus to ensure low values of the electrochemical corrosion potential (ECP). This type of water chemistry control is called hydrogen water chemistry (HWC). In addition to the oxidising character of the NWC coolant, chlorides and sulphates are the most detrimental impurities with respect to EAC. Therefore, their concentration is kept as low as possible and the allowable concentration is strictly limited by water chemistry guidelines.

The Russian design VVER reactor is a PWR and represents a closed system in relation to the mass flow of the coolant without a phase transition to steam within the primary coolant circuit. Therefore, also non-volatile chemicals may be used for technological purposes as well as for water chemistry adjustment. For example, the pH value of the PWR coolant is controlled in order to ensure minimum corrosion and activity build-up conditions. From neutron physical reasons the main PWR coolant contains boric acid, which, however, would lead to an acidification of the water and thus to an increase of the coolant aggressiveness. In order to avoid this effect, KOH is dosed into the main coolant as an alkalisating medium. In the closed cooling system of a PWR, the formation of oxidising radiolysis products easily may be suppressed by dosing hydrogen gas into the coolant. In VVER reactors ammonia (NH<sub>3</sub>) is used which is subject to radiolysis and generates hydrogen by this way. Furthermore, NH<sub>3</sub> leads to an additional slight alkalisating of the coolant, which is beneficial with regard to the aggressiveness of the water. As the concentration of boric acid decreases in the course of a reactor operation cycle, also the amount of other coolant ingredients may change. Due to ammonia dosing and to the suppression of the radiolysis products, the oxygen concentration in the primary coolant of a PWR remains during normal power operation usually in the range of the detection limit.

One of the aims of CASTOC was to investigate the effect of chemical transients on the crack growth behaviour under constant and cyclic loading conditions. The EAC crack growth response during and in particular after water chemistry transients is of practical relevance because BWR/VVER operation inevitably involves short-term variations in water chemistry. Conductivity and oxygen/hydrogen peroxide/ECP transients occur during start-up and occasionally during steady-state power operation (e.g., ion exchanger resin intrusions, condenser leakages). Accordingly, in different work-packages environmental parameters were chosen which clearly exceed the normal operation values for stationary BWR and VVER power operation. In some experiments single values even exceeded the EPRI Action Level 3 limits and the allowable concentrations, respectively, taking into account that those water chemistry conditions would not allow to continue operation of the plant but are necessary to evaluate the effect of worst case conditions. Therefore, the crack growth results of these experimental investigations are highly conservative with respect to the water chemistry parameters of normal plant operation.

## **6 Experimental simulation of EAC**

Environmentally assisted cracking (EAC) in pressure retaining components is controlled by a variety of parameters of the environment and of the loading conditions as well as of the susceptibility of the material. The understanding of the acting mechanisms is a key factor not only for the evaluation of the behaviour of a component in practice but also for adequate experimental simulation of the conditions in the plant. Therefore, in laboratory tests all major parameters that may affect EAC have to be considered and to be applied accordingly. In case of insufficient knowledge of the effect of individual parameters, conditions have to be selected which cover uncertain effects in a conservative way.

The laboratory test units presently operated by the CASTOC partners enable precise adjustment and control of the water and loading conditions. By means of the direct current potential drop (DCPD) technique, on-line crack length measurements can be performed with high resolution in crack length and time. This gives access to explore the immediate response of the material behaviour to applied transient conditions.

The factors, which have to be considered with regard to a reliable experimental simulation of the conditions in the plant are dealt with in the following sub-chapters.

## **6.1 Time effect**

With regard to the long lifetime of a component in service of 40 years or more and the strong time dependence of EAC processes, the necessary time reduction in laboratory tests is a major concern to describe reliably the long-term behaviour of components in practice. Therefore, it is vital to understand the crack growth behaviour as a function of time dependent parameters, which are mainly:

- the load rise time leading to a certain strain rate in the crack tip region
- the hold time at constant static load during which cessation of a growing crack or enhanced crack growth due to stress corrosion cracking may occur
- the frequency, combined with the loading pattern (sine wave, saw tooth, periodical partial unloading), of cyclic loading

A particular problem is associated with the investigation of environmentally assisted cracking under static load since this process may be preceded by a long incubation time. This effect cannot be investigated on a "condensed" time scale. To overcome this generic problem an advanced test technique was applied – and this was in particular possible by means of the DCPD measurement technique – which enables a conservative description of the crack growth behaviour under constant static load. This test technique comprises a sufficiently long conditioning phase in the specified environment to build-up a stable oxide layer and a cyclic load phase to generate an actively growing crack due to EAC. Finally, the static load phase is usually introduced at the maximum load level of the cyclic phase or even at higher loads. By these means a possible incubation phase is eliminated. If crack cessation occurs, it can be concluded that the material is not susceptible to EAC under the applied conditions. If continuous crack growth occurs, relevant crack growth rates can be determined since the detection limit of the DCPD technique is of the order of 2 to 10  $\mu\text{m}$ . This correlates to a detection limit of crack growth rates during a 300 h test period of  $5 \cdot 10^{-12}$  m/s (160  $\mu\text{m/a}$ ). Test periods of up to 500 h were applied to reliably describe the crack growth behaviour.

## **6.2 Water conditions**

All partners of the project used sophisticated autoclave systems and the above-mentioned test and measurement technique so that the major parameters such as oxygen, sulphate and chloride content could precisely be controlled and maintained over a long period of time.

To simulate BWR conditions an overpressure was used to avoid a phase transition to steam. This is the common practice and is acceptable since the major concern of EAC is related to the water phase and not to the steam phase.

## **6.3 Flow rate and water volume**

From own experience and various literature data there is clear evidence that the flow rate may be a significant parameter with respect to EAC since it affects the local chemistry of

the water and in particular the mass transport of "critical" species into and out of the crevices (cracks). However, the most severe conditions establish under stagnant or quasi-stagnant flow. Such quasi-stagnant conditions are mainly applied in laboratory tests with the exception where the effect of flow rate is deliberately investigated to study this effect. With very few exceptions, which are mentioned explicitly, the CASTOC tests were performed under quasi-stagnant flow conditions with a low refreshing rate to generate conservative data with respect to plant conditions.

A further simplification has to be made in laboratory tests concerning the ratio of specimen surface to water volume. Since an improper increase in ion concentration due to general corrosion in the system is eliminated by the refreshing procedure, similar low ion concentration can be sustained as in the plant and thus the deviation from plant conditions is not of relevance for the laboratory results.

#### **6.4 Radiolysis**

One parameter, the radiolysis of the water due to the field of ionising radiation, cannot be simulated easily. The impact of radiolysis products H and O radicals is a certain concern for RPV internals of austenitic stainless steel, however, at the RPV wall and at the adjacent feed water lines there is still a high radiation field to produce a significant amount of radiolysis products. The hydrogen water chemistry applied in the plant suppresses the effect of radiolysis to a great amount by reducing the concentration of free oxygen, however, in crevices a residual effect of radiolysis products, mainly atomic oxygen, or the diffusion of hydrogen into the metal cannot be excluded. A special project has been launched in Germany to investigate the effect of radiolysis on austenitic stainless steel and on low alloy steel [12]. The CASTOC investigations do not account for radiolysis effects. In some tests, the high electrochemical corrosion potential (ECP) of about +150 mV<sub>SHE</sub>, which is present at the inner wall of the RPV due to radiolysis products (e.g. H<sub>2</sub>O<sub>2</sub>) was simulated by an elevated oxygen content of 8000 µg/kg.

#### **6.5 Crack geometry**

In the postulated cases of cracked components, the geometry of the crack is more or less semi-elliptical providing an access of the water to the crack tip region differently from that in a small compact tension C(T) specimen commonly used for laboratory tests. Therefore, a few screening tests with differently pre-cracked C(T) specimens and flat bar tension specimens containing a semi-elliptical surface crack were performed in the CASTOC project to obtain a rough picture about a possible significance of this effect. For the evaluation of the results, it has to be taken into account that not only the access of the water to the crack tip region is different compared with that in a C(T) specimen but also the local stress state (different constraint).

#### **6.6 Stress state**

The common practice in laboratory testing is the use of compact tension specimens C(T)25 with a thickness of 25 mm. Since a pre-requisite for the transferability of results is the equality of the acting mechanisms it has to be considered whether the stress state in a component differs from that in the specimen and thus can contribute to a change in corrosion

mechanism. As long as the stress intensity factor does not exceed the limit for plane-strain conditions according to ASTM E 399 [13] only very limited plastic deformation has occurred in the crack tip region (small scale yielding) during the loading phase and the data are considered to be transferable.

From the basic equation:

$$B, a \geq 2.5 \cdot \left( \frac{K_I}{\sigma_{YS}} \right)^2 \quad (1)$$

B = specimen thickness in m

a = crack length in m

$K_I$  = stress intensity factor in MPa $\sqrt{m}$

$\sigma_{YS}$  = yield strength in MPa

the range in  $K_I$  for the valid application of linear elastic fracture mechanics (LEFM) is limited

for a C(T)25 specimen by  $K_{I \text{ E 399}}^{C(T)25} = 0.1 \cdot \sigma_{YS} \quad [\text{MPa}\sqrt{m}]$

and for a C(T)50 specimen by  $K_{I \text{ E 399}}^{C(T)50} = 0.14 \cdot \sigma_{YS} \quad [\text{MPa}\sqrt{m}]$

It is supposed that the component with the postulated flaw is loaded in the LEFM regime and thus relevant tests to represent the service conditions must assure that small scale yielding is not exceeded. In case of material A (20MnMoNi5-5) with a yield strength at 288 °C of 462 MPa the admissible  $K_I$  ranges are up to 46 MPa $\sqrt{m}$  for the C(T)25 specimen and up to 65 MPa $\sqrt{m}$  for the C(T)50 specimen.

According to ASTM E 1681 the criterion for the remaining ligament ( $W - a$ ) has also to be fulfilled to meet the validity of LEFM.

$$(W - a) \geq 2.5 \cdot \left( \frac{K_I}{\sigma_{YS}} \right)^2 \quad (2)$$

W = specimen width; W = 2·B for C(T) specimens

A second limitation for the remaining ligament is set in both ASTM E 647 [14] and ASTM E 1681 [15]. The crack may not grow so far that the ligament criterion according to equation (3) is violated.

$$(W - a) \geq \frac{4}{\pi} \cdot \left( \frac{K_I}{\sigma_{YS}} \right)^2 \quad (3)$$

In equation (3) for the calculation of the ligament limitation, the effective yield strength (flow strength)  $\sigma_{FS}$  may be used instead of  $\sigma_{YS}$  if the work hardening ratio  $\sigma_{ULT}/\sigma_{YS}$  exceeds the value of 1.3, which is usually the case for RPV materials.

$$\sigma_{FS} = \frac{\sigma_{YS} + \sigma_{ULT}}{2} \quad (4)$$

$\sigma_{FS}$  = effective yield strength (flow strength) in MPa

$\sigma_{ULT}$  = ultimate tensile strength in MPa

For specimens of material A with an a/W ratio of e.g. 0.65 the limits for the stress intensity factors of a C(T)25 and a C(T)50 specimen are according to equation (3) on the basis of  $\sigma_{YS}$ :

$$K_{I \frac{C(T)25}{E 1681}} = 61.0 \text{ MPa}\sqrt{\text{m}}$$

$$K_{I \frac{C(T)50}{E 1681}} = 86.3 \text{ MPa}\sqrt{\text{m}}$$

This ligament requirement does not comply with the LEFM conditions and is not necessarily a sufficient condition for the transferability of results to components. In case that the validity criterion of ASTM E 399 is violated, the application of results from small specimen testing to plant components may not be considered without detailed analyses of the real stress/strain state in the component.

Nevertheless, tests were also performed in the regime exceeding these criteria, however, sustained "low temperature creep" processes in the crack tip region cannot be excluded in this range. This may result in a continuous destruction of the protecting oxide layer and thus to sustained crack growth due to strain induced corrosion cracking.

In order to confirm the trend of the effect of specimen size on EAC some tests were performed with C(T)50 specimens to compare the results with those from C(T)25 specimens. This implies, however, an additional effect with regard to the access of the water and especially its dissolved ingredients to the crack tip.

## 6.7 General conditions

In summary, the tests performed within the CASTOC project comply with the current knowledge of science and technology in laboratory testing of EAC processes. The investigated materials represent nuclear grade and lower bound materials, see chapter 4 of this report. With regard to the selected environmental conditions, enveloping parameters were applied.

The tests under cyclic load were usually performed with a high number of cycles to achieve sufficient stable crack growth conditions and sufficient crack advance to consider this data as reliable. Under static load, the duration of the tests was extended up to 500 h to generate a database for statistical evaluation of the crack growth rate.

BWR water was mostly simulated with an oxygen content of 400  $\mu\text{g}/\text{kg}$  representing steady state operation in a conservative way. An oxygen content of up to 8000  $\mu\text{g}/\text{kg}$  was applied additionally to investigate the effect of oxygen during start-up phases in the plant and at the same time to simulate a realistic ECP. If not stated otherwise, the term "BWR water" is used for water of high purity with an electrical conductivity of  $\kappa < 0.2 \mu\text{S}/\text{cm}$  in the outlet water.

In case of VVER water, start-up phases were simulated with an oxygen content of about 200  $\mu\text{g}/\text{kg}$  and steady state conditions with technically oxygen-free water of less than 20  $\mu\text{g}/\text{kg}$  dissolved oxygen. In all cases, the VVER water contained boric acid in a concentration representative for plant operation.

## 7 Conclusions from the project

The objective of the CASTOC project was to screen the EAC behaviour of low alloy RPV steel in high temperature water during load transients that may occur during start-up and shut down, steady state operation and load following mode. This is in contrast to the worldwide activities in the past, which focused mainly on either cyclic loading or static loading. The main focus of the project was directed to the interaction between static and cyclic loading which was realised e.g. by periodical partial unloading with different rise and hold times. In conjunction with the different load spectra, the effect of transients in water chemistry was investigated. The major results obtained in this project are summarised in the following sub-chapters.

### 7.1 Reproducibility of test results

The project was designed in a way that different partners contributed results partly to the same objective but with different parameter sets. To assure that the individual results can be comprised to describe the complex interactions of the different parameters, an inter-laboratory comparison test was performed to demonstrate the reproducibility and, at the same time, to generate data which describe the crack growth behaviour of material A in high purity BWR water [6], [16].

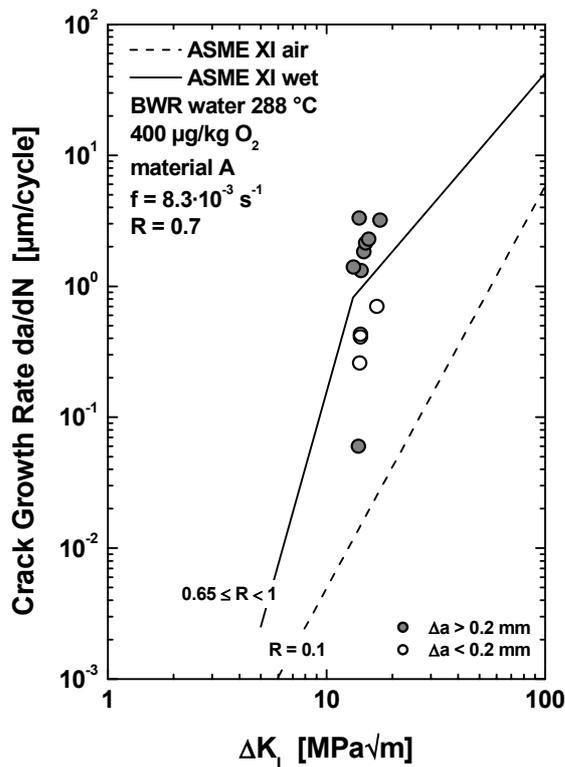
The tests were carried out under nominally identical conditions, firstly under cyclic load and in a second phase under static load. It was confirmed that all tests were performed under proper control of all important "external" parameters, e.g. load and environment and that sufficient crack advance mostly was achieved in the cyclic phase to obtain reliable data.

The obtained crack growth rates  $da/dN$  under cyclic load are spread over a range of almost two orders of magnitude, see Figure 1 and 2. Although EAC is in general a deterministic process, there exist besides the "external" parameters "internal" parameters, which cannot be controlled such as:

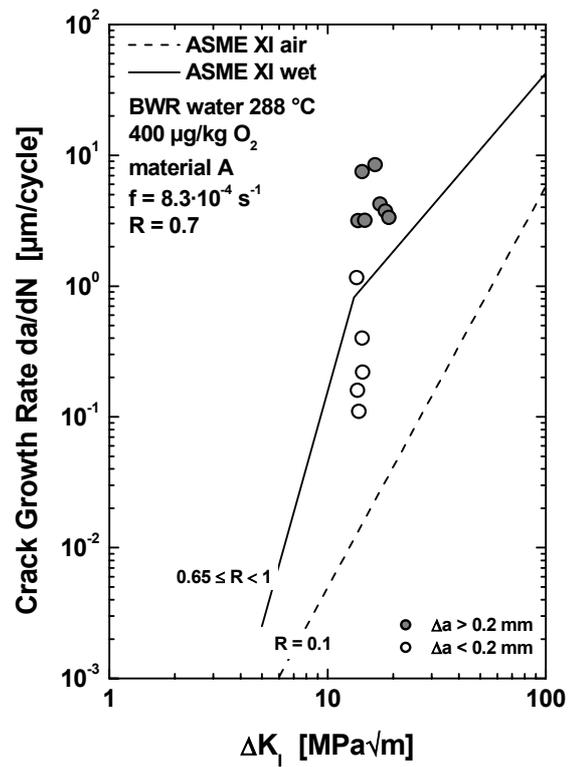
- inhomogeneities in the material with respect to chemical composition and microstructure
- residual stresses
- local water chemistry, e.g. due to different amount of dissolved manganese sulphides present in the crack plane
- crack cessation/arrest, local pinning and re-initiation phenomena

which add a probabilistic term to EAC. Furthermore, crack growth data, which were derived from test periods with not long enough crack advance ( $\Delta a < 0.2 \text{ mm}$ ) with regard to the resolution of fractographic crack length determination and DCPD technique for crack length measurement, in particular in the lower range of  $da/dN$ , are associated with a higher uncertainty and thus are less reliable. This has to be considered with regard to practical applications.

The data were compared with the prediction line as presented in the ASME Boiler and Pressure Vessel Code, Section XI, Appendix A [17]. This comparison reveals clearly that a significant number of data, in particular those which were derived from test periods with sufficient crack advance, exceed the ASME prediction line. It can further be concluded that the lower cycling frequency ( $8.3 \cdot 10^{-4} \text{ s}^{-1}$ ) tends to cause higher crack growth rates, Figure 2, than the higher frequency ( $8.3 \cdot 10^{-3} \text{ s}^{-1}$ ), Figure 1. This is consistent with the general experience that EAC is a strong time dependent process.



**Figure 1:** Range of crack growth rates of material A at a frequency of  $8.3 \cdot 10^{-3} \text{ s}^{-1}$  in oxygenated high purity BWR water of 288 °C.



**Figure 2:** Range of crack growth rates of material A at a frequency of  $8.3 \cdot 10^{-4} \text{ s}^{-1}$  in oxygenated high purity BWR water of 288 °C.

A second very important result could be concluded from these tests. After changing from cyclic loading to static load, immediate cessation of crack growth was observed at the applied stress intensity factors of up to almost  $60 \text{ MPa}\sqrt{\text{m}}$ . This confirms that material A, tested under these conditions, is not susceptible to EAC under static load (stress corrosion cracking).

## 7.2 Results from cyclic loading and load transients

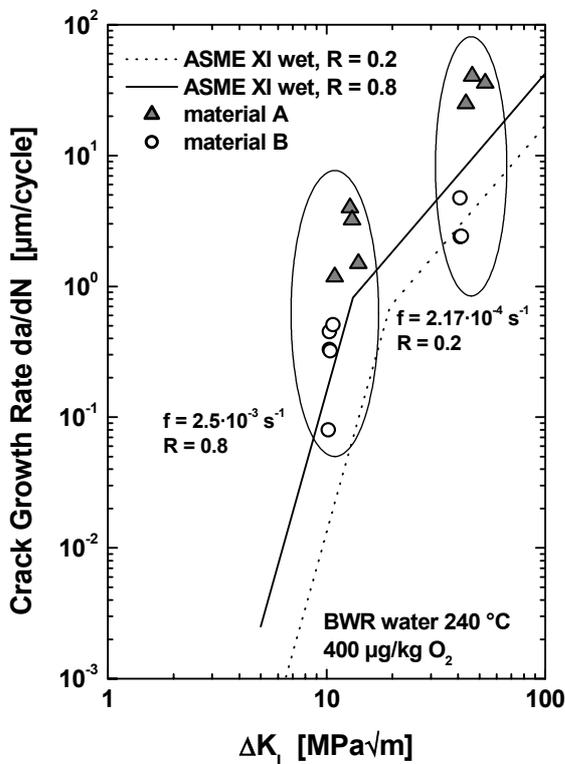
### 7.2.1 Effect of material

A direct comparison of all materials under identical experimental conditions is not possible and was not the aim of this project. Therefore, the material behaviour is evaluated individually to identify specific features.

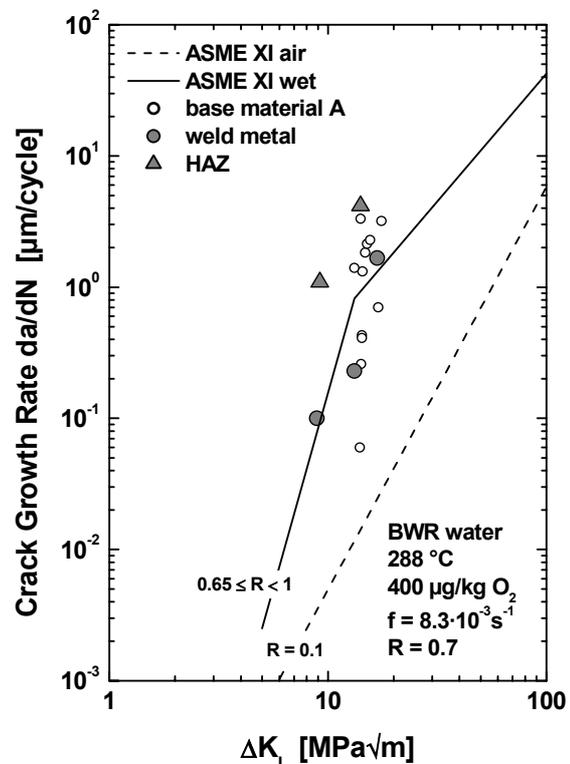
Material A was investigated extensively and showed consistently, that most of the  $da/dN$  data exceed the ASME XI prediction curve in high purity water, compare Figure 1 and

2. However, the material showed a specific feature of pronounced portions of intergranular cracking in several specimens even in the fatigue pre-crack area produced in air. This can be attributed to enhanced phosphorus segregations at the grain boundaries which was verified by Auger Electron Spectroscopy and is not surprising since this material was fabricated as lower bound material with enhanced phosphorus content of 0.014 wt.%.

Material B representing optimised nuclear grade material showed significantly lower susceptibility to EAC. The range of  $da/dN$  data is almost one order of magnitude lower than that of material A, see Figure 3. In some cases it was even difficult to initiate crack growth at all under cyclic load. The lower susceptibility to EAC appeared also in tests with periodical partial unloading and during the applied chloride transient, compare chapter 7.2.7. However, if once fast crack growth was initiated, the crack growth rates of material B, e.g. during slow load transients, were in the same ranges as those of material A.



**Figure 3:** Comparison of crack growth rates of material A and B under low frequency fatigue in oxygenated high purity BWR water of 240 °C.

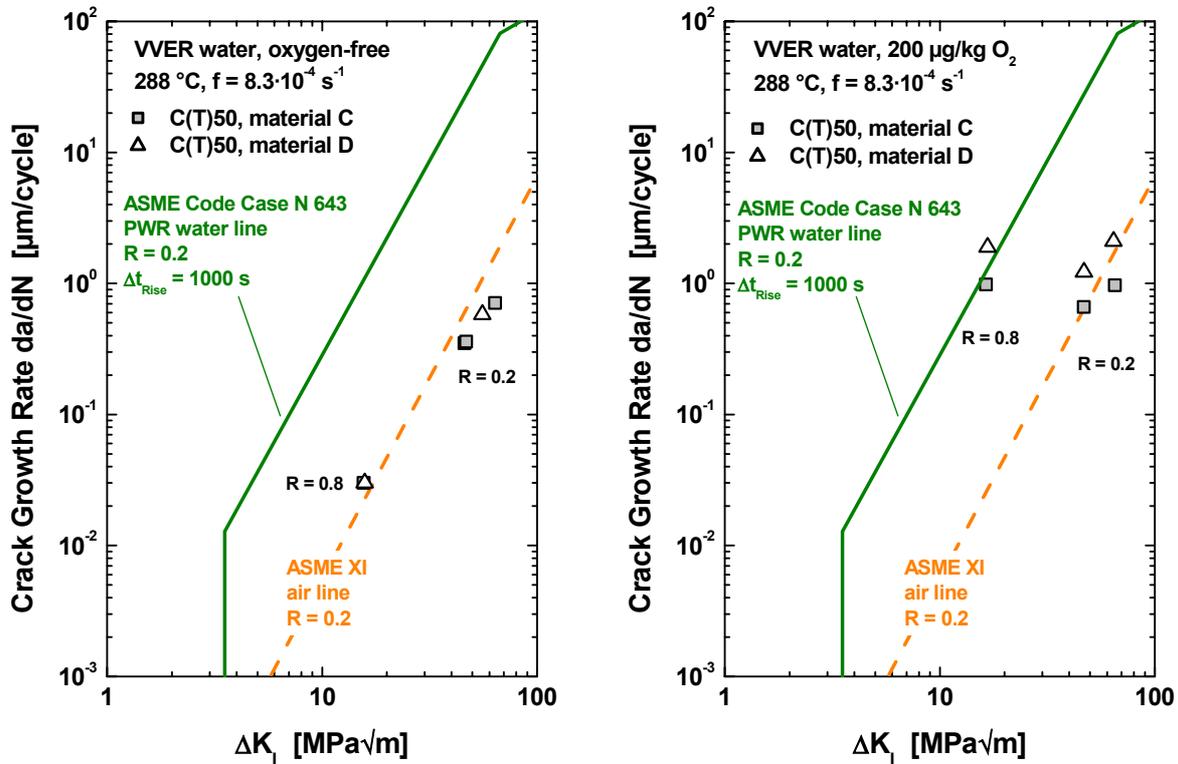


**Figure 4:** Crack growth behaviour of weld metal and HAZ compared to data for base material A under low frequency fatigue in oxygenated high purity BWR water of 288 °C.

The weld metal of material A showed similar behaviour as the base material A, see Figure 4. Opposite to that, a tendency towards higher crack growth rates under cyclic loading was observed for the heat affected zone (HAZ) of the joint weld of material A, see Figure 4.

Under cyclic loading, there was almost no difference in behaviour of material C and D in both oxygen-free and oxygenated VVER water, see Figure 5 and 6. All  $da/dN$  data are well represented by the prediction curve of the ASME Code Case 643 [18] for PWRs and in par-

particular in oxygen-free VVER water the data are even close to the ASME prediction line for air, see chapter 7.2.2.



**Figure 5 and 6:** Crack growth behaviour of material C and D under low frequency fatigue in VVER water of 288 °C (oxygen-free, left, and 200 µg/kg oxygen, right).

### 7.2.2 Effect of oxygen

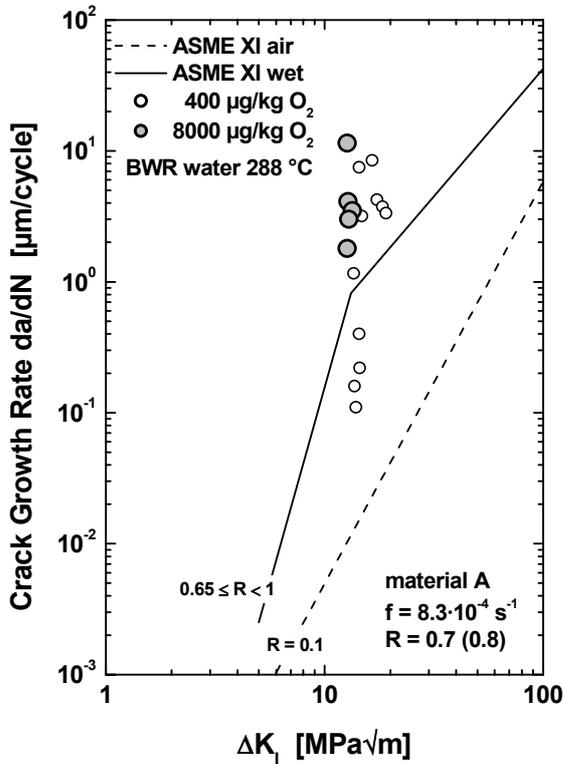
The effect of oxygen was investigated on material A in high purity BWR water and on material C and D in VVER water environment. In BWR water no significant effect of oxygen on EAC was observed at concentrations between 400 and 8000 µg/kg, see Figure 7, which is consistent with the only small differences in the measured ECP values. However, the crack growth rates in highly oxygenated water cover predominantly the upper range of the data field.

The crack growth rates in oxygen-free VVER water are low and comparable with the behaviour predicted for inert environment such as air, compare Figure 5 and 6. At the enhanced oxygen content of 200 µg/kg a crack growth rate at the high R ratio ( $R = 0.8$ ) was observed, which is about one order of magnitude higher than in oxygen-free VVER water, whereas at the low R ratio ( $R = 0.2$  and  $0.1$ ) almost no accelerating effect on crack growth was found.

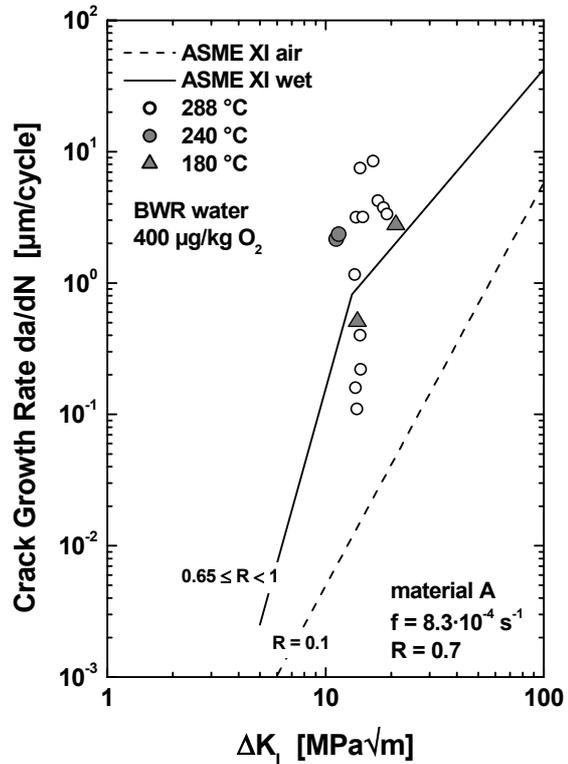
### 7.2.3 Effect of temperature

In BWR water environment experiments were carried out with material A and B at temperatures of 240 °C and 180 °C in addition to those at 288 °C. In this temperature range, no

consistent effect of the temperature was observed due to the wide range of data. An example is presented in Figure 8 for material A, but material B showed a similar behaviour. However, this statement may not be generalised since in case of materials which show dynamic strain ageing effects, a maximum in susceptibility to EAC may exist in a temperature regime below the operation temperature of 288 °C [19].



**Figure 7:** Effect of oxygen on crack growth rate under low frequency fatigue in BWR water of 288 °C.



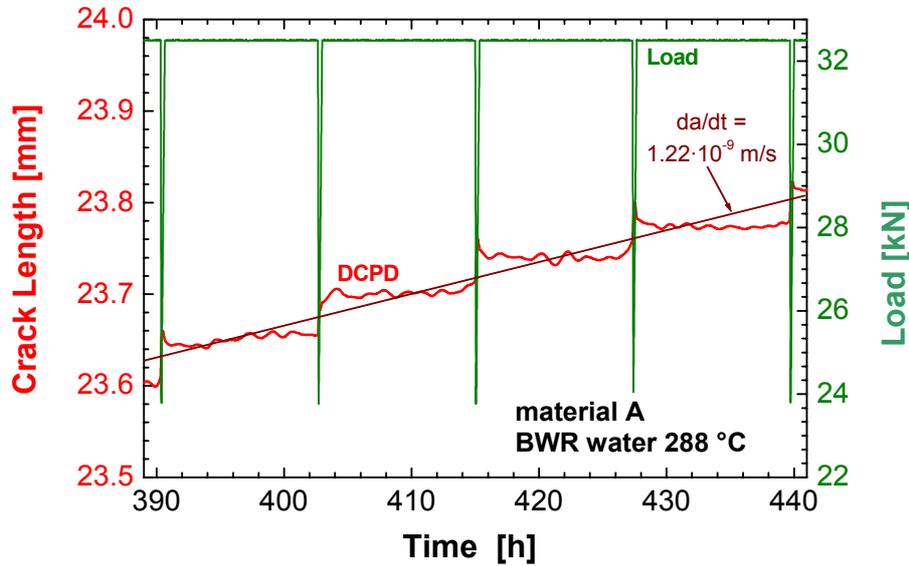
**Figure 8:** Effect of temperature on crack growth rate under low frequency fatigue in oxygenated high purity BWR water.

#### 7.2.4 Effect of load transients and frequency

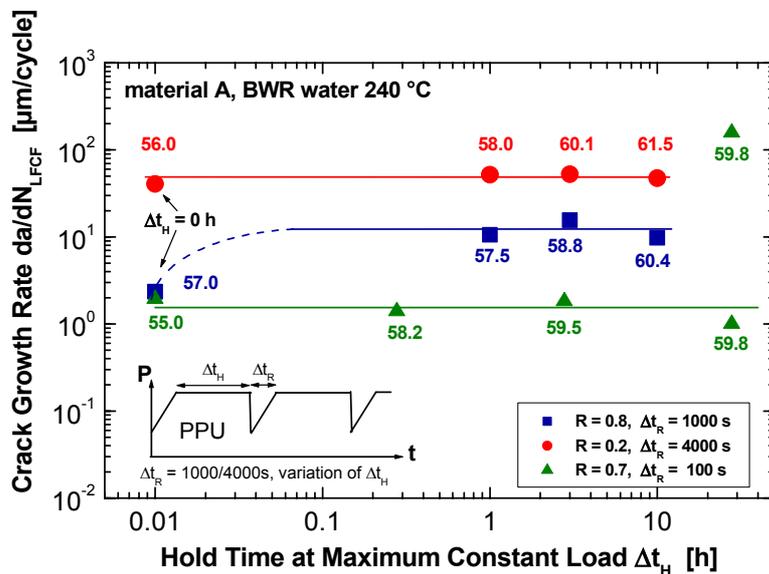
By means of the DCPD measurement technique detailed insight into the crack growth behaviour as a function of time could be obtained. Tests performed with periodical partial unloading (PPU) revealed very clearly that crack advance in high purity BWR water occurs only in the phases of rising load, example see Figure 9. Therefore it is not adequate to evaluate crack growth rates resulting from load transients on a time basis as indicated by the regression line in Figure 9, but evidently based on the number of loading events and the load steps  $\Delta K_I$ . The same processes have to be considered when tests or events are evaluated which consist of load transients with periods of differently long hold times. Figure 10 shows an example of PPU tests in which the hold time was varied from 0 to  $10^5$  s (0 to 28 h). In the test with the longest hold time, a sudden change in crack growth behaviour occurred leading to an about 100 times higher crack growth rate  $da/dN$ . However, the reason for this could not be clarified.

As long as environmentally assisted cracking under static load during the hold time period at maximum load does not occur, the low frequency corrosion fatigue (LFCF) crack

growth rate  $da/dN$  depends only on the number of loading events and thus the curve in Figure 10 must result in a horizontal line. Differences appear in the crack growth rate due to different applied R ratios ( $R = 0.2$  and  $0.8$ , respectively) and different rise times to maximum load (100 s and 1000 s, respectively). With the higher rise time (1000 s), the load increase is slower, causing a lower strain rate in the crack tip region and hence the contribution of EAC is more pronounced and results in a higher crack growth rate  $da/dN$ .

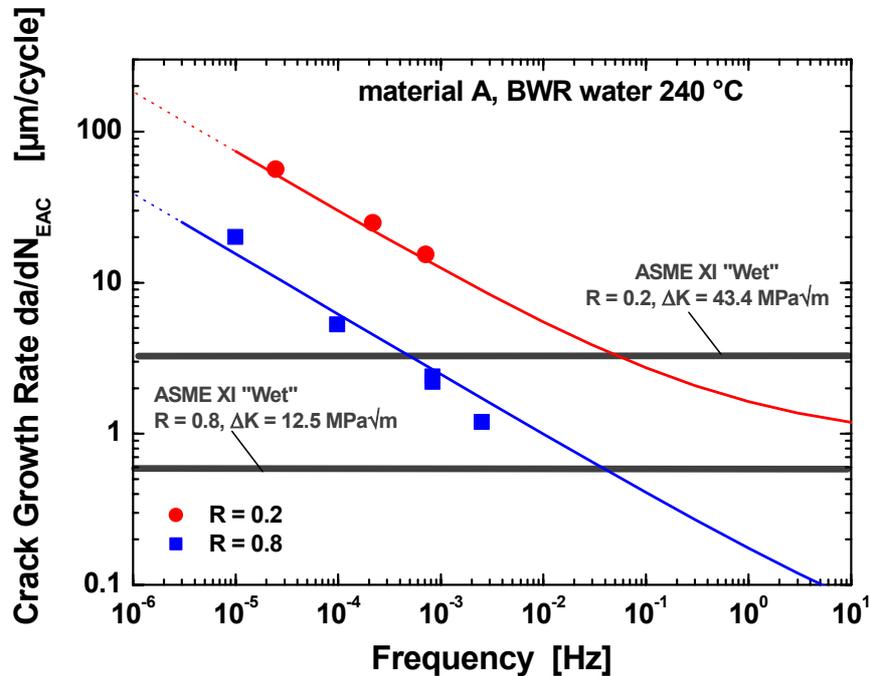


**Figure 9:** Effect of load transients (periodical partial unloading) on the crack advance during the load transient and during the hold time period; material A, high purity BWR water of 288 °C.



**Figure 10:** Effect of hold time at maximum load after a load transient (periodical partial unloading) on crack advance per reloading event; numbers in the diagram indicate the maximum stress intensity factor during the hold time.

This applies also when the loading frequency is varied. With increasing frequency the crack growth rate decreases towards the crack growth rates obtained in inert environment (air), see Figure 11. This behaviour is consistent with the basic mechanism of strain-induced corrosion cracking.



**Figure 11:** Effect of frequency on crack growth rate in oxygenated high purity BWR water of 240 °C.

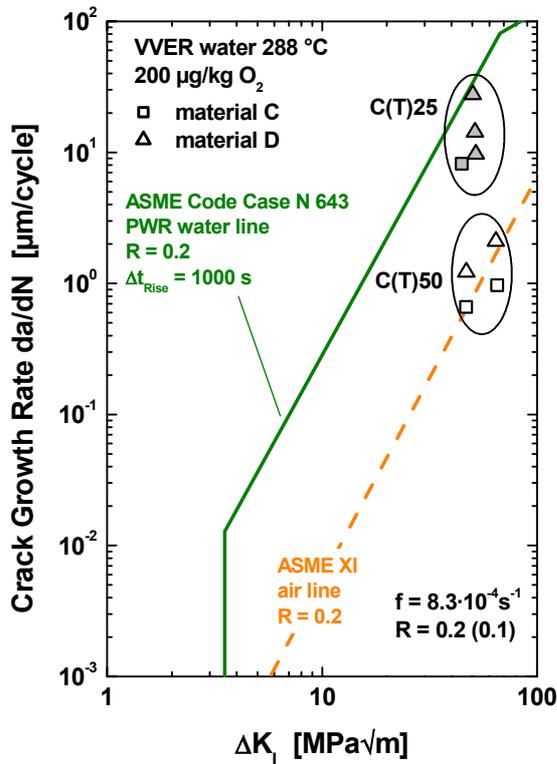
### 7.2.5 Effect of stress state

The effect of stress state in specimens and components is a key issue with regard to the transferability of EAC results as stated in chapter 6.6. Since particular equipment is needed to perform tests with large C(T) specimens or surface cracked tension specimens, only a few screening tests could be performed within this project.

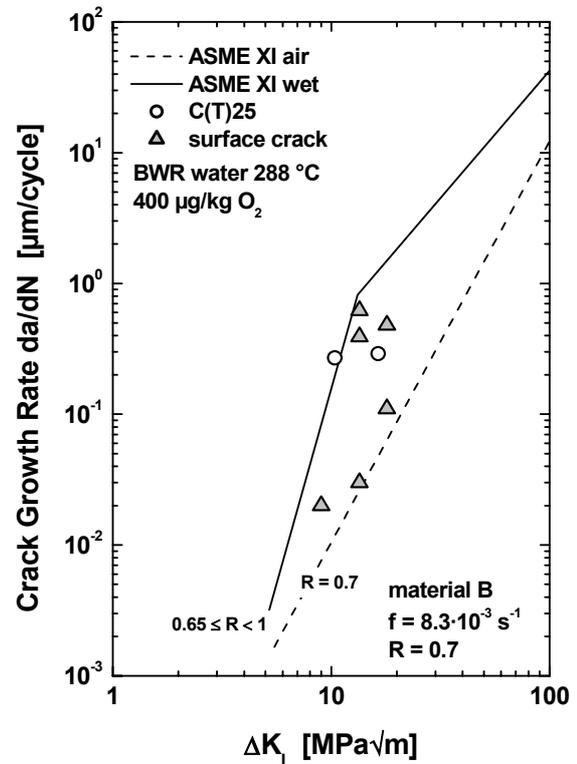
In oxygenated VVER water environment results from C(T)25 and C(T)50 specimens show a tendency of lower crack growth rates in the larger specimen by about one order of magnitude, Figure 12. The applied stress intensity factors were in the range from about 60 to 80 MPa√m for the C(T)50 specimens and from about 55 to 65 MPa√m for the C(T)25 specimens. Since for the small specimens as well as for the large specimen the ASTM criteria of specimen thickness B and size of the ligament (W – a), see chapter 6.6, were exceeded in some cases, it is not clear if the observed size effect appears due to the particular stress state or due to differences in the access of the water and its dissolved ingredients to the crack tip region. However, a major result of this investigation is that the smaller specimens tended to provide conservative crack growth rates compared to the larger ones.

To obtain complementary information about the stress state effect, a test was performed with a tension specimen containing a semi-elliptical surface flaw. The range of crack growth rates is not different from that obtained with C(T) specimens, see Figure 13. In this experi-

ment, the flow rate at the specimen surface was varied in a wide range, additionally. In contrast to data from literature [20], no effect of the flow rate was observed in this test.



**Figure 12:** Effect of specimen size (C(T)25 and C(T)50) on crack growth rate under low frequency fatigue in oxygenated VVER water of 288 °C.



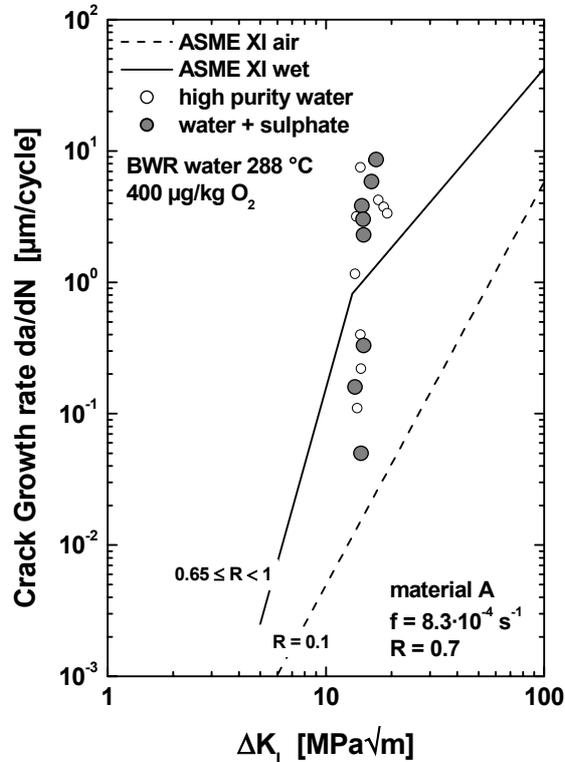
**Figure 13:** Crack growth rates of surface cracked tension specimen in comparison with results from C(T)25 specimens of material B in high purity BWR water of 288 °C.

Since in both cases – different sizes of C(T) specimens and tension specimen with surface crack – the stress state and the access of the water to the crack tip region varies, the present data obtained in this project are not sufficient to make a clear statement about the effect of stress state although significant differences in the behaviour of differently thick C(T) specimens were observed.

### 7.2.6 Effect of sulphate

The effect of sulphate in BWR water, added as  $\text{Na}_2\text{SO}_4$  and  $\text{H}_2\text{SO}_4$ , respectively, was predominantly investigated on material A. Although the sulphate content was realised up to values far beyond the onset of Action Level 3 of the EPRI Water Chemistry Guidelines according to the sulphate content of up to 1400  $\mu\text{g}/\text{kg}$ , no enhanced crack growth rates were observed, see Figure 14. This is in good agreement with model predictions and most investigations under BWR/NWC conditions known from literature [21]. In some few other experiments under BWR/NWC conditions, an accelerating effect of sulphate was observed, in particular in low frequency fatigue tests with low sulphur steels at lower corrosion potentials, where crack growth rates in high purity water were close to those measured in air. In the CASTOC experiments, however, the effect of sulphate content in the water externally added was shaded because the investigated material has relatively high sulphur content, so that the

dissolved manganese sulphides intersected by the plane of the growing crack strongly control the local water chemistry. The ranges of crack growth rate data without and with additional sulphate overlap completely and there is no tendency that crack growth data corresponding to EPRI Action Level 3 are higher than those corresponding to EPRI Action Level 1 or 2.



**Figure 14:** Effect of sulphate content in BWR water of 288 °C on the crack growth rate of material A under low frequency fatigue, sulphate content up to 150 µg/kg.

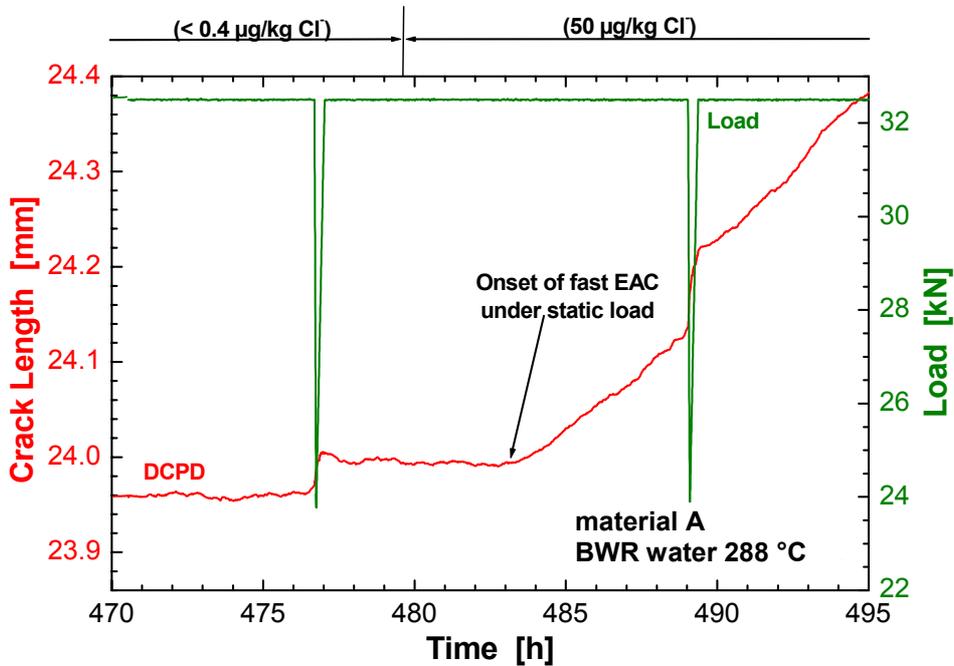
### 7.2.7 Effect of chloride

The detrimental effect of chloride on EAC of austenitic stainless steel is well established. For low alloy steel, enhancement of crack growth rate was not yet considered seriously, since the level of chloride contamination is kept very low with regard to the austenitic stainless steel and low alloy steels were considered much less susceptible to chloride effects.

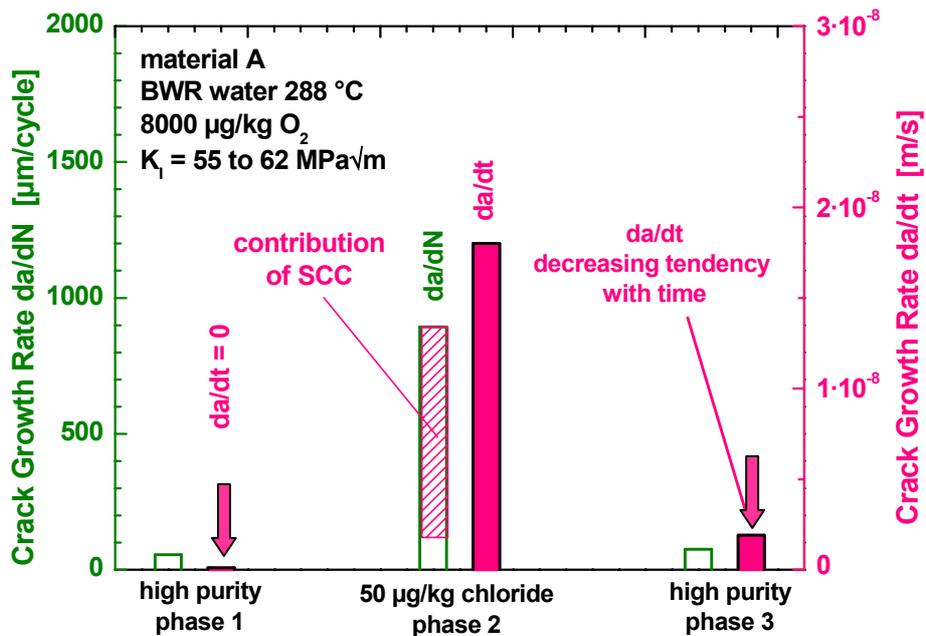
To screen the effect of chloride on low alloy steel a test with periodic partial unloading (PPU) was performed introducing a chloride transient of about 50 µg/kg for a time period of 40 h. According to the chloride content, this water condition corresponds to Action Level 2 of the EPRI Water Chemistry Guidelines, whereas the electrical conductivity, which is monitored continuously in the plant resulted in a value of about 0.27 µS/cm, which is still below EPRI Action Level 1.

Starting in BWR water of high purity but with enhanced oxygen content of about 8000 µg/kg, crack advance was observed typical for PPU tests, i.e. crack growth occurred only in phases of rising load, compare chapter 7.2.4 and Figure 9. For the test period with the chloride transient, a hold time at maximum load of 12 h was applied. After an incubation time

of about 3 h, onset of fast crack growth under static load (SCC) occurred in the specimen of material A was initiated under static load, see Figure 15, and the crack continued to grow. The specimen of material B, which was in daisy chain with the specimen of material A in the same experiment, exhibited retarded crack initiation only after 32 h, i.e. after two reloading events in chloride containing water.



**Figure 15:** Crack initiation in a C(T)25 specimen of material A during the phase of constant static load due to a chloride transient ( $50 \mu\text{g/kg}$ ) in oxygenated ( $8000 \mu\text{g/kg O}_2$ ) BWR water of  $288 \text{ }^\circ\text{C}$ .



**Figure 16:** Crack growth behaviour ( $da/dN$  and  $da/dt$ ) of material A before, during and after a chloride transient in oxygenated BWR water of  $288 \text{ }^\circ\text{C}$ .

The detailed analysis of the DCPD signal showed that the chloride transient affected both, the crack growth behaviour under static load  $da/dt$  and the crack growth rate under cyclic load  $da/dN$  determined based on the number of reloading events, see Figure 16. The crack advance  $\Delta a$  during reloading, however, was only slightly increased. This indicates that the mechanism of strain-induced corrosion cracking (SICC) which is acting during the reloading phase is not much affected by the presence of chlorides. The high value for the cycle based crack growth rate  $da/dN$  has mainly to be attributed to the mechanism of stress corrosion cracking (SCC) which occurs under static load at the level of the maximum stress intensity factor  $K_{I \max}$ .

After returning to high purity water, crack growth in the phase of constant static load was still observed, however, with strongly decreasing tendency over two more load cycles. This observation indicates that a long-term effect ("memory effect") of a chloride transient cannot be fully excluded. Similar behaviour was observed for material B but as already mentioned with retarded crack initiation, lower crack growth rate under static load and less crack advances during reloading.

### 7.3 Results from static loading

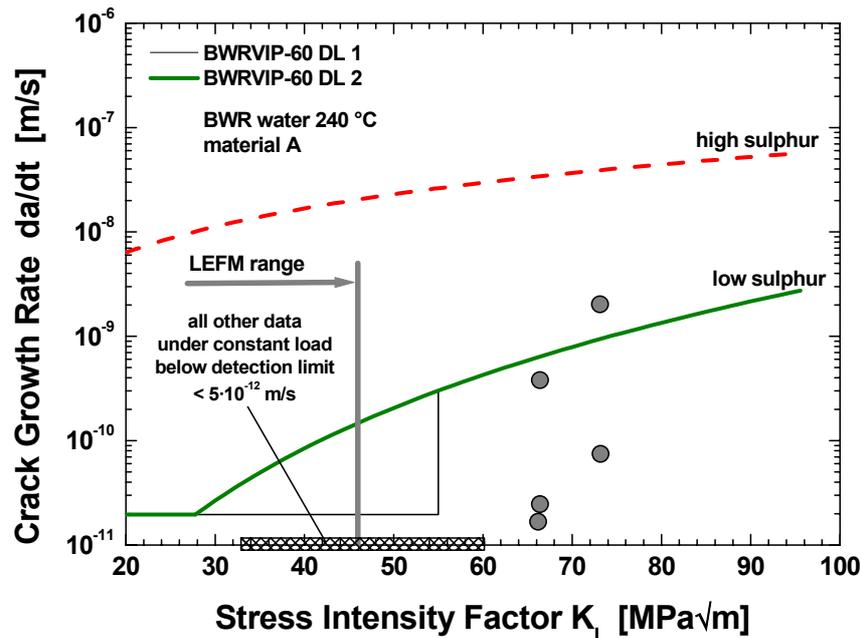
In the past, crack growth rates  $da/dt$  were not always determined from tests with pure static loading. Periodical partial unloading e.g. was used to on-line monitor EAC by compliance measurement technique. Because of limited on-line crack length measurements a variety of results were generated only from the fractographically determined crack advance after the test related to the total test time. This includes at least the crack advance from the initial loading event at the beginning of the test. The BWRVIP-60 Disposition Lines DL 1 and DL 2 [22] in general cover most of the data obtained under static load even those, which include crack advance during the initial loading phase.

For comparison purposes crack growth rate data of material A obtained from tests in high purity BWR water under constant load are displayed together with the Disposition Lines, see Figure 17.

For stress intensity factors in the range of up to about  $60 \text{ MPa}\sqrt{\text{m}}$  crack growth was not observed in any of the C(T)25 specimens, which were tested in high purity BWR water. When the stress intensity factor was increased far beyond the validity limits for LEFM continuous crack growth was observed even in high purity BWR water obviously due to yielding processes in the crack tip region. Although this plastic deformation occurs under constant static load, the EAC process may mechanistically be attributed to strain induced corrosion cracking. However, most of the data fall below the Disposition Line DL 2 [22]. These data in general are not relevant for application to thick walled pressure boundary components, which are loaded in the LEFM regime during operation, as e.g. the RPV, because the LEFM validity criteria are violated. For thin walled components, e.g. pipes, a careful assessment of LEFM applicability has to be performed depending on the load and flaw size.

The shaded range in Figure 17 shows the results from tests in the lower  $K_I$  range in which the crack growth rate was below the detection limit of the DCPD method of  $5 \cdot 10^{-12} \text{ m/s}$  ( $160 \text{ }\mu\text{m/a}$ ).

The most important result from the investigations under static load was the reproducible observation of immediate crack cessation of growing cracks after changing from cyclic loading to static load for all investigated base materials in high purity BWR water and in oxygen-free VVER water, respectively, at stress intensity factors below  $60 \text{ MPa}\sqrt{\text{m}}$ . From this, it can be concluded that the materials are not susceptible to environmentally assisted cracking under pure static load. The applied test procedure starting with an actively growing crack and immediate crack cessation at static load conditions eliminates the concern of possible incubation phases which would be impossible to simulate in short-term laboratory tests.



**Figure 17:** Crack growth behaviour of material A under constant static load in high purity BWR water of  $288 \text{ }^\circ\text{C}$ , range of plane-strain LEFM validity indicated.

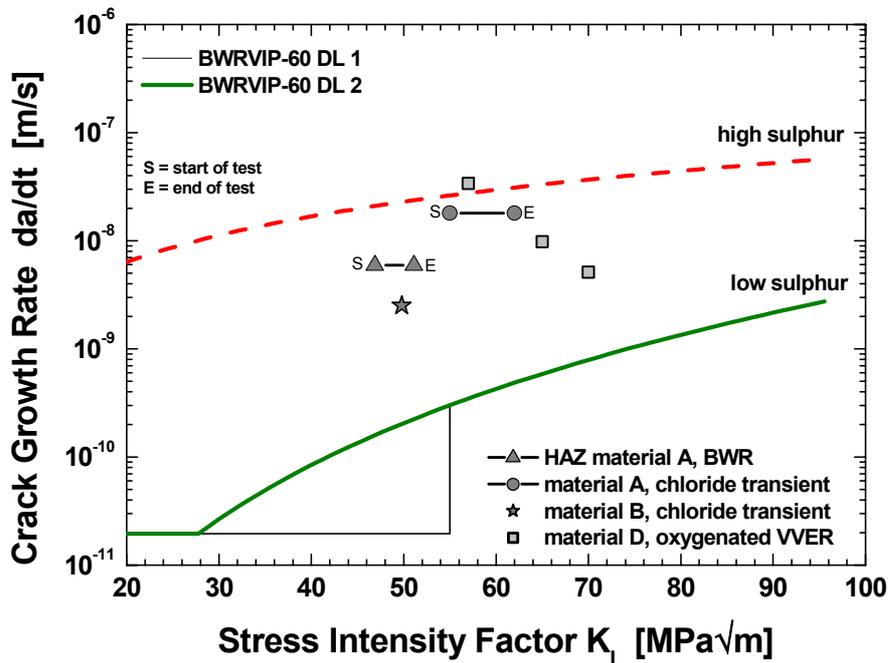
There were only few exceptions in which continuous crack advance was detected. These are described in the following sections.

### 7.3.1 Effect of material

As stated above, none of the investigated base materials showed any susceptibility to EAC under constant static load in the relevant stress intensity range and normal BWR and VVER water chemistry. This behaviour could also be confirmed for the weld metal of the joint weld in material A.

A behaviour different from that was observed in a test with a specimen from the heat affected zone (HAZ) of the joint weld in material A. Even at a stress intensity factor of  $K_I = 47 \text{ MPa}\sqrt{\text{m}}$ , using a C(T)25 specimen, sustained crack growth occurred with a crack growth rate beyond the Disposition Line DL 2, see Figure 18. Based on hardness measurements at room temperature in the base material (235 HV) and the HAZ (340 HV) and also, based on general experience, it may be concluded that the limit for plane-strain LEFM even at elevated temperature is significantly higher for the HAZ as compared to the base material.

Therefore, the applied stress intensity factor in this experiment is still supposed to fulfil the LEFM criteria.



Limits for plane-strain LEFM

$$K_{I E 399}^{C(T)25}$$

material A: 46 MPa√m  
HAZ: ≥46 MPa√m

material B: 40 MPa√m

material D: 49 MPa√m

**Figure 18:** Summary of conditions under which continuous crack growth was observed under constant static load in oxygenated high purity BWR and BWR water containing 50 µg/kg chloride and in oxygenated VVER water.

### 7.3.2 Effect of environment

As already stated, see chapter 7.2.6, additional high sulphate content in BWR water did not enhance the crack growth rate under cyclic load. The same is true for static load. In the relevant range of stress intensity crack cessation occurred in all cases even at a sulphate concentration corresponding to Action Level 3 of the EPRI Water Chemistry Guidelines.

Enhanced oxygen content in VVER water of 200 µg/kg led to continuous crack growth in C(T)25 specimens of material D when the mode of loading was changed from cyclic to static load even at stress intensity factors slightly below 60 MPa√m. This behaviour was not observed in tests with C(T)50 specimens under similar conditions. Even at stress intensity factors of up to 90 MPa√m, C(T)50 specimens showed immediate crack cessation. The results show at least that the smaller specimens tend to provide more conservative results. Since the applied stress intensity factors were partly in a range where the criteria for LEFM are exceeded for both specimen sizes, it may be considered that both EAC processes strain induced corrosion cracking and stress corrosion cracking may have been acting in the C(T)25 specimens of material D in combination with some load fluctuations during the phase of static load. A significant number of regions showing intergranular fracture were observed in material D that might be a specific feature of this particular heat and may not necessarily be a characteristic feature of this type of steel.

Clear evidence of crack growth under static load was obtained from tests with materials A and B when introducing a chloride transient. According to the chloride content, the conditions corresponded to Action Level 2 of the EPRI Water Chemistry Guidelines but the electrical conductivity was still in the range below Action Level 1. Crack initiation occurred during the phase of static load after a relatively short incubation time of 3 h and 32 h, respectively, compare chapter 7.2.7 of this report. The crack growth rate  $da/dt$  significantly exceeds the Disposition Line DL 2, see Figure 18. For material A at a stress intensity factor of about  $55 \text{ MPa}\sqrt{\text{m}}$  a crack growth rate of  $1.8 \cdot 10^{-8} \text{ m/s}$  (570 mm/a) was determined. Material B showed a longer incubation time and lower crack growth rate under static load of  $2.5 \cdot 10^{-9} \text{ m/s}$  (80 mm/a). Details are already shown in chapter 7.2.7 and Figure 15 and 16. After returning to high purity water, a decreasing tendency of the crack growth rate with some delay was observed indicating a kind of "memory" effect due to the residence time of the chloride ions in the crevice.

Figure 18 shows also crack growth rate data of material D, tested in oxygenated VVER water, although the Disposition Lines should only be considered with regard to BWR water conditions. This comparison, however, displays the only case for which crack growth under static load was observed in the Russian type steel D at moderate stress intensity factors.

### 7.3.3 General conclusions from static load tests

For the assessment of the EAC behaviour of thick walled components, which fulfil the LEFM criteria under operational load, crack growth rates from experiments with specimens fulfilling the same criteria may be transferred without further consideration. Consequently there is no concern with respect to EAC under static load for the investigated typical RPV base materials up their individual linear elastic limit load for plane-strain conditions (e. g.  $46 \text{ MPa}\sqrt{\text{m}}$  for C(T)25 specimen of material A). Even for stress intensity factors up to  $57 \text{ MPa}\sqrt{\text{m}}$ , which is a slight overload based on LEFM criteria from ASTM E 399, crack growth was not observed in base materials A and B, which complies with the BWR VIP-60 Disposition Line DL 1 for steady state operation.

The use of crack growth rates from clearly "overloaded" specimens is also possible, since they are conservative, however this may create overconservatism. For component assessment it has to be clarified whether this data have to be considered in relation to the stress state of the component.

Regarding the range of stress intensity factors below  $57 \text{ MPa}\sqrt{\text{m}}$  there were only a few cases of continuous crack growth under static load, which are summarised in Figure 18:

- During the chloride transient applied to material A and B crack initiation and continuous crack growth occurred in the phase of static load
  - Continuous crack growth after changing from cyclic loading to static load was observed in high purity BWR water in case of the HAZ of the joint weld of material
  - It should also be noted that rates for continuous crack growth observed in oxygenated VVER water in case of material D exceed the current BWRVIP-60 Disposition Line
- All other tests performed in this stress intensity range showed immediate crack cessation when changing from cyclic to static load

## 8 Consequences for practical application

The CASTOC project, supported by the present state-of-the-art knowledge on EAC, has given more insight into both the phenomenology and the acting mechanisms on corrosion cracking in BWR and VVER water environment and the effect of transients. However, due to the limited number of tests in this complex field critical thresholds for the effect of single parameters could not be established in a satisfactory way in all cases. There are some effects which now are well understood, some for which a tendency in material behaviour could clearly be recognised and some for which no clear trends could be established.

- Items well understood:
  - \* crack growth under cyclic load and effect of frequency and periodic partial unloading (load transients)
  - \* crack growth and crack cessation under static load
  - \* crack growth in combination with transients in BWR water chemistry caused by addition of sulphates and chlorides
- Items for which a tendency in material behaviour could clearly be recognised:
  - \* effect of oxygen in VVER water environment
  - \* behaviour of the HAZ of a joint weld
  - \* effect of specimen size
- Items for which no clear trends could be established:
  - \* effect of temperature
  - \* behaviour of surface cracked tension specimens without and with austenitic stainless steel cladding in conjunction with different water flow rates
  - \* effect of stress state outside the range of LEFM

Nevertheless, regarding the application of the results from the CASTOC project for the assessment of components in LWRs, the following aspects shall be considered:

- Low alloy steel base materials for RPV application revealed resistance to crack growth under constant static load up to stress intensity factors of about  $60 \text{ MPa}\sqrt{\text{m}}$  in BWR and VVER normal water chemistry. The proposed BWRVIP-60 Disposition Line for steady state conditions was essentially confirmed for base materials.
- The observed crack growth behaviour is consistent with plant experience in general, and especially in those cases, where austenitic stainless steel cladding is not applied or was removed deliberately or by chance. Examples for such incidences are:
  - \* nozzles in some BWR plants in Europe (e.g. Switzerland) and in the U.S.A., which are without cladding
  - \* nozzles in PWR plants in Germany with partially removed cladding
  - \* uncladded RPVs in some VVER plants
- Under certain environmental and material conditions, however, experimental results from tests performed under static load give reason for a more careful consideration of

the assessment of components. The screening experiments of this project revealed crack growth under constant load for the following conditions:

- \* heat affected zone of the joint weld of material A
  - \* material D in oxygenated VVER water
  - \* materials A and B during environmental transient with chloride
- The proposed BWRVIP-60 Disposition Line DL 1 for crack growth under steady state conditions was essentially confirmed. With respect to the Disposition Line DL 2 for transients in load, however, further consideration is recommended based on the results of this project.
  - The project has clearly shown that different laboratories can achieve similar results (e.g. da/dt) or at least similar trends (e.g. da/dN). The scatter in the case of da/dN observations were mainly attributed to inhomogeneities in the tested material in combination with rather small crack increments in some cases, which lead to higher uncertainties in the crack growth rate data. The crack increments during the test periods from which da/dN data are displayed in the Figures range from about 30  $\mu\text{m}$  to more than 1000  $\mu\text{m}$  in some cases.  
However, based on data which are considered to be reliable with regard to the requirements for measurement accuracy (crack advance  $\Delta a > 0.2$  mm, see Figure 1 and 2), the project has revealed the general trend that the existing prediction curve presented in the ASME Boiler and Pressure Vessel Code, Section XI, Appendix A for da/dN assessment of existing flaws in low alloy steels may not be conservative under specific conditions, e.g. low loading frequencies, since the observed crack growth rates at low frequency cyclic loading exceeded the maximum rates of the Code. In contrary to that, the curves provided in the ASME Code case 643 for PWR water environment cover fairly well the data obtained in VVER environment for Russian type steels even at increased oxygen content.
  - Care has also to be taken concerning the transferability of data to service components. The applicability has to be checked and proved with respect to material, mechanical, chemical/electrochemical and stress state aspects.

The CASTOC results have provided an important contribution to the understanding of crack growth behaviour on the one hand as a function of time and on the other hand as a consequence of the number and height of loading events. This is an important key for the evaluation of transient events, which may occur in a plant.

## 9 References

- [1] J. Föhl, U. Ehrnstén, M. Ernestová, D. Gómez-Briceño, J. Lapeña, S. Ritter, A. Roth, B. Devrient, H.P. Seifert, T. Weissenberg, M. Žamboch, "Crack growth behaviour of low alloy steel for pressure boundary components under transient light water reactor operating conditions – CASTOC", FISA Conference on EU Research in Reactor safety, Luxembourg, November 12-14, 2001.
- [2] Föhl, J., U. Ehrnstén, M. Ernestová, D. Gómez-Briceño, J. Lapeña, S. Ritter, A. Roth, B. Devrient, H.P. Seifert, T. Weissenberg, M. Žamboch, "Crack Growth Behaviour of Low-Alloy Steels for Pressure Boundary Components under Transient Light Water Reactor Operating Conditions – CASTOC", FISA Conference on EU Research in Reactor Safety, Luxembourg, November 10 – 12, 2003.
- [3] D. Blind, F. Hüttner, A. Wünsche, K. Küster, H.P. Seifert, A. Roth, P. Karjalainen-Roikonen, U. Ehrnstén, "European Round Robin on Constant Load EAC Test of Low Alloy Steel under BWR Conditions", Proc. 9<sup>th</sup> Int. Conf. on Env. Deg. of Materials in Nuclear Power Systems – Water Reactors, Newport Beach, CA, 1999, pp. 911-919.
- [4] V. Läßle, D. Blind, P. Deimel, "Stand der Forschung zum korrosionsgestützten Risswachstum niedriglegierter ferritischer Stähle in sauerstoffhaltigem Hochtemperaturwasser", VGB Kraftwerkstechnik, 77, 1997, pp. 754-761.
- [5] F. P. Ford, R. M. Horn, J. Hickling, R. Pathania, G. Brümmer, "Stress Corrosion Cracking of Low Alloy Steels under BWR Conditions; Assessment of Possible Crack Growth Rate Algorithms", Proc. 9<sup>th</sup> Int. Conf. on Env. Deg. of Materials in Nuclear Power Systems – Water Reactors, Newport Beach, CA, 1999, pp. 855-864.
- [6] U. Ehrnstén, "Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components Under Transient Light Water Reactor Operating Conditions", EU project CASTOC", Technical Report WP1, 2002.
- [7] J. Lapeña, D. Gómez-Briceño, "Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components Under Transient Light Water Reactor Operating Conditions", EU project CASTOC", Technical Report WP2, (2003).
- [8] Cheng, B., J. Gilman, L. Nelson, R. Pathania, C. Wood, "BWR Water Chemistry Guidelines – 1996 Revision", EPRI Report TR-103515-R1, Palo Alto, December 1996.
- [9] M. Žamboch, J. Föhl, "Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components Under Transient Light Water Reactor Operating Conditions", EU project CASTOC", Technical Report WP3, 2003.
- [10] A. Roth, B. Devrient, J. Föhl, "Crack Growth Behaviour of Low Alloy Steels for Pressure Boundary Components Under Transient Light Water Reactor Operating Conditions", EU project CASTOC", Technical Report WP4, 2003.
- [11] U. Staud, M. Lasch, "Die VGB-Richtlinie für Chemie in SWR-Anlagen – aktueller Stand"; VGB-Konferenz "Chemie im Kraftwerk 1995", VGB-Speisewassertagung 1995, Vortrag KKW3.
- [12] J. Kysela, G. Brümmer, H. Hoffmann, F. Hüttner, U. Ilg, O. Wachter, M. Widera, A. Brozova, M. Ernestová, M. Postler, J. Burda, R. Vsolak, "Investigation on Environmentally Assisted Cracking (EAC) Behaviour of a Ferritic Reactor Pressure Vessel Steel under Simultaneous Influence of Simulated BWR Coolant and Irradiation"

- 11<sup>th</sup> Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Stevenson, WA, USA, August 10 – 14, 2003.
- [13] ASTM E 399, "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials".
- [14] ASTM E 647, "Standard Test Method for Measurements of Fatigue Crack Growth Rates".
- [15] ASTM E 1681, "Standard Test Method for Determining a Threshold Stress Intensity Factor for Environment-Assisted Cracking of Materials under Constant Load".
- [16] U. Ehrnstén, D. Gómez-Briceño, J. Lapeña, M. Ernestová, M. Žamboch, S. Ritter, H.P. Seifert, A. Roth, J. Föhl, F. Hüttner, T. Weissenberg, "Inter-laboratory crack growth test on pressure vessel steel 20MnMoNi5-5 in simulated BWR environment", 11<sup>th</sup> Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Stevenson, WA, USA, August 10 – 14, 2003.
- [17] ASME Boiler and Pressure Vessel Code, Section XI, "Rules for In-service Inspection of Nuclear Power Plant Components", Appendix A, Article A-4000, "Material Properties".
- [18] Cases of ASME Boiler & Pressure Vessel Code, Case N-643; "Fatigue Crack Growth rate Curves for Ferritic Steels in PWR Water Environment", Section XI, Division 1, May 2000.
- [19] A. Roth, et al., "Experimental investigations concerning the possible effect of dynamic strain ageing in the environmentally assisted cracking of low alloy steels in oxygenated high temperature water", 29. MPA Seminar on safety and reliability in energy technology, Stuttgart, October 09 and 10, 2003.
- [20] E. Lenz, N. Wieling, H. Münster, "Influence of Variation of Flow Rates and Temperature on the Cyclic Crack Growth Rate under BWR Conditions", Proc. 3<sup>rd</sup> Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Traverse City, Michigan, USA, August 30 – September 03, 1988, pp. 283 – 288.
- [21] H.P. Seifert, S. Ritter, J. Hickling, "Environmentally Assisted Cracking of Low Alloy RPV and Piping Steel under LWR Conditions", 11<sup>th</sup> Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Stevenson, WA, USA, August 10 – 14, 2003.
- [22] BWR Vessel and Internals Project, "Evaluation of Stress Corrosion Crack Growth in Low Alloy Steel Vessel Materials in BWR Environment (BWRVIP-60)" EPRI technical Report TR 108709 1999.