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# Crack Growth Behaviour of Low-Alloy Steels for Pressure Boundary Components under Transient Light Water Reactor Operating Conditions – CASTOC, Part II: VVER Conditions

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## 1 Abstract

One of the ageing phenomena of pressure boundary components of light water reactors (LWRs) is environmentally-assisted cracking (EAC). The project CASTOC ($5^{th}$ Framework Programme of the EU) was launched September 2000 with six European partners and terminated August 2003. It focused in particular on the EAC behaviour of low-alloy steels (LAS) and to some extent to weld metal, heat affected zone and the influence of an austenitic cladding. The main objective was directed to the clarification of crack growth behavior of LAS in high-temperature water due to EAC under constant load (steady-state power operation), to study the effect of transient conditions (during operation or start-up/shut-down of a plant) using their impact on time-based and cycle-based crack growth rates and to a more detailed understanding of the acting mechanisms. Autoclave tests were performed with Western and Russian type reactor pressure vessel steels under simulated boiling water reactor (BWR)/normal water chemistry (NWC) and pressurized water reactor (VVER) conditions. The investigations were performed with fracture mechanics specimens of different sizes and geometries. The applied loading comprised cyclic loads, static loads and load spectra where the static load was periodically interrupted by partial unloading. With regard to water chemistry, the oxygen content (VVER) and impurities of sulphate and chlorides (BWR) were varied beyond allowable limits for continuous operation.

The current paper summarizes the most important crack growth results obtained under simulated VVER conditions. The influence of oxygen content and the effect of specimen size (C(T)25 versus C(T)50 specimens) on the crack growth rates are shown. The results are discussed in the context of the current crack growth rate curves in the corresponding nuclear codes.

**Keywords:** Environmentally-assisted cracking, corrosion fatigue, stress corrosion cracking, low-alloy steels, VVER conditions.

## 2 Introduction

Ageing of pressure boundary components is one of the main factors controlling the lifetime of nuclear power plants. EAC under certain circumstances can be one of the major ageing mechanisms of LAS in high-temperature water. The project "Crack Growth Behaviour of Low-Alloy Steels for Pressure Boundary Components under Transient Light Water Reactor

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Operating Conditions" (CASTOC), was performed within the 5$^{th}$ EC framework programme and addressed the problem of EAC of Western and Eastern type steels used for pressure boundary components [1, 2].

The objective of the CASTOC project was to screen the EAC behaviour of low-alloy reactor pressure vessel (RPV) steels in high-temperature water during transients of load and water chemistry that may occur during start-up and shut-down, steady-state operation and load following mode of commercially operating LWRs. This is in contrast to the worldwide activities in the past, which focused mainly on either cyclic loading or static loading and steady-state operating conditions. The main focus of the project was directed to the interaction between static and cyclic loading which was realised, e.g., by low frequency corrosion fatigue (LFCF) phases followed by static load or by periodical partial unloading (PPU) with different rise and hold times. In conjunction with the different load spectra, the effect of transients in water chemistry was investigated. A more detailed description of the project is available in [1] and [2].

The results of the project should in particular be assessed with respect to quality, reliability and their 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. With regard to the specific situation in Europe, the materials and water environment conditions were chosen to address both the concerns of BWRs and VVERs.

In the current paper only some important crack growth results obtained in simulated VVER environment on materials representing VVER RPVs are presented. The main focus of the tests performed in VVER environment was directed to the crack growth rate (CGR) data during cyclic and static loadings and to investigate the effect of materials, oxygen content and the effect of different constraint situations realised by different specimen size. The tests were performed at NRI within the CASTOC project subsequently after the inter-laboratory comparison test. The results of the tests performed under simulated BWR/NWC conditions are summarised in [3]. For a detailed description of all results see [4 – 8].

## 3 Experimental Procedure

The tests performed within the CASTOC project comply with the current state-of-the-art knowledge of science and technology in laboratory testing of EAC processes. The investigated materials represent nuclear grade materials. With regard to the selected environmental conditions, enveloping parameters were applied.

### 3.1 Materials

The ferritic LAS 15Ch2MFA (material C) and 15Ch2NMFA (material D), used as RPV steels at VVER 440 and VVER 1000, respectively, were investigated under simulated VVER conditions. The chemical composition are summarized in Tab. 1. The steels were quenched and tempered followed by air cooling [6]. Both base materials have a fine-grained bainitic microstructure. Mechanical properties are given in Tab. 2.

- **Material C, base material:** Forged plate 15Ch2MFA (thickness of the plate 140 mm), fabricated according to nuclear grade quality with enhanced sulphur content.
- **Material D, base material:** Forged plate 15Ch2NMFA (thickness of the plate 320 mm), fabricated according to nuclear grade quality.

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***Table 1:*** *Chemical composition( in wt.%) of the investigated materials.*

| Base material | Chemical composition [wt.%] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | P | S | Ni | Cr | Mo | Cu | V | Co | As |
| **Material C** | 0.15 | 0.40 | 0.24 | 0.013 | 0.015 | 0.30 | 2.78 | 0.64 | 0.08 | 0.29 | 0.009 | 0.011 |
| **Material D** | 0.14 | 0.45 | 0.25 | 0.009 | 0.007 | 1.23 | 2.15 | 0.57 | 0.05 | 0.08 | * | * |

* not determined

***Table 2***: *Mechanical properties of the investigated materials.*

| | Temperature [°C] | $R_p0.2$ [MPa] | $R_m$ [MPa] | $A_5$ [%] | RA [%] |
|---|---|---|---|---|---|
| **Material C** | 20 | 545 | 651 | 22.6 | 75.0 |
| | 350 | 469 | 544 | 17.8 | 75.0 |
| **Material D** | 22 | 570 | 674 | 19.7 | 75.3 |

### 3.2 Specimen preparation

The C(T)25 and C(T)50 samples were manufactured from forged plates, material C specimens in L-S direction and material D specimens in S-L direction. The specimen had been pre-cracked in air using parameters which fulfill the demand of ASTM E399, 1990 to the final $a_0/W \sim 0.5$.

### 3.3 Experimental Facilities

The test equipment at NRI consists of a heated autoclave vessel with an integrated bellow system to apply the mechanical load, a water refreshing system to adjust desired water conditions, the high pressure pump, and measuring equipment to control the water chemistry [6]. The autoclave has the capacity to install either two C(T)25 or C(T)50 specimens in a daisy chain, whereas each specimen is galvanostatically isolated by ceramic and mica spacers.

The laboratory test unit enables control of the water and loading conditions. The reversed direct current potential drop (DCPD) system for on-line crack length monitoring was used. The detection limit of the DCPD technique is of the order of 10 µm. On-line monitoring was performed on load, pressure and temperature. The outlet conductivity and defining the outlet oxygen concentration as the target value of oxygen were measured continuously. The external Ag/AgCl/deionate reference electrode and a platinum probe were used for continuous measurement of the corrosion and redox potentials.

### 3.4 Testing Procedure and Environment

Each autoclave test was divided into a stabilisation phase covering the time needed for heating and pressurizing the autoclave (of about 100 h) and a conditioning phase taking at least 100 h at stable conditions before the test phase was started by fatigue loading followed by constant loading. The main objective of the fatigue loading part of the test was to create an actively growing crack before switching to constant load, and to investigate, whether sustained crack growth occurs at desired K value in simulated VVER water.

Normal operation of VVER reactors is characterized by very low oxygen concentration (< 10 µg/kg). In order to investigate the effect of higher oxygen levels – e.g. as residual oxygen after reactor start-up or as a result of oxygen ingress during power operation – the tests were performed in oxygenated (~ 200 µg/kg) or oxygen-free (< 20 µg/kg) water with boric acid at 288 °C to generate conservative data with respect to plant conditions. The VVER water chemistry parameters are listed in Tab. 3.

*Table 3: Water chemistry parameters in simulated VVER water.*

| Boric acid | Potassium hydroxide | Ammonia | Conductivity (in the outlet) | $O_2$ concentration (in the outlet) |
|---|---|---|---|---|
| 6.8 g/kg | 23.5 mg/kg | 20 mg/kg | ~130 µS/cm | < 20 µg/kg or ~ 200 µg/kg |

The aim of the project was to obtain the data at stress intensity factor levels outside the range of linear elastic fracture mode (LEFM). The testing procedure included loading of the specimens to a stress intensity ranging from 56 to 88 MPa√m starting of fatigue loading using a positive saw tooth waveform with a rise time of 1000 s and a decline time of 200 s (f = $8.3 \cdot 10^{-4}$ $s^{-1}$) and a load ratio of R = 0.1, 0.2 or 0.8. After the crack activation, constant load was applied for at least 300 h.

After termination of the autoclave testing the cracks were opened at liquid nitrogen temperature. The pre-crack length $a_0$ and EAC advance were measured at 25/50 (C(T)25/C(T)50) equidistant locations on fracture surface along the notch. Fracture surface investigations were performed before and after electrochemical cleaning using scanning electron microscope.

# 4 Results and Discussion

## 4.1 Results from Cyclic Loading

The CGRs obtained from the experiments were compared with the prediction line of the ASME Boiler and Pressure Vessel Code Case N 643, Section XI, Div. 1 [9]. In this Code Case the prediction line is determined by a threshold value in $\Delta K_I$, the load ratio R and the rise time $\Delta t_r$ of the cycle. Despite the fact that the Code Case was established from Western type PWR water environment, the data obtained from tests in simulated VVER environment within this project are compared with the Code Case prediction line. The crack growth rates in µm/cycle have been calculated using the average crack increment for cyclic test period, the amount of cycles and the rise time.

### *4.1.1 Effect of Material*

The tested materials differentiate in sulphur, chromium, phosphorus and vanadium content. Although material C has a higher sulphur content (0.015 wt.%) compared to material D (0.007 wt.%) the CGRs of material D tend to be higher than those of material C under comparable conditions (Fig. 1 and 2). This observations indicates that the sulphur content of the steel is not the sole material parameter controlling EAC.

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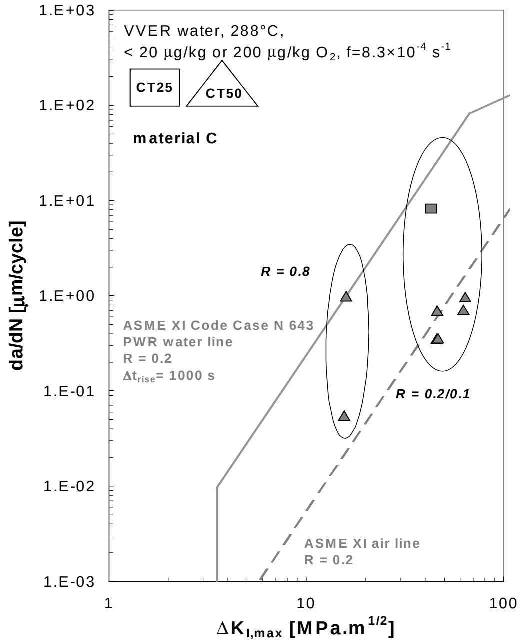


**Figure 1:** *CGRs of material C at a frequency of 8.3·10$^{-4}$ s$^{-1}$ in oxygenated and oxygen-free VVER water of 288 °C.*

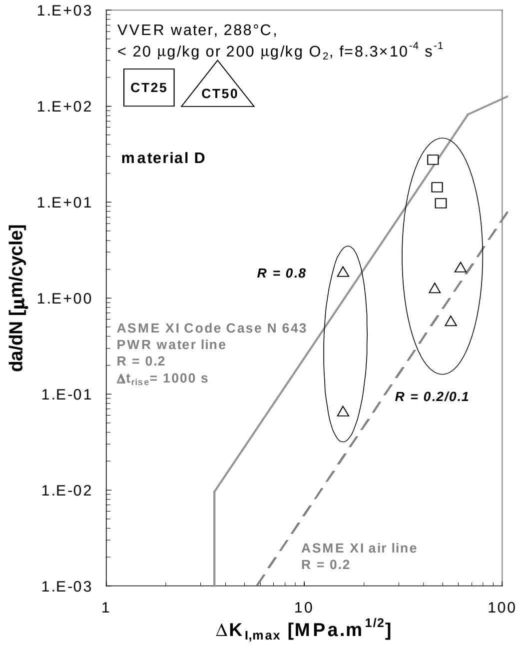


**Figure 2:** *CGRs of material D at a frequency of 8.3·10$^{-4}$ s$^{-1}$ in oxygenated and oxygen-free VVER water of 288 °C.*

### *4.1.2 Effect of Oxygen Content*

The effect of dissolved oxygen in VVER water environment on the crack growth behaviour can be established only from the tests performed with C(T)50 specimens. At low loading ratio (R = 0.2 and R = 0.1) the CGRs tend to be slightly higher in oxygenated water than in oxygen-free water. At the higher loading ratio (R = 0.8) the CGRs in water with enhanced dissolved oxygen content were more than one order of magnitude higher than in oxygen-free environment (Fig. 3 and 4).

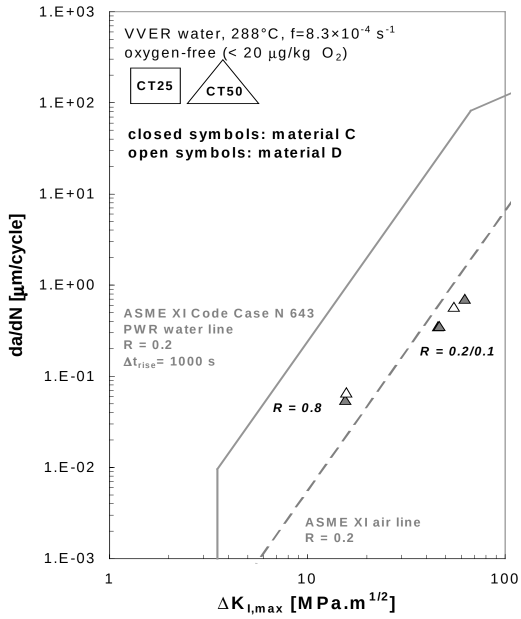


**Figure 3:** *CGRs of material C and D at a frequency of 8.3·10$^{-4}$ s$^{-1}$ in oxygen-free VVER water of 288 °C.*

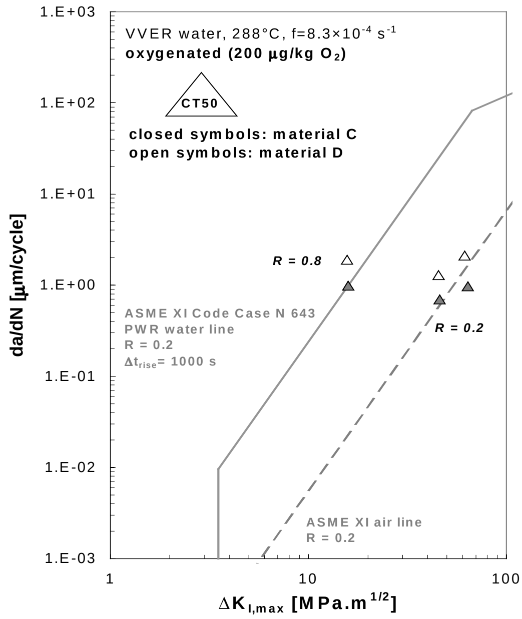


**Figure 4:** *CGRs of material C and D at a frequency of 8.3·10$^{-4}$ s$^{-1}$ in oxygenated VVER water of 288 °C.*

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### *4.1.3 Effect of Specimen Size*

The effect of specimen size can be evaluated from the tests performed in oxygenated water with loading ratio of 0.2 and 0.1, respectively (Fig. 5). It becomes obvious that the crack growth per cycle in small C(T)25 specimen is about one order of magnitude higher than that of the large C(T)50 specimen for both materials. This might be caused by higher plastic deformation in the crack tip area of the smaller specimen in particular at the low load ratio R since the prevailing mechanism is strain induced corrosion cracking. With regard to the transferability of laboratory results to the large component the smaller specimens obviously provide more conservative data.

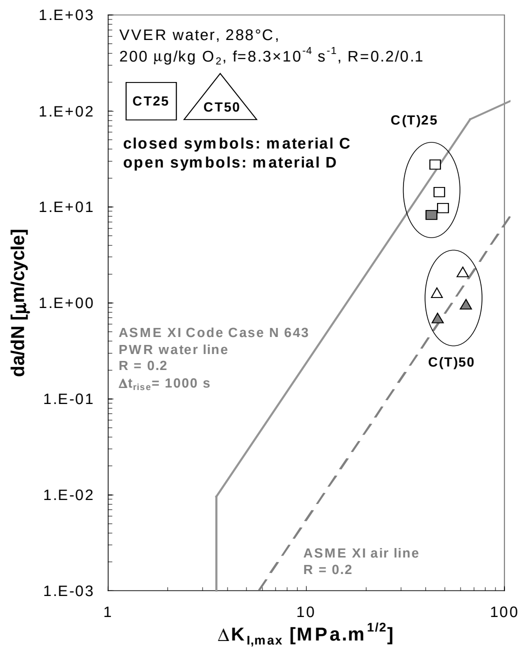


***Figure 5:*** *CGRs of material C and D at a frequency of $8.3\cdot10^{-4}$ $s^{-1}$ in oxygenated VVER water of 288 °C; C(T)25 and C(T)50 specimens.*

## 4.2 Results from Constant Loading

Although the BWRVIP-60 SCC Disposition Lines (DL) [10] apply to BWR/NWC conditions the da/dt obtained from the experiments were compared to these DLs. In most of the tests the crack, activated during cyclic loading, arrested after switching to static load. There were only few exceptions in which continuous crack advance was detected under static load. The crack growth rates da/dt have been calculated using the average crack increment for static test period and the whole period time.

### *4.2.1 Effect of Material*

The corrosion fatigue crack activated by cyclic loading arrested after the change to constant static load during all tests in oxygenated (~ 200 µg/kg) and oxygen-free (< 20 µg/kg) simulated VVER water performed with C(T)25 and C(T)50 specimens from material C. During the test phases at static load of at least 300 h duration no crack growth could be detected at the applied stress intensity factors ranging from 56 to 88 MPa√m.

Concerning the material D, the corrosion fatigue crack, activated by cyclic loading, arrested after switching to constant static load during all tests performed on C(T)50 specimens in

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oxygenated and oxygen-free simulated VVER water. Similar to the behaviour of material C no crack growth was observed during the phases of static load. However, crack growth under static load was observed in C(T)25 specimens tested in oxygenated VVER water at stress intensity factors in the range from 58 to 70 MPa√m.

For comparison the results are displayed together with the BWRVIP-60 SCC DLs in Fig. 6. For stress intensity factors in the range of up to about 56 MPa√m crack growth was not observed in any of the specimens of material C and in any of the C(T)50 specimens of material D, which were tested in oxygenated and oxygen-free VVER water. When during the constant load period the stress intensity factor was increased beyond the validity limits for linear elastic fracture mode (LEFM) continuous crack growth was observed on C(T)25 specimens of material D in oxygenated VVER water and the da/dt data (~$10^{-8}$ m/s) are higher than the ones expected from DL 2.

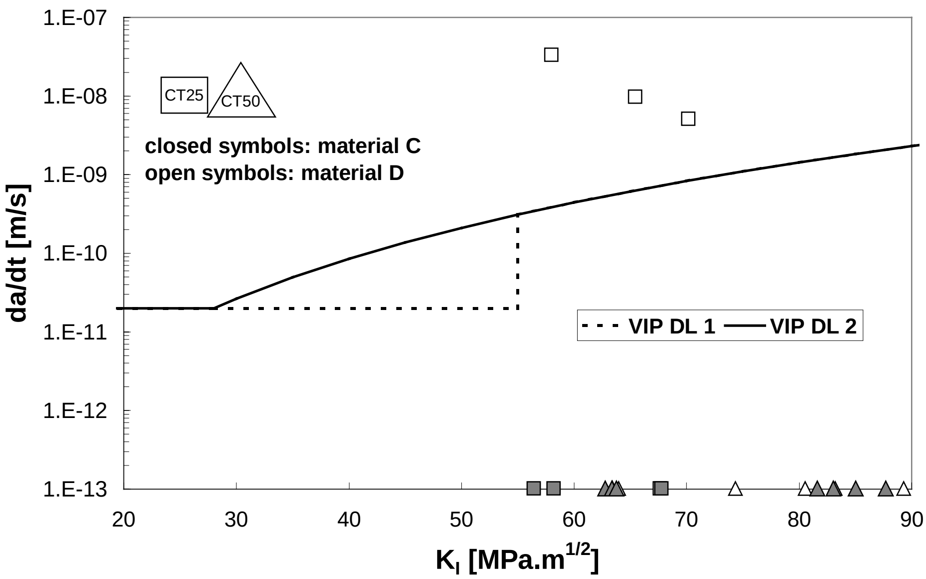


**Figure 6*:*** *Crack growth behaviour of material C and D under constant static load in oxygenated and oxygen-free VVER water of 288 °C; the data bellow detection limit ~ $10^{-13}$ m/s.*

The investigation of the fracture surfaces on C(T)25 specimens of material D which showed crack growth under static load revealed a small portion of intergranular (IG) cracking during cyclic phase and high portion of IG cracking during the constant load phase (Fig. 7).

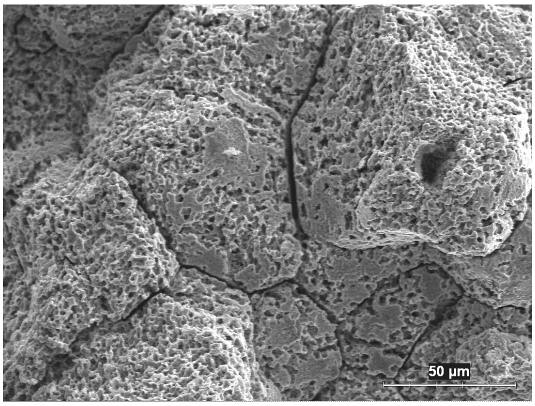


***Figure 7:*** *Typical intergranular attack in C(T)25 specimen of material D tested in oxygenated VVER water environment of 288 °C.*

#### *4.2.2 Effect of Oxygen*

The effect of oxygen could not be demonstrated on material C and D in VVER water because of crack arrest on most of the specimens. The only possibility give the da/dt data obtained on C(T)25 specimens of material D in oxygenated (~ 200 µg/kg) VVER water which could be compared with data in oxygen-free VVER water. The ongoing test with C(T)25 specimens of C and D materials in oxygen-free VVER water is out of the CASTOC project and will document the possible effect of oxygen.

#### *4.2.3 Effect of Specimen Size*

The effect of specimen size on the crack growth rate under static load could not be clearly demonstrated. In tests with material C no crack growth was observed for both specimen sizes and in material D crack growth was only detected in C(T)25 specimens, however associated with IG cracking. At least it can be concluded that the smaller specimen size C(T)25 – at equal nominal stress intensity factors – provides more conservative data than the larger one which points to the mechanism of strain induced corrosion cracking because more extended yielding is anticipated in the smaller specimen at high $K_I$ values.

## 5 Summary and Conclusions

The PWR part of CASTOC project addresses environmentally-assisted crack growth phenomena in low-alloy steels used for pressure boundary components in Russian type pressurised water reactors (VVER). The number of tests using sophisticated test facility and measurement technique for the on-line detection of crack advance have provided a more detailed understanding of the mechanism of environmentally assisted cracking and provided quantitative data of CGRs as a function of loading events and time, respectively. The work was focussed on the evaluation of crack growth under cyclic load, crack growth and crack cessation under static load, and on the determining of the effect of oxygen content, constraint and 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 MPa√m in VVER normal water chemistry.
- [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.]
- 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 condition: material D in oxygenated (~ 200 µg/kg) VVER water and stress intensity factor beyond the validity limit for linear elastic fracture mode.
- The proposed BWRVIP-60 SCC Disposition Line 1 [10] for crack growth under steady-state BWR/NWC conditions was essentially confirmed also for steady-state VVER conditions. With respect to the Disposition Line 2 for transients in load and water

chemistry, however, further consideration is recommended based on the results of this project.

- The curves provided in the ASME Code Case N 643 for PWR water environment cover fairly well the data obtained in VVER environment for Russian type RPV steels even at increased oxygen content.

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 power plant.

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