Fatigue behaviour and crack growth of ferritic steel under environmental conditions

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Abstract

The assessment of fatigue and cyclic crack growth behaviour of safety relevant components is of importance for the ageing management with regard to safety and reliability. For cyclic stress evaluation different codes and standards provide fatigue analysis procedures to be performed considering the various mechanical and thermal loading histories and geometric complexities of the components. For the fatigue design curves used as a limiting criteria the influence of different factors like e.g. environment, surface finish and temperature must be taken into consideration in an appropriate way.

Fatigue tests were performed in the low cycle fatigue (LCF) und high cycle fatigue (HCF) regime with low alloy steels as well as with Nb- and Ti-stabilized German austenitic stainless steels in air and high temperature (HT) boiling water reactor environment to extend the state of knowledge of environmentally assisted fatigue (EAF) as it can occur in boiling water reactor (BWR) plants.

Using the reactor pressure vessel (RPV) steel 22NiMoCr3-7 experimental data were developed to verify the influence of BWR coolant environment (high purity water as well as sulphate containing water with 90 ppb SO$_4$ at a test temperature of 240 °C and an oxygen content of 400 ppb) on the fatigue life and to extend the basis for a reliable estimation of the remaining service life of reactor components. Corresponding experiments in air were performed to establish reference data to determine the environmental correction factor $F_{en}$ accounting for the environment.

The experimental results are compared with international available mean data curves, the new design curves and on the basis of the environmental factor $F_{en}$.

Furthermore the behaviour of steel 22NiMoCr3-7 in oxygenated high temperature water under transient loading conditions was investigated with respect to crack initiation and cyclic crack growth. In this process the stress state of the specimen and the chemical composition of the high temperature water play an important role for the transferability to real components. Environmentally assisted cracking (EAC) experiments were performed with fracture mechanics C(T)-specimens of different size in high temperature water autoclaves under simulated BWR water conditions. In some of the experiments the influence of chloride transients on crack initiation and crack propagation was investigated.

In this paper the position of MPA University of Stuttgart concerning material fatigue data, mean data curves and fatigue design curves including environmental effects is demonstrated.

1 Introduction

The basis for construction, design and operation of nuclear systems, structures and components (SSC) are national technical codes and standards like the ASME-Code Section III [1], the French RCC-M Code [2] or the German Nuclear Safety Standards KTA [3]. The basic philosophy in the design of SSC is to demonstrate that the function and the integrity are guaranteed throughout the lifetime. It is important that the design concept accounts for most possible failure modes and provides rational margins of safety against each type of failure mode. Some of the potential failure modes which SSC designers should take into account are for example: Excessive elastic deformation including elastic instability, excessive plastic deformation, brittle fracture, fatigue and corrosion.

During design stage a complete picture of the state of stresses within the SSC obtained by calculation or measurement of both mechanical and thermal stresses during steady state operation and transient loading has to be created. It has to be demonstrated that all stresses (primary, secondary) as well as environmental loading are within the allowable stress limits given by the codes and standards, and the usage factor developed by a fatigue analysis (peak stresses) is well below the limiting value (cumulative fatigue life usage factor $U$).
It is possible to prevent failure modes caused by fatigue by imposing distinct limits on the peak stresses at the highest loaded regions of the SSC or by reducing the load cycles since fatigue failure is related to and initiated by high local stresses respectively strains. The design rules according to the technical codes and standards [1], [2] and [3] provides for explicit consideration of cyclic operation using design fatigue curves of allowable alternating loads (allowable stress or strain amplitudes) vs. number of loading cycles (S/N-curves) specific rules for assessing the cumulative fatigue damage caused by different specified or monitored load cycles. The influence of different factors like welds, environment, surface finish, temperature, mean stress and size must be taken into consideration in an appropriate way.

Fatigue analysis can be performed by different concepts which must not necessarily yield in the same result, Fig. 1. In nuclear codes and standards usually local concepts are used (local notch strain or stress concepts).

**Fig. 1:** Different Methods to perform fatigue analysis

2 Fatigue analysis in nuclear codes and standards

2.1 Fatigue design curves

Reviewing fatigue analyses to be performed for nuclear pressure vessels and piping it becomes apparent that the majority is similar to or identical with those included in the ASME-Code Section III [1], like the German KTA Standards [3].

Fatigue data are generally obtained from unwelded smooth cylindrical specimens which were tested under strain control at room temperature (RT) and in air environment with a fully reversed loading, i.e. strain ratio of \( R_e = -1 \), and are plotted in the form of nominal stress amplitude \( S_a \) vs. the number of cycles \( N \) to failure [4], [5], [6] and [7]. The total strain range \( \Delta \varepsilon_{at} \) obtained from the tests is converted to nominal stress range \( 2S_a \) by multiplying the strain range by the modulus of elasticity \( E \) at test temperature:
The design curves (S/N-curves) were derived by introducing factors of 2 on stress ($S_{\sigma}$) and 20 on cycles ($S_N$) on the best-fit curves, whichever gave the lowest curve and is meant to account for real effects (“scatter of data and material variability”, “size effects”, “surface finish and environment”, e.g. [7], [8], [9]) occurring during plant operation. All of the pressure vessel and piping fatigue design rules are based essentially on the same approach based on data from primarily low-cycle fatigue (LCF) tests. Conservative S/N-curves are developed and used for the fatigue analysis in conjunction with stress concentration factors $K_t$ or fatigue strength reduction factors $K_f$ to take into account the structural discontinuities in the SSC including welds [8].

The fatigue life is defined as the number of cycles, $N_{25}$, necessary for the tensile stress to drop 25% from its peak or steady-state value during test. For a specimen size usually used in fatigue testing, e.g. 5-12 mm diameter cylindrical specimens, this corresponds to a ≈3 mm deep crack [9].

The existing fatigue $\varepsilon$–N data to develop the S/N-curves are categorized by the types of material like austenitic stainless steels, Fig. 2, and carbon steels and low alloy steels, Fig. 3. Therefore most of the S/N-curves given in the codes and standards are to be applied for specific steels (e.g. distinguish between steels of different ultimate tensile strength $R_m$).

\[
2S_{\alpha} = E \cdot \frac{\Delta \varepsilon_{at}}{2}
\]  

(1)

Based on experimental $\varepsilon$–N data of the last twenty years fatigue life models for estimating the fatigue lives of these steels in air have been redeveloped at ANL [9] (NUREG/CR-6090) as best-fit or mean data curves of a Langer type equation [4], [5] and [6]. Based on these data new fatigue design curves were developed different from the curves included in ASME-Code Section III (ed. 2008 and earlier) and KTA Standard [3]. The new carbon steel best-fit curve, Fig. 4, is represented by

\[
\ln(N) = 6.614 - 0.00124 T - 1.975 \ln (\varepsilon_{a} - 0.113)
\]

(2)

and for low alloy steels, Fig. 5, by

\[
\ln(N) = 6.480 - 0.00124 T - 1.808 \ln (\varepsilon_{a} - 0.151)
\]

(3)
where $\varepsilon_a$ is the applied strain amplitude (\%), and T is the test temperature (°C). For austenitic stainless steels in air at temperatures up to 400 °C the fatigue data are best represented by the best-fit curve, Fig. 6.

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112)$$  \hfill (4)

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**Fig. 3:** Fatigue design curves carbon steels and low alloy steels [3]

**Fig. 4:** Fatigue design curve for carbon steels in air, developed from the ANL model [9] and based on factors of 12 on life and 2 on stress

### 2.2 Effects influencing the fatigue life

The use of the fatigue design curves is restricted in the nuclear codes and standards to a specific maximum temperature below the creep range. Using design fatigue curves it is necessary to adjust the allowable stresses if the modulus of elasticity $E$ at operating temperature is different from that one used for the design curves. In air, the fatigue life of ferritic steels decreases with increasing temperature; however the effect is relatively small, whereas for austenitic steels according to [9] the temperature has no significant effect on the
fatigue life. In the design S/N-curves any temperature effects are accounted for in the subfactor for “data scatter and material variability”.

**Fig. 5:** Fatigue design curve for low alloy steels in air, developed from the ANL model [9] and based on factors of 12 on life and 2 on stress

**Fig. 6:** Fatigue design curve for austenitic stainless steels in air, developed from the ANL model [9] and based on factors of 12 on life and 2 on stress

In the codes and standards there are different and specific requirements concerning the surface finish of components especially for welded regions, for different vessel and piping products and different joints. A special regard to the influence of surface finish depending upon peak-to-valley height $R_z$ is obvious. Depending on $R_z$ for carbon steel, low–alloy steel and for austenitic steels the surface finish would decrease fatigue life. This effect is accounted for in the subfactor for “surface finish and environment”. Stress indices are available for use of the code equations determining the stress amplitudes. This includes also different weld configurations. Fatigue tests with weld metal showed a tendency for shorter fatigue life compared to the base metal [14].

During the last two decades great endeavors have been made to investigate the influence of the coolant environment on fatigue life, e.g. [10], [11], [12], [13], [14], [15]. Today it is
generally accepted that the Light Water Reactor (LWR) environment can have a significant impact on the fatigue life of carbon and low alloy steels as well as on austenitic stainless steels and has to be involved in cumulative fatigue life considerations.

The U.S. Nuclear Regulatory Commission (NRC) issued the Regulatory Guide 1.207 “Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors” [16]. This Guide is based on the research work and publications by ANL [9]. The ANL fatigue life model for LWR environments includes parameters for the effects of temperature, strain rate, dissolved oxygen content in water and, in case of ferritic steels, sulphur content of the steel. The environmental effects are expressed in terms of an environmental correction factor $F_{en}$ as the ratio of fatigue life in a RT at air environment to fatigue life in LWR coolant at operating temperature

$$F_{en} = \frac{N_{air}}{N_{water}}$$

also depending on the above-mentioned parameters, which are used to estimate the environmental fatigue usage

$$U_{en} = \sum U_i \times F_{en_i}$$

3 Experimental investigations

3.1 Materials and test parameters

For the tests performed at MPA different nuclear grade materials manufactured according to the requirements of KTA safety standard are available:

- Low alloy ferritic steel 22NiMoCr3-7
- Low alloy ferritic steel 20MnMoNi5-5
- Ni stabilized austenitic stainless steel X10CrNiNb18-9 and X6CrNiNb18-10
- Ti stabilized austenitic stainless steel X10CrNiTi18-9

The material strength parameter yield strength and ultimate tensile strength at room temperature are respectively (all mean values)

- 459 MPa and 613 MPa for material 22NiMoCr3-7 (rolled plate)
- 503 MPa and 653 MPa for material 20MnMoNi5-5 (rolled plate)
- 245 MPa and 573 MPa for material X6CrNiNb18-10 (rolled bar)
- 239 MPa and 548 MPa for material X6CrNiNb18-10 (seamless pipe)
- 292 MPa and 564 MPa for material X10CrNiNb18-9 (seamless pipe)
- 240 MPa and 600 MPa for material X10CrNiTi18-9 (seamless pipe)

All test materials fulfilled the requirements according to KTA safety standard, e.g. chemical composition, mechanical properties (yield strength, ultimate tensile strength, elongation at fracture, percentage reduction of area) and absorbed impact energy.

The smooth cylindrical fatigue test specimens are machined from the plate and pipe materials respectively in rolling and in longitudinal directions. Specimen surface was mechanically polished with a surface roughness of $R_z<2\ \mu m$. The specimens were tested under strain control at RT and elevated temperatures up to 350 °C with fully reversed loading conditions at different strain amplitudes, i.e. strain ratio of $R_\varepsilon=-1$. 
3.2 LCF tests in air environment

3.2.1 Austenitic material

In addition to more than 60 fatigue data available at MPA Stuttgart in total a data pool of 158 fatigue tests at RT for the stabilized austenitic stainless steels X10CrNiNb18-9, X6CrNiNb18-10 and X10CrNiTi18-9 including the data of different laboratories (MPA Darmstadt, E.ON, MPA Stuttgart) is shown in Fig. 7. The data are best represented by the equation (best-fit or mean data curve, procedure according to [17])

$$\ln(N) = 6.706 - 2.172 \ln(\varepsilon_a - 0.136)$$

(7)

This equation fits also load controlled tests at $10^7$ load cycles as well as the approximation of the endurance limit based on the ultimate tensile strength.

![Fig. 7: Fatigue life of stabilized austenitic stainless steels at RT in air](image1)

![Fig. 8: Fatigue life of stabilized austenitic stainless steels at elevated temperatures in air](image2)
In addition to more than 80 fatigue data available at MPA Stuttgart in total a data pool of 138 fatigue tests at temperatures between 240 °C and 350 °C for the stabilized austenitic stainless steels X10CrNiNb18-9, X6CrNiNb18-10 X10CrNiTi18-9 from different laboratories (MPA Darmstadt, MPA Stuttgart, AREVA) is shown in Fig. 8. The data are best represented by the equation (best-fit or mean data curve, procedure according to [17])

\[
\ln(N) = 6.850 - 2.255 \ln (\varepsilon_a - 0.078)
\] (8)

This equation covers also load controlled tests at 10⁶ load cycles as well as the approximation of the endurance limit based on the ultimate tensile strength.

### 3.2.2 Austenitic cladding

To evaluate the fatigue behaviour of the austenitic cladding of pressurized components, the fatigue design curves are usually based on experiments on specimens taken from plates, pipes or bars. Due to the rapid heat transport into the ferritic base material, the cladding has a distinctive anisotropic structure that results from the manufacturing process. Therefore, it may not be assumed a priori that the fatigue life curves of the various austenitic product forms used in the Safety Standards are also representative for the material of the austenitic cladding. Fatigue tests were performed to determine and assure experimentally a fatigue life curve of the cladding material of pressurized components and to compare the results with the database of the stabilized austenitic stainless steels used in German nuclear power plants.

To carry out fatigue tests with cladding material, flat specimens specially adapted to the geometric conditions were prepared out of the austenitic cladding of a reactor pressure vessel which had been manufactured according to nuclear specifications. Due to the small thickness of the cladding (max. 7 mm), specially designed flat specimens (thickness of 2 mm) had to be used instead of the normal cylindrical fatigue specimens. To check a possible influence of this specimen geometry, flat specimens were prepared in advance from an austenitic pipe of known fatigue behaviour and tested at two different strain amplitudes. A comparison of the results with the fatigue life curve determined with conventional cylindrical specimens showed no influence at the higher strain amplitudes, Fig. 9. At the lower strain amplitude, a small influence of the specimen geometry becomes apparent. The flat specimens show a slightly lower fatigue life than cylindrical specimens.

24 strain-controlled uniaxial fatigue tests under fully reversed conditions (R=-1) were carried out at RT with flat specimen, Fig. 10.

![Fatigue life of stabilized austenitic stainless steels at RT in air, comparison between cylindrical and flat specimen](image-url)

**Fig. 9**: Fatigue life of stabilized austenitic stainless steels at RT in air, comparison between cylindrical and flat specimen.
At the highest strain amplitude (0.8 %), a slightly higher fatigue life was detected, whereas at the lowest strain amplitude (0.22 %), the fatigue life is slightly lower than that of the austenitic base material. Altogether, the fatigue life data with flat specimen made of the material of austenitic cladding fit well into the scatter band of the fatigue database of the austenitic base materials tested with cylindrical specimens.

Fig. 10: Fatigue life of stabilized austenitic stainless steel and austenitic cladding at RT in air

3.2.3 Ferritic material

More than 80 fatigue data available at MPA at RT for the low alloy ferritic steel 20MnMoNi5-5 are shown in Fig. 11. It includes is also the best-fit curve representing the low alloy steel data of [9], by

\[
\ln(N) = 6.449 - 1.808 \ln(\varepsilon_a - 0.151)
\]

(7)

The MPA data are represented by this equation developed at ANL [9].

Fig. 11: Fatigue life of low alloy steel 20MnMoNi5-5 at RT in air
More than 60 fatigue data available at MPA at temperatures between 240 °C and 350 °C for the low alloy ferritic steels 20MnMoNi5-5 and 22NiMoCr3-7 are shown in Fig. 12. It includes also the best-fit curve representing the low alloy steel data of ANL [9] for a temperature of 300 °C according to equation (3).

Fig. 12: Fatigue life of low alloy steel 20MnMoNi5-5 and 22NiMoCr3-7 at temperatures between 240 °C and 350 °C in air

3.3 LCF tests in BWR environment

The investigations of environmental effects on fatigue life of stainless steels performed in the USA, e.g. [9], and in Japan, e.g. [12], are predominantly based on unstabilized austenitic stainless steels. There is a need to investigate whether the fatigue behaviour of the niobium or titanium stabilized austenitic stainless steels used in German nuclear power plants in contact with oxygenated high temperature (HT) water of boiling water reactor (BWR) coolant can be predicted by the curves and methods developed in the USA and in Japan. For the experiments a test facility was available including a miniature autoclave positioned on the specimen shoulders.

3.3.1 Austenitic material

The specimens are machined from 2 nuclear grade pipe materials of the stabilized austenitic stainless steels X10CrNiNb18-9 and X10CrNiTi18-9 (see chapter 3.1). The specimens of steel X10CrNiTi18-9 are additionally tested in a sensitized material state after an annealing treatment at 620 °C for 8 hours.

Low cycle fatigue (LCF) tests are conducted in simulated BWR HT-water environment at 240°C, the oxygen content of the water is adjusted to 400 ppb, [18] and [19]. In addition to high purity water, few tests are performed at an increased conductivity of 0.8 µS/cm by dosing sulphate (90 ppb SO\(_4\)). The flow velocity is quasi stagnant (0.004 m/s). All experiments in water were preceded by a soaking period of 100 h at test conditions. The LCF tests were conducted with strain amplitudes of 0.3 %, 0.6 %, 0.9 % and 1.2 % and an uniform strain rate of 0.01 %/s.

The fatigue life in simulated BWR environment with high purity is conservatively covered by the ANL mean water curve [9], Fig. 13. The influence of the simulated BWR environment (N\(_\text{air}]/N_{\text{water}}\) tends to decrease with increasing strain amplitude. Included in Fig. 13 is the
effective $F_{en}$ value based on the test parameters and MPA test results in air. All $F_{en}$ values are well below the value of 3.55 calculated by the ANL equation.

**Fig. 13**: Fatigue life of stabilized austenitic stainless steels in high purity HT-water compared with ANL mean water curve [9] and fatigue design curves

**Fig. 14**: Fatigue life of Ti-stabilized austenitic stainless steel (as delivered and sensitized material state) in high purity and sulphate HT-water compared with ANL mean water curve [9] and fatigue design curves

Under the given test parameters the sensitized material state of material X10CrNiTi18-9 as well as dosing a sulphate content of 90 ppb result only in a minor reduction of fatigue life,
Fig. 14: Included in Fig. 14 are again the effective $F_{en}$ values based on the test parameters. Again all $F_{en}$ values are below value of 3.55 calculated by the ANL equation.

### 3.3.2 Ferritic material

Fatigue experiments up to more than $10^6$ load cycles were performed in high purity water as well as in sulphate (90 ppb $SO_4^{2-}$) and chloride (50 ppb $Cl^{-}$) respectively at a test temperature of 240 °C and an oxygen content of 400 ppb (simulated BWR coolant) [20]. The specimens are machined from a reactor pressure vessel (RPV) shell of low alloy steel 22NiMoCr3-7.

In the LCF tests strain amplitudes of 0.3 %, 0.5 % and 0.9 % were applied at strain rates of both 0.1 %/s and 0.01 %/s. The HCF experiments were conducted as stress-controlled cyclic tests (R=-1) at a loading frequency of 1 Hz (stress amplitude 325 MPa, nominal strain amplitude 0.166 %).

In high purity water at the “fast” strain rate of 0.1 %/s the decrease in fatigue life is in the range of the ANL prediction (mean curve), Fig. 15. On the contrary, the “slow” strain rate of 0.01 %/s causes a drop of fatigue life in high purity water, Fig. 15. The effect of sulphate and chloride on the fatigue life is hardly more pronounced than of high purity water whereas the corrosive effect of the medium, in particular of the sulphate, increases with decreasing strain rate, Fig. 16.

Fig. 15: Fatigue life of low alloy steel 22NiMoCr3-7 in high purity HT-water compared with ANL mean water curve [9] and fatigue design curves

Fig. 17 shows the results in high purity and sulphate containing HT-water at the slow strain rate of 0.01 %. Obviously the sulphate causes a concentration of the fatigue life results at the lower bound of the water results.

### 3.4 Crack growth tests in BWR environment

Crack growth tests were performed with fracture mechanics specimen C(T)25, C(T)50 and C(T)100 in high purity water with an oxygen content of 400 ppb as well as in chloride containing water (50 ppb $Cl^{-}$) at a test temperature of 288 °C (simulated BWR coolant) [21]. The specimens are machined from a reactor pressure vessel (RPV) shell of low alloy steel 22NiMoCr3-7.
All specimen were pre-cycled in high purity water to create a detectable crack size, typically in 120 sec time period (100 sec load increase, 20 sec load decrease), in few cases in 12 sec time period.

![Fatigue life of low alloy steel 22NiMoCr3-7 in high purity, sulphate and chloride HT-water compared with ANL mean water curve [9] and fatigue design curves](image1)

**Fig. 16:** Fatigue life of low alloy steel 22NiMoCr3-7 in high purity, sulphate and chloride HT-water compared with ANL mean water curve [9] and fatigue design curves

![Fatigue life of low alloy steel 22NiMoCr3-7 in high purity and sulphate HT-water at slow strain rate compared with ANL mean water curve [9] and fatigue design curves](image2)

**Fig. 17:** Fatigue life of low alloy steel 22NiMoCr3-7 in high purity and sulphate HT-water at slow strain rate compared with ANL mean water curve [9] and fatigue design curves

The data of all measured crack growth rates for the specimen geometries tested and the applied R ratios are between the ASME air and water curves, **Fig. 18** and **Fig. 19**, with the
exception of 2 C(T)25 specimen with R=0.7 located on the ASME water curve. Thus the measured crack growth rates can be rated as moderate.

A reduction of the 120 sec time period to 12 sec increases the crack growth rate up to a factor of 2, i.e. a reduced velocity in load increase under high purity water conditions is not connected with an increase in crack growth. The cyclic crack growth rates increase as expected with higher values of $\Delta K$.

Fig. 18: Cyclic crack growth in high purity water at 288 °C with R ratio 0.7

Fig. 19: Cyclic crack growth in high purity water at 288 °C with R ratio 0.1
To investigate the influence of specimen size and R ratio ($K_{I\min}/K_{I\max}$) on the crack growth behaviour tests were performed with the three specimen sizes and the loading sequence as shown in Fig. 20 and Fig. 21. Subsequent to the cyclic loading 9 partial unloading/reloadings (PUR) each followed by a constant load phase of 50 h at a $K_I$ value of 80 MPa$\sqrt{m}$ were applied.

![Fig. 20](loading_sequence_R_0.7.png)  
**Fig. 20**: Loading sequence (PUR) for R ratio 0.7 (schematic)

![Fig. 21](loading_sequence_R_0.1.png)  
**Fig. 21**: Loading sequence (PUR) for R ratio 0.1 (schematic)

During PUR and the constant load phases at no test pronounced crack growth was observed. Crack Growth measurement by DCPD under high purity water conditions is shown for C(T)50 with $R=0.7$ in Fig. 22 and for C(T)100 with $R=0.1$ in Fig. 23. The crack growth rates caused by PUR are in the same range as per load cycle during cyclic loading. For the C(T)50 specimen crack growth during cyclic loading accounts 0.26 µm/cycle, 0.11 µm for PUR and the C(T)100 specimen crack growth during cyclic loading 3.48 µm/cycle, 5.78 µm for PUR.

As a result for the high $K_{I\max}$ value of 80 MPa$\sqrt{m}$ under high purity water conditions no significant influence of specimen size at cyclic and transient loading to crack growth behaviour was observed. The fractographical analysis showed no indications of stress corrosion cracking (SCC).
To investigate the influence of chloride C(T)25 and C(T)50 specimen with $K_{\text{I max}}$ values of 40 and 55 MPa√m were tested. Loading scheme see Fig. 24.

Fig. 22: DCPD crack growth measurement, C(T)50 specimen with R ratio 0.7

After starting the chloride transient of 50 ppb during the first phase of constant load no crack growth was detected, i.e. no SCC occurred in chloride containing water under static load conditions. In contrary, severe SCC crack growth was caused by the load transients, which can be divided into a first phase (phase 1) with a high crack growth rate and a second one (phase 2) with a decreasing crack growth rate. The total SCC crack propagation during these experiments was in the range between 270 and 1150 µm, example see Fig. 25.

The crack growth behaviour caused by the load transients (PUR) at a chloride content of 50 ppb was similar for the stress intensities of 40 and 55 MPa√m. Compared to the BWR VIP-60 disposition lines (DL) [22] the crack growth rates during phase 1 are between the low sulphur line and the high sulphur line, whereas for 55 MPa√m most of the crack growth rates of phase 2 are below DL2 and the crack growth rates of phase 2 are between DL2 and DL1, Fig. 26.
Based on the evaluations of fatigue data at ANL [9] (NUREG/CR-6090) new fatigue design curves are implemented in ASME-Code Section III (since ed. 2008 and later) [1] for austenitic stainless steels, Fig. 6. To develop a fatigue design curve factors on stress respectively strain and cycles shall be applied to the best-fit curve as already mentioned (for austenitic stainless steel factors $S_\sigma=2$ and $S_N=12$ are implemented).

Fatigue test data at RT and at elevated temperatures for the German stabilized austenitic stainless steels X10CrNiNb18-9, X6CrNiNb18-10 and X10CrNiTi18-9 are represented by the best-fit curves according to eq. (7), Fig. 7, respectively eq. (8), Fig. 8.
To define the factor on stress useful values for surface, size and mean stress (verified by tests and used in conventional vessel and piping standards) as well as the data scatter for RT date result in a value of $S_{\sigma}=1.88$, Fig. 27. In this way in connection with $S_{N}=12$ especially in the range of endurance limit this new fatigue design curve for RT based on the best-fit curve eq. (7) is approximately 1.4 above the ASME-Code design curve.

![Fatigue Design Curve](image)

**Fig. 26**: Crack growth under chloride transient loading compared to BWRVIP-60 Disposition Lines [22]

**Fig. 27**: Design curve at room temperature
To define the factor on stress in the same way like for RT a value of $S_{\sigma}=1.79$ shall be used. In this way in connection with $S_N=12$ the new fatigue design curve based on the best-fit curve eq. (8) shows nearly the same behavior like the ASME-Code design curve, Fig. 28.

![Figure 28: Design curve at elevated temperatures](image)

**References**


Criteria of the ASME Boiler and Pressure Vessel Code for design by analysis in Section III and VIII, Division 2, ASME 1969, Library of Congress Catalog Card Number: 56-3934


[22] BWR VIP-60, BWR Vessel and Internals Project, "Evaluation of Stress Corrosion Crack Growth in Low Alloy Steel Vessel Materials in BWR Environment (BWRVIP-60)"