Approval Date: May 4, 2004

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-643-2
Fatigue Crack Growth Rate Curves for Ferritic Steels in PWR Water Environment
Section XI, Division 1

Inquiry: As an alternative to the fatigue crack growth rate da/dN characterized in A-4300, what crack growth behavior characterization may be used for ferritic material in PWR primary water environments when information on the susceptibility of the material to environmentally assisted cracking is available?

Reply: It is the opinion of the Committee that as an alternative to the fatigue crack growth rate behavior characterized in A-4300, the following characterization may be used for ferritic material in PWR primary water environments when information on the susceptibility of the material to environmentally assisted cracking is available.

1 INTRODUCTION

The fatigue crack growth behavior of ferritic materials can be greatly affected by exposure to light-water reactor environments. Some combinations of material and environment are susceptible to enhanced crack growth rates, referred to herein as environmentally assisted cracking (EAC). Susceptibility to EAC during fatigue cycling is controlled by

(a) metallurgical factors such as material chemistry, particularly sulfur content and morphology,

(b) environmental factors such as water chemistry and temperature, and

(c) factors affecting crack-tip properties such as electrochemical corrosion potential (ECP), water flow rate as it flushes the crack-tip region, and crack-face surface conditions as they affect mass transport of particles into and out of the crack-tip region.

This Case provides criteria for determining the susceptibility of ferritic materials to EAC, reference fatigue crack growth rate behavior for material susceptible to EAC, and reference fatigue crack growth rate behavior for material not susceptible to EAC.

2 NOMENCLATURE

The symbols used in this Case are defined as follows:

a = flaw depth, in.
Δa = increment of flaw growth in depth direction, in.
Δa_i = increment of flaw growth in depth direction in time increment Δt_i, in.
Δa_{cr} = flaw growth increment required for EAC initiation, in.
C_o = fatigue crack growth rate scaling constant, $(\text{in./cycle})\cdot(\text{ksi}\sqrt{\text{in.}})^{-n}$
da/dN = fatigue crack growth rate, in./cycle
i = time increment index, I = 1, ..., N i X
K_{max} = maximum stress intensity factor during cycle, $\text{ksi}\sqrt{\text{in.}}$
K_{min} = minimum stress intensity factor during cycle, $\text{ksi}\sqrt{\text{in.}}$
ΔK = $K_{max} - K_{min}$ = range of applied stress intensity factor, $\text{ksi}\sqrt{\text{in.}}$
ΔK_b, ΔK_c = ΔK values defining regions of enhanced crack growth, $\text{ksi}\sqrt{\text{in.}}$
ΔK_{th} = mechanical threshold ΔK value, $\text{ksi}\sqrt{\text{in.}}$
ℓ = flaw length, in.
$\Delta \ell$ = increment of flaw growth in length direction, in.
n = fatigue crack growth rate exponent
N = number of increments in evaluation period
R = K_{min}/K_{max} = R ratio
S = bulk sulfur content in weight percent
Δt_i = time increment, yr.
V_i = crack-tip velocity adjusted for calculational uncertainty, in./sec
V_{in} = crack-tip velocity required for EAC initiation, in./sec
α = crack-tip velocity calculational uncertainty factor
θ = load rise time, sec

4.1 MATERIAL SUSCEPTIBLE TO EAC

The fatigue crack growth rate for material susceptible to EAC depends on bulk sulfur content and rise time.

For bulk sulfur content $S \leq 0.013$ wt-percent and rise time $\theta \leq 1$ second, the crack growth parameters of 4.2 shall be used.

For bulk sulfur content $S \leq 0.013$ wt-percent and rise time $\theta > 1$ sec the fatigue crack growth rate is given by eq. 4(1), with C_o and n given by (see Figure 2):

for $\Delta K < \Delta K_{th}$

$$C_o = 0 \tag{2a}$$

for $\Delta K \geq \Delta K_{th}$

$$C_o = 6.13 \times 10^{-8} / (2.88 - R)^{3.07}, \quad n = 3.07 \tag{2b}$$

For bulk content $S > 0.013$ wt-percent, the fatigue crack growth rate is given by eq. 4(1), with C_o and n given by (see Figure 2):

for $\Delta K < \Delta K_{th}$

$$C_o = 0 \tag{3a}$$

for $\Delta K_{th} \leq \Delta K \leq K_b$

$$C_o = 7.47 \times 10^{-6} / (2.88 - R)^{6.65}, \quad n = 3.07 \tag{3b}$$

for $\Delta K_b < \Delta K \leq K_c$

$$C_o = 1.39 \times 10^{-6} \, \theta^{0.691} / (2.88 - R)^{0.948}, \quad n = 0.948 \tag{3c}$$

for $\Delta K > \Delta K_c$

$$C_o = 1.45 \times 10^{-8} / (2.88 - R)^{3.07}, \quad n = 3.07 \tag{3d}$$

The mechanical threshold ΔK value, below which the fatigue crack growth rate is negligible, is given by the following:

for $0 \leq R < 1.0$

$$\Delta K_{th} = 5.0(1 - 0.8R) \tag{4}$$

The values of ΔK_b and ΔK_c that delineate the regions of enchanced fatigue crack growth for $S > 0.013$ wt-percent as shown in Figure 2 are given by the following:

$$\Delta K_b = 0.453 \, \theta^{0.326} (2.88 - R)^{2.69} \tag{5}$$

$$\Delta K_c = 8.57 \, \theta^{0.326} (2.88 - R) \tag{6}$$

The load rise time, θ, is the period of time in seconds for which the stress is increasing during a stress cycle. The rise time, which excludes hold times and time periods for which the stress is decreasing during the cycle, includes the time periods from minimum stress to steady state and from steady state to maximum stress. Hold times include periods in which the change in stress does not exceed 1000 psi/hr. For material susceptible to EAC with $S > 0.013$ wt-percent and for transients for which θ is not available, reference fatigue crack growth behavior is given by eq. 4(1), with C_o and n given by Eqs. (3a) and (3b) for the entire range of ΔK. For $\Delta K > \Delta K_b$, the lower of the curves corresponding to $S > 0.013$ wt-percent [eq. (3c), (3d), and (6)] or $S \leq 0.013$ wt-percent eq. (2b) may be used for $S \leq 0.013$ wt-percent material.

4.2 MATERIAL NOT SUSCEPTIBLE TO EAC

Reference fatigue crack growth behavior for material not susceptible to EAC is given by eq. 4(1), with C_o and n given by (see Figure 3):

(a) for $\Delta K < \Delta K_{th}$

$$C_o = 0 \tag{7a}$$

(b) for $\Delta K \geq \Delta K_{th}$

$$C_o = 1.45 \times 10^{-8} / (2.88 - R)^{3.07}, \quad n = 3.07 \tag{7b}$$

5 SI UNITS

It is recommended that the flaw growth evaluation using the procedures of this Case be performed in U.S. Customary units, since the equations and figures contained in this Case were developed in these units. Conversion from U.S. Customary units to SI units can be performed employing the following conversions:

1 in.	=	25.4 mm
1 ksi in.$^{0.5}$	=	1.0988 MPa m$^{0.5}$
T [°F]	=	1.8T [°C] + 32

where T is temperature.