ANL/ET/CP-97665

METHODS FOR INCORPORATING EFFECTS OF LWR COOLANT ENVIRONMENT INTO ASME CODE FATIGUE EVALUATIONS*

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April 1999

Invited paper to be presented at the Symposium on Fatigue and Fracture in Pressure Vessels and Piping, 1999 ASME/JSME Joint Pressure Vessel and Piping Conf., Boston, August 1-5, 1999.

*Work supported by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, FIN Number W6610.

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ABSTRACT

The ASME Boiler and Pressure Vessel Code provides rules for the construction of nuclear power plant components. Appendix I to Section III of the Code specifies design fatigue curves for structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. Recent test data illustrate potentially significant effects of LWR environments on the fatigue resistance of carbon and low–alloy steels and austenitic stainless steels (SSs). Under certain loading and environmental conditions, fatigue lives of carbon and low–alloy steels can be a factor of ≈70 lower in an LWR environment than in air. These results raise the issue of whether the design fatigue curves in Section III are appropriate for the intended purpose. This paper presents the two methods that have been proposed for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations. The mechanisms of fatigue crack initiation in carbon and low–alloy steels and austenitic SSs in LWR environments are discussed.

INTRODUCTION

Cyclic loadings on a structural component occur because of changes in mechanical and thermal loadings as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to any other load set. For each set of load pairs, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the lifetime of the component to the allowable cycles. Figures I–9.1 through I–9.6 of Appendix I to Section III of the ASME Boiler and Pressure Vessel Code specify design fatigue curves that define the allowable number of cycles as a function of applied stress amplitude. The cumulative usage factor (CUF) is the sum of the individual usage factors, and the ASME Code Section III requires that the CUF at each location must not exceed 1.

The Code design fatigue curves were based on strain–controlled tests of small polished specimens at room temperature in air. The design fatigue curves were obtained by adjusting the best–fit curves to the experimental data for the effect of mean stress and then decreasing the mean-stress-adjusted curves by a factor of 2 on strain or 20 on cycles, whichever was more conservative, at each point on the best–fit curve. As described in the Section III criteria document, these factors were intended to account for the differences and uncertainties in relating the fatigue lives of laboratory test specimens to those of actual reactor components. The factors of 2 and 20 are not safety margins but rather conversion factors that must be applied to the experimental data to obtain reasonable estimates of the lives of actual reactor components; in a benign environment, some fraction (e.g., ≈25%) of the factors actually represents a safety margin.

Subsection NB–3121, of Section III of the Code states that the data on which the design fatigue curves (Figs. I–9.1 through I–9.6) are based did not include tests in the presence of corrosive environments that might accelerate fatigue failure. Article B–2131 in Appendix B to Section III states that the owner's design specifications should provide information about any reduction to design fatigue curves that has been necessitated by environmental conditions. Recent fatigue strain–vs.–life (S–N) data illustrate potentially significant effects of light water reactor (LWR) coolant environments on the fatigue resistance of carbon steels (CSs) and low–alloy steels (LASs) (Ranganath et al., 1982; Higuchi and Iida, 1991; Nagata et al., 1991; Van Der Sluys, 1993; Kanasaki et al., 1995; Nakao et al., 1995; Higuchi et al., 1997; Chopra and Shack, 1997, 1998a, b, c, 1999), as well as of austenitic stainless steels (SSs) (Fujiwara et al., 1986; Mimaki et al., 1996; Higuchi and Iida, 1997; Kanasaki et al., 1997a, b; Hayashi, 1998; Hayashi et al., 1998; Chopra and Gavenda, 1997, 1998; Chopra and Smith, 1998; Chopra, 1999), (Fig. 1).

The existing fatigue S–N data have been analyzed to establish the effects of various material, loading, and environmental parameters on the fatigue life of carbon and low–alloy steels and austenitic SSs; the

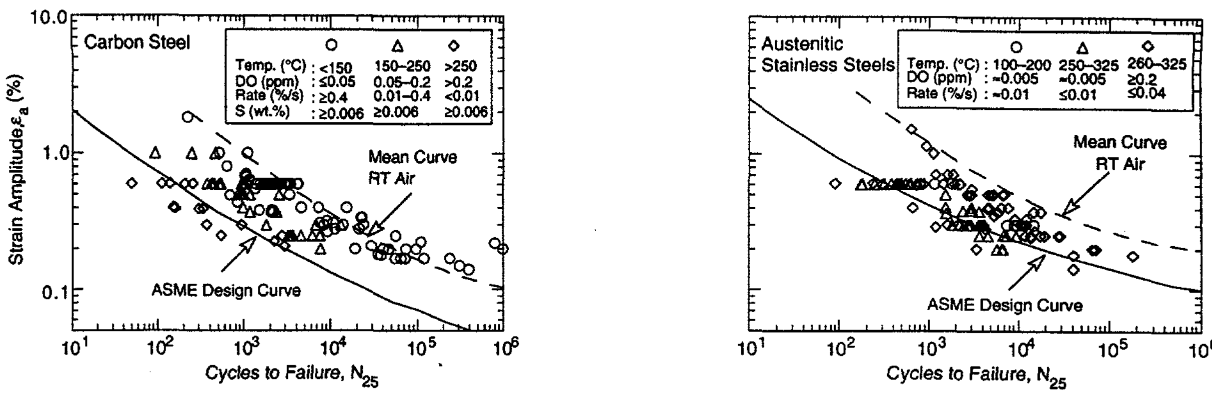

Figure 1. Fatigue S–N data for CSls and austenitic SSs in water; RT = room temperature

results have been summarized for carbon and low–alloy steels (Chopra and Shack,1998b) and for austenitic SSs (Chopra, 1999). Under certain environmental and loading conditions, fatigue lives of CSs can be a factor of 70 lower in the environment than in air (Higuchi and Iida, 1991; Chopra and Shack, 1998b). Therefore, the margins in the ASME Code may be less conservative than originally intended.

Two approaches have been proposed for incorporating the effects of LWR environments into ASME Section III fatigue evaluations: (a) develop new design fatigue curves for LWR applications, and (b) use a fatigue life correction factor to account for environmental effects. Both approaches are based on the existing fatigue S–N data in LWR environments, i.e., the best–fit curves to the experimental fatigue S–N data on LWR environments are used to obtain the design curves or fatigue life correction factor. As and when more data became available, the best–fit curves have been modified and updated to include the effects of various material, loading, and environmental parameters on fatigue life. Interim design fatigue curves that address environmental effects on fatigue life of carbon and low–alloy steels and austenitic SSs were first proposed by Majumdar et al. (1993). Design fatigue curves based on a rigorous statistical analysis of the fatigue S–N data in LWR environments were developed by Keisler et al. (1995, 1996). Results of the statistical analysis have also been used to estimate the probability of fatigue cracking in reactor components. The design curves and statistical models for estimating fatigue lives in LWR environments have recently been updated for carbon and low–alloy steels (Chopra and Shack, 1998b, c, 1999) and austenitic SSs (Chopra and Smith, 1998; Chopra, 1999).

The alternative approach, proposed initially by Higuchi and Iida (1991), considers the effects of reactor coolant environments on fatigue life in terms of a fatigue life correction factor F_{en}, which is the ratio of the life in air to that in water. To incorporate environmental effects into the ASME Code fatigue evaluations, a fatigue usage for a specific load pair, based on the current Code design curves, is multiplied by the correction factor. Specific expressions for F_{en}, based on the statistical models (Chopra and Shack, 1998b, c, 1999; Chopra, 1999; Mehta and Gosselin, 1996) and on the correlations developed by the Environmental Fatigue Data Committee of Thermal and Nuclear Power Engineering Society of Japan (Higuchi, 1996), have been proposed.

This paper summarizes the data that are available on the effects of various material, loading, and environmental parameters on the fatigue lives of carbon and low–alloy steels and austenitic SSs. The two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented. Differences between the methods and their significance on the design fatigue curves are discussed.

FATIGUE S–N DATA IN LWR ENVIRONMENTS

Carbon and Low–Alloy Steels

The fatigue life of both carbon and low–alloy steels is decreased significantly when five conditions are satisfied simultaneously, viz., strain amplitude, temperature, dissolved oxygen (DO) level in water, and sulfur content of the steel are above a minimum level, and strain rate is below a threshold value. Although the microsturctures and cyclic–hardening behavior of CSs and LASs differ significantly, environmental degradation of fatigue life of these steels is very similar. For both steels, only moderate decrease in life (by a factor of <2) is observed when any one of the threshold conditions is not satisfied. The effects of the critical parameters on fatigue life and their threshold values are summarized below.

(a) *Strain:* A minimum threshold strain is required for environmentally assisted decrease in fatigue life of carbon and low–alloy steels (Chopra and Shack, 1998b, c, 1999). The threshold value most likely corresponds to the rupture strain of the surface oxide film. Limited data suggest that the threshold value is ≈20% higher than the fatigue limit for the steel.

(b) *Strain Rate*: Environmental effects on fatigue life occur primarily during the tensile–loading cycle, and at strain levels greater than the threshold value required to rupture the surface oxide film. When any one of the threshold conditions is not satisfied, e.g., DO <0.05 ppm or temperature <150°C, the effects of strain rate are consistent with those in air, i.e., heats that are sensitive to strain rate in air, also show a decrease in life in water. When all other threshold conditions are satisfied, fatigue life decreases logarithmically with decreasing strain rate below 1%/s (Higuchi and Iida, 1991; Katada et al., 1993; Nakao et al., 1995); the effect of environment on life saturates at ≈0.001%/s (Chopra and Shack, 1998b, c, 1999).

(c) *Temperature*: When other threshold conditions are satisfied, fatigue life decreases linearly with temperature above 150°C and up to 320°C (Higuchi and Iida, 1991; Nagata et al., 1991; Nakao et al., 1995). Fatigue life is insensitive to temperatures below 150°C or when any other threshold condition is not satisfied.

(d) *Dissolved Oxygen in Water*: When other threshold conditions are satisfied, fatigue life decreases logarithmically with DO above 0.05 ppm; the effect saturates at ≈0.5 ppm DO (Nagata et al., 1991; Nakao et al., 1995).

(e) *Sulfur Content of Steel*: Although sulfur content and morphology are the most important parameters that determine susceptibility of carbon and low–alloy steels to environmentally enhanced fatigue crack growth rates, existing fatigue S–N data are inadequate to unequivocally establish the effect of sulfur content on the fatigue life of carbon and low–alloy steels. When any one of the threshold conditions is not satisfied, environmental effects on life are minimal and relatively insensitive to changes in sulfur content. When the threshold conditions are satisfied, i.e., high–temperature high–DO water, the fatigue life of LASs decreases with increasing sulfur content. Limited data suggest that the effects of environment on life saturate at a sulfur content above 0.012 wt.% (Chopra and Shack, 1998b). However, the fatigue life of CSs in high–temperature high–DO water seems to be insensitive to sulfur content in the range of 0.002–0.015 wt.% (Higuchi, 1995).

Austenitic Stainless Steels

The fatigue life of austenitic SSs is decreased in LWR environments; the reduction in life depends on strain rate, level of DO in water, and temperature (Chopra and Gavenda, 1998; Chopra and Smith, 1998; Kanasaki et al., 1997a). The effects of LWR environments on fatigue life of wrought materials are comparable for Types 304, 316, and 316NG SSs. Although the fatigue lives of cast SSs are relatively insensitive to changes in ferrite content in the range of 12–28% (Kanasaki et al., 1997a), the effects of loading and environmental parameters on the fatigue life of cast SSs differ somewhat. The significant results and threshold values of critical parameters are summarized below.

(a) *Strain*: A minimum threshold strain is required for environmentally assisted decrease in fatigue life of austenitic SSs. The threshold value most likely corresponds to the rupture strain of the surface oxide film. Limited data suggest that the threshold strain range is between 0.32 and 0.36% (Chopra and Smith, 1998; Kanasaki et al., 1997b).

(b) *Dissolved Oxygen in Water*: Environmental effects on fatigue life are more pronounced in low–DO, i.e., <0.01 ppm DO, than in high–DO, i.e., ≥0.1 ppm DO, water, (Chopra and Smith, 1998; Kanasaki et al., 1997a). The reduction in life is greater by a factor of ≈2 in a simulated PWR environment than in high–DO water. The fatigue lives of cast SSs are approximately the same in both high– or low–DO water and are comparable to those observed for wrought SSs in low–DO water (Chopra and Smith, 1998). Recent data suggest that the fatigue life of austenitic SSs may depend on parameters other than DO level in water, e.g., conductivity of the water may be important.

(c) *Strain Rate*: Fatigue lives decrease with decreasing strain rate; the effect is greater in a low–DO PWR environment than in high–DO water. The results indicate that the strain rate below which effects of strain rate on fatigue life saturate may depend on both steel type and DO level. In low–DO environments, saturation strain rate appears to be at ≈0.0004%/s for Type 304 SS and somewhat higher for Type 316 SS (Chopra and Smith, 1998; Kanasaki et al., 1997b). Existing data are inadequate to define the saturation strain rate in high–DO water or that for cast SSs.

(d) *Temperature*: Existing data are inadequate to establish the functional form for the dependence of life on temperature. Limited data indicate that environmental effects on fatigue life are significant at temperatures above 250°C and minimal below 200°C (Kanasaki et al., 1997b). At 250–330°C, fatigue life appears to be relatively insensitive to changes in temperature.

MECHANISM OF FATIGUE CRACK INITIATION

The formation of surface cracks and their growth to an "engineering" size (3 mm deep) constitute the fatigue life of a material, which is represented by the fatigue S–N curves. Fatigue life has conventionally been divided into two stages: (a) initiation, expressed as the cycles needed to form microcracks on the surface; and (b) propagation, expressed as cycles needed to propagate the surface cracks to an engineering size. The reduction in fatigue life in high–temperature water has often been attributed to easier crack initiation, because surface micropits that are present in high–temperature water act as stress raisers and provide preferred sites for the formation of fatigue cracks (Nagata et al., 1991). However, experimental data do not support this argument; the fatigue lives of carbon and low–alloy steel specimens that have been preoxidized at 288°C in high–DO water and then tested in air are identical to those of unoxidized specimens (Chopra and Shack, 1998b). If the presence of micropits was responsible for the reduction in life, specimens preexposed to high–DO water and tested in air should show a decrease in life. Also, the fatigue limit of these steels should be lower in water than in air. Data obtained from specimens in high–DO water indicate that the fatigue limit is either the same as or ≈20% higher in water than in air (Chopra and Shack, 1998b).

An alternative approach to the description of fatigue life considers fatigue life to be entirely composed of crack propagation (Miller, 1995). In polycrystalline metals and alloys, the period for the formation of surface cracks is negligible; surface cracks, 10 μm or longer, form quite early in life (Miller, 1985; Tokaji et al., 1988; Gavenda et al., 1997; Obrtlik et al., 1997; Sundara Raman et al., 1997; Chopra and Shack, 1998a). The growth of these short fatigue cracks may be divided into three regimes: (a) an initial period, which is very sensitive to microstructure, involves growth of microstructurally small cracks (MSCs) and is characterized by decelerating growth rate; (b) a final period of growth that can be predicted from fracture mechanics methodology and is characterized by accelerating crack growth rate; and (c) a transition period that is controlled by a combination of the two regimes. Fatigue cracks greater than the critical length of MSCs show little or no influence of microstructure and are called mechanically small cracks. The transition from an MSC to a mechanically small crack has been estimated to occur at a crack size ≈8 times the unit size of the microstructure, i.e., 100–150 μm crack size. The reduction in life in LWR environments may arise from an increase in growth rates of cracks during the initial stage of MSC and shear crack growth and/or during the transition and final stage of tensile–crack growth.

The enhanced growth rates of long cracks in pressure vessel and piping steels in LWR environments have been attributed to either slip oxidation/dissolution (Ford, 1986) or hydrogen–induced cracking (Hänninen et al., 1986) mechanisms. Both mechanisms depend on the rates of oxide rupture, passivation, and liquid diffusion. Therefore, it is often difficult to differentiate between the two processes or to establish their relative contributions to crack growth in LWR environments.

Studies on crack initiation in smooth fatigue specimens indicate that the decrease in fatigue life of carbon and low–alloy steels in LWR environments is caused primarily by the effects of environment on the growth of cracks <100 µm deep (Gavenda et al., 1997, Chopra and Shack, 1998b). When compared with crack growth rates in air, growth rates in high–DO water are nearly two orders of magnitude higher for cracks that are <100 µm and one order of magnitude higher for cracks that are >100 µm. Metallographic examinations of test specimens indicate that, in high–DO water, surface cracks grow entirely as tensile cracks normal to the stress, whereas, in air or simulated PWR environments, they are at an angle of 45° to the stress axis (Gavenda et al., 1997). Also, for CSs, cracks propagate across both ferrite and pearlite regions. These results indicate that growth of MSCs occurs by slip oxidation/dissolution.

In high–DO water, crack initiation in carbon and low–alloy steels may be explained as follows: (a) surface microcracks form quite early in fatigue life; (b) during cyclic loading, the protective oxide film is ruptured at strains greater than the fracture strain of surface oxides, and the microcracks grow by anodic dissolution of the freshly exposed surface to crack depths greater than the critical length of MSCs; and (c) these mechanically small cracks grow to engineering size, and their growth, which is characterized by accelerating rates, can be predicted by fracture mechanics methodology.

Studies on crack initiation in austenitic SSs yield similar results, i.e., that the decrease in fatigue life in LWR environments is caused primarily by the effects of environment on the growth of cracks that are <500 µm deep (Smith and Chopra, 1999). However, fatigue lives that are lower in low–DO water than in high–DO water are difficult to reconcile in terms of the slip oxidation/dissolution mechanism. Also, austenitic SS specimens tested in LWR environments show well–defined fatigue striations, indicating that mechanical factors and not the slip dissolution/oxidation process are important (Chopra and Smith, 1998). The results indicate that environmentally assisted reduction in fatigue life of austenitic SSs is most likely caused by hydrogen–induced cracking.

INCORPORATING ENVIRONMENTAL EFFECTS INTO ASME FATIGUE EVALUATIONS

Two procedures are currently being proposed for incorporating effects of LWR coolant environments into the ASME Section III fatigue evaluations; (a) develop a new set of environmentally adjusted design fatigue curves (Chopra and Shack, 1998b, 1999; Chopra, 1999; Chopra and Smith 1998) or (b) use fatigue life correction factors, K_{en}, to adjust the current ASME Code fatigue usage values for environmental effects (Chopra and Shack, 1999; Chopra, 1999; Mehta and Gosselin, 1996). For both approaches, the range and bounding values must be defined for key service parameters that influence fatigue life. It has been demonstrated that both approaches give similar results for carbon and low-alloy steels (Chopra and Shack, 1998b) but the results for austenitic SSs differ (Chopra, 1999) because the existing ASME mean curve for SS in air is not consistent with the exiting fatigue S–N data.

Design Fatigue Curves

A set of environmentally adjusted design fatigue curves can be developed from the best–fit curves to the experimental data in LWR environments by using the same procedure that has been used to develop the current ASME Code design fatigue curves. The best–fit experimental curves are first adjusted for the effect of mean stress by using the modified Goodman relationship

$$S'_a = S_a\left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y, \qquad (1a)$$

$$\text{and} \quad S'_a = S_a \qquad \text{for } S_a > \sigma_y, \qquad (1b)$$

where S'_a is the adjusted value of stress amplitude, and σ_y and σ_u are yield and ultimate strengths of the material, respectively. The design fatigue curves are then obtained by lowering the adjusted best–fit curve by a factor of 2 on stress or 20 on cycles, whichever is more conservative, to account for differences and uncertainties in fatigue life that are associated with material and loading conditions.

Statistical models based on the existing fatigue S–N data have been developed for estimating the fatigue lives of pressure vessel and piping steels in air and LWR environments (Chopra and Shack, 1998b, 1999; Chopra, 1999; Chopra and Smith, 1998). In air at room temperature, the fatigue data for CSs are best represented by

$$\ln(N) = 6.564 - 1.975 \ln(\varepsilon_a - 0.113) \qquad (2a)$$

and for LASs, by

$$\ln(N) = 6.627 - 1.808 \ln(\varepsilon_a - 0.151), \qquad (2b)$$

where N is fatigue life of a smooth test specimen and ε_a is applied strain amplitude (%). In LWR environments, the fatigue data for CSs are best represented by

$$\ln(N) = 6.010 - 1.975 \ln(\varepsilon_a - 0.113) + 0.101\, S^* T^* O^* \dot{\varepsilon}^* \qquad (3a)$$

and for LASs, by

$$\ln(N) = 5.729 - 1.808 \ln(\varepsilon_a - 0.151) + 0.101\, S^* T^* O^* \dot{\varepsilon}^*, \qquad (3b)$$

where S^*, T^*, O^*, and $\dot{\varepsilon}^*$ are transformed sulfur content, temperature, DO, and strain rate, respectively, defined as follows:

$$S^* = S \qquad (0 < S \le 0.015 \text{ wt.\%})$$
$$S^* = 0.015 \qquad (S > 0.015 \text{ wt.\%}) \qquad (4a)$$

$$T^* = 0 \qquad (T < 150°C)$$
$$T^* = T - 150 \qquad (T = 150\text{–}350°C) \qquad (4b)$$

$$O^* = 0 \qquad (DO < 0.05 \text{ ppm})$$
$$O^* = \ln(DO/0.04) \qquad (0.05 \text{ ppm} \le DO \le 0.5 \text{ ppm})$$
$$O^* = \ln(12.5) \qquad (DO > 0.5 \text{ ppm}) \qquad (4c)$$

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 1\%/s)$$
$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}) \qquad (0.001 \le \dot{\varepsilon} \le 1\%/s)$$
$$\dot{\varepsilon}^* = \ln(0.001) \qquad (\dot{\varepsilon} < 0.001\%/s). \qquad (4d)$$

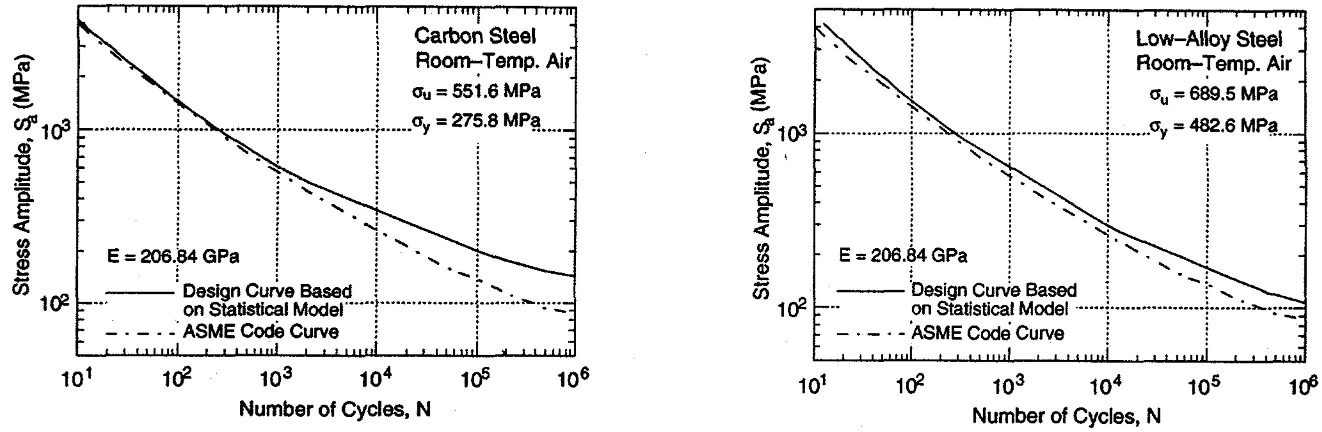

Figure 2. Design fatigue curves developed from statistical model for carbon and low–alloy steels in air at room temperature

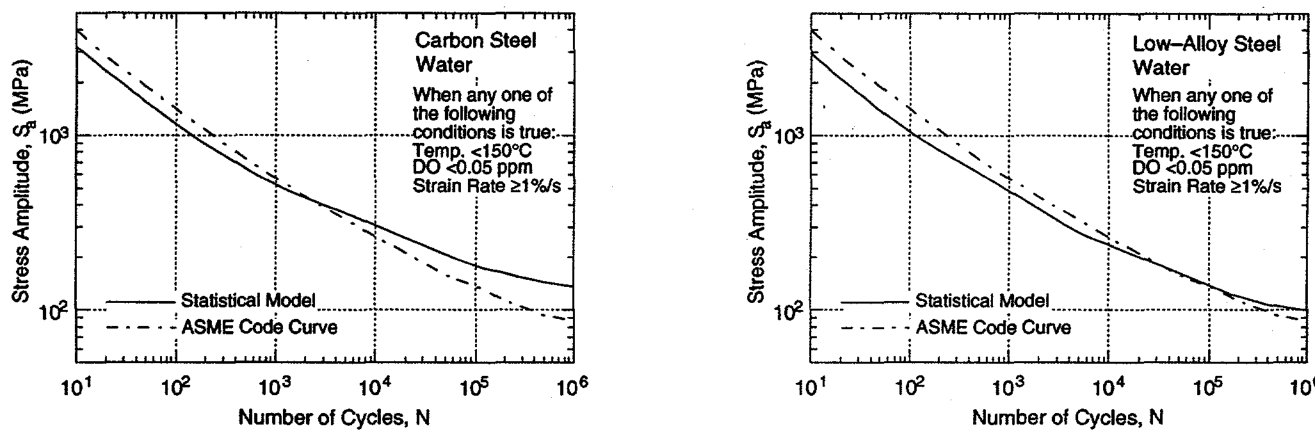

Figure 3. Design fatigue curves developed from statistical model for carbon and low–alloy steels under service conditions where one or more critical threshold values are not satisfied

The discontinuity in the value of O^* at 0.05 ppm DO is due to an approximation and does not represent a physical phenomenon. In air at room temperature, the fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 6.703 - 2.030 \ln(\varepsilon_a - 0.126) \quad (5a)$$

and for Type 316NG, by

$$\ln(N) = 7.422 - 1.671 \ln(\varepsilon_a - 0.126), \quad (5b)$$

where N is fatigue life of a smooth test specimen and ε_a is applied strain amplitude (%).

In LWR environments, the fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 5.768 - 2.030 \ln(\varepsilon_a - 0.126) + T' \dot{\varepsilon}' O' \quad (6a)$$

and for Type 316NG, by

$$\ln(N) = 6.913 - 1.671 \ln(\varepsilon_a - 0.126) + T' \dot{\varepsilon}' O' \quad (6b)$$

where T', $\dot{\varepsilon}'$, and O' are transformed temperature, strain rate, and DO, respectively, defined as follows:

$$T' = 0 \quad (T < 200°C)$$
$$T' = 1 \quad (T \geq 200°C) \quad (7a)$$

$$\dot{\varepsilon}' = 0 \quad (\dot{\varepsilon} > 0.4\%/s)$$
$$\dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4) \quad (0.0004 \leq \dot{\varepsilon} \leq 0.4\%/s)$$
$$\dot{\varepsilon}' = \ln(0.0004/0.4) \quad (\dot{\varepsilon} < 0.0004\%/s) \quad (7b)$$

$$O' = 0.260 \quad (DO < 0.05 \text{ ppm})$$
$$O' = 0.172 \quad (DO \geq 0.05 \text{ ppm}). \quad (7c)$$

The models are recommended for predicted fatigue lives $\leq 10^6$ cycles. The stress–vs.–life curves are obtained from the strain–vs.–life curves, e.g., stress amplitude is the product of strain amplitude and elastic modulus. The room–temperature value for the elastic modulus is used in converting the curves.

The environmentally adjusted design fatigue curves were obtained by using the procedure that was used to develop the current ASME Code curves and the statistical models represented by Eqs. 2–6. The design fatigue curves for carbon and low–alloy steels and austenitic Types 304 and 316 SS in air and LWR environments are shown in Figs. 2–6. Because the fatigue life of Type 316NG is superior to that of Types 304 or 316 SS, Figs. 5 and 6 may be used conservatively for Type 316NG SS.

The best–fit curves were adjusted for the effect of mean stress by using the modified Goodman relationship (Eqs. 1a and 1b), which assumes the maximum possible mean stress and typically gives a conservative adjustment for mean stress, at least when environmental effects are not significant. To be consistent with the current Code design curves, the mean–stress–adjusted best–fit curves were decreased by the same margins on stress and cycles that are present in the current Code curves. The mean–stress–adjusted best–fit curves were decreased by a factor of 2 on stress for carbon and low–alloy steels and by a factor of 1.5 for austenitic SSs. A factor of 20 on life was used for all curves, although the actual margin on life is ≈10 for austenitic SSs because of the differences between the ASME mean curve and the best–fit curve to existing fatigue data.

For all of the design curves, we define a minimum threshold strain amplitude, below which environmental effects either do not occur or are modest. As discussed earlier, the threshold strain for carbon and low–alloy steels appears to be ≈20% higher than the fatigue limit of the steel. This translates into strain amplitudes of 0.140 and 0.185%, respectively, for CSs and LASs. These values must be adjusted for mean stress effects and variability due to material and

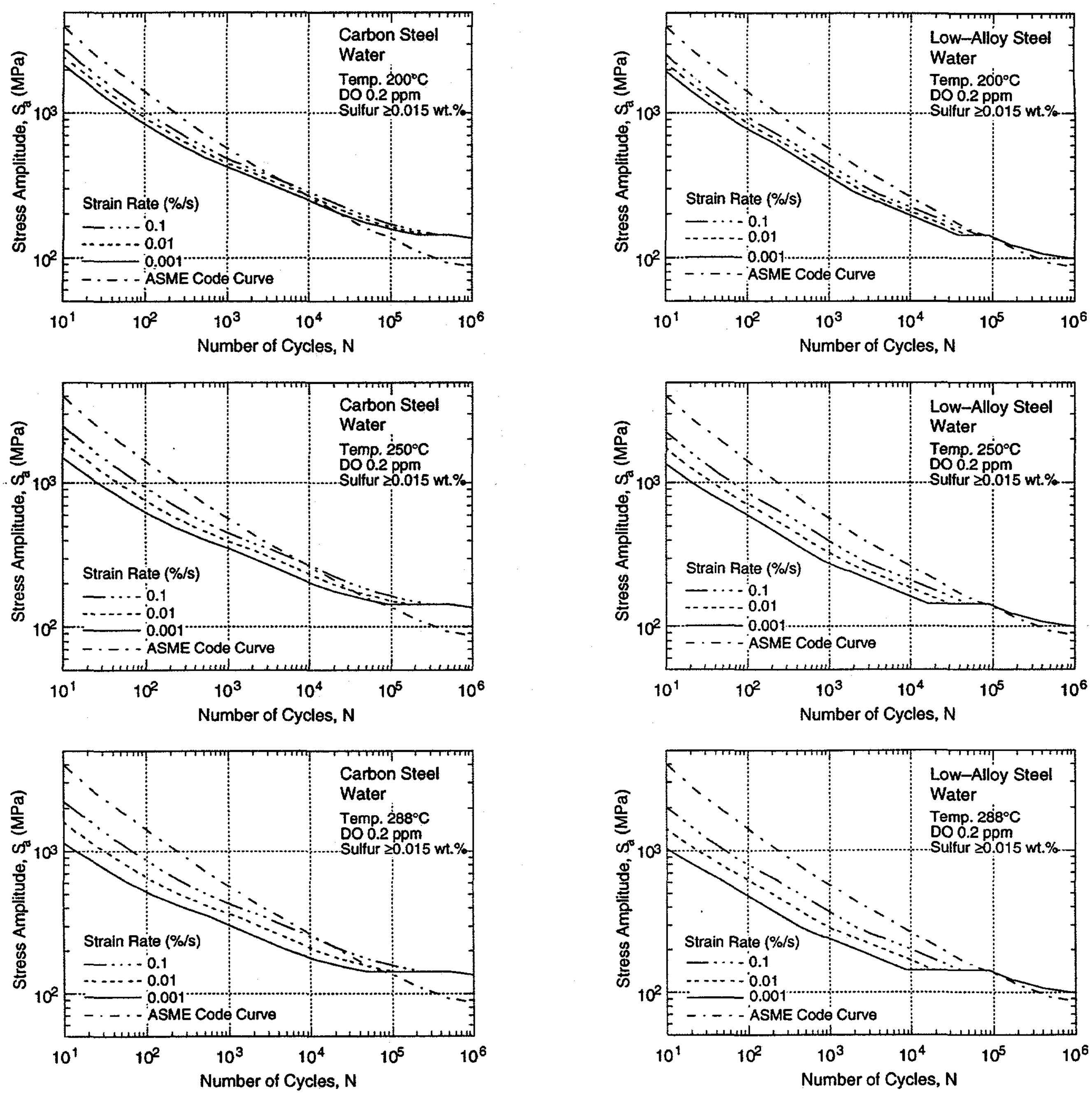

Figure 4. Design fatigue curves developed from statistical model for carbon and low–alloy steels under service conditions where all critical threshold values are satisfied

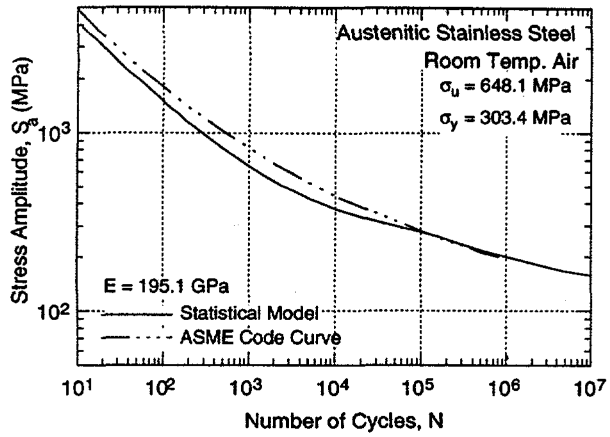

Figure 5.
Design fatigue curve developed from statistical model for Types 304 and 316 SS in air

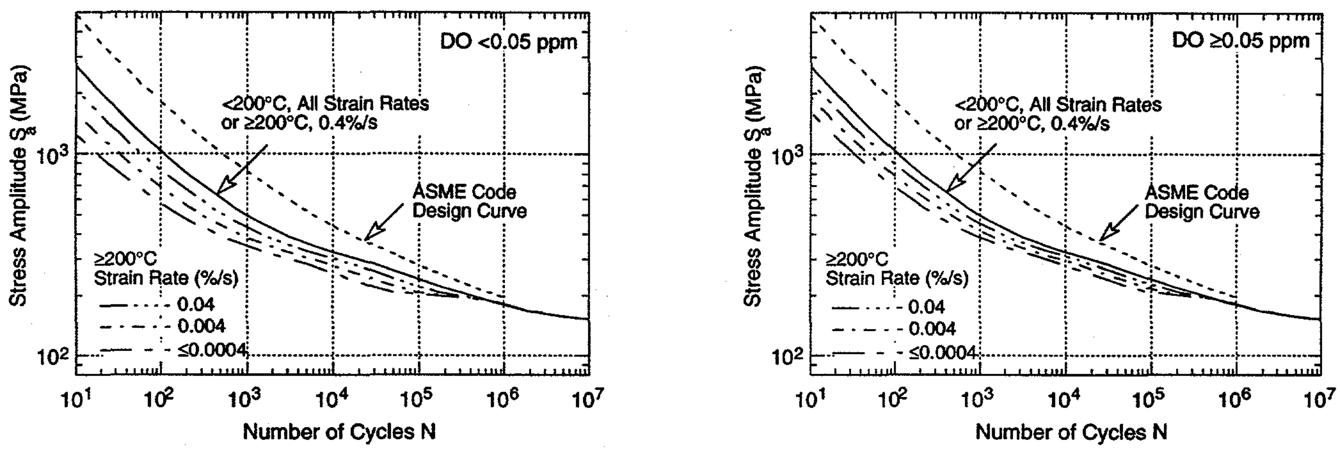

Figure 6. Design fatigue curves developed from statistical models for Types 304 and 316 SS in water with <0.05 and ≥0.05 ppm DO

experimental scatter. To account for the effects of mean stress, the threshold strain amplitudes are decreased by ≈15% for CSs and by ≈40% for LASs. These decreases produce a threshold strain amplitude of ≈0.12% for both steels. A factor of 1.7 on strain provides 90% confidence for the variations in fatigue life that are associated with material variability and experimental scatter (Keisler et al., 1995). Thus, a threshold strain amplitude of 0.07% (or a stress amplitude of 145 MPa) was selected for both carbon and low-alloy steels. The existing fatigue data indicate a threshold strain range of ≈0.32% for austenitic SSs. This value is decreased by ≈10% to account for mean stress effects and by a factor of 1.5 to account for uncertainties in fatigue life that are associated with material and loading variability. Thus, a threshold strain amplitude of 0.097% (stress amplitude of 189 MPa) was selected for austenitic SSs.

Fatigue Life Correction Factor

The effects of reactor coolant environments on fatigue life have also been expressed in terms of a fatigue life correction factor F_{en}, which is the ratio of the life in air at room temperature to that in water at the service temperature (Higuchi and Iida, 1991). A similar approach has been proposed by the Electric Power Research Institute (Mehta and Gosselin, 1996), however, they defined F_{en} as the ratio of the life in air to that in water, both at service temperature. A nonmandatory appendix, based on this procedure, is being proposed for inclusion in Section III of the ASME Code. To incorporate environmental effects into the Section III fatigue evaluation, a fatigue usage for a specific stress cycle, based on the current Code design fatigue curve is multiplied by the correction factor. A fatigue life correction factor F_{en} can be obtained from the statistical model (Eqs. 2–7), where

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \quad (8)$$

The fatigue life correction factor for CSs is given by

$$F_{en} = \exp(0.554 - 0.001515T^{*}\ \dot{\varepsilon}^{*}\ O^{*}), \quad (9a)$$

for LASs, by

$$F_{en} = \exp(0.898 - 0.001515T^{*}\ \dot{\varepsilon}^{*}\ O^{*}), \quad (9b)$$

and for austenitic SSs, by

$$F_{en} = \exp(0.935 - T'\ \dot{\varepsilon}'\ O'), \quad (9c)$$

where the constants T^*, $\dot{\varepsilon}^*$ and O^* are defined in Eqs. 4a–4c, and T', $\dot{\varepsilon}'$ and O' are defined in Eqs. 7a–7c. Because the fatigue life of CSs in high–temperature high–DO water seems to be insensitive to the sulfur content of the steel (Higuchi, 1995), a value of 0.015 wt.% sulfur was assumed in Eq. 4a to obtain the fatigue life correction factors for carbon and low–alloy steels given by Eqs. 9a and 9b.

Conservatism in Design Fatigue Curves

The overall conservatism in ASME Code fatigue evaluations has also been demonstrated in fatigue tests on piping welds and components (Mayfield et al., 1979). In air, the margins on the number of cycles to failure for elbows and tees were 118–2500 and 123–1700, respectively, for CSs, and 40–310 and 104–510, respectively, for austenitic SSs. The margins for girth butt welds were significantly lower at 14–128 and 6–77, respectively, for CSs and SSs. In these tests, fatigue life was expressed as the number of cycles for the crack to penetrate through the wall, which ranged in thickness from 6 to 18 mm (0.237 to 0.719 in.). The ASME design fatigue curves represent the number of cycles that are necessary to form a 3–mm–deep crack. Consequently, depending on wall thickness, the actual ASME margins to failure may be lower by a factor of >2.

Deardorff and Smith (1994) have also discussed the types and extent of conservatisms present in the ASME Section III fatigue evaluations and the effects of LWR environments on fatigue margins. The sources of conservatism include design transients that are considerably more severe than those experienced in service, grouping of transients, and simplified elastic–plastic analysis. Environmental effects on two components, the BWR feedwater nozzle/safe end and PWR steam generator feedwater nozzle/safe end, both constructed from LAS and known to be affected by severe thermal transients, were also investigated in the study. When environmental effects on fatigue life were not considered, Deardorff and Smith (1994) estimated that, for the PWR and BWR nozzles, the ratios of the CUFs computed with the Code design fatigue curve to CUFs computed with the mean experimental curve for test specimen data were ≈60 and 90, respectively. To maintain the factor of 20 on life that was used in the present Code design fatigue curves to account for the uncertainties due to material and loading variability, the margins for the PWR and BWR nozzles are reduced to 3 and 4.5, respectively. The studies by Mayfield et al. (1979) and Deardorff and Smith (1994) demonstrate the overall conservatism in the current ASME Section III Code fatigue evaluation procedures.

Data available in the literature have been reviewed to evaluate the conservatism in the ASME Code design fatigue curves. The subfactors that may be used to account for the effects of various material, loading, and environmental variables on the fatigue life of structural materials are summarized in Table 1 (Keisler et al., 1995). The factors on strain primarily account for the variation in the fatigue limit of a material that is caused by material variability, component size and surface finish, and loading history. Because the reduction in fatigue life is associated with the growth of short cracks (<100 μm), the effects of these variables on fatigue limit are typically not cumulative but rather are controlled by the variable that has the largest effect. The values in Table 1 suggest that a factor of at least 1.5 on strain and 10 on cycles is needed to account for the differences and uncertainties of relating fatigue lives of laboratory test specimens to those of large components. Because carbon and low–alloy steels and austenitic SSs develop a corrosion scale in LWR environments, the effect of surface finish may not be significant, i.e., the effects of surface roughness are included in environmentally assisted decrease in fatigue life in LWR coolant environments. In water, the subfactor on life to account for surface finish effects may be as low as 1.5 or may be eliminated completely; a factor of 1.5 on strain and 7 on cycles is adequate to account for the uncertainties that arise from material and loading variability. Therefore, the factor of 20 on life that is used in developing the design fatigue curves includes, as a safety margin, a factor of 3 or 4 on life that may be used to account for the effects of environment on the fatigue lives of these steels.

Table 1. *Subfactors that may be used to account for effects of various variables on fatigue life*

Variable	Factor on Life	Factor on Strain
Material variability and experimental scatter	2.5	1.4–1.7
Size	1.4	1.25
Surface finish	2.0–3.0	1.3
Loading history	1.5–2.5	1.5
Total adjustment	10.5–26.3	1.5–1.7

These results are consistent with the conclusions of the pressure vessel research council (PVRC) working group on fatigue S–N data analysis (Van Der Sluys and Yukawa, 1995). One of the tasks in the PVRC activity consisted of defining a set of values for material, loading, and environmental variables that result in "moderate" or "acceptable" effects of environment on fatigue life. A factor of 4 on the ASME mean life was chosen as a working definition of acceptable effects of environment, i.e., up to a factor of 4 decrease in fatigue life due to environment is considered acceptable and does not require further fatigue evaluation. The basis for this criterion is that a factor of 4 on life constitutes normal data scatter and/or at least that much conservatism is included in the design fatigue curves.

FATIGUE EVALUATIONS IN LWR ENVIRONMENTS

Section III, NB–3200– or NB–3600–type analyses for components for service in LWR environments can be performed with either the design fatigue curves or the fatigue life correction factors. Both of these approaches require information about the service conditions, e.g., temperature, strain rate, and DO level.

Fatigue Evaluations Based on Environmentally Corrected Design Fatigue Curves

Fatigue evaluations that are based on the design fatigue curves may be performed as follows:

(a) For each stress cycle or load pair, determine the alternating stress amplitude according to the guidelines of NB 3222.4 (design by analysis) or NB 3650 (analysis of piping products), and the total number of cycles anticipated during the lifetime of the component.

(b) For each stress cycle or load pair, obtain information about the service conditions, e.g., temperature, strain rate, and DO level. The procedure for obtaining these parameters depends on the details of the available information, i.e., whether the elapsed time–vs.–temperature information for the transient is available.

Fatigue tests in oxygenated water under combined mechanical and thermal cycling (Kanasaki et al., 1995, 1997b) indicate that an average temperature may be used if the time–vs.–temperature information is available; highest temperature can be used for a conservative estimate of life. Because environmental effects on fatigue life are modest at temperatures <150°C and at strains below the threshold value, average temperature may be determined by the average of the maximum temperature and either 150°C or the temperature at threshold strain, whichever is higher. An average strain rate is generally used for each load state; it is obtained from the peak strain and elapsed time for the transient. However, fatigue–monitoring data indicate that actual strain rates may vary significantly during a transient. The slowest strain rate can be used for a conservative estimate of life.

(c) For each alternating stress amplitude and corresponding service condition, obtain a partial usage factor from the appropriate design fatigue curve (Figs. 3, 4, and 6). For carbon and low–alloy steels, design fatigue curves in Fig. 3 are used when any one of the threshold condition is not satisfied, i.e., when any one of the following conditions is true:

Temperature:	< 150°C
DO:	< 0.05 ppm
Strain Rate:	≥ 1%/s.

The design curves in Fig. 4 are used for carbon and low–alloy steels when all of the threshold conditions are satisfied, i.e., temperature ≥150°C, DO ≥0.05 ppm, and strain rate <1%/s; the curves shown in Fig. 4 are for 200, 250, and 288°C; 0.2 ppm DO level; and 0.1, 0.01, and ≤0.001%/s strain rate.

Similarly, the design curves in Fig. 6 are used for austenitic SSs under various service conditions. The two sets of curves are for <0.05 and ≥0.05 ppm DO in water. In both sets, the solid curve represents service the condition when any one of the two threshold conditions is not satisfied, i.e., when any one of the following condition is true:

Temperature:	< 200°C
Strain Rate:	≥ 0.4%/s.

The design curves shown by chain dash lines in Fig. 6 are used for austenitic SSs when both of the threshold conditions are satisfied, i.e., temperature ≥200°C and strain rate <0.4%/s; the three curves shown in Fig. 6 are for 0.04, 0.004, and ≤0.0004%/s strain rate, and temperatures between 200 and 320°C.

(d) Calculate the CUF for the component; it is the sum of the partial usage factors. As discussed in the previous section, the design fatigue curves include a factor of 3 or 4 on life that may be used to account for the effects of environment on the fatigue lives of these steels. To avoid adding additional conservatism, the environmentally adjusted CUF for the component may be decreased by a factor of 3.

Fatigue Evaluations Based on Fatigue Life Correction Factor

Fatigue evaluations that are based on the fatigue life correction factor may be performed as follows: steps
(a) and (b) are the same as described above.

(c) For each alternating stress amplitude, obtain a partial usage factor from the current Code design curves in Figs. I–9.1 through I–9.6 of Appendix I to Section III of the Code.

(d) The partial usage factors are adjusted for environmental effects by multiplying by F_{en}, which is calculated from Eqs. 9a–9c and the service condition for the stress cycle. F_{en} is calculated for only those stress cycles that satisfy all of the threshold conditions. For carbon and low–alloy steels, F_{en} is calculated when all of the following conditions are true

Temperature:	≥ 150°C
DO:	≥ 0.05 ppm
Strain Rate:	< 1%/s.

For austenitic SSs, F_{en} is calculated when the following two conditions are true:

Temperature:	≥ 200°C
Strain Rate:	< 0.4%/s.

Because the design fatigue curves include a margin that may be used to account for the effects of environment, to avoid adding additional conservatism, F_{en} valves calculated from Eqs. 9a–9c are decreased by this ammount. For carbon and low–alloy steels, F_{en} is decreased by a factor of 3 but not less than a value of 1. For austenitic SSs, F_{en} is decreased by a factor of 1.5 because, as discussed earlier, the actual margin on life is ≈10 for austenitic SSs in as much as the ASME mean curve and the best–fit curve to existing fatigue data differ.

(e) Finally, calculate the CUF for the component; it is the sum of the partial usage factors.

CONCLUSIONS

Both design fatigue curve method and the fatigue life correction factor method of evaluating fatigue lives are based on the statistical models for estimating fatigue lives of carbon and low–alloy steels and austenitic SSs in LWR environments. The environmentally adjusted design fatigue curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. All of the design curves maintain the margin of 20 on life. However, to be consistent with the current ASME Code curves, the margin on stress is 2 for carbon and low–alloy steels and 1.5 for austenitic SSs.

In the F_{en} method, environmental effects on life are estimated from the statistical models but the correction is applied to fatigue lives estimated from the current Code design curves. Therefore, estimates of fatigue lives that are based on the two methods may differ because of differences in the ASME mean curve and the best–fit curve to existing fatigue data. Figure 2 indicates that the current Code design curve for carbon steels is comparable to the statistical–model curve for LASs, whereas, it is somewhat conservative at stress levels <500 MPa when compared with the statistical–model curve for CSs. Consequently, usage factors based on the F_{en} method would be comparable to those based on the environmentally adjusted design fatigue curves for LASs and would be somewhat higher for CSs.

Figure 5 indicates that, for austenitic SSs, the current Code design fatigue curve is nonconservative when compared with the statistical–model curve, i.e., it predicts longer fatigue lives than the best–fit curve to the existing S–N data. Consequently, usage factors that are based on the F_{en} method would be lower than those determined from the environmentally corrected design fatigue curves. However, because the usage factors are decreased by a factor of 1.5 in the F_{en} method and 3 in the design curve method, the values from the two methods would be comparable after they are adjusted.

ACKNOWLEDGMENTS

This work was sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, FIN Number W6610; Program Manager: Dr. M. McNeil.

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