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ENVIRONMENTAL EFFECTS ON FATIGUE CRACK INITIATION IN PIPING AND PRESSURE VESSEL STEELS

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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 fatigue design curves for structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. Test data illustrate potentially significant effects of LWR environments on the fatigue resistance of carbon and low–alloy steels and austenitic stainless steels. This paper summarizes the work performed at Argonne National Laboratory on the fatigue of piping and pressure vessel steels in LWR coolant environments. The existing fatigue S–N data have been evaluated to establish the effects of various material and loading variables, such as steel type, strain range, strain rate, temperature, and dissolved–oxygen level in water, on the fatigue lives of these steels. Statistical models are presented for estimating the fatigue S–N curves for carbon and low–alloy steels and austenitic stainless steels as a function of material, loading, and environmental variables. Methods for incorporating environmental effects into the ASME Code fatigue evaluations are discussed. Differences between the methods and their impact on the design fatigue curves are also 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 load set, 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 ASME Code fatigue design curves, given in Appendix I of Section III, are based on strain–controlled tests of small polished specimens at room temperature in air. The fatigue design curves were developed from the best–fit curves of the experimental data by first adjusting for the effects of mean stress on fatigue life and then reducing the fatigue life at each point on the adjusted curve by a factor of 2 on strain or 20 on cycles, whichever was more conservative. As described in the Section III criteria document, these factors were intended to account for data scatter (heat–to–heat variability), effects of mean stress or loading history, and differences in surface condition and size between the test specimens and actual 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. However, because the mean fatigue curve used to develop the current Code design curve for austenitic stainless steels (SSs) does not accurately represent the available experimental data (Jaske and O'Donnell, 1977; Chopra, 1999), the current Code design curve for SSs includes a reduction of only ≈1.5 and 15 from the mean curve for the SS data, not the 2 and 20 originally intended.

As explicitly noted in Subsection NB–3121 of Section III of the Code, 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. Existing 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) and of austenitic 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). 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: develop new design fatigue curves for LWR applications, and use a fatigue life correction factor to account for environmental effects. Both approaches are based on the existing fatigue S–N data for LWR environments, i.e., the best–fit curves to the experimental fatigue S–N data in 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 Idaho National Engineering Laboratory assessed the significance of the interim fatigue design curves by evaluating samples of components in the reactor coolant pressure boundary (Ware et al., 1995). Six locations were evaluated from facilities designed by each of the four U.S. nuclear steam supply system (NSSS) vendors. Selected components from older vintage plants, designed according to the B31.1 Code, were also included in the evaluation. 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 set, 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, 1998) and on the correlations developed by the Environmental Fatigue Data Committee of the 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. Although estimates of fatigue lives based on the two methods may differ because of differences between the ASME mean curves that were used to develop the current design curves and the best–fit curves to the existing data that were used to develop the environmentally adjusted curves, either method provides an acceptable approach to account for environmental effects.

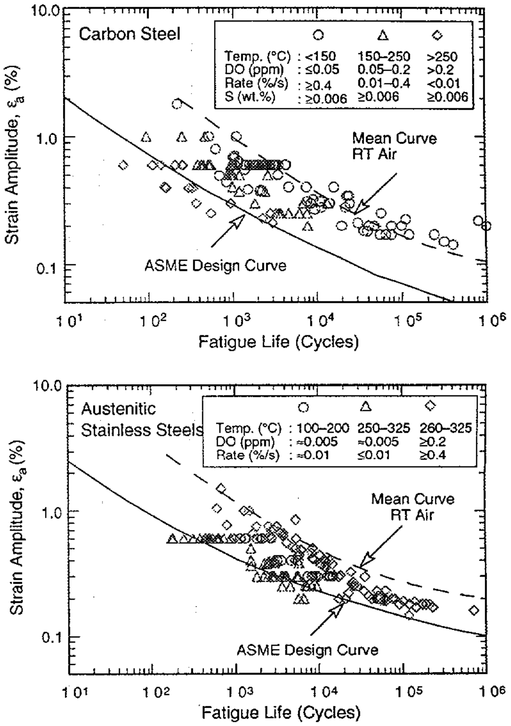

Fig. 1. Fatigue S–N data for carbon steels and austenitic stainless steels in water; RT = room temperature

FATIGUE S–N DATA IN LWR ENVIRONMENTS

Carbon and Low–Alloy Steels

The fatigue lives of both CSs and LASs are decreased in LWR environments; the reduction depends on temperature, strain rate, dissolved oxygen (DO) level in water, and S content of the steel. Fatigue life is decreased significantly when four conditions are satisfied simultaneously, viz., strain amplitude, temperature, and DO in water are above a minimum level, and strain rate is below a threshold value. The S content in the steel is also important; its effect on life depends on the DO level in

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water. Although the microstructures 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 lives of CSs and LASs (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., only the heats that are sensitive to strain rate in air 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). The dependence of fatigue life on strain rate for A106–Gr B CS and A533–Gr B LAS is shown in Fig. 2. For A533–Gr B steel, the fatigue life at a strain rate of 0.0004%/s in high–DO water (≈0.7 ppm DO) is more than a factor of 40 lower than that in air.

(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). Fatigue life is insensitive to DO level below 0.05 ppm or when any other threshold condition is not satisfied.

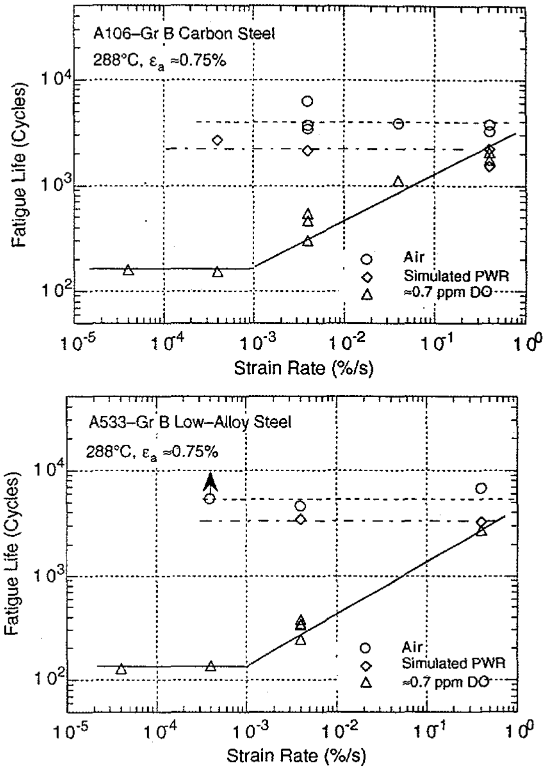

Fig. 2. Dependence of fatigue life of carbon and low–alloy steels on strain rate

(e) *S Content of Steel*: The effect of S content on fatigue life depends on the DO content of the water. When the threshold conditions are satisfied and for DO content ≤1.0 ppm, the fatigue life decreases with increasing S content. Limited data suggest that environmental effects on life saturate at a S content of ≈0.015 wt.% (Chopra

Table 1. Fatigue test results for Type 304 austenitic SS at 288°C

Test No.	Dis. Oxygen[a] (ppb)	Dis. Hydrogen (cc/kg)	Li (ppm)	Boron (ppm)	Pre-soak (days)	pH at RT	Conduc -tivity[b] (µS/cm)	ECP[a] Steel mV (SHE)	Ten. Rate (%/s)	Stress Range (MPa)	Strain Range (%)	Life N_{25} (Cycles)
1805	–	–				–	–	–	4.0E-3	467.9	0.76	14,410
1808	4	23	2	1000	1	6.4	18.87	–686	4.0E-3	468.3	0.77	2,850
1821	2	23	2	1000	1	6.5	22.22	–693	4.0E-3	474.3	0.76	2,420
1859	2	23	2	1000	1	6.5	18.69	–692	4.0E-3	471.7	0.77	2,420
1861	1	23	–	–	1	6.2	0.06	–610	4.0E-3	463.0	0.79	2,620
1862	2	23	–	–	5	6.2	0.06	–603	4.0E-3	466.1	0.78	2,450
1863	1	–	–	–	5	6.3	0.06	–520	4.0E-3	476.5	0.77	2,250

[a] DO and ECPs measured in effluent.

[b] Conductivity of water measured in feedwater supply tank.

and Shack, 1998b). At high DO levels, e.g., >1.0 ppm, fatigue life seems to be insensitive to S content in the range of 0.002–0.015 wt.% (Higuchi, 1995). When any one of the threshold conditions is not satisfied, environmental effects on life are minimal and relatively insensitive to changes in S content.

Austenitic Stainless Steels

The fatigue lives of austenitic SSs are decreased in LWR environments; the reduction depends on strain rate, level of DO in water, and temperature (Chopra and Gavenda, 1997, 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 SS. Although the fatigue lives of cast SSs are relatively insensitive to changes in ferrite content in the range of 12 to 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. Limited data suggest that the threshold strain range is 0.32 to 0.36% (Chopra and Smith, 1998; Kanasaki et al., 1997b).

(b) *Dissolved Oxygen in Water*: For wrought austenitic SSs, 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). In high–DO water, environmental effects are moderate (less than a factor of 2 decrease in life) when conductivity is maintained at <0.1 μS/cm and electrochemical potential (ECP) of the steel has reached a stable value (Fig. 3). For fatigue tests in high–DO water, the SS specimens must be soaked for 5 to 6 days for the ECP of the steel to reach a stable value. Figure 3 shows that although fatigue life is decreased by a factor of ≈2 when conductivity of water is increased from ≈0.07 to 0.4 μS/cm, the period for presoaking appears to have a larger effect on life than the conductivity of water. In low–DO water, the additions of Li and B, or low conductivity, or preexposing the specimen for ≈5 days before the test, or dissolved H, have no effect on fatigue life of Type 304 SS (Table 1). Also, for cast austenitic SSs, the effect of DO content is somewhat different; the fatigue lives 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).

(c) *Strain Rate*: In high–DO water (conductivity <0.1 μS/cm and stable ECP of the steel), fatigue life is insensitive to changes in strain rate. In low–DO water, fatigue life decreases logarithmically with decreasing strain rate below ≈0.4%/s; the effect of environment on life saturates at ≈0.0004%/s for wrought SSs (Chopra and Smith, 1998; Kanasaki et al., 1997b). Existing data are too sparse to define the saturation strain rate for cast austenitic SSs.

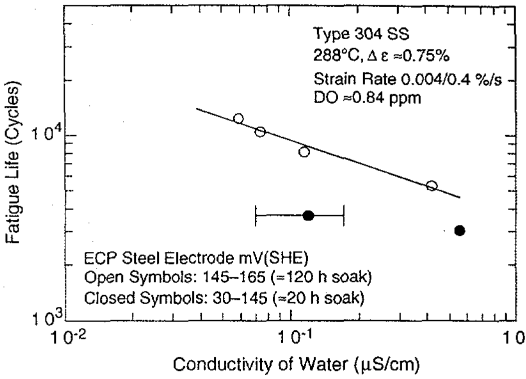

Fig. 3. Effects of conductivity of water and soak period on fatigue life of Type 304 SS in high–DO water

(d) *Temperature*: Existing data are too sparse to establish the effects of temperature on fatigue life over the entire range from room temperature to reactor operating temperatures. Limited data indicate that environmental effects on fatigue life are minimal below 200°C and significant at temperatures above 250°C (Kanasaki et al., 1997b); life appears to be relatively insensitive to changes in temperature in the range of 250–330°C. The pressure vessel research council (PVRC) steering committee for cyclic life and environmental effects (CLEE) has proposed a ramp function to describe temperature effects on the fatigue lives of austenitic SSs; environmental effects are moderate at temperatures below 180°C, significant above 220°C, and increase linearly from 180 to 220°C (Yukawa, 1999).

OPERATING EXPERIENCE IN NUCLEAR POWER INDUSTRY

Experience with operating nuclear power plants worldwide reveals that many failures may be attributed to fatigue; examples include piping components, nozzles, valves, and pumps (Kussmaul et al., 1983; Iida, 1992). In most cases, these failures have been associated with thermal loading due to thermal stratification and striping, or mechanical loading due to vibratory loading. Significant thermal loadings due to flow stratification were not included in the original design basis analysis. The effect of these loadings may also have been aggravated by corrosion effects due to a high–temperature aqueous environment. A review of significant occurrences of corrosion fatigue damage and failures in various nuclear power plant systems has been presented in an EPRI report (Dooley and Pathania, 1997); the results are summarized below.

Cracking in Feedwater Nozzle and Piping

Fatigue cracks have been observed in feedwater piping and nozzles of the pressure vessel in boiling water reactors (BWRs) and steam generators in pressurized water reactors (PWRs) (Kussmaul et al., 1984; NRC 1979, 1993). The mechanism of cracking has been attributed to corrosion fatigue (Watanabe, 1980; Gordon et al., 1987) or strain–induced corrosion cracking (SICC) (Lenz et al., 1983). Case histories and identification of conditions that lead to SICC of LASs in LWR systems have been summarized by Hickling and Blind (1986).

In BWR nozzle cracking, initiation has been attributed to high–cycle fatigue caused by the leakage of cold water around the thermal sleeve junction area, and crack propagation has been attributed to low–cycle fatigue due to plant transients such as startup/shutdowns and any feedwater on/off transients. The frequency of the high–cycle fatigue phenomenon due to leakage around the sleeve is ≈0.5–1 Hz and therefore is not expected to be influenced by the reactor coolant environment. Estimates of strain range and strain rates for typical transients associated with low–cycle fatigue are given in Table 2 (Ford et al., 1993). Under these loading and environmental conditions, significant reduction in fatigue life has been observed for carbon and low–alloy steels (Chopra and Shack, 1998b, 1999).

Table 2. Typical chemical and cyclic strain transients

Component	Operation	DO (ppb)	Temp. (°C)	Strain Range (%)	Strain Rate (%/s)
FW Nozzle	Startup	20/200	216/38	0.2-0.4	10^{-2}
FW Piping	Startup	20/200	216/38	0.2-0.5	10^{-3}–10^{-2}
FW Piping	Startup	20/200	288/38	0.07-0.1	4–8x10^{-6}
FW Piping	Turbine Roll	<200	288/80	0.4	3–6x10^{-3}
FW Piping	Hot Standby	<200	288/90	0.26	4x10^{-4}
FW Piping	Cool Down	<20	288/RT	0.2	6x10^{-4}
FW Piping	Stratification	200	250/50	0.2-0.7	10^{-4}–10^{-3}

In PWR feedwater pipe cracking, cracking has been attributed to a combination of thermal stratification and thermal striping (Dooley and Pathania, 1997). Environmental factors, such as high DO in the feedwater, are believed to also have played a significant role in crack initiation. The thermal stratification is caused by the injection of low–flow, relatively cold feedwater during plant startup, hot standby, and variations below 20% of full power, whereas thermal striping is caused by rapid, localized fluctuations of the interface between hot and cold feedwater.

Lenz et al. (1983) showed that in feedwater lines, the strain rates are 10^{-3}–10^{-5}%/s due to thermal stratification and 10^{-1}%/s due to thermal shock and that thermal stratification is the primary cause of crack initiation due to SICC. Also, the results from small–size specimens, medium–size components (model vessels), and full–size thermal–shock experiments suggest an influence of oxygen content in pressurized water on crack initiation behavior (Kussmaul et al., 1984).

A detailed examination of cracking in a CS elbow adjacent to the steam generator nozzle weld (Enrietto et al., 1981) indicates crack morphologies that are identical to those observed in smooth specimens tested in high–DO water. For example, the deepest crack was straight, nonbranching, transgranular through both the ferrite and pearlite regions without any preference, and showed considerable oxidation and some pitting at the crack origin. In fatigue test specimens, near–surface cracks grow entirely as tensile cracks normal to the stress and across both the soft ferrite and hard pearlite regions, whereas in air, cracks grow at an angle of 45° to the stress axis and only along the ferrite regions (see Fig. 4 of a companion paper at this conference by Chopra and Park). The identical crack morphologies indicate that environment played a dominant role in crack initiation. Similar characteristics of transgranular crack propagation through both weld and base metal, without regard to microstructural features, have also been identified in German reactors (Hickling and Blind, 1986).

Components tests have also been conducted to validate the calculation procedures and the applicability of the test results from specimen to actual reactor component. Tests on pipes, plates, and nozzles, under cyclic thermal loading in aqueous environment (Kussmaul et al., 1983) indicate that crack initiation in simulated LWR environments may occur earlier than the values of the ASME Section III fatigue design curve; environmental effects are more pronounced in the ferritic steel than in the austenitic cladding. Tests at the HDR–facility (Katzenmeier et al., 1990) have also shown good agreement between the fatigue lives applicable to specimens and components, e.g., first incipient crack on pipes appeared in 1200 cycles, compared with 1400 cycles for a test specimen made of the same material and tested under comparable conditions (8 ppm DO).

Safety Injection System and Pressurizer Surge Line

Significant cracking has also occurred in unisolable pipe sections in the safety injection system piping connected to the PWR coolant system (NRC 1988a, b). This phenomenon, which is similar to the nozzle cracking discussed above, is caused by thermal stratification. Also, regulatory evaluation has indicated that thermal stratification can occur in all PWR surge lines (NRC 1988c). In PWRs, the pressurizer water is heated to ≈227°C (440°F). The hot water, flowing at a very slow rate from the pressurizer through the surge line to the hot–leg piping, rides on a cooler water layer. The thermal gradients between the upper and lower parts of the pipe can be as high as 149°C (300°F).

Full–scale mock-up tests to generate thermal stratification in a pipe in a laboratory have confirmed the applicability of laboratory data to component behavior (Lenz et al., 1990). The material, loading, and environmental conditions were simulated on a 1:1 scale, using only thermohydraulic effects. Under the loading conditions, i.e., strain rate and strain range typical of thermal stratification in these piping systems, the coolant environment is known to have a significant effect on fatigue crack initiation (Chopra, 1999; Kanasaki et al., 1997a, b).

Steam Generator Girth Weld cracking

Another instance of thermal–fatigue–induced cracking where environmental effects are believed to have played a role in crack initiation has been observed at the weld joint between the two shells of a steam generator (Foley et al., 1991). The feedwater temperature in this region is nominally 204–227°C (440–440°F), compared with the steam generator temperature of 288°C (550°C). The primary mechanism of cracking has been considered corrosion fatigue with possible slow crack growth due to stress corrosion cracking. A detailed analysis of girth–weld cracking indicates that crack initiation was dominated by environmental influences, particularly under relatively high–DO content and/or oxidizing potential (Bamford et al., 1991).

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; develop a new set of environmentally adjusted design fatigue curves (Chopra and Shack, 1998b, 1999; Chopra, 1999; Chopra and Smith 1998) or use fatigue life correction factors F_{en} to adjust the current ASME Code fatigue usage values for environmental effects (Chopra and Shack, 1999; Chopra, 1999; Mehta and Gosselin, 1996, 1998). For both approaches, the range and bounding values must be defined for key service parameters that influence fatigue life. It has been demonstrated that estimates of fatigue lives based on the two methods may differ because of differences between the ASME mean curves used to develop the current design curves and the best–fit curves to the existing data used to develop the environmentally adjusted curves. However, either of these methods provides an acceptable approach to account for environmental effects.

Design Fatigue Curves

A set of environmentally adjusted design fatigue curves can be developed from the best–fit stress–vs.–life 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 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 best–fit experimental curves are first adjusted for the effect of mean stress by using the modified Goodman relationships

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

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

where S'_a is the adjusted value of stress amplitude S_a, and σ_y and σ_u are yield and ultimate strengths of the material, respectively. Equations 1a and 1b assume the maximum possible mean stress and typically yield a conservative adjustment for mean stress, at least when environmental effects are not significant. 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 life N of CSs is represented by

$$\ln(N) = 6.564 - 1.975\ \ln(\varepsilon_a - 0.113), \tag{2a}$$

and of LASs by

$$\ln(N) = 6.627 - 1.808\ \ln(\varepsilon_a - 0.151), \tag{2b}$$

where ε_a is applied strain amplitude (%). In LWR environments, the fatigue life of CSs is represented by

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

and of LASs by

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

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

$$\begin{array}{lll}
S^* = 0.015 & (\text{DO} > 1.0\ \text{ppm}) & \\
S^* = S & (\text{DO} \le 1.0\ \text{ppm}\ \&\ 0 < S \le 0.015\ \text{wt.\%}) & \\
S^* = 0.015 & (\text{DO} \le 1.0\ \text{ppm}\ \&\ S > 0.015\ \text{wt.\%}) & (4a) \\
T^* = 0 & (T < 150°\text{C}) & \\
T^* = T - 150 & (T = 150\text{–}350°\text{C}) & (4b) \\
O^* = 0 & (\text{DO} < 0.05\ \text{ppm}) & \\
O^* = \ln(\text{DO}/0.04) & (0.05\ \text{ppm} \le \text{DO} \le 0.5\ \text{ppm}) & \\
O^* = \ln(12.5) & (\text{DO} > 0.5\ \text{ppm}) & (4c) \\
\dot{\varepsilon}^* = 0 & (\dot{\varepsilon} > 1\%/\text{s}) & \\
\dot{\varepsilon}^* = \ln(\dot{\varepsilon}) & (0.001 \le \dot{\varepsilon} \le 1\%/\text{s}) & \\
\dot{\varepsilon}^* = \ln(0.001) & (\dot{\varepsilon} < 0.001\%/\text{s}). & (4d)
\end{array}$$

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 Eq. 5a

$$\ln(N) = 6.703 - 2.030\ \ln(\varepsilon_a - 0.126), \tag{5a}$$

and for Type 316NG, by Eq. 5b

$$\ln(N) = 7.422 - 1.671\ \ln(\varepsilon_a - 0.126). \tag{5b}$$

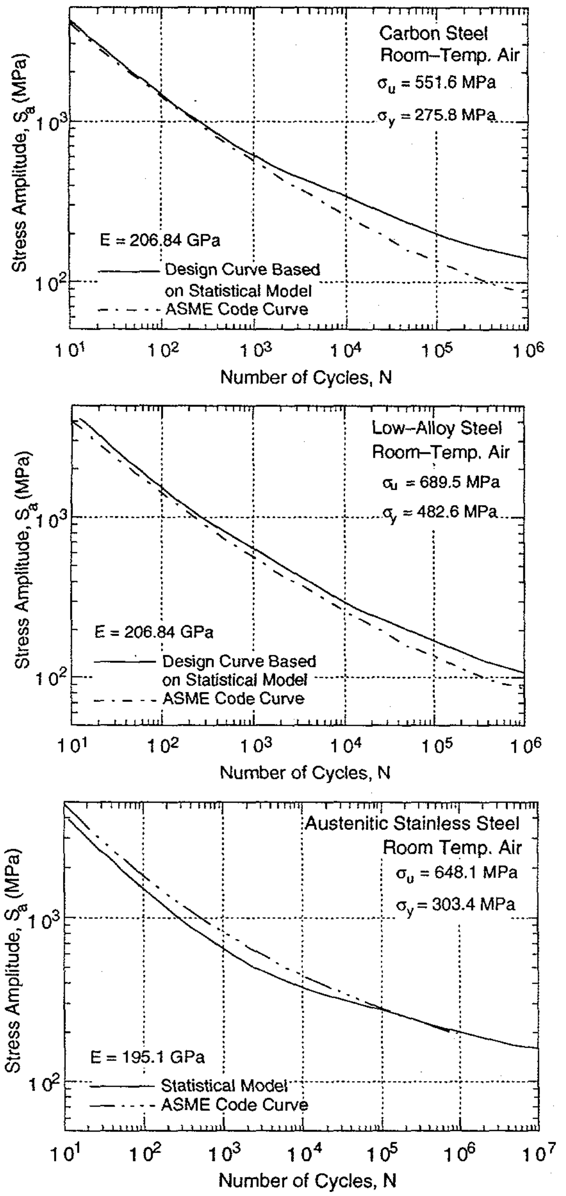

Fig. 4. Design fatigue curve developed from statistical model in air at room temperature

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

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

and for Type 316NG, by

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

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

$$\begin{array}{ll} T' = 0 & (T < 180°C) \\ T' = (T - 180)/40 & (180 \le T < 220°C) \\ T' = 1 & (T \ge 220°C) \end{array} \tag{7a}$$

$$\begin{array}{ll} \dot{\varepsilon}' = 0 & (\dot{\varepsilon} > 0.4\%/s) \\ \dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4) & (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\ \dot{\varepsilon}' = \ln(0.0004/0.4) & (\dot{\varepsilon} < 0.0004\%/s) \end{array} \tag{7b}$$

$$\begin{array}{ll} O' = 0.260 & (DO < 0.05\ ppm) \\ O' = 0 & (DO \ge 0.05\ ppm). \end{array} \tag{7c}$$

The models are recommended for predicted fatigue lives of $\le 10^6$ cycles.

The design fatigue curves were obtained from the best–fit curves, represented by Eqs. 2a–3b for CSs and LASs, and by Eqs. 5a and 6a for austenitic SSs. 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 imposed in the current Code curves, e.g., the adjusted best–fit curves were decreased by a factor of 2 on stress for CSs and LASs and by a factor of 1.5 for austenitic SSs. A factor of 20 on life was used for all of the curves, although the actual margin on life is 10–16 for SSs because of the differences between the ASME mean curve and the best–fit curve to existing fatigue data.

The new design fatigue curves for CSs and LASs and austenitic SS in air are shown in Fig. 4, whereas those in LWR coolant environments are shown in Figs. 5–7; only the portions of the environmentally adjusted curves that fall below the current ASME Code curve are shown in Figs. 5–7. Because the fatigue life of Type 316NG is superior to that of Types 304 or

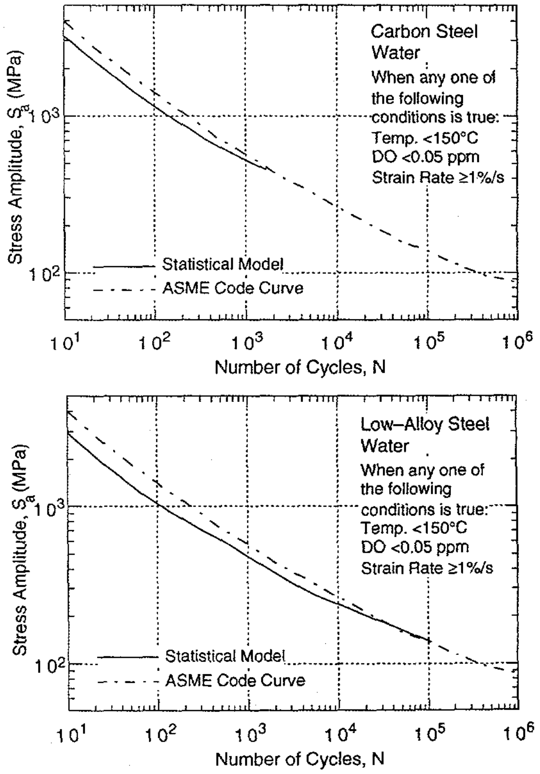

Fig. 5. Design fatigue curves developed from statistical model under service conditions where one or more critical threshold values are not satisfied

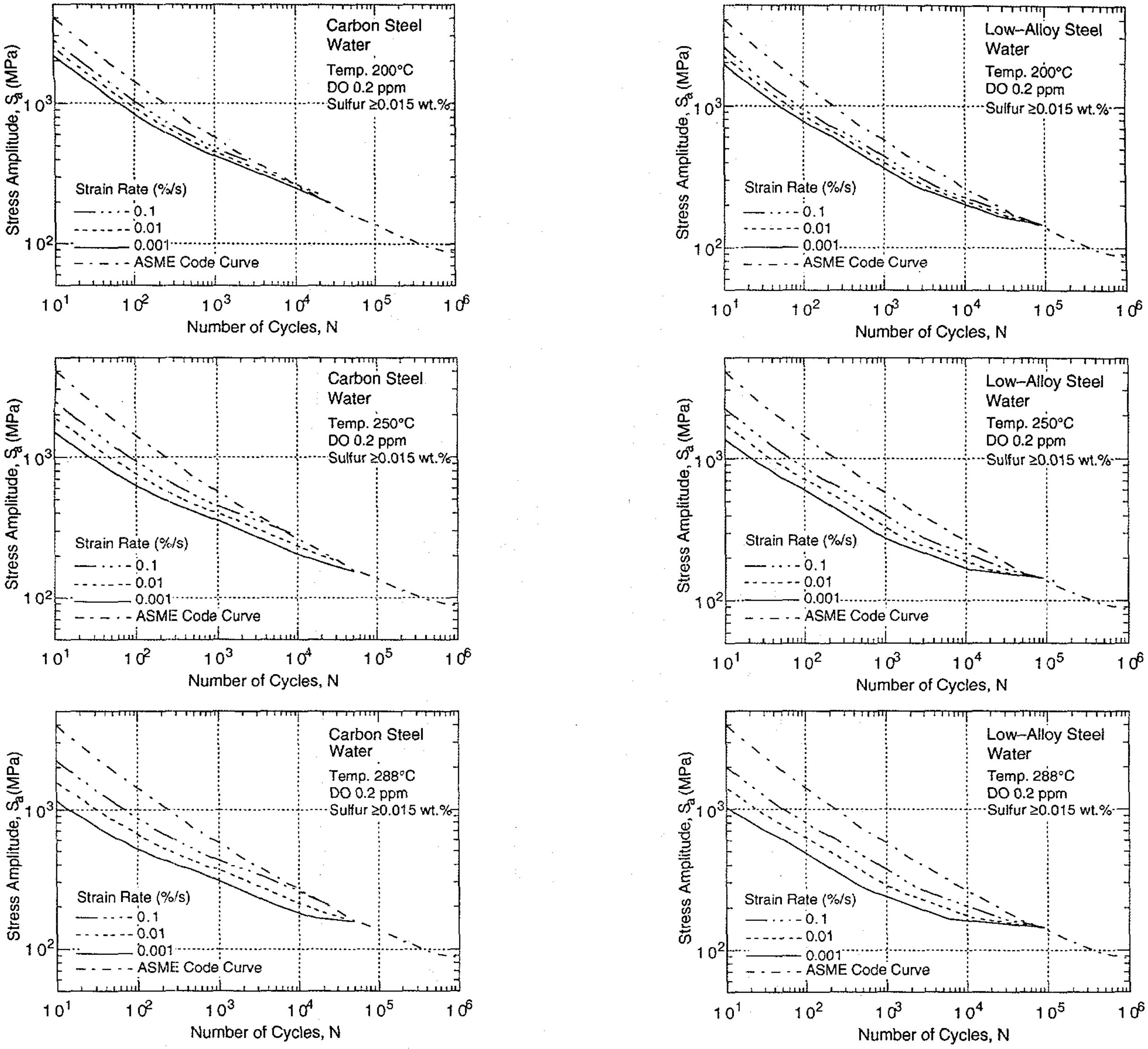

Fig. 6. Design fatigue curves developed from statistical model for carbon and low–alloy steels under service conditions where all critical threshold values are satisfied

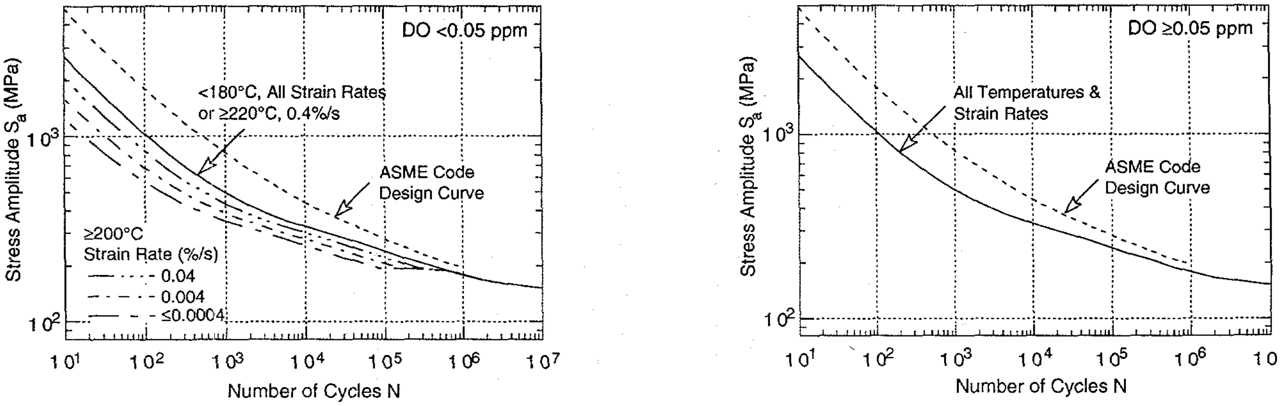

Fig. 7. Design fatigue curves developed from statistical models for Types 304 and 316 SS in water with <0.05 and ≥0.05 ppm DO

316 SS, the design curves in Figs. 4 and 7 will be somewhat conservative for Type 316NG SS. For carbon and low–alloy steels, a set of design curves similar to those shown in Fig. 6 can be developed for low–S steels, i.e., steels with ≤0.007 wt.% S. The results indicate that in room–temperature air, the current ASME Code design curves for CSs and LASs are conservative with respect to the curves based on the statistical models, and those for austenitic SSs are nonconservative at stress levels above 300 MPa.

For environmentally adjusted design fatigue curves (Figs. 5–7), we define a minimum threshold strain, below which environmental effects are modest. The threshold strain for CSs and LASs 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 experimental scatter. The threshold strain amplitudes are decreased by ≈15% for CSs and by ≈40% for LASs to account for the effects of mean stress, and by a factor of 1.7 on strain to provide 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) is obtained for both CSs and LASs. 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) is obtained for austenitic SSs. The PVRC steering committee for CLEE (Yukawa, 1999) has proposed a ramp for the threshold strain; a lower strain amplitude below which environmental effects are insignificant, a slightly higher strain amplitude above which environmental effects decrease fatigue life, and a ramp between the two values. The two strain amplitudes are 0.07 and 0.08% for carbon and low–alloy steels, and 0.10 and 0.11% for austenitic SSs (both wrought and cast SS). These threshold values have been used to develop Figs. 6 and 7.

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 life in air at room temperature to that in water at the service temperature (Higuchi and Iida, 1991). A fatigue life correction factor F_{en} can be obtained from the statistical model (Eqs. 2–7), where

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

The fatigue life correction factor for CSs is given by

$$F_{en} = \exp(0.554 - 0.101\,S^*\,T^*\,O^*\,\dot{\varepsilon}^*), \tag{9a}$$

for LASs, by

$$F_{en} = \exp(0.898 - 0.101\,S^*\,T^*\,O^*\,\dot{\varepsilon}^*), \tag{9b}$$

and for austenitic SSs, by

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

where the constants S^*, T^*, $\dot{\varepsilon}^*$ and O^* are defined in Eqs. 4a–4d, and T', $\dot{\varepsilon}'$ and O' are defined in Eqs. 7a–7c. A strain threshold is also defined, below which environmental effects are modest. The strain threshold is represented by a ramp, i.e., a lower strain amplitude below which environmental effects are insignificant, a slightly higher strain amplitude above which environmental effects are significant, and a ramp between the two values. Thus, the negative terms in Eqs. 9a–9c are scaled from zero to their actual value between the two strain thresholds. The two strain amplitudes are 0.07 and 0.08% for CSs and LASs, respectively, and 0.10 and 0.11% for austenitic SSs (both wrought and cast SS). 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. The experimental data adjusted for environmental effects, i.e., the product of experimentally observed fatigue life in LWR environments and F_{en}, are presented with the best–fit S–N curve in room–temperature air in Fig. 8.

A similar approach has been proposed by Mehta and Gosselin (1996, 1998); however, they defined F_{en} as the ratio of the life in air to that in water, both at service temperature. The F_{en} approach, also known as the EPRI/GE approach, has recently been updated to include the revised statistical models and the PVRC discussions on environmental fatigue evaluations (Mehta, 1999). An "effective" fatigue life correction factor, expressed as $F_{en,eff} = F_{en}/Z$, is defined where Z is a factor that constitutes the perceived conservatism in the ASME Code design curves. The $F_{en,eff}$ approach presumes that all uncertainties have been anticipated and accounted for.

CONCLUSIONS

The work performed at Argonne National Laboratory on fatigue of carbon and low–alloy steels in LWR environments is summarized. The existing fatigue S–N data have been evaluated to establish the effects of various material and loading variables such as steel type, strain range, strain rate, temperature, sulfur content in steel, orientation, and DO level in water on the fatigue life of these steels. Statistical models are presented for estimating the fatigue S–N curves as a function of material, loading, and environmental variables. Case studies of fatigue failures in nuclear power plants are presented and the contribution of environmental effects on crack initiation is discussed.

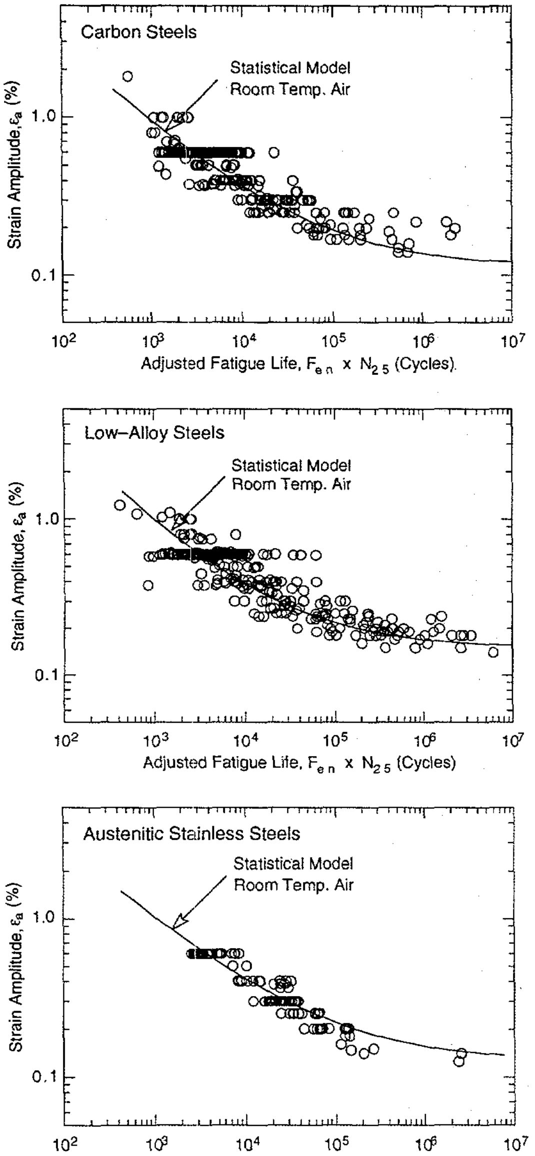

Fig. 8. Comparison of experimental data adjusted for environmental effects with best–fit fatigue S–N curve in room–temperature air

The current two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations, i.e., the design fatigue curve method and the fatigue life correction factor method, are presented. Both methods are based on the statistical models for estimating fatigue lives of carbon and low–alloy steels and austenitic SSs in LWR environments. Although estimates of fatigue lives based on the two methods may differ because of differences between the ASME mean curves used to develop the current design curves and the best–fit curves to the existing data used to develop the environmentally adjusted curves, either of these methods provides an acceptable approach to account for environmental effects.

The environmentally adjusted design fatigue curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. The new 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. The current Code design curve for CSs is comparable to the statistical–model curve for LASs, whereas it is somewhat conservative at stress levels of <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 4 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. Therefore, usage factors that are based on the F_{en} method would be lower than those determined from the environmentally corrected design fatigue curves.

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