DEVELOPMENT OF FATIGUE DESIGN CURVE FOR AUSTENITIC STAINLESS STEELS IN LWR ENVIRONMENTS: A REVIEW

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ABSTRACT

The ASME Boiler and Pressure Vessel Code provides rules for the construction of nuclear power plant components and 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. Existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of LWR coolant environments on the fatigue resistance of pressure vessel and piping steels. This paper reviews the existing fatigue ε–N data for austenitic stainless steels in LWR coolant environments. The effects of key material, loading, and environmental parameters, such as steel type, strain amplitude, strain rate, temperature, dissolved oxygen level in water, and flow rate, on the fatigue lives of these steels are summarized. Statistical models are presented for estimating the fatigue ε–N curves for austenitic stainless steels as a function of the material, loading, and environmental parameters. Two methods for incorporating environmental effects into the ASME Code fatigue evaluations are presented. Data available in the literature have been reviewed to evaluate the conservatism in the existing ASME Code fatigue design curves.

INTRODUCTION

Experience with operating nuclear power plants worldwide reveals that many failures may be attributed to fatigue; examples include piping components, nozzles, valves, and pumps.[1–5] In most cases, these failures have been associated with thermal loading due to thermal stratification and striping, or with mechanical loading due to vibration. The effect of these loadings may also have been aggravated by the high–temperature aqueous environments of nuclear power plants. The mechanism of cracking in feedwater nozzles and piping has been attributed to corrosion fatigue[6,7] or strain–induced corrosion cracking (SICC).[8,9] Significant cracking has also occurred in nonisolable piping connected to a pressurized water reactor (PWR) coolant system.[10–12] Significant occurrences of corrosion fatigue damage and failures in various nuclear power plant systems have been reviewed in an Electric Power Research Institute (EPRI) report.[13] The U.S. experience related to PWR primary–system leaks observed during the period 1985 through 1996 has been assessed by Shah et al.[14]

Section III, Subsection NB, of the ASME Boiler and Pressure Vessel Code contains rules for the design of Class 1 components of nuclear power plants. Figures I–9.1 through I–9.6 of Appendix I to Section III specify the Code design fatigue curves for applicable structural materials. These design curves were based primarily on strain–controlled fatigue tests of small polished specimens at room temperature in air. Best–fit curves to the experimental test data were first adjusted to account for the effects of mean stress and then lowered by a factor of 2 on stress and 20 on cycles (whichever was more conservative) to obtain the design fatigue curves. These factors are not safety margins but rather adjustment factors that must be applied to experimental data to obtain estimates of the fatigue lives of components.

However, the mean stress–corrected fatigue curve used to develop the current Code fatigue design curve for austenitic stainless steels (SSs) does not accurately represent the available experimental data.[15,16] 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. Also, because, for the current Code mean curve, the fatigue strength at 10^6 cycles is greater than the monotonic yield strength of austenitic SSs, the current Code design curve for austenitic SSs does not include a mean stress correction.

Existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of LWR coolant environments on the fatigue resistance of carbon and low–alloy steels,[17,18] as well as austenitic SSs.[16,18] Therefore, the margins in the ASME Code may be less conservative than originally intended. Section III, Subsection NB–3121, of the Code states that the effects of the coolant environment on fatigue resistance of a material were not intended to be addressed in these design curves.

Two approaches have been proposed for incorporating the effects of LWR environments into ASME Section III fatigue evaluations: (a) develop new fatigue design curves for LWR applications and (b) use an environmental correction factor to account for the effects of the coolant environment. Both approaches are based on existing fatigue ε–N data in LWR environments, i.e., the best–fit curves to the experimental fatigue ε–N data in LWR environments are used to obtain both the design curves and the environmental correction factor.

Environmentally adjusted fatigue design curves have been developed from the best fit to the experimental data in LWR environments by using the procedure used to develop the current ASME Code fatigue design curves. These curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. Interim fatigue design curves that address environmental effects on fatigue life of carbon and low–alloy steels and austenitic SSs were first proposed by Majumdar et al.[19] Fatigue design curves based on a rigorous statistical analysis have been developed by Keisler et al.[20,21] Design curves based on updated statistical models have been presented in NUREG/CR–5704[16] and NUREG/CR–6717.[18] Results of the statistical analysis have also been used to interpret ε–N curves in terms of the probability of fatigue cracking.

The second approach, proposed by Higuchi and Iida,[22] considers the effects of reactor coolant environments on fatigue life in terms of an environmental correction factor F_{en}, which is the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into the Code fatigue evaluations, a fatigue usage factor 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 statistical models[18,23–25] and on the correlations developed by the Environmental Fatigue Data Committee of the Thermal and Nuclear Power Engineering Society of Japan,[26] have been proposed.

This paper reviews the existing fatigue ε–N data for wrought and cast austenitic SSs in LWR coolant environments. The effects of key material, loading, and environmental parameters, such as steel type, strain amplitude, strain rate, temperature, and dissolved oxygen (DO) level in water, on the fatigue lives of these steels are summarized. Statistical models are presented for estimating the fatigue ε–N curves as a function of material, loading, and environmental parameters. Two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented.

OVERVIEW OF FATIGUE ε–N DATA

The relevant fatigue ε–N data for austenitic SSs in air include the data compiled by Jaske and O'Donnell[15] for developing fatigue design criteria for pressure vessel alloys, the JNUFAD* data base from Japan, and the results of Conway et al.[27] and Keller.[28] In water, the existing fatigue ε–N data include the tests performed by General Electric Co. (GE) in a test loop at the Dresden 1 reactor,[29] the JNUFAD data base, studies at Mitsubishi Heavy Industries, Ltd. (MHI),[30–35] Ishikawajima Harima Heavy Industries Co. (IHI),[36,37] and Hitachi[38,39] in Japan, and the present work at Argonne National Laboratory (ANL).[16,40–43] In these studies, various criteria are used to define the fatigue life of a test specimen. In the present study, fatigue life N for strain–controlled tests is defined as the number of cycles for tensile stress to decrease by 25% from its peak or steady–state value. Fatigue lives defined by other criteria, e.g., a 50% decrease in peak tensile stress or complete failure, have been converted by solving the equation

$$N = N_X / (0.947 + 0.00212\,X), \qquad (1)$$

where X represents the failure criteria, i.e., 25, 50, or 100% decrease in peak tensile stress.

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*M. Higuchi, Ishikawajima–Harima Heavy Industries Co., Japan, private communication to M. Prager of the Pressure Vessel Research Council, 1992.

In air, the data base for austenitic SSs is composed of 500 tests: 240 on 26 heats of Type 304 SS, 170 on 15 heats of Type 316 SS, and 90 on 4 heats of Type 316NG. Most of the tests have been conducted on cylindrical gauge specimens with fully reversed axial loading; ≈75 tests were on hourglass specimens, and ≈40 data points were from bending tests on flat-sheet specimens with rectangular cross section. Nearly 60% of the tests in air were conducted at room temperature, 20% at 250–325°C, and 20% at 350–450°C. The results indicate that specimen geometry has little or no effect on the fatigue life of austenitc SSs; the fatigue lives of hourglass specimens are comparable to those of gauge specimens.

In water, the existing fatigue ε–N database consists of 310 tests: 150 on 9 heats of Type 304 SS, 60 on 3 heats of Type 316 SS, and 100 on 4 heats of Type 316NG. Nearly 90% of the tests in water were conducted at temperatures between 260 and 325°C. The data on Type 316NG in water have been obtained primarily at DO levels ≥0.2 ppm and those on Type 316 SS, at ≤0.005 ppm DO; half of the tests on Type 304 SS were at low DO levels, the remaining half, at high DO levels.

The existing ε–N data for cast SS are very limited; a total of 64 tests on 5 heats of CF–8M SS.[18,32,34] Nearly 90% of the tests have been conducted in simulated PWR water at 325°C. Although fatigue ε–N data have also been obtained on SS welds in LWR environments, the results were not included in the present review.

Air Environment

The fatigue ε–N behavior of austenitic SSs is shown in Fig. 1, where the designated three curves are based on the current ASME Code mean curve, the best–fit curve developed by Jaske and O'Donnell,[15] and an updated statistical model that is discussed later. The fatigue lives of Types 304 and 316 SS are comparable; those of Type 316NG are slightly higher at high strain amplitudes. The results indicate that the fatigue life of austenitic SSs in air is independent of temperature in the range from room temperature to 427°C. Also, although the effect of strain rate on fatigue life seems to be significant at temperatures above 400°C, variation in strain rate in the range of 0.4–0.008%/s has no effect on the fatigue lives of SSs at temperatures up to 400°C.[44] The fatigue ε–N behavior of cast CF–8 and CF–8M SSs is similar to that of wrought austenitic SSs.[16]

Under cyclic loading, austenitic SSs exhibit rapid hardening during the first 50–100 cycles; the extent of hardening increases with increasing strain amplitude and decreasing temperature and strain rate.[16,44] The initial hardening is followed by softening and a saturation stage at high temperatures, and by continuous softening at room temperature (RT).

Some of the tests on Type 316 SS in room–temperature air have been conducted in load–control mode at stress levels in the range of 190–230 MPa. For these tests, the strain amplitudes were calculated only as elastic strains, i.e., strain amplitudes of 0.1–0.12% (the data are shown as circles in Fig. 1, with fatigue lives of 4×10^5–3×10^7). Based on cyclic stress–vs.–strain correlations for Type 316 SS,[16] actual strain amplitudes for these tests should be 0.23–0.32%. These data were excluded from the analysis in NUREG/CR–5704[16] for updating the statistical model for estimating the fatigue life of austenitic SSs in air.

Figure 1 also shows that the ASME mean curve is not consistent with the existing fatigue ε–N data for austenitic SSs. At strain amplitudes <0.5%, the mean curve predicts significantly longer fatigue lives than those observed experimentally.

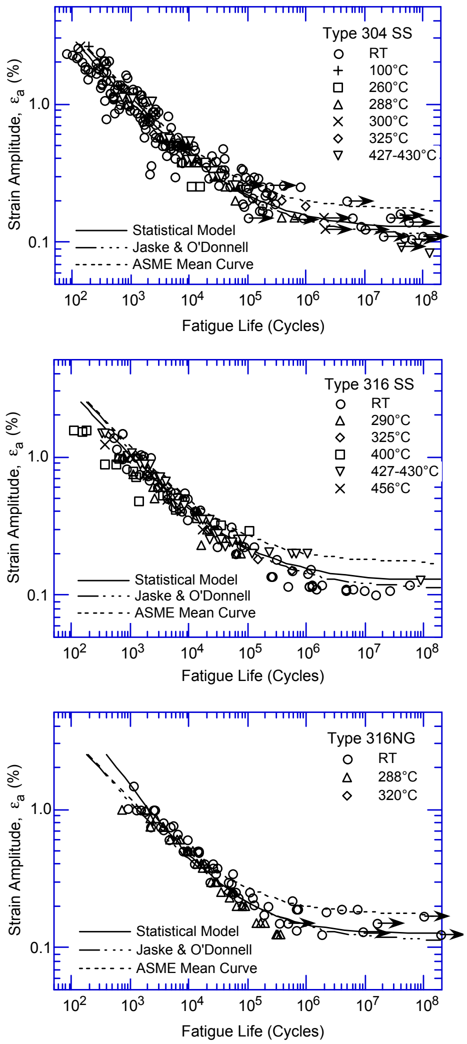


Figure 1. Fatigue ε–N behavior of Types 304, 316, and 316NG austenitic stainless steel in air at various temperatures (Refs. 15,16,18,27,28,JNUFAD data)

LWR Environment

The fatigue lives of austenitic SSs are decreased in LWR environments; the reduction depends on strain rate, level of DO in the water, and temperature.[16,18,30–43] The effects of LWR environments on the fatigue lives of wrought materials are comparable for Types 304, 316, and 316NG SSs, whereas the effects on cast materials differ somewhat. The critical parameters that influence fatigue life and the threshold values of these parameters for environmental effects to be significant are summarized below.

Strain Amplitude: A minimum threshold strain is required for environmentally assisted decrease in the fatigue life of SSs. The threshold strain appears to be independent of material type (weld or base metal) and temperature in the range of 250–325°C, but it tends to decrease as the strain amplitude is decreased.[35] The results suggest that the threshold strain is related to the elastic strain range of the test, and does not correspond to the strain at which the crack closes. For fully reversed cyclic loading, the crack opening point can be identified as the point where the curvature of the load–vs.–displacement line changes before the peak compressive load. In the present study, evidence of a crack opening point was observed for cracks that had grown relatively large, i.e., near the end of life. Also, the threshold strain does not correspond to the rupture strain of the surface oxide film. The fatigue life of a Type 304 SS in low–DO water at 288°C with a 2–min hold period at zero strain during the tensile rise portion of the cycle was identical to that observed without the hold period.[18] If this threshold strain corresponds to the rupture strain of the surface oxide film, a hold period at the middle of each cycle should allow repassivation of the oxide film, and environmental effects on fatigue life should diminish.

Hold–Time Effects: Environmental effects on fatigue life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Consequently, loading and environmental conditions during the tensile–loading cycle, e.g., strain rate, temperature, and DO level, are important for environmentally assisted reduction of the fatigue lives of these steels. Limited data indicate that hold periods during peak tensile or compressive strain have no effect on the fatigue life of austenitic SSs in high–DO water. The fatigue lives of Type 304 SS tested in high–DO water with a trapezoidal waveform (i.e., hold periods at peak tensile and compressive strain)[29] are comparable to those tested with a triangular waveform.[36]

Strain Rate: Fatigue life decreases with decreasing strain rate. In low–DO PWR environments, fatigue life decreases logarithmically with decreasing strain rate below ≈0.4%/s; the effect of environment on life saturates at ≈0.0004%/s (Fig. 2).[16,32–36,42] A decrease in strain rate from 0.4 to 0.0004%/s decreases the fatigue life of austenitic SSs by a factor of ≈10. For some SSs, the effect of strain rate may be less pronounced in high–DO water than in low–DO water; the effect of DO level on the fatigue life of austenitic SSs is discussed below. For cast SSs, the effect of strain rate on fatigue life is the same in low– and

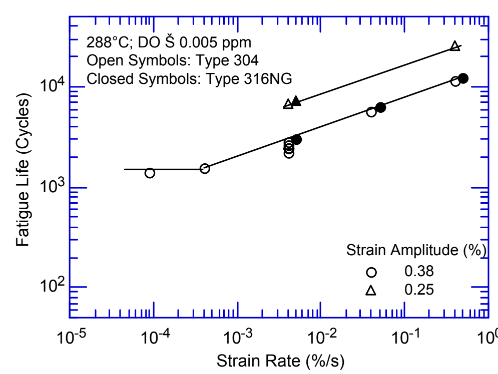


Figure 2. Dependence of fatigue life of austenitic stainless steels on strain rate in low—DO water (Refs.16,42)

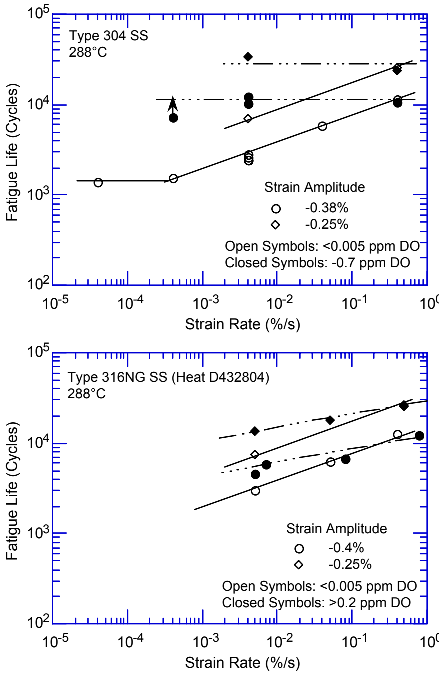


Figure 3. Dependence of fatigue life of austenitic stainless steel on strain rate in high– and low–DO water at 288°C (Refs. 16,18)

high–DO water and is comparable to that observed for the wrought SSs in low–DO water.[32,34,42]

Dissolved Oxygen in Water: The fatigue lives of wrought and cast SSs are decreased significantly in low–DO (i.e., <0.01 ppm) water; the effect is greater at low strain rates and high temperatures.[30-42] Environmental effects on the fatigue lives of these steels in high–DO water are not well known; the magnitude of environmental effects in high–DO water may be influenced by the composition or heat treatment of the steel. The fatigue lives of wrought SSs in high–DO water are comparable[32,34] for some steels and higher[16] for other steels than those in low–DO water. The existing fatigue ε–N data indicate that in low–DO water, the fatigue lives of cast SSs are comparable to those for wrought SSs.[16,32,34,42] Limited data suggest that the fatigue lives of cast SSs in high–DO water are approximately the same as those in low–DO water.[16]

Only moderate environmental effects were observed for Type 304 SS when the conductivity of the water was maintained at <0.1 µS/cm and the electrochemical potential (ECP) of the steel was above 150 mV.[18] During a laboratory test, the time to reach these stable environmental conditions depends on test parameters such as the autoclave volume, flow rate, etc. In the ANL test facility, fatigue tests on austenitic SSs in high–DO water required a soaking period of 5–6 days for the ECP of the steel to stabilize. The steel ECP increased from zero or a negative value to above 150 mV during this period. The fatigue lives of Type 304 SS specimens soaked for ≈5 days in high–DO water before testing in high–DO water at 289°C and ≈0.38 and 0.25% strain amplitude, are plotted as a function of strain rate in Fig. 3a. Similar results for Type 316NG specimens that were soaked for only one day before testing are shown in Fig. 3b. For Type 304 SS, fatigue life decreases linearly with decreasing strain rate in low–DO water, whereas in high–DO water, strain rate has no effect on fatigue life. For example, the fatigue life at ≈0.38% strain amplitude and 0.0004%/s strain rate is ≈1500 cycles in low–DO water and >7300 cycles in high–DO water. At all strain rates, the fatigue life of Type 304 SS is 30% lower in high–DO water than in air. However, the results obtained at MHI, Japan, on Types 304 and 316 SS show a different behavior; environmental effects are observed to be the same in high– and low–DO water.[32,]

For 316NG, some effect of strain rate is observed in high–DO water, although it is smaller than that in low–DO water (Fig. 3b). The different strain rate effect for the two steels has been explained on the basis of the shorter soak period for Type 316NG specimens, e.g., 24 h for Type 316NG and ≈120 h for Type 304 SS.[18] Environmental conditions may not have been stable for the tests on Type 316NG in high–DO water.

The effect of the conductivity of water and the ECP of the steel on the fatigue life of austenitic SSs is shown in Fig. 4. Environmental effects are significant for the specimens that were soaked for 24 h. For these tests, the ECP of steel was very low initially and increased during the test. Also, in high–DO water, fatigue life is decreased by a factor of ≈2 when conductivity of water is increased from ≈0.07 to 0.4 µS/cm.

The effects of water chemistry and soaking period on the fatigue life of austenitic SSs in low–DO water have also been investigated; the results are presented in Table 1. In low–DO water, the following have no effect on the fatigue life of Type 304 SS: the addition of lithium and boron, low conductivity, soak period of ≈5 days before the test, and dissolved hydrogen.

These results suggest that the existing fatigue ε–N data on austenitic SSs in high–DO environments should be reevaluated; some

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

Test No.	Dis. Oxygen[b] (ppb)	Dis. Hydrogen (cc/kg)	Li (ppm)	Boron (ppm)	Pre–soak (days)	pH at RT	Conduc-tivity[c] (µS/cm)	ECP SS[b] mV (SHE)	Ten. Rate (%/s)	Stress Amplitude (MPa)	Strain Amplitude (%)	Life N_{25} (Cycles)
1805	–	–	–	–	–	–	–	–	4.0E-3	234.0	0.38	14,410
1808	4	23	2	1000	1	6.4	18.87	–690	4.0E-3	234.1	0.39	2,850
1821	2	23	2	1000	1	6.5	22.22	–697	4.0E-3	237.1	0.38	2,420
1859	2	23	2	1000	1	6.5	18.69	–696	4.0E-3	235.9	0.38	2,420
1861	1	23	–	–	1	6.2	0.06	–614	4.0E-3	231.5	0.39	2,620
1862	2	23	–	–	5	6.2	0.06	–607	4.0E-3	233.0	0.39	2,450
1863	1	–	–	–	5	6.3	0.06	–540	4.0E-3	238.2	0.38	2,250
1871[d]	5	–	–	–	7	6.1	0.09	–609	4.0E-3	239.0	0.38	2,180

[a]Fully reversed axial fatigue tests at 288°C, ≈0.77% strain range, sawtooth waveform with 0.004/0.4%/s strain rates.
[b]Measured in effluent.
[c]Measured in feedwater supply tank.

[d]Test conducted with a 2–min hold period at zero strain.

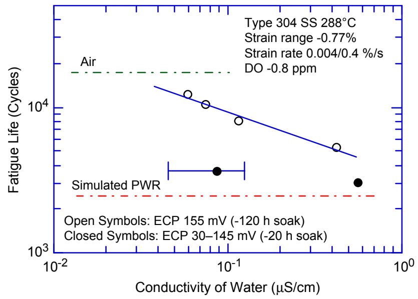


Figure 4. Effects of conductivity of water and soaking period on fatigue life of Type 304 SS in high–DO water (Ref. 18)

of the data may have been obtained under varying environmental conditions. For example, the ECP of the steel may have been negative at the start of the test, and low–DO environment or negative ECP is known to decrease fatigue life of austenitic SSs. Also, the composition or heat treatment of the steel may have an important impact on the magnitude of environmental effects in high–DO environments. Additional data are needed to improve our insight into the effect of DO content on the fatigue life of austenitic SSs in LWR environments.

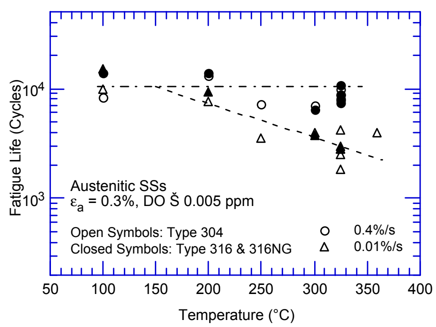


Figure 5. Change in fatigue lives of austenitic stainless steels in low–DO water with temperature (Refs.16,18,32,34,36)

Temperature: The change in fatigue lives of austenitic SSs with test temperature at ≈0.3% strain amplitude and two strain rates is shown in Fig. 5. The results suggest a threshold temperature of 150°C, above which the environment decreases fatigue life in low–DO water if the strain rate is below the threshold of 0.4%/s. In the range of 150–325°C, the logarithm of fatigue life decreases linearly with temperature. Only a moderate decrease in life is observed in water at temperatures below the threshold value of 150°C.

Actual loading histories encountered during service in nuclear power plants involve variable loading conditions, whereas the existing fatigue ε–N data have been obtained at constant strain rate, temperature, and strain amplitude. Fatigue tests have been conducted at MHI Japan on Type 316 SS under conditions of combined mechanical and thermal cycling.[33] Triangular waveforms were used for both strain and temperature cycling. Two sequences were selected for temperature cycling: an in–phase sequence in which temperature cycling was synchronized with mechanical strain cycling, and a sequence in which temperature and strain were out–of–phase, i.e., maximum temperature occurred at minimum strain level and vice versa. Two temperature ranges, 100–325°C and 200–325°C, were selected for the tests.

The results are shown in Fig. 6, with the data obtained from tests at constant temperature. If we require that the applied strain and temperature be above a minimum threshold value for environmental effects to occur, then life should be longer for out–of–phase than for in–phase tests. For the thermal cycling tests represented in Fig. 6, the temperature was the average of the temperature at peak strain and the temperature at threshold strain or 150°C (whichever was higher). The threshold strain of 0.46% was assumed for the test. Thus, for the tests at 100–325°C, the temperatures plotted in Fig. 6 are the average of 239 and 150°C for out–of–phase tests, and the average of 186 and 325°C for in–phase tests. The results from thermal cycling tests agree well with those from constant–temperature tests (open circles in Fig. 6). The data suggest a linear decrease in life at temperatures above 150°C.

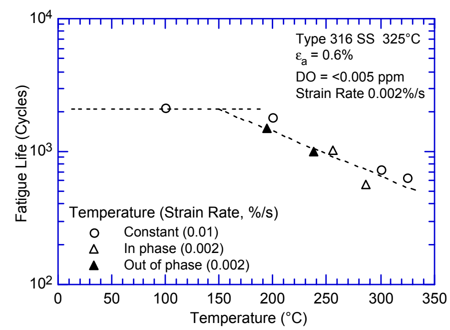
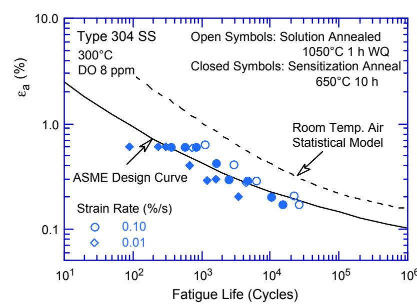


Figure 6. Fatigue life of Type 316 stainless steel under constant and varying test temperature (Ref. 33)

Sensitization Anneal: In low–DO water, a sensitization anneal has no effect on fatigue life of Types 304 and 316 SS, whereas environmental effects are larger in high–DO water (Fig. 7). For



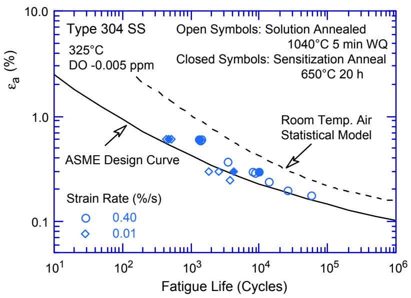


Figure 7. Effect of sensitization anneal on fatigue lives of Type 304 stainless steel in (a) high– and (b) low–DO water (Refs. 32,34)

example, the fatigue life of sensitized steel is a factor of ≈2 lower than that of solution–annealed material in high–DO water.[32,34] Sensitization has little or no effect on the fatigue life of Type 316NG SS in low– and high–DO water. The influence of the conductivity of water and the ECP of steel on the fatigue life of sensitized SS in high–DO water should be further investigated.

Flow Rate: The effect of flow rate on the fatigue life of austenitic SSs has not been evaluated. The data for carbon steels indicate that, under the environmental conditions typical of operating BWRs, environmental effects on the fatigue life of carbon steels are a factor of ≈2 lower at high flow rates (7 m/s) than at 0.3 m/s or lower.[45,46] Because the mechanism of fatigue crack initiation in LWR environments appears to be different in austenitic SSs than in carbon steels, the effect of flow rate on fatigue life may be different for SSs.

THE ANL STATISTICAL MODEL

Air Environment

Fatigue ε–N data are generally expressed in terms of the modified Langer equation,[47] which correlates fatigue life N with the applied strain amplitude ε_a as

$$\ln(N) = A - B \ln(\varepsilon_a - C), \qquad (2)$$

For Types 304 and 316 SS, the model coefficients A and B obtained from a reevaluation of the data did not significantly differ from those obtained earlier; the values from NUREG/CR–5704 were retained. However, different coefficients were obtained for Type 316NG SS because a larger data base was used in the present than in the earlier analysis. In air at temperatures up to 400°C, the fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 6.703 - 2.030 \ln(\varepsilon_a - 0.126), \qquad (3)$$

and for Type 316NG, by

$$\ln(N) = 7.433 - 1.782 \ln(\varepsilon_a - 0.126). \qquad (4)$$

These correlations are recommended for predicted fatigue lives $\leq 10^6$ cycles.

LWR Environments

As more fatigue ε–N data became available, the statistical model for austenitic SSs in LWR environments was updated.[16,18,20] In NUREG/CR–5704, separate correlations were proposed for low– and high–DO levels (< or ≥0.05 ppm), and low and high temperatures (< or ≥200°C).[16] The temperature dependence proposed by the Pressure Vessel Research Council (PVRC) steering committee for cyclic life and environmental effects (CLEE) was adopted in NUREG/CR–6717; environmental effects were considered moderate at temperatures below 180°C, significant above 220°C, and increased linearly between 180 and 220°C.[18] Also, in NUREG/CR–6717, environmental effects were considered moderate for wrought austenitic SSs in high–DO water with ≥0.05 ppm DO; for cast austenitic SSs, environmental effects were considered the same in both low– and high–DO water and equal to those for wrought SSs in low–DO water.

The critical parameters that influence fatigue life and the threshold values of these parameters for environmental effects to be significant have been summarized in the previous section. In LWR environments, the fatigue life of austenitic SSs depends on strain rate, DO level, and temperature. The functional forms for the effects of strain rate and temperature are shown in Figs. 2 and 5, respectively. For both wrought and cast austenitic SSs, the model assumes threshold and saturation values of 0.4 and 0.0004%/s, respectively, for strain rate, and a threshold value of 150°C for temperature. The influence of DO level on the fatigue life of austenitic SSs is not well understood. The fatigue lives are decreased significantly in low–DO, whereas in high–DO they are either comparable or, for some steels, higher than those in low–DO water. The composition or heat treatment of the steel may influence the magnitude of environmental effects on austenitic SSs. For example, in low–DO water, the fatigue life of sensitized Types 304 and 316 SS is the same as that of solution–annealed steel, whereas, in high–DO water, it is lower for the sensitized steel.

The least–squares fit of the experimental data in water yields a steeper slope for the ε–N curve than the slope of the curve obtained in air, i.e., coefficient B in Eq. 2 is smaller in water than in air. These results indicate that environmental effects are more pronounced at low than at high strain amplitudes. Such a behavior is difficult to rationalize in terms of the slip oxidation/dissolution or hydrogen enhanced crack growth model. Furthermore, different slopes for the ε–N curves in air and water environments would add complexity to the determination of the environmental correction factor F_{en}, discussed later in this paper. In NUREG/CR–5704 and NUREG/CR–6717, the slope of the ε–N curve was assumed to be the same in LWR and air environments.[16,18]

The mechanism of fatigue crack initiation in austenitic SSs in LWR environments has been examined in a companion paper included in these proceedings. Fatigue crack initiation has been divided into two stages: an initiation stage that involves the growth of microstructurally small cracks (MSCs) (i.e., cracks smaller than ≈200 µm), and a propagation stage that involves the growth of mechanically small cracks. The reduction in fatigue life of these steels is caused primarily by the effects of environment on the growth of MSCs and, to a lesser extent, on enhanced growth rates of mechanically small cracks. Environmental effects on the growth of MSCs may be more pronounced at low strain amplitudes and should be further investigated. Until further data become available to establish the effects of DO level in the water and composition and heat treatment of the steel on the fatigue life of austenitic SSs, the slope of the ε–N curve is assumed to be the same in LWR and air environments.

The existing fatigue ε–N data were reanalyzed to determine the coefficients of the statistical model for austenitic SSs in LWR environments. Certain data sets were excluded from the analysis. For example, because environmental effects are significantly greater on sensitized steels in high–DO water than on solution–annealed steels, the data for sensitized Types 304 and 316 SS in high–DO water were excluded. Also, based on the test results obtained at ANL (Fig. 3a)[18] the data in high–DO (>0.1 ppm) water that were obtained at temperatures >150°C and strain rates <0.4%/s were also excluded from the analysis; for these tests, the environmental conditions may not have been stable.

The model coefficients obtained from a reevaluation of the data did not significantly differ from those reported earlier in NUREG/CR-5704.[16] The results indicate that, in LWR environments, fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 5.768 - 2.030 \ln(\varepsilon_a - 0.126) + T' \dot{\varepsilon}' O' \quad (5)$$

and for Type 316NG, by

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

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

$$\begin{aligned} &T' = 0 && (T < 150°C) \\ &T' = (T - 150)/175 && (150 \le T < 325°C) \\ &T' = 1 && (T \ge 325°C) \end{aligned} \quad (7)$$

$$\begin{aligned} &\dot{\varepsilon}' = 0 && (\dot{\varepsilon} > 0.4\%/s) \\ &\dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4) && (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\ &\dot{\varepsilon}' = \ln(0.0004/0.4) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad (8)$$

$$O' = 0.260 \quad \text{(all DO levels and wrought and cast SS).} \quad (9)$$

These correlations are recommended for predicted fatigue lives $\le 10^6$ cycles. As noted earlier, the influence of DO level on the fatigue life of austenitic SSs is not well understood. Until more data are available to clearly establish the effects of DO level on fatigue life, the transformed parameter O' is assumed to be the same in low– and high–DO water and for wrought and cast austenitic SSs. These models may be somewhat conservative for some SSs in high–DO water.

JAPANESE MITI GUIDELINES

The guidelines proposed by the Japanese Ministry of International Trade and Industry (MITI) for assessing the decrease in fatigue life in LWR environments have been presented by Iida et al.[26] The reduction in fatigue life of various pressure vessel and piping steels in LWR environments is expressed in terms of an environmental fatigue life correction factor F_{en}, which is the ratio of the fatigue life in air at ambient temperature to that in water at the service temperature.[22] For austenitic SSs, F_{en} is expressed in terms of strain rate $\dot{\varepsilon}$ (%/s), temperature T (°C), and strain amplitude ε_a (%) as follows:

$$\ln(F_{en}) = 1.233 - P \ln(\dot{\varepsilon}^*/0.4), \quad (10)$$

where

$$\begin{aligned} &P = 0.04 && (T \le 100°C) \\ &P = 9.33 \times 10^{-4}\, T - 0.053 && (100 < T < 325°C) \\ &P = 0.25 && (T \ge 325°C) \end{aligned} \quad (11)$$

$$\begin{aligned} &\dot{\varepsilon}^* = 0.4 && (\dot{\varepsilon} > 0.4\%/s) \\ &\dot{\varepsilon}^* = \dot{\varepsilon} && (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\ &\dot{\varepsilon}^* = 0.0004 && (\dot{\varepsilon} < 0.0004\%/s). \end{aligned} \quad (12)$$

$$F_{en} = 1 \quad (\varepsilon_a \le 0.11\%). \quad (13)$$

To incorporate environmental effects on fatigue life, a fatigue usage for a specific stress cycle, based on the current Code fatigue design curve, is multiplied by the correction factor.

MODEL DEVELOPED BY THE BETTIS LABORATORY

A model based on the available fatigue ε–N data has been developed by the Bettis Laboratory.[48] In this model, the Smith–Watson–Topper (SWT) equivalent strain parameter[49] is used to predict the fatigue life of austenitic SSs in LWR environments under prototypical temperatures and loading rates. The model indicates that the fatigue life of Type 304 SS in water depends on the temperature, strain rate, applied strain amplitude, and water oxygen level. For low–DO water, the fatigue life can be reduced by as much as a factor of 13 at high temperatures and low strain rates. The Bettis model for predicting fatigue life N in LWR environments is of the following form:

$$N = A \cdot (\varepsilon_{SWT} - \varepsilon_0)^b \cdot \left[P + (1 - P) \cdot e^{-kZ^m}\right], \quad (14)$$

where A, b, P, k, ε_0, and m are model constants, and the SWT parameter ε_{SWT} is given by

$$\varepsilon_{SWT} = (\varepsilon_a)^c \cdot (\sigma_{max}/E)^{1-c}, \quad (15)$$

in which maximum stress σ_{max} is the sum of the cyclic stress amplitude σ_a and mean stress σ_{mean} (i.e., = $\sigma_a + \sigma_{mean}$), E is the elastic modulus, and c is a constant determined from fatigue tests in air, some of which had an imposed mean stress. The effects of temperature T (K) and strain rate $\dot{\varepsilon}$ (s^{-1}) are incorporated into the model by using the Zener–Hollomon parameter Z, given by

$$Z = \dot{\varepsilon} \cdot e^{Q/RT}, \quad (16)$$

where R is the gas constant, and Q is the fitted value of the activation energy. The model constants in Eqs. 14–16 were determined from the existing fatigue ε–N data in water.[48] The constant A is given by

$$\ln(A) = -4.010 + 0.438\, \text{Mat} + 1.030\, O_2, \quad (17)$$

where Mat = 1 for Type 316NG SS and 0 otherwise, and $O_2 = 1$ for high–DO water and 0 otherwise. The values of other constants in Eqs. 14 and 16 are as follows:

$$\begin{aligned} &b = -2.10 \\ &\varepsilon_0 = 8.75 \times 10^{-4}\ \text{mm/mm} \\ &P = 0.0359 \\ &k = 9.65 && \text{(low DO)} \\ &k = 20.0 && \text{(high DO)} \end{aligned}$$

Q = 94.56 kJ/mol (22.6 kcal/mol)
m = – 0.187.

The cyclic stress amplitude σ_a (MPa), corresponding to a given strain amplitude ε_a (mm/mm), is obtained from the cyclic stress–vs.–strain curves in air, given by

$$\sigma_a = (175 - 0.342\ T + 7.10 \times 10^{-4}\ T^2) + (24010 - 4.54 \times 10^{-2}\ T^2 + 156\ \sigma_{mean})\ \varepsilon_a, \qquad (18)$$

where T is the temperature (°C), and σ_{mean} is the mean stress (MPa). This cyclic stress–strain curve is valid for stresses above the proportional limit. Below the proportional limit, the stress amplitude is simply the product of the elastic modulus and strain amplitude. The fatigue ε–N curve at zero mean stress can be obtained from Eqs. 14–18 by substituting a value of zero for σ_{mean} in Eqs. 15 and 18.

COMPARISON OF VARIOUS ESTIMATION SCHEMES

The experimental fatigue ε–N data for Types 304 and 316 SS in low–DO water at 325°C and 0.4%/s strain rate, and the corresponding fatigue ε–N curves predicted from the Bettis, ANL, and MITI models are shown Fig. 8. The fatigue lives in LWR environments predicted from the MITI model were determined by multiplying the values obtained from the ASME Code mean fatigue curve by F_{en} calculated from Eq. 10. The Code mean curve is given by

$$\ln(N) = 6.954 - 2.0\ \ln(\varepsilon_a - 0.167), \qquad (19)$$

where N is the fatigue life, and ε_a is the applied strain amplitude (%). The estimated lives from all models are comparable in the low–cycle regime, i.e., fatigue lives $<10^4$ cycles. The fatigue lives estimated from the MITI guidelines show poor agreement with the experimental data at fatigue lives $>10^3$ cycles, e.g., the estimated lives are longer than those observed experimentally. The poor agreement is primarily due to the difference between the ASME Code mean fatigue curve and the experimental data. Figure 1 shows that the ASME mean curve is not consistent with the existing fatigue ε–N data for austenitic SSs; at strain amplitudes <0.5%, the mean curve predicts significantly longer fatigue lives than those observed experimentally. Because the fatigue life correction factor F_{en} in the MITI guidelines is applied to fatigue lives determined from the ASME Code curves, estimated fatigue lives at low strain amplitudes (e.g., ≤0.5%) in these guidelines are expected to be longer than those observed experimentally.

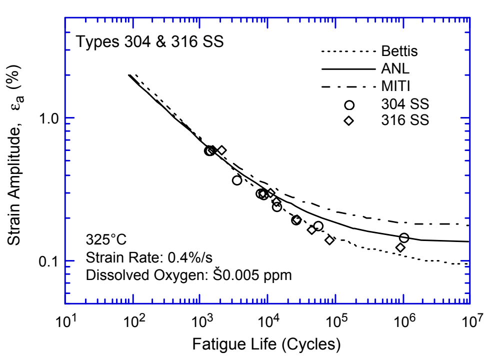


Figure 8. Experimental and predicted ε–N behavior for Types 304 and 316 SS in low–DO water at 325°C

In the high–cycle regime, the Bettis model predicts lower lives than the other models. The fatigue ε–N behavior in the high–cycle regime in LWR environments cannot be accurately established because the experimental data are very limited. Exploratory tests in LWR environments indicate that a minimum threshold strain is required for environmentally assisted decrease in the fatigue life of austenitic SSs.[33,35] The threshold strain is comparable to the fatigue limit for the material. In the ANL model, constant C in Eq. 2 (which is related to the fatigue limit) is considered to be the same in air and water environments. In the Bettis model, constant ε_0 in Eq. 14 was determined from the best–fit of existing fatigue ε–N data in LWR environments, which included the results of fatigue tests with mean stress.

The experimentally observed dependence on temperature and strain rate of the fatigue life of austenitic SSs in LWR environments, and that predicted from the Bettis, ANL, and MITI models is shown in Figs. 9 and 10, respectively. Except for the estimates of the MITI model at low strain ranges, the fatigue lives predicted from all models show good agreement with the experimental data.

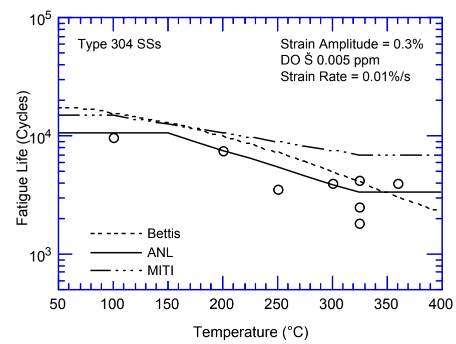


Figure 9. Experimental and predicted change in the fatigue lives of Type 304 SS with temperature in low–DO water at 0.3 and 0.6% strain amplitudes and 0.01%/s strain rates

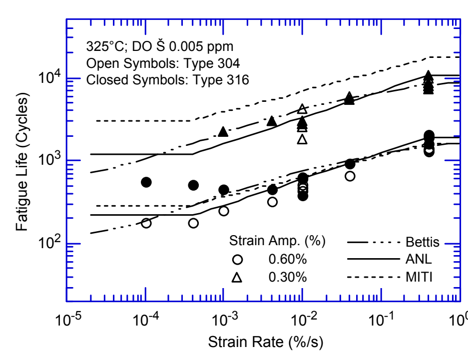


Figure 10. Experimental and predicted change in the fatigue lives of austenitic SS with strain rate in low–DO water at 325°C

INCORPORATING ENVIRONMENTAL EFFECTS

Two approaches are currently being proposed for incorporating the effects of LWR coolant environments into the ASME Section III fatigue evaluations: either develop a new set of environmentally adjusted fatigue design curves[16,18,42] or use a fatigue life correction factor F_{en} to adjust the current ASME Code fatigue usage values for environmental effects.[16,18,22–25] For both approaches, the range and bounding values must be defined for key loading and environmental parameters that influence fatigue life. It has been demonstrated that estimates of fatigue life based on the two approaches 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 that are used to develop the environmentally adjusted curves. However, either method provides an acceptable approach to account for environmental effects.

Fatigue Design Curves

A set of environmentally adjusted fatigue design curves may be developed from the best–fit stress–vs.–life curves to the experimental data in LWR environments by using the procedure that was used to develop the current ASME Code fatigue design curves. The stress–vs.–life curve is obtained from the ε–N curve, 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. The current ASME Code fatigue design curve for austenitic SSs does not include a mean stress correction below 10^6 cycles because, for the current Code mean curve, the fatigue strength at 10^6 cycles is greater than the monotonic yield strength of these steels. However, studies by Wire et al.[50] to establish the effect of mean stress on the fatigue life of Type 304 SS indicate an apparent reduction of up to 26% in strain amplitude in the low– and intermediate–cycle regime (i.e., $<10^6$ cycles) for a mean stress of 138 MPa. Also, the fatigue strength at 10^6 cycles for the best fit of the existing fatigue ε–N data (Eqs. 3 or 5) is lower than the monotonic yield strength of austenitic SSs. The best–fit curve was corrected for mean stress effects with the modified Goodman relationship which assumes the maximum possible mean stress and typically gives a conservative adjustment for mean stress, at least when environmental effects are not significant. The fatigue design 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.

The new fatigue design curve for austenitic SS in air is shown in Fig. 11, and those in LWR coolant environments at 289°C corresponding to strain rates of 0.4, 0.04, 0.004, and a saturation value of 0.0004%/s, are shown in Fig. 12. Because the fatigue life of Type 316NG is superior to that of Types 304 or 316 SS at high strain amplitudes, the design curves in Figs. 11 and 12 will be somewhat conservative for Type 316NG SS. The results indicate that, in room–temperature air, the current ASME Code design curve for austenitic SSs is nonconservative with respect to the design curve based on the statistical model. The margins between the current Code design curve and the best-fit of existing experimental data are ≈1.5 on stress and 10–16 on cycles instead of the 2 and 20 originally intended.

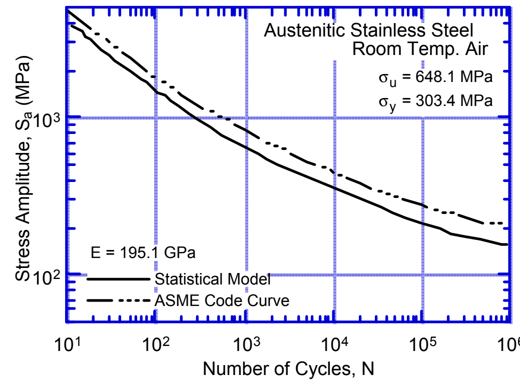


Figure 11. Fatigue design curves developed from statistical model for austenitic stainless steels in air at room temperature

For environmentally adjusted fatigue design curves, a minimum threshold strain is defined, below which environmental effects are modest. The existing fatigue data indicate a threshold strain range of ≈0.32% for austenitic SSs. These values must be adjusted for mean stress effects and variability due to material and experimental scatter. The threshold strain amplitude 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 ≈0.1% (stress amplitude of 189 MPa) is obtained for austenitic SSs. The PVRC steering committee for CLEE has proposed ramps 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 0.10 and 0.11% for austenitic SSs (both wrought and cast).

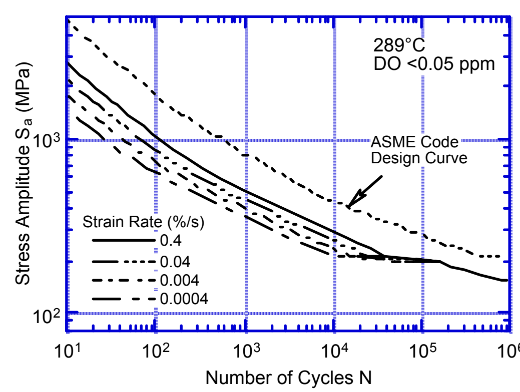


Figure 12. Fatigue design curves developed from statistical models for austenitic stainless steels in water with <0.05 ppm DO at 289°C

*Welding Research Council Progress Report, Vol. LIX No. 5/6, May/June 1999.

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.[22] A fatigue life correction factor F_{en} can be obtained from the statistical model (Eqs. 3–9), where

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \quad (20)$$

The fatigue life correction factor for austenitic SSs is given by

$$\ln(F_{en}) = 0.935 - T'\,\dot{\varepsilon}'\,O', \quad (21)$$

where the constants T', $\dot{\varepsilon}'$, and O' are defined in Eqs. 7–9. To incorporate environmental effects into the Section III fatigue evaluation, a fatigue usage for a specific stress cycle, based on the current Code fatigue design curve, is multiplied by the correction factor. A strain threshold, shown in Fig. 12, is also defined, below which environmental effects are modest.

The F_{en} correction factor approach (or the EPRI/GE approach) for incorporating environmental effects into fatigue evaluations has been proposed by Mehta and Gosselin.[23,24] The approach has recently been updated to include the revised statistical models and the PVRC discussions on evaluating environmental fatigue.[25] In the EPRI/GE approach, an "effective" fatigue life correction factor, expressed as $F_{en,eff} = F_{en}/Z$, is also defined, where Z is a factor that represents the perceived conservatism in the ASME Code design curves. The $F_{en,eff}$ approach presumes that all uncertainties have been anticipated and accounted for. The possible conservatism in the current ASME Code design curves is discussed in the next section.

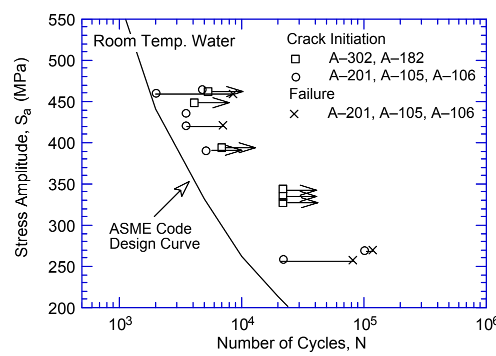
CONSERVATISM IN FATIGUE DESIGN CURVES

The conservatism in the ASME Code fatigue evaluations may arise from (a) the fatigue evaluation procedures and/or (b) the Code fatigue design curves. The overall conservatism in ASME Code fatigue evaluation procedures has been demonstrated in fatigue tests on piping welds and components.[51] In air, the margins on the number of cycles to failure for austenitic SS elbows and tees were 40–310 and 104–510, respectively. The margins for girth butt welds were significantly lower at 6–77. 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. The fatigue design curves represent the number of cycles to form a 3–mm–deep crack. Consequently, depending on wall thickness, the actual margins to failure may be lower by a factor of more than 2.

Deardorff and Smith[52] discussed the types and extent of conservatisms present in the ASME Section III fatigue evaluation procedures and the effects of LWR environments on fatigue margins. The sources of conservatism include design transients that are significantly 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, which are known to be affected by severe thermal transients, were also investigated in the study. When environmental effects on fatigue life were not considered, these authors estimated that the ratio of the cumulative usage factors (CUFs) computed with the mean experimental curve for test specimen data to the CUFs computed with the Code fatigue design curve were ≈60 and 90, respectively, for the PWR and BWR nozzles. They estimated the reductions in these margins due to environmental effects to be factors of 5.2 and 4.6 for PWR and BWR nozzles, respectively. Deardorff and Smith[52] argue that, after accounting for environmental effects, there is a factor of 12 and 20 margin on life, respectively, for PWR and BWR nozzles, to account for uncertainties due to material variability, surface finish, size, mean stress, and loading history.

Much of the margin arises from the current design procedures, e.g., stress analysis rules, cycle counting, etc., which, as discussed by Deardorff and Smith,[52] are quite conservative. However, the ASME Code permits new improved approaches to fatigue evaluations, e.g., finite–element analyses, fatigue monitoring, improved K_e factors, etc.; these can significantly decrease the conservatisms. Fatigue tests conducted on vessels at Southwest Research Institute for the PVRC[53] show that ≈5–mm–deep cracks can form in carbon and low–alloy steels very close to the fatigue cycles predicted by the ASME Code design curve (Fig. 13). The tests were performed in room–temperature water on vessels with a 0.914–m diameter and 19–mm walls. These results demonstrate clearly that the Code fatigue design curves do not ensure large margins of safety.

The factors of 2 and 20 were intended to cover several variables that can influence fatigue life. The contributions of four groups of variables, namely, material variability and data scatter, size and geometry, surface finish, and loading history (Miner's rule), must be considered in developing the fatigue design curves that are applicable to components. Data available in the literature have been reviewed in NUREG/CR–6717 to determine the effect of these variables on the fatigue life of components.[18] Factors of 2.5 on life and 1.7 on strain provide a 90% confidence for the variations in fatigue life associated with compositional and metallurgical differences, material processing, and experimental scatter. The factor of 1.7 on strain has been estimated from the standard deviation on cycles and, therefore, may be a conservative value. Factors of ≈1.4 on cycles and ≈1.25 on strain can be used to account for size and geometry.



(c)

Figure 13. Fatigue data for carbon and low–alloy steel vessels tested in room–temperature water (Ref. 53)

Fatigue life is sensitive to surface finish; cracks can initiate at surface irregularities that are normal to the stress axis. The height, spacing, shape, and distribution of surface irregularities are important for crack initiation. Investigations of the effects of surface roughness on the low–cycle fatigue of Type 304 SS in air at 593°C indicate that fatigue life decreases as surface roughness increases.[54,55] The results indicate that typical surface roughness associated with metal–working processes, such as drawing/extrusion, grinding, honing, and polishing, would decrease fatigue life by a factor of ≈3.[54] Fatigue test data on rectangular bars of austenitic SSs with differing surface finish, under compressive load, indicate a factor of ≈1.6 decrease in stress (or strain) in the high–cycle–fatigue regime (i.e., >10^5 cycles).[56] In the same study, the effect of grinding on the fatigue limit of welds was very large, e.g., a factor of 3–4 decrease in fatigue limit.

In an earlier report,[16] it was argued that, because austenitic SSs develop a corrosion scale in LWR environments, the effect of surface finish may not be significant; the subfactor on life to account for surface finish effects may be as low as 1.5 or may be eliminated completely. To check the validity of this argument, fatigue tests were conducted on Type 304 specimens that had been scarred under controlled conditions, in a lathe, with 50–grit sandpaper to produce circumferential scratches. The average surface roughness R_a was 1.2 μm and the RMS value of surface roughness R_q was 1.6 μm (61.5 micro–inch). The fatigue tests were conducted in air and low–DO water (i.e., <5 ppb DO and ≈23 cc/kg dissolved hydrogen) at 289°C, 0.25% strain amplitude, fully reversed saw–tooth wave form with 0.004 and 0.4%/s strain rates, respectively, in tension and compression. The results of these tests and data obtained earlier on Type 304 SS are shown in Fig. 14. In both air and low–DO water environments, the fatigue life of scarred specimens is a factor of ≈3 lower than that of smooth specimens. Thus, a factor of 2–3 on cycles and 1.3 on strain is needed to account for the effects of surface finish.

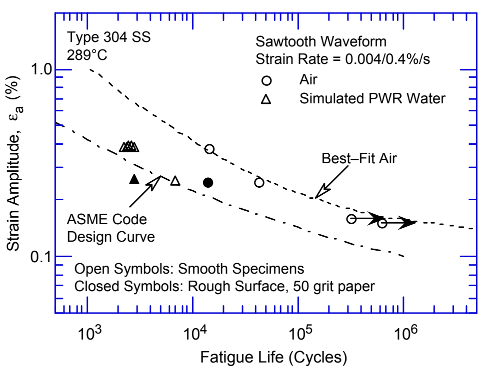


Figure 14. Effect of surface roughness on fatigue life of Type 304 stainless steel in air and low–DO water at 289°C

A PVRC working group has been compiling and evaluating fatigue ε–N data related to the effects of LWR coolant environments on the fatigue lives of pressure boundary materials.[57] One of the tasks in the PVRC activity consisted of defining a set of values for material, loading, and environmental variables that lead to 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 "moderate" or "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 was the discussion presented by Cooper[58] regarding the initial scope and intent of the Section III fatigue design procedures. Cooper states that the factor of 20 on life is the product of the following three subfactors: scatter of data (minimum to mean) 2.0; size effect 2.5; and surface finish, atmosphere, etc., 4.0.

The criterion for "acceptable" effects of environment assumes that the current Code design curve includes a factor of 4 (i.e., the third subfactor listed above) to account for the effects of environment. However, Cooper[58] further states that the term "atmosphere" was intended to reflect the effects of an industrial atmosphere in comparison with an air–conditioned laboratory, and not the effects of a specific coolant environment. Furthermore, the third subfactor includes the effect of surface finish on fatigue life. Figure 14 shows that surface finish can decrease the fatigue life of austenitic SSs by a factor of 3 in both air and water environments.

The effects of load history during variable amplitude fatigue of smooth specimens are well known.[59–62] The presence of a few cycles at high strain amplitude in a load history causes the fatigue life at smaller strain amplitude to be significantly lower than that at constant amplitude loading. Also, fatigue damage and crack growth in smooth specimens occur at strain levels below the fatigue limit of the material. Studies on fatigue damage in Type 304 SS under complex loading histories[63] indicate that the loading sequence of decreasing strain levels (i.e., high strain level followed by low strain level) is more damaging than that of increasing strain levels. The fatigue life of the steel decreased by a factor of 2–4 under a decreasing–strain sequence. In another study, the fatigue limit of medium carbon steels was lowered even after low–stress high–cycle fatigue; the higher the stress, the greater the decrease in fatigue threshold.[64] In general, the mean fatigue ε–N curves are lowered to account for damaging cycles that occur below the constant–amplitude fatigue limit of the material.[65,66] A factor of 1.5–2.5 on cycles and 1.3–1.6 on strain may be used to incorporate the effects of load histories on fatigue life.

The subfactors that may be used to account for the effects of various material, loading, and environmental variables on fatigue life are summarized in Table 2. A factor of at least 10 on cycles is needed to account for the differences and uncertainties in relating the fatigue lives of laboratory test specimens to those of actual reactor components. The factors on strain primarily account for the variation in the fatigue limit of the material caused by material variability, component size and surface finish, and load history. Because these parameters influence the growth of short cracks (<100 μm), the adjustments on strain to account for the effects of material variability, component size, surface finish, and loading history are typically not cumulative but rather are controlled by the parameter that has the largest effect on life. Thus, a factor of at least 1.6 on strain is needed to account for the differences and uncertainties in relating the fatigue lives of laboratory test specimens to those of actual reactor components. These results suggest that the current ASME Code requirements of a factor of 2 on stress and 20 on cycle to account for differences and uncertainties in fatigue life that are associated with material and loading conditions are quite reasonable.

Table 2. Factors on cycles and strain applied to mean ε–N curve

Parameter	Factor on Life	Factor on Strain
Material variability & experimental scatter	2.5	1.4–1.7
Size effect	1.4	1.25
Surface finish	2.0–3.0	1.6

Loading history	1.5–2.5	1.3–1.6
Total adjustment	10.0–26.0	1.6–1.7

SUMMARY

The existing fatigue ε–N data for wrought and cast austenitic SSs in air and LWR environments have been evaluated to establish the effects of material and loading variables, such as steel type, strain amplitude, strain rate, temperature, and DO level in water, on the fatigue lives of these steels.

In air, the fatigue lives of Types 304 and 316 SS are comparable and those of Type 316NG are superior at high strain amplitudes. The fatigue life of austenitic SSs in air is independent of temperature in the range from room temperature to 427°C. Also, variation in strain rate in the range of 0.4–0.008%/s has no effect on the fatigue lives of SSs at temperatures up to 400°C. The fatigue ε–N behavior of cast SSs is similar to that of wrought austenitic SSs.

The fatigue lives of cast and wrought austenitc SSs are decreased in LWR environments; the decrease depends on strain rate, DO level in water, and temperature. A minimum threshold strain is required for environmentally assisted decrease in the fatigue life of SSs, and this strain appears to be independent of material type (weld or base metal) and temperature in the range of 250–325°C. Environmental effects on fatigue life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Strain rate and temperature have a strong effect on fatigue life in LWR environments. Fatigue life decreases logarithmically with decreasing strain rate below 0.4%/s; the effect saturates at 0.0004%/s. Similarly, the fatigue ε–N data suggest a threshold temperature of 150°C; in the range of 150–325°C, life decreases linearly with temperature.

The fatigue lives of wrought and cast austenitic SSs are decreased significantly in low–DO (i.e., <0.01 ppm DO) water. However, environmental effects on the fatigue lives of these steels in high–DO water are not well known. In high–DO water the magnitude of environmental effects may be influenced by the composition or heat treatment of the steel. The existing fatigue ε–N data indicate that the fatigue lives of cast SSs are approximately the same in low– and high–DO water and are comparable to those observed for wrought SSs in low–DO water. The fatigue lives of wrought SSs in high–DO water are comparable for some steels and higher for other steels than the lives in low–DO water. Also, environmental effects on fatigue life are greater for sensitized than solution–annealed steels in high–DO water, whereas in low–DO water, a sensitization anneal has no effect on fatigue life.

Statistical models are presented for estimating the fatigue life of austenitic SSs as a function of material, loading, and environmental parameters. Functional form and bounding values of these parameters are based on experimental observations and data trends. The models are recommended for predicted fatigue lives $\leq 10^6$ cycles. The results indicate that the ASME mean curve for SSs is not consistent with the experimental data; the current ASME mean curve is nonconservative.

Two approaches have been proposed for incorporating the effects of LWR environments into ASME Section III fatigue evaluations. Both approaches are based on the best–fit curves to the experimental fatigue ε–N data in LWR environments. In the first approach, environmentally adjusted fatigue design curves have been developed by adjusting the best–fit experimental curve for the effect of mean stress and by setting margins of 20 on cycles and 2 on strain to account for the uncertainties in life associated with material and loading conditions. These curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. The second approach considers the effects of reactor coolant environments on fatigue life in terms of an environmental correction factor F_{en}, which is the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into the ASME Code fatigue evaluations, a fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the correction factor. Data available in the literature have been reviewed to evaluate the conservatism in the existing ASME Code fatigue design curves. The results suggest that the current ASME Code requirements of a factor of 2 on stress and 20 on life are quite reasonable.

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REFERENCES

1. K. Kussmaul, R. Rintamaa, J. Jansky, M. Kemppainen, and K. Törrönen, *On the Mechanism of Environmental Cracking Introduced by Cyclic Thermal Loading*, in IAEA Specialists Meeting Corrosion and Stress Corrosion of Steel Pressure Boundary Components and Steam Turbines, VTT Symp. 43, Espoo, Finland, pp. 195–243 (1983).
2. K. Iida, *A Review of Fatigue Failures in LWR Plants in Japan*, Nucl. Eng. Des. **138**, 297–312 (1992).
3. NRC IE Bulletin No. 79–13, *Cracking in Feedwater System Piping*, U.S. Nuclear Regulatory Commission, Washington, DC (June 25, 1979).
4. NRC Information Notice 93–20, *Thermal Fatigue Cracking of Feedwater Piping to Steam Generators*, U.S. Nuclear Regulatory Commission, Washington, DC (March 24, 1993).
5. K. Kussmaul, D. Blind, and J. Jansky, *Formation and Growth of Cracking in Feed Water Pipes and RPV Nozzles*, Nucl. Eng. Des. **81**, 105–119 (1984).
6. H. Watanabe, *Boiling Water Reactor Feedwater Nozzle/Sparger, Final Report*, NEDO–21821–A, General Electric Co., San Jose, CA, (1980).
7. B. M. Gordon, D. E. Delwiche, and G. M. Gordon, *Service Experience of BWR Pressure Vessels,* in Performance and Evaluation of Light Water Reactor Pressure Vessels, PVP Vol.–119, American Society of Mechanical Engineers, New York, pp. 9–17 (1987).
8. E. Lenz, B. Stellwag, and N. Wieling, *The Influence of Strain–Induced Corrosion Cracking on the Crack Initiation in Low–Alloy Steels in HT–Water – A Relation Between Monotonic and Cyclic Crack Initiation Behavior*, in IAEA Specialists Meeting Corrosion and Stress Corrosion of Steel Pressure Boundary Components and Steam Turbines, VTT Symp. 43, Espoo, Finland, pp. 243–267 (1983).

9. J. Hickling and D. Blind, *Strain–Induced Corrosion Cracking of Low–Alloy Steels in LWR Systems – Case Histories and Identification of Conditions Leading to Susceptibility*, Nucl. Eng. Des. **91**, 305–330 (1986).
10. P. Hirschberg, A. F. Deardorff, and J. Carey, *Operating Experience Regarding Thermal Fatigue of Unisolable Piping Connected to PWR Reactor Coolant Systems,* Int. Conf. on Fatigue of Reactor Components, Napa, CA, July 31–August 2, 2000.
11. NRC Information Notice 88–01, *Safety Injection Pipe Failure*, U.S. Nuclear Regulatory Commission, Washington, DC (Jan. 27, 1988).
12. NRC Bulletin No. 88–08, *Thermal Stresses in Piping Connected to Reactor Coolant Systems*, U.S. Nuclear Regulatory Commission, Washington, DC (June 22; Suppl. 1, June 24; Suppl. 2, Aug. 4, 1988; Suppl. 3, April 1989).
13. R. B. Dooley, and R. S. Pathania, *Corrosion Fatigue of Water Touched Pressure Retaining Components in Power Plants*, EPRI TR–106696, Electric Power Research Institute, Palo Alto, CA (1997).
14. V. N. Shah, M. B. Sattison, C. L. Atwood, A. G. Ware, G. M. Grant, and R. S. Hartley, *Assessment of Pressurized Water Reactor Primary System Leaks*, NUREG/CR–6582, INEEL/EXT–97–01068 (Dec. 1998).
15. C. E. Jaske and W. J. O'Donnell, *Fatigue Design Criteria for Pressure Vessel Alloys*, Trans. ASME J. Pressure Vessel Technol. **99**, 584–592 (1977).
16. O. K. Chopra, *Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels*, NUREG/CR–5704, ANL–98/31 (1999).
17. O. K. Chopra and W. J. Shack, *Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low–Alloy Steels*, NUREG/CR–6583, ANL–97/18 (March 1998).
18. O. K. Chopra and W. J. Shack, *Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels*, NUREG/CR–6717, ANL–00/27 (May 2001).
19. S. Majumdar, O. K. Chopra, and W. J. Shack, *Interim Fatigue Design Curves for Carbon, Low–Alloy, and Austenitic Stainless Steels in LWR Environments*, NUREG/CR–5999, ANL–93/3 (1993).
20. J. Keisler, O. K. Chopra, and W. J. Shack, *Fatigue Strain–Life Behavior of Carbon and Low–Alloy Steels, Austenitic Stainless Steels, and Alloy 600 in LWR Environments*, NUREG/CR–6335, ANL–95/15 (1995).
21. J. Keisler, O. K. Chopra, and W. J. Shack, *Statistical Models for Estimating Fatigue Strain–Life Behavior of Pressure Boundary Materials in Light Water Reactor Environments*, Nucl. Eng. Des. **167**, 129–154 (1996).
22. M. Higuchi and K. Iida, *Fatigue Strength Correction Factors for Carbon and Low–Alloy Steels in Oxygen–Containing High–Temperature Water*, Nucl. Eng. Des. **129**, 293–306 (1991).
23. H. S. Mehta and S. R. Gosselin, *An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations*, in Fatigue and Fracture Volume 1, PVP Vol. 323, H. S. Mehta, ed., American Society of Mechanical Engineers, New York, pp. 171–185 (1996).
24. H. S. Mehta and S. R. Gosselin, *Environmental Factor Approach to Account for Water Effects in Pressure Vessel and Piping Fatigue Evaluations*, Nucl. Eng. Des. **181**, 175–197 (1998).
25. H. S. Mehta, *An Update on the EPRI/GE Environmental Fatigue Evaluation Methodology and its Applications*, in Probabilistic and Environmental Aspects of Fracture and Fatigue, PVP Vol. 386, S. Rahman, ed., American Society of Mechanical Engineers, New York, pp. 183–193 (1999).
26. K. Iida, T. Bannai, M. Higuchi, K. Tsutsumi, and K. Sakaguchi, *Comparison of Japanese MITI Guideline and Other Methods for Evaluation of Environmental Fatigue Life Reduction*, in Pressure Vessel and Piping Codes and Standards, PVP Vol. 419, M. D. Rana, ed., American Society of Mechanical Engineers, New York, pp. 73–81 (2001).
27. J. B. Conway, R. H. Stentz, and J. T. Berling, *Fatigue, Tensile, and Relaxation Behavior of Stainless Steels*, TID–26135, U.S. Atomic Energy Commission, Washington, DC (1975).
28. D. L. Keller, *Progress on LMFBR Cladding, Structural, and Component Materials Studies During July, 1971 through June, 1972, Final Report*, Task 32, BMI–1928, Battelle–Columbus Laboratories (1977).
29. D. A. Hale, S. A. Wilson, E. Kiss, and A. J. Gianuzzi, *Low Cycle Fatigue Evaluation of Primary Piping Materials in a BWR Environment*, GEAP–20244, U.S. Nuclear Regulatory Commission (Sept. 1977).
30. M. Fujiwara, T. Endo, and H. Kanasaki, *Strain Rate Effects on the Low–Cycle Fatigue Strength of 304 Stainless Steel in High–Temperature Water Environment; Fatigue Life: Analysis and Prediction*, in Proc. Intl. Conf. and Exposition on Fatigue, Corrosion Cracking, Fracture Mechanics, and Failure Analysis, ASM, Metals Park, OH, pp. 309–313 (1986).
31. H. Mimaki, H. Kanasaki, I. Suzuki, M. Koyama, M. Akiyama, T. Okubo, and Y. Mishima, *Material Aging Research Program for PWR Plants*, in Aging Management Through Maintenance Management, PVP Vol. 332, I. T. Kisisel, ed., American Society of Mechanical Engineers, New York, pp. 97–105 (1996).
32. H. Kanasaki, R. Umehara, H. Mizuta, and T. Suyama, *Fatigue Lives of Stainless Steels in PWR Primary Water*, Trans. 14th Intl. Conf. on Structural Mechanics in Reactor Technology (SMiRT 14), Lyon, France, pp. 473–483 (1997).
33. H. Kanasaki, R. Umehara, H. Mizuta, and T. Suyama, *Effects of Strain Rate and Temperature Change on the Fatigue Life of Stainless Steel in PWR Primary Water*, Trans. 14th Intl. Conf. on Structural Mechanics in Reactor Technology (SMiRT 14), Lyon, France, pp. 485–493 (1997).
34. K. Tsutsumi, H. Kanasaki, T. Umakoshi, T. Nakamura, S. Urata, H. Mizuta, and S. Nomoto, *Fatigue Life Reduction in PWR Water Environment for Stainless Steels*, in Assessment Methodologies for Preventing Failure: Service Experience and Environmental Considerations, PVP Vol. 410-2, R. Mohan, ed., American Society of Mechanical Engineers, New York, pp. 23–34 (2000).
35. K. Tsutsumi, T. Dodo, H. Kanasaki, S. Nomoto, Y. Minami, and T. Nakamura, *Fatigue Behavior of Stainless Steel under Conditions of Changing Strain Rate in PWR Primary Water*, in Pressure Vessel and Piping Codes and Standards, PVP Vol. 419, M. D. Rana, ed., American Society of Mechanical Engineers, New York, pp. 135–141 (2001).

36. M. Higuchi and K. Iida, *Reduction in Low–Cycle Fatigue Life of Austenitic Stainless Steels in High–Temperature Water*, in Pressure Vessel and Piping Codes and Standards, PVP Vol. 353, D. P. Jones, B. R. Newton, W. J. O'Donnell, R. Vecchio, G. A. Antaki, D. Bhavani, N. G. Cofie, and G. L. Hollinger, eds., American Society of Mechanical Engineers, New York, pp. 79–86 (1997).
37. M. Higuchi, K. Iida, and K. Sakaguchi, *Effects of Strain Rate Fluctuation and Strain Holding on Fatigue Life Reduction for LWR Structural Steels in Simulated PWR Water*, in Pressure Vessel and Piping Codes and Standards, PVP Vol. 419, M. D. Rana, ed., American Society of Mechanical Engineers, New York, pp. 143–152 (2001).
38. M. Hayashi, *Thermal Fatigue Strength of Type 304 Stainless Steel in Simulated BWR Environment*, Nucl. Eng. Des. **184**, 135–144 (1998).
39. M. Hayashi, K. Enomoto, T. Saito, and T. Miyagawa, *Development of Thermal Fatigue Testing with BWR Water Environment and Thermal Fatigue Strength of Austenitic Stainless Steels*, Nucl. Eng. Des. **184**, 113–122 (1998).
40. O. K. Chopra and D. J. Gavenda, *Effects of LWR Coolant Environments on Fatigue Lives of Austenitic Stainless Steels*, in Pressure Vessel and Piping Codes and Standards, PVP Vol. 353, D. P. Jones, B. R. Newton, W. J. O'Donnell, R. Vecchio, G. A. Antaki, D. Bhavani, N. G. Cofie, and G. L. Hollinger, eds., American Society of Mechanical Engineers, New York, pp. 87–97 (1997).
41. O. K. Chopra and D. J. Gavenda, *Effects of LWR Coolant Environments on Fatigue Lives of Austenitic Stainless Steels*, J. Pressure Vessel Technol. **120**, 116–121 (1998).
42. O. K. Chopra and J. L. Smith, *Estimation of Fatigue Strain–Life Curves for Austenitic Stainless Steels in Light Water Reactor Environments*, in Fatigue, Environmental Factors, and New Materials, PVP Vol. 374, H. S. Mehta, R. W. Swindeman, J. A. Todd, S. Yukawa, M. Zako, W. H. Bamford, M. Higuchi, E. Jones, H. Nickel, and S. Rahman, eds., American Society of Mechanical Engineers, New York, pp. 249–259 (1998).
43. O. K. Chopra and J. Muscara, *Effects of Light Water Reactor Coolant Environments on Fatigue Crack Initiation in Piping and Pressure Vessel Steels*, in Proc. 8th Intl. Conf. on Nuclear Engineering, 2.08 LWR Materials Issue, Paper 8300, American Society of Mechanical Engineers, New York (2000).
44. C. Amzallag, P. Rabbe, G. Gallet, H. –P. Lieurade, *Influence des Conditions de Sollicitation Sur le Comportement en Fatigue Oligocyclique D'aciers Inoxydables Austénitiques*, Memoires Scientifiques Revue Metallurgie Mars, pp. 161–173 (1978).
45. A. Hirano, M. Yamamoto, K. Sakaguchi, K. Iida, and T. Shoji, *Effects of Water Flow Rate on Fatigue Life of Carbon Steel in High–Temperature Pure Water Environment*, in Assessment Methodologies for Predicting Failure: Service Experience and Environmental Considerations, PVP Vol. 410–2, R. Mohan, ed., American Society of Mechanical Engineers, New York, pp. 13–18 (2000).
46. E. Lenz, N. Wieling, and H. Muenster, *Influence of Variation of Flow Rates and Temperature on the Cyclic Crack Growth Rate under BWR Conditions*, in Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, The Metallurgical Society, Warrendale, PA (1988).
47. B. F. Langer, *Design of Pressure Vessels for Low–Cycle Fatigue*, ASME J. Basic Eng. **84**, 389–402 (1962).
48. T. R. Leax, *Statistical Models of Mean Stress and Water Environment Effects on the Fatigue Behavior of 304 Stainless Steel*, in Probabilistic and Environmental Aspects of Fracture and Fatigues, PVP Vol. 386, S. Rahman, ed., American Society of Mechanical Engineers, New York, pp. 229–239 (1999).
49. K. N. Smith, P. Watson, and T. H. Topper, *A Stress–Strain Function for the Fatigue of Metals*, J. Mater., JMLSA **5** (4), 767–778 (1970).
50. G. L. Wire, T. R. Leax, and J. T. Kandra, *Mean Stress and Environmental Effects on Fatigue in Type 304 Stainless Steel*, in Probabilistic and Environmental Aspects of Fracture and Fatigues, PVP Vol. 386, S. Rahman, ed., American Society of Mechanical Engineers, New York, pp. 213–228 (1999).
51. M. E. Mayfield, E. C. Rodabaugh, and R. J. Eiber, *A Comparison of Fatigue Test Data on Piping with the ASME Code Fatigue Evaluation Procedure*, ASME Paper 79–PVP–92, American Society of Mechanical Engineers, New York (1979).
52. A. F. Deardorff and J. K. Smith, *Evaluation of Conservatisms and Environmental Effects in ASME Code, Section III, Class 1 Fatigue Analysis*, SAND94–0187, prepared by Structural Integrity Associates, San Jose, CA, under contract to Sandia National Laboratories, Albuquerque, NM (1994).
53. L. F. Kooistra, E. A. Lange, and A. G. Pickett, *Full–Size Pressure Vessel Testing and Its Application to Design*, J. Eng. Power **86**, 419–428 (1964).
54. P. S. Maiya and D. E. Busch, *Effect of Surface Roughness on Low–Cycle Fatigue Behavior of Type 304 Stainless Steel*, Met. Trans. **6A**, 1761–1766 (1975).
55. P. S. Maiya, *Effect of Surface Roughness and Strain Range on Low–Cycle Fatigue Behavior of Type 304 Stainless Steel*, Scripta Metall. **9**, 1277–1282 (1975).
56. C. Faidy, T. Le Courtois, E. de Fraguier, J–A Leduff, A. Lefrancois, and J. Dechelotte, *Thermal Fatigue in French RHR System*, Int. Conf. on Fatigue of Reactor Components, Napa, CA, July 31–August 2, 2000.
57. W. A. Van Der Sluys and S. Yukawa, *Status of PVRC Evaluation of LWR Coolant Environmental Effects on the S–N Fatigue Properties of Pressure Boundary Materials*, in Fatigue and Crack Growth: Environmental Effects, Modeling Studies, and Design Considerations, PVP Vol. 306, S. Yukawa, ed., American Society of Mechanical Engineers, New York, pp. 47–58 (1995).
58. W. E. Cooper, *The Initial Scope and Intent of the Section III Fatigue Design Procedure*, in Technical Information from Workshop on Cyclic Life and Environmental Effects in Nuclear Applications, Clearwater, Florida, January 20–21, 1992, Welding Research Council, Inc. New York, 1992.
59. M. A. Pompetzki, T. H. Topper, and D. L. DuQuesnay, *The Effect of Compressive Underloads and Tensile Overloads on Fatigue Damage Accumulation in SAE 1045 Steel*, Int. J. Fatigue **12** (3), 207–213 (1990).
60. A. Conle and T. H. Topper, *Evaluation of Small Cycle Omission Criteria for Shortening of Fatigue Service Histories*, Int. J. Fatigue **1**, 23–28 (1979).

61. A. Conle and T. H. Topper, *Overstrain Effects During Variable Amplitude Service History Testing*, Int. J. Fatigue **2**, 130–136 (1980).
62. Li Nian and Du Bai–Ping, *Effect of Monotonic and Cyclic Prestrain on the Fatigue Threshold in Medium–Carbon steels*, Int. J. Fatigue **14** (1), 41–44 (1992).
63. M. J. Manjoine, *FatigueDamage Models for Annealed Type 304 Stainless Steel under Complex Strain Histories*, Trans. 6th Intl. Conf. on Structural Mechanics in Reactor Technology (SMiRT), Vol. L, 8/1, North–Holland Publishing Co., pp. 1–13 (1981).
64. Li Nian and Du Bai–Ping, *The Effect of Low–Stress High–Cycle Fatigue on the Microstructure and Fatigue Threshold of a 40Cr Steel*, Int. J. Fatigue **17** (1), 43–48 (1995).
65. E. Haibach and D. Schutz, *Fatigue Life Evaluation with Particular Attention to Local Strain and Stress Time Histories*, Proc. Inst. Mech. Eng. (1974).
66. D. J. Dowdell, H. H. E. Leipholz, and T. H. Topper, *The Modified Life Law Applied to SAE–1045 Steel*, Int. J. Fract. **31**, 29–36 (1986).