5 Estimating Fatigue Life of Austenitic Stainless Steels

Several models have been developed for estimating fatigue lives of austenitic SSs in LWR environments, and the models are based on roughly the same database. Although the formulation, threshold, and saturation values of the key parameters that influence fatigue life differ, differences in the estimates of fatigue life based on these models for specific loading and environmental conditions are insignificant. Any one of these models may be used to estimate fatigue life of austenitic SSs.

5.1 ANL Statistical Model

A statistical model based on the existing fatigue ε–N data has been developed at ANL for estimating the fatigue lives of wrought and cast austenitic SSs in air and LWR environments. The model assumes that the fatigue life in air is independent of temperature and strain rate. Separate models have been developed for Type 304 or 316 SS and Type 316NG SS. In air at temperatures up to 400°C, the fatigue data for Types 304 and 316 SS are best represented by the equation:

$$\ln(N) = 6.703 - 2.030 \ln(\varepsilon_a - 0.126), \tag{4}$$

and for Type 316NG, by the equation

$$\ln(N) = 7.433 - 1.782 \ln(\varepsilon_a - 0.126). \tag{5}$$

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 were based on the data trends shown in Figs. 19 and 23, 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. As discussed in Section 3.1, the fatigue lives of austenitic SSs are decreased significantly in low–DO water, whereas in high–DO water they are either comparable or, for some steels, higher than those in low–DO water. In high–DO water, the composition and heat treatment of the steel may influence the magnitude of environmental effects on austenitic SSs. Until more data are available to clearly establish the effects of DO level on fatigue life, the effect of DO level on fatigue life is assumed to be the same in low– and high–DO water and for wrought and cast austenitic SSs.

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. These results indicate that environmental effects are more pronounced at low than at high strain amplitudes. Differing 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 the ANL statistical model, the slope of the ε–N curve is assumed to be the same in LWR and air environments. In LWR environments, fatigue data for Types 304 and 316 SS are best represented by the equation:

$$\ln(N) = 5.675 - 2.030 \ln(\varepsilon_a - 0.126) + T' \, \dot{\varepsilon}' \, O', \tag{6}$$

and that of Type 316NG, as

$$\ln(N) = 7.122 - 1.671\ \ln(\varepsilon_a - 0.126) + T'\ \dot{\varepsilon}'\ O', \tag{7}$$

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

$$\begin{array}{ll} T' = 0 & (T < 150°C) \\ T' = (T - 150)/175 & (150 \le T < 325°C) \\ T' = 1 & (T \ge 325°C) \end{array} \tag{8}$$

$$\begin{array}{ll} \dot{\varepsilon} = 0 & (\dot{\varepsilon} > 0.4\%/s) \\ \dot{\varepsilon} = \ln(\dot{\varepsilon}/0.4) & (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\ \dot{\varepsilon} = \ln(0.0004/0.4) & (\dot{\varepsilon} < 0.0004\%/s) \end{array} \tag{9}$$

$$\begin{array}{ll} O' = 0.281 & (\text{all DO levels}). \end{array} \tag{10}$$

These models are recommended for predicted fatigue lives of $\le 10^6$ cycles. Equations 6 and 8–10 should also be used for cast austenitic SSs such as CF-3, CF-8, and CF–8M. As noted earlier, because the influence of DO level on the fatigue life of austenitic SSs may be influenced by the material heat treatment, the statistical model may be somewhat conservative for some SSs in high–DO water.

5.2 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 Higuchi et al.[40] 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. 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:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*)\ T^*, \tag{11}$$

where

$$\begin{array}{ll} C = 1.182 & (BWR) \\ C = 3.910 & (PWR) \end{array} \tag{12}$$

$$\begin{array}{ll} \dot{\varepsilon}^* = \ln(\dot{\varepsilon}) & (0.0004 \le \dot{\varepsilon}) \\ \dot{\varepsilon}^* = \ln(0.0004) & (\dot{\varepsilon} < 0.0004\%/s). \end{array} \tag{13}$$

$$\begin{array}{ll} T^* = 0.000813\ T & (BWR) \\ T^* = 0.000782\ T & (PWR, T \le 325°C) \\ T^* = 0.254 & (PWR, T > 325°C) \end{array} \tag{14}$$

$$\begin{array}{ll} F_{en} = 1 & (\varepsilon_a \le 0.11\%). \end{array} \tag{15}$$

The fatigue life in water is determined by dividing the life in air at ambient temperature by F_{en}. The fatigue life N in air is expressed in terms of the strain amplitude ε_a as

$$\ln(N) = 6.871 - 2.118\ \ln(\varepsilon_a - 0.110). \tag{16}$$

5.3 Model Developed by the Bettis Laboratory

A model based on available fatigue ε–N data, has been developed by the Bettis Laboratory.[41] In this model, the Smith–Watson–Topper (SWT) equivalent strain parameter[42] 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:

$$N = A \cdot (\varepsilon_{SWT} - \varepsilon_0)^b \cdot \left[P + (1 - P) \cdot e^{-kZ^m}\right], \qquad (17)$$

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

$$\varepsilon_{SWT} = (\varepsilon_a)^c \cdot \left(\frac{\sigma_{max}}{E}\right)^{1-c}, \qquad (18)$$

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, in some of which a mean stress had been imposed. 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

$$Z = \dot{\varepsilon} \cdot e^{\frac{Q}{RT}}, \qquad (19)$$

where R is the gas constant and Q is the fitted value of the activation energy. The model constants were determined from the existing fatigue ε–N data in water.[41] The values are as follows:*

$A = 1.185 \times 10^{-2}$ (wrought SSs, other than 316NG, in PWR water)
$A = 1.185 \times 10^{-2}$ (wrought SSs, other than 316NG, in BWR water)
$b = -2.097$
$\varepsilon_0 = 9.068 \times 10^{-4}$ mm/mm
$P = 0.109$ (wrought SSs and welds)
$c = 0.7$
$k = 149.0$ (in PWR water)
$k = 383.7$ (in BWR water)
Q = 147.15 kJ/mol (35.17 kcal/mol)
R = 8.314 J/mol K (1.987 cal/mol K)
$m = -0.2233$.

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

$$\sigma_a = (175 - 0.342\,T + 7.10 \times 10^{-4}\,T^2) + (24010 - 4.54 \times 10^{-2}\,T^2 + 156\,\sigma_{mean})\,\varepsilon_a, \qquad (20)$$

---

* T. R. Leax and D. P. Jones, Development of a Water Environment Fatigue Design Curve for Austenitic Stainless Steels, presented to ASME Subgroup on Fatigue Strength of Subcommittee Design, Sept. 24, 2002.

where T is the temperature (°C), and σ_m 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. 17–20 by substituting a value of zero for σ_{mean} in Eqs. 18 and 20.

6 Incorporating Environmental Effects into Fatigue Evaluations

The effects of LWR coolant environments may be incorporated into the ASME Section III fatigue evaluations by either developing a new set of environmentally adjusted fatigue design curves or by using a fatigue life correction factor F_{en} to adjust the current ASME Code fatigue usage values for environmental effects. For both approaches, the magnitude of key loading and environmental parameters that influence fatigue life must be known. 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.

6.1 Fatigue Design Curves

A set of environmentally adjusted fatigue design curves may be developed from the best–fit of stress–vs.–life curves to the experimental data in LWR environments by following 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. As mentioned earlier 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. The best–fit curve in a specific environment is corrected for mean stress effects with the modified Goodman relationship given by:

$$S'_a = S_a\left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y, \qquad (21)$$

and

$$S'_a = S_a \qquad \text{for } S_a > \sigma_y, \qquad (22)$$

where S'_a is the adjusted value of stress amplitude, and σ_y and σ_u are yield and ultimate strengths of the material, respectively. Equations 21 and 22 assume the maximum possible mean stress and typically give 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. S'_a

For environmentally adjusted fatigue design curves, a minimum threshold strain is defined, below which environmental effects are insignificant. The Pressure Vessel Research Council steering committee for Cyclic Life Environmental Effects* has endorsed this threshold value and 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 0.10 and 0.11% for austenitic SSs (both wrought and cast).

---

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

An example of fatigue design curves for austenitic SSs in LWR environments at 289°C is shown in Fig. 29. 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 Fig. 29 may be somewhat conservative for Type 316NG SS.

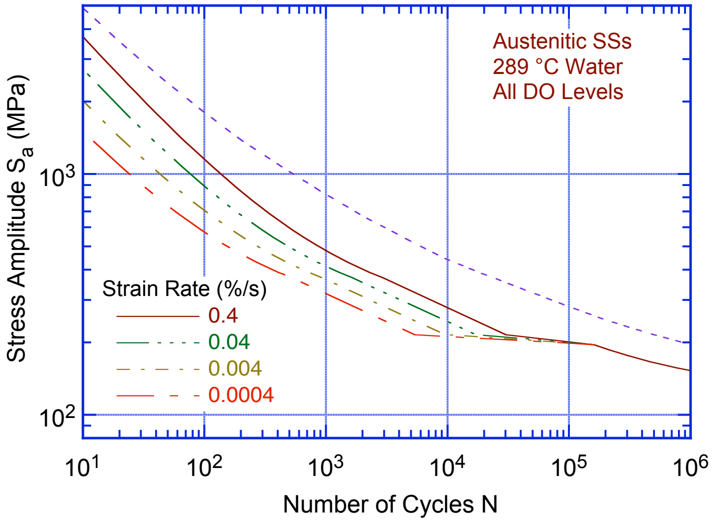

Figure 29. Fatigue design curves developed from statistical model for austenitic stainless steels in LWR environments at 289°C under service conditions where all threshold values are satisfied.

6.2 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 defined as the ratio of life in air at room temperature to that in water at the service temperature. Values of F_{en} can be obtained from the statistical model, where:

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \tag{23}$$

The fatigue life correction factor for austenitic SSs, based on the ANL model, is given by

$$F_{en} = \exp(1.028 - T' \; \dot{\varepsilon}' \; O'), \tag{24}$$

where the constants T', $\dot{\varepsilon}'$, and O' are defined in Eqs. 8–10. F_{en} based on the MITI guidelines is given in Eqs. 11–15. To incorporate environmental effects into a Section III fatigue evaluation, the fatigue usage for a specific stress cycle, based on the current Code fatigue design curve, is multiplied by the correction factor.

7 Summary

Fatigue tests have been conducted on two heats of Type 304 SS under various material conditions to determine the effect of heat treatment on fatigue crack initiation in these steels in air and LWR environments. A detailed metallographic examination of fatigue test specimens was performed, with special attention to crack morphology at the sites of initiation, the fracture surface, and the occurrence of striations.

The results indicate that heat treatment has little or no effect on the fatigue life of Type 304 SS in air and low–DO PWR environments. In a high–DO BWR environment, fatigue life is lower for sensitized SSs; life continues to decrease as the degree of sensitization is increased. The cyclic strain–hardening behavior of Type 304 SS under various heat treatment conditions is identical, only the fatigue life varies in different environments.

In air, irrespective of the degree of sensitization, the fracture mode for crack initiation (crack lengths up to ≈200 μm) and crack propagation (crack lengths >200 μm) is transgranular (TG), most likely along crystallographic planes, leaving behind relatively smooth facets. With increasing degree of sensitization, cleavage–like or stepped TG fracture, and occasionally ridge structures on the smooth surfaces were observed. In the BWR environment, the initial crack appeared intergranular (IG) for all heat–treatment conditions, implying a weakening of the grain boundaries. For all four conditions tested, the initial IG mode transformed within 200 μm into a TG mode with cleavage–like features. It appears, however, that the size of the IG portion of the crack surface increased with the degree of sensitization. By contrast, for all of the samples tested in PWR environments, the cracks initiated and propagated in a TG mode irrespective of the degree of sensitization. Prominent features of all fracture surfaces in the PWR case were highly angular, cleavage–like fracture facets that exhibited well–defined “river” patterns. Intergranular facets were rarely observed, but when they were found, it was mostly in the more heavily sensitized alloys.

Fatigue striations normal to the crack advance direction were clearly visible beyond ≈200 μm on the fracture surfaces for all material and environmental conditions. Striations were found on both the TG and IG facets of the samples tested in BWR conditions, or co-existing with the “river” patterns specific to the samples tested in the PWR environment. Evidence of extensive rubbing due to repeated contact between the two mating surfaces was also found.

The orientation of the cracks as they initiated at the specimen surface was also a function of the test environment. For air tests, cracks initiated obliquely, approaching 45°, with respect to the tensile axis. By contrast, for tests in either BWR or PWR environment cracks tended to initiate perpendicular to the tensile axis. In all environments, the overall orientation of the crack became perpendicular to the tensile axis as the crack grew beyond the initiation stage.

In air, the fatigue lives of Types 304 and 316 SS are comparable; those of Type 316NG are superior to those of Types 304 and 316 SS at high strain amplitudes. The fatigue lives of austenitic SSs in air are 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.

Review of the available data show that the fatigue lives of cast and wrought austenitic 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, the logarithm of 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. In these environments, the composition or heat treatment of the steel has little or no effect on fatigue life. However, in high–DO water the environmental effects on fatigue life are influenced by the composition and heat treatment of the steel. For a high–carbon heat of Type 304 SS, environmental effects were significant only for the sensitized steel. For a low–carbon heat of Type 316NG SS, some effect of environment was observed even for MA steel in high–DO water, although the effect was smaller than that observed in low–DO water. Limited 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.

Statistical models for the fatigue life of austenitic SSs as a function of material, loading, and environmental parameters have been developed. The functional form of the model and bounding values of the important parameters are based on experimental observations and data trends. The models are recommended for predicted fatigue lives of $\leq 10^6$ cycles. Consistent with previous work by Jaske and O'Donnell, the present results indicate that even in air the ASME mean curve for SSs is not consistent with the experimental data. The ASME curve is nonconservative. The results that correspond to the 50th percentile of the statistical model are considered to be the best fit to the experimental data.

Two approaches are presented for incorporating the effects of LWR environments into ASME Section III fatigue evaluations**.** In the first approach, environmentally adjusted fatigue design curves are 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.

References

1. Langer, B. F., “Design of Pressure Vessels for Low–Cycle Fatigue,” ASME J. Basic Eng. 84, 389–402, 1962.

2. Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels, The American Society of Mechanical Engineers, New York, 1964.

3. Chopra, O. K., 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.

4. Chopra, O. K., and W. J. Shack, “Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels,” NUREG/CR–6717, ANL–00/27, May 2001.

5. Chopra, O. K., and W. J. Shack, “Review of the Margins for ASME Code Design Curves – Effects of Surface Roughness and Material Variability,” NUREG/CR–6815, ANL–02/39, Sept. 2003.

6. Chopra, O. K., “Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels,” NUREG/CR–5704, ANL–98/31, 1999.

7. Chopra, O. K., “Mechanisms and Estimation of Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments,” NUREG/CR–6787, ANL–01/25, Aug. 2002.

8. Majumdar, S., 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.

9. Keisler, J., 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.

10. Higuchi, M., 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.

11. Iida, K., 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.

12. Park, J. Y., and W. J. Shack, “Intergranular Crack Propagation Rates in Sensitized Type 304 Stainless Steel in an Oxygenated Water Environment,” ANL–83–93, Dec. 1983.

13. Ruther, W. E., W. K. Soppet, and T. F. Kassner, “Evaluation of Environmental Corrective Actions,” in Materials Science and Technology Division Light–Water–Reactor Safety Research Program: Quarterly Progress Report, October–December 1983, NUREG/CR–3689 Vol. IV, ANL–83–85 Vol. IV, pp. 51–57, Aug. 1984.

14. Macdonald, D. D., A. C. Scott, and P. Wentrcek, “External Reference Electrodes for Use in High Temperature Aqueous Systems,” J. Electrochem. Soc. 126, 908–911, 1979.

15. Smith, J. L., O. K. Chopra, and W. J. Shack, “Effect of Water Chemistry on the Fatigue Life of Austenitic Stainless Steels in LWR Environments,” in Environmentally Assisted Cracking in Light Water Reactors, Semiannual Report, January 1999–June 1999, NUREG/CR–4667, Vol. 28, ANL–00/7, pp. 13–27, July 2000.

16. Jaske, C. E., and W. J. O’Donnell, “Fatigue Design Criteria for Pressure Vessel Alloys,” Trans. ASME J. Pressure Vessel Technol. 99, 584–592, 1977.

17. Conway, J. B., 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.

18. Keller, D. L., “Progress on LMFBR Cladding, Structural, and Component Materials Studies During July, 1971 through June, 1972, Final Report,” Task 32, Battelle–Columbus Laboratories, BMI–1928, 1977.

19. Hale, D. A., 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.

20. Fujiwara, M., 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.

21. Mimaki, H., 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.

22. Kanasaki, H., 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.

23. Kanasaki, H., 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.

24. Tsutsumi, K., 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.

25. Tsutsumi, K., 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.

26. Higuchi, M., 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.

27. Higuchi, M., 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.

28. Hayashi, M., "Thermal Fatigue Strength of Type 304 Stainless Steel in Simulated BWR Environment," Nucl. Eng. Des. 184, 135–144, 1998.

29. Hayashi, M., 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.

30. Chopra, O. K., 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.

31. Chopra, O. K., and D. J. Gavenda, "Effects of LWR Coolant Environments on Fatigue Lives of Austenitic Stainless Steels," J. Pressure Vessel Technol. 120, 116–121, 1998.

32. Chopra, O. K., 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.

33. Amzallag, C., P. Rabbe, G. Gallet, and 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.

34. Wire, G. L., 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.

35. Hirano, A., 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.

36. Lenz, E., 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.

37. Slama, G., P. Petrequin, and T. Mager, "Effect of Aging on Mechanical Properties of Austenitic Stainless Steel Castings and Welds," in Assuring Structural Integrity of Steel Reactor Pressure Boundary Components, SMiRT Post Conference Seminar 6, Monterey, CA, 1983.

38. Chopra, O. K., "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," NUREG/CR–4513, ANL–93/22, Aug. 1994.

39. Chopra, O. K., "Effect of Thermal Aging on Mechanical Properties of Cast Stainless Steels," in Proc. of the 2nd Int. Conf. on Heat–Resistant Materials, K. Natesan, P. Ganesan, and G. Lai, eds., ASM International, Materials Park, OH, pp. 479–485, 1995.

40. Higuchi, M., K. Iida, A. Hirano, K. Tsutsumi, and K. Sakaguchi, "A Proposal of Fatigue Life Correlation Factor F_{en} for Austenitic Stainless Steels in LWR Water Environments," in Pressure Vessel and Piping Codes and Standards – 2002, PVP Vol. 439, M. D. Rana, ed., American Society of Mechanical Engineers, New York, pp. 109–117, 2002.

41. Leax, T. R., "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.

42. Smith, K. N., P. Watson, and T. H. Topper, "A Stress–Strain Function for the Fatigue of Metals," J. Mater., JMLSA 5 (4), 767–778, 1970.

NRC FORM 335
(2–89)
NRCM 1102,
3201, 3202

U. S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR–6878
ANL–03/35

2. TITLE AND SUBTITLE

Effect of Material Heat Treatment on Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments

3. DATE REPORT PUBLISHED

MONTH	YEAR
July	2005

4. FIN OR GRANT NUMBER

Y6388

5. AUTHOR(S)

O. K. Chopra, B. Alexandreanu, and W. J. Shack

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION – NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above": if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

10. SUPPLEMENTARY NOTES

William H. Cullen, Jr., NRC Project Manager

11. ABSTRACT (200 words or less)

The ASME Boiler and Pressure Vessel Code provides 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 of the Code specify design curves for applicable structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. The 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. Under certain environmental and loading conditions, fatigue lives of austenitic stainless steels (SSs) can be a factor of 20 lower in water than in air. This report presents experimental data on the effect of heat treatment on fatigue crack initiation in austenitic Type 304 SS in LWR coolant environments. A detailed metallographic examination of fatigue test specimens was performed to characterize the crack morphology and fracture morphology. The key material, loading, and environmental parameters and their effect on the fatigue life of these steels are also described. Statistical models are presented for estimating the fatigue ε–N curves for austenitic SSs 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.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating this report.)*

Fatigue Strain–Life Curves
Fatigue Design Curves
Fatigue Crack Initiation
LWR Environment
Austenitic Stainless Steels
Cast Austenitic Stainless Steels

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16.ICE PR