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Effect of LWR Water Environments on the Fatigue Life of Reactor Materials

Final Report

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Effect of LWR Water Environments on the Fatigue Life of Reactor Materials

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ABSTRACT

The American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME 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, "Rules for Construction of Nuclear Facility Components," of the ASME Code specify fatigue design curves for applicable structural materials. However, the ASME Code design curves do not explicitly address the effects of light-water reactor (LWR) water environments. The existing fatigue strain vs. life (ε–N) data illustrate potentially significant effects of LWR water environments on the fatigue resistance of pressure vessel and piping steels. Under certain environmental and loading conditions, the fatigue lives of reactor components in water relative to those in air can be a factor of approximately 12 lower for austenitic stainless steels, approximately 3 lower for nickel-chromium-iron alloys, and approximately 17 lower for carbon and low-alloy steels. The original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, which is the technical basis document for Regulatory Guide 1.207, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors," issued March 2007, summarizes the work performed at Argonne National Laboratory on the fatigue of piping and pressure vessel steels in LWR environments. That document evaluates the existing fatigue ε–N data to identify the various material, environmental, and loading parameters that influence fatigue crack initiation and to establish the effects of key parameters on the fatigue lives of these steels. The report presents fatigue life models for estimating fatigue lives as a function of material, loading, and environmental conditions and describes the environmental fatigue correction factor (F_{en}) for incorporating the effects of LWR environments into ASME Code Section III fatigue evaluations. The report also presented a critical review of the ASME Code Section III fatigue adjustment factors of 2 on stress (or strain) and 20 on life and assessed the possible conservatism in the choice of these adjustment factors.

This report provides updates and improvements to the F_{en} approach based on an extensive update to the fatigue ε–N data from testing and results available over the past decade since this report was first published. The updated expressions also address concerns from interested stakeholders related to (1) the constants in the F_{en} expressions that result in F_{en} values of approximately 2 even when the strain rate is very high or the temperature is very low, (2) the temperature dependence of F_{en} for carbon and low-alloy steels, and (3) the dependence of F_{en} on water chemistry for austenitic stainless steels. The F_{en} methodology was validated by comparing the results of five different experimental datasets obtained from fatigue tests that simulate actual plant conditions with estimates of fatigue usage adjusted for environmental effects using the updated F_{en} expressions. The potential effects of dynamic strain aging on cyclic deformation and environmental effects are also discussed.

FOREWORD

This report summarizes, reviews, and quantifies the effects of the light-water reactor (LWR) environments on the fatigue lives of reactor materials, including carbon steels, low-alloy steels, nickel-chromium-iron (Ni-Cr-Fe) alloys, and austenitic stainless steels. The primary purpose of this report is to provide the background and technical bases to support the revision of Regulatory Guide 1.207, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors," issued March 2007.

The original version of this report included a review of the fatigue strain vs. life (ε–N) data available at that time for carbon steels, low-alloy steels, Ni-Cr-Fe alloys, and austenitic stainless steels to define the potential effects of key material, loading, and environmental parameters on the fatigue lives of the steels. This database was used to update the fatigue life models in use at the time to estimate the fatigue curves as a function of key material, loading, and environmental parameters. The original version of this report also provided a procedure for incorporating environmental effects into fatigue evaluations. This revision of the report incorporates additional fatigue ε–N data available since the original publication of this report, most particularly from Japan, into the database and updates the fatigue life models. In addition, feedback from interested stakeholders obtained since the original publication of this report has been evaluated and incorporated in the report, as appropriate.

The database summarized in this report demonstrates that the previously published guidance in Regulatory Guide 1.207 for incorporating the LWR environmental effects in fatigue life evaluations should be revised. Toward that end, this report maintains the previously established methods for establishing reference air fatigue curves and defines updated environmental fatigue correction factors for use in evaluating the fatigue lives of reactor components exposed to LWR water environments.

The database described in this revised report has been used to verify that the previously developed fatigue design curves in air are consistent with the available fatigue data. Specifically, the existing curves from American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), Section III, "Rules for Construction of Nuclear Facility Components," are appropriate for austenitic stainless steels (e.g., Types 304, 316, and 316NG) and nickel-based alloys and are conservative for carbon and low-alloy steels. Revision 1 of Regulatory Guide 1.207 endorses the fatigue design curves presented herein for incorporation in fatigue analyses for new and operating reactors.

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EXECUTIVE SUMMARY

Cyclic loadings on a reactor pressure boundary component occur because of changes in mechanical and thermal loadings as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to another. Subsection NB, "Class 1 Components," of Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) contains rules for the design of Class 1 components of nuclear power plants and recognizes fatigue as a possible mode of failure in pressure vessel steels and piping materials. ASME Code Section III fatigue analysis procedures consider all fatigue cycles based on the anticipated number of thermal and pressure transients. In addition, for each load cycle or load set pair, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the design lifetime of the component, as specified by the Owner, to the number of allowable cycles. Figures I-9.1 through I-9.6 of Mandatory Appendix I to Section III of the ASME Code specify fatigue design curves that define the allowable number of cycles as a function of applied stress amplitude. Those fatigue design curves have evolved significantly since the initial publication of ASME Code Section III in 1963. However, Paragraph NB-3121 of the 2011 Addenda to ASME Code Section III continues to state that the effects of water environments on the fatigue resistance of materials were not addressed in the fatigue design curves. Therefore, the effects of water environments on the fatigue resistance of materials used in operating pressurized-water reactors and boiling-water reactors, whose components were designed in accordance with ASME Code Section III, may not adequately address long-term environmental effects on fatigue based on the data available at the time the fatigue design curves were derived.

The current design fatigue curves in air contained in ASME Code Section III were based primarily on strain-controlled fatigue tests of small polished specimens at room temperature in laboratory air environments. 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 air curves. These factors were not intended as "safety margins"; instead, they were intended as "adjustment factors" that were applied to the experimental laboratory data to obtain estimates of the fatigue lives of actual reactor components. Recent fatigue strain vs. life (ε–N) data obtained primarily in the United States and Japan demonstrate that light-water reactor (LWR) environments have potentially significant effects on the fatigue resistance of materials. Specimen lives obtained from laboratory tests in simulated LWR environments were much shorter than those obtained from corresponding tests in an air environment.

The original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, evaluates the existing fatigue ε–N data for carbon and low-alloy steels, wrought and cast austenitic stainless steels (SSs), and nickel-chromium-iron (Ni-Cr-Fe) alloys in air and LWR environments to identify the various material, environmental, and loading parameters that influence fatigue crack initiation. The results of those evaluations were used to establish the effects of key parameters on the fatigue lives of steels. The fatigue lives of materials were decreased in LWR environments; the magnitude of the reduction depended on the temperature, strain rate, and dissolved oxygen (DO) level in the water and, for carbon and low-alloy steels, the sulfur content of the steels. For all steels, environmental effects on fatigue lives were significant only when critical parameters (temperature, strain rate, DO level, and strain amplitude) met certain threshold values. Environmental effects were moderate (e.g., less than a factor of 2 decrease in fatigue lives) when any one of the threshold conditions was not satisfied. The threshold values of the critical

parameters and the effects of other parameters (such as water conductivity, water flow rate, and material heat treatment) on the fatigue lives of the steels were also discussed.

This report reevaluates the fatigue ε–N data for nuclear power plant piping and pressure vessel steels presented in the original version of NUREG/CR-6909 using a much larger database. The results were updated to include this reevaluation and to address concerns from interested stakeholders about the environmental fatigue correction factor (F_{en}) methodology for incorporating environmental effects into ASME Code Section III fatigue cumulative usage factor evaluations. This report summarizes the resulting effects of various material, loading, and environmental parameters on the fatigue lives of steels. Note that, as with the original evaluation, the reevaluation in this report was still based on various compositions of wrought Type 304 and 316 SSs, associated weld metals, and a few heats of CF-8M cast austenitic SSs. The reevaluation did not consider other grades of austenitic SSs, particularly the titanium- or niobium-modified SSs, which have better fatigue resistance. Therefore, fatigue lives based on the proposed fatigue design curve are expected to be conservative for SSs with improved fatigue resistance, such as the titanium- or niobium-modified steels.

The results indicate that the ASME Code Section III mean air curve for low-alloy steels is in good agreement with the available experimental data and that the ASME Code Section III mean air curve for carbon steels is conservative. In addition, the best-fit mean air curve used to develop the fatigue design air curve for austenitic SSs in ASME Code Section III editions before publication of the 2009 Addenda is not consistent with the experimental data at strain amplitudes of less than 0.5%; fatigue lives predicted by the ASME Code Section III mean air curve were longer than those obtained from experiments. Therefore, in the initial version of NUREG/CR-6909, new fatigue design air curves were developed for carbon and low-alloy steels and austenitic SSs that were based on the Argonne National Laboratory (ANL) fatigue life models and were consistent with the fatigue ε–N data available at that time. The air design curves were extended up to 10^{11} cycles using available high-cycle fatigue data. In 2009, the ANL design air curve for austenitic SSs was adopted into Mandatory Appendix I to ASME Code Section III. The reevaluation of the fatigue ε–N behavior of austenitic SS materials using a much larger database indicates that the air fatigue design curves previously developed by ANL are consistent with the available fatigue data and do not warrant any modifications. However, the present report modifies the extension of the air fatigue design curves for carbon and low-alloy steels up to 10^{11} cycles to be consistent with the extension of the current ASME Code Section III fatigue design curve beyond 10^6 cycles.

The reevaluation results also indicate that the fatigue data for Ni-Cr-Fe alloys were not consistent with the current ASME Code mean air curve for austenitic SSs. The rather limited fatigue ε–N data for Ni-Cr-Fe alloys, such as Alloys 600, 690, and 800 and their welds, are consistent with the best-fit mean air curve for austenitic SSs at fatigue lives less than 10^4 cycles and show longer fatigue lives than the predicted values for fatigue lives greater than 10^4 cycles. However, a separate air fatigue design curve was not developed for Ni-Cr-Fe alloys, and the current ASME Code fatigue air design curve for austenitic SSs, which is based on the ANL model, was used to represent the fatigue ε–N behavior of Ni-Cr-Fe alloys and associated weld metals. The data also indicate that the fatigue resistance of Inconel 718 is superior to that of the other Ni-Cr-Fe -alloys. The slope of the Inconel 718 fatigue ε–N curve is flatter, and the fatigue limit is higher than those for austenitic SSs. Therefore, the current ASME Code fatigue air design curve for austenitic SSs curve is conservative for representing the fatigue ε–N behavior of Inconel 718.

The fatigue lives of carbon and low-alloy steels, austenitic SSs, and Ni-Cr-Fe alloys were decreased in LWR environments. The reduction depended on some key material, loading, and environmental parameters. The fatigue ε–N data were consistent with the much larger database on enhancement of crack growth rates in these materials in LWR environments. The key parameters that influenced fatigue lives in these environments (e.g., temperature, DO level in the water, strain rate, strain (or stress) amplitude, and, for carbon and low-alloy steels, sulfur content of the steel) were identified. In addition, the functional form of the dependence of fatigue lives on these parameters and the range of the values of these parameters within which environmental effects were significant was defined. If these critical loading and environmental conditions exist during reactor operation, environmental effects may be significant and should be included in any relevant ASME Code Section III fatigue evaluations.

The initial version of NUREG/CR-6909 developed fatigue life models to predict the fatigue lives of small smooth specimens of carbon and low-alloy steels, wrought and cast austenitic SSs, and Ni-Cr-Fe alloys as a function of material, loading, and environmental parameters using the existing fatigue ε–N database. The functional form and bounding values of these parameters were based on experimental observations and data trends. An approach was presented that incorporates the effects of LWR coolant environments into the ASME Code Section III fatigue evaluations based on the F_{en}. The fatigue usage for a specific stress cycle or load set pair derived using the ASME Code Section III fatigue design air curves was multiplied by the F_{en} to account for environmental effects. Note that the F_{en} approach described in this report is only applicable for use as part of an ASME Code fatigue evaluation. Further, this report does not address any conservatisms associated with the ASME Code fatigue evaluation procedures.

The present report updates the F_{en} expressions using a much larger fatigue ε–N database, primarily derived from extensive additional data provided from Japan. The updated expressions also address comments provided by interested stakeholders related to (1) the constants in the F_{en} expressions that result in an F_{en} value of approximately 2 even when the strain rate is very high or the temperature is very low, (2) the temperature dependence of F_{en} for carbon and low-alloy steels, and (3) the dependence of F_{en} on water chemistry for austenitic SSs.

This report also briefly describes the mechanisms for fatigue cracking in air and LWR water environments. Fatigue life is conventionally divided into two stages—initiation and propagation. In LWR environments, the initiation stage involves the growth of microstructurally small cracks characterized by decelerating crack growth. The propagation stage involves the growth of mechanically small cracks characterized by accelerating crack growth. The available fatigue ε–N data indicated that LWR environments affect both the initiation and propagation of fatigue cracks. Two mechanisms are described in this report that potentially enhance both fatigue crack initiation and fatigue crack growth rates in LWR environments—slip oxidation/dissolution and hydrogen-induced cracking. The potential effects of dynamic strain aging on cyclic deformation and environmental effects are also discussed.

This report also presents a critical review of the ASME Code Section III fatigue adjustment factors of 2 on stress and 20 on life and assesses the possible conservatism in the choice of adjustment factors. Although these factors were intended to be conservative, they were not considered to be safety margins in the work presented in this report. Instead, these factors cover the effects of variables that influence fatigue lives but were not investigated in the experiments that were used to obtain the air fatigue design curves. Data available in the literature were reviewed to evaluate the factors on cycles that are needed to account for such differences and uncertainties. Monte Carlo simulations were performed to determine the factor on cycles needed to obtain a fatigue design curve in air that provided a conservative estimate of

the number of cycles required to initiate a fatigue crack in reactor components. The results presented in the original version of NUREG/CR-6909 indicate that, for carbon and low-alloy steels and austenitic SSs, the current ASME Code Section III requirements for a factor of 20 on cycles to account for the effects of material variability and data scatter, size, surface finish, and loading history may be decreased by at least a factor of 1.7. Thus, to reduce conservatism, fatigue design curves were developed based on the ANL fatigue life models, and those curves were then adjusted for mean stress effects and by factors of 2 on stress and 12 on cycles. These adjustments were made to account for the effects of (1) material variability and data scatter, (2) size, (3) surface finish, and (4) loading sequence. For this report, the range of these four parameters were modified, and Monte Carlo simulations were repeated to determine the factor on cycles needed to obtain fatigue design curves in air. The results indicate that, for carbon and low-alloy steels and austenitic SSs, factors of 2 on stress and 10 on cycles are adequate to develop air fatigue design curves from the best-fit mean air curves. However, until these results are further validated with applicable fatigue data ε–N data, the air fatigue design curves presented in this report are based on factors of 2 on stress and 12 on life.

The F_{en} methodology was also validated by comparing the results of several experimental datasets obtained from fatigue tests that simulated actual plant conditions with estimated fatigue usage using the updated F_{en} expressions. The datasets represent fatigue tests with changing strain rate or temperature, or both; complex loading that simulated a pressurized-water reactor safety injection transient; spectrum loading (i.e., random strain amplitudes); and pipe U-bend tests. In all cases, the results indicate that the predicted fatigue lives were in good agreement with the experimental values; the differences between the experimental and predicted fatigue lives were within a factor of 2, which is within the experimental data scatter. The predicted fatigue lives for the tests with the complex strain loading cycle were lower than the experimental values by a factor of about 2. The reason for this deviation was not clear but may be unique to the specific test loading cycle. Nonetheless, although the predicted lives were all lower, the estimated values were within the range of data scatter.

This report also presents a detailed procedure for incorporating environmental effects into ASME Code Section III fatigue evaluations. This procedure applies to any component exposed to the LWR environment that requires an ASME cumulative usage factor calculation either as part of its design, for the component's safety basis, or as part of the plant current licensing basis, unless otherwise justified. This procedure allows evaluation using either a modified rate or an average rate approach. F_{en} calculations based on an average strain rate for the transient are expected to yield conservative estimates of fatigue lives as long as the calculations use appropriate temperatures selected in accordance with the recommended procedures in Section 4.4. Using an average transient temperature within the average strain rate approach does not always yield a conservative estimate of F_{en}. Therefore, an average temperature should only be used if it has been demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach. The ASME Code Section III fatigue design curves for carbon and low-alloy steels and austenitic SSs apply to various grades and compositions of materials having a wide range of tensile strength. Furthermore, the criterion used in establishing the fatigue design curve ensures that the proposed curve bounds 95% of the available fatigue data with 95% confidence. In addition, the mean stress correction for the design curves is based on a conservative value of mean stress at room temperature. Finally, the fatigue loading in laboratory specimens is uniformly tensile, which is more severe than in many applications where the loading decreases through the thickness. Therefore, the design curves should be conservative for most materials and applications, particularly at reactor operating temperatures where mean stresses are likely to be lower.

The criteria used for establishing the adjustment factors to account for the parameters that influence fatigue life, but were not considered in the experimental data used to develop the fatigue design curves (Section 5), also yield conservative values of fatigue life in applications. These adjustment factors may be further optimized. It should be stressed that other factors (e.g., component size) may lead to decreases in fatigue life in applications compared to laboratory testing. Therefore, any modifications of the design curves or adjustment factors should be performed holistically to develop a technical basis that addresses all the sources of conservatism and uncertainty mentioned above. Further, guidance should be provided for using the high-cycle portion of the design curves for mechanical loading. This guidance is necessary because strain-controlled fatigue test data are used to develop the ASME Code strain vs. life fatigue design curves, and these must be converted to pseudo-stress vs. life curves in most applications.

Revision 1 of this report represents a comprehensive and detailed expansion of the Revision 0 manuscript that incorporates significant additional background, test data, and test data descriptions. In addition, the content layout of the report was revised for clarity. As a result, the changes made to the Revision 0 manuscript are not specifically identified throughout the text of this revision.

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ABBREVIATIONS AND ACRONYMS

ANL	Argonne National Laboratory
ANN	artificial neural network
ASME	American Society of Mechanical Engineers
ASME Code	American Society of Mechanical Engineers Boiler and Pressure Vessel Code
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
BTP	branch technical position
BNCS	Board on Nuclear Codes and Standards
BWR	boiling water reactor
^{o}C	degrees Celsius
CGR	crack growth rate
CLEE	cyclic life environmental effects
cm^3/kg	cubic centimeters per kilogram
CT	compact tension
CUF	cumulative usage factor
CVCS	chemical and volume control system
CW	cold worked
da/dN	fatigue crack growth rate (expressed as the change in crack depth, da, divided by the number of applied cycles, dN)
DO	dissolved oxygen
DSA	dynamic strain aging
E	Energy
EAC	environmentally assisted cracking
EBR II	Experimental Breeder Reactor II
ECP	electrochemical potential
EFD	environmental fatigue data
EFT	environmental fatigue testing
EPR	electrochemical potentiodynamic reactivation
EPRI	Electric Power Research Institute
ETR	Experimental Test Reactor
ε–N	fatigue strain vs. life
F_{en}	environmental fatigue correction factor
^{o}F	degrees Fahrenheit
FAP	fatigue action plan
GE	General Electric Company
GSI	generic safety issue
H	Hydrogen
HS	hydrosulfide ion
HAZ	heat affected zone
He	Helium
HWC	hydrogen water chemistry
ID	internal diameter
IG	Intergranular
in.	Inches
IHI	Ishikawajima-Harima Heavy Industries
INEL	Idaho National Engineering Laboratory
JAPEIC	Japan Power Engineering and Inspection Corporation

JNES	Japan Nuclear Energy Safety Organization
JNUFAD	revised and renamed fatigue database “FADAL” from Japan
KWU	Kraftwerk Union Laboratories
L/h	liters per hour
LEFM	linear elastic fracture mechanics
LWR	light-water reactor
LWR water environment	light-water reactor water environment
μS/cm	microsiemens per centimeter
MA	mill annealed
MEA	Materials Engineering Associates
MeV	million electron volts
MHI	Mitsubishi Heavy Industries
m	Meters
μm	Micrometers
mm	Millimeters
MnS	manganese sulfide
MOU	memorandum of understanding
MPa	Megapascals
m/s	meters per second
MPA	Materialprufungsanstalt
MSC	microstructurally small crack
N	number of cycles
N_{air}	number of cycles in air
N_{water}	number of cycles in water environment
NASA	National Aeronautics and Space Administration
n/cm^2	neutrons per centimeter squared
Ni-Cr	Nickel-chromium
Ni-Cr-Fe	nickel-chromium-iron
Ni-Fe-Cr	nickel-iron-chromium
n/m^2	neutrons per meter squared
NPS	nominal pipe size
NRC	U.S. Nuclear Regulatory Commission
NWC	normal water chemistry
OD	outer diameter
ORNL	Oak Ridge National Laboratory
ppb	parts per billion
ppm	parts per million
PSB	persistent slip band
psi	pounds per square inch
PVRC	Pressure Vessel Research Council
PWR	Pressurized-water reactor
R_a	average surface roughness (μm)
R_q	root-mean-square value of surface roughness (μm)
R_t	maximum height of the surface roughness profile (μm)
RCS	reactor coolant system
RG	regulatory guide
RHR	residual heat removal
RMS	root mean square
RT	room temperature (77°F [25°C])

S	Sulfur
S^{2-}	sulfide ion
SICC	strain-induced corrosion cracking
SS	stainless steel
T	Temperature
TENPES	Thermal and Nuclear Power Engineering Society
Ti	Titanium
TG	Transgranular
TMI	Three Mile Island
UTS	ultimate tensile strength
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Center of Finland)
VVER	Voda-Vodyanoi Energetichesky Reaktor (Russian PWR)
WRC	Welding Research Council
YS	monotonic yield strength

1 INTRODUCTION

The structural integrity of a metal component may gradually degrade when it is subjected to cyclic loading, even at magnitudes less than the design static loads, caused by a well-known degradation mechanism called fatigue. The mechanism of fatigue can damage flaw-free components by causing them to develop cracks during service. Subsection NB "Class 1 Components," of Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), which contains rules for the design of Class 1 components for nuclear power plants, recognizes fatigue as a possible mode of failure in pressure vessel steels and piping materials. Fatigue is a major consideration in the design of rotating machinery and aircraft in which the components are subjected to a very large number of cycles (i.e., high-cycle fatigue). In these situations, the primary concern is the endurance limit, which is the stress level below which an infinite number of cycles can be applied without fatigue failure. However, cyclic loadings on a reactor pressure boundary component occur because of changes in mechanical and thermal loadings as the system goes from one load state to another. The number of cycles applied during the design life of the component seldom exceeds 100,000 and is typically less than a few thousand (e.g., low-cycle fatigue). The main difference between high-cycle and low-cycle fatigue is that the former involves little or no plastic strain, whereas the latter involves strains in excess of the yield strain. Therefore, design curves for low-cycle fatigue are based on tests in which strain rather than stress is the controlled variable.

Subarticles NB-3200, "Design by Analysis," and NB-3600, "Piping Design," of ASME Code Section III describe the fatigue evaluation procedures. The ASME Code fatigue analysis considers all transient loads based on the anticipated number of thermal and pressure transients, and for each load cycle or load set pair, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the lifetime of the component to the allowable cycles. Figures I-9.1 through I-9.6 of Mandatory Appendix I to ASME Code Section III specify fatigue design curves for various materials that define the allowable number of cycles as a function of applied stress amplitude. The cumulative usage factor (CUF) is the sum of the individual usage factors for all load set pairs, and ASME Code Section III requires that at each location, the CUF, which is calculated based on Miner's rule, must not exceed unity for acceptable fatigue design.

Although the ASME Code Section III rules apply to Class 1 components, those fatigue design rules are sometimes applied to other classes of components to provide a robust fatigue design in situations where known fatigue issues exist or fatigue duty is high (e.g., Class 2 pressurized-water reactor (PWR) feedwater nozzles). As such, the methods described in this report are intended to apply to all components exposed to any water environment in a light-water reactor (LWR) that uses the fatigue calculation procedures from ASME Code Section III. References made to an "LWR environment" throughout this report refer to any water environment at a temperature greater than 50°C in an LWR power plant and encompasses both steady-state and transient conditions, such as during a reactor shutdown.

This revision represents a comprehensive and detailed expansion of the Revision 0 manuscript (i.e., the original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, as depicted throughout this report) that incorporates significant additional background, test data, and test data

descriptions. In addition, the content layout of the report was revised for clarity. As a result, the changes made to the Revision 0 manuscript are not specifically identified throughout the text of this revision.

1.1 Definition of Fatigue Life

Before discussing the fatigue design curves used in the ASME Code Section III fatigue CUF analysis, the use of the term "fatigue life" in this report should first be described. American Society for Testing and Materials (ASTM) Designation E 1823-09a, "Standard Terminology Relating to Fatigue and Fracture Testing,"[1] issued March 2009, defines fatigue life as "the number of cycles of a specified character that a given specimen sustains before failure of a specified nature occurs. Fatigue life, or the logarithm of fatigue life, is a dependent variable." Accordingly, the ASME Code fatigue design curves [i.e., stress amplitude (S_a) vs. number of cycles (N) curves] are generally considered to represent the allowable number of cycles to failure. However, note that ASTM Standard E1823-09a states that fatigue life is "failure of a specified nature." Furthermore, Section 8.9 of ASTM Standard E606-04, "Standard Practice for Strain-controlled Fatigue Testing,"[2] issued July 2005, states that the definition of failure may vary with the ultimate use of the fatigue life information, and provides the following acceptable alternatives for determination of failure:

(i) *Separation*: Total separation or fracture of the specimen into two parts at (1) some location within the uniform section of the uniform-gauge specimen, or (2) the vicinity of the minimum diameter in the hourglass specimen.

(ii) *Modulus Method*: For any specified number of cycles, N, during a fatigue test, the modulus for unloading following a peak tensile stress is defined as E_{NT} and the modulus for loading following a peak compressive stress is E_{NC}. Failure is defined as the number of cycles where the ratio E_{NT}/E_{NC} reaches one-half the value for the first cycle (i.e., is reduced by 50%). However, if total separation occurs first, as in item (i) above, fatigue life is defined by the number of cycles to separation.

(iii) *Microcracking*: The existence of surface microcracks (e.g., as observed optically or by replicas) that are larger than some preselected size consistent with the test objective.

(iv) *Force (Stress) Drop*: Failure is defined as the ability of a test specimen to sustain a tensile force (or stress). Failure is often defined as the point at which the maximum force (stress) or elastic modulus (as measured when unloading from a peak tensile stress) decreases by approximately 50% because of the presence of cracks. The exact method and the percentage drop should be documented.

In the fatigue strain vs. life (ε–N) data used to develop the original ASME Code best-fit or mean-data curves, failure was primarily defined as total separation or fracture of the specimen into two parts. In the fatigue tests performed during the last four decades, failure was defined according to the force (stress) drop method. In most of these tests, fatigue life was defined in terms of the number of cycles for the tensile stress to decrease 25% from its peak or steady-state value (i.e., 25% load drop). For the typical 9.5-mm diameter cylindrical specimens used in these studies, this load drop corresponded to the number of cycles needed to produce approximately 3-mm-deep cracks in test specimens.

Based on the foregoing discussion and the results of the majority of the test data evaluated, fatigue life is defined in this report as the number of cycles of a specified strain amplitude that a specimen can sustain before the formation of a 3-mm-deep crack (i.e., an "engineering crack"). Thus, the fatigue life of a material can be described in terms of three parameters: strain or stress, cycles, and crack depth. The best–fit curve to the existing fatigue ε–N data describes, for a given strain or stress amplitude, the number of cycles needed to develop a 3–mm deep crack. This number of cycles also equates to a 25% load drop in a solid 9.5-mm test specimen, and is assumed to equate to crack initiation in an actual component. Using this definition, a calculated fatigue CUF of less than unity provides reasonable assurance that a fatigue crack has not formed in a component, and indicates that the probability of forming a crack in the component is low.

1.2 Air Fatigue Design Curves in ASME Code Section III

The ASME Code fatigue design curves, as given in Mandatory Appendix I to ASME Code Section III, are based on strain–controlled tests of small polished specimens at room temperature in air. The data are typically obtained from fatigue tests conducted in accordance with ASTM Standard E606-04. This practice covers the determination of fatigue properties of nominally homogeneous materials by the use of uniform gauge section specimens subjected to axial strain-controlled, fully reversed (strain ratio, R, equal to -1) cycling. The practice also applies to hourglass specimens. The practice may be adapted to guide more general testing where strain or temperature may be varied according to application specific histories. The presentation and analysis of data are performed in accordance with ASTM Standard E468, "Standard Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials,"[3] issued October 2004, and ASTM Standard E739, "Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S–N) and Strain-Life (ε–N) Fatigue Data,"[4] issued May 2006. The guidance in Volume 8, "Fatigue Data Analysis,"[5] issued 1985, of the *Metals Handbook* can also be used. ASTM Standard E1823, "Standard Terminology Relating to Fatigue and Fracture Testing,"[6] issued March 2009, defines the terms related to fatigue testing.

The design curves were developed from the best–fit curves to the experimental fatigue ε–N data, which are expressed in terms of the Langer equation[7] of the form

$$\varepsilon_a = A1(N)^{-n1} + A2, \tag{1}$$

where ε_a is the applied strain amplitude, N is the fatigue life, and A1, A2, and n1 are coefficients of the model. Equation 1 may be written in terms of stress amplitude S_a instead of ε_a. The stress amplitude is the product of ε_a and elastic modulus E (i.e., $S_a = E \cdot \varepsilon_a$) (stress amplitude is one-half the applied stress range). The current ASME Code best-fit or mean curve described in ASME Code Section III criteria document[8] for various steels is given by

$$S_a = \frac{E}{4\sqrt{N_f}} \ln\left(\frac{100}{100 - A_f}\right) + B_f, \tag{2}$$

where E is the elastic modulus (MPa), N_f is the number of cycles to failure, and A_f and B_f are constants related to reduction in area in a tensile test (percent) and endurance limit of the material at 10^7 cycles (MPa), respectively.[7] The current Code mean curves were obtained from Equation 2 and A_f and B_f values of 68.5% and 149.2 MPa, 61.4% and 265.4 MPa, and 72.6% and 299.9 MPa, respectively, for carbon steels, low-alloy steels, and austenitic stainless steels

(SSs).[8] Thus, using an elastic modulus of 206,843 MPa for carbon and low-alloy steels and 179,264 MPa for austenitic SSs, the mean curves are expressed for carbon steels, as

$$S_a = 59{,}734\ (N_f)^{-0.5} + 149.2, \quad (3)$$

for low-alloy steel, as

$$S_a = 49{,}222\ (N_f)^{-0.5} + 265.4, \quad (4)$$

and for austenitic SSs, as

$$S_a = 58{,}020\ (N_f)^{-0.5} + 299.9. \quad (5)$$

The fatigue ε–N data are typically expressed by rewriting Equation 1 as

$$\ln(N) = A - B \ln(\varepsilon_a - C), \quad (6)$$

where A, B, and C are constants; C represents the fatigue limit of the material; and B is the slope of the log-log plot of fatigue ε–N data. The ASME Code mean-data curves (i.e., Equations 3-5) may be expressed in terms of Equation 6 as follows. The fatigue life of carbon steels is given by

$$\ln(N) = 6.726 - 2.0 \ln(\varepsilon_a - 0.072), \quad (7)$$

and for low-alloy steels by

$$\ln(N) = 6.339 - 2.0 \ln(\varepsilon_a - 0.128). \quad (8)$$

For austenitic SSs, the fatigue life corresponding to the fatigue design curve originally published in ASME Code Section III prior to the 2009 Addenda is given by

$$\ln(N) = 6.954 - 2.0 \ln(\varepsilon_a - 0.167), \quad (9)$$

and, as derived in Section 3.2.6, the fatigue life corresponding to the fatigue design curves in the 2009 Addenda and later editions of the ASME Code is given by

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112), \quad (10)$$

where strain amplitude ε_a is in percent. The ε–N curve for austenitic SSs is also used for nickel-chromium-iron (Ni-Cr-Fe) alloys (e.g., Alloy 600).

The best-fit or mean-data curves (e.g., Equations 7-10) provide an estimate of the fatigue life that would lead to failure in 50% of the population under a given loading. However, this report includes a rigorous evaluation for defining an adjustment factor to derive the fatigue design curve from the mean-data curve, to account for the variability resulting from data scatter, size, surface roughness, and loading sequence.

Another term that is often used in ASME Code Section III fatigue evaluations is fatigue limit (or endurance limit), which is defined as “the limiting value of the median fatigue strength as the fatigue life, N_f, becomes very large.”[1] However, certain materials (e.g., carbon and low-alloy steels and austenitic SSs) and environments preclude the attainment of a fatigue limit. Therefore, in the

literature, fatigue limit is typically defined as a value of stress, S_N, for failure at a specified number of cycles, N (e.g., at 10^6 or 10^{11} cycles).

The above ε–N curves describe the formation of engineering fatigue cracks in small, smooth test specimens in an air environment. To use the small-specimen data for actual reactor components, the best-fit ε–N curves for specimen data must be adjusted to account for the effects of variables that are known to affect fatigue life but were not accounted for in the small-specimen data. Such variables include mean stress, surface finish, size, and loading history. Furthermore, the best-fit curve represents the average behavior of the material. To obtain a curve that ensures a low probability for formation of fatigue cracks, the small specimen curve must also be adjusted to account for data scatter and material variability.

The procedure used to develop the ASME Code fatigue design curves from the best-fit (or mean-data) curves for small specimens is as follows. First, the best-fit curves are adjusted to account for the effects of mean stress. This is necessary to account for mean stress effects that were not considered during specimen testing, such as weld residual stress. Mean stress was accounted for using the modified Goodman relationship given by

$$S'_a = S_a \left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a} \right) \quad \text{for } S_a < \sigma_y \,, \tag{11}$$

and

$$S'_a = S_a \qquad \text{for } S_a > \sigma_y \,, \tag{12}$$

where S'_a is the adjusted value of stress amplitude, and σ_y and σ_u are the monotonic yield and ultimate strengths of the material, respectively. Equations 11 and 12 assume the maximum possible mean stress and typically give a conservative adjustment for mean stress. The original ASME Code Section III fatigue design curves were obtained by reducing the fatigue life at each point on the adjusted best-fit curve by a factor of 2 on strain (or stress) or 20 on cycles, whichever was more conservative.

As described in the ASME Code Section III criteria document,[8] the factors of 2 and 20 are not safety margins, but rather adjustment factors that were applied to the small–specimen data to account for the effects of variables that are known to affect fatigue life but were not accounted for in the small-specimen data. These factors include (1) data scatter and material variability, (2) the differences in surface condition and size between the test specimens and actual reactor components, and (3) random load cycles as compared to constant strain cycles used to obtain the fatigue ε–N data.

1.3 Subfactors Included in ASME Code Section III Air Fatigue Design Curves

In comments about the initial scope and intent of the ASME Code Section III fatigue design procedures, Cooper[9] states that the factor of 20 on life was regarded as the product of the following three subfactors:

(1)	scatter of data (minimum to mean):	2.0
(2)	size effect:	2.5
(3)	surface finish, atmosphere, and other such subfactors:	4.0

Although the ASME Code Section III criteria document[8] states that these factors were intended to cover such effects as environment, Cooper[9] further states that the term “atmosphere” was intended to reflect the effects of an industrial atmosphere compared to an air-conditioned laboratory, which are different

than the effects of a specific water environment. In addition, surface finish represented surface roughness of an industrial-Grade component surface compared to that of a polished test specimen. Subsubarticle NB-2160 (or Subsubarticle NG-2160 for core support structures) of ASME Code Section III states, "It is the responsibility of the Owner to select material suitable for the conditions stated in the Design Specifications (NCA-3250), with specific attention being given to the effects of service conditions upon the properties of the material." Paragraph NCA-3252 of ASME Code Section III specifies the minimum contents of the design specifications. Subparagraph NCA-3252(a)(3) states that the design specifications shall include "the environmental conditions, including radiation." The environmental conditions that are likely to influence the properties of materials used in nuclear power plant structures and components include temperature, water environment, and neutron irradiation.

Furthermore, Paragraph NB–3121 of ASME Code Section III (or Paragraph NG-3121 for core support structures) states, "It should be noted that the tests on which the fatigue design curves (Figures I-9.0) are based did not include tests in the presence of corrosive environments which might accelerate fatigue failure." Paragraph B-2131 in Nonmandatory Appendix B, "Owner's Design Specifications," to ASME Code Section III states that the Owner's design specification should provide information about, "any reduction to design stress intensity values, allowable stress, or fatigue design curves that is necessitated by environmental conditions."

1.3.1 Effects of Water Environment on Fatigue Lives

Existing fatigue ε–N data (Figure 1-1) illustrate potentially significant effects of light water reactor (LWR) coolant environments on the fatigue resistance of carbon and low-alloy steels, wrought and cast austenitic SSs, and Ni-Cr-Fe alloys.[10-75] Small-scale laboratory fatigue test data indicate that under certain reactor operating conditions, the fatigue lives of carbon and low-alloy steels can be a factor of 17 lower in the water environment than in air. Therefore, the factors in the ASME Code may be less conservative than originally intended.

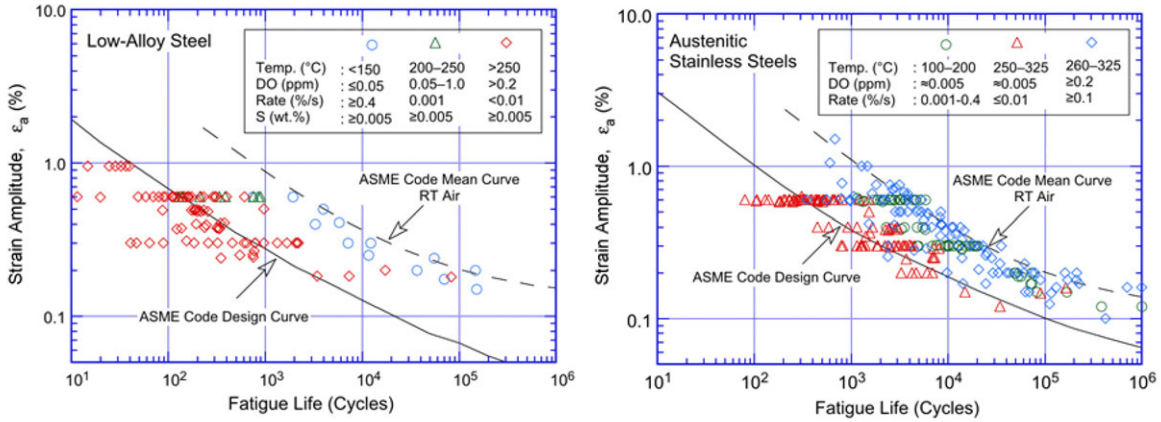


Figure 1-1 Fatigue ε–N data for low-alloy steels and austenitic SSs in water compared to the ASME Air Design Curve; RT = room temperature [77°F (25°C)].

The fatigue ε–N data are consistent with the much larger database on enhancement of crack growth rates (CGRs) in these materials in simulated LWR environments. The key parameters that influence fatigue life in these environments are temperature, the dissolved–oxygen (DO) level in the water, strain rate, strain (or stress) amplitude, and, for carbon and low-alloy steels, the sulfur content of the steel. The range of the values for these parameters within which environmental effects are significant has also been defined. If these critical loading and environmental conditions exist during reactor operation, then environmental effects may be

significant and should be included in any associated ASME Code fatigue evaluations. Experience with nuclear power plants worldwide indicates that the critical range of loading and environmental conditions that leads to environmental effects on formation of fatigue cracks can and do occur during plant operation.[56,76-92] Therefore it is important that component design considers environmental effects to prevent premature fatigue failures.

Experience with operating nuclear power plants worldwide reveals that many reactor component failures were attributed to fatigue; examples include piping, nozzles, valves, and pumps.[76-83] In most cases, these failures were associated with thermal loading due to thermal stratification and striping, or mechanical loading due to vibratory loading that was not originally considered in the component design. Thermal stratification was typically caused by the injection of low-flow, relatively cold feedwater during plant startup, hot standby, and variations below 20% of full power, whereas thermal striping was caused by rapid, localized fluctuations of the interface between hot and cold feedwater. In addition, for most of these cases, the additional thermal loading had high through-wall stress gradients that are not considered in the development of the ASME Code design air fatigue curves (see Section 1.5, item xxi). Considering through-wall stress gradients instead of assuming uniform stress in analyses may significantly increase the calculated fatigue lives of components.

The original design basis analyses for most U.S. nuclear power plants typically did not include thermal loading caused by flow stratification or striping. Regulatory evaluation indicated that high-cycle thermal–stratification loading can occur in PWR surge lines as a result of in-surge and out-surge during heatup/cooldown transients.[93] During heatup or cooldown, when, the pressurizer water is heated to approximately 227°C (440°F), the hotter water can flow at a very low rate from the pressurizer through the surge line to the hot–leg piping over the cooler water layer in the piping. The thermal gradients between the upper and lower parts of the pipe can be as high as 149°C (300°F). As a result, all U.S. PWRs performed revised fatigue analyses to address thermal stratification effects in surge lines. Furthermore, corrosion effects caused by a high-temperature aqueous environment may also aggravate the effect of these loadings. The increased fatigue duty caused by such thermal loading increases the importance of evaluating environmental effects.

The mechanism of cracking in feedwater nozzles and piping was attributed to corrosion fatigue or strain–induced corrosion cracking (SICC).[84-86] Hickling and Blind summarized case histories and identified conditions that lead to SICC in low-alloy steels in LWR systems. An Electric Power Research Institute (EPRI) report presented a review of significant occurrences of corrosion fatigue damage and failures in various nuclear power plant systems.[56] Shah et al. presented an assessment of the U.S. experience related to PWR primary system leaks observed during the period 1985 through 1996.[88]

Hirschberg et al. summarized the operating experience regarding thermal fatigue of nonisolable piping connected to PWR reactor coolant system (RCS).[87] Significant cracking occurred in nonisolable sections of the safety injection system and residual heat removal (RHR) system piping connected to the PWR coolant system.[89,90] At Joseph M. Farley Nuclear Plant, cracking occurred in the heat affected zone (HAZ) of the weld between the first elbow and the horizontal pipe, approximately 0.9 m (36 in.) from the RCS cold–leg nozzle. At Tihange Nuclear Power Station, the crack was located in the base metal of an elbow, approximately 0.6 m (24 in.) from the RCS hot–leg nozzle. At the Genkai Nuclear Power Plant (Genkai), cracking occurred in the RHR suction line at the weld between the first elbow downstream of the hot–leg nozzle and the horizontal pipe section. Cracking due to thermal fatigue also occurred in the safety injection system at Dampierre Nuclear Power Plant, Units 1 and 2 plants, and in the chemical and

volume control system (CVCS) in Obrigheim Nuclear Power Plant. In all cases, thermal cycling was caused by interaction of hot RCS fluid from turbulent penetration at the top of the pipe, and cold valve leakage fluid that stratified at the bottom of the pipe. At Genkai, the valve internals alternately shrunk and expanded causing periodic leakage of hot fluid through the stem packing and leak-off line into the elbow.

However, thermal stratification can occur even in the absence of valve leakage. The results of fatigue monitoring indicate that many PWR plants measured thermal–stratification cycling in the RHR suction line because of turbulence penetration of the hot leg fluid extending into the horizontal pipe section, which then stratified due to normal convection. [87] For thermal stratification, the length of the vertical pipe section of the RHR suction line must be short enough for the hot fluid to reach the horizontal pipe section, and the length of the horizontal pipe section must be long enough to cause sufficient heat losses for stratification to develop. A typical temperature gradient of 49°C (120°F) was observed for typical cases of stratification, and temperature gradients as high as 177°C (350°F) were measured in some plants.

Nonisolable leaks due to thermal-stratification cycling also occurred in reactor coolant loop drain lines, excess letdown lines, and makeup/high pressure injection lines at the Three Mile Island Nuclear Station (TMI), Loviisa Nuclear Power Plant, Unit 2, Mihama Nuclear Power Plant (Mihama), and Oconee Nuclear Station (Oconee).[87,88] A leak in the cold–leg drain line [1.5 in. or 2 in. nominal pipe size (NPS)] occurred in the weld between the first elbow downstream of the loop nozzle and the horizontal pipe section at TMI, and in the elbow extrados at Oconee. In both cases, thermal stratification was caused by turbulence penetration of the RCS fluid periodically extending into the horizontal section and it stratified due to heat loss because the pipe was not insulated. The same mechanism caused a leak in the 2 in. NPS excess letdown line at Mihama. Although the Mihama line was insulated, stratification still occurred because the length of the horizontal section to the isolation valve was very long, thus resulting in significant heat loss.

Thermal fatigue caused leaks in a connecting pipe and shell of the regenerative heat exchanger in the CVCS at Tsuruga Nuclear Power Plant (Tsuruga), Unit 2,[91,92] and in a 250–mm pipe section of the heat exchanger bypass on the RHR system at Civaux Nuclear Power Plant, Unit 1.[76] Thermal-hydraulic mockup tests indicate that at Tsuruga, superposition of low-frequency temperature gradients caused by changes in the flow pattern and high frequency temperature fluctuations resulting from mixing of the bypass flow and main flow caused thermal fatigue. [91,92]

Cracking also occurred in austenitic SS channel heads in an experimental test loop used for stress corrosion cracking studies in a simulated PWR environment.[94] Cracks were observed in a region that was subjected to temperature fluctuations between 170°C and 190°C at a frequency of 0.05 Hz. The cracks initiated on the inner surface; the cracking morphology was essentially transgranular with fatigue–like striations visible in some regions of the fracture surface. Thermal fatigue, with possible effects of the PWR coolant environment, was determined to be the root cause of these failures.[94]

Such cracking in nonisolable pipe sections due to thermal cycling was generally termed as high-cycle fatigue, i.e., it occurs at stress levels that correspond to allowable fatigue cycles of 10^5 or higher. The current understanding of turbulent penetration is not sufficient to accurately predict the frequency of thermal cycling associated with that phenomenon. Environmental effects on fatigue crack initiation may be significant in low-DO water at stress levels above the threshold value and at strain rates less than 0.4%/s.

Lenz et al.[85] showed that in feedwater lines, the strain rates are 10^{-3} to 10^{-5} %/s due to thermal stratification and 10^{-1} %/s due to thermal shock. They also reported that thermal stratification is the primary cause of crack initiation resulting from SICC. Stephan and Masson[95] subjected a full–scale mockup of the steam generator feedwater system to various regimes of stratification. After 4,000 cycles of applied loading, destructive examination performed between two locations where stable states of stratification occurred revealed small cracks, 1.4 to 2.0 mm deep, in the weld region. The fatigue usage factors calculated with elastic and cyclic elastic–plastic computations gave values of 1.3 to 1.9. Because the average DO level in the water was approximately 5 ppb, which corresponds to the maximum admissible value under normal operating conditions (power greater than 25% nominal power) in French PWRs, environmental effects on life were expected to be minimal and environmental fatigue correction factors were not applied in the computations of the fatigue usage factor.

Full–scale mockup tests designed to generate thermal stratification in a pipe in a laboratory confirmed the applicability of laboratory data to component behavior.[96] The material, loading, and environmental conditions were simulated on a 1:1 scale using only thermohydraulic effects. Under the conditions of strain rate and strain range typical of thermal stratification in these piping systems, the coolant environment has a significant effect on fatigue crack initiation.[12,29,30]

Finally, a study conducted on SS pipe bend specimens in simulated PWR primary water at 240°C concluded that reactor coolant environment has a significant effect on the fatigue life of SSs.[97-99] Relative to fatigue lives in an inert environment, lives in a PWR environment at strain amplitudes of 0.4% and 0.6% were decreased by factors of 2.9 and 1.4 at strain rates of 0.0005%/s and 0.01%/s, respectively. These values show very good agreement with the values predicted from the Argonne National Laboratory (ANL) models presented later in this report for incorporating environmental effects into the ASME Code Section III fatigue evaluations.

1.3.2 Effects of Neutron Irradiation

The potential effects of neutron irradiation on the fatigue life of reactor structural materials such as low-alloy pressure vessel steel, austenitic SSs, and Ni-Cr-Fe alloys and their weld metals, are not fully characterized. Irradiation effects were not included in the ASME Code Section III fatigue evaluations performed for reactor core support structures and reactor internal components. The majority of the existing data on the effects of neutron irradiation resulted from fatigue crack growth tests on austenitic SSs that were irradiated in fast reactors [primarily Experimental Breeder Reactor II (EBR-II)] at test temperatures of 427 (800°F) and 593°C (1100°F).[100-104] The CGR test results indicated that for Type 304 and 316 SS irradiated at 405-410°C (760-770°F) to 1.2×10^{22} n/cm^2 (E>0.1 MeV) fluence, the fatigue CGRs at 427°C (800°F) were up to a factor of 2 higher than those for unirradiated material at low values of stress intensity factor range (ΔK) [less than 40 ksi in$^{1/2}$ (43.9 MPa m$^{1/2}$)], but were lower for higher ΔK values. These observations were reversed at 593°C (1100°F). Crack growth rates were comparable or lower at higher values of ΔK. A similar behavior was observed for Type 316 weld metal. Tests on Type 304 and 316 SSs irradiated in a thermal reactor [the Advanced Test Reactor (ATR)] at 288°C (550°F) to 1.8×10^{21} n/cm^2 (E>0.1 MeV) and tested at 427°C (800°F) showed superior resistance to crack growth; CGRs were 25 to 50% lower than those for unirradiated material.[105] Based on these studies EPRI concluded that "[t]he work of several researchers suggest that neutron irradiation does not result in a further reduction in fatigue properties and in some cases suggest an improvement."[106]

Other limited fatigue ε–N data on materials irradiated under LWR conditions and tested at LWR operating temperatures also showed significant differences in the microstructure and

microchemistry of LWR irradiated materials, and materials irradiated in fast neutron test reactors. Specifically, cavities and helium (He) bubbles were observed in austenitic SSs irradiated at a temperature of 320°C (608°F) to high neutron fluence levels in PWRs. Such microstructures could lead to embrittlement of the material.[107] Therefore, fatigue data on LWR irradiated materials should be developed to further quantify the effects of neutron irradiation on fatigue lives.

Fatigue ε–N data on irradiated Type 308 SS weld metals showed moderate decreases in fatigue lives in the low-cycle regime and superior fatigue lives in the high-cycle regime.[108] Similar effects from neutron irradiation were also observed on the room-temperature fatigue ε–N behavior of Type 347 SSs irradiated in the Engineering Test Reactor (ETR) at 60°C (140°F) to total integrated fast flux (>1 MeV) exposures of 5.5×10^{25}, 1.1×10^{26}, and 1.6×10^{26} n/m^2, as shown in Figure 1-2(a).[109] Neutron irradiation decreased the room-temperature fatigue lives of Type 347 SSs at high strain amplitudes (above 0.35%) and had beneficial effects on fatigue lives at low strain amplitudes (below 0.25%). The decreases in fatigue lives increased with increased total neutron doses. The reductions in fatigue lives were likely related to the irradiation-induced decreases in ductility of the materials.

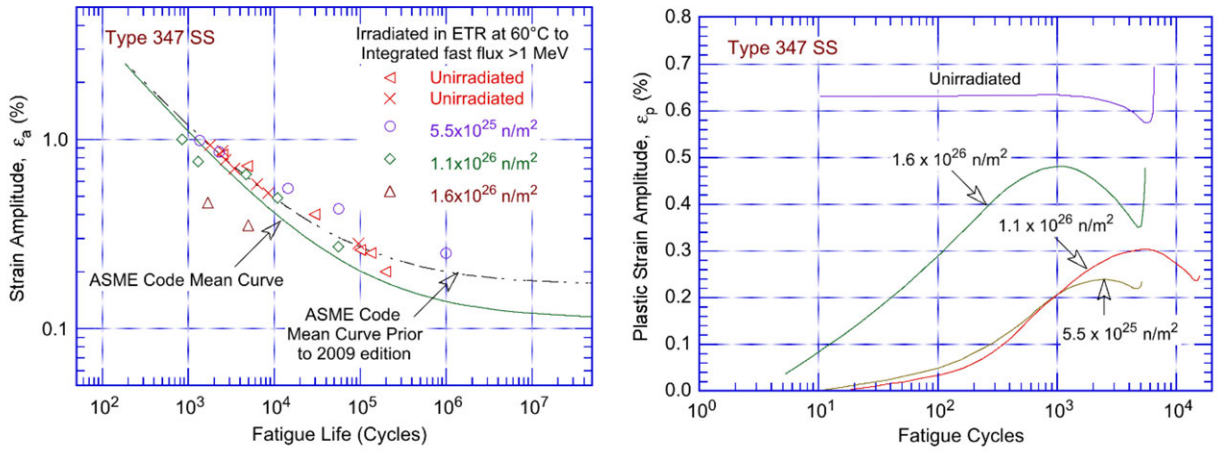


Figure 1-2 The effects of neutron irradiation on fatigue lives of Type 347 SSs at room temperature: (a) the fatigue ε–N behavior, and (b) variations in plastic strain amplitude as a function of fatigue cycles (Ref. 109).

The fatigue test results also indicated significant differences in the cyclic hardening behavior of the irradiated materials relative to unirradiated materials. Typically, at room temperature, austenitic SSs exhibited strain softening after the initial cyclic hardening during the first ten cycles. For the irradiated Type 347 SSs, although total strain was held constant, the plastic strain varied significantly during the fatigue tests, as shown in Figure 1-2(b). The plastic strains were insignificant initially and increased gradually during the fatigue tests due to strain softening until a later stage where plastic strains started to decrease due to secondary strain hardening and formation of fatigue cracks in the specimens. The extent of strain softening increased with increased neutron doses (Figure 1-2(b)). The rapid increases in plastic strains near the end of the tests were associated with specimen fracture. In contrast, the unirradiated Type 347 SSs exhibited slight strain hardening and plastic strain decreased at a very low rate; the materials later showed faster decreases in plastic strains because of secondary strain hardening and formation of fatigue cracks. Thus, the impact of irradiation on fatigue life is not readily apparent from these data because of several competing factors.

The fatigue ε–N data on cold-worked (CW) Type 316 SS tube materials and solution-annealed Type 304 bar materials removed from an operating PWR are shown in Figure 1-3 and Figure 1-4, respectively.[110] The data were obtained in simulated PWR water at 325°C (617°F) on CW Type 316 SS tube specimens with a 6.48 mm outer diameter and a 0.71 mm wall thickness. The tube specimens were irradiated to fluence values of less than 10^{22}, 2 - 6x10^{25}, and greater than 3x10^{26} n/m^2 (E > 0.1 MeV), while the 5.08-mm diameter cylindrical specimens of Type 304 SS were irradiated to fluence levels ranging from 5x10^{25} to 10^{26} n/m^2 (E > 0.1 MeV). However, the baseline fatigue data for the unirradiated materials for the same heats of SSs were not available. To determine the possible effects of specimen configuration (i.e., solid cylindrical vs. thin-walled tube specimens), fatigue tests using the two specimen geometries were conducted on another heat of CW Type 316 SS in air at 325°C. The results indicated that the fatigue strengths of the solid specimens were 1.4 times those of the cylindrical tube specimens. The ASME Code Section III best-fit mean air curves for austenitic SSs are also shown in Figure 1-3 and Figure 1-4 for comparison. Based on these test results, the authors concluded that "[t]he fatigue life of irradiated SS was longer than that of unirradiated SS in the range of this research, that is, strain amplitude was less than 0.6%. This increase in fatigue strength was considered due to an increase of tensile strength after irradiation."

In the absence of sufficient baseline fatigue data on unirradiated materials, the above conclusion that the fatigue lives of irradiated materials are longer than those of unirradiated materials is not fully justified. For example, the fatigue lives of irradiated Type 304 SSs in air are close to the ASME Code Section III best-fit mean curves. However, the effects of neutron irradiation are not available because there is insufficient fatigue ε–N data in air on unirradiated materials for these heats of Type 304 SSs. The fatigue data for irradiated CW Type 316 SSs were obtained on thin-walled tube specimens, and were not consistent with the ASME Code Section III mean air curve for austenitic SSs because the majority of the data were obtained from solid cylindrical specimens. The experimental ε–N behavior showed a lower ε–N slope than that for the ASME Code Section III mean curve (Figure 1-3). Even after adjusting by a factor of 1.4 on strain to account for the effect of specimen geometry, the fatigue lives in air at 0.3% strain amplitude fall to the right of the ASME Code Section III mean curve, whereas, the fatigue lives at 0.6% strain amplitude are significantly to the left. The primary reason for this inconsistency is likely caused by inadequate specimen size (tube specimens with a 0.71-mm thick wall) for fatigue tests performed at high strain amplitudes. However, the fatigue data in Figure 1-3 and Figure 1-4 show that fatigue lives of austenitic SSs were decreased in a PWR primary water environment. Except for the data on CW Type 316 SSs irradiated to a fluence greater than 3x10^{26} n/m^2, the data for irradiated materials and the data for irradiated Type 304 SSs show lower fatigue lives in PWR primary water environment compared to those in air. The effects of the environment increase with decreasing strain rates.

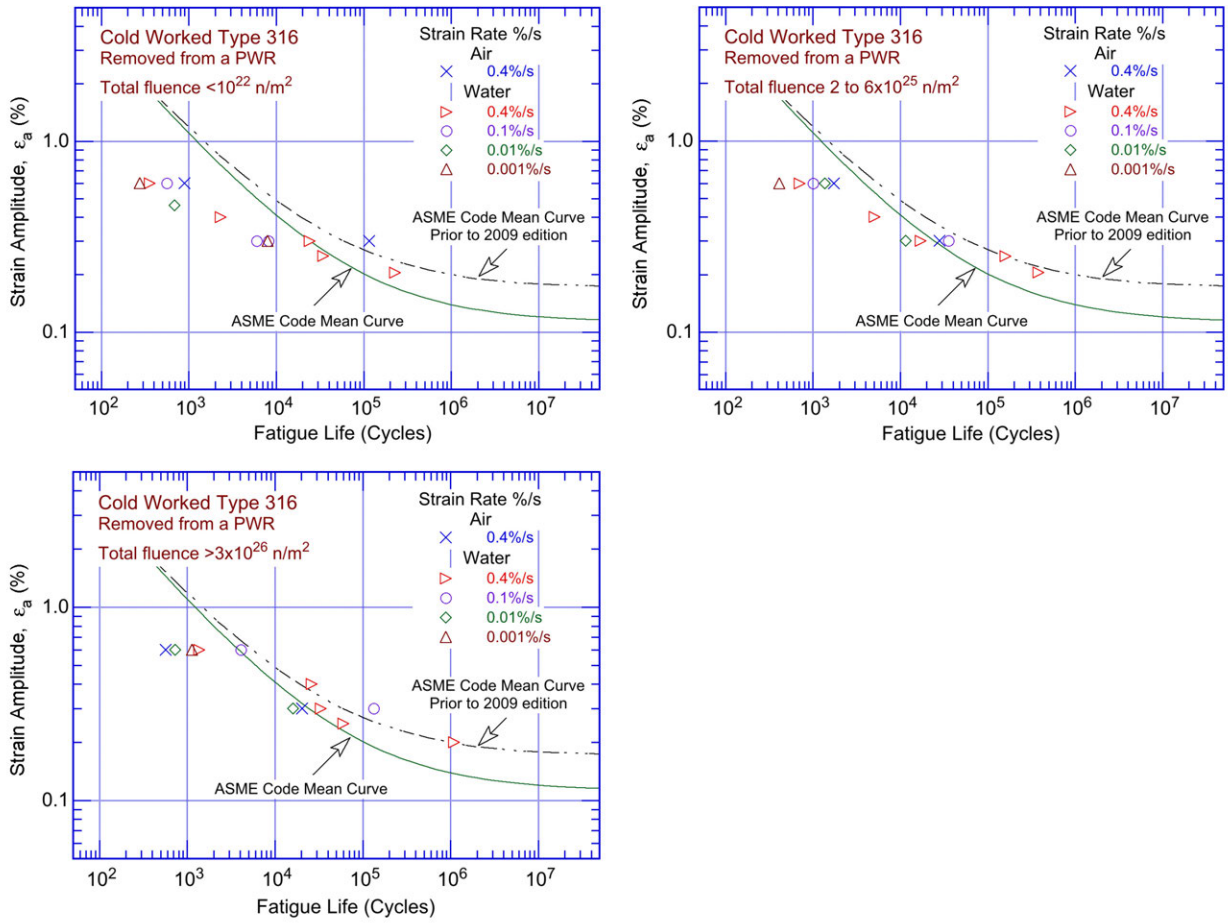


Figure 1-3 Strain amplitude vs. fatigue life data in 325°C air and simulated PWR primary water environments for CW Type 316SS irradiated to (a) less than 10^{22}, (b) 2-6x10^{25}, and (c) greater than 3x10^{26} n/m^2 (E > 0.1 MeV) (Ref. 110).

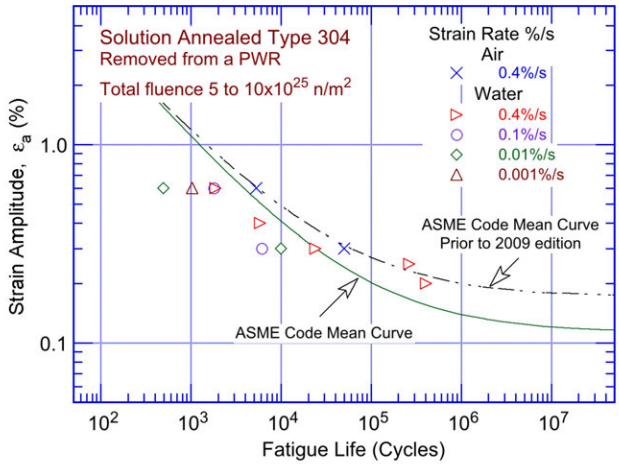


Figure 1-4 Strain amplitude vs. fatigue life data in 325°C air and simulated PWR primary water environments for Type 304 SS irradiated to 5x10^{25}–10^{26} n/m^2 (E > 0.1 MeV) (Ref. 110).

The limited available data are inconclusive with regard to the impact of irradiation on the fatigue lives of materials exposed to LWR environments. Although some small-scale laboratory fatigue ε–N test data indicate that neutron irradiation decreases the fatigue lives of austenitic SSs, particularly at high strain amplitudes, quantifying the impact of irradiation on the prediction of fatigue lives is not possible because of the limited data currently available. Additional fatigue data on reactor structural materials irradiated under LWR operating conditions are needed to determine whether neutron irradiation causes measurable effects on the fatigue lives of these materials and, if so, to better define how those impacts may be quantified. In the absence of such data, the methods described in this report are considered appropriate for application to materials exposed to significant levels of irradiation, such as SS reactor internals components, when mandated by regulation or required by the current licensing basis.

1.4 Modeling of Environmental Effects

In 1991, the U.S. Nuclear Regulatory Commission (NRC) issued a draft Branch Technical Position (BTP) for fatigue evaluation of nuclear plant components for license renewal. The BTP raised a concern about the adequacy of the ASME Code in addressing environmental effects on fatigue resistance of materials for operating PWRs and boiling water reactors (BWRs), whose primary–coolant pressure boundary components were constructed as specified in ASME Code Section III. In 1993, the Commission directed the NRC staff to treat fatigue as a potential safety issue within the existing regulatory process for operating reactors. The staff developed a Fatigue Action Plan (FAP) to resolve three principal issues: (1) adequacy of fatigue resistance of older vintage plants designed to the United States of America Standard B31.1 that did not require an explicit fatigue analysis of components, (2) effect of LWR environments on the fatigue resistance of primary pressure boundary materials, and (3) appropriate corrective action required when ASME Code fatigue allowable limits are exceeded (i.e., when the CUF is greater than unity).

Idaho National Engineering Laboratory (INEL) assessed the significance of ANL-developed interim fatigue design curves, by performing fatigue evaluations of a sample of components in the reactor coolant pressure boundary.[111] In all, six locations were evaluated from facilities designed by each of the four U.S. nuclear steam supply system vendors. Selected components from older vintage plants designed according to the B31.1 code were also included in the evaluation. Conservatism in the original fatigue evaluations (e.g., actual loading cycles instead of assumed cycles) was removed, and fatigue usage was evaluated with a fatigue design curve that considered the effects of the coolant environment. The results indicated that most of the locations had a CUF of less than the ASME Code limit of 1.0 for 40 years. The risk to reactor coolant pressure boundary components from failure due to fatigue was assessed under Generic Safety Issue (GSI) 78, “Monitoring of Fatigue Transient Limits for the Reactor Coolant System,” and GSI 166, “Adequacy of Fatigue Life of Metal Components,” in NUREG-0933, “Resolution of Generic Safety Issues,” dated March 29, 2012.”[112] Based on these studies, it was concluded[113] that no immediate action was necessary to address the three fatigue issues identified in the FAP. A risk study indicated that fatigue failure of piping was not a significant contributor to core damage frequency. Based on the risk assessment, a backfit to incorporate environmental effects into the fatigue analyses of operating plants was not justified.[114]

However, because the NRC studies were less certain that the conservatism in the original fatigue calculations could be used to account for an additional 20–years of operation, the NRC staff recommended that environmental effects be considered by evaluating the sample locations in the INEL study (NUREG/CR-6260, “Application of NUREG/CR-5999 Interim Design Curves to Selected Nuclear Power Plant Components,” issued March 1995) [111] for plants pursuing license renewal. GSI 190, “Fatigue Evaluation of Metal Components for 60-year Plant Life, documents

these recommendations.[112] Based on probabilistic analyses and sensitivity studies, interactions with the industry, and various programs available to licensees to manage the effects of aging, the NRC concluded that no generic regulatory action was required. For some components, although cumulative probabilities of crack initiation and through-wall cracks approached 1.0 for the renewal period, the maximum failure rate was generally low, in the range of 10^{-2} through-wall cracks per year.

In addition, the predicted failure rates were generally associated with high CUF locations and components with thin walls; in most cases, any leakage that might result from these through-wall cracks was estimated to be small and not likely to lead to core damage. However, the calculations that supported the resolution of this issue indicated the potential for an increase in the frequency of pipe leaks as plants continue to operate. Thus, the NRC staff recommended that aging management programs for license renewal should address component fatigue, including the effects of the reactor coolant environment. However, note that, when the INEL study was performed, it was not known that the effects of high-temperature water environment on fatigue cracking of austenitic SSs are greater in low-DO environments than they are in high-DO environments. Thus, the six sample locations evaluated in the INEL study may not necessarily be the bounding locations for some plants, and fatigue CUF evaluations should include additional plant-specific component locations along with those considered in NUREG/CR-6260, including the effects of the environment.

In 1991, the ASME Board on Nuclear Codes and Standards (BNCS) requested that the Pressure Vessel Research Council (PVRC) examine the existing worldwide ε–N data and develop recommendations for the ASME. The PVRC compiled and evaluated fatigue ε–N data related to the effects of LWR coolant environments on the fatigue life of pressure boundary materials; Van Der Sluys and Yukawa summarized the results.[115,116] The staff agreed with the concept of using an environmental fatigue correction factor (F_{en}) approach to obtain fatigue usage reflecting environmental effects for ASME Code Section III fatigue evaluations. This information was forwarded to the appropriate ASME Code committee.[117]

An analysis of the existing fatigue ε–N data and the procedures for incorporating environmental effects into ASME Code Section III fatigue evaluations were presented in several review articles[115,116,118-126] and ANL reports.[10,12,13,45-47] The fatigue ε–N data in air and LWR environments were also examined from the standpoint of fracture mechanics and CGR data.[127,128] Section 2.0 of this report presents further details. The key material, loading, and environmental parameters that influence the fatigue lives of carbon, low-alloy, and austenitic SSs were identified, and the range of these key parameters where environmental effects are significant, was defined. Two approaches were proposed for incorporating the environmental effects into ASME Section III fatigue evaluations for primary pressure boundary components in operating nuclear power plants: (1) develop new fatigue design curves for LWR applications, or (2) use an environmental fatigue correction factor to account for the effects of the coolant environment.

In the first approach, following the same procedures used to develop the fatigue design curves in ASME Code Section III, environmentally adjusted fatigue design curves were developed from fits to experimental data obtained in LWR environments. Interim fatigue design curves that address environmental effects on the fatigue life of carbon, low-alloy, and austenitic SSs were first proposed by Majumdar et al.[129] However, as mentioned above, the “interim” fatigue design curve for austenitic SSs was based on little or no data in low-DO environments. As a result, at the time of the development of the interim design curves, it was not known that the effects of high-temperature water environment on fatigue lives are greater in low-DO environments than in

high-DO environments. Keisler et al.[130] developed fatigue design curves based on a more rigorous statistical analysis of experimental data. These design curves were subsequently revised based on updated ANL models.[10,12,45,46] However, in LWR environments, the fatigue life of carbon and low-alloy steels, Ni-Cr-Fe alloys, and austenitic SSs depends on several loading and environmental parameters. Therefore, such an approach requires the development of several design curves to cover all possible environmental conditions encountered during plant operation. Depending on the number of such design curves for the desired loading and environmental conditions, development of additional curves may be a significant undertaking.

The second approach, proposed by Higuchi and Iida in 1991,[19] considers the effects of reactor coolant environments on fatigue life in terms of an F_{en} that is defined as the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into fatigue evaluations, this approach requires multiplying the fatigue usage factor for a specific stress cycle or load set pair, based on the ASME Code Section III design fatigue curves, by the F_{en}. Specific expressions for F_{en}, based on the ANL fatigue life models, were developed.[10,45] Such an approach is relatively simple for application to previously developed fatigue analyses and is recommended in this report. A similar methodology was also developed in Japan by the Environmental Fatigue Data (EFD) Committee of the Thermal and Nuclear Power Engineering Society (TENPES) under the Environmental Fatigue Testing (EFT) Project. The EFT was also supported by the Japan Power Engineering and Inspection Corporation (JAPEIC) and the Japan Nuclear Energy Safety (JNES) Organization, and some utilities.[131-135] Updated technical results appear in JNES-SS-1005 “Environmental Fatigue Evaluation Method for Nuclear Power Plants,” issued March 2011.[136] All of these data were considered in the results documented in this report.

In 2007, the original version of NUREG/CR-6909,[137] which is the technical basis document for NRC Regulatory Guide 1.207, “Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors,” Revision 0, issued March 2007, presented an overview of the existing fatigue ε–N data for carbon and low-alloy steels, Ni-Cr-Fe alloys, and wrought and cast austenitic SSs in air and LWR environments. The existing fatigue ε–N data were evaluated to (1) identify the various material, environmental, and loading parameters that influence fatigue cracking, and (2) establish the effects of key parameters on the fatigue lives of these steels. Fatigue life models, presented in earlier reports for estimating fatigue life as a function of material, loading, and environmental conditions were updated using the fatigue ε–N database available at that time. The report also described the F_{en} approach for incorporating effects of LWR environments into ASME Code Section III fatigue evaluations, and presented a critical review of the ASME Code fatigue adjustment factors of 2 on stress (or strain) and 20 on life to assess the possible conservatism in the choice of adjustment factors. The F_{en} methodology was identified as applicable to all reactor coolant pressure boundary components exposed to reactor water that require an ASME Code Section III fatigue CUF calculation.

This report presents a revision to the original version of NUREG/CR-6909 in its entirety. The F_{en} expressions were updated using a much larger fatigue ε–N database. The additional data include the JNES data summarized in JNES-SS-1005 on carbon and low-alloy steels, wrought and cast austenitic SSs, and Ni-Cr-Fe alloys, and their associated weld metals, tested in air and LWR environments, [136] and fatigue ε–N test results from the open literature on several heats of carbon and low-alloy steels tested in BWR environments.[138-146] Most of the data evaluated for this report were obtained from completely reversed, axial, strain-controlled tests on small laboratory specimens. The results from a small number of bending tests were also considered for austenitic

SSs in air (see Table 3-6 in Section 3.2.1), Ni-Cr-Fe alloy steels in air (see Table 3-9 in Section 3.3), and carbon and low-alloy steels in water (see Table 4-1 in Section 4.1.1). These data were included to improve the best-fit evaluation of the fatigue life data. Section 3.2.2 includes figures that support the use of these bending test data for austenitic SSs, which show that the bending test data points fall evenly on both side of the best fit curve of all the data. Only a small number of high-cycle fatigue tests conducted in load control were considered.

The updated environmental fatigue expressions in this report also address comments from interested stakeholders related to (1) the constants in the F_{en} expressions that results in a F_{en} value of approximately 2 even when the strain rate is very high or temperature is very low, (2) the temperature dependence of F_{en} for carbon and low-alloy steels, and (3) the dependence of F_{en} on water chemistry for austenitic SSs. Finally, the updated methodology described in this report applies to any component exposed to the LWR environment that requires an ASME CUF calculation as part of its design, if required by the safety basis for the component, or if it is required by the plant current licensing basis, unless otherwise justified. Note that the F_{en} approach described in this report is only applicable for use as part of an ASME Code fatigue evaluation.

In addition, the report evaluates the appropriateness of a strain threshold and the possible effects of hold periods. It also discusses the potential effects of dynamic strain aging (DSA) on cyclic deformation and environmental effects.[147-153] The F_{en} methodology proposed in this report was validated by comparing the results of five different experimental datasets obtained from fatigue tests that simulate actual plant conditions with estimates of fatigue usage adjusted for environmental effects using the updated F_{en} expressions. The five datasets represent fatigue tests with (1) changing strain rate or temperature, or both,[154] (2) complex loading (actual PWR transient),[155-157] (3) spectrum loading (random strain amplitudes),[158,159] (4) thermal fatigue of a stepped pipe,[160] and (5) pipe U-bend tests.[98,99] Appendix C to this report presents a sample application of F_{en} using the methodology in ASME Code Section III, Subarticle NB-3200 that is intended to address some of the practical issues identified by interested stakeholders associated with the F_{en} calculations.[161]

1.5 Bases and Assumptions

This section describes the bases and assumptions used to develop the air fatigue design curves, the F_{en} relationships, and the guidance for addressing environmental effects in a fatigue evaluation as documented in this report. It is recognized that additional research may lead to further improvements in the modeling and analysis of environmental fatigue effects. Therefore, documentation of these assumptions and bases is intended to inform further research efforts that may be undertaken in the future.

The following represents the major assumptions or bases for the work documented in this report:

(i) **Light-Water Reactor Water Environment.** This term, (and other similar terms such as LWR reactor coolant environment, reactor coolant environment and LWR environment) which is used throughout the report, represents any transient or steady-state water environment in a light-water commercial nuclear power plant where the component of interest is exposed to water above 50°C. Environmental effects on fatigue life can occur in any such environment. Examples of systems in commercial nuclear power plants where such an environment is present include the primary pressure boundary system, the secondary side system, and the service water system. The terms “PWR environment” and “BWR environment” (and other similar terms) are also used

throughout the report to describe testing conditions that have been used to simulate steady-state water environments in PWR and BWR reactor coolant systems, respectively.

(ii) **Definition of Fatigue Life.** As discussed extensively in Section 1.1, fatigue life is described in this report as the number of cycles of a specified strain amplitude that a specimen can sustain before the formation of a 3-mm-deep crack (i.e., an "engineering crack"). However, the total fatigue life consists of two parts: (1) crack initiation (Stage I, for crack sizes up to approximately 0.2 mm) and crack propagation (Stage II, for crack growth from approximately 0.2 to 3.0 mm), as indicated in Figure 2-4. Using this definition, a calculated fatigue CUF less than unity provides reasonable assurance that a fatigue crack has not formed in a component, and indicates that the probability of forming a crack in the component is low.

The 3-mm crack depth is not intended to define the size of crack-like defects in actual components for flaw tolerance or other related analyses, particularly in thin-walled components (such as steam generator tubes). Obviously, a 3 mm definition of crack initiation is not an appropriate definition of fatigue life in thin-walled components where such a crack could result in a leak or even structural failure. Rather, fatigue life in a component or structure should be defined as the formation of an engineering-sized crack, which is the intent and use of this definition in this report. Consequently, as indicated in Section 4.2.12, the method may not be conservative for specimens with less than a 3 mm wall thickness. The report also recognizes that once such an engineering-sized crack has formed, the component or structure still has remaining life before it structurally fails, leaks, or cannot perform its intended function. The remaining life can be assessed through a defect fatigue crack growth analysis to determine margins and appropriate mitigation measures. The details and acceptance criteria of such an analysis are outside the scope of report; however, ASME Code Section XI addresses such topics.

(iii) **Modulus of Elasticity.** In developing the air design fatigue curves, the studies documented in this report assumed Young's modulus, E, values consistent with existing ASME Code design fatigue curves to convert all available strain data to stress. No attempts were made to determine new and more accurate E values for developing the new air design curves. Because the strain vs. fatigue life data used in developing the ASME Code fatigue design curve is applicable up to reactor operating temperatures, the conversion of strain to stress at higher temperatures should use elastic moduli values applicable at these temperatures. ASME Code Section III requires this practice. Note that the ASME Code Section III fatigue design curves are expressed as pseudo-stress amplitude (in ksi or MPa) vs. the number of fatigue cycles, where the pseudo-stress amplitude is the product of applied strain amplitude and room-temperature modulus of elasticity.

(iv) **Material Tensile Properties.** In developing the air design fatigue curves, the studies documented in this report assumed yield strength, YS, and ultimate tensile strength, UTS, values consistent with existing ASME Code design fatigue curves for performing mean stress adjustments. Limited investigation indicated that this assumption for strength values was accurate to within approximately 10% to 20% of the values obtained by averaging available tensile property data for some of the test data for low-alloy and carbon steels, respectively. No attempts were made to determine new and more accurate YS and UTS values for developing the new air design curves.

(v) **Environmental Loading.** In developing the environmental design fatigue curves, the studies documented in this report were based on available fatigue test data on small-scale laboratory specimens, the majority of which were performed under constant temperature, water chemistry, and uniform strain rate. The effects of varied temperature, water chemistry, strain rate, transient hold times, and other important test parameters on fatigue life were not investigated.

(vi) **Testing Procedures for High-Cycle Fatigue.** The ASME Code, Section III fatigue design curves for structural materials are based on strain-controlled, completely reversed, fatigue tests on smooth cylindrical test specimens in air. Typically, these tests are conducted at a strain rate of 0.4%/s. Therefore, to reduce test duration, fatigue tests at low strain amplitude (i.e., fatigue lives > 10^5 cycles) are often conducted at higher strain rates under load control. However, structural materials such as austenitic SSs or carbon steels strain harden during the initial 200–500 cycles to reach a steady-state condition where the cyclic stress remains essentially constant during the rest of test. As a result, load-controlled fatigue tests conducted at constant load result in very high strains during the initial fatigue cycles, which results in lower fatigue lives compared to tests under constant strain condition. Therefore, such tests are started under strain control and are switched later to load control after a steady-state condition is achieved.

(vii) **Material Grouping.** In developing both the air design fatigue curves and the environmental fatigue correction factors for LWR environments, the studies documented in this report were based on the following large material groupings: carbon and low-alloy steels, austenitic and cast SSs, and Ni-Cr-Fe alloys and their weld metals. Table B-1, Table B-2, and Table B-3 in Appendix B to this report list the applicable material grades covered by these groupings. This approach is consistent with the grouping used in the fatigue curves in ASME Code Section III. Fatigue curves were not developed for specific materials or for subsets of materials within the aforementioned broader groupings that share common properties. An example of such a subset is obtained by grouping ferritic materials as a function of their ultimate tensile strength. The development of both material-specific and property-specific fatigue curves is possible as long as an appropriate technical basis is established. The fatigue design curve in air and the F_{en} approach are applicable to the materials listed in Table B-1, Table B-2, and Table B-3, with the exception of Inconel 718. For Inconel 718, the SS fatigue design curves in either this report or in ASME Code Section III should be used but it is recognized that these design curves are conservative for Inconel 718. Environmental fatigue data are also not available for Inconel 718; therefore, this report does not include an F_{en} for Inconel 718. Further, additional data are required to develop unique curves for other Ni-Cr-Fe alloys in LWR environments. However, as demonstrated in Section 4.3, the existing Ni-Cr-Fe data (except for Inconel 718) are generally well predicted by the curves for SS alloys.

(viii) **Weld Data.** In developing the air design fatigue curves, the studies documented in this report were based on larger material groupings (as discussed in item vii) that included data for weld metals as opposed to developing fatigue curves for specific weld materials. Fatigue data on sensitized material were used to estimate the effects of heat affected zones (HAZs) on fatigue life. The analysis in this report is based on consideration of all available weld data. Although there is less weld data than base material data, the weld data analyzed generally falls within the statistical distribution of the base metal data. Section 3.2.9 notes some possible bias between the weld data and the design curves; however, it is not considered to be significant enough to warrant a separate weld metal curve without the development of additional data.

(ix) **Hardening.** The effects of material hardening, such as due to cold work or similar effects, were not investigated.

(x) **Radiation.** Limited test data indicate that neutron irradiation generally increases material strength, which may improve the fatigue lives of materials, especially in the high-cycle regime. In the absence of data that address neutron irradiation effects more completely, the methods described in this report are considered appropriate for application to materials exposed to irradiation, such as SS reactor internals components.

(xi) **Dynamic Strain Aging.** The potential effects of dynamic strain aging (DSA) discussed throughout this report, particularly in Sections 2.2.1.3 and 2.2.2.3, are provided for information. None of the evaluations contained in this report include these effects. The information is presented to identify an area that requires further research.

(xii) **Material Variability and Data Scatter.** The effects of material (heat-to-heat) variability and data scatter on fatigue life were addressed as part of the life reduction factor applied in the development of the air design fatigue curve based on limited available data (see Section 5). However, it is recognized that some of the scatter and variability results from the variety of materials that are covered both in this report and in the fatigue curves in ASME Code Section III and are a function of the material groupings selected (see item vii on material grouping for additional information). A more detailed, separate treatment of material (heat-to-heat) variability and data scatter effects was not investigated.

(xiii) **Surface Finish.** In developing the mean air fatigue curves, the studies documented in this report were based on available fatigue test data on small-scale laboratory specimens, the majority of which were polished. Consistent with ASME Code Section III, the effects of surface roughness on fatigue life were addressed as part of the life adjustment factor applied in the development of the air design fatigue curve based on the limited available data. The surface roughness values considered are representative of component surface finishes. Section 5.3 provides additional detail. A more detailed treatment of surface finish effects was not investigated.

(xiv) **Loading Sequence.** In developing the air design fatigue curves, the studies documented in this report were based on available fatigue test data on small-scale laboratory specimens loaded under constant, uniaxial membrane loading. The effects of loading sequence on fatigue life compared to actual components were addressed as part of the life adjustment factor applied in the development of the air design fatigue curve based on limited available data (see Section 5). A more detailed treatment of loading sequence effects was not investigated.

(xv) **Size and Geometry.** In developing the air design fatigue curves, the studies documented in this report are based on available fatigue test data on small-scale laboratory specimens. The effects of size and geometry on fatigue life compared to actual components was addressed as part of the life adjustment factor applied in the development of the air design fatigue curve based on limited available data (see Section 5). A more detailed treatment of size and geometry effects was not investigated.

(xvi) **Development of Adjustment Factors.** As documented in Section 5, several material, loading, and environmental factors affect fatigue life. Many of these factors have been addressed by the construction of the ASME Code, Section III fatigue design curves and the F_{en} method. Of those remaining factors, two of them—surface preparation and

reactor water flow rate—are not explicitly considered but are expected to be conservatively addressed by the design curves and F_{en} method. Section 5 explicitly considers the effects of the remaining four factors—material variability and data scatter, size and geometry, surface finish, and loading sequence. As discussed in this section, at higher cyclic fatigue lives, only the single dominant factor for a given set of conditions affects fatigue life. At lower cyclic fatigue lives, all factors affect fatigue life. These effects are conservatively considered to be independent even though some factors may be correlated. The current data are insufficient to develop quantitative correlation factors needed for a more rigorous analysis. As discussed in Section 5, a Monte Carlo analysis has also been used to determine the adjustment factors to account for the fact that most service conditions will not lead to the worse-case combination of these factors.

(xvii) **Factor of Two on Strain (or Pseudo-Stress).** In developing the air design fatigue curves, the studies documented in this report assumed a factor of 2 reduction on strain (or pseudo-stress). The factor of 2 reduction was selected to be consistent with ASME Code practices. At present, the adjustment factor of 2 on strain is used to account not only for data scatter, size, surface finish, and loading sequence, but also for the potential effects of a combination of temperature and strain rate on secondary hardening and dynamic strain aging. These effects are not cumulative within the high-cycle fatigue region, and only the most dominant of these effects controls the net adjustment factor. However, these parameters principally affect the growth of microstructurally small cracks, and their significance depends on the operating conditions, environment, material, and the fabrication process. Therefore, the effect that dominates is a function of material and environmental conditions. The factor of 2 on strain is sufficient to account for the dominant effect within the high-cycle fatigue region. It is recognized that, based on existing data, a factor of 2 on strain may be conservative for some materials, especially when the loading cycles exceed 10^4. Given sufficient data, it may be possible to refine this factor either generically or for specific materials.

(xviii) **F_{en} Assumptions.** As mentioned previously in the report, the F_{en} approach has been developed for use with ASME Code, Section III fatigue evaluation procedures. It is recognized that other design and evaluation procedures are used internationally. The use of the F_{en} approach with any other procedure has not been evaluated in this report. Further, the F_{en} approach presumes that the slope of the strain (or stress) vs. life fatigue curve is the same in air and water environments. Based on the totality of the data in this report, this assumption appears reasonable. If environmental effects increase with decreasing strain, the use of an adjustment factor would be a function of strain and the concept becomes more complex. It is not clear whether the apparent increase in environmental effects with decreasing strain is a true strain dependence or just an artifact of the dataset being used to evaluate environmental effects. Most of the fatigue data on austenitic SSs in PWR environments are for low-carbon Type 304L or 316NG materials. As mentioned in the report, the slope of the fatigue strain vs. life curve in air for these low-carbon SS materials is steeper than that for the high-carbon SS materials. Additional data are needed to investigate this topic more completely.

(xix) **Limits of Validity.** The report defines the limits of validity for all parameters affecting the F_{en} relationships for each of the materials investigated. In some cases, the limits of applicability have been extended a small amount beyond the limits defined in the applicable tests so that the relationships cover most anticipated LWR operating conditions. For example, for carbon and low-alloy steels, the maximum temperature of the data presented in the report was 290°C (see Table 4-1), but the upper temperature

limit of the F_{en} expressions is 325°C. In other cases, extension of the limits was judged to be reasonable based on limited review of other test data not explicitly presented in the report. Additionally, the cyclic limits of the air design fatigue curves were selected to match the limits currently defined in the ASME Code, Section III fatigue design curves.

(xx) **Applicability of Method and Future Work.** The fatigue design curves developed in this report for carbon and low-alloy steels and austenitic SSs are applicable to various grades and compositions of materials having a wide range of tensile strength. Furthermore, the criterion used in establishing the fatigue design curve ensures that the proposed curve bounds 95% of the available fatigue data with 95% confidence. In addition, the mean stress correction for the design curves is based on a conservative value of mean stress at room temperature. Finally, the fatigue loading in laboratory specimens is uniformly tensile which is more severe than in many applications where the loading decreases through the thickness. Therefore, the fatigue design curves should be conservative for most materials and applications, particularly at reactor operating temperatures where mean stresses are likely to be lower.

The criteria used for establishing the adjustment factors to account for the parameters that influence fatigue life that were not considered in the experimental data used to develop the fatigue design curves (Section 5) are also expected to yield conservative estimates of fatigue life in most applications. These adjustment factors may be further optimized. Note that other factors (e.g., component size) may lead to decreases in fatigue life in field applications compared to laboratory testing. Therefore, any modifications of the design curves or adjustment factors should be performed holistically to develop a technical basis that addresses all the sources of conservatism and uncertainty mentioned above.

Guidance should be provided for using the high-cycle portion of the curves for mechanical loading. This guidance is necessary because strain-controlled fatigue test data are used to develop the ASME Code ε–N fatigue design curves, and these must be converted to pseudo-stress vs. life curves in most applications.

(xxi) **Gradient Effects.** As mentioned previously, both the air fatigue design curves and the F_{en} method used to account for the effects of the LWR environment are based on small-scale laboratory specimens tested under uniaxial membrane loading. It is recognized that fatigue transients in components and structures are typically not uniaxial and also vary through the component thickness as a result of bending or other localized effects. The effects of through-thickness gradient loading or multiaxial loadings on fatigue life were not specifically investigated in this report. However, it is recognized that such effects often increase the number of cycles needed both to form an engineering-size crack (i.e., the definition of fatigue life used in this report) and the subsequent growth of such a crack through the component thickness. Therefore, the current design curves and F_{en} method are generally expected to be conservative with respect to these effects.

(xxii) **Use of Method.** Generally, the provisions of this document can be used to predict fatigue lives of any component, or portion of a component, that is exposed to water and has been evaluated for CUF using the rules in either Subarticles NB-3200 or NB-3600 of ASME Code, Section III, or in another applicable subarticle. Use extends to both Class 1 and non-Class 1 components. Such components may include piping, pumps, valves, and reactor internals components.

(xxiii) **Use of F_{en} in NB-3600 Analyses.** Generally, much of the discussion, examples, and the sample problem in this report reference the method in Subarticle NB-3200 of ASME Code Section III. The majority of evaluations that address environmental fatigue effects are expected to be performed using Subarticle NB-3200 methods. Although the experience with application of F_{en} methods to evaluations in Subarticle NB-3600 of ASME Code Section III is more limited, there are examples evaluations using Subarticle NB-3600 methods available in the literature (e.g., H.S. Mehta, EPRI Report 107943, June 1998). In addition, at the time of publication of this report, ASME committees were evaluating sample problems using Subarticle NB-3600 methods and considering further ASME guidance on the use of these methods. Therefore, the authors believe that the F_{en} methods in this report are equally applicable to Subarticle NB-3600 methods.

(xxiv) **ASME Code Class 1 Fatigue Exemption.** Generally, if the ASME Code, Section III provisions in Subparagraph NB-3222.4(d) for components not requiring analysis for cyclic service are satisfied using the air design curves in this document, an F_{en} assessment is not required for those components.

(xxv) **ASME Code Procedures.** It is generally recognized that some of the ASME Code, Section III methods for computing CUF are conservative. For example, load pairing in ASME Code fatigue calculations generally assumes the most severe ordering. Analysts address some of these conservatisms when fatigue calculations are revised or revisited. Section 4.3 of NUREG/CR-6260 cites several examples of such conservatisms. This report did not address conservativisms when computing CUF using ASME Section III methods.

(xxvi) **Clad Components.** The interiors of LWR reactor vessels and nozzles made of carbon and low-alloy steel are typically clad with stainless steel. This report does not address separate treatment of cladding. ASME Code Section III requirements (Paragraph NB-3122) specify that no structural strength shall be attributed to the cladding in satisfying primary stress limits, but the thermal and stress analyses shall consider the presence of the cladding when determining the secondary and peak stresses for the base material. Thus, consistent with the discussion in Section 4.2.2 of NUREG/CR-6260, it is appropriate to neglect fatigue of the cladding and compute the CUF and CUF_{en} for the base metal in most fatigue analyses.

2 MECHANISM OF FATIGUE

2.1 Formation of an Engineering Crack in Air

Deformation and microstructural changes in the surface grains of metals are responsible for fatigue cracking. During cyclic straining, the irreversibility of dislocation glide leads to the development of surface roughness. Strain localization in persistent slip bands (PSBs) results in the formation of extrusions and intrusions. With continued cycling, microcracks ultimately form in PSBs or at the edges of slip-band extrusions. At high strain amplitudes, microcracks form in notches that develop at grain, twin, or phase boundaries (e.g., ferrite/pearlite) or by cracking of second-phase particles (e.g., sulfide or oxide inclusions).

Once a microcrack forms, it continues to grow along its primary slip plane or a PSB as a Mode II (shear) crack in Stage I growth (where the orientation of the crack is usually at 45° to the stress axis). At low strain amplitudes, a Stage I crack may extend across several grain diameters before the increasing stress intensity of the crack promotes slip on planes other than the primary slip plane. A dislocation cell structure normally forms at the crack tip. Because slip is no longer confined to planes at 45° to the stress axis, the crack begins to propagate as a Mode I (tensile) crack, normal to the stress axis in Stage II growth. At high strain amplitudes, the stress intensity is quite large and the crack propagates entirely by the Stage II process. Stage II crack propagation continues until the crack reaches an engineering size. Figure 2-1 shows the two stages of fatigue crack growth in smooth specimens.

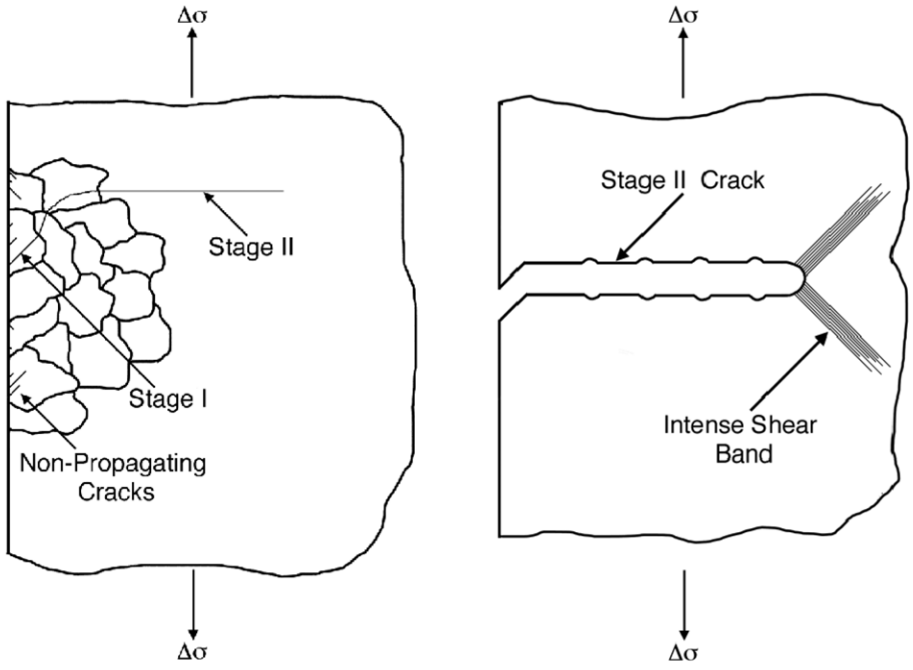


Figure 2-1 Two stages of fatigue crack growth in smooth test specimens.

In air or mildly corrosive environments, Stage II cracking is characterized by fatigue striations. Figure 2-2 illustrates the process of Stage II fatigue crack growth and formation of fatigue striations[162]. As tensile load is applied, slip bands form at the double notch or “ears” of the crack tip (Figure 2-2(b)). The slip bands widen with further straining, causing blunting of the crack tip

(Figure 2-2(c)). Crack surfaces close during compressive loading and slip is reversed, producing ears at the edges of the blunt crack tip (Figure 2-2(d) and Figure 2-2(e)). The ears are observed as fatigue striations on the fracture surface. However, there is not necessarily a 1:1 correlation between striation spacing and fatigue cycles. At high strain amplitudes, several striations may be created during one cycle, whereas at low strain amplitudes, one striation may represent several cycles.

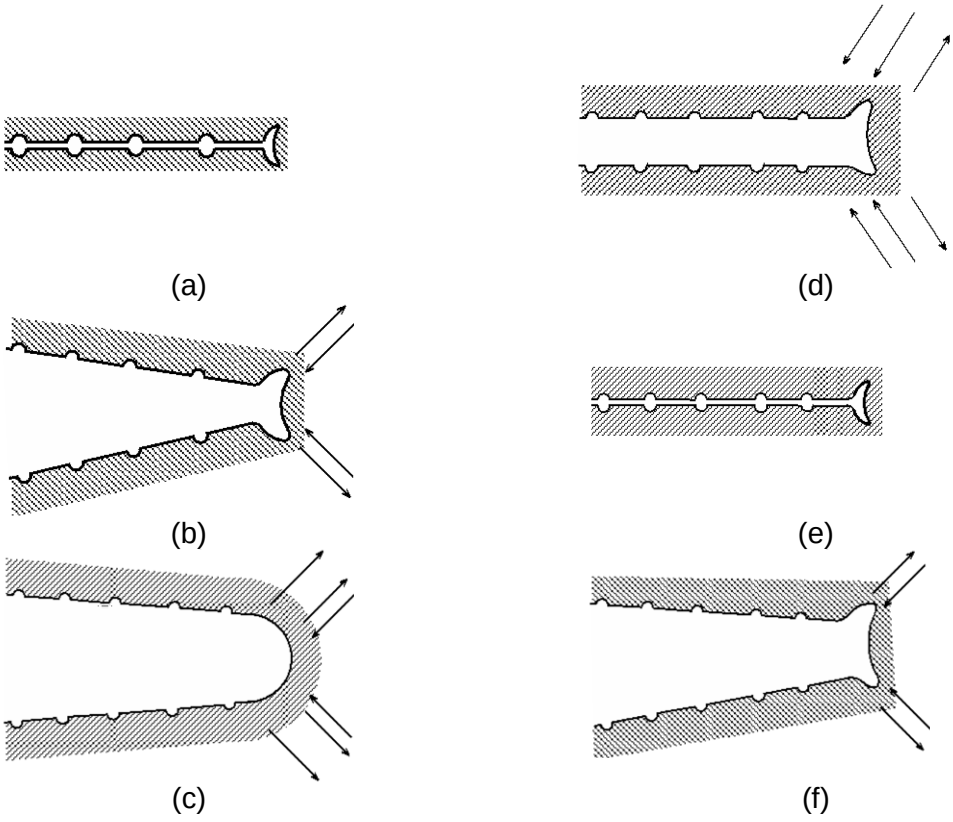


Figure 2-2 Schematic illustration of the plastic blunting process of fatigue crack growth in Stage II: (a) zero load, (b) small tensile load, (c) maximum tensile load with widening of slip bands, (d) crack closure and formation of "ears" at crack tip, (e) maximum compressive load, and (f) small tensile load in the subsequent cycle.

Thus, the formation of surface cracks and their growth as shear and tensile cracks (Stages I and II growth) to an "engineering"-size (e.g., a 3-mm-deep) crack constitute the fatigue life of a material, which is represented by the fatigue strain vs. life (ε–N) curves. Fatigue life is conventionally divided into two stages: (1) initiation, which is expressed as the number of cycles required to form microcracks on the surface, and (2) propagation, which is expressed as the number of cycles required to propagate the surface cracks to an engineering size. Thus, the definition of a cumulative usage factor (CUF) value of unity, as described in Section 1.1, conventionally includes both initiation and some amount of propagation.

An alternative approach considers fatigue life of engineering structures and components to be entirely composed of the growth of short fatigue cracks (i.e., cracks less than "engineering" size).[163,164] For polycrystalline materials, the time for the formation of surface cracks is negligible. During cyclic loading, surface cracks, 5 μm or longer, form early in life at surface

irregularities that either already exist or were produced by slip bands, grain boundaries, second-phase particles, or other such features (Figure 2-3)[11,165-167] Thus, fatigue life may be considered to constitute propagation of cracks from 10 to 3000 μm long, and fatigue damage in a material may be considered as the current size of the fatigue crack.[164] However, the growth rates of short cracks cannot be predicted accurately from fracture mechanics methodology based on the range of stress intensity factor (ΔK) alone. Under the same ΔK loading, short fatigue cracks (i.e., cracks having lengths comparable to the unit size of the microstructure) grow at a faster rate than longer fatigue cracks.[168] In addition, shorter cracks can grow at ΔK values below those predicted from linear elastic fracture mechanics (LEFM). The differences between the growth rates of short and long cracks are attributed to interactions with microstructural features, contributions of crack closure with increasing crack length, effects of mixed mode crack propagation, and an inadequate characterization of the crack tip stress/strain fields associated with short cracks.

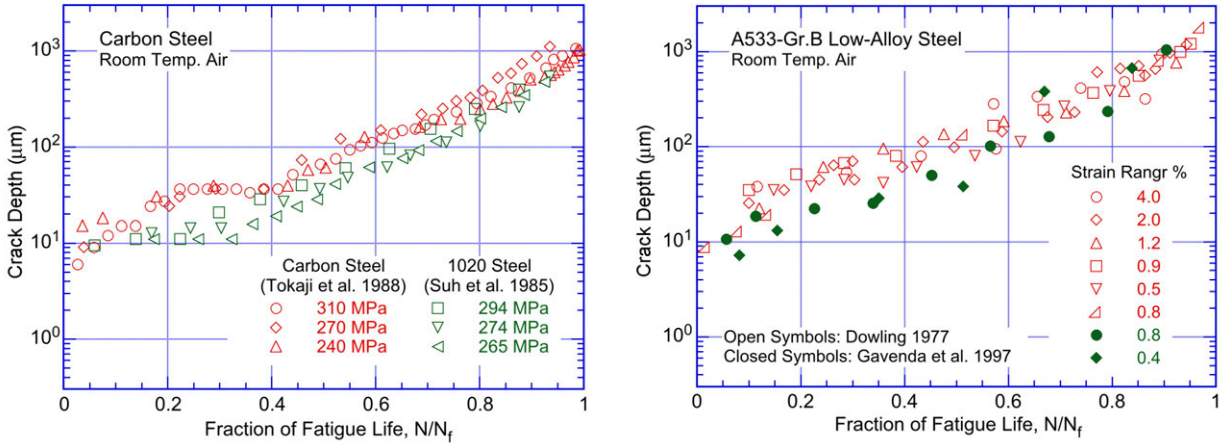
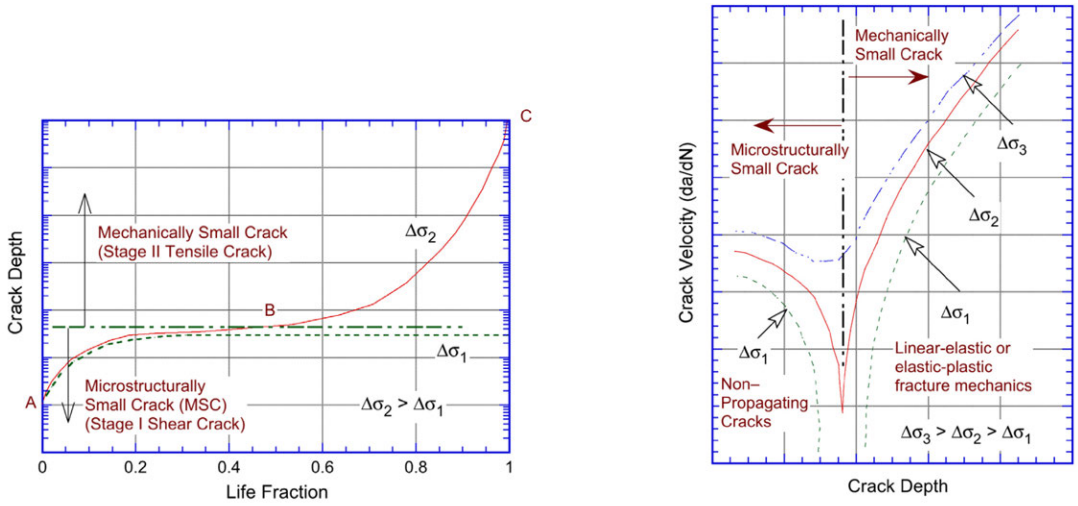


Figure 2-3 Crack depth plotted as a function of fractional life for carbon and low-alloy steels tested in air (Refs. 11 and 165-167).

Figure 2-4 shows a schematic illustration of the two stages of fatigue crack growth including (a) initiation, and (b) propagation. The initiation stage involves growth of "microstructurally small cracks" (MSCs), characterized by decelerating crack growth (Region AB in Figure 2-4(a)). The propagation stage involves growth of "mechanically small cracks," characterized by accelerating crack growth (Region BC in Figure 2-4(a)). The MSCs correspond to Stage I cracks and grow along slip planes as shear cracks in the early stage of growth. The growth of the MSCs is very sensitive to microstructure.[11,166-171] For MSCs, microstructural effects are strong because of Stage I growth (i.e., crystallographic growth). The growth rates are markedly decreased by grain boundaries, triple points, and phase boundaries. In ferritic-pearlitic steels, fatigue cracks initiate and propagate preferentially in the ferrite phase that forms as long allotriomorphs at prior austenite phase boundaries.[166,170,171] The ferrite/pearlite phase boundaries act as strong barriers to crack propagation, and growth rates decrease significantly when small cracks grow into the pearlite from the ferrite.[166] Limited data suggest that microstructural effects are more pronounced at negative stress ratios; the compressive component of the applied load plays an important role in the formation of Stage I facets and formation of cracks.[169]



(a) (b)

Figure 2-4 Schematic illustration of (a) growth of short cracks in smooth specimens as a function of fatigue life fraction, and (b) crack velocity as a function of crack depth.

Fatigue cracks greater than a critical size show little or no influence of microstructure and are considered mechanically small cracks.[169] Mechanically small cracks correspond to Stage II (tensile) cracks, which are characterized by striated crack growth, with the fracture surface normal to the direction of maximum principal stress. The growth of mechanically small cracks is characterized in terms of the J-integral range (ΔJ) and crack growth rate (CGR) data in air and light-water reactor (LWR) environments. The CGRs estimated from smooth specimen ε–N data show good agreement with CGRs obtained on fracture mechanics compact tension (CT) specimens in air and water environments.[13]

Various criteria, summarized in Section 5.4.1 of NUREG/CR-6717, "Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels," issued May 2001,[12] are used to define the crack depth for transition from microstructurally to mechanically small cracks. The transition crack depth is a function of applied stress (σ) and the microstructure of the material. For completely reversed fatigue straining, the transition from an MSC to a mechanically small crack for several materials is estimated to be approximately eight times the unit size of the microstructure,[169] actual values may range from 150 to 250 μm.

At low stress levels ($\Delta\sigma_1$) (Figure 2-4(a)), the transition from MSC growth to accelerating crack growth does not occur. This circumstance represents the fatigue limit for a smooth specimen. Although cracks can form below the fatigue limit, they grow to engineering size only at stresses greater than the fatigue limit. The fatigue limit for a material is applicable only for constant loading conditions. Under variable loading conditions, MSCs can grow at high stresses ($\Delta\sigma_3$) (Figure 2-4(b)) to depths larger than the transition crack depth, and then continue to grow at stress levels below the fatigue limit ($\Delta\sigma_1$).

As discussed in Section 1.1, fatigue life is described in this report as the number of cycles of a specified strain amplitude that a specimen can sustain before the formation of a 3-mm-deep crack (i.e., an "engineering crack"). This is assumed throughout this report to equate to crack initiation in an actual component. Using this definition, a calculated fatigue CUF less than unity

provides reasonable assurance that a fatigue crack has not formed in a component, and indicates that the probability of forming a crack in the component is low.

2.2 Fatigue Cracking in LWR Environments

The available small-scale laboratory fatigue test data indicate a significant decrease in fatigue life of reactor structural materials in LWR environments. The extent of environmental effects depends on the applied strain, temperature, strain rate, dissolved oxygen (DO) in the water, and for carbon and low-alloy steels, the sulfur content in the steel. Although the structure and cyclic hardening behavior of carbon and low-alloy steels are distinctly different, there is little or no difference in susceptibility to environmental degradation of fatigue life of these steels. Reduction in fatigue life in LWR water environments may arise from easy formation of surface microcracks consisting of the growth of MSCs (i.e., the initiation stage) or an increase in growth of mechanically small cracks, or both (i.e., propagation stage). The following sections discuss the formation and growth characteristics of fatigue cracks in detail for carbon and low-alloy steels and wrought and cast austenitic stainless steels (SSs). Similar information for nickel-chromium-iron (Ni-Cr-Fe) alloys is very limited.

2.2.1 Carbon and Low-Alloy Steels

Carbon and low-alloy steels tested in air show slight discoloration, while those tested in water develop a gray/black corrosion scale and are covered with magnetite (Fe_3O_4) at all DO levels. Hematite (α-Fe_2O_3) forms on these materials at DO levels above 200 parts per billion (ppb).[20,22,172] The amount of hematite increases with increasing DO levels in the water.[20] Studies on the pitting behavior of carbon and low-alloy steels[173,174] in high-purity water indicate that pitting corrosion does not occur in these steels at reactor operating temperatures in low-DO pressurized-water reactor (PWR) environments (typically less than 0.01 parts per million (ppm) DO), and at temperatures above 200°C in water that contains 0.1–0.2 ppm DO, which represents normal boiling-water reactor (BWR) water chemistry. However, even under these conditions, micropits form in both types of steels due to dissolution of manganese sulfide (MnS) inclusions[18] or by anodic reaction in the sulfur-contaminated matrix[175] close to sulfide inclusions. These micropits and cavities can act as stress raisers and provide preferred sites for the formation of fatigue cracks.

2.2.1.1 Effects of Surface Micropits

The strain rate effects in water are such that fatigue life decreases with decreasing strain rate. These effects are often explained by a higher density of micropits at lower strain rates. Some investigators argue that the longer test durations for slow strain rate tests result in a higher density of micropits and, therefore, shorter periods for the formation of surface microcracks.[18] However, if the presence of micropits was responsible for the reduction in fatigue lives of carbon and low-alloy steels in LWR environments, then specimens pre-exposed to high-DO water followed by testing in air should also show a decrease in fatigue life.

Figure 2-5 shows a comparison of the fatigue lives of carbon and low-alloy steels tested in high-DO water at 288°C with the fatigue lives of carbon and low-alloy steels preoxidized at 288°C for 30–100 hours in water with 0.6–0.8 ppm DO and then tested in either air or low-DO water with less than 0.01 ppm DO.[40,41,176] Runouts, in this and subsequent figures, are identified in the traditional manner of using arrows after the data-point. The fatigue lives of the preoxidized specimens were identical to those of the unoxidized specimens; life was expected to decrease if surface micropits facilitate the formation of fatigue cracks. Only a moderate

decrease in life was observed for both preoxidized and unoxidized specimens tested in low-DO water. Furthermore, if micropits were responsible for the decrease in fatigue lives in LWR environments, then the fatigue limit of these steels should be lower in water than in air.

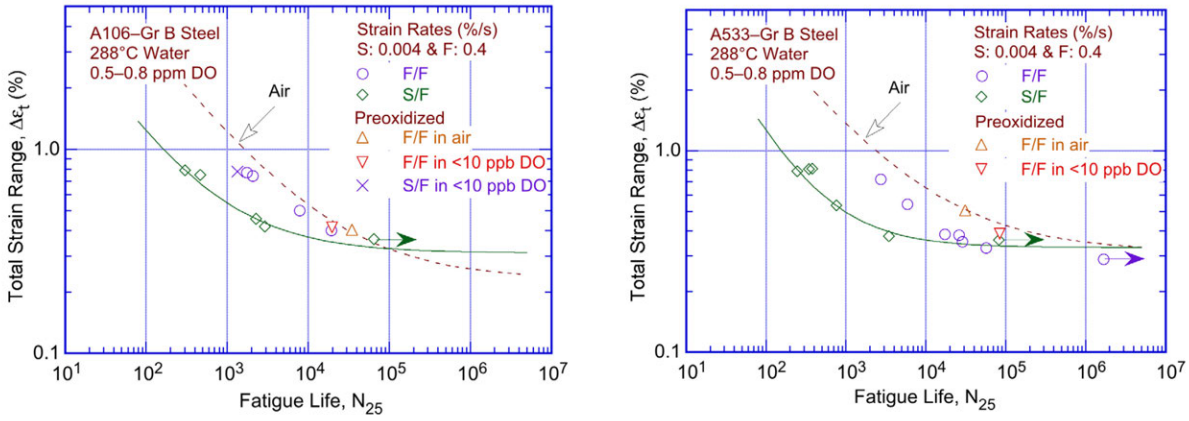


Figure 2-5 Fatigue life of carbon and low-alloy steel specimens in high-DO water at 288°C compared with the fatigue life of specimens preoxidized in high-DO water and tested in either air or low-DO water at 288°C (Refs. 40, 41, and 176) (Runouts, in this and subsequent figures, are identified in the traditional manner of using arrows after the data-point).

The extent of fatigue cracking, as measured by the number of cracks with depths greater than 10 μm, along longitudinal sections of carbon and low-alloy steel specimens as a function of strain range in air, simulated PWR, and high-DO water was also investigated.[176] The results indicated that, with the exception of low-alloy steel tested in simulated PWR water, the water environment had no effect on the frequency (number per unit gauge length) of cracks. For similar loading conditions, the number of cracks in the specimens tested in air and high-DO water was identical, although fatigue lives were lower by a factor of approximately 8 in water. If the reduction in life was caused by enhanced crack nucleation, the specimens tested in high-DO water should have shown a higher number of cracks. Detailed metallographic evaluations of the fatigue test specimens[176] also indicated that, irrespective of environment, cracks in carbon and low-alloy steels nucleated along slip bands, carbide particles, or at the ferrite/pearlite phase boundaries.[11,176]

2.2.1.2 Mechanisms of Corrosion Fatigue

The environmental enhancement of fatigue crack growth in pressure vessel steels in high-temperature oxygenated water and the effects of sulfur content, loading rate, and flow velocities are well documented.[177-189] Dissolution of MnS inclusions changes the water chemistry near the crack tip, making it more aggressive. This results in enhanced CGRs because either (1) the dissolved sulfides decrease the repassivation rate, which increases the amount of metal dissolution for a given oxide rupture rate;[189] or (2) the dissolved sulfide poisons the recombination of hydrogen (H) atoms liberated by corrosion, which enhances H uptake by the steel at the crack tip.

The enhanced CGRs in LWR environments are attributed to either slip oxidation/dissolution[189-193] or hydrogen-induced cracking mechanisms.[194-196] For the slip oxidation/dissolution mechanism, a critical concentration of sulfide (S^{2-}) or hydrosulfide (HS^{-}) ions, which are

produced by the dissolution of sulfide inclusions in the steel, is required at the crack tip for environmental effects to occur. The crack tip is supplied with S^{2-} and HS^{-} ions as the advancing crack intersects the sulfide inclusions, and the inclusions dissolve in the high-temperature water environment. S^{2-} ions are removed from the crack tip by one or more of the following processes: (1) diffusion due to a concentration gradient, (2) ion transport due to an electrochemical potential (ECP) gradient, (3) pumping action due to cyclic loading on the crack, and/or (4) fluid flow induced within the crack due to the flow of water outside the crack. The morphology, size, and distribution of sulfide inclusions and the probability of advancing the crack to intercept the sulfide inclusions are important parameters affecting growth rates of carbon and low-alloy steels in LWR environments.[183,185-188]

The requirements for a slip dissolution model are that a protective oxide film is thermodynamically stable to ensure that a crack will propagate with a high aspect ratio without degrading into a blunt pit and that a strain increment occurs to rupture that film and thereby expose the underlying matrix to the environment (Figure 2-6). Once the passive oxide film is ruptured, crack extension is controlled by dissolution of freshly exposed surfaces and by the oxidation characteristics. The effect of the environment increases with decreasing strain rate. The mechanism assumes that environmental effects do not occur during the compressive load cycle because during that period water does not have access to the crack tip. Ford et al.[191,192] proposed that the average environmentally assisted CGR, $\overline{V}_t$ (centimeters per second), is related to the crack tip strain rate, $\dot{\varepsilon}_{ct}$, by the relationship

$$\overline{V}_t = A(\dot{\varepsilon}_{ct})^n \,, \tag{13}$$

where the constants A and n depend on the material and environmental conditions at the crack tip. There is a lower limit of crack propagation rate associated either with blunting when the crack tip cannot keep up with the general corrosion rate of the crack sides, or with the fact that a critical level of S^{2-} ions cannot be maintained at the crack tip. For example, the latter condition may occur when the CGR falls below a critical value such that a high concentration of S^{2-} ions cannot be maintained at the crack tip. The critical crack growth rate at which this transition occurs depends on the DO level, flow rate, and sulfur (S) content of the steel.

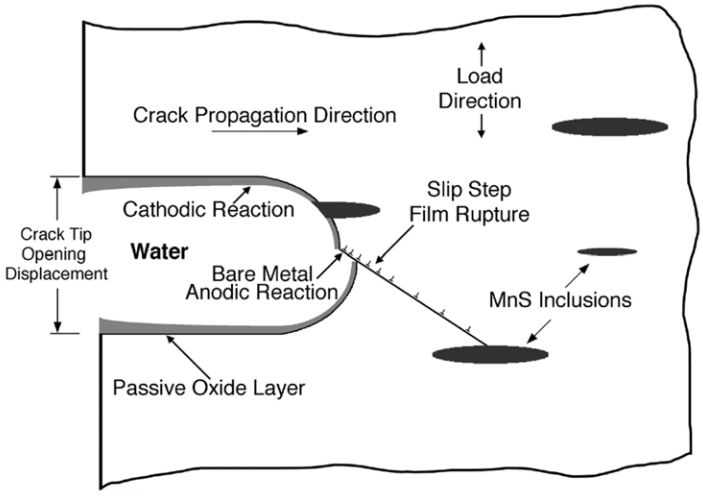


Figure 2-6 Schematic illustration of slip oxidation/dissolution process.

The average critical velocity, $\bar{V}_{in}$, (millimeters per second), for initiation or cessation of environmentally assisted cracking (EAC), was shown to depend on the balance between sulfide supply rate and mass transport away from the crack tip.[178,182] Initiation of EAC requires a critical concentration of sulfide ions at the crack tip, which is supplied with sulfide ions as the advancing crack intersects the sulfide inclusions, and the inclusions dissolve in the high-temperature water. Crack growth studies in high-temperature, low-DO environment (i.e., less than 0.05 ppm DO) indicate that $\bar{V}_{in}$ is given by

$$\bar{V}_{in} = \frac{1.27 \times 10^{-6}}{a}, \quad (14)$$

where a is the crack depth (millimeters). Thus, for a 2.54-mm crack depth, a minimum average crack velocity of 5×10^{-7} mm/s is required to produce the S^{2-} ion concentration for environmental effects on crack growth to be pronounced.[182] In addition, the critical velocity must be maintained for a minimum crack extension of 0.33 mm to achieve the concentration of S^{2-} ions needed for initiating environmental enhancement of growth rates.[178] Equation 14 indicates that the minimum crack velocity to initiate environmental effects increases with decreasing crack depth. For crack depths between 0.01 and 3 mm, crack velocities in the range of 1.27×10^{-4} to 4.23×10^{-7} mm/s are required to cause a measurable reduction in fatigue lives of carbon and low-alloy steels in low-DO water. For smooth cylindrical fatigue specimens, these growth rates are not achieved under the loading conditions typically used for fatigue ε–N data, which suggests that environmental effects on fatigue lives in low-DO environments are not significant. This behavior is consistent with the existing fatigue ε–N data; for most compositions of carbon and low-alloy steels, only moderate reductions in fatigue life (less than a factor of 2) are observed in 288°C water containing less than 0.01 ppm DO, which is within the data scatter.

In addition, consistent with the slip dissolution mechanism assumption mentioned previously, it is assumed that environmental enhancement of crack propagation does not occur during the compressive load cycle because, during that period, the water does not have access to the crack tip due to crack closure. The total crack advance during a fatigue cycle is given by the summation of crack advance in air due to mechanical factors, and crack advance during the tensile load cycle (i.e., increasing strain) from a slip-dissolution mechanism, once the tensile strain increment exceeds the fracture strain of the oxide.

Hydrogen-induced cracking (Figure 2-7) of carbon and low-alloy steels is caused by hydrogen produced by the oxidation reaction at the crack tip that is partly absorbed into the metal; it interacts with MnS inclusions and leads to the formation of cleavage cracks at the inclusion matrix interface. Crack extension occurs by linkage of the cleavage cracks. Other hydrogen-induced fracture processes may also enhance growth rates in LWR environments. According to the decohesion mechanism, significant accumulation of hydrogen at or near the crack tip decreases the cohesive interatomic strength of the lattice.[197] Hydrogen-induced bond rupture ahead of the crack tip links up with the main crack resulting in discontinuous, but enhanced crack growth. Furthermore, adsorbed hydrogen lowers the surface energy of the metal, thus facilitating crack growth at a lower fracture stress level. In addition, hydrogen can cause localized crack tip plasticity by reducing the stress required for dislocation motion.[198] Note that the hydrogen produced at the crack tip by this mechanism is not related to the hydrogen content of the bulk fluid; as a result, hydrogen content of the bulk fluid is not a parameter in the environmental fatigue correction factor (F_{en}) expressions.

Both the slip-oxidation/dissolution and hydrogen-induced cracking mechanisms are dependent on oxide rupture rates, passivation rates, and liquid diffusion rates. Therefore, it is difficult to

differentiate between the two mechanisms or to establish their relative contribution to crack growth rates in LWR environments. However, fatigue crack morphologies in test specimens indicate that both the slip-oxidation/dissolution and hydrogen-induced cracking mechanisms are important for environmental effects of the fatigue lives of carbon and low-alloy steels in LWR environments. A change in fracture appearance from ductile striations in air to brittle facets or cleavage-like fracture in LWR environments lends the greatest support for hydrogen–induced cracking.[142,143,187,195,196]

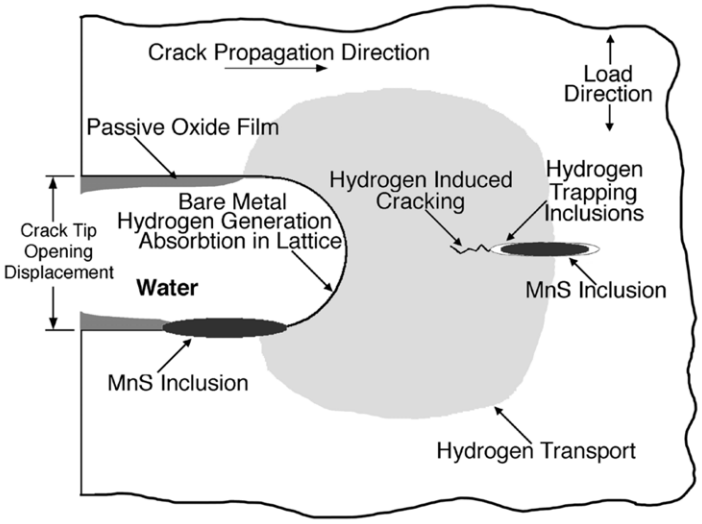
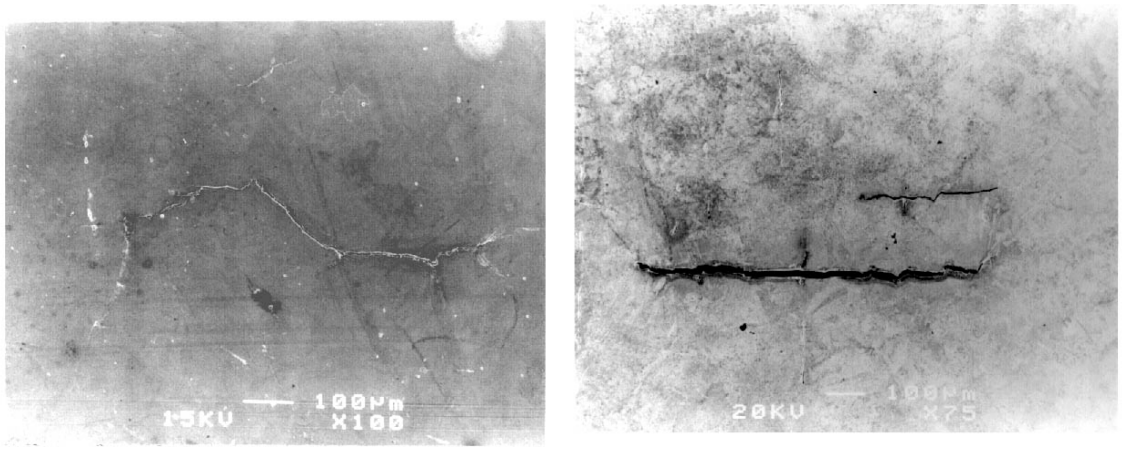


Figure 2-7 Schematic illustration of hydrogen-induced cracking of low-alloy steel.

The fatigue crack morphologies of carbon and low-alloy steels in a BWR environment also show a strong dependence and change with strain rate. At high strain rates, surface crack morphology is predominantly a zigzag pattern and is inclined to the loading axis, whereas entirely straight crack morphology normal to the loading axis is observed at slow strain rates.[10,139,143] Figure 2-8 shows the surface crack morphology in A106-Gr. B carbon steel tested in air and high-DO water at 288°C. In addition, high strain rates lead to a rough fracture surface with the typical fan-like or quasi-cleavage cracking pattern, and slow strain rates result in a flat, nondescript fracture surface.[139,142] Figure 2-9 shows the propagation of fatigue cracks in A106-Gr. B carbon steel. In air, fatigue cracks grow along relatively soft ferrite regions and avoid the hard pearlite regions. In contrast, in a high-DO BWR environment, fatigue cracks appear to grow straight, normal to the stress axis, and through both the soft ferrite and the hard pearlite regions. Such crack growth characteristics are consistent with the slip-oxidation/dissolution mechanism and crack extension by anodic dissolution of the matrix in a corrosive environment.

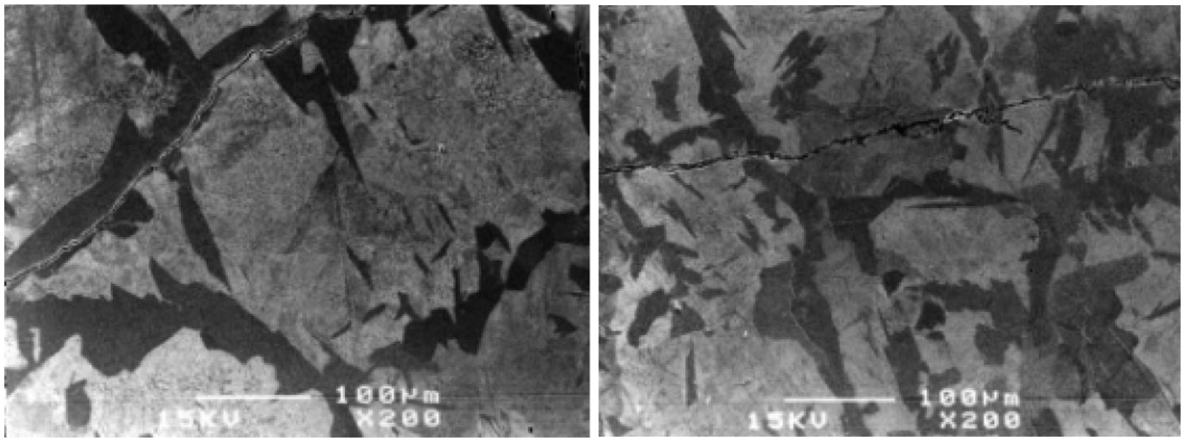
Wu and Katada[142] attributed the change in crack morphology to a change in the corrosion fatigue mechanism from hydrogen-induced cracking to a slip-oxidation/dissolution mechanism with decreasing strain rate. The authors reasoned that, during cyclic loading in high-temperature water, plastic deformation induces slip bands at the crack tip along the maximum shear or preferred slip directions. The extrusion of slip bands may rupture the protective oxide film at the crack tip. The slip bands are the favored path for hydrogen transportation, and the interfaces between the matrix and inclusions or precipitations in the region of maximum hydrostatic tension are the preferred traps for hydrogen. Thus, hydrogen tends to accumulate at these sites and embrittle them. As a result, at high strain rates, fatigue cracking preferentially occurs along the

slip bands or preferred slip directions and the matrix/inclusions interfaces, which results in macroscopically tortuous fatigue cracks and a rough fracture surface. However, at low strain rates, fatigue crack growth in high-temperature water is controlled by the film-rupture/oxidation-dissolution mechanism, which results in macroscopically straight fatigue cracks and a relatively flat, featureless fracture surface.



(a) (b)

Figure 2-8 Fatigue cracks on gauge surfaces of A106–Gr. B carbon steel tested in (a) air and (b) high-DO water at 288°C (Ref. 10).



(a) (b)

Figure 2-9 Fatigue cracks along longitudinal sections of A106-–Gr. B carbon steel tested in (a) air and (b) high-DO water at 288°C (Ref. 10).

2.2.1.3 Effects of Dynamic Strain Aging

Several studies showed that dynamic strain aging (DSA) may play a significant role in the cyclic deformation process of carbon and low-alloy steels in LWR environments.[147-151] DSA occurs in alloys containing solutes that segregate strongly to dislocations resulting in strong interactions between the solute and the stress-strain field of the dislocations, which leads to dislocation pinning (Figure 2-10). In carbon and low-alloy steels, the occurrence of DSA is due to interstitial elements such as nitrogen and carbon. DSA is sufficiently rapid to occur during fatigue straining

and produces a variety of inhomogeneous deformations such as serrated yielding, jerky or serrated flow, or other such deformations. These effects depend on temperature and strain rate.

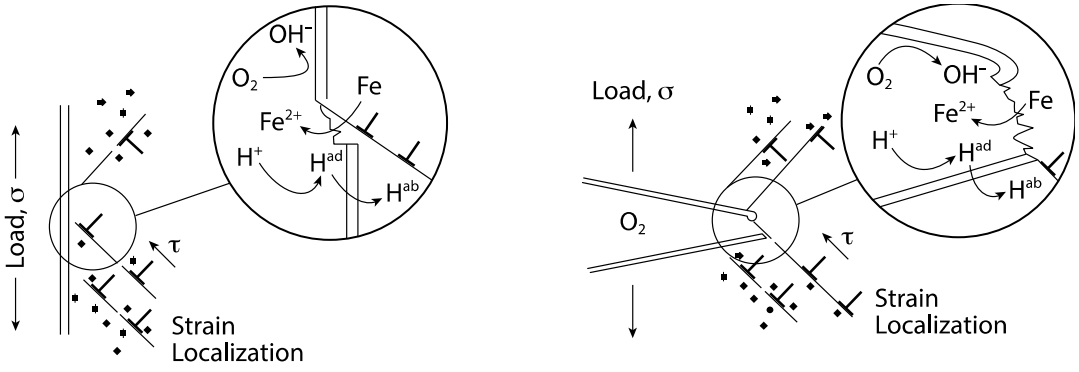


Figure 2-10 (a) Fatigue crack initiation and (b) crack growth in DSA susceptible low-alloy steel exposed to a high-temperature water environment (Ref. 147).

Under certain combinations of temperature and strain rate conditions, DSA may significantly affect the EAC behavior of carbon and low-alloy steels by increasing the monotonic yield and tensile strength, the strain hardening exponent, the creep rate, and the crack-tip strain and strain rate.[149] DSA also results in planar deformation, an increase in dislocation density and inhomogeneous localization of deformation. These factors favor brittle crack extension and rupture of the protective oxide film, thereby enhancing crack advance by either anodic dissolution or hydrogen embrittlement processes. In high-temperature water, the synergistic interactions between EAC and DSA during fatigue straining may be rationalized as follows:[149]

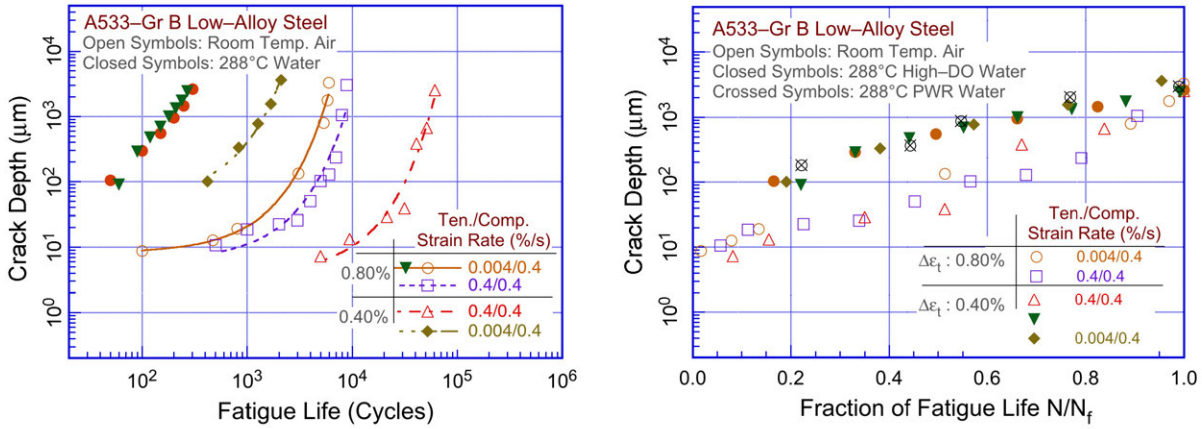
- Hydrogen vacancies produced by the corrosion reaction at the crack tip enter the steel and hydrogen diffuses to strong trapping sites inside the crack-tip maximum hydrostatic stress region (e.g., MnS inclusions) ahead of the crack tip.
- These sites act as initiation sites for local quasi-cleavage cracking, as well as void formation, and these microcracks link with the main crack.
- In addition, at a given macroscopic strain caused by external loads, the microscopic strain in steels that are susceptible to DSA is higher because of strain localization to small areas, which leads to higher rates and larger steps of oxide film rupture. As a result, the slip oxidation/dissolution process enhances fatigue crack initiation or fatigue CGRs.
- Such interactions, however, occur only under certain conditions of temperature, strain rate, and DO level in the environment.

In carbon and low-alloys steels, the interaction of nitrogen and dislocations during plastic deformation reduces plasticity, which causes strain localization in the material.[147] Small areas can deform plastically adjacent to areas that might be blocked by nitrogen/dislocation interactions. For a given macroscopic strain, the microscopic strain is higher due to strain localization in steels that are susceptible to DSA. Thus, because of strain localization, stress concentrations at active slip planes lead to higher rates and larger steps of oxide rupture and, simultaneously, to a decreased repassivation rate.[147,148] Consequently, both crack initiation and growth rates may be enhanced in carbon and low-alloy steels.

2.2.1.4 Crack Growth Rates in Smooth Fatigue Specimens

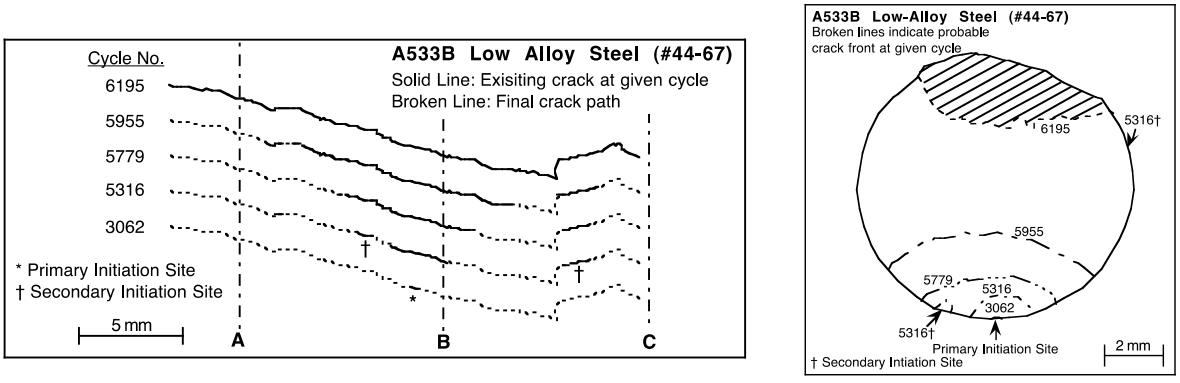
Studies on the formation and growth characteristics of short cracks in smooth fatigue specimens in LWR environments indicated that the decrease in fatigue life in LWR environments is caused primarily by the effects of the environment on the growth of MSCs (i.e., cracks less than 200 μm deep) and, to a lesser extent, on the growth of mechanically small cracks.[10,11]

Figure 2-11 shows measured crack lengths as a function of fatigue cycles and fraction of fatigue life for smooth cylindrical specimens of A533-Gr. B low-alloy steel in air, simulated PWR environment, and high-DO water. Figure 2-12 shows an example of the growth of a surface crack in A533-Gr. B steel tested in air at room temperature, and shows the fracture surface and probable crack front for the crack. The results indicate that, for this example, three cracks merged to form the final fracture surface. The primary crack initiated near an inclusion and reached a surface length of approximately 100 μm after 3,062 cycles (i.e., approximately 50% of the fatigue life). Two secondary cracks merged with the primary crack after approximately 5,700 and 6,000 cycles. Crack depth was determined by dividing the surface crack length by pi (π).



(a) (b)

Figure 2-11 Depth of largest crack plotted as a function of (a) fatigue cycles and (b) fraction of fatigue life for A533–Gr B low-alloy steel in air and water environments (Ref. 11).



(a) (b)

Figure 2-12 (a) Morphology and length of surface crack after various numbers of cycles for A533–Gr. B steel in air at room temperature, and (b) fracture surface and probable crack front for surface cracks shown in (a) (Ref. 11).

Figure 2-13 plots the CGRs corresponding to the data shown in Figure 2-12 as a function of crack depth. The results indicate that, in LWR environments, the period spent in the growth of MSCs is decreased. At approximately 0.8% strain range, only 30-50 cycles are needed to form a 100-μm crack in high-DO water, whereas approximately 450 cycles are required to form a 100-μm crack in a low-DO PWR environment and more than 3,000 cycles are required to form a 100-μm crack in air. These values correspond to average growth rates of approximately 2.5, 0.22, and 0.033 μm/cycle in high-DO water, low-DO PWR environment, and air, respectively. The results also indicate that, relative to air, CGRs in high-DO water are nearly two orders of magnitude higher during the initial stages of fatigue life (i.e., for crack sizes less than 100 μm) and are one order of magnitude higher for crack sizes greater than 100 μm.

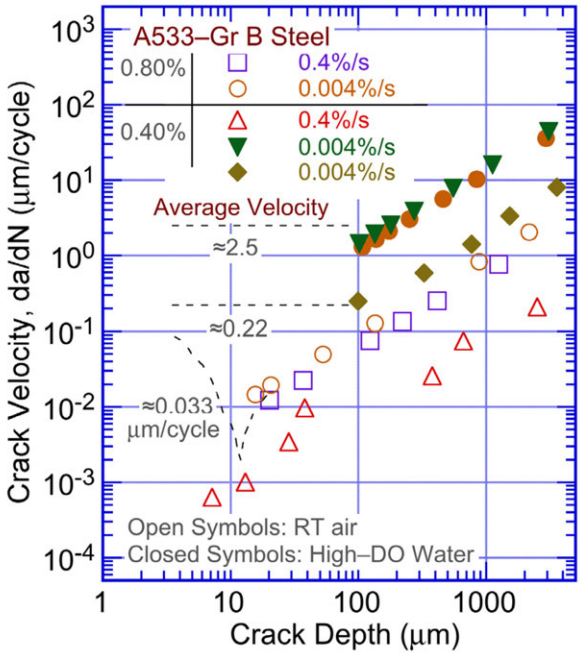


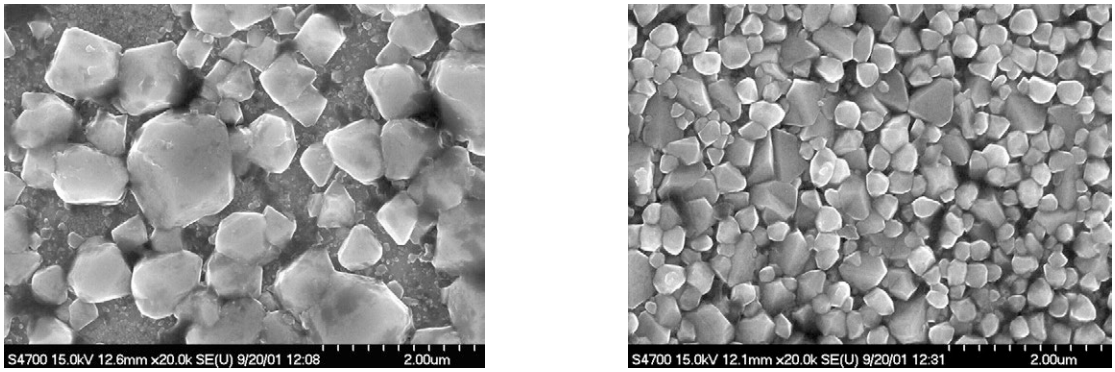
Figure 2-13 Crack growth rates plotted as a function of crack depth for A533–Gr B low-alloy steel tested in air and water environments (Ref. 11).

The surface crack and fracture surface morphologies of the test specimens indicate that, in high-temperature, high-DO water with slow strain rates, the surface cracks appear to grow entirely in Stage II growth as Mode I tensile cracks normal to the stress axis (Figure 2-8 and Figure 2-9). In air and low-DO PWR environments, both Stage I and Stage II growths are observed. Surface cracks grow initially as Mode II (shear) cracks along planes 45° to the stress axis and, when the stress intensities are large enough to promote slip on axes other than the primary slip axis, they grow as Mode I (tensile) cracks normal to the stress axis. In addition, for A106-Gr. B carbon steel, Stage I crack growth in air and low-DO water occurs entirely along the soft ferrite grains, whereas in high-DO water, cracks propagate across both ferrite and pearlite regions. These results are consistent with the slip-oxidation/dissolution mechanism in high-DO water.

2.2.2 Austenitic Stainless Steels

Austenitic SSs exposed to LWR environments develop an oxide film that consists of two layers: (1) a fine-grained, tightly-adherent, chromium-rich inner layer, and (2) a crystalline, nickel–rich outer layer composed of large and intermediate-sized particles. Figure 2-14 shows

photomicrographs of the gauge surface of Type 316NG specimens tested in simulated PWR water and high-DO water. The inner layer forms by solid-state growth, whereas the crystalline outer layer forms by precipitation or deposition from the solution. Figure 2-15 shows a schematic representation of the surface oxide film.



(a) (b)

Figure 2-14 Photomicrographs of oxide films that formed on Type 316NG SS in (a) simulated PWR water and (b) high-DO water (Ref. 13).

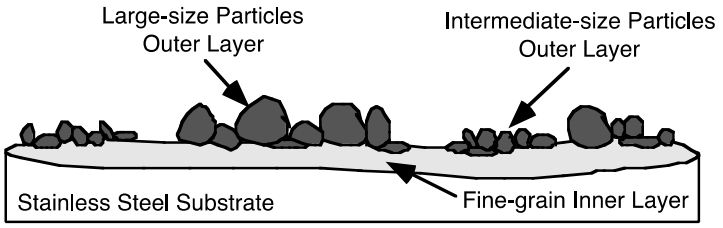


Figure 2-15 Schematic of the corrosion oxide film formed on austenitic SSs in LWR environments.

Several studies characterized the oxide films that form on austenitic SSs in LWR environments.[199-205] The inner layer consists of a chromium-rich spinel ($Ni_xCr_yFe_{3-x-y}O_4$) with a nonstoichiometric composition; the actual composition of spinels varies with environmental conditions. Da Cunha Belo et al.[203] determined that the inner layer that formed on Type 316L SS in a PWR environment at 350°C consisted of mixed chromium oxides (Cr_2O_3 + $FeCr_2O_4$) and Fe_3O_4. Nakayama and Oshida[205] characterized the oxide film on SSs exposed to high-DO (8 ppm) water at 300°C as chiefly composed of $NiO{\cdot}(Cr,Fe)_2O_3$ and/or $NiFe_2O_4$, which may be formed by a solid reaction between NiO and $(Cr,Fe)_2O_3$ or α-Fe_2O_3. Kim[199,200] identified the $FeCr_2O_4$ spinel chromite (or $Fe_xCr_{3-x}O_4$), along with $NiFe_2O_4$, in the inner layer formed on Types 304 and 316 SSs exposed at 288°C under BWR normal water chemistry (NWC) or BWR hydrogen water chemistry (HWC) conditions. Kim also noted that the inner oxide layer formed in an NWC BWR environment contained a lower concentration of chromium than that formed in an HWC low-DO environment. Such differences were attributed to chromium oxidation in high-DO water.

The structure and composition of the crystalline outer layer vary with the water chemistry. In BWR environments, the large particles in the outer layer are primarily composed of γ-Fe_2O_3 hematite in NWC, and Fe_3O_4 magnetite in HWC.[199,200] The intermediate particles in the outer

layer are composed of α-Fe_2O_3 in NWC and Fe_3O_4 in HWC. The structure of the outer layer varies when the water chemistry is cycled between NWC and HWC. In PWR environments, the large particles were identified as $Ni_{0.75}Fe_{2.25}O_4$ spinel and the intermediate particles as $Ni_{0.75}Fe_{2.25}O_4 + Fe_3O_4$.[203] Section 2.2.2.1 discusses the possible effects of minor differences in the surface oxide film on fatigue crack initiation.

2.2.2.1 Effects of Surface Micropits

The characteristics of the surface oxide films that form on austenitic SSs in LWR water environments influence the mechanism and kinetics of corrosion processes and thereby influence the initiation stage (i.e., the growth of MSCs). As discussed earlier, the reduction of fatigue lives in high-temperature water may be due to the presence of surface micropits. To investigate the effect of surface micropits, fatigue tests were conducted on Type 316NG (Heat P91576) specimens that were preexposed to either low-DO or high-DO water and then tested in air or water environments.[13] Figure 2-16 plots the results of these tests, as well as data obtained earlier on this heat and Heat D432804 of Type 316NG SS in air and low-DO water at 288°C. The fatigue lives of specimens preoxidized in high-DO water and then tested in low-DO water were identical to those of specimens tested without preoxidation. In addition, fatigue lives of specimens preoxidized at 288°C in low-DO water and then tested in air were identical to those of unoxidized specimens (Figure 2-16). If micropits were responsible for the reduction in life, the preexposed specimens should have shown a decrease in life. Furthermore, the fatigue limit of these steels should have also been lower in water than in air, but the data indicate that this limit was the same in both water and air environments. These results indicate that surface micropits or minor differences in the composition or structure of the surface oxide film had little or no effect on the formation of fatigue cracks.

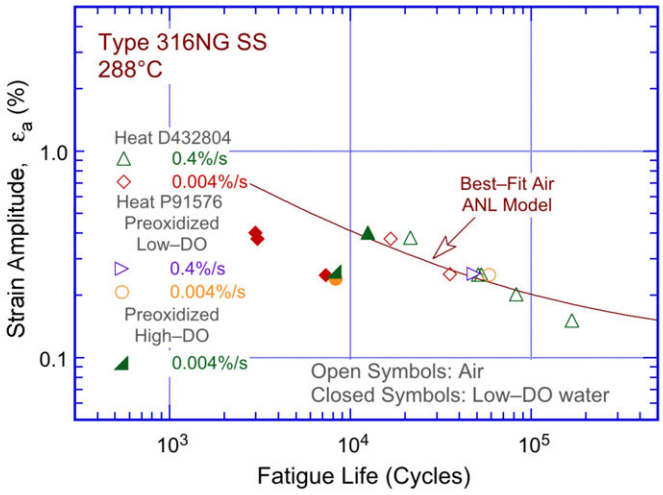
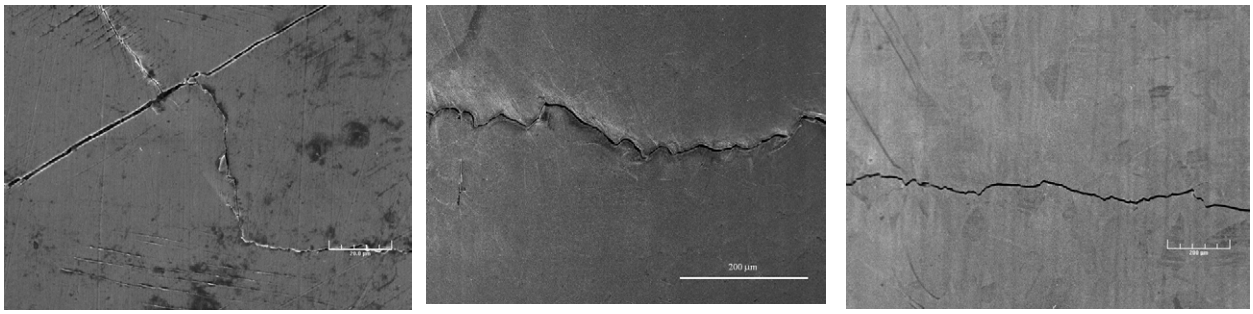


Figure 2-16 Effects of environment on formation of fatigue cracks in Type 316NG SS in air and low-DO water at 288°C (Preoxidized specimens were exposed for 10 days at 288°C in water that contained either less than 5-ppb DO and approximately 23 cm^3/kg dissolved H_2 or approximately 500-ppb DO and no dissolved H_2 (Ref. 13).

2.2.2.2 Mechanisms of Corrosion Fatigue

Both the slip oxidation/dissolution and the hydrogen-induced cracking mechanisms depend on the rates of oxide rupture, passivation, and liquid diffusion. Therefore, it is difficult to differentiate between the two processes or to establish their relative contribution to fatigue cracking in LWR environments. However, for austenitic SSs, lower fatigue lives in low-DO water vs. high-DO water are difficult to reconcile in terms of the slip-oxidation/dissolution mechanism, which assumes that CGRs increase with increasing DO in the water. Metallographic examination of fatigue test specimens suggested that hydrogen-induced cracking may have played an important role in environmentally assisted reduction in fatigue lives of austenitic SSs.[47] For example, hydrogen can cause localized crack tip plasticity by reducing the stress required for dislocation motion, which leads to higher rates and larger steps of oxide film rupture. Thus, fatigue lives may be decreased, not because of increased growth rates but because of increased film rupture frequency.

A detailed metallographic evaluation of austenitic SS fatigue test specimens was performed to characterize the crack and fracture morphology of the various heats under various heat treatment conditions.[47] Figure 2-17 presents photomicrographs of the crack morphology of Type 304 SS specimens under all test and environmental conditions. In all cases, the tensile axis was vertical (parallel to the plane of each photomicrograph). For austenitic SSs, the fatigue crack surface morphology was similar to that observed for carbon and low-alloy steels. In an air environment, fatigue cracks were more likely to be oblique, approaching 45° with respect to the tensile axis. By contrast, the cracks that formed in either BWR or PWR environments tended to be perpendicular to the tensile axis.



(a) (b) (c)

Figure 2-17 Photomicrographs of the fatigue crack morphology of Type 304 SS in (a) air, (b) high-DO BWR water, and (c) low-DO PWR water at 289°C (Ref. 47).

Figure 2-18 presents photomicrographs of the crack morphology of Type 304 SS under all test and environmental conditions. In air, the fracture mode for crack initiation (i.e., crack depths up to 200 μm) and crack propagation (i.e., crack depths greater than 200 μm) was transgranular (TG), most likely along crystallographic planes, leaving behind relatively smooth surfaces. With an increasing degree of sensitization, cleavage-like, or stepped, TG fracture and ridge structures were observed on the smooth surfaces. In simulated NWC BWR environments, the initial crack appeared intergranular (IG) under all heat treatment conditions, implying a weakening of the grain boundaries. The extent of IG fracture increased with the degree of sensitization. Nevertheless, for crack depths beyond 200 μm, the initial IG mode transformed into a TG mode with cleavage-like features. In simulated PWR environments, however, fatigue cracks initiated and propagated in a TG mode irrespective of the degree of sensitization.

Prominent features of the fracture surfaces included highly angular, cleavage-like fracture facets that exhibited well-defined “river” patterns.[47] IG facets were rarely observed; however, when they were found, it was mostly in the more heavily sensitized alloys.

In addition, fatigue striations normal to the crack advance direction were clearly visible beyond approximately 200-μm crack depths on the fracture surfaces of all materials under all environmental conditions. Figure 2-19 shows an example of the fatigue striations observed in Type 304 SS in different environments. Striations were found on both the TG and IG facets of the samples tested under BWR NWC conditions, or coexisting with the “river” patterns specific to the samples tested in the PWR environments. However, the striations on specimens tested in PWR water were quite faint compared to those tested in NWC BWR water. Furthermore, examination of the specimens after chemical cleaning suggested that some striations were produced by rupture of the surface oxide film rather than the formation of double notches or “ears” at the crack tip.

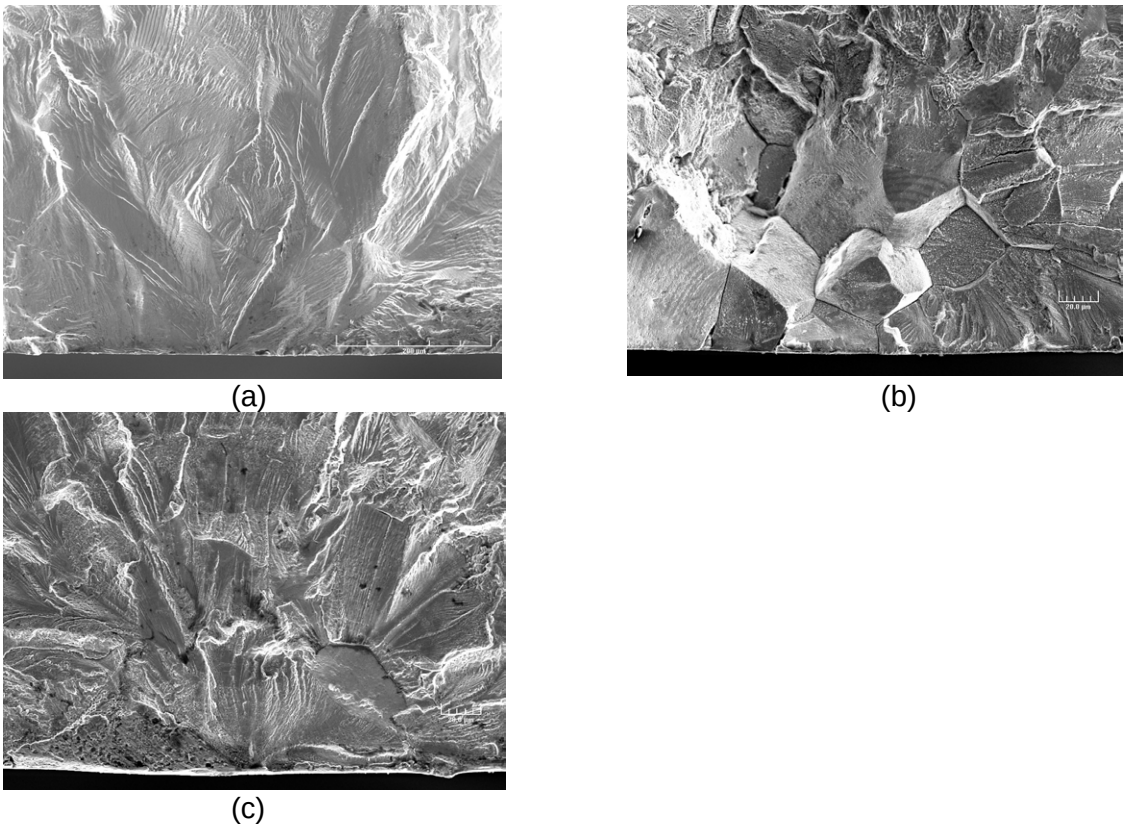


Figure 2-18 Photomicrographs showing sites of fatigue crack initiation on fracture surfaces of Type 304 SS tested at 289°C in (a) air, (b) high-DO BWR water, and (c) low-DO PWR water (Ref. 47).

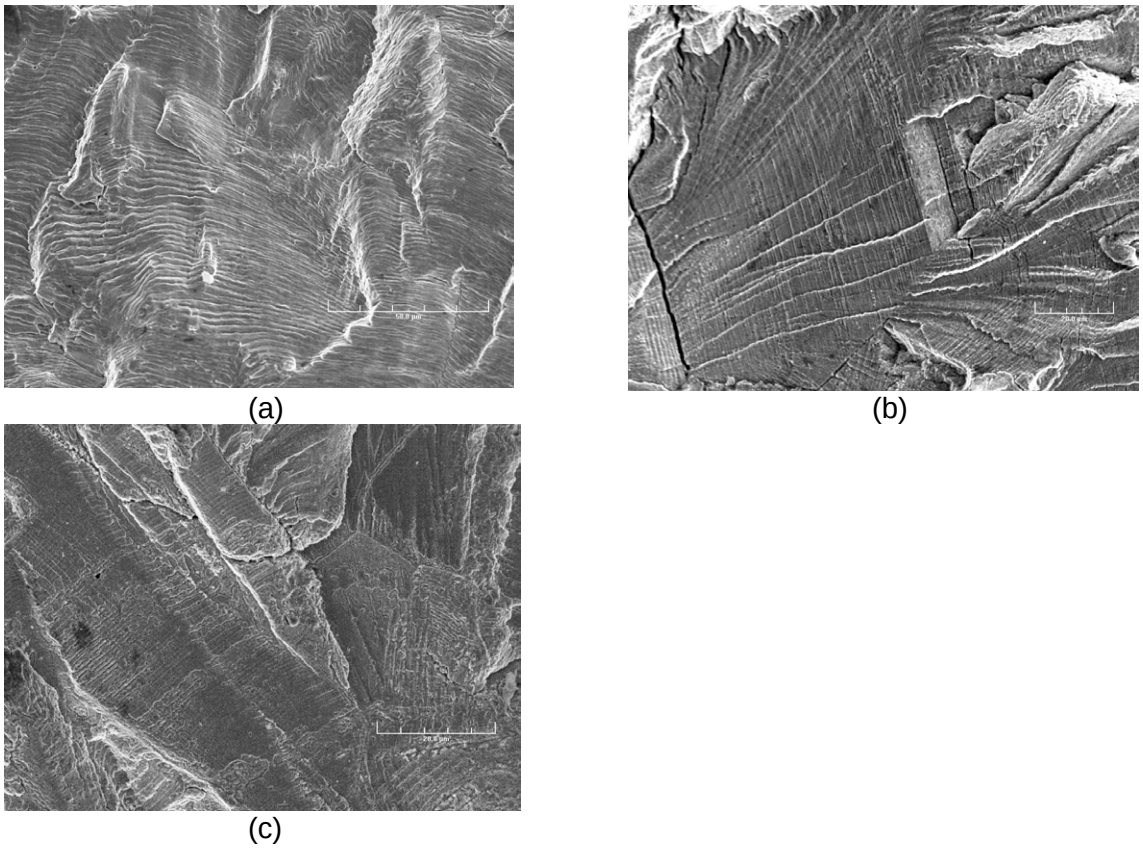


Figure 2-19 Photomicrographs showing fatigue striations on fracture surfaces of Type 304 SS tested at 289°C in (a) air, (b) high-DO BWR water, and (c) low-DO PWR water (Ref. 47).

The characterization of surface cracks and fracture morphology in austenitic SSs suggests that, in LWR environments, although film rupture was apparent, the formation and growth of fatigue cracks were primarily caused by hydrogen-induced cracking.

2.2.2.3 Effects of Dynamic Strain Aging

DSA was observed in austenitic SSs in air at strain rates below 0.3%/s and temperatures in the range of 300–600°C; the peak effects occurred at 500–600°C.[206] The fatigue life of a heat of Type 316LN SS at low strain rates was greater at 600°C than at 500°C. Typically at temperatures above 400°C, the fatigue life of austenitic SSs decreased with an increase in temperature or a decrease in strain rate.[57] DSA increased the dislocation density at slow strain rates, which enhanced the degree of inhomogeneity of deformation during fatigue loading.

DSA was also observed in Type 304L SS under LWR operating conditions. At a 0.4%/s strain rate, the fatigue life and fatigue limit in air were higher at 300°C than at 150°C (due to secondary strain hardening at 300°C).[58] A similar behavior was observed for this heat of SS in PWR water. At 0.4%/s, fatigue life decreased in PWR water relative to that in air at 150°C, but not at 300°C. This difference was identified as secondary hardening at 300°C, which was not observed at 150°C. The secondary hardening at 300°C may be due to DSA, although the temperature was relatively low.

2.2.2.4 Crack Growth Rates in Smooth Fatigue Specimens

Studies on the formation and growth characteristics of short cracks in smooth fatigue specimens of austenitic SSs in LWR environments indicated that, although the growth rates of mechanically small cracks were greater in water than in air, the decrease in fatigue lives was caused predominantly by the effects of the environment on the growth of MSCs.[44] Figure 2-20 shows the growth of the largest crack in austenitic SSs with respect to fatigue cycles in air and water environments. In the figure, the crack length for the test in air at 288°C and 0.75% strain range was measured only near the end of the test. The data obtained by Orbtlik, et al.[207] for Type 316L SS in air at 25°C and approximately 0.2% strain range were used to estimate the crack growth in air at 0.75% strain range. Similar studies on carbon and low-alloy steels indicate[11,165-167] that the fatigue crack size at various life fractions was independent of strain range, strain rate, and temperature; consequently, the depth of the largest crack at various life fractions was approximately the same at strain ranges of 0.75% and 0.3%. The curve for the test in air at 0.75% (shown as a dashed line in Figure 2-20) was calculated from the best-fit equation of the experimental data for Type 316L SS at 0.3% strain range. As expected, at a given strain range (i.e., 0.75%), more fatigue cycles are needed to reach a specific crack depth in air than in water. Conversely, for a specific number of cycles, the crack depth is longer in high-DO (BWR) water than in air, and the crack depth in low-DO PWR water is longer than in high-DO (BWR) water (i.e., After 1,500 cycles, the crack depth in air, high-DO (BWR) water, and low-DO (PWR) water was approximately 40, 300, and 1,100 μm, respectively). The growth of cracks during the initiation stage (i.e., growth of MSCs) was enhanced in water; the fatigue cycles needed to form a 500-μm crack were a factor of approximately 12 lower in low-DO water than in air. Figure 2-20 shows that the number of cycles required to produce a 500-μm crack is 800, 3,000, and 9,000 in low-DO (PWR) water, high-DO (BWR) water, and air environments, respectively; therefore, the number of cycles was more than a factor of 10 lower in low-DO water than in air.

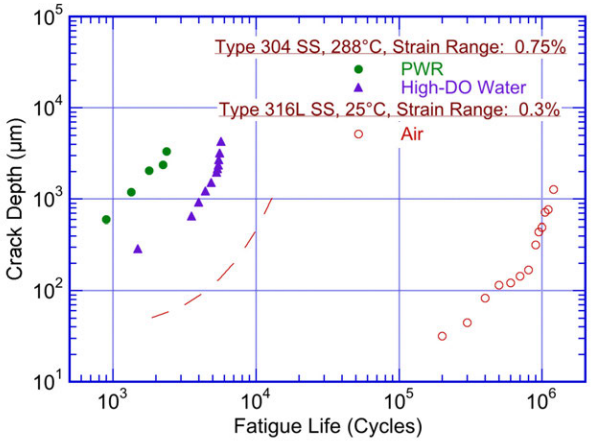
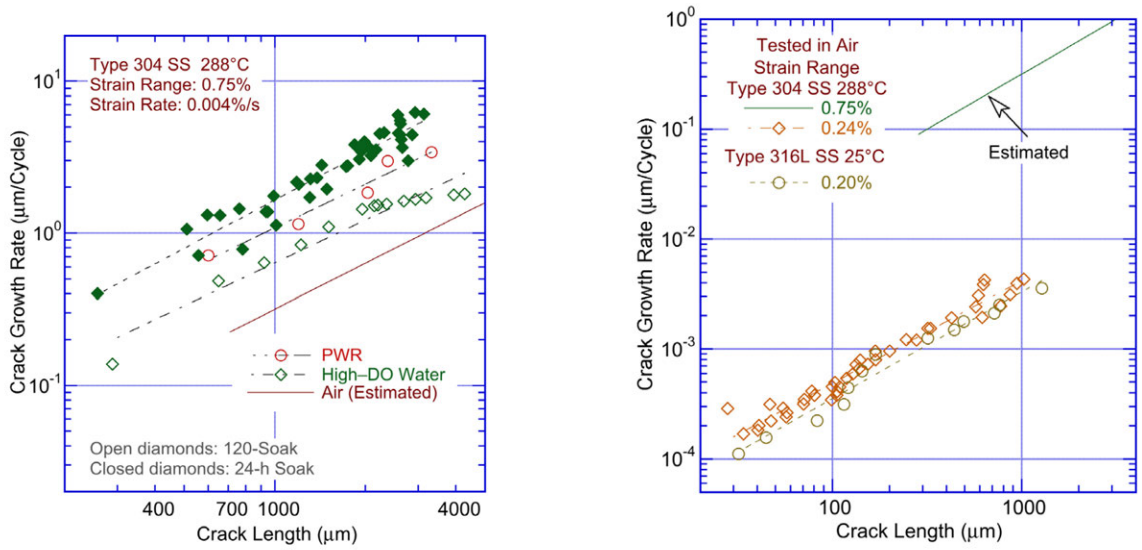


Figure 2-20 Depth of largest crack plotted as a function of fatigue cycles for austenitic SSs in air and water (Refs. 13 and 207).

Figure 2-21 plots the CGRs during the propagation stage (i.e., growth of mechanically small cracks) in air and water environments as a function of crack length; these rates were calculated from the best fit of the data in Figure 2-20. The CGRs in high-DO water for the specimen with a 24-hour soak period (closed diamonds in Figure 2-21) were determined from measurements of fatigue striations. The CGRs were a factor of 2 to 6 higher in water than in air. Growth rates in

PWR water or high-DO water with a 24-hour soak period were higher than those in high-DO water with a 120-hour soak period. At a crack length of approximately 1,000 μm, the CGRs in air, high-DO water, and low-DO water were 0.30, 0.64, and 1.05 μm/cycle, respectively. For the 0.75% strain range and 0.004%/s strain rate, these values corresponded to growth rates of approximately 1.6×10^{-9}, 3.4×10^{-9}, and 5.6×10^{-9} m/s in air, high-DO water, and low-DO water, respectively. Thus, growth rates were a factor of 3.5 greater in low-DO water than in air.



(a) (b)

Figure 2-21 Crack growth rates plotted as a function of crack length for austenitic SSs in (a) water and (b) air environments (Refs. 13, 44, and 207).

Shack and Kassner[208] reviewed fatigue crack growth (da/dN) data obtained from fracture-mechanics tests on CT specimens of wrought and cast SSs in LWR environments. The results indicate significant enhancement of CGRs in high-DO water; at CGRs of less than 10^{-10} m/s in air, the rates in BWR NWC conditions exceeded the air curve in ASME Code Section III by a factor of approximately 20 to 30. Figure 2-22(a) plots the experimental CGRs for sensitized Type 304 SS in high-DO water and those predicted in air for the same mechanical loading conditions. The fatigue CGRs in air, $\dot{a}_{air}$, (meters per second), were determined from a correlation at 288°C given by

$$\dot{a}_{air} = 3.43 \times 10^{-12}\, S(R)\, \Delta K^{3.3}/T_R, \qquad (15)$$

where the function S(R) is expressed as

$$\begin{aligned} S(R) &= 1.0 && R \le 0 \\ S(R) &= 1.0 + 1.8R && 0 < R \le 0.79 \\ S(R) &= -43.35 + 57.97R && 0.79 < R < 1.0, \end{aligned} \qquad (16)$$

and T_R is the rise time (seconds) of the loading waveform, R is the load ratio (K_{min}/K_{max}), and ΔK is $K_{max} - K_{min}$. The fatigue CGR in water [$\dot{a}_{env}$ (meters per second)] with 0.2-ppm DO

(i.e., BWR NWC) is expressed in terms of the fatigue CGR in air ($\dot{a}_{air}$) by the relationship

$$\dot{a}_{env} = \dot{a}_{air} + 4.5\times10^{-5} (\dot{a}_{air})^{0.5}. \quad (17)$$

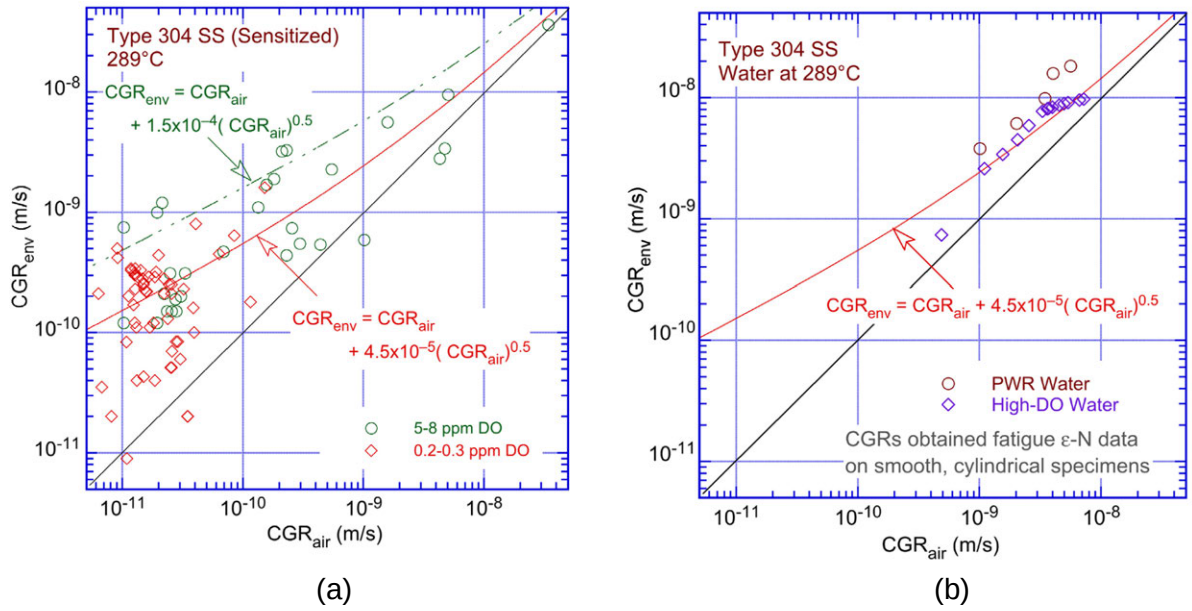


Figure 2-22 Crack growth rate data for Type 304 SS in high temperature water determined from (a) fracture mechanics CT specimens and (b) smooth cylindrical fatigue specimens (Ref. 208).

The CGR data from fracture-mechanics tests in low-DO PWR environments (Figure 2-22(b)) are sparse, particularly at rates that are less than 10^{-9} m/s. At high CGRs, the observed enhancement in both low- and high-DO environments was relatively small, and the magnitude of the enhancement under the same loading conditions was comparable in the two environments. At the time, few data were available for low CGRs in simulated PWR water. Therefore, Shack and Kassner[208] recommended that the environmental enhancement represented by Equation 17 for 0.2 ppm DO water should also be considered for PWR environments.[A]

Figure 2-22(b) plots the CGRs determined from fatigue ε–N tests on smooth, cylindrical specimens in high-DO and low-DO (PWR) water environments at 289°C. The rates in high-DO and low-DO (PWR) water represent the measured values shown as open diamonds and circles, respectively, from Figure 2-21(a). The CGRs in air for the same loading conditions (i.e., the same crack length) were determined from the estimated rates in air, shown by the solid line in Figure 2-21(a). The results from fatigue ε–N tests showed good agreement with the data obtained from the fracture–mechanics tests. The CGRs in high-DO water were consistent with the trend predicted from Equation 17. The rates in low-DO water were slightly higher.

A Since the study by Shack and Kassner was completed, American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Case 809, "Reference Fatigue Crack Growth Rate Curves for Austenitic Stainless Steels in Pressurized Water Reactor Environments," dated June 23, 2015, has been approved. ASME Code Case 809 is based on a more extensive data base than the Shack and Kassner expressions. While there are differences in the CGR parameters used in the Code Case and the Shack and Kassner expressions, these differences are not expected to affect the conclusions drawn in this section on the importance of the effects of environment on the growth of MSCs.

The large reductions in fatigue life of austenitic SSs in PWR environments cannot be explained entirely on the basis of enhanced CGRs during the propagation stage (i.e., growth of mechanically small cracks). For example, the CGRs in low-DO water are a factor of 1.6 greater than those in high-DO water, but fatigue lives are approximately a factor of 4 lower in low-DO water than in high-DO water. As indicated by the results shown in Figure 2-21(a), the decrease in fatigue lives of austenitic SSs in PWR environments was caused predominantly by the effects of environment on the growth of MSCs. Thus, the reduction in fatigue life in LWR environments relative to that in air cannot be explained on the basis of enhanced CGRs in LWR environments. In LWR environments, the growth of MSCs is increased much more than the growth of mechanically small cracks. The data in Figure 2-21(a) demonstrate that the environmental effects on the growth of cracks less than or equal to 200 μm (i.e., Stage I of crack initiation) are significantly higher than on the growth of cracks greater than 200 μm (i.e., Stage II of crack initiation).

3 FATIGUE STRAIN VS. LIFE BEHAVIOR IN AIR

During the 1990s, the Pressure Vessel Council (PVRC) Working Group on ε–N Curve and Data Analysis compiled existing strain vs. life (ε–N) fatigue data developed at various establishments and research laboratories worldwide. The database, used in the Argonne National Laboratory (ANL) studies, and presented in the original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, was an extended version of the PVRC database. The reanalysis of the fatigue ε–N data presented in this report is based on a much larger fatigue ε–N database. The additional data include the Japan Nuclear Energy Safety Organization (JNES) data summarized in JNES-SS-1005, "Environmental Fatigue Evaluation Method for Nuclear Power Plants," issued March 2011, on carbon and low-alloy steels, wrought and cast austenitic stainless steels (SSs), nickel-chromium-iron (Ni-Cr-Fe) alloys, and their associated weld metals tested in air and light-water reactor (LWR) environments.[136] Additional data was also obtained from open literature fatigue ε–N test results on several heats of carbon and low-alloy steels tested in boiling-water reactor (BWR) environments.[138-146] Nearly 60% of the data in the more recent JNES database were included in the old JNUFAD[210] database. The JNUFAD database formed a portion of the PVRC database, which was used in the original version of the NUREG/CR-6909 report.

Unless otherwise mentioned, the fatigue database was obtained from smooth cylindrical gauge specimens that were tested under strain control with fully reversed loading (i.e., strain ratio, R, of -1). Tests on notched specimens or at R values other than -1 were excluded from the fatigue ε–N data analysis performed for this report. For the previous fatigue testing performed at ANL, the estimated uncertainty in the strain measurements was about 4% of the reported values. For the data obtained in other laboratories, the uncertainty in the reported values of strain is unknown but was assumed to be small enough such that the results were not significantly impacted.

In nearly all tests, fatigue life was defined as the number of cycles necessary for the tensile stress to drop 25% from its peak or steady-state value, N_{25}. As discussed in Section 1.1, for the specimen sizes used in these studies (e.g., 5.1 to 9.5 mm (0.2 to 0.375 in.) diameter cylindrical specimens) failure corresponds to an approximately 3-mm-deep crack. Some of the earlier tests in air were carried out to complete failure of the specimens; in some other tests, fatigue lives were defined as the number of cycles for peak tensile stresses to decrease by 10 or 50%. Therefore, fatigue lives defined by a criterion other than a 25% load drop were converted to consistent N_{25} values according to the following formula:

$$N_{25} = N_X/(0.947 + 0.00212X), \tag{18}$$

where X is the failure criterion (e.g., 10, 50 or 100% decrease in peak tensile stress).[10] The estimated uncertainty in fatigue life determined by this procedure is about 2%, which is within the strain measurement uncertainty.

The 25% load-drop criterion was not used for the tests that were performed using tube specimens. For tube specimens, fatigue lives were represented by the number of cycles to develop a leak because, with the exception of a few specimens, all tube specimens had 3-mm wall thicknesses.

3.1 Carbon and Low-Alloy Steels and Weld Metals

3.1.1 Experimental Data

The primary sources of fatigue ε–N data for carbon and low-alloy steels are the tests performed by General Electric Company (GE) in a test loop at the Dresden Nuclear Power Station, Unit 1;[14,15] work sponsored by the Electric Power Research Institute (EPRI) at GE;[16,17] the work of Terrell at Materials Engineering Associates (MEA);[48-50] the work at ANL on fatigue of pressure vessel and piping steels;[10-13,40-47] the large JNES database;[136] studies at Ishikawajima-Harima Heavy Industries (IHI), Hitachi, and Mitsubishi Heavy Industries (MHI) in Japan;[18-36] and the studies at Kraftwerk Union Laboratories (KWU) and Materialprufungsanstalt (MPA) in Germany.[55,56] From these sources, the total database for fatigue tests in air comprises 684 tests—254 tests on carbon steels and 430 tests on low-alloy steels. Carbon steels include 19 heats of A106-Grs. B and C, A333-Gr. 6, A508-Gr. 1, and A333-Gr. 6 weld metals. Low-alloy steels include 22 heats of A302-Gr. B, A508-Grs. 2 and 3, and A533-Gr. B steel. Table 3-1 summarizes the sources included in the updated database used for the present analyses, as categorized by material type and test environment. Appendix B provides other material information such as chemical composition, heat treatment, and room temperature tensile properties of the various types and heats of materials.

Table 3-1 Sources of the Fatigue ε–N Data on Carbon and Low-alloy Steels in an Air Environment.

ANL Mat. ID	Material Specification	Sulfur Content (wt.%)	Test Temperature (°C)	Number of Data Points	Source	Applicable Reference
Carbon Steels						
1	A106-Gr.B	0.015	25, 288	3, 17	ANL	10
3	A106-Gr.B	0.020	25, 288	13, 12	MEA	48-50
4	A106-Gr.C (STS480)	0.006	25	5	JNES (Kanasaki)	136
-	A106-Gr.C (STS480)	0.003	25	2	JNES (Kanasaki)	136
6	A106-Gr.B (STS49)	0.007	25	9	JNES (Higuchi)	136
9	A333-Gr.6 (STS42)	0.015	25, 250, 290	13, 7, 3	JNES (Higuchi)	136
10	A333-Gr.6 (STS42)	0.014	25	7[a]	JNES (Higuchi)	136
11	A333-Gr.6	0.006	288	1	JNES (Higuchi)	136
12	A333-Gr.6 (STS410)	0.012	25, 100, 200, 288	5, 4, 4, 2	JNES (Nakao), ANL	136,10
13	A333-Gr.6	0.030	25, 288	7, 6	GE	14-17
14	A333-Gr.6 (STS410)	0.008	25, 289	24, 10	JNES (Hirano)	136
15	A333-Gr.6 (STS410)	0.016	25, 289	12, 5	JNES (Hirano)	136
18	A508-Gr.1 (SFVC2B)	0.004	25, 289	6, 5	JNES (Hirano)	136
19	A508-Gr.1[b]	0.008	25	14	JNES (PLEX)	136
24	CS	-	25, 170	10, 28	MPA	55, 56
Carbon Steel Weld Metals						
-	A336-Gr.6 (STS410)	0.001	25, 288	6, 4	JNES (Hirano)	136
-	A336-Gr.6 (STS410)	0.010	25, 289	5, 5	JNES (Hirano)	136
Low-alloy Steels						
1	A302-Gr.B	0.027	288	7	ANL	10
2	A508-Gr.2	0.003	25	9	JNES (Nakao/Higuchi)	136
6	A508-Gr. 3 (SFVV3)	0.003	25, 288	6, 14	JNES (Nagata)	136

ANL Mat. ID	Material Specification	Sulfur Content (wt.%)	Test Temperature (°C)	Number of Data Points	Source	Applicable Reference
7	A508-Gr. 3 (SFVV3)	0.002	25, 288	7, 8	JNES (Narumoto)	136
8	A508-Gr. 3 (SFVV3)	0.003	25	8	JNES (Narumoto)	136
9	A508-Gr. 3 (SFVV3)	0.005	25, 200	31, 2	JNES (Ikemoto, Iwadate, Kou, Nihei, Fukakura)	136
10	A508-Gr. 3 (SFVV3)	0.003	150, 200, 290	18, 15, 13	JNES (Kou, Fukakura, Iida)	136
11	A508-Gr. 3 (SFVV3)	0.003	25, 200, 290	11, 17, 24	JNES (Nihei, Kou, Fukakura, Iwadate,)	136
12	A508-Gr. 3 (SFVV3)	0.003	25	10	JNES (Higuchi, Endou)	136
13	A508-Gr. 3 (SFVV3)	0.008	25	8[b]	JNES (Kanasaki)	136
14	A508-Gr. 3	0.002	288	14	Wu & Katada	141
16	A533-Gr. B	0.012	25, 288	6, 16	ANL	10,11,12
17	A533-Gr. B (SQV2A)	0.007	25, 288	14, 14	JNES (Nagata), Wu & Katada	136,141
18	A533-Gr. B (SQV2A)	0.001	25, 350	34, 10	JNES (Kazuo Toyam)	136
19	A533-Gr. B (SQV2A)	0.003	25, 300	6, 6	JNES (Narumoto)	136
20	A533-Gr. B (SQV2A)	0.002	25, 286	9, 8	JNES (Narumoto)	136
21	A533-Gr. B (SQV2A)	0.010	25	18[c]	JNES (Iida)	136
22	A533-Gr. B (SQV2A)	0.008	25, 150, 200, 250, 289	19,[b] 1, 1, 1, 4	JNES (Hirano)	136
23	A533-Gr. B	0.013	288	7	Wu & Katada	143
28	A533-Gr. B	0.014	270	2	MPA	55,56
29	LAS	-	25, 170	16, 16	MPA	55,56
31	17MnMoV64	0.018	200	3	S/KWU	55,56

[a] Six tests performed under load control were excluded.

[b] Includes test results for thermally aged materials.

[c] Tests performed using a sine waveform, and data include results for thermally aged materials.

In air, the fatigue lives of both carbon and low-alloy steels depend on steel type; temperature; and, for some compositions, applied strain rate and sulfide morphology. Figure 3-1 shows fatigue ε–N data from various investigations on carbon and low-alloy steels. The plots in this figure also include the best-fit air curves based on the ANL models (i.e., Equations 24 and 25 from Section 3.1.6) and the mean–data air curves at room temperature from Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) (i.e., Equations 7 and 8 from Section 1.2). The results indicate that, although significant scatter is apparent due to material variability, the fatigue lives of these steels are comparable at less than $5x10^5$ cycles, and those of low-alloy steels are greater than carbon steels for greater than $5x10^5$ cycles. In addition, the fatigue life at 10^6 cycles of low-alloy steels is higher than that of carbon steels.

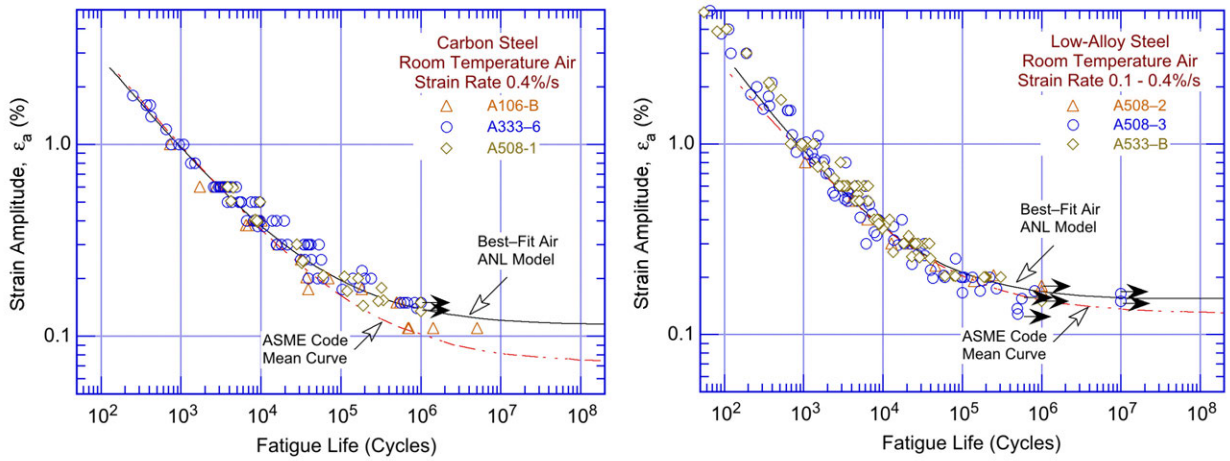


Figure 3-1 Fatigue strain vs. life data for carbon and low-alloy steels in air at room temperature (JNUFAD database and Refs. 10, 18, 19 and 48).

The results also indicate that the existing fatigue ε–N data for low-alloy steels are in good agreement with the ASME Code mean-data curve. The existing data for carbon steels are consistent with the ASME Code mean-data curve for fatigue lives below $5x10^5$ cycles, and are above the ASME Code mean-data curve at longer lives. Thus, for carbon steels above $5x10^5$ cycles, the ASME Code mean-data curve is conservative with respect to the existing fatigue ε–N data.

- *The ASME Code mean-data air curves for carbon and low-alloy steels (Equations 7 and 8) are either consistent with the existing fatigue ε–N data or are somewhat conservative under some conditions.*

3.1.2 Temperature

In air, the fatigue lives of both carbon and low-alloy steels decrease with increasing temperature; however, the effect is relatively small (less than a factor of 1.5). Figure 3-2 shows the existing fatigue ε–N data in air at 25–290°C. As discussed in Section 3.1.1 for each grade of steel, the data represent several heats of material. The solid lines in the plots represent the temperature dependence defined by Equation 22 in Section 3.1.6. The results indicate a factor of approximately 1.5 decrease in fatigue lives of both carbon and low-alloy steels as the temperature is increased from room temperature to 300°C.

- *Variations in the fatigue lives in air due to the effects of temperature for carbon and low-alloy steels were accounted for in the subfactor for "data scatter and material variability."*

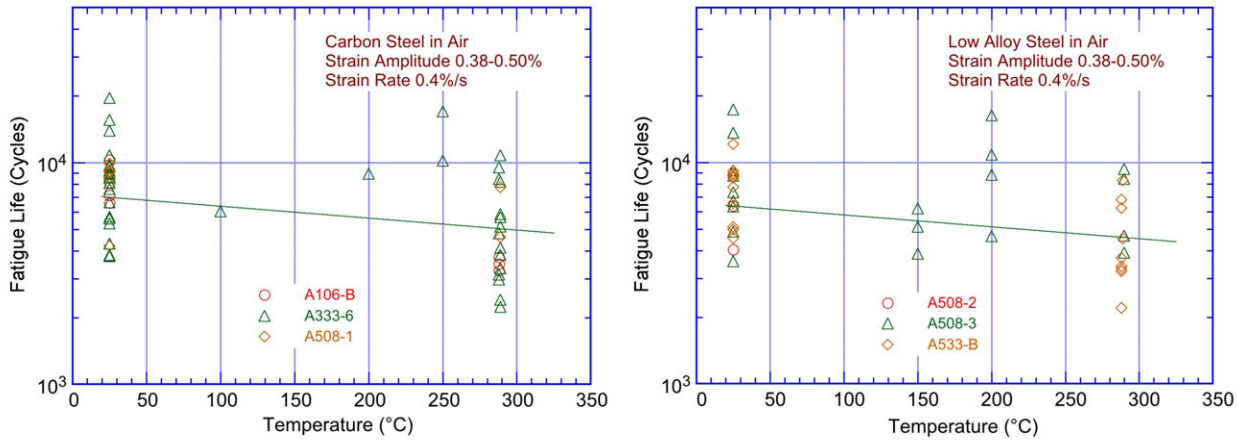


Figure 3-2 The change in fatigue lives of carbon and low-alloy steels in air as a function of temperature.

3.1.3 Strain Rate

The effect of strain rate on the fatigue lives of carbon and low-alloy steels in air appears to depend on the material composition. The existing data indicate that in the temperature range of dynamic strain aging (200–370°C), some heats of carbon and low-alloy steels were sensitive to strain rate; with decreasing strain rate, the fatigue lives in air were either unaffected,[10] decreased for some heats,[211] or increased for others.[212] The carbon and nitrogen contents in the steel are considered to have an important influence on strain rate effects. Inhomogeneous plastic deformation can result in localized plastic strains. This localization retards blunting of propagating cracks that is usually expected when plastic deformation occurs and can result in higher crack growth rates.[211] The increases in fatigue lives were attributed to retardation of CGRs due to crack branching and suppression of the plastic zone.[212] Furthermore, as discussed earlier, the formation of cracks may be enhanced in the presence of dynamic strain aging (DSA).

- *Variations in fatigue lives in air due to the effects of strain rate for carbon and low-alloy steels were accounted for in the subfactor for "data scatter and material variability."*

3.1.4 Sulfide Morphology

Some high-sulfur steels exhibit very poor fatigue properties in certain orientations because of structural factors such as the distribution and morphology of sulfides in the steel. For example, fatigue tests on a high-sulfur heat of A302–Gr. B steel in three orientations[B] in air at 288°C indicated that the fatigue life and fatigue limit in the radial (T2) orientation are lower than those in the rolling (R) and transverse (T1) orientations.[10] At low strain rates, fatigue lives in the T2 orientation were nearly one order of magnitude lower than in the R orientation. In the orientation

[B] The three orientations were represented by the direction that was perpendicular to the fracture plane. Both T1 and T2 directions were perpendicular to the R direction, but the fracture plane was across the thickness of the plate in the T1 orientation and parallel to the plate surface in the T2 orientation.

with poor fatigue resistance, crack propagation occurred preferentially along the sulfide stringers and was facilitated by sulfide cracking.

- *Variations in fatigue lives in air due to differences in sulfide morphology for carbon and low-alloy steels were accounted for in the subfactor for "data scatter and material variability."*

3.1.5 Cyclic Strain Hardening Behavior

The cyclic stress-strain response of carbon and low-alloy steels varies with steel type, temperature, and strain rate. In general, these steels show initial cyclic hardening followed by cyclic softening or a saturation stage at all strain rates. Carbon steels, with a pearlite and ferrite structure and low monotonic yield stress, exhibit significant initial hardening. Low-alloy steels, with a tempered bainite and ferrite structure and a relatively high monotonic yield stress, show little or no initial hardening and may exhibit cyclic softening with continued cycling. For both steels, the maximum stress increases as applied strain increases and generally decreases as temperature increases. However, at 200–370°C, these steels exhibited DSA, which resulted in enhanced cyclic hardening, a secondary hardening stage, and negative strain rate sensitivity.[211,212] The temperature range and extent of DSA varied with composition and structure.

Figure 3-3 shows the effects of strain rate and temperature on the cyclic stress response of A106-Gr. B carbon steel and A533–Gr. B low-alloy steel. For both steels, cyclic stresses were higher at 288°C than at room temperature. At 288°C, all steels exhibited greater cyclic and secondary hardening because of DSA. The extent of hardening increased as the applied strain rate decreased.

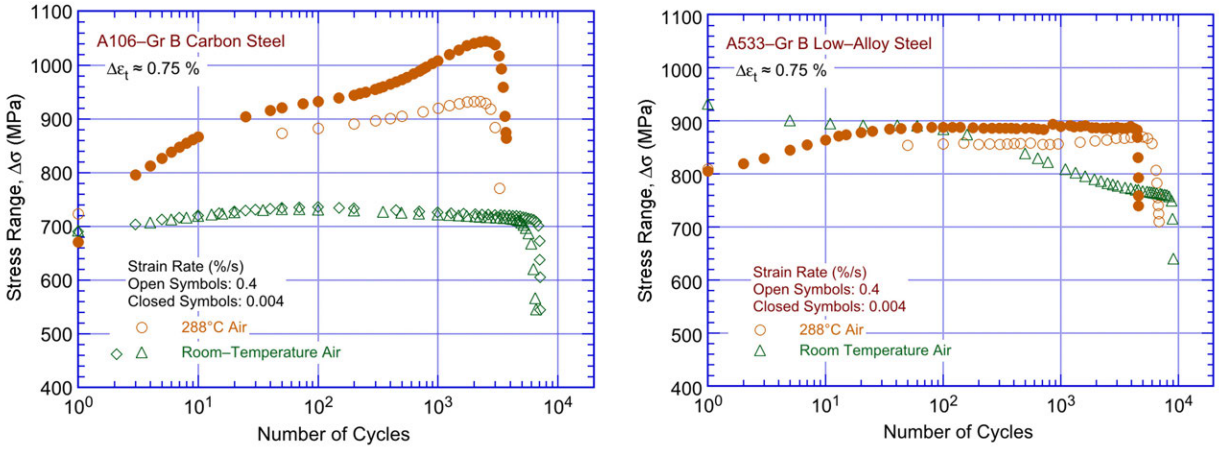


Figure 3-3 Effect of strain rate and temperature on cyclic stress of carbon and low-alloy steels.

- *Cyclic strain hardening behavior influenced the fatigue limits of materials; variations in fatigue lives in air due to the effects of strain hardening for carbon and low-alloy steels were accounted for in the subfactor for "data scatter and material variability."*

3.1.6 Fatigue Life Model

American Society for Testing and Materials Standard E739, "Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S–N) and Strain-Life (ε–N) Fatigue Data,"[4] issued May 2016, treats fatigue life, N (or the logarithm of the fatigue life), as the dependent variable, and either of the controlled variables (e.g., stress or strain) as the independent variable. The coefficients of a "linear" model are commonly established through least-squares curve-fitting of the data using fatigue life as the dependent variable. An optimization program sets the coefficients to minimize the sum of the square of the residual errors, which are the differences between the predicted and actual values of N or ln(N). However, such an approach may not adequately determine the optimum coefficients for a nonlinear expression such as the Langer curve (Equation 6), which includes a constant term, C, related to the fatigue limit. The model does not address the fact that at low strain amplitudes, most of the error in life is due to uncertainty associated with either measurement of stress or strain or variation in threshold strain caused by material variability. A predictive model based on a least-squares fit on N or ln(N) is biased for low strain amplitude (ε_a). In addition, the data obtained at strain amplitudes less than the constant C in Equation 6 (e.g., most runouts) cannot be included in the analysis. On the other hand, a least-squares fit on ε_a does not work well for higher strain amplitudes. The two kinds of models are transformations of each other, although the precise values of the coefficients differ.

In the statistical model presented in References 130 and 10, the two approaches were combined by minimizing the sum of the squared Cartesian distances from the data points to the predicted curve (Figure 3-4). For low ε_a, this is very close to optimizing the sum of squared errors in predicted ε_a; at high ε_a, this is very close to optimizing the sum of squared errors in predicted life; and at medium ε_a, this model combines both factors. Therefore, the use of this model addresses the weaknesses identified previously for the model based on residual errors alone. To perform this alternate optimization, it was necessary to normalize the x and y axes by assigning relative weights that are used in combining the error in life and strain amplitude because the x and y axes are not in comparable units. In this analysis, errors in strain amplitude (%) were weighted 20 times as heavily as errors in ln(N). A value of 20 was selected for two related reasons. First, this factor led to approximately equal weighting of low and high strain amplitude data in the least-squared error computation of model coefficients. Second, when the factor was applied to the model to generate probability curves, it yielded a standard deviation on strain amplitude comparable to that obtained from the best fit of the high-cycle fatigue data to Equation 1.[130] Because there was judgment applied in the selection of this value, a sensitivity analysis was performed that demonstrated that the coefficients of the model do not change significantly for weight factors between 10 and 25.

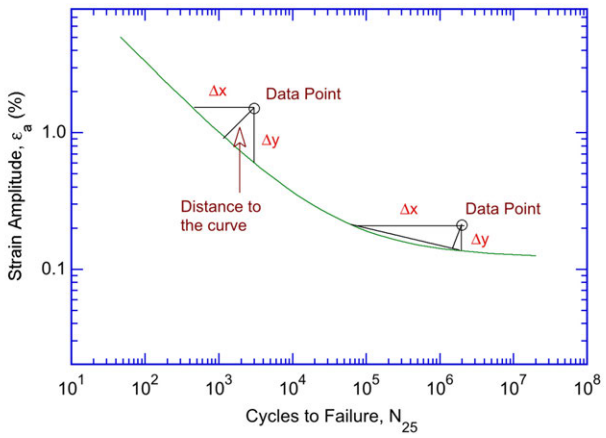


Figure 3-4 Schematic diagram of the best-fit of the experimental data by minimizing the distance between the data point and the S–N curve.

The normal distance from the best-fit curve was estimated as

$$D = \{(x-\hat{x})^2 + [k(y-\hat{y})]^2\}^{1/2}, \quad (19)$$

where $\hat{x}$ and $\hat{y}$ represent predicted values, and k = 20. Although R-squared is only applicable for linear regression, an approximate value for combined R-squared was derived for illustrative purposes. The combined R-squared was defined as

$$1 - \left(\frac{\Sigma D^2}{\Sigma Z^2}\right), \quad (20)$$

where

$$Z = \{(x-x')^2 + [k(y-y')]^2\}^{1/2} \quad (21)$$

and x' and y' represent the 25th percentile of x and y, respectively. The 25th percentile is selected instead of the mean because the mean values are exaggerated due to the nonlinearity of the equations, and because higher values are less influential to the model. The value from Equation 20 is not a true R-squared value, but often falls between the x-based R-squared and the y-based R-squared values; therefore, it is considered to be a better qualitative measure of the model's predictive accuracy because it is not distorted in the way x-based R-squared and y-based R-squared measures would be.

Fatigue life models presented in the original version of NUREG/CR-6909 for estimating the fatigue lives in air of carbon and low-alloy steels in air were developed at ANL as best fits of a Langer curve to an updated version of the PVRC database.[10,46] From those best fits, the fatigue lives, N, of carbon steels was represented by

$$\ln(N) = 6.614 - 0.00124\,T - 1.975\,\ln(\varepsilon_a - 0.113), \quad (22)$$

and that of low-alloy steels by

$$\ln(N) = 6.480 - 0.00124\,T - 1.808\,\ln(\varepsilon_a - 0.151), \quad (23)$$

where ε_a is applied strain amplitude (%), and T is the test temperature (°C). Thus, in room-temperature (25°C) air, the fatigue lives of carbon steels were expressed as

$$\ln(N) = 6.583 - 1.975 \ln(\varepsilon_a - 0.113), \quad (24)$$

and that of low-alloy steels, by

$$\ln(N) = 6.449 - 1.808 \ln(\varepsilon_a - 0.151). \quad (25)$$

Note that Equations 24 and 25 were based on incorporation of additional fatigue data and the analysis presented in Section 4.1.7 of Reference 137; the values of the constant A in the equations were updated from the values reported in NUREG/CR-6583, "Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels," issued February 1998,[10] and NUREG/CR-6815, "Review of the Margins for ASME Code Design Curves—Effects of Surface Roughness and Material Variability," issued September 2003.[46] As in these earlier analyses, the current analysis includes all reported runout data. Section 3.1.7 of this report further discusses the heat-to-heat variability of these equations. Relative to the models presented in NUREG/CR-6583, the fatigue lives predicted by the models in the original version of NUREG/CR-6909 were approximately 2% higher for carbon steel and approximately 16% lower for low-alloy steels. The predicted fatigue lives showed good agreement with the experimental values; the experimental and predicted values were within a factor of 3. Figure 3-5 shows the experimental and predicted fatigue lives of carbon and low-alloy steel data using the expressions defined by Equations 24 and 25. As discussed in Section 3.1.7, the greater-than-observed fatigue lives for A106-Gr. B steel at room temperature and for A216-Gr. WCC at 325°C appear to be due to heat-to-heat variability and not temperature effects.

- *The fatigue life models for carbon and low-alloy steels represent mean values of fatigue lives in air for specimens tested under fully reversed strain-controlled loading. The effects of parameters (such as mean stress, surface finish, size and geometry, and loading history) known to influence fatigue lives were accounted for in the several subfactors that were applied to the mean-data air curve to obtain the fatigue design air curve.*

3.1.7 Heat-to-heat Variability

Several factors, such as small differences in material composition and structure, can change the tensile and fatigue properties of materials. Sections 3.1.5 and 3.1.4 discuss the effect of interstitial element content on DSA and the effect of sulfide morphology on fatigue lives, respectively. The effect of tensile strength on fatigue lives was included in the expression for the ASME Code mean-data air curve described in the ASME Code Section III criteria document (i.e., constant A_f in Equation 2). In addition, the material fatigue limit was correlated with tensile strength (e.g., the fatigue limit increases with increasing monotonic tensile yield stress).[213]

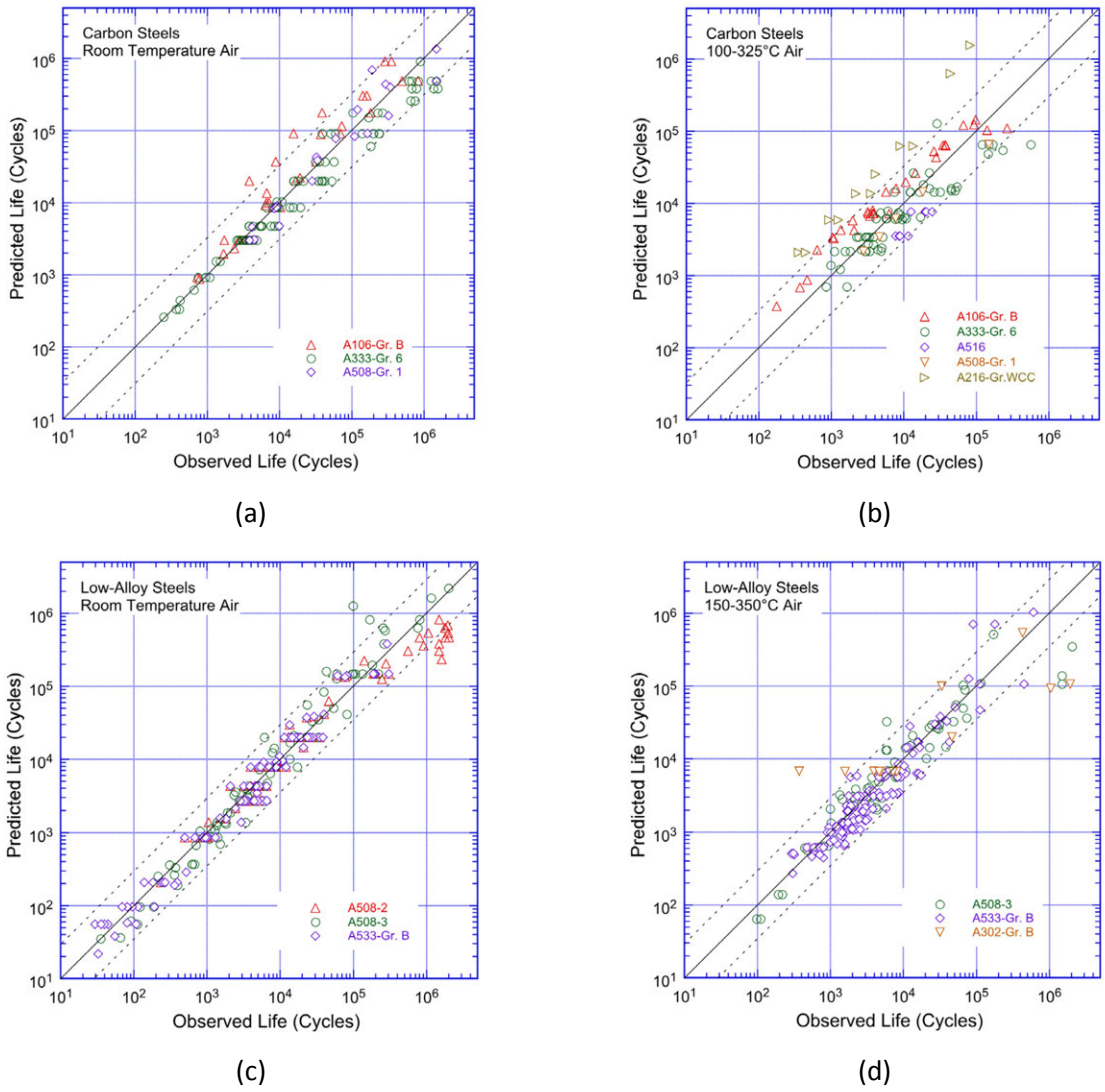


Figure 3-5 Experimental and predicted fatigue lives of (a,b) carbon steels and (c, d) low-alloy steels in air.

The effects of material variability and data scatter must be included in the data evaluation to ensure that the resulting design curves not only describe the available test data adequately but also adequately describe the fatigue lives of the much larger number of heats of material that are found in the field compared to the limited number of heats used for testing. The effects of material variability and data scatter are often evaluated by comparing the experimental data to a specific model for fatigue crack initiation (e.g., the best fit (in some sense) to the data). The adequacy of the evaluation depends on the sample of data used in the analysis. For example, if most of the data were obtained from a heat of material that has poor resistance to fatigue damage or under loading conditions that show significant environmental effects, the results may be conservative for most of the materials or service conditions of interest. Conversely, if most data are from a heat of material with a high resistance to fatigue damage, the results may be nonconservative for many heats in service.

Another method to assess the effect of material variability and data scatter is to consider the best-fit curves determined from tests on individual heats of materials or loading conditions as samples of a

much larger population of heats of materials and service conditions of interest. To do this, the fatigue behavior of each of the heats or loading conditions was characterized by the value of the constant A in Equation 6. The values of A for the various datasets were rank-ordered, and median ranks were used to estimate the cumulative distribution of A for the population.[214,215] The distributions were fit to lognormal curves. No rigorous statistical evaluation was performed for these curves, but the fits appeared reasonable and described the observed variability adequately. The data were normalized to room-temperature values using Equations 22 and 23 (Section 3.1.6). The median value of the constant A reported in the original version of NUREG/CR-6909 was 6.583 and 6.449, respectively, for the fatigue lives of carbon steels and low-alloy steels in room-temperature air. Figure 3-6 shows the estimated cumulative distributions of constant A in the ANL model for fatigue lives for heats of carbon and low-allow steels included in the original version of NUREG/CR-6909 and those included in this report.

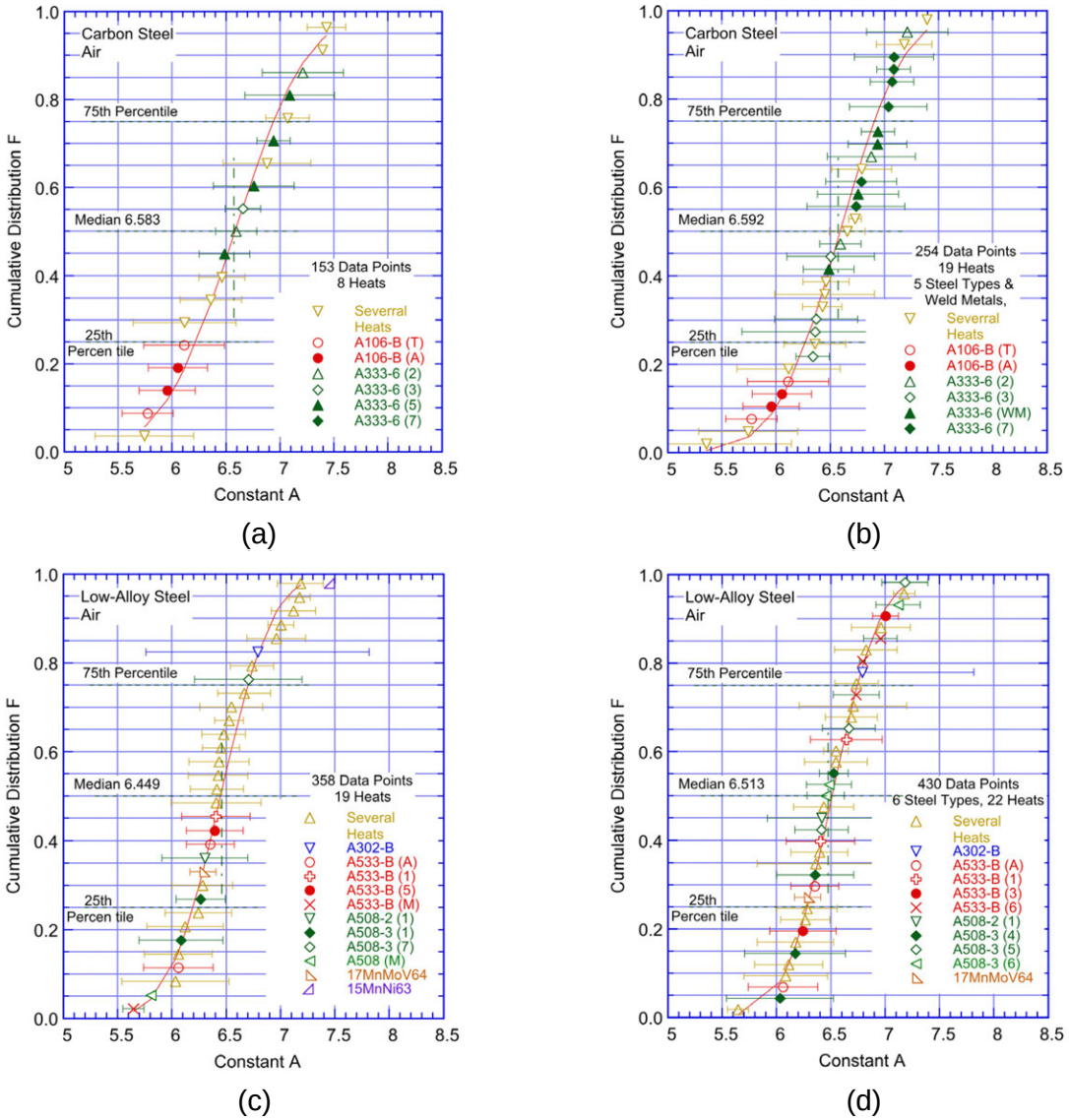


Figure 3-6 Estimated cumulative distribution of constant A in the ANL models for fatigue life data in the original version of NUREG/CR 6909 (a,c) and in this report (b,d) for heats of carbon steels (a,b) and low-alloy steels (c,d) in air.

The results indicate that the ANL fatigue models presented in the original version of NUREG/CR-6909 for predicting fatigue lives of carbon and low-alloy steels in air remain valid.

In spite of a significant increase in the number of data points, the median value of the constant A in Equation 6 did not change significantly for carbon steels (changed from 6.583 to 6.593) or for low-alloy steels (changed from 6.449 to 6.513). Note that the two heats of A106–Gr. B carbon steel were in the 10th to 25th percentile of the data (i.e., the fatigue lives of these heats were much lower than the average value for carbon steels). In addition, the average value of the constant A for the A216-Gr. WCC steel at 325°C (after adjusting for temperature effects) was 4.899, which is significantly lower than the median value of 6.583 for carbon steels. Therefore, it was not included in the reanalysis of the updated fatigue ε–N database, and Figure 3-6 does not show the value of the constant A for A216-Gr. WCC.

As discussed in the original version of NUREG/CR-6909, the A values that describe the 5th percentile of these distributions give fatigue ε–N curves that are expected to bound the fatigue lives of 95% of the heats of the materials tested. The cumulative distributions of A values in Figure 3-6 contain two potential sources of error. The means and standard deviations of the populations must be estimated from the means and standard deviations of the samples,[216] and confidence bounds must be obtained on the population means and standard deviations in terms of the sample means and standard deviations. Secondly, even these conditions did not fully address the uncertainties in the distributions because of the large uncertainties in the sample values themselves (i.e., the "horizontal" uncertainty in the actual value of A for a heat of material as indicated by the error bars in Figure 3-6). Therefore, a Monte Carlo analysis was performed to address both sources of uncertainty. The results for the median values and standard deviations of the constant A from the Monte Carlo analysis did not differ significantly from those determined directly from the experimental values.

Table 3-2 and Table 3-3 summarize the results for carbon and low-alloy steels, respectively, in terms of values for the constant A that provide bounds for the portion of the population and the confidence that is desired in the estimates of the bounds. In air, the 5th-percentile value of constant A at a 95% confidence level was 5.559 for carbon steels and 5.689 for low-alloy steels. Because the reanalysis did not change the constants significantly, the median values of the constant A for carbon and low-alloy steels were not changed in this report. Thus, constant A for the sample remains 6.583 for carbon steels and 6.449 for low-alloy steels, and the 95/95 values of the factor to account for material variability and data scatter are 2.8 and 2.1 on life for carbon and low-alloy steels, respectively. These factors provide 95% confidence that the resultant lives are greater than those observed for 95% of the materials of interest.

- *The mean-data air curves for carbon and low-alloy steels used to develop the fatigue design air curves represented the average fatigue behavior; heat-to-heat variability was included in the subfactor that was applied to the mean-data air curve to obtain the fatigue design air curve to account for "data scatter and material variability."*

Table 3-2 Values of Constant A in the ANL Fatigue Life Model for Carbon Steels in Air and the Factors on Life as a Function of Confidence Level and Percentage of the Population Bounded.

Confidence	Percentage of Population Bounded (Percentile Distribution of A)				
Level	95 (5)	90 (10)	75 (25)	67 (33)	50 (50)
			Values of Constant A		
50	5.798	5.971	6.261	6.373	6.583
75	5.700	5.883	6.183	6.295	6.500
95	5.559	5.756	6.069	6.183	6.381
			Factors on Life		
50	2.2	1.8	1.4	1.2	1.0
75	2.4	2.0	1.5	1.3	1.1
95	2.8	2.3	1.7	1.5	1.2

Table 3-3 Values of Constant A in the ANL Fatigue Life Model for Low-Alloy Steels in Air and the Factors on Life as a Function of Confidence Level and Percentage of the Population Bounded.

Confidence	Percentage of Population Bounded (Percentile Distribution of A)				
Level	95 (5)	90 (10)	75 (25)	67 (33)	50 (50)
			Values of Constant A		
50	5.832	5.968	6.196	6.284	6.449
75	5.774	5.916	6.150	6.239	6.403
95	5.689	5.840	6.085	6.175	6.337
			Factors on Life		
50	1.9	1.6	1.3	1.2	1.0
75	2.0	1.7	1.3	1.2	1.0
95	2.1	1.8	1.4	1.3	1.1

3.1.8 Fatigue ε–N Behavior of Weld Metals

Figure 3-7 plots available fatigue ε–N data for carbon and low-alloy steel weld metals in air at room temperature and 289°C. The results indicated that, in air, the fatigue lives of carbon and low-alloy steel weld metals were slightly lower than the mean ε–N behavior of nonwelded carbon or low-alloy steel test specimens. Except for one data set for CM-US-56B/MF-27 weld metal for which fatigue lives were a factor two lower than the mean-data curves, the fatigue lives of the other datasets were marginally lower. The results also indicated that the fatigue lives at 289°C were slightly lower than at room temperature. Despite these observations, the available fatigue ε–N data for carbon and low-alloy steel weld metals were insufficient to accurately establish their fatigue behavior relative to the mean-data air curve for carbon steels or low-alloy steels, respectively.

- *Until additional fatigue ε–N data for carbon and low-alloy steel weld metals are available, the fatigue mean air curves for carbon steel or low-alloy steels may also be used for weld metals.*

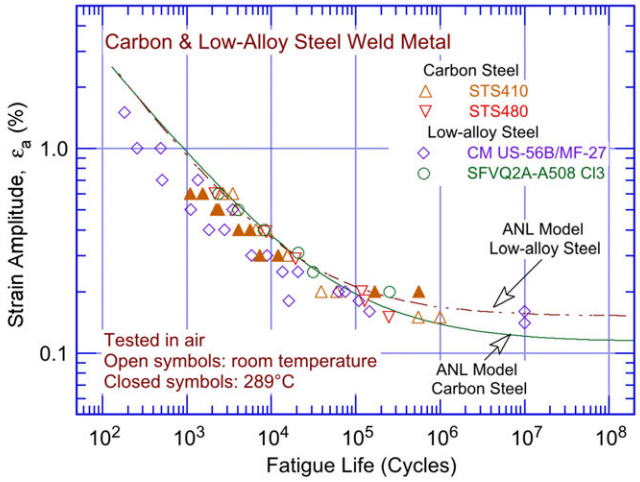


Figure 3-7 Fatigue ε–N behavior for carbon and low-alloy steel weld metals in air at room temperature and 289°C (Ref. 136).

3.1.9 Surface Finish

The effect of surface finish was considered to account for the difference in fatigue lives expected in an actual component with an industrial-grade surface finish compared to the smooth, polished surface of test specimens. Fatigue lives are sensitive to surface finish; cracks can initiate at surface irregularities that are normal to the axis of applied stress. The height, spacing, shape, and distribution of surface irregularities are important for crack initiation. The most common measure of roughness is average surface roughness, R_a, which is a measure of the height of the irregularities. Investigations of the effects of surface roughness on the low-cycle fatigue of Type 304 SS in air at 593°C indicated that fatigue lives decreased as surface roughness increased.[217,218] The effect of roughness on crack initiation, $N_i(R)$, is given by

$$N_i(R) = 1012\ R_q^{-0.21}, \tag{26}$$

where the root-mean-square (RMS) value of the average surface roughness, R_q, is in micrometers. Typical values of R_a for surfaces finished by different metalworking processes in the automotive industry[219] indicated that a value of R_a of 3 μm (or an R_q of 4 μm) represented the maximum surface roughness for drawing/extrusion, grinding, honing, and polishing processes, and a mean value for the roughness range for milling or turning processes. For carbon or low-alloy steels, an R_q of 4 μm in Equation 26 would decrease fatigue life by a factor of 3.7 (i.e., the R_q of a smooth polished specimen is approximately 0.0075 μm).[217]

A fatigue test was conducted on an A106–Gr. B carbon steel specimen that was intentionally roughened in a lathe under controlled conditions with 50-grit sandpaper to produce circumferential scratches with an average roughness of 1.2 μm and an R_q of 1.6 μm (approximately 62 μin.).[46] Figure 3-8 shows the results for smooth and roughened specimens. In air, the fatigue life of a roughened A106–Gr. B specimen was a factor of approximately 3 lower than that of smooth specimens. Another study of the effect of surface finish on the fatigue lives of carbon steels in room–temperature air showed a factor of 2 decrease in life when R_a was increased from 0.3 to 5.3 μm.[220] These results are consistent with Equation 26. Thus, a

factor of 2 to 3 on cycles is necessary to account for surface finish effects on the fatigue lives of carbon and low-alloy steels.

- *The effect of surface finish was included as part of the "surface finish and environment" subfactor that was applied to the mean-data air curves to obtain the fatigue design air curves for carbon and low-alloy steels.*

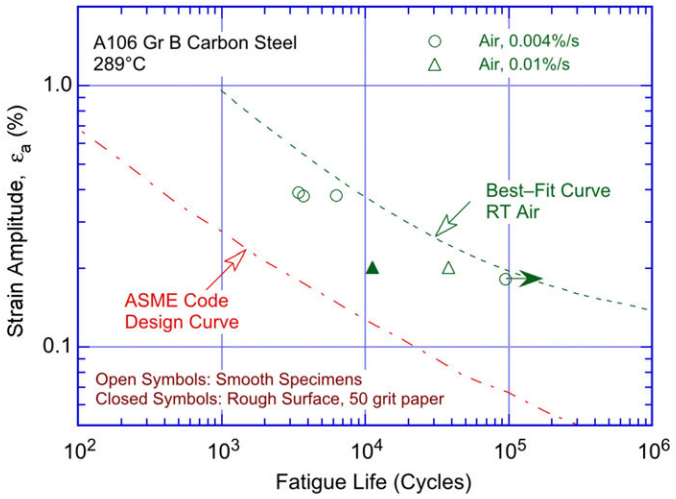


Figure 3-8 Effect of surface finish on the fatigue life of A106–Gr. B carbon steel in air at 289°C (Ref. 46).

3.1.10 Extension of the Best-Fit Mean Curve from 10^6 to 10^{11} Cycles

The experimental fatigue ε–N air curves that were used to develop the fatigue design air curve for carbon and low-alloy steels in the 2011 Addenda of ASME Code Section III were based on low-cycle fatigue data (less than $2x10^5$ cycles). The design air curves proposed in this report were developed from a larger database that included fatigue lives up to 10^8 cycles. Both the ASME Code mean air curves and the ANL models in this report used the modified Langer equation to express the best-fit mean air curves; they are not recommended for estimating fatigue lives beyond the range of the experimental data (i.e., in the high-cycle fatigue regime).

An extension of the current high-cycle fatigue design curves in Section III and Section VIII of Division 2 of the ASME Code for carbon and low-alloy steels from 10^6 to 10^{11} cycles was proposed by O'Donnell to the ASME Section III Subgroup on Fatigue Strength.[C] In the

high-cycle regime at temperatures not exceeding 371°C (700°F), the stress amplitude (S_a) vs. life relationship is expressed as

$$S_a = E\varepsilon_a = C_1 N^{-0.05}, \quad (27)$$

where ε_a is applied strain amplitude, E is the elastic modulus, N is the fatigue life, and C_1 is a constant. A fatigue life exponent of -0.05 was selected based on the fatigue stress range vs.

[C] W.J. O'Donnell, "Proposed Extension of ASME Code Fatigue Design Curves for Carbon and Low-Alloy Steels from 10^6 to 10^{11} Cycles for Temperatures Not Exceeding 700°F," was presented to the ASME Subgroup on Fatigue Strength on December 4, 1996.

fatigue life data on plain plates, notched plates, and typical welded structures given in Welding Research Council (WRC) Bulletin 398, "Reduction of S–N Curves for Ship Structural Details," issued January 1995.[221] Because the data were obtained from load-controlled tests with an R ratio of zero, they take into account the effect of maximum mean stresses and may overestimate the effect of mean stress under strain-controlled loading conditions. In addition, the fatigue data presented in WRC Bulletin 398 extend only up to 5×10^6 cycles; extrapolation of the results to 10^{11} cycles using a fatigue life exponent of -0.05 may yield overly conservative estimates of fatigue life. Finally, ASME received feedback from the evaluation of plant trouble reports, laboratory tests of socket welded joints, and plant operating experience that supported its use of Equation 27.

Manjoine and Johnson[213] developed fatigue design curves up to 10^{11} cycles for carbon steels and austenitic SSs from inelastic and elastic strain relationships, which were correlated with ultimate tensile strength. The log-log plots of the elastic strain amplitudes vs. fatigue life data were represented by a bilinear curve. In the high-cycle regime, the elastic strain vs. life curve had a small negative slope instead of a fatigue limit.[213] For carbon steel data at room temperature and 371°C (700°F) and fatigue lives extending up to 4×10^7 cycles, Manjoine and Johnson obtained an exponent of -0.01. The fatigue ε–N data used in this report at room temperature and with fatigue lives up to 10^8 cycles yielded a fatigue life exponent of approximately -0.007 for both carbon and low-alloy steels. Because the data are limited, the more conservative exponent value (i.e., -0.01) obtained by Manjoine and Johnson[213] was used in the original version of NUREG/CR-6909. In the high-cycle regime, the applied stress amplitude was expressed by the relationship

$$S_a = E\varepsilon_a = C_2 N^{-0.01}. \quad (28)$$

In the original version of NUREG/CR-6909, Equation 28 was used to extend the best-fit mean air curves beyond 10^6 cycles (in the high-cycle regime); therefore, the mean stress-life curves exhibited a small negative slope instead of the fatigue limit predicted by the modified Langer equation. The selection of a smaller value for the fatigue life exponent to extend the best-fit curve was based on evaluation of thermal fatigue data, which are bounded by Equation 28. However, the high-cycle thermal fatigue data are limited, and the data do not consider mechanical fatigue (i.e., vibration).

As discussed earlier in this report, the classical fatigue limit for ferrous alloys is a consequence of performing fatigue tests at constant cyclic stress or strain range and determining the threshold range below which cracks cannot propagate beyond microstructural barriers and fatigue failures do not occur. Miller and O'Donnell[222] discussed the causes that lead to elimination of the fatigue limit, including the introduction of transitory cyclic processes or time-dependent mechanisms that permit a previously nonpropagating crack to grow across microstructural barriers. The authors argued that the most probable significant condition for engineering plants designed to last beyond 10^6 cycles is the introduction of very low cyclic stress vibrations at high mean stress levels, with or without other mechanisms such as corrosion or time-dependent mechanisms. Therefore, in this report, to better accommodate the vibration data (e.g., Ref. 221), the extension of the fatigue stress or strain-life curves beyond 10^6 cycles is based on the more conservative Equation 27 rather than Equation 28 (i.e., an exponent of -0.05 is used). The value of constant C_1 was determined from the value of strain amplitude at which the slope of the curve expressed by Equation 27 is the same as that of the fatigue ε–N curve expressed by Equation 24 for carbon steels or Equation 25 for low-alloy steels.

- *The fatigue design air curves for carbon and low-alloy steels were extended beyond 10^6 cycles using Equation 27, which is consistent with the methodology used to*

develop the fatigue design air curve for carbon and low-alloy steels in the 2011 Addenda of ASME Code Section III.

3.1.11 Fatigue Design Curves

Although the two equations for the ASME Code mean air curves for carbon and low-alloy steels (i.e., Equations 7 and 8) are significantly different (because the mean stress correction is much larger for the low-alloy steels), the differences between the curves are much smaller when mean stress corrections are considered. Thus, ASME Code Section III provides one common fatigue design air curve for both carbon and low-alloy steels. The ASME Code fatigue design air curves for carbon and low-alloy steels were obtained from the best-fit curves in air (i.e., Equations 7 and 8, respectively) by first correcting for mean stress effects by using the modified Goodman relationship, followed by reducing the mean stress adjusted curves by factors of 2 on stress or 20 on cycles, whichever was more conservative. The discussions presented in Section 7.5 of the original version of NUREG/CR-6909 indicated that the current ASME Code requirement of a factor of 20 on cycles to account for the effects of material variability and data scatter, specimen size, surface finish, and loading history was conservative by at least a factor of 1.7 for these steels. To reduce this conservatism, separate fatigue design air curves based on the ANL models for carbon and low-alloy steels were developed using factors of 12 on life and 2 on stress. Figure 3-9 shows the fatigue design air curves developed following this approach for carbon and low-alloy steels. The difference between the design air curves based on the ANL models and the ASME Code design air curve is due to the difference in the factor on life used to obtain these curves (i.e., 20 for the ASME Code curve and 12 for the ANL curves). In addition, for the carbon steel design air curve, the conservatism in the high-cycle regime was corrected in the ANL models.

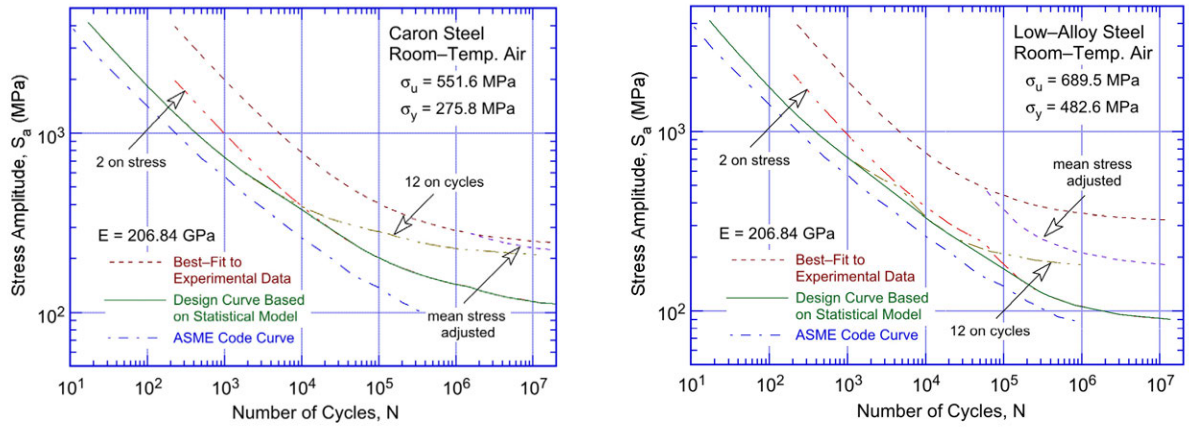


Figure 3-9 Fatigue design curves based on the ANL model for (a) carbon steels and (b) low-alloy steels in air.

The ASME Code fatigue design air curve for carbon and low-alloy steels with ultimate tensile strength (UTS) less than 552 MPa (80 ksi) included an extension of the design curve to 10^{11} cycles, which was proposed by O'Donnell and was based on Equation 27 in this report. In the original version of NUREG/CR-6909, the fatigue design air curves developed based on the ANL fatigue ε–N models were extended in the high-cycle regime beyond 10^6 cycles using Equation 28 instead of Equation 27. However, as discussed in Section 3.1.10, and to better

accommodate the field vibration data, the extension of the fatigue design curves beyond 10^6 cycles is based on Equation 27. Table 3-4 lists the values of stress amplitude (S_a) vs. cycles for the ASME Code Section III fatigue design air curve with O'Donnell's extension, and the design curve based on Equation 27 with either the ANL fatigue life models from Equation 24 for carbon steels or Equation 25 for low-alloy steels. Figure 3-10 and Figure 3-11 show the corresponding fatigue design air curves for carbon and low-alloy steels, respectively. For comparison, Table 3-5 presents the values of stress amplitude vs. cycles from the original version of NUREG/CR-6909 for the fatigue design air curves based on the ANL fatigue ε–N models and Equation 28.

- *Separate fatigue design air curves were developed for carbon and low-alloy steels from the ANL models using factors of 12 on life and 2 on stress. The results indicated that the ASME Code Section III fatigue design air curve for carbon and low-alloy steels for ultimate tensile strengths less than 552 MPa (80 ksi) was conservative with respect to the existing fatigue ε–N data, particularly for carbon steels. In this report, the extension of the fatigue design air curves beyond 10^6 cycles was based on Equation 27 instead of Equation 28 as in the original version of NUREG/CR-6909.*

Table 3-4 Fatigue Design Curves for Carbon and Low-Alloy Steels Including the Proposed Updated Extension to 10^{11} Cycles.

	Stress Amplitude (MPa/ksi)				Stress Amplitude (MPa/ksi)		
Cycles	ASME Code Curve	Eqs. 24 & 27 Carbon Steel	Eqs. 25 & 27 Low-alloy Steel	Cycles	ASME Code Curve	Eqs. 24 & 27 Carbon Steel	Eqs. 25 & 27 Low-alloy Steel
1 E+01	3999 (580)	5355 (777)	5467 (793)	2 E+05	114 (16.5)	176 (25.5)	141 (20.5)
2 E+01	2827 (410)	3830 (556)	3880 (563)	5 E+05	93.1 (13.5)	154 (22.3)	116 (16.8)
5 E+01	1896 (275)	2510 (364)	2438 (354)	1 E+06	86.2 (12.5)	142 (20.6)	106 (15.4)
1 E+02	1413 (205)	1820 (264)	1760 (255)	2 E+06		130 (18.9)	98 (14.2)
2 E+02	1069 (155)	1355 (197)	1300 (189)	5 E+06		120 (17.4)	94 (13.6)
5 E+02	724 (105)	935 (136)	900 (131)	1 E+07	76.8 (11.1)	115 (16.7)	91 (13.2)
1 E+03	572 (83)	733 (106)	720 (104)	2 E+07		110 (16.0)	88 (12.7)
2 E+03	441 (64)	584 (84.7)	576 (83.5)	5 E+07		105 (15.2)	84 (12.2)
5 E+03	331 (48)	451 (65.4)	432 (62.7)	1 E+08	68.5 (9.9)	101 (14.7)	81 (11.8)
1 E+04	262 (38)	373 (54.1)	342 (49.6)	1 E+09	61.1 (8.8)	90 (13.1)	72.3 (10.5)
2 E+04	214 (31)	305 (44.2)	276 (40.0)	1 E+010	54.4 (7.9)	81 (11.7)	64.4 (9.3)
5 E+04	159 (23)	238 (34.5)	210 (30.5)	1 E+011	48.5 (7.0)	72 (10.4)	57.4 (8.3)
1 E+05	138 (20.0)	201 (29.2)	172 (24.9)				

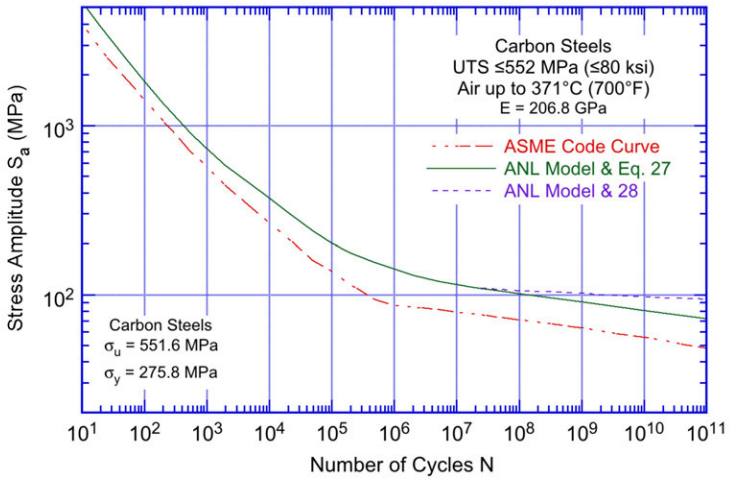


Figure 3-10 Fatigue design curve for carbon steels in air (The curve developed from the ANL model is based on factors of 12 on life and 2 on stress).

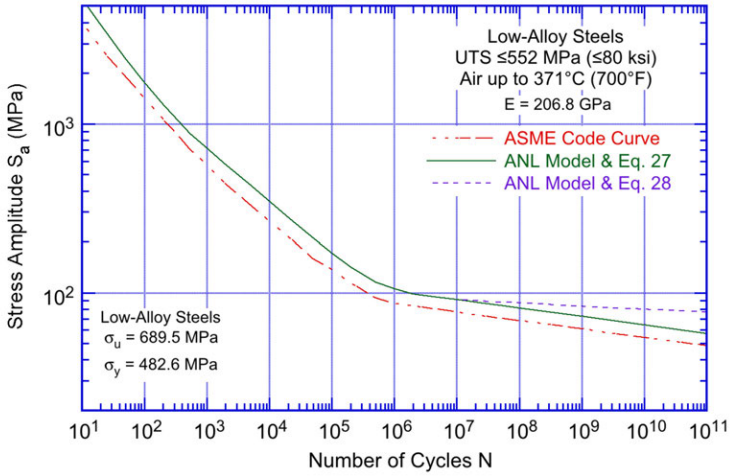


Figure 3-11 Fatigue design curve for low-alloy steels in air (The curve developed from the ANL model is based on factors of 12 on life and 2 on stress).

Table 3-5 Fatigue Design Curves for Carbon and Low-Alloy Steels and the Extension to 10^{11} Cycles Proposed in the Original Version of NUREG/CR 6909.

	Stress Amplitude (MPa/ksi)				Stress Amplitude (MPa/ksi)		
Cycles	ASME Code Curve	Eqs. 24 & 28 Carbon Steel	Eqs. 25 & 28 Low-alloy Steel	Cycles	ASME Code Curve	Eqs. 24 & 28 Carbon Steel	Eqs. 25 & 28 Low-alloy Steel
1 E+01	3999 (580)	5355 (777)	5467 (793)	2 E+05	114 (16.5)	176 (25.5)	141 (20.5)
2 E+01	2827 (410)	3830 (556)	3880 (563)	5 E+05	93 (13.5)	154 (22.3)	116 (16.8)
5 E+01	1896 (275)	2510 (364)	2438 (354)	1 E+06	86 (12.5)	142 (20.6)	106 (15.4)
1 E+02	1413 (205)	1820 (264)	1760 (255)	2 E+06		130 (18.9)	98 (14.2)
2 E+02	1069 (155)	1355 (197)	1300 (189)	5 E+06		120 (17.4)	94 (13.6)
5 E+02	724 (105)	935 (136)	900 (131)	1 E+07	76.5 (11.1)	115 (16.7)	91 (13.2)
1 E+03	572 (83)	733 (106)	720 (104)	2 E+07		110 (16.0)	90 (13.1)
2 E+03	441 (64)	584 (84.7)	576 (83.5)	5 E+07		107 (15.5)	88 (12.8)
5 E+03	331 (48)	451 (65.4)	432 (62.7)	1 E+08	68.3 (9.9)	105 (15.2)	87 (12.6)
1 E+04	262 (38)	373 (54.1)	342 (49.6)	1 E+09	60.7 (8.8)	102 (14.8)	83 (12.0)
2 E+04	214 (31)	305 (44.2)	276 (40.0)	1 E+010	54.5 (7.9)	97 (14.1)	80 (11.6)
5 E+04	159 (23)	238 (34.5)	210 (30.5)	1 E+011	48.3 (7.0)	94 (13.6)	77 (11.2)
1 E+05	138 (20.0)	201 (29.2)	172 (24.9)				

3.2 Wrought and Cast Austenitic Stainless Steels and Weld Metals

3.2.1 Experimental Data

The relevant fatigue ε–N data used to evaluate wrought and cast austenitic SSs in air include the large JNES database;[136] data developed at ANL[45] and GE;[14,15] results of Keller;[63] and the data[64,65,70,73] compiled by Jaske and O'Donnell[61] for developing fatigue design criteria for pressure vessel alloys. The database comprises 770 tests from which 622 data points were obtained—332 tests (267 data points) on Type 304 SS, 315 tests (244 data points) on Type 316 SS, 96 tests (77 data points) on SS weld metals (i.e., 34 tests (23 data points) on Type 304 SS weld metals and 62 tests (54 data points) on Type 316 SS weld metals), and 37 tests (34 data points) for CF-8M grade of cast austenitic SSs. Both low-carbon and high-carbon grades of Types 304 and 316 SS are included in the database. Out of these, 432 data points were obtained at room temperature, 7 data points were obtained at 100–200°C, and 183 data points were obtained at 250–325°C. Another 70 data points obtained at temperatures of 400°C and above were not included in the present reanalysis to verify the fatigue ε–N expression for austenitic SSs in air because they were outside of the temperature range experienced in LWRs. As discussed in Section 3.2.4, the fatigue ε–N data for austenitic SSs shows some temperature dependence above 460°C. Table 3-6 summarizes the points included in the updated database used for the present analyses, as categorized by material type and test environment. Appendix B presents other material information such as chemical composition, heat treatment, and room temperature tensile properties of the various types and heats of materials. Please note that grades of austenitic SSs that have better fatigue resistance, particularly the titanium- or niobium-modified SSs, were not considered in the analysis. Fatigue lives for such alloys are expected to be greater than the proposed fatigue design curve.

Table 3-6 Sources of the Fatigue ε–N Data on Wrought and Cast Austenitic SSs in an Air Environment.

ANL Mat. ID	Material Heat Designation[a]	Carbon Content (wt.%)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
Type 304 Stainless Steels						
1	304-1	0.050	288	10	JNES (Tokimasa)	136
2	304-30, 31	0.050	25	10, 4	JNES (Yamanaka),	136
3	304-3H	0.060	25	8	JNES (Enomoto),	136
4	304-4B	0.050	25	10	JNES (Kitigawa)	136
5	304-5B	0.060	25	3	JNES (Sakamoto)	136
6	304-6B	0.060	25	11	JNES (Tsunenari)	136
7	304-7B	0.059	25	10	JNES (Kasahara)	136
8	304-8B	0.060	25	6	JNES (Ichihara)	136
10	304-10, 10H	0.060	25, 300, 100	2, 7, 2	JNES (Usami)	136
11	304-11H	0.070	25	7	JNES (Yamanaka)	136
12	304-12	-	25	11	JNES (Nishijima)	136
13	304-13	0.026	21	10	Jaske & O'Donnell	64
14	304-14	0.026	21	9	Jaske & O'Donnell	64
15	304-15	-	21	6	Jaske & O'Donnell	63
16	304-16	0.060	21	8	Jaske & O'Donnell	70
17	304-17	-	21	6	Jaske & O'Donnell	65
18	304-18	0.020	27	8	Jaske & O'Donnell	73
20	304-G	0.060	25, 260	9, 9[b]	GE	14,15
21	304-A2	0.060	288	4	ANL	45
22	304-21, 21T	0.060	25, 325	2, 7	JNES (Kanasaki, Tsutsumi)	136
23	304-32	0.070	300	3	JNES (Endo)	136
24	304-35	0.070	25, 289	8,[c] 5	JNES (Hirano)	136
26	304HP-1	0.050	25	6	JNES (Nishijima)	136
27	304HP-2	0.060	25	17,[c] 14[c,d]	JNES (Nishijima)	136
28	304L-E	0.039	150,300	5, 11	Solomon	58-60
29	304L-1	0.017	25	5	JNES (Hirano)	136
30	304L-G	0.022	260	7	GE	14,15
31	304L	0.013	25	9	JNES (Suzuki)	136
Type 316 Stainless Steels						
32	316-1H	0.055	25, 290	7, 8	JNUFAD (Tokimasa)	210
33	316-2	0.050	25	6	JNES (Kaneo)	136
34	316-3H	0.040	25	6	JNES (Ikemoto)	136
35	316-4	0.060	21	4	Jaske & O'Donnell	63
38	316-7	-	21	8	Jaske & O'Donnell	61
39	316-8	-	22	3	Jaske & O'Donnell	61
40	316-9	-	21	5	Jaske & O'Donnell	61
41	316-10	-	21	4	Jaske & O'Donnell	61
42	316-12T, 25T	0.060	325, 25	7, 5	JNES (Kanasaki, Tsutsumi)	136
45	316-25, -25, -27T	0.040, 0.060	25, 325, 25	4, 6, 6	JNES (EFT, PLEX)	136
46	316-26T	0.057	25	10[e]	JNES (EFT)	136
47	316-1H, 316L-1H	0.055, 0.015	25, 290	7, 7	JNES (Tokimasa)	136

ANL Mat. ID	Material Heat Designation[a]	Carbon Content (wt.%)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
48	316N-1	0.010	25, 288	25[b], 18[b]	JNES (Yamauchi, Matsuno, Tokimasa)	136
50	316N-3H	0.012	25, 290	7, 7	JNES (Tokimasa)	136
51	316N-6	0.007	25	12	JNES (Higuchi)	136
52	316N-7	0.008	25, 290	25, 14	JNES (Utsunomiya, Nagata, Higuchi, Kanasaka, Ogawa)	136
53	316N-8	0.011	25, 289	5, 8	JNES (Hirano)	136
54	316N-A	0.013	22, 288, 320	12, 6, 3	ANL	45
Stainless Steel Weld Metals						
55	304HP-WM-1	0.058	25	7[d], 10	JNES (Nishijima)	136
56	304-WM-2	0.034	25	6	JNES (Kanasaki)	136
57	316-WM	0.020	25	6[f]	JNES (EFT)	136
58	316N-WM-1	0.018	25, 290	13, 11	JNES (Ogawa, Nagata)	136
59	316N-WM-2	0.017	25, 289	10, 7	JNES (Hirano)	136
60	316N-WM-3	0.002	25	7	JNES (Kanasaki)	136
Cast Austenitic Stainless Steels						
61	CF–8M-1	0.053	325	12	JNES (Tsutsumi)	136
62	CF–8M-2	0.050	25	10	JNES (Hirano)	136
63	CF–8M-3	0.050	25	6	JNES (Kanasaki)	136
68	CF–8M-8	0.064	288	5[b]	ANL	45
69	CF–8M-9	0.065	288	1[b]	ANL	45

[a] The last letter at the end of the material heat designation refers to the following: H = hourglass specimens, T = tube specimens, and B = bending tests.

[b] This data point Includes thermally aged specimens.

[c] Half of the tests were performed on hourglass specimens.

[d] Tests were performed in axial load-control using a sinusoidal waveform.

[e] Five tests each were performed on solid cylindrical specimens and tube specimens.

[f] Tests were performed on tube specimens.

Figure 3-12 shows the fatigue ε–N data for Types 304, 304L, 316, and 316NG SSs in air at temperatures between room temperature and 400°C. The plots in this figure include the best–fit air curve based on the updated ANL fatigue life model (Equation 29 in Section 3.2.6) and the mean-data air curve from ASME Code Section III before publication of the 2009 Addenda. The results indicated that the fatigue lives of Types 304, 304L, and 316 SS are comparable and generally show good agreement with the ANL model with respect to the mean-data air curve. The fatigue lives of Type 316NG are slightly higher than those for Types 304, 304L, and 316 SS at high strain amplitudes.

A few heats of Type 304L and 316NG show poor agreement with the ANL best-fit curve. Typically, for such heats, the slope of the fatigue ε–N curve is steeper; therefore, fatigue lives are slightly longer at high strain amplitudes and lower at low strain amplitudes. This behavior is also observed in PWR environments, as shown in Figure 4-28 and Figure 4-30 in Section 4.2.1. Because the methodology is applicable to several grades, heat-treatments, and compositions of materials, a single slope of the fatigue ε–N curve is assumed for all materials.

However, all of the data are evenly distributed within the scatter band along the ANL mean air curve for austenitic SSs. Some of the tests on Type 316 SS in room–temperature air were conducted in load-control mode at stress levels in the range of 190–230 MPa. The data are

shown as triangles in Figure 3-12, with strain amplitudes of 0.1 to 0.12% and fatigue lives in the range of $7x10^4$ to $3x10^7$ cycles. For these tests, the strain amplitude was calculated only as elastic strain rather than also including the portion of the strain from plastic loading. When plastic strain was considered, based on cyclic stress vs. strain correlations for Type 316 SS,[45] actual strain amplitudes for these tests ranged from 0.23 to 0.32%. Therefore, these results were excluded from the analysis of the fatigue ε–N data to develop the model for estimating the fatigue lives of these steels in air to ensure that an inconsistent bias would not be interjected in the evaluation.

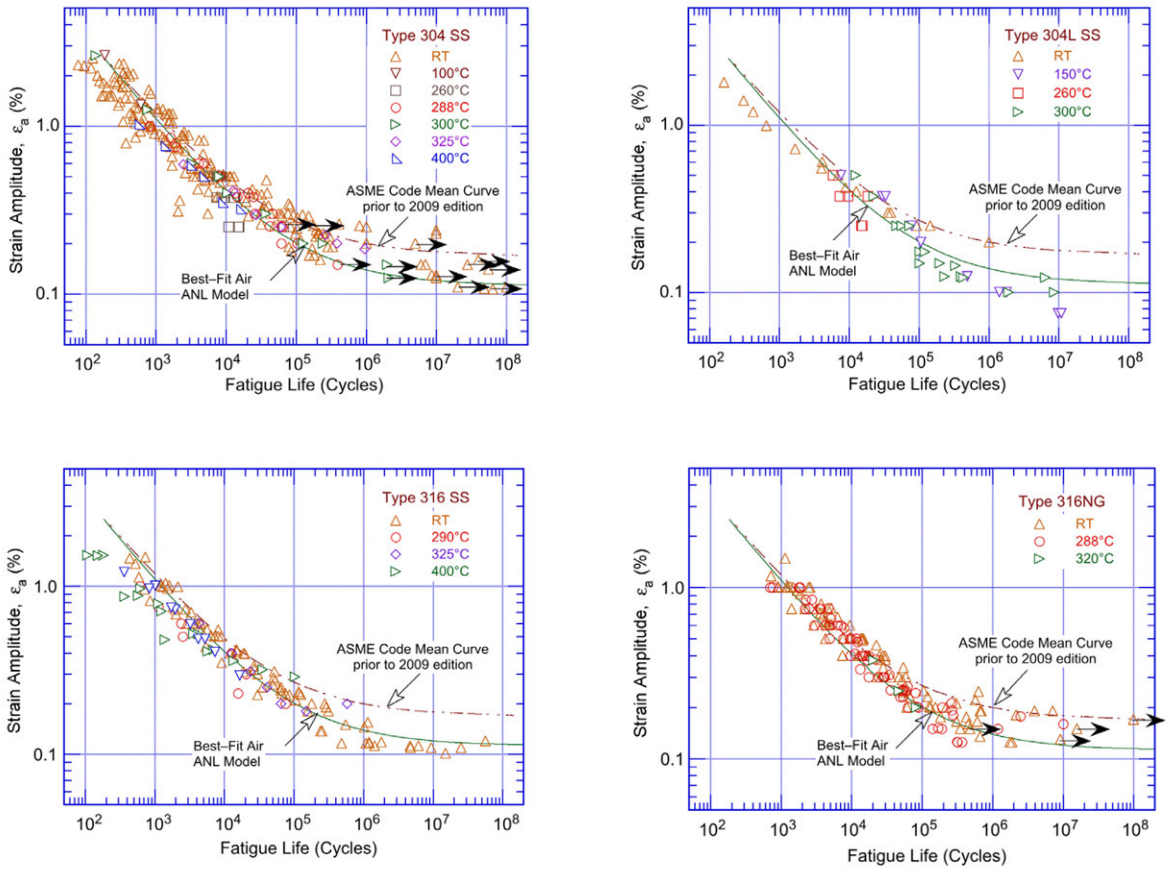


Figure 3-12 Fatigue ε–N behavior for Types 304, 304L, 316, and 316NG austenitic SSs in air at various temperatures up to 400°C (Refs. 13, 42, 47, 61, and 136).

The results in Figure 3-12 indicated that the mean-data air curve in ASME Code Section III before publication of the 2009 Addenda was not consistent with the existing fatigue ε–N data for austenitic SSs. At strain amplitudes less than 0.3% (i.e., stress amplitudes less than 585 MPa (84.9 ksi)), the ASME Code mean air curve predicted significantly longer fatigue lives than those observed experimentally for several heats of austenitic SSs with compositions and tensile strengths within the ASME Code specifications. The difference between the ASME Code Section III mean air curve and the best fit of the available experimental data was caused by differences in the tensile strengths of the steels. The ASME Code Section III mean air curve represents SSs with relatively high tensile strengths; the fatigue ε–N data obtained during the last 30 years were obtained on SSs with lower tensile strengths. Furthermore, for the mean air curve in ASME Code Section III before publication of the 2009 Addenda, the 10^6-cycle fatigue

limit (i.e., the stress amplitude at a fatigue life of 10^6 cycles) was 389 MPa, which is greater than the upper range of the room-temperature monotonic yield strength of austenitic SSs used for the mean stress correction in this report (approximately 303 MPa in Table B-2 in Appendix B). Consequently, the fatigue design air curve for austenitic SSs in ASME Code Section III did not include a mean stress correction for fatigue lives below 10^6 cycles. Studies by Wire et al.[223] and Solomon et al.[58] on the effects of residual stress on fatigue lives demonstrated that mean stress decreased the 10^6-cycle fatigue limit of materials; the extent of these effects depended on the cyclic-hardening behavior of the materials and the resultant decreases in strain amplitudes developed during load-controlled cycling. Strain hardening is more pronounced at high temperatures (e.g., 288–320°C) or at high mean stress values (e.g., greater than 70 MPa); therefore, as observed by Wire et al. and Solomon et al., fatigue lives for load-controlled tests with mean stress were actually increased at high temperatures or large values of mean stress. In both studies, under load controlled conditions, mean stress effects were observed at low temperatures (150°C) or at relatively low mean stress values (less than 70 MPa).

Wire et al.[223] performed fatigue tests on two heats of Type 304 SS to establish the effects of mean stress under both strain-controlled and load-controlled conditions. The strain-controlled tests indicated that "an apparent reduction of up to 26% in strain-amplitude occurred in the low and intermediate cycle regime ($<10^6$ cycles) for a mean stress of 138 MPa." However, the results were affected by both mean stress and cold work. Although the composition and vendor-supplied tensile strengths for the two heats of Type 304 SS were within ASME Code specifications, the measured mechanical properties showed much larger variations than indicated by the vendor properties. Wire et al. stated, "[a]t 288°C, monotonic yield strength varied from 152–338 MPa. These wide variations are attributed to variations in [cold] working from the surface to the center of the thick cylindrical forgings." After separating the individual effects of mean stress and cold work, the Wire et al. results indicated a 12% decrease in strain amplitude for a mean stress of 138 MPa. These results were consistent with the predictions based on conventional mean stress models such as the Goodman correlation.

The current ASME Code Section III fatigue design air curve (i.e., 2009 Addenda or later editions of the ASME Code) is based on the ANL model presented in Equation 29. This curve is consistent with the extensive fatigue ε–N data analyzed in this report. Section 3.2.6 presents additional details of the analysis.

- *The ASME Code Section III fatigue design air curve is now based on the ANL model and is consistent with the existing fatigue ε–N data for austenitic SSs.*

3.2.2 Specimen Geometry and Type of Loading

Figure 3-13 shows the influence of specimen geometry (hourglass vs. gauge-length specimens) on the fatigue lives of Types 304 and 316 SS. At temperatures up to 300°C, specimen geometry had little or no effect on the fatigue lives of austenitic SSs; the fatigue lives of hourglass specimens were comparable to those of gauge specimens.

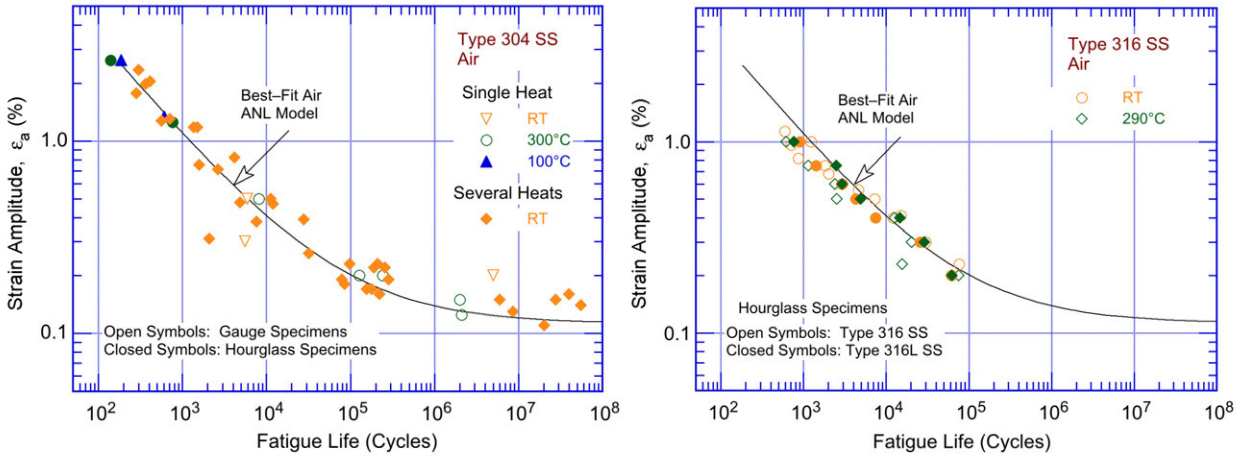


Figure 3-13 Influence of specimen geometry on fatigue lives of Types 304 and 316 SSs (JNUFAD data).

Figure 3-14 shows the results of strain-controlled bending fatigue tests tested on rectangular bar specimens of Type 304 SS in room-temperature air. Although all of the fatigue tests were performed at high strain amplitudes (i.e., producing fatigue lives less than 10^4 cycles), the bending-test data were evenly distributed along the ANL mean-data air curve for austenitic SSs.

- *Fatigue ε–N data obtained on hourglass specimens, straight gauge specimens, or bending test specimens may be used to develop the fatigue design air curves.*

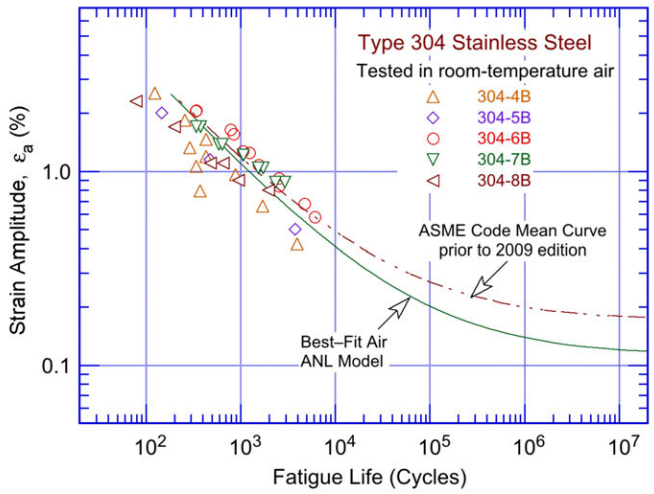


Figure 3-14 Influence of bending loading on fatigue lives of Types 304 and 316 SSs (JNUFAD data).

3.2.3 Strain Rate

A statistical analysis of the fatigue ε–N data presented in Reference 45 indicated that the fatigue lives of austenitic SSs in an air environment decreased with decreasing strain rate at temperatures between 400 and 430°C. However, studies at Électricité de France (EdF) indicated that variations in strain rate in the range of 0.4 to 0.008%/s had no effect on the

fatigue lives of SSs at temperatures up to 400°C.[57] Thus, for the fatigue data analysis presented in this report, strain rate effects on fatigue lives in air were considered insignificant.

- *Effects of strain rate on the fatigue lives of austenitic SSs in air were considered insignificant.*

3.2.4 Temperature

Figure 3-12 plots the fatigue lives of austenitic SSs in air at temperatures between room temperature and 400°C. The results indicated that the fatigue lives of Types 304, 304L, 316, and 316NG SS did not show any dependence on temperature from room temperature up to 400°C. These results are consistent with the observation of Amzallag et al.[57]

Figure 3-15 plots additional fatigue data at temperatures between 427 and 456°C.[61-63] The results indicated that the fatigue ε–N data at temperatures between 400 and 460°C were evenly distributed along the ANL best-fit air curve. Furthermore, for austenitic SSs, DSA is typically observed at temperatures of 500-600°C.[206] Therefore, for these results, the fatigue ε–N data for austenitic SSs in air are well represented by a single curve, the ANL model.

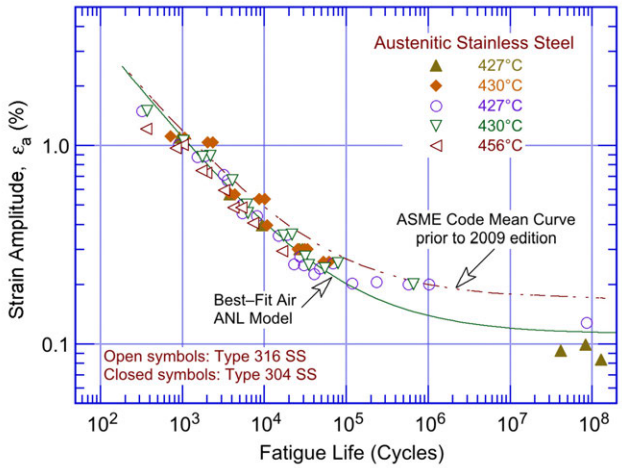


Figure 3-15 Influence of temperature on fatigue lives of austenitic SSs in air (Refs. 61-63).

However, studies at GE by Solomon et al. indicate that temperature influenced the fatigue limit of austenitic SSs because of differences in the secondary hardening behavior of the material.[60] Secondary hardening is the transformation of retained austenite to martensite causing an increase in hardness. This frequently occurs in high-alloy steels due to precipitation of carbides during the tempering process.

- *Temperature had no significant effect on the fatigue lives of austenitic SSs in air at temperatures below 400°C. Limited additional data also showed no temperature effects up to 450°C. However, the existing fatigue data are inadequate to establish the effects of secondary hardening on fatigue life, especially at temperatures above 400°C. In the proposed methodology, these secondary hardening effects are accounted for in the factor applied on stress that was applied to obtain the design curve from the mean-data curve.*

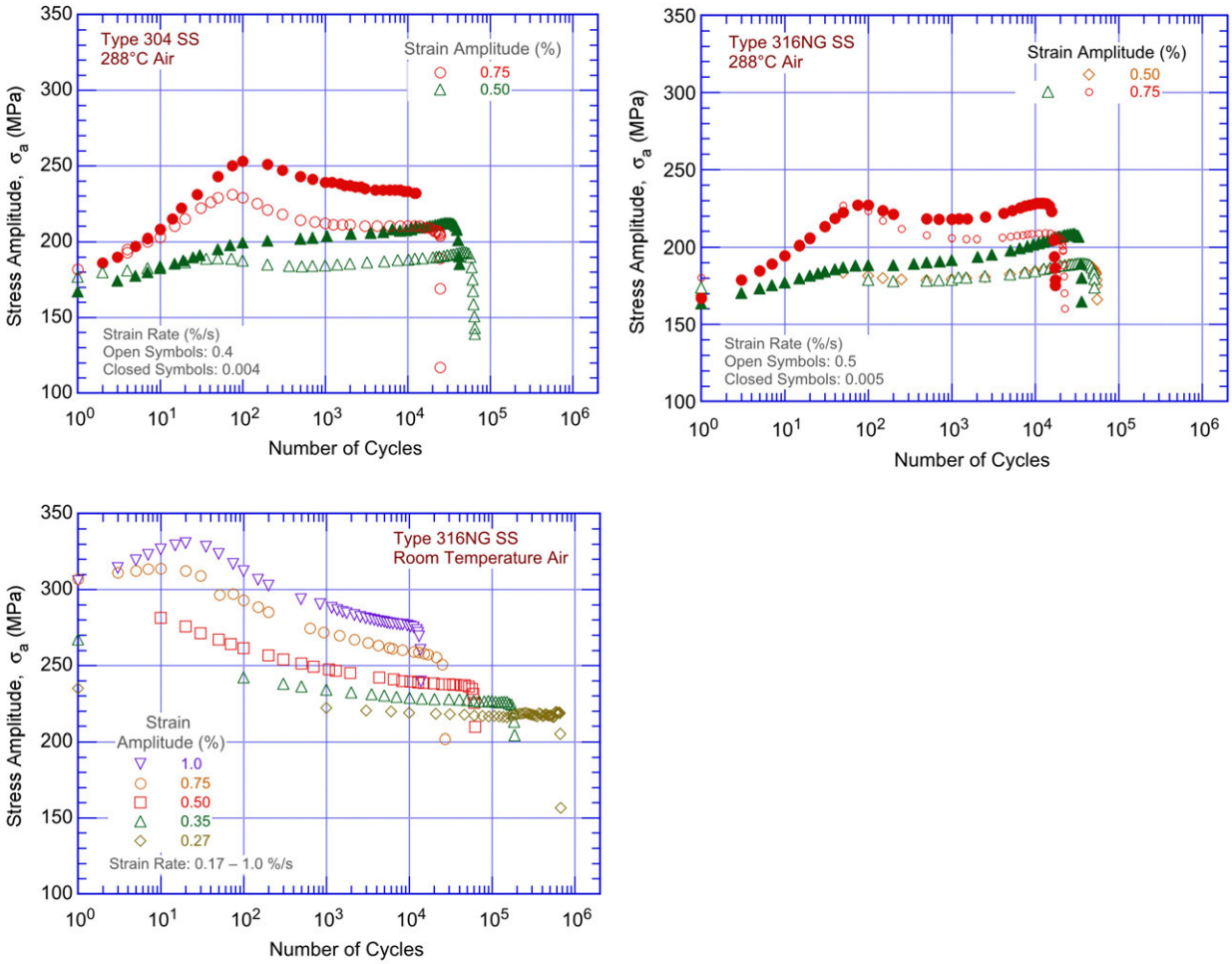


Figure 3-16 Effects of strain amplitude, temperature, and strain rate on cyclic strain–hardening behavior of Types 304 and 316NG SSs in air at 288°C and room temperature.

3.2.5 Cyclic Strain Hardening Behavior

Under cyclic loading, austenitic SSs exhibited rapid hardening during the first 50 to 100 cycles. As shown in Figure 3-16, the extent of hardening increased with increasing strain amplitude and decreasing temperature and strain rate.[45] The initial hardening was followed by a softening and saturation stage at high temperatures and by continuous softening at room temperature.

Figure 3-17 shows the cyclic stress vs. strain curves for Types 316, 304, and 316NG SSs at room temperature and 288°C. In this figure, cyclic stress corresponds to the value at half-life at a strain rate of 0.4%/s. For the various steels, cyclic stresses increased in magnitude in the following order: Types 316NG, 304, and 316.[45]

- *Cyclic strain hardening behavior influenced the fatigue lives of SS materials. The ASME Code accounted for variations in fatigue lives due to such effects by applying the factor of 2 on stress to obtain the design air curve from the mean-data air curve.*

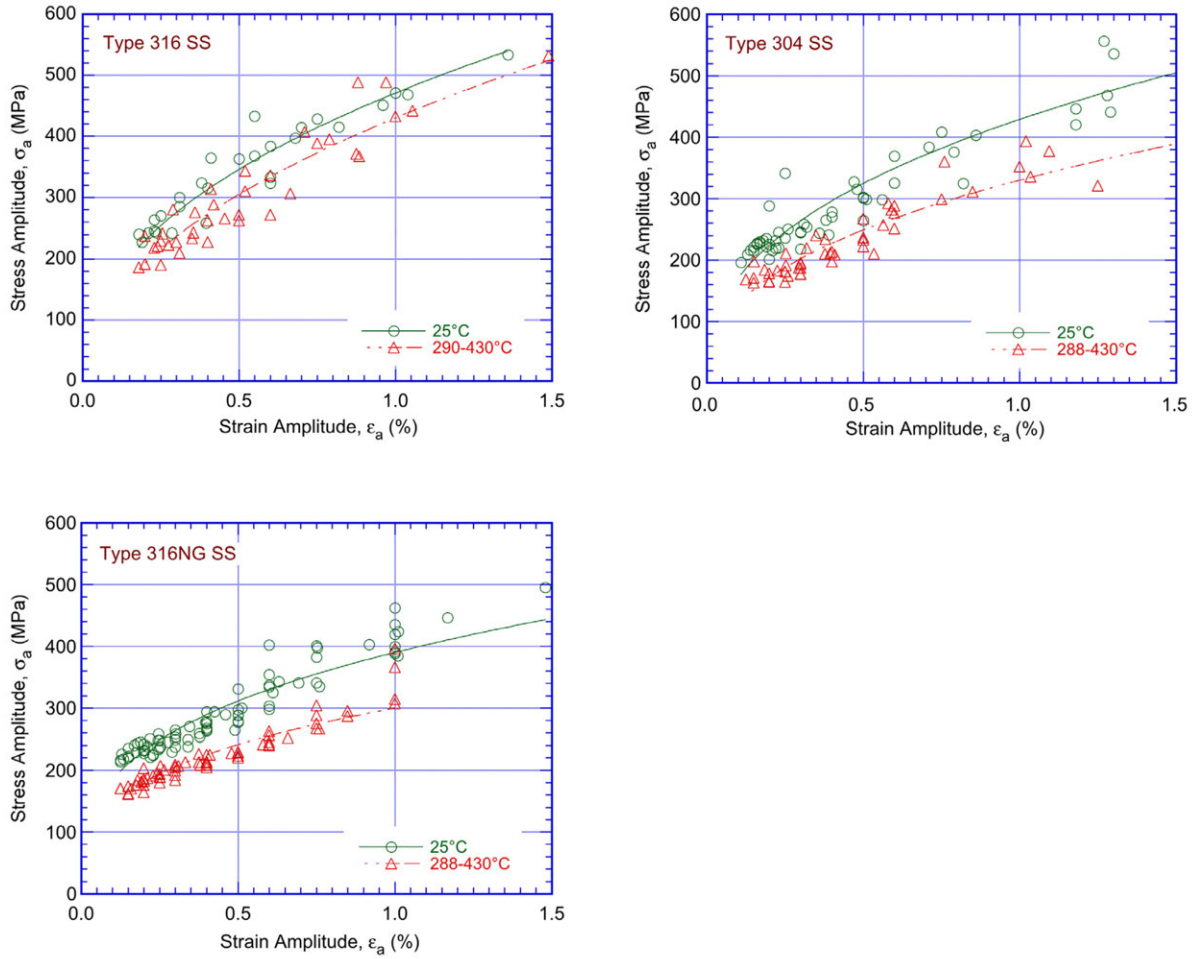


Figure 3-17 Cyclic stress-strain curves for Types 316, 304 and 316NG SSs in air at room temperature and 288°C.

3.2.6 Fatigue Life Model

In the original version of NUREG/CR-6909,[137] an updated version of the PVRC database was used to develop the best-fit mean air curve for austenitic SSs. The sources were listed in Table 1 of the report. The data were obtained on smooth specimens tested under strain-controlled conditions with fully reversed loading (i.e., R = -1) in compliance with consensus standard approaches used for the development of such data. The database consisted of 520 tests on Types 304, 316, 304L, 316L and 316NG SSs; approximately 220 of the tests were for Type 304 SS; 150 tests were for Type 316 SS; and 150 tests were for Types 316NG, 304L, and 316L SSs. The austenitic SSs used in these studies complied with the compositional and strength requirements of ASME Code specifications. The best-fit methodology described in Section 3.1.6 for carbon and low-alloy steels was also used for the analysis of the fatigue ε–N data for austenitic SSs.

Several different best-fit mean ε–N curves for austenitic SSs were previously proposed in the literature. Examples include Jaske and O'Donnell,[61] Diercks,[224] Chopra,[45] Tsutsumi et al.,[34] and Solomon and Amzallag.[225] These curves differ by up to 50%, particularly in the regime of 10^4 to 10^7 cycles. The constant C in Equation 6 (related to the fatigue limit of the material) varied from

a value of 0.110 proposed by Tsutsumi et al., a value of 0.112 proposed by Jaske and O'Donnell, and a value of 0.167 proposed in the original ASME Code Section III mean air curve. The differences primarily occurred because different databases were used in developing these models for the mean ε–N curves. The analyses by Jaske and O'Donnell and by Diercks were based on Jaske and O'Donnell's data.

Tsutsumi et al. used the JNUFAD data, which are included in the JNES database.[136] In the original version of NUREG/CR-6909, the updated PVRC data were analyzed to develop the ANL model for austenitic SSs; the updated PVRC data included the JNUFAD database. In addition, unlike the earlier ANL reports that proposed separate expressions for high-carbon and low-carbon grades of SSs, a single expression was developed for the fatigue ε–N behavior of austenitic SSs. The model assumed that fatigue lives in air were independent of temperature and strain rate. Consistent with the models proposed by Tsutsumi et al.[34] and by Jaske and O'Donnell,[61] the value of the constant C in the modified Langer equation (Equation 6) was lower than that in earlier reports (i.e., 0.112 instead of 0.126). The proposed curve yielded an R^2 value of 0.851 when compared with the updated PVRC data; the R^2 values for the mean curves derived by Tsutsumi et al., Jaske and O'Donnell, and the ASME Code were 0.839, 0.826, and 0.568, respectively.

In air at temperatures up to 400°C, the fatigue lives for Types 304, 304L, 316, 316L, and 316NG SSs were represented by the following expression:

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112) \quad (29)$$

where ε_a is applied strain amplitude (%). Figure 3-18 plots the experimental values of fatigue lives and those predicted by Equation 29 for austenitic SSs in air. The predicted lives showed good agreement with the experimental values; for most tests, the differences between the experimental and predicted values were within a factor of 3. For some tests, the observed fatigue lives at low strain amplitudes (i.e., amplitudes that yielded fatigue lives greater than $5x10^4$ cycles) were significantly longer than the predicted values.

- *The ANL fatigue life model for austenitic SSs represents mean values of fatigue lives in air. The effects of parameters (such as mean stress, surface finish, size and geometry, and loading history) known to influence fatigue lives were accounted for in the factors of 12 on life and 2 on stress that were applied to the mean-data air curve to obtain the fatigue design air curve.*

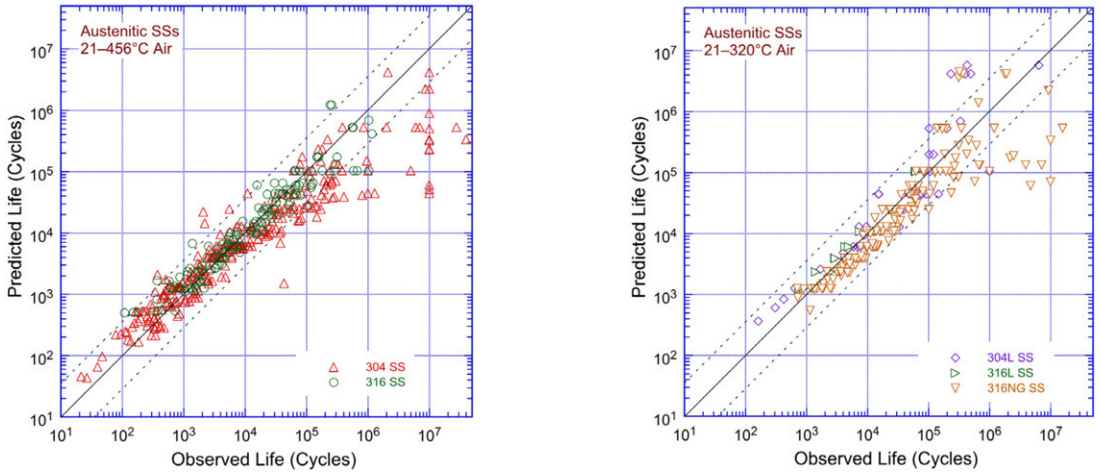


Figure 3-18 Experimental and predicted fatigue lives (using the ANL model) for austenitic SSs in air.

3.2.7 Heat-to-heat Variability

The effects of material (heat-to-heat) variability and data scatter were included in the fatigue model to ensure that the design curves adequately describe both the available test data and the fatigue lives of the much larger number of heats of materials found in the field compared to the limited numbers of heats tested in the laboratory. As mentioned earlier for carbon and low-alloy steels, heat-to-heat variability and data scatter in the fatigue ε–N data for austenitic SSs were also evaluated by considering the best–fit curves determined from tests on individual heats of materials or loading conditions as samples of the much larger population of heats of materials and service conditions of interest. The fatigue lives of each of the heats or loading conditions were characterized by the value of the constant A in Equation 6. The values of A for the various datasets were rank-ordered, and median ranks were used to estimate the cumulative distribution of A for the population. The distributions were fit to lognormal curves. Figure 3-19 shows the estimated cumulative distributions of constant A in the ANL model for fatigue lives of heats of wrought and cast austenitic SSs included in the original version of NUREG/CR-6909 and those included in this report. Note that the new updated database used in this report consisted of 622 data points, which is a significant increase (74%) compared to the 357 data points used in the original version of NUREG/CR-6909. The data were obtained on five types of austenitic SSs, four types of associated SS weld metals, and one type of cast austenitic SS. There are a total of 86 different heats of these materials.

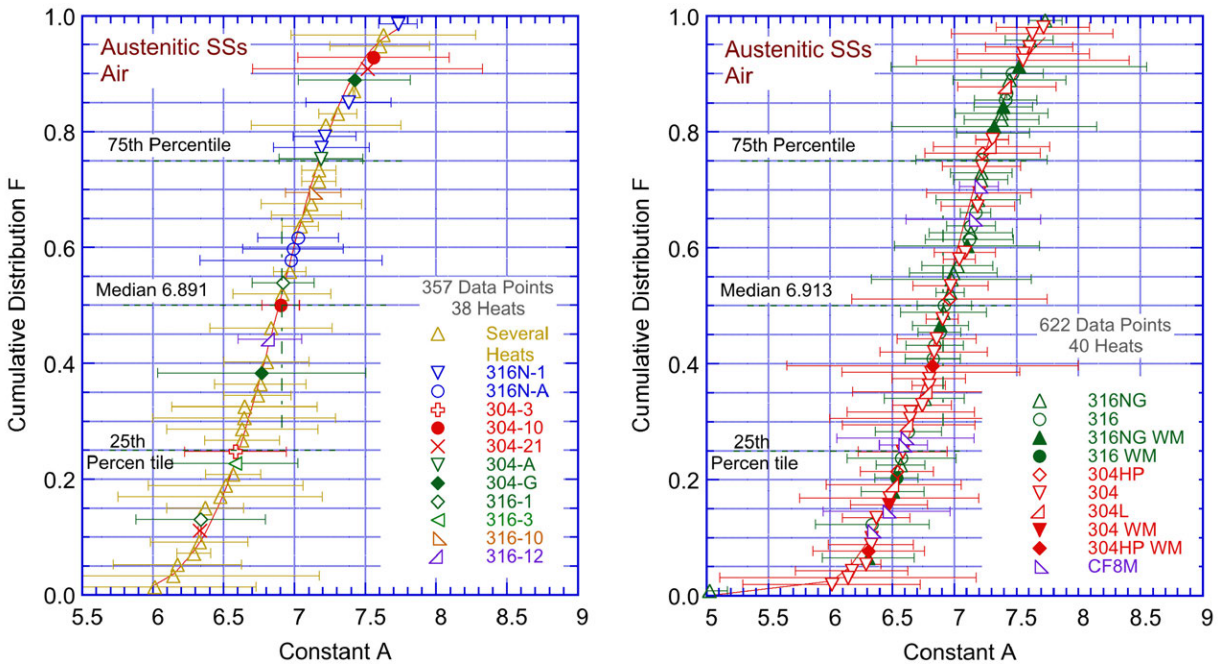


Figure 3-19 Estimated cumulative distribution of constant A in the ANL model for fatigue lives for heats of austenitic SSs in air included in (a) the original version of NUREG/CR 6909 and (b) those included in this report.

The results of the reanalysis indicated that the ANL fatigue model presented in the original version of NUREG/CR-6909 for predicting fatigue lives of austenitic SSs in air was adequate and remains representative of the updated (larger) database. Despite the significant increase in data, the reanalysis of the much larger updated database yielded an insignificant change in the median value of the constant A in Equation 6. The constant A increased from 6.891 to 6.913. In addition, Figure 3-19 indicates that the various heats of wrought austenitic SSs and the associated SS weld metals were evenly distributed about the median value of constant A. The few heats of CF–8M cast austenitic SS were in the 15th to 30th percentile of the data (i.e., the fatigue lives of the heats of CF–8M were lower than the average values for austenitic SSs). However, this does not necessarily indicate that cast CF–8M materials have marginally lower fatigue lives than the average wrought SS material. This behavior is representative for this specific sample. Additional fatigue ε–N data are needed on cast austenitic SSs to better establish the typical fatigue behavior of cast SS materials.

The values of the constant A that describe the 5th percentile of the statistical distributions produced a fatigue ε–N curve that bounded the fatigue lives of 95% of the heats of austenitic SSs. A Monte Carlo analysis was performed to address the data uncertainties in the median value and standard deviation of the sample used for the analysis. For austenitic SSs, Table 3-7 summarizes the values for A that provided bounds for the portion of the population and the confidence that was desired in the estimates of the bounds. Because the reanalysis summarized in Figure 3-19 and Table 3-7 indicated that the constant A did not change significantly from the original version of NUREG/CR-6909, the median value of the constant A for austenitic SSs remains 6.891, and was not changed in this report. Also from Table 3-7, the 95/95 value of the factor to account for material variability and data scatter is 2.3 on life. This factor is needed to provide reasonable confidence that the resultant lives are greater than those

observed for 95% of the SS materials of interest. Note that a relatively large value of 2.3 for the adjustment factor for material variability and data scatter is due to the fact that the ASME Code fatigue design curve for SSs is applicable to a wide range of material grades; heat-treatments; and compositions, particularly the low-C and high-C grades of SSs.

Table 3-7 Values of Constant A in the ANL Fatigue Life Model for Austenitic SSs and the Factors on Fatigue Lives for Austenitic SSs in Air as a Function of Confidence Level and Percentage of the Population Bounded.

Confidence Level	Percentage of Population Bounded (Percentile Distribution of A)				
	95 (5)	90 (10)	75 (25)	67 (33)	50 (50)
			Values of Constant A		
50	6.205	6.356	6.609	6.707	6.891
75	6.152	6.309	6.569	6.668	6.851
95	6.075	6.241	6.510	6.611	6.793
			Factors on Life		
50	2.0	1.7	1.3	1.2	1.0
75	2.1	1.8	1.4	1.2	1.0
95	2.3	1.9	1.5	1.3	1.1

- *The mean-data air curve for austenitic SSs used to develop the fatigue design air curve represented the average fatigue behavior; heat-to-heat variability was included in the subfactor that was applied to the mean-data air curve to obtain the fatigue design air curve to account for "data scatter and material variability."*

3.2.8 Fatigue ε–N Behavior of Cast Austenitic Stainless Steels

Available fatigue ε–N data[29,34,43,45] indicated that the fatigue lives of cast CF–8M SSs in air were similar to those of wrought austenitic SSs. Figure 3-20 plots the fatigue ε–N data for CF–8M cast austenitic SS in air, at temperatures between room temperature and 325°C. The results indicated that the fatigue lives of cast SSs were evenly distributed along the ANL best-fit curve for the mean data for wrought austenitic SSs.

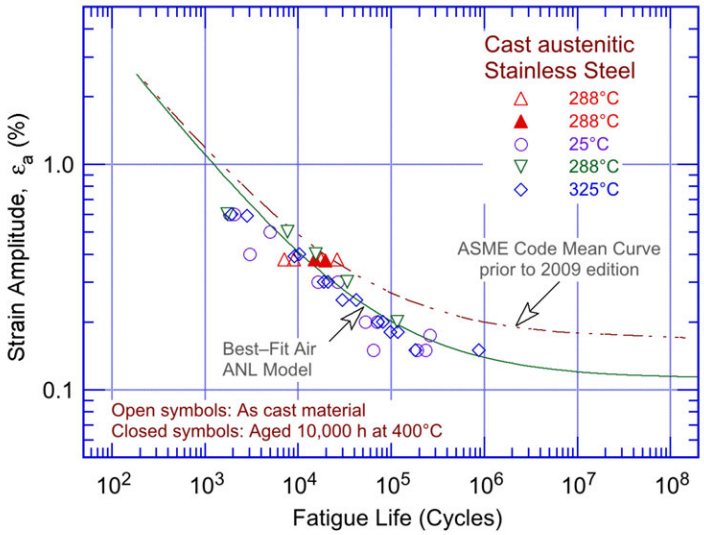


Figure 3-20 Fatigue ε–N behavior for several heats of CF-8M cast austenitic SSs in air at various temperatures.

The effects of thermal aging at 250–400°C on the fracture toughness properties of cast austenitic SSs are well established. Fracture toughness decreased significantly after thermal aging because of the spinodal decomposition of the ferrite phase to form a Cr-rich α' phase.[229-232] The cyclic-hardening behavior of cast austenitic SSs was also influenced by thermal aging.[45] The spinodal decomposition of the ferrite phase during thermal aging at 400°C strengthened the ferrite phase and increased cyclic hardening. At 288°C, cyclic stresses of cast SSs aged for 10,000 hours at 400°C were higher than those for unaged material or wrought SSs. The existing data were too sparse to establish the effects of thermal aging on strain-rate effects on the fatigue lives of cast SSs in air.

- *The fatigue mean-data air curve for wrought austenitic SSs may be used for cast austenitic SSs.*

3.2.9 Fatigue ε–N Behavior of Weld Metals

Figure 3-21 plots available fatigue ε–N data for Types 304, 304HP (i.e., high purity), 316, and 316NG weld metals in air at room temperature. The results indicated that the fatigue lives of SS weld metals were slightly lower than the mean ε–N air curve for austenitic SSs in the low-cycle fatigue regime (i.e., fatigue lives less than 10^4 cycles) and generally longer in the high-cycle regime. However, the weld metal data were within the scatter band for the various grades and heats of austenitic SSs such that the differences between the weld and base materials are not significant enough to warrant a separate weld metal curve without the development of additional data.

- *The limited fatigue ε–N air data indicate that the mean-data air curve for wrought austenitic SSs may be used for SS weld metals.*

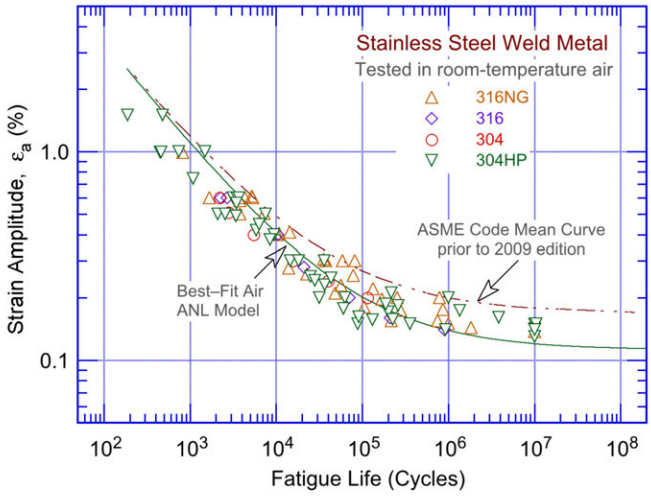


Figure 3-21 Fatigue ε–N behavior for austenitic SS weld metals in air at room temperature.

3.2.10 Surface Finish

Fatigue tests were conducted on Types 304 and 316NG SS specimens that were intentionally roughened in a lathe under controlled conditions with 50-grit sandpaper to produce circumferential scratches with an average surface roughness of 1.2 μm.[46] Figure 3-22(a) and (b) show the results for Types 316NG and 304 SS, respectively. For both steels, the fatigue lives of the roughened specimens were a factor of approximately 3 lower than those of the smooth specimens.

- *The effect of surface finish was included as part of the "surface finish and environment" subfactor that was applied to the mean-data air curve to obtain the fatigue design air curve for austenitic SSs."*

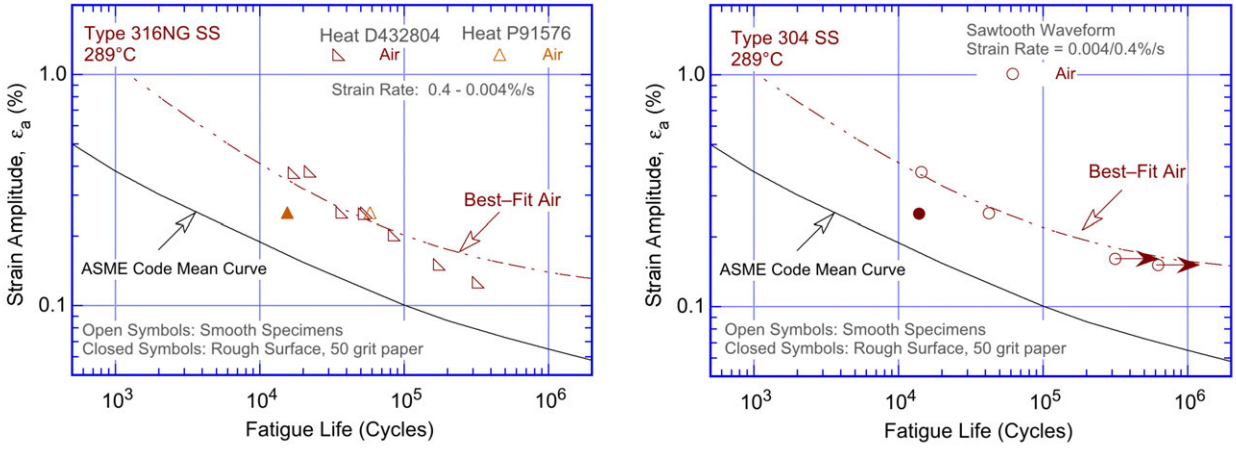


Figure 3-22 Effects of surface roughness on fatigue lives of (a) Type 316NG and (b) Type 304 SSs in air (Ref. 46).

3.2.11 Fatigue Design Curve

As discussed in Section 3.2.1, the ASME Code mean data that were used to develop the current ASME Code Section III fatigue design air curve were not consistent with the existing fatigue ε–N data. Therefore, a fatigue design air curve that was consistent with the existing database was derived from the ANL model (Equation 29) by following the same procedure that was used to develop the ASME Code Section III fatigue design air curve. The discussion presented in Section 5.5 indicated that the current ASME Code Section III requirement for a factor of 20 on cycles to account for the effects of material variability and data scatter, specimen size, surface finish, and loading history was conservative by at least a factor of 1.7. Therefore, to reduce this conservatism, an fatigue design air curve based on the ANL model for austenitic SSs (Equation 29) was developed by correcting for mean-stress effects using the modified Goodman relationship and then by lowering the mean-stress-adjusted curve by a factor of 2 on stress and 12 on cycles, whichever was more conservative. The resulting fatigue design air curve and the fatigue design air curve in ASME Code Section III before publication of the 2009 Addenda were presented in the original version of NUREG/CR-6909. The two fatigue design air curves were identical beyond 10^8 cycles. In 2009, the new fatigue design air curve that was based on the ANL model for austenitic SSs was adopted into Mandatory Appendix I of ASME Code Section III. Figure 3-23 shows both of the ASME Code Section III air fatigue design air curves,[D] and Table 3-8 lists the values of stress amplitude vs. cycles for the current and the proposed design air curves.

- *A new fatigue design air curve for austenitic SSs that is consistent with the existing data was developed from the ANL model using factors of 12 on life and 2 on stress. This curve is the same as the ASME Code Section III fatigue design air curve implemented in 2009.*

Table 3-8 The ASME Code Fatigue Design Curves for Austenitic SSs in Air.

No. of Applied Cycles	Stress Amplitude MPa (ksi)		No. of Applied Cycles	Stress Amplitude MPa (ksi)	
	Current ASME Code Design Curve	ASME Code Design Curve Prior to 2009		Current ASME Code Design Curve	ASME Code Design Curve Prior to 2009
1 E+01	6000 (870)	4881 (708)	2 E+05	168 (24.4)	248 (35.9)
2 E+01	4300 (624)	3530 (512)	5 E+05	142 (20.6)	214 (31.0)
5 E+01	2748 (399)	2379 (345)	1 E+06	126 (18.3)	195 (28.3)
1 E+02	1978 (287)	1800 (261)	2 E+06	113 (16.4)	157 (22.8)
2 E+02	1440 (209)	1386 (201)	5 E+06	102 (14.8)	127 (18.4)
5 E+02	974 (141)	1020 (148)	1 E+07	99 (14.4)	113 (16.4)
1 E+03	745 (108)	820 (119)	2 E+07		105 (15.2)
2 E+03	590 (85.6)	669 (97.0)	5 E+07		98.6 (14.3)
5 E+03	450 (65.3)	524 (76.0)	1 E+08	97.1 (14.1)	97.1 (14.1)
1 E+04	368 (53.4)	441 (64.0)	1 E+09	95.8 (13.9)	95.8 (13.9)
2 E+04	300 (43.5)	383 (55.5)	1 E+10	94.4 (13.7)	94.4 (13.7)
5 E+04	235 (34.1)	319 (46.3)	1 E+11	93.7 (13.6)	93.7 (13.6)
1 E+05	196 (28.4)	281 (40.8)			

[D] Because the data used in developing the fatigue design curve (Figure 3-23) were obtained from strain-controlled tests, the fatigue ε–N curve is valid up to 371°C, as stated in the figure. However, when converting the strain to a pseudo-stress, the elastic modulus used for the conversion should be a function of temperature as required by ASME Code Section III.

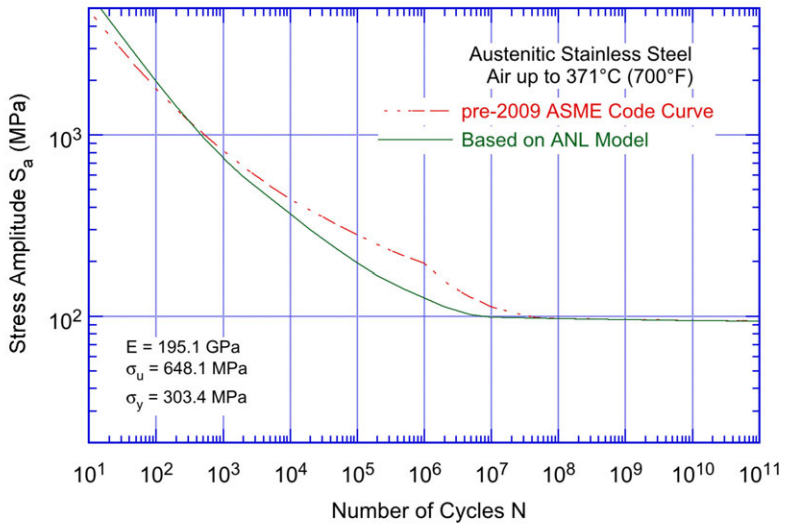


Figure 3-23 Fatigue design curves for austenitic SSs in air.

3.3 Ni-Cr-Fe Alloys and Weld Metals

The relevant fatigue ε–N data in air environments for Ni-Cr-Fe alloys, their weld metals, and limited Alloy 800 heats, include the data compiled by Jaske and O'Donnell[61] for developing fatigue design criteria for pressure vessel alloys; the JNES database from Japan, which included studies by Mitsubishi Heavy Industries (MHI), Ishikawajima-Harima Heavy Industries (IHI), and Hitachi;[39,136,210] studies by Bettis Atomic Power Laboratory,[70] Knolls Atomic Power Laboratory,[67,68] the National Aeronautics and Space Administration (NASA),[73] Battelle's Columbus Laboratories,[69] and GE;[71,72,14] work sponsored by EPRI at Westinghouse Electric Corporation,[66] and the tests performed by Van Der Sluys et al.[75] The database comprises 588 tests from which 559 data points were obtained—191 data points for 17 heats of Alloy 600, 17 data points for 3 heats of Alloy 690, 23 data points for 2 heats of Alloy 800, 196 data points for 7 heats of Alloy 718; and 140 tests of Ni-Cr-Fe weld metals from which 132 data points were obtained for 1 heat of Alloy 690 weld metal, 5 heats of Alloy 82 weld metal, 4 heats of Alloy 182 weld metal, and 6 heats of other Ni-Cr-Fe weld metals. Out of these, 427 data points were obtained from tests conducted at room temperature, 40 data points were obtained from tests conducted at 260–316°C, and 92 data points were obtained from tests conducted at 427°C. Table 3-9 summarizes the sources included in the updated database used for this report, as categorized by material type and test environment. Appendix B provides other material information such as chemical composition, heat treatment, and room temperature tensile properties of these various alloys and associated weld metals.

Table 3-9 Sources of the Fatigue ε–N Data in an Air Environment for Ni Cr Fe Alloys, Their Weld Metals, and Limited Alloy 800 Heats.

ANL Mat. ID	Material Heat Designation[a]	Monotonic Yield Strength (MPa)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
Alloy 600						
1	Alloy 600-1	310	25	12	JNES (Higuchi)	136
2	Alloy 600-2	294	25	9	JNES (Nakao),	136
3	Alloy 600-3	-	25	6	JNES (Hirano),	136
4	Alloy 600-4	289	25	6	JNES (Hirano)	136
5	Alloy 600-5	264	25	11	JNES (Hirano)	136
6	Alloy 600-6	303	25	6	JNES (Kanasaki)	136
7	Alloy 600-7	253	24, 93, 204, 316	5, 5, 10, 7	KAPL (Dinerman)	67
8	Alloy 600-8	-	24	8[a]	KAPL (Mowbray)	68
9	Alloy 600-9	-	24	10[a]	KAPL (Mowbray)	68
10	Alloy 600-10	-	24	8[a]	KAPL (Mowbray)	68
11	Alloy 600-11	-	24	13[a]	KAPL (Mowbray)	68
12	Alloy 600-12	-	24	7[a]	KAPL (Mowbray)	68
13	Alloy 600-13	-	24, 316	9, 9	EPRI (Jacko)	66
14	Alloy 600-14	-	21	19	Bettis (McGowan&Faber)	70
15	Alloy 600-15	386	260	6	GE (Hale)	14
16	Alloy 600-16	-	21	15	Jaske & O'Donnell	61
17	Alloy 600-17	-	24, 83	5, 5	Jaske & O'Donnell	61
Alloy 690						
20	Alloy 690-1	280	25	6	JNES (Kanasaki)	136
21	Alloy 690-2	-	25	5	PVP (Higuchi)	39
22	Alloy 690-3	-	315	6	PVP (Van der Sluys)	75
Alloy 800						
25	Alloy 800-1	-	21	7	BMI (Jaske et al.)	69
26	Alloy 800-2	-	427	6, 10	BMI (Jaske et al.), GE (Conway)	69,71
Alloy 718						
30	Inconel 718-1	-	21	18	ASME Data File	210
31	Inconel 718-2	-	21	4	J. Miller (J of Mat.)	72
32	Inconel 718-3	-	24, 427	17, 31	ASME Data File	61
33	Inconel 718-4	-	24, 427	30, 10	ASME Data File	61
34	Inconel 718-5	-	21, 427	34, 4	ASME Data File	61
35	Inconel 718-6	-	27, 427	12, 8	ASME Data File, NASA (Natchigall)	61,73
36	Inconel 718-7	-	22, 427	5, 23	ASME Data File	61
Ni-Cr-Fe Alloy Weld Metals						
38	Alloy 690 WM	431	25	6	JNES (Kanasaki)	136
39	Alloy 62	-	24	9[a]	KAPL (Mowbray)	68
40	Alloy 82-1	-	24	8[b]	KAPL (Mowbray)	68
41	Alloy 82-2	-	24	8[a]	KAPL (Mowbray)	68
42	Alloy 82-3	-	24	17[a]	KAPL (Mowbray)	68
43	NiCrFe WM-1	-	24	9	Higuchi, Iida	SGFS 1988
44	Arcaloy 8N12	-	24	6[a]	KAPL (Mowbray)	68

ANL Mat. ID	Material Heat Designation[a]	Monotonic Yield Strength (MPa)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
45	NiCrFe WM-2	-	25	9, 5	JNUFAD (Higuchi, Nakao)	210
46	Alloy 82-4	322	260	7	KAPL (Mowbray)	68
47	Alloy 182-1	-	25	13	PVP (Higuchi)	39
48	Alloy 182-2	456	290	7	JNES (Higuchi)	136
49	Alloy 182-3	405	25	5	JNES (Nakao)	136
50	Alloy 182-4	409	25	6	JNES (Kanasaki)	136
51	Alloy 82-5	339	315	5	PVP (Van der Sluys)	75
52	Alloy 152	-	25	6	PVP (Higuchi)	39
53	Alloy 132	-	25	6	PVP (Higuchi)	39

[a] The tests were performed under bending fatigue.

[b] Six tests performed under bending fatigue, and four were performed under rotating bending.

3.3.1 Experimental Data

Figure 3-24 shows the fatigue ε–N data for Ni-Cr-Fe alloys such as Alloys 600, 690, and Alloy 800 in air at temperatures between room temperature and 427°C. Figure 3-25 presents the fatigue ε–N data for Alloys 62, 82, 132, 152, 182, and other Ni-Cr-Fe alloy weld metals in air at temperatures between room temperature and 315°C. Figure 3-26 shows the fatigue ε–N data for Inconel 718 in air at room temperature and 427°C. Fatigue CUF evaluations for Ni-Cr-Fe alloy and Alloy 800 components are performed using the fatigue design air curve for austenitic SSs because ASME Code Section III does not have a separate curve for these materials. Therefore, these three figures include the best–fit air curve for austenitic SSs based on the ANL model (Equation 29 in Section 3.2.6). The results indicated that, although the data for Alloys 690 and 800 are limited, the fatigue lives of these alloys were comparable to those of Alloy 600 (Figure 3-24). The fatigue ε–N data for Ni-Cr-Fe alloy weld metals indicated that the fatigue lives of the various weld metals were comparable, although the data for Alloy 82 at 260 to 315°C showed significant scatter (Figure 3-25).

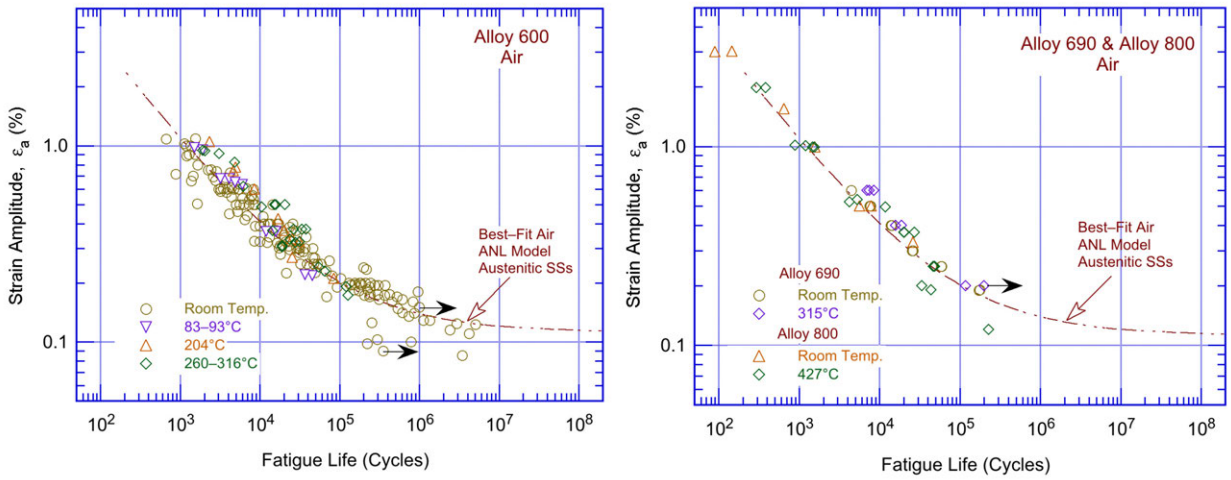


Figure 3-24 Fatigue ε–N behavior for Alloys 600, 690 and 800 in air at temperatures between room temperature and 427°C (Refs. JNUFAD data, 61, and 66–75).

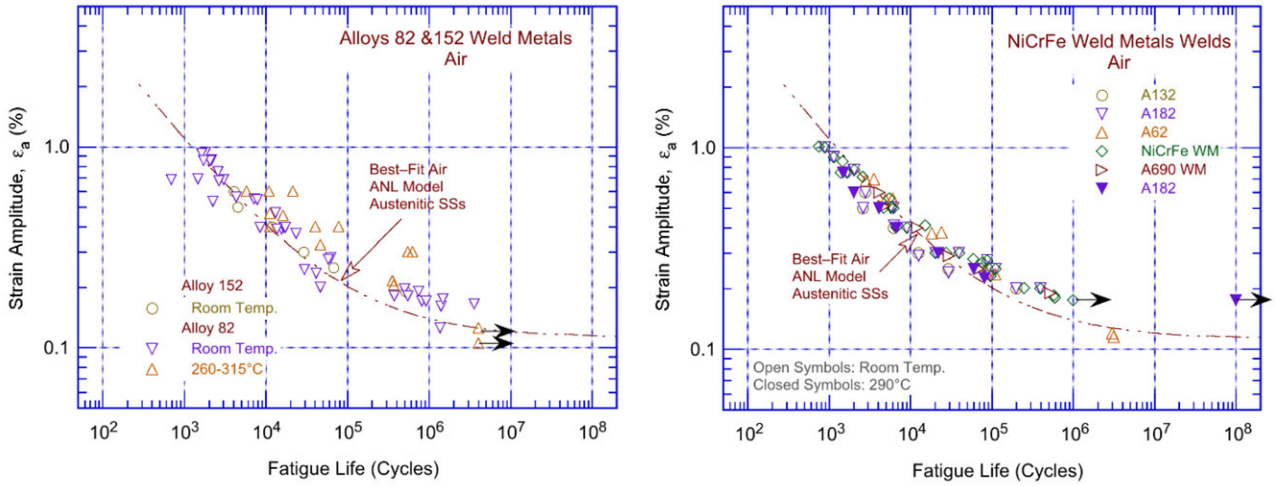


Figure 3-25 Fatigue ε–N behavior for Alloys 62, 82, 132, 152 and 182 welds in air at various temperatures (Refs. JNUFAD data, 61, and 66–75).

The fatigue lives of the Ni-Cr-Fe alloy weld metals were comparable to those of the wrought Alloys 600 and 690 in the low-cycle regime (i.e., less than 10^5 cycles) and were slightly superior to the lives of wrought materials in the high-cycle regime. The results also indicated that the fatigue limit for the weld metals was higher than that for wrought materials. Overall, the available fatigue ε–N data indicated that the fatigue lives of Ni-Cr-Fe alloys and Alloy 800 were represented by the fatigue design air curve for austenitic SSs; however, fatigue evaluations for Ni-Cr-Fe weld metals were conservative using these curves.

The fatigue ε–N data in Figure 3-26 indicate that the fatigue lives of Inconel 718 were greater than those for austenitic SSs and other Ni-Cr-Fe alloys and their weld metals, particularly at strain amplitudes less than 0.5% (i.e., in the high-cycle regime). The fatigue limit for Inconel 718 was much higher than that of austenitic SSs. Therefore, fatigue analyses for Inconel 718 that used the fatigue design air curve for austenitic SSs yielded conservative estimates of fatigue usage. To avoid this conservatism, Jaske and O'Donnell proposed the following expression for fatigue lives of Inconel 718 in air,

$$\ln(N) = 6.859 - 2.0 \ln(\varepsilon_a - 0.210). \quad (30)$$

Figure 3-26 also shows the Jaske and O'Donnell best-fit air curve for Inconel 718.

The available fatigue ε–N data for Ni-Cr-Fe alloys also indicated that, unlike austenitic SSs that do not show temperature dependencies of fatigue lives under LWR operating conditions, the fatigue lives of Alloy 600 were generally longer at high temperatures compared to those at room temperature, particularly for Alloy 82 weld metal (Figure 3-25(a)).[66-68] Similar behavior was observed for Inconel 718 (Figure 3-26). However, limited data for Alloy 690 (Figure 3-24(b)) and Alloys 62, 132, 182, and 690 weld metals (Figure 3-25(b)), indicated little or no effects of temperature on their fatigue lives. The existing data were insufficient to adequately determine the effect of strain rate on the fatigue lives of Ni-Cr-Fe alloys.

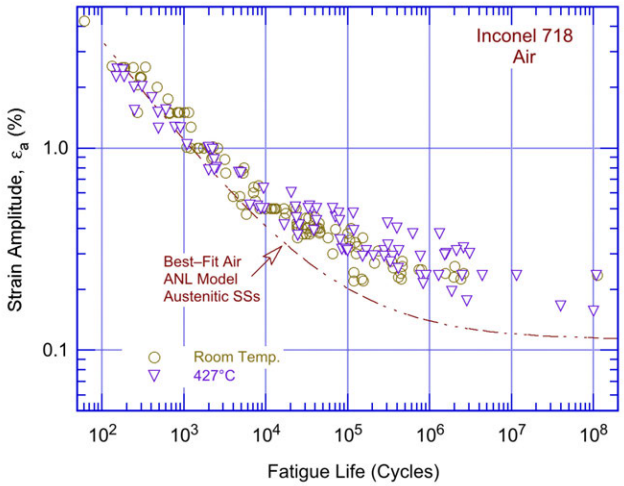


Figure 3-26 Fatigue ε–N behavior for Inconel 718 in air at room temperature and 427°C (Refs. 61, 72, 73, 136, and 210).

Overall, the results indicated that the best-fit mean air curve for austenitic SSs adequately represented the available fatigue ε–N data of Ni-Cr-Fe alloys, their weld metals, and Alloy 800 in the low-cycle regime (i.e., fatigue lives less than $5x10^4$ cycles) while these curves provided slightly conservative estimates of the fatigue lives for Ni-Cr-Fe alloys in the high-cycle regime (i.e., fatigue lives greater than $5x10^4$ cycles), particularly for Ni-Cr-Fe alloy weld metals. However, the best-fit mean-data curve for austenitic SSs yielded very conservative estimates of fatigue lives for Inconel 718 for fatigue lives greater than 10^4 cycles. A separate fatigue ε–N curve is needed within ASME Code Section III to reduce this conservatism and better represent the fatigue behavior of Inconel 718. In the interim, the fatigue design air curve for austenitic SSs for austenitic SSs in ASME Code Section (or equivalently the SS fatigue design air curve for austenitic SSs in this report) can be conservatively used for Inconel 718.

- *For Ni-Cr-Fe alloys and their welds, the ANL fatigue life air model proposed in this report for austenitic SSs (Equation 29) was either consistent or conservative with respect to the fatigue ε–N data. This curve is significantly conservative for Inconel 718.*

3.3.2 Fatigue Life Model

For Ni-Cr-Fe alloys (and Alloy 800), fatigue evaluations are based on the fatigue design air curve for austenitic SSs because it also applies to Ni-Cr-Fe alloys in ASME Code Section III. The rather limited fatigue ε–N data for Ni-Cr-Fe alloys (such as Alloys 600, 690, and 800 and their welds) were consistent with the best-fit mean air curve for austenitic SSs for fatigue lives less than 10^4 cycles. The data also showed longer fatigue lives than the estimated values for fatigue lives greater than 10^4 cycles. The data were comparable or slightly conservative with respect to the ANL model for austenitic SSs (e.g., Equation 29). Estimates of the cumulative distribution of constant A in the fatigue ε–N curve for the various heats of Alloys 600, 690, and 800, and their associated weld metals, yielded a median value of 7.129. This value was slightly greater than the value of constant A derived for austenitic SSs. In other words, the fatigue lives of these Ni-Cr-Fe alloys (and Alloy 800) were approximately 25% greater than those for austenitic SSs. Based on these findings, the current ASME Code Section III fatigue design air curve for austenitic SSs, which is the same as the ANL model presented in Figure 3-23 and

Table 3-8, appropriately represented (albeit slightly conservatively) the fatigue ε–N behavior of Ni-Cr-Fe alloys and their welds.

- *The ASME Code Section III fatigue design air curve for austenitic SSs, which is the same as the ANL air model for austenitic SSs, is applicable for Ni-Cr-Fe alloys, their welds, and Alloy 800. The current design fatigue air curve for austenitic SSs yielded conservative estimates of fatigue lives for Inconel 718.*

4 FATIGUE ε–N BEHAVIOR IN LWR ENVIRONMENTS

Several review articles[118-126] and ANL topical reports[10,12,13,45-47] present an analysis of the existing fatigue strain vs. life (ε–N) data and the procedures for incorporating environmental effects into the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) fatigue evaluations. The key material, loading, and environmental parameters that influenced the fatigue lives of carbon and low-alloy steels and austenitic stainless steels (SSs) were identified, and the ranges of these key parameters where environmental effects were significant were defined. Sections 4.1, 4.2, and 4.3 discuss in detail how various material, loading, and environmental parameters affected fatigue lives and how these effects are incorporated into the ASME Code fatigue evaluations for carbon and low-alloy steels, wrought and cast SSs, and nickel-chromium-iron (Ni-Cr-Fe) alloys. As subsequently discussed, the environmental fatigue correction factor (F_{en}) approach presumes that the slope of the fatigue strain (or stress) vs. life curve is the same in air and water environments. Based on the totality of the data in the report, this assumption appears reasonable. If environmental effects increase with decreasing strain, the use of an adjustment factor would be a function of strain and the concept becomes more complex.

4.1 Carbon and Low-Alloy Steels

Fatigue life models for estimating the fatigue life of carbon and low-alloy steels in light-water reactor (LWR) environments presented in the original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, were based on the updated Pressure Vessel Research Council (PVRC) database available at that time. The effects of key parameters, such as temperature, strain rate, dissolved oxygen (DO) content in water, and sulfur content in the steel, were included in the correlations. The functional forms for the effects of strain rate, temperature, DO level in water, and sulfur content in the steel were based on the data trends. For both carbon and low-alloy steels, the model assumed threshold and saturation values of 1.0 and 0.001%/s, respectively, for strain rate; 0.001 and 0.015 weight percent (wt.%), respectively, for sulfur; and 0.04 and 0.5 parts per million (ppm), respectively, for DO. The model also considered a threshold value of 150°C for the temperature below which environmental effects were considered to be insignificant. The fatigue ε–N data in LWR environments were fitted to a modified version of Equation 6 expressed as

$$\ln(N) = A - B \ln(\varepsilon_a - C) + D\, S^*\, T^*\, O^*\, \dot{\varepsilon}^*, \tag{31}$$

where S^*, T^*, O^*, and $\dot{\varepsilon}^*$ are transformed sulfur content, temperature, DO level, and strain rate, respectively, and D is a constant. The slope, B, of the fatigue ε–N behavior in LWR environments was considered to be the same as in air, and the constant C was also considered the same because, as discussed in Section 4.1.3, environmental effects on fatigue were not observed below a threshold strain level. The constants A and D were determined from the best-fit of the fatigue ε–N data in LWR environments. The constant A in the Argonne National Laboratory (ANL) models presented in the original version of NUREG/CR-6909 differed from the value reported earlier in NUREG/CR-6583, "Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels," issued February 1998, and NUREG/CR-6815, "Review of the Margins for ASME Code Design Curves—Effects of Surface Roughness and Material Variability," issued September 2003. Relative to the earlier model, the fatigue lives predicted by the updated model in the original version of NUREG/CR-6909 were approximately 6% lower for carbon steels and approximately 2% higher for low-alloy steels.

The effects of water environments on fatigue lives were expressed in terms of an F_{en}, which was defined as the ratio of life in air at room temperature, N_{RTair}, to that in water at the service temperature, N_{water}. Values of F_{en} were obtained from the ANL fatigue life models, where

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \quad (32)$$

Thus, because constants B and C are identical in both air and water environments, using Equation 6 for air and Equation 31 for water environment, Equation 32 can be rewritten for carbon and low-alloy steels as

$$\ln(F_{en}) = A_{air} - A_{water} - D_{water}\, S^*\, T^*\, O^*\, \dot{\varepsilon}^*. \quad (33)$$

In the original version of NUREG/CR-6909, fatigue lives in water were different for carbon and low-alloy steels. Therefore, separate F_{en} expressions were developed for carbon steels and for low-alloy steels. The F_{en} expressions developed in the original version of NUREG/CR-6909 for carbon and low-alloy steels are provided in Appendix E, Equations E0.27 and E0.28, respectively, and the transformed parameters are given in Appendix E, Equations E0.22– E0.25.

Section 4.2.7 of the original version of NUREG/CR-6909 notes that the effect of sulfur on the fatigue lives of carbon and low-alloy steels depended on the DO level in water. Therefore, the F_{en} determined from the expressions presented in the original version of the report probably yielded nonconservative estimates of fatigue life for low-sulfur (less than 0.005 wt.%) steels in high-temperature water containing greater than 1 ppm of DO. However, because this behavior was observed in laboratory data at DO concentrations (i.e., 2 ppm) that are much greater than those in LWR environments, the behavior is not likely to be applicable to LWR operating conditions.

During the time since the publication of the original version of NUREG/CR-6909, the U.S. Nuclear Regulatory Commission received several comments from interested stakeholders on the fatigue life models proposed therein. These comments have focused on the constants in the F_{en} expressions, which result in F_{en} values of approximately 2 even at temperatures below 150°C or at very high strain rates. Although this behavior seems inconsistent with the mechanisms that were proposed for environmental fatigue effects (because the calculated cumulative usage factor (CUF) step increases at the time environmental effects are applied), the constants were appropriate based on analyses of the fatigue ε–N data and assumed constraints that were applied in the data reduction and analysis. Figure 4-1 shows the fatigue ε–N behavior for carbon and low-alloy steels in air at room temperature and high-purity water at temperatures below 150°C. These results indicated that in environments of both pressurized-water reactors (PWRs) with low-DO and boiling-water reactors (BWRs) with normal water chemistry (NWC), the fatigue lives of carbon and low-alloy steels were a factor of 2 lower, thereby indicating the need for the constant terms in the F_{en} equations. Another comment received from interested stakeholders was in regards to the temperature range specified in the F_{en} expressions. The maximum temperature limit was specified as 350°C even though data on carbon and low-alloys steels at temperatures above 300°C were sparse.

In this report, the F_{en} expressions presented in the original version of NUREG/CR-6909 for incorporating environmental effects on the fatigue lives of carbon and low-alloy steels have been updated to address the stakeholders' comments using the much larger database described in Section 4.1.1. In LWR environments, the fatigue lives of carbon and low-alloy steels remain dependent on strain rate, DO level, temperature, and sulfur content of the steel. However, because the fatigue life of carbon and low-alloy steels is considered to be the same in

LWR environments, a single F_{en} expression is developed for both carbon and low-alloy steels. The sections below discuss the effects of various material and environmental parameters on the fatigue lives of these materials.

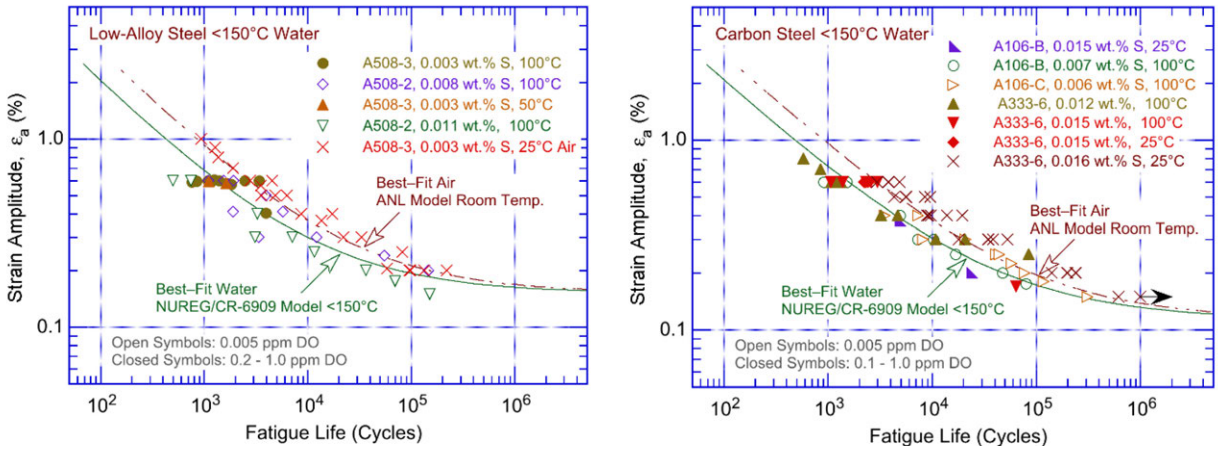


Figure 4-1 Fatigue ε–N behavior for carbon and low alloy steels in air at room temperature and high-purity water at temperatures below 150°C (Ref. 137).

4.1.1 Experimental Data

The primary sources of fatigue ε–N data for carbon and low-alloy steels in LWR environments are the tests performed by General Electric Company (GE) in a test loop at the Dresden Nuclear Power Station, Unit 1 reactor;[14,15] the work of Terrell at Materials Engineering Associates (MEA);[48-50] the work at ANL on fatigue of pressure vessel and piping steels;[10-13,40-47] the large Japan Nuclear Energy Safety Organization (JNES) database[136] that includes studies at Ishikawajima-Harima Heavy Industries, Hitachi, and Mitsubishi Heavy Industries (MHI) in Japan,[18-36] the work at Kraftwerk Union Laboratories (KWU) and Materialprufungsanstalt (MPA) in Germany;[55,56] and some recent investigations by Wu and Katada.[138-144] The database in LWR environments used in this report comprises a total of 1,174 tests, which represented 638 tests on carbon steels and 536 tests on low-alloy steels. The carbon steel tests included 21 heats of A106–Grs. B and C, A333–Gr. 6, A508–Gr. 1, A226 Cl. 4, A516–G70, and A516–KC70 steels. The low-alloy steel tests included 20 heats of A302–Gr. B, A508–Grs. 2 and 3, A533–Gr. B, 15MnNi63, and 17MnMoV64 steels. Table 4-1 summarizes the data sources for the updated database used in this report, as categorized by material type and test environment. Appendix B provides other material information, such as chemical composition, heat treatment, and room temperature tensile properties, for the various types and heats of materials.

Figure 4-2 presents a sampling of fatigue ε–N data on carbon and low-alloy steels in air and high-DO water at 288°C. The figure also shows curves based on the ANL air models (Equations 24 and 25 in Section 3.1.6). The fatigue data in LWR environments indicated a significant decrease in fatigue lives for carbon and low-alloy steels when the following four key threshold conditions were satisfied simultaneously: applied strain range (Δε) above a threshold value, service temperature above a threshold value, DO in the water above a minimum threshold level, and the loading strain rate below a threshold value. The sulfur content of the steel was also an important parameter for environmental effects on the fatigue lives for carbon and low-alloy steels. Although the microstructures and cyclic-hardening behavior of carbon and

low-alloy steels were significantly different, environmental degradation of the fatigue lives for these steels was nearly identical. As shown in Figure 4-2, for both steels, environmental effects on the fatigue lives were moderate for both steels (i.e., a factor of approximately 2 lower) if any one of the key threshold conditions was not satisfied.

Table 4-1 Sources of the Fatigue ε–N Data for Carbon and Low-Alloy Steels in LWR Environments.

ANL Mat. ID	Material Specifications	Sulfur Content (wt.%)	Dissolved Oxygen (ppm)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
Carbon Steels							
1	A106-Gr.B[a]	0.015	0.001-8.0	288	35	ANL, JNES (Higuchi)	10-13,136
2	A106-Gr.B	0.007	0.005	100, 290	8, 7	JNES (Kanasaki)	136
3	A106-Gr.B	0.020	0.01	288	18	MEA	48
4	A106-Gr.C (STS480)	0.006	0.005	100, 290	12, 9	JNES (Tsutsumi)	136
5	A106-Gr.C (STS480)	0.020	0.005	290	4	JNES (Tsutsumi)	136
7	A226-Cl.4 (SFVC2B)	0.004	0.05-8.0	289	15	JNES (Hirano)	136
8	A333-Gr.6 (STS42)	0.015	8.0	250	8	JNES (Ishihara)	136
9	A333-Gr.6 (STS42)	0.015	0.01-8.0	100, 150, 200, 250, 290	6, 12, 11, 32, 13	JNES (Higuchi)	136
10	A333-Gr.6 (STS42)	0.014	0.2	288	12	JNES (Higuchi, Emnomoto)	136
11	A333-Gr.6 (STS410)	0.006	8.0	288	5	JNES (Higuchi)	136
12	A333-Gr.6 (STS410)[b]	0.012	0.01-8.0	25, 50, 100, 150, 200, 250, 288/290	1, 3, 18, 19, 22, 13, 62	JNES (Higuchi, Hirano, Kanasaki, Nakao), ANL	136,10-13
14	A333-Gr.6 (STS410)	0.008	0.01-8.0	50, 100, 150, 200, 250, 289/290	2, 1, 5, 5, 5, 105	JNES (Abe, Higuchi, Kanasaki, Hirano)	136
15	A333-Gr.6 (STS410)	0.016	0.01-8.0	100, 200, 250, 289/290	7, 12, 4, 91	JNES (Hirano, Higuchi, Kanasaki)	136
16	A333-Gr.6 (STS410)	0.026	0.05-8.0	289	12	JNES (Hirano)	136
17	A508-Gr.1 (SFVV1)	0.008	8.0	300	14	JNES (Kitagawa)	136
21	A516-KC70	0.033	0.2	260	14[c]	GE	14, 15
22	A516-G70 (SGV480)	0.002	8.0	290	3	JNES (Higuchi)	136
23	CS tube	0.025	0.01-8.0	240	13	S/KWU	55, 56
Low-alloy Steels							
1	A302-Gr.B	0.027	0.001-0.9	288	9	ANL	10-13
2	A508-Gr.2	0.003	0.2	288	21[d]	JNES (Nakao, Higuchi)	136

ANL Mat. ID	Material Specifications	Sulfur Content (wt.%)	Dissolved Oxygen (ppm)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
4	A508-Gr.2[e]	0.008	0.05-8.0	200, 250, 289	6, 9, 39	JNES (Hirano)	136
5	A508-Gr.2[e]	0.008	0.005	100, 150, 200, 250, 290	10, 2, 10, 2, 13	JNES (Nomura)	136
6	A508-Gr. 3 (SFVV3)	0.003	0.1	288	9	JNES (Nagata)	136
12	A508-Gr. 3 (SFVV3)	0.003	0.05-8.0	50, 100, 150, 200, 250, 283/ 288/290	2, 12, 29, 27, 8, 60	JNES (Endou, Kasai, Higuchi)	136
14	A508-Gr. 3	0.002	0.1	288	16	Wu & Katada	141,143
15	A508-Gr. 3	0.018	0.5	285	3	MPA	55,56
16	A533-Gr. B	0.012	0.001-0.9	288	30	ANL	10-13
17	A533-Gr. B (SQV2A)	0.007	0.1, (0.01-4.0)	288, (20, 100, 147/150, 200, 250, 288)	8, (1, 4, 2, 2, 1, 23)	JNES (Nagata), Wu & Katada	136, 141,143
21	A533- Gr. B (SQV2A)	0.010	0.2-8.0	288/290	53[e]	JNES (Nakao, Higuchi)	136
23	A533-Gr. B	0.013	0.1	288	27	Wu & Katada	139,142, 143
24	A533-Gr. B	0.025	0.1	288	6	Wu & Katada	143
25	A533-Gr. B	0.038	0.1, 2.0	200, 288	6, 13	Wu & Katada	139
26	A533- Gr. B (SQV2A)	0.021	0.05-1.0	200, 289	5, 29	JNES (Higuchi)	136
27	A533-Gr. B Cl. 2	<0.001	1.0	289	3	JNES (Hirano)	136
28	A533-Gr. B	0.003, 0.005, 0.014	2.0	285	3, 2, 5	MPA	55,56
30	15MnNi63	0.003	0.4, 8.0	240	1, 4	MPA	55,56
31	17MnMoV64	0.018	0.45	210	21	S/KWU	55,56

[a] This material was tested at ANL and IHI (Higuchi).

[b] This material was also tested at ANL.

[c] Tests performed on rectangular bars under bending fatigue.

[d] Four tests performed under load control using sine waveform.

[e] Data include results for thermally aged materials.

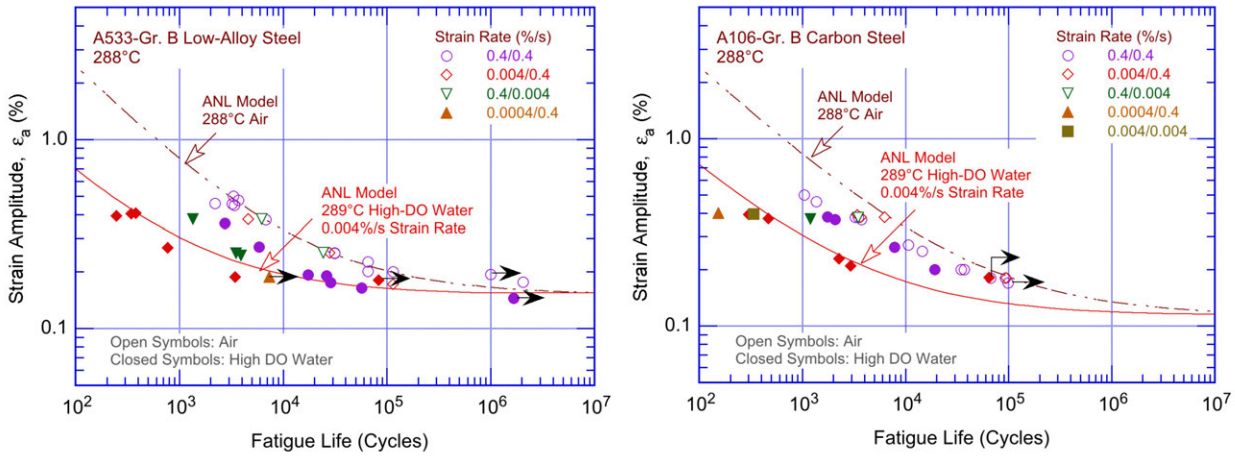


Figure 4-2 Strain amplitude vs. fatigue life data for (a) A533–Gr B and (b) A106–Gr B steels in air and high-DO water at 288°C (Ref. 10).

The existing fatigue data indicated that slow strain rates applied during tensile–loading cycles were primarily responsible for environmentally assisted reduction in the fatigue lives of these steels.[10] The mechanism of environmentally assisted reduction in the fatigue lives of carbon and low-alloy steels was termed strain-induced corrosion cracking (SICC).[78,85,86] Slow strain rates applied during both the tensile–load and compressive–load portions of load cycles (i.e., slow/slow strain rate test) did not further decrease the fatigue lives, e.g., refer to the solid diamond and solid square symbols in Figure 4-2(b) for A106–Gr B carbon steel. Limited data from fast/slow tests indicated that slow strain rates during compressive load cycles also decreased fatigue lives. However, the decrease in life was relatively small. For fast/slow strain rate tests, the major contribution of environment occurred during the slow reducing strain, but just after the peak tensile condition. For example, the fatigue lives of A533–Gr B low-alloy steels at 288°C, 0.7 ppm DO, and approximately 0.5% strain range decreased by factors of 5, 8, and 35 for the fast/fast, fast/slow, and slow/fast tests, respectively, i.e., refer to the solid circle, diamond, and inverted triangle symbols in Figure 4-2(a). Similar results were observed for A333–Gr. 6 carbon steel;[23] relative to the fast/fast test, the fatigue lives for the slow/fast and fast/slow tests at 288°C, 8 ppm DO, and 0.6% strain amplitude decreased the fatigue lives by factors of 7.4 and 3.4, respectively.

Environmental effects on the fatigue lives of carbon and low-alloy steels were consistent with the slip oxidation/dissolution mechanism for crack propagation, particularly at slow strain rates.[189,190] A critical concentration of sulfide (S^{2-}) or hydrosulfide (HS^-) ions, which is produced by the dissolution of sulfide inclusions in the steel, is required at the crack tip for environmental effects to occur. For this mechanism, a model for the initiation or cessation of environmentally assisted cracking (EAC) of these steels in low-DO PWR environments was also proposed.[182] Initiation of EAC requires a critical concentration of S^{2-} ions at the crack tip, which is supplied with the S^{2-} ions as the advancing crack intersects the sulfide inclusions, and the inclusions dissolve in the high-temperature water. Thus, environmental fatigue is controlled by the synergistic effects of sulfur content, environmental conditions, and flow rate. The EAC initiation/cessation model was used to determine the minimum crack extension and crack growth rates (CGRs) that are required to maintain the critical S^{2-} ion concentration at the crack tip and sustained environmental enhancement of growth rates.

- *LWR environments have significant effects on the fatigue lives of carbon and low-alloy steels; such effects were not considered in the original ASME Code fatigue design curves. Environmental effects for carbon and low-alloy steels may be incorporated into ASME Code fatigue evaluations using the F_{en} expression given in Equation 34 (Section 4.1.11).*

4.1.2 Strain Rate

The effects of strain rate on the fatigue lives of carbon and low-alloy steels in LWR environments were determined to be significant when other key threshold conditions (e.g., strain amplitude, temperature, and DO content), were satisfied. When any one of the threshold conditions was not satisfied (e.g., if low-DO PWR environments or temperatures less than 150°C were not present), the effects of strain rate were consistent with those observed in air.

When all threshold conditions were satisfied, the fatigue lives of carbon and low-alloy steels decreased logarithmically with decreasing strain rate. Figure 4-3 plots the fatigue lives of A106–Gr B and A333–Gr. 6 carbon steels and A533–Gr B low-alloy steel[10,23] as a function of strain rate. The lines in this figure represent the predicted fatigue lives determined from the updated F_{en} expressions presented later in Section 4.1.10 (for water for the two DO values identified on each plot) and either Equations 24 or 25 (for air). The decrease in fatigue lives in simulated (low-DO) PWR environments (e.g., DO levels ≤ 0.04 ppm) was less than in high-DO environments (i.e., a maximum of a factor of 3.5 to 4.5 lower). For the heats of A106–Gr. B and A333-Gr. 6 carbon steel and A533–Gr. B low-alloy steel, the effects of strain rate on fatigue lives saturated between values of 0.004 and 0.0004%/s strain rate. Although the data for A333–Gr. 6 carbon steel at 250°C and 8 ppm DO did not indicate saturation for strain rates up to 0.0001%/s, the results were comparable to those for the other two steels. The F_{en} expressions proposed by JNES for incorporating environmental effects on the fatigue lives of carbon and low-alloy steels recommended a saturation strain rate of 0.0004%/s for DO levels up to 0.7 ppm and 0.0001%/s above 0.7 ppm. Based on the data shown in Figure 4-3, the saturation strain rate in the ANL model was also changed to 0.0004%/s for all DO levels.

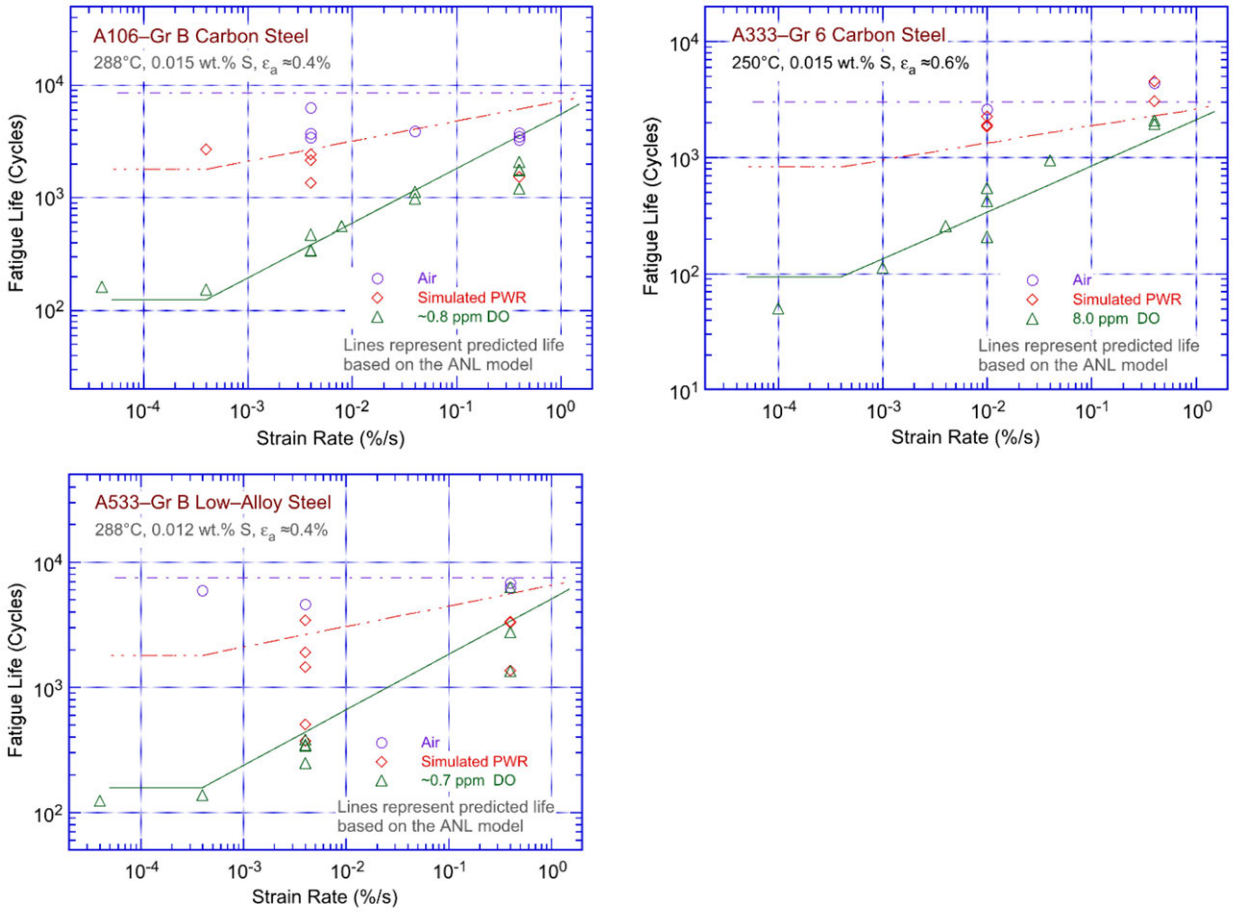


Figure 4-3 Dependence of fatigue lives of carbon and low-alloy steels on strain rate (Refs. 10 and 23).

For carbon and low-alloy steels, the potential effects of dynamic strain aging (DSA) are also likely to affect fatigue lives. Figure 4-4 shows the strain-rate dependence of fatigue life of A533-Gr. B low-carbon steel at 288°C and 200°C in high-purity water with 0.1 and 2.0 ppm DO. The lines represent the predicted fatigue lives based on the revised F_{en} expressions given in Equation 34. The results indicated that the predicted fatigue lives at 0.001%/s strain rate were greater than the experimental values, particularly at 200°C (i.e., the ANL models yielded nonconservative estimates for these environmental and loading conditions). This behavior was attributed to DSA. However, the difference between the estimated and experimental values was a factor of 2, which is within the range of data scatter for the fatigue ε–N data for carbon and low-alloy steels in LWR environments. Therefore, no additional adjustments were made to accommodate DSA effects in the revised ANL model for carbon and low-alloy steels.

Section 4.4 discusses the methodology for calculating F_{en} under conditions where temperature and strain rate are changing (i.e., actual load transients), and guidance is provided for defining the strain rate for a specific load cycle or load set pair.

- *The effect of strain rate on the fatigue lives of carbon and low-alloy steels in LWR environments were explicitly considered in the F_{en} expression given in Equation 34 (Section 4.1.11); the saturation strain rate limit was changed from the value of 0.001%/s, specified in the original version of NUREG/CR-6909, to 0.0004%/s to more appropriately reflect the data in the updated database.*

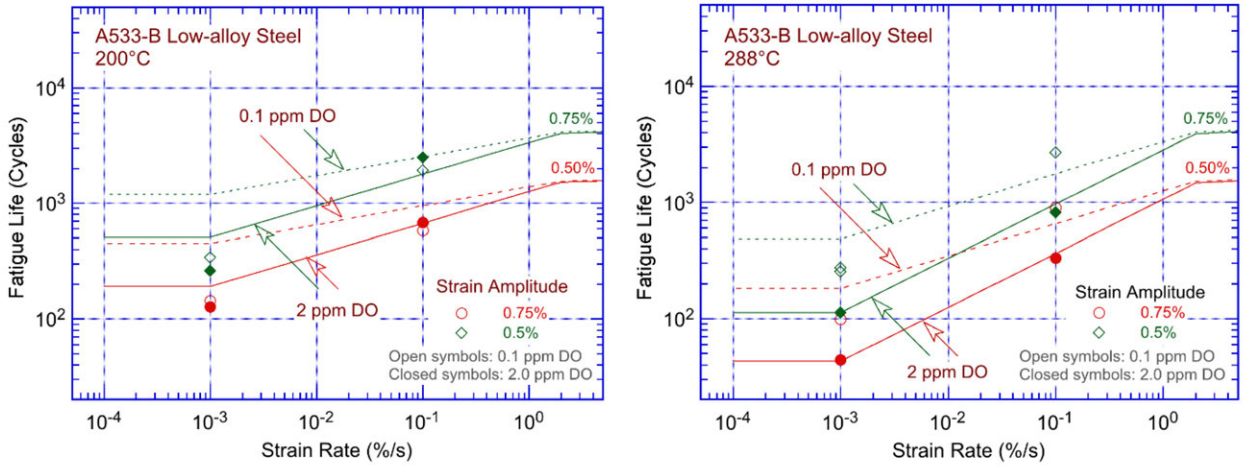


Figure 4-4 Fatigue life of A533–Gr. B low-alloy steel as a function of strain rate in high-purity water with 0.1 or 2.0 ppm DO (Refs. 141 and 143).

4.1.3 Strain Amplitude

The fatigue lives of carbon and low-alloy steels in LWR environments were observed to be lower than those in air. However, limited data indicated that at strain amplitudes below 0.3%, the fatigue lives of A533-Gr. B and A508-3 low-alloy steels were greater than those in air Figure 4-5). The reasons for this behavior were not clear. However, under the environmental and loading conditions that resulted in such behavior, estimates of fatigue lives of low-alloy steels were conservative. Therefore, in this report, this behavior was not explicitly addressed in the F_{en} methodology for estimating environmental effects on fatigue lives.

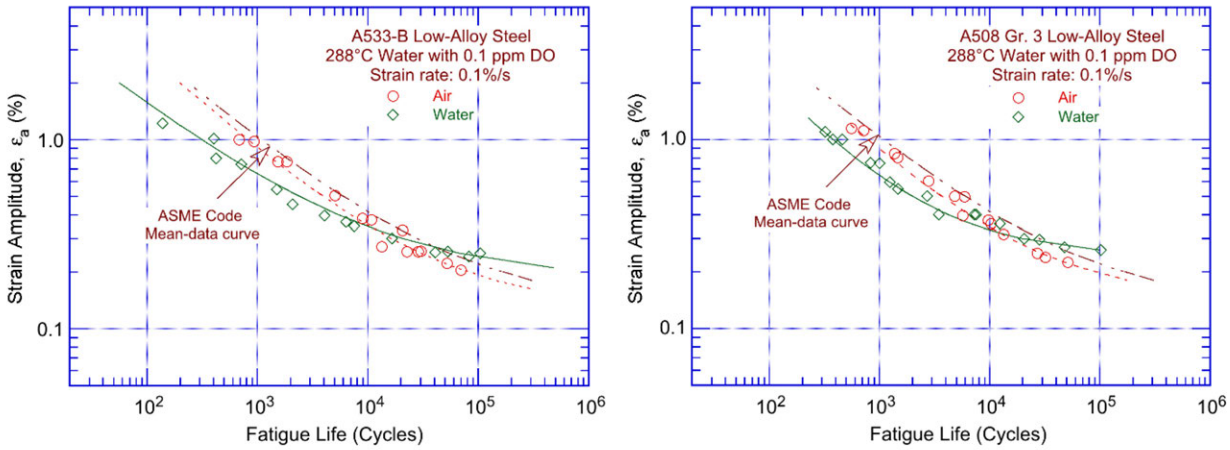


Figure 4-5 Fatigue strain-life behavior of A533–Gr. B and A508–Gr. 3 low-alloy steels at 288°C in air and high-purity water with 0.1 ppm DO (Ref. 151).

The available small-scale laboratory fatigue test data indicated that a minimum threshold strain range, $\Delta\varepsilon_{th}$, was required to cause an environmentally assisted decrease in fatigue lives (i.e., LWR water environments had no effect on the fatigue lives of these steels at strain ranges below the threshold value). Figure 4-2 shows the fatigue lives of A533–Gr B and A106–Gr B steels in high-DO water at 288°C and various strain rates.[10] Fatigue tests at low strain amplitudes were rather limited. Because environmental effects on fatigue lives increased with decreasing strain rates, fatigue tests at low strain amplitudes and strain rates that would result in significant environmental effects are restrictively time consuming. For the limited data that were available, the threshold strain amplitude (one-half of the threshold strain) was slightly above the fatigue limits for these steels.

Exploratory fatigue tests with changing strain rate were conducted to determine the $\Delta\varepsilon_{th}$ beyond which environmental effects were significant. The tests were performed with waveforms in which slow strain rates were applied during a portion of the tensile loading cycles (Figure 4-6).[10,24] Figure 4-7 summarizes the results for A106–Gr B steel tested in air and low- and high-DO environments at 288°C and approximately 0.75% strain range. The loading waveforms implemented in the tests consisted of segments of loading and unloading at fast and slow strain rates. Figure 4-7 plots the variation in fatigue lives of two heats of carbon steel and one heat of low-alloy steel[10,24] as a function of the fraction of the loading strain at slow strain rate. Open symbols indicate tests where the slow strain rate loading occurred near the maximum tensile strain, and closed symbols indicate tests where the slow strain rate loading occurred near the maximum compressive strain. If the relative damage was the same at all strain levels, fatigue lives should have decreased linearly from A to C along the chain–dot lines in Figure 4-7. Instead, the results indicated that, during a strain cycle, the relative damage due to slow strain rate occurred only after the strain level exceeded a threshold value. The $\Delta\varepsilon_{th}$ for these steels was in the range of 0.32 to 0.36%.

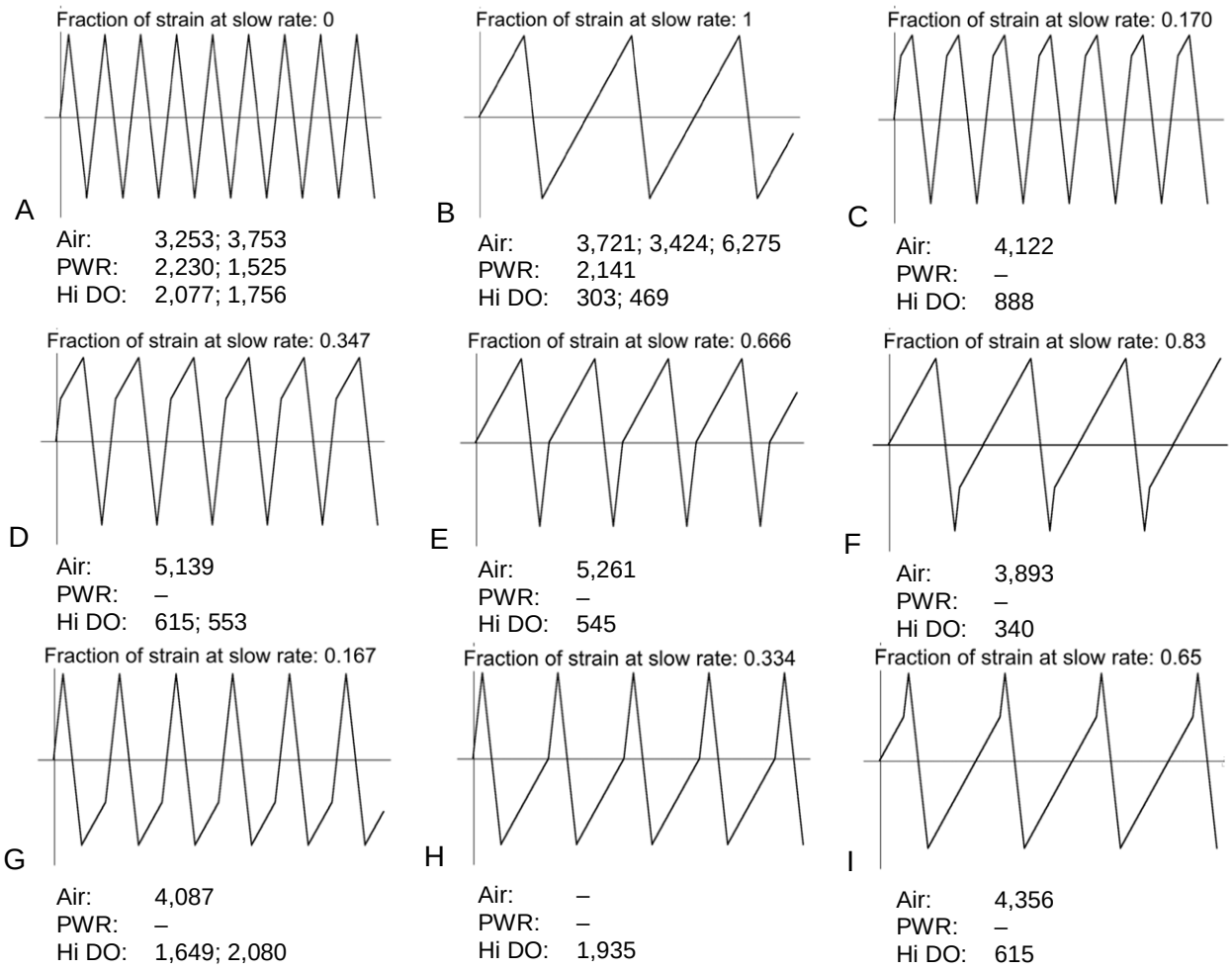


Figure 4-6 Fatigue life of A106–Gr B carbon steel at 288°C and 0.75% strain range in air and water environments under different loading waveforms (Ref. 10).

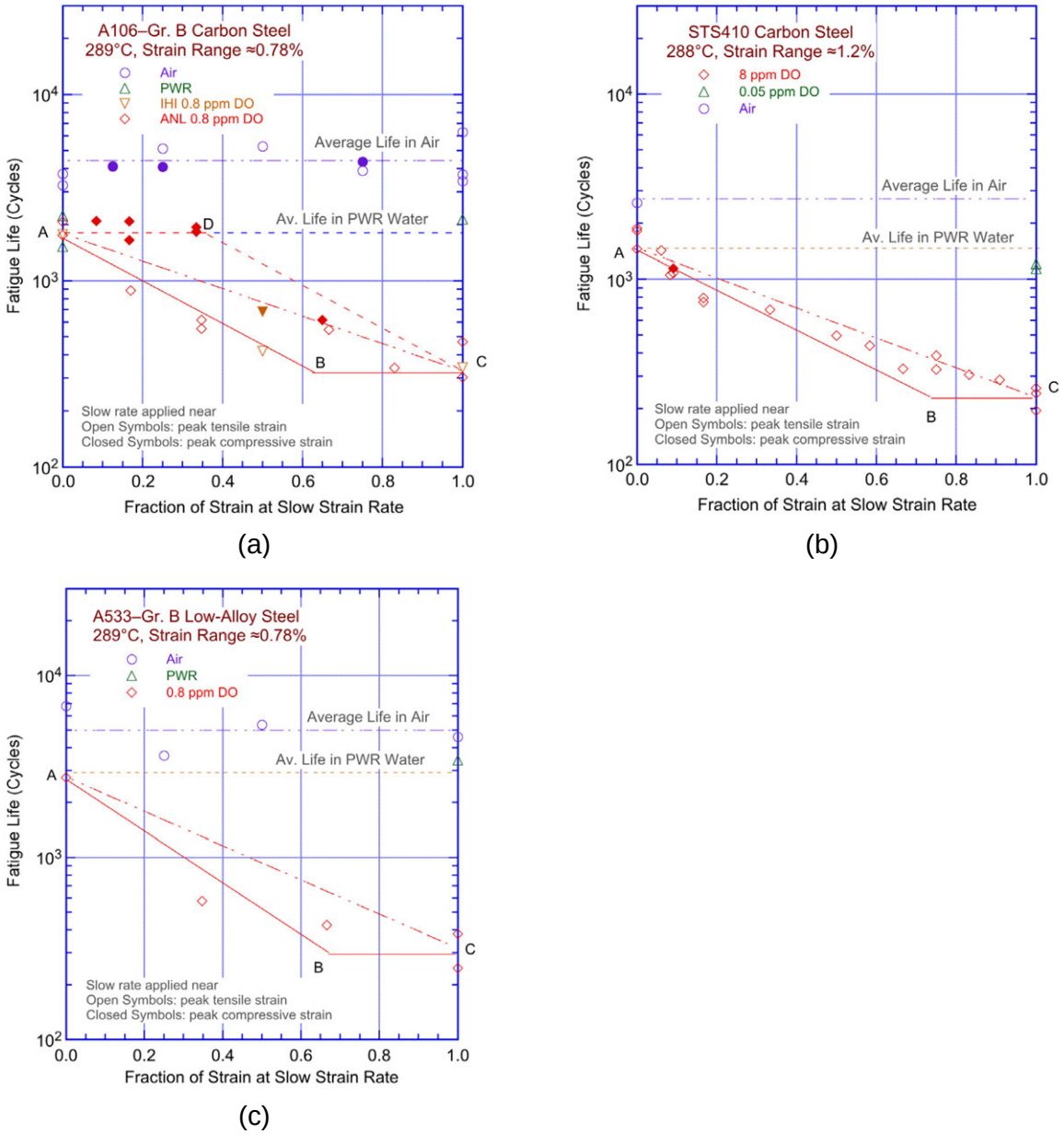


Figure 4-7 Fatigue lives of carbon and low-alloy steels tested with loading waveforms where slow strain rate was applied during a fraction of the tensile loading cycle (Refs. 10 and 24).

Loading histories with slow strain rate applied near the maximum tensile strain (i.e., waveforms C, D, E, or F in Figure 4-6) showed continuous decreases in fatigue lives (lines AB in Figure 4-7), followed by saturation when a portion of the slow strain rate occurred at strain levels below the threshold value (lines BC in Figure 4-7). In contrast, loading histories with slow strain rates applied near the maximum compressive strain (i.e., waveforms A, G, H, or I in Figure 4-6) did not produce any fatigue damage (line AD in Figure 4-7(a)) until the fraction of the strain was sufficiently large such that the slow strain rates occurred at strain levels greater than the threshold value. However, tests with such loading histories often showed lower fatigue lives than the predicted values (e.g., the solid inverted triangle or solid diamond symbols in

Figure 4-7(a)). The fatigue ε–N data presented in Figure 4-2 indicated that the threshold strain was between 0.25 and 0.40%. As discussed in Section 4.2.2, similar tests on austenitic SSs in PWR environments also showed the existence of a strain threshold below which the material was insensitive to environmental effects.[35] The $\Delta\varepsilon_{th}$ was independent of material type (weld metal or base metal) and temperature in the range of 250–325°C, but it tended to decrease as the strain range was decreased. For austenitic SSs, the threshold strain was expressed in terms of $\Delta\varepsilon$ (Equation 42 in Section 4.2.3). At a low strain amplitude (e.g., 0.3%), the proposed expression yielded a strain threshold of approximately 0.28%. Because the contribution of strain threshold was more significant at low strain amplitudes, a value of 0.28% was proposed in the original version of NUREG/CR-6909. After applying a factor of 2 on strain to account for the uncertainties associated with material variability and experimental scatter, a threshold "strain amplitude" of 0.07% (or a stress amplitude of 145 MPa (21 ksi)) was specified in the original version of NUREG/CR-6909 for use when performing ASME Code fatigue CUF evaluations for both carbon and low-alloy steels. The modified rate approach, described in Section 4.4, was used to predict the results from tests on A106-B and A333-6 carbon steels and A533-Gr. B low-alloy steel that were conducted with changing strain rate in high-DO water (0.8 to 8.0 ppm DO) at 289°C.[136]

Figure 4-8 shows the experimental values of fatigue lives and those predicted from the modified rate approach, with and without the consideration of a threshold strain. Most of the scatter in the data was due to heat-to-heat variations. The results indicated that estimates of fatigue lives based on the modified rate approach, without the consideration of a strain threshold, were in good agreement with the experimental values for A106-B and A333-6 carbon steels (Figure 4-8(a)). However, the data for A533-Gr. B low-alloy steel (shown as circular symbols in Figure 4-8) show an unusual behavior. First, the material showed a very strong dependence of environmental effects on applied strain amplitude. For example, for the tests with no strain rate change (shown by closed symbols), the fatigue lives at 0.6% strain amplitude (i.e., fatigue lives in the range of 100 to 800 cycles) showed excellent agreement with the experimental values.

However, the predicted fatigue lives at 0.4% strain amplitude (i.e., fatigue lives in the range of 250 to 1,500 cycles) were a factor of 2 higher and, at 0.3% strain amplitude (i.e., fatigue lives in the range of 350 to 3,300 cycles), the predicted fatigue lives were more than a factor of 3 higher. In addition, nearly all fatigue tests where slow strain rates were applied near the compressive strain peak, particularly the tests at 0.4% or 0.3% strain amplitudes, exhibited unusually low fatigue lives. The reasons for such a dependence of environmental effects on applied strain amplitude are not understood.

The results shown in Figure 4-8(b) included a threshold strain of 0.28%. It was assumed that, during a strain cycle beginning from the peak compressive strain, environmental effects on fatigue lives occurred only when the strain exceeded the strain threshold (i.e., the F_{en} was determined in accordance with the modified rate approach). Once again, the results for A106-B and A333-6 carbon steel either showed little or no changes in the resulting fatigue lives, or showed better agreement with the experimental values; however, the data for A533-Gr. B low-alloy steel, particularly for tests with slow strain rate imposed at the peak compressive strain, exhibited an unusual behavior. These results indicated that the modified rate approach, without consideration of a strain threshold, yielded the best estimates of fatigue lives of carbon and low-alloy steels in LWR environments.

- *Section 4.1.11 describes the procedure for calculating F_{en} in LWR water environments and Section 4.4 discusses the modified rate approach. However, while using the modified rate approach to determine F_{en} for a stress cycle or load set pair, inclusion of a threshold strain may yield nonconservative estimates for fatigue lives.*

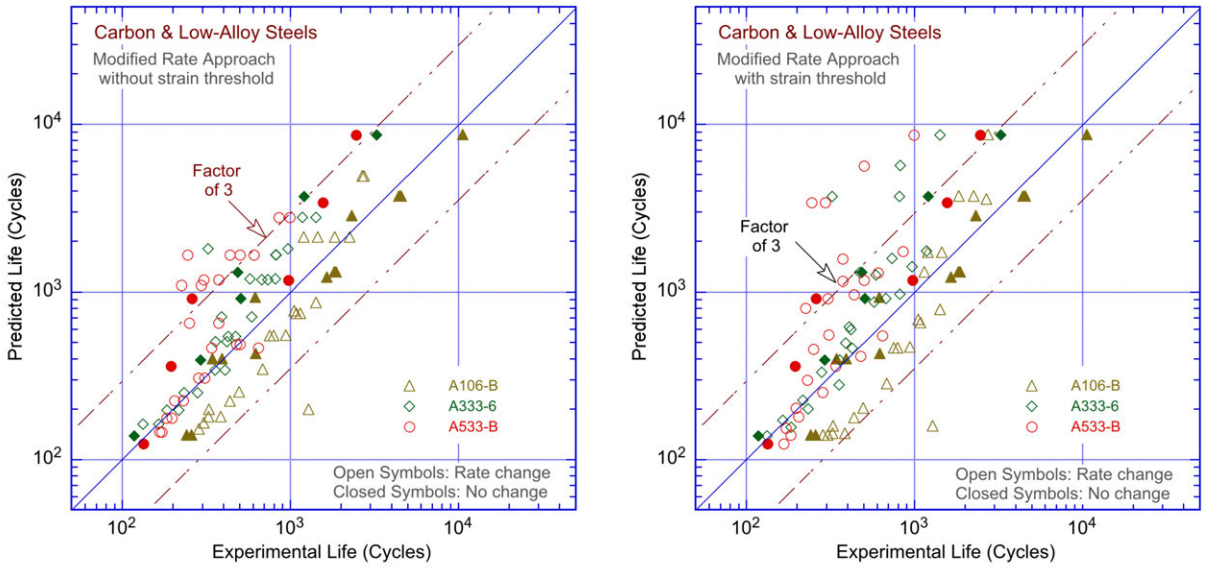


Figure 4-8 Experimental values of fatigue life and those predicted from the modified rate approach (a) without and (b) with consideration of a threshold strain (Ref. 136).

4.1.4 Temperature

Figure 4-9 shows the change in fatigue lives of two heats of A333–Gr. 6 carbon steel[18,19,22] as a function of test temperature at different levels of DO and strain rates. The sulfur content of the two heats of A333-Gr. 6 carbon steel was 0.015% and 0.012 wt.%. For all these tests, the strain amplitude was 0.6%, which is above the threshold strain limit for environmental effects. In air, both heats had a fatigue life of 2,993 cycles. The results indicated a threshold temperature of 150°C, above which the environment decreased the fatigue life if the DO content in the water was also above the critical level of 0.05 ppm. An artificial neural network (ANN) was used to find patterns and identify the threshold temperature below which environmental effects were moderate.[226] The main benefits of the ANN approach were that estimates of lives were based purely on the data and not on preconceptions and that, by learning trends, the network interpolated effects where data were not present. The factors that affected fatigue lives had synergistic effects on one another. The neural network detected and used these effects in its predictions. The training of the neural network was all based on the same dataset, but the order in which the data were presented to the ANN for training was varied, and the initial ANN weights were randomized to guard against overtraining and to ensure that the network did not arrive at a solution that was a local minimum. The results indicated that at high strain rates (0.4%/s), fatigue lives were relatively insensitive to temperature. At low strain rates (0.004%/s), fatigue lives decreased with an increase in temperature beyond a threshold value of approximately 150°C.[226] The precision of the data indicated that this trend was present in the data used to train the ANN. Only a moderate decrease in fatigue lives was observed in water at temperatures below the threshold value of 150°C or at DO levels less than or equal to 0.05 ppm. Under these conditions, fatigue lives in water were a factor of approximately 2 lower than in air. Figure 4-9 shows an average life of approximately 2,000 cycles for the 0.015 wt.% sulfur steel and approximately 1,200 cycles for the 0.012 wt.% sulfur steel.

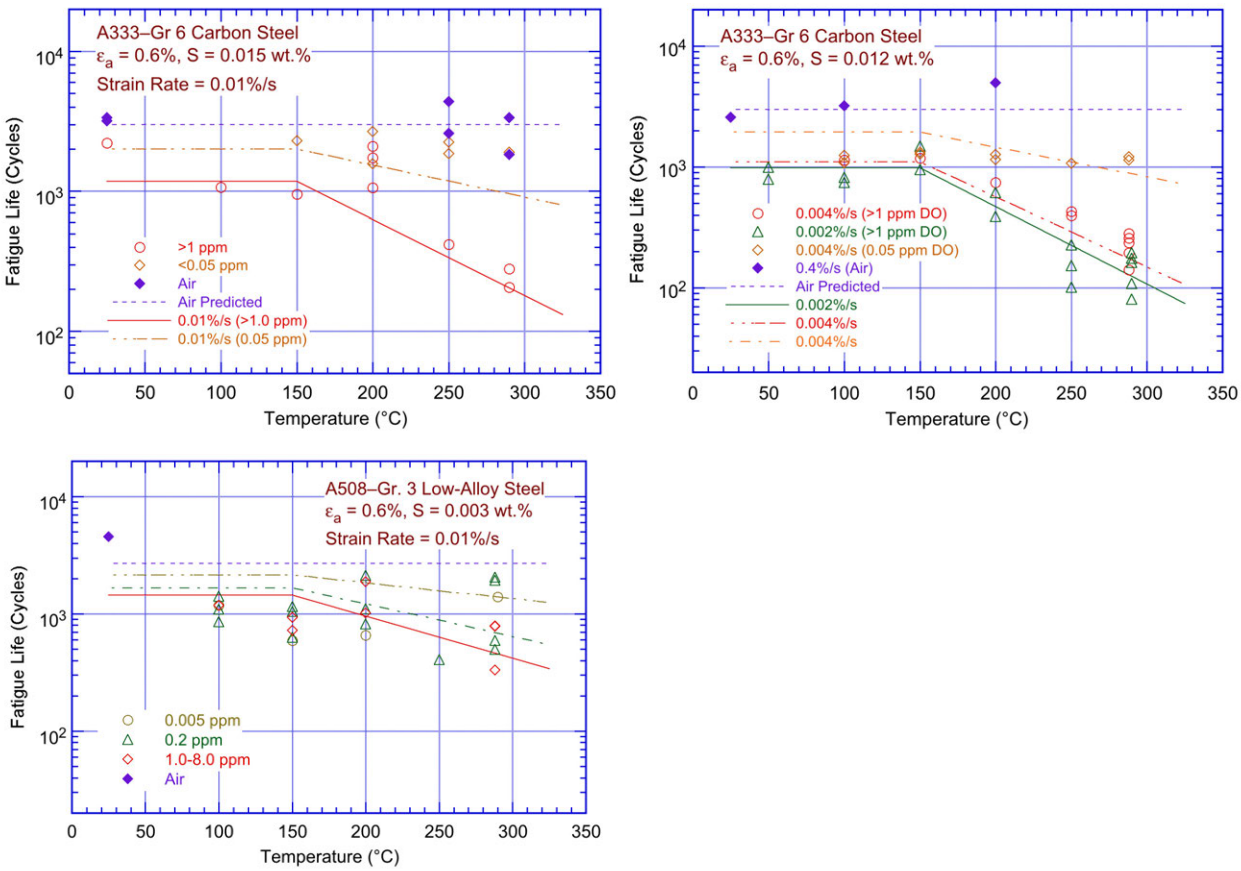


Figure 4-9 Change in fatigue life of A333–Gr. 6 carbon steel and A508 Gr. 3 low-alloy steel with temperature and DO (Ref. 136).

At temperatures above 150°C, the logarithm of fatigue life decreased linearly with temperature; the decrease in fatigue life was greater at higher temperatures and DO levels. However, as mentioned earlier, the temperature range specified in the original version of NUREG/CR-6909 for environmental effects for carbon and low-alloy steels in LWR environments extended beyond the range of actual fatigue ε–N data. An insignificant amount of fatigue ε–N data were available at temperatures above 290°C. Consequently, as discussed in Section 1.5, item xix and Section 4.1.11, the maximum temperature limit was extended slightly to 325°C as a reasonable bound to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions, especially when considering the use of average temperature.

Nearly all of the fatigue ε–N data available for evaluation for this report were obtained under loading histories with constant strain rates, temperatures, and strain amplitudes. However, the operating experience for U.S. LWRs indicates that the actual loading histories encountered during normal operation involves variable loading and environmental conditions. Some fatigue tests were conducted in Japan on 12 mm outer diameter tube specimens (1- and 3-mm wall thicknesses) of A333–Gr. 6 carbon steel in oxygenated water under combined mechanical and thermal cycling.[21] Triangular waveforms were used for both strain and temperature cycling. Two sequences were selected for temperature cycling (Figure 4-10): (1) an in-phase sequence in which the temperature cycling was synchronized with the mechanical strain cycling and (2) another sequence in which the temperature and strain cycling were out of phase (i.e., the maximum temperature occurred at the time of minimum strain level and vice versa). Three

temperature ranges, 50–290°C, 50–200°C, and 200–290°C, were selected for the tests. The results are shown in Figure 4-11; an average temperature was used to plot the thermal cycling tests. Because environmental effects on fatigue lives were moderate and independent of temperature below 150°C, the temperatures for the tests cycled in the ranges of 50–290°C or 50–200°C were determined from the average of the threshold temperature of 150°C and the maximum temperature of the test (i.e., 220°C and 175°C, respectively). The results (Figure 4-11) indicated that load cycles involving variable temperature conditions represented by an average temperature (e.g., the fatigue lives from variable temperature tests were comparable with those from constant temperature tests).

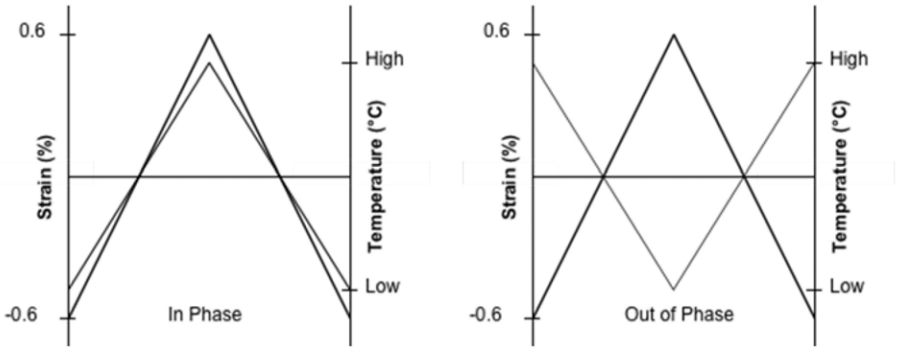


Figure 4-10 Waveforms for changes in temperature and strains during exploratory fatigue test (Ref. 21).

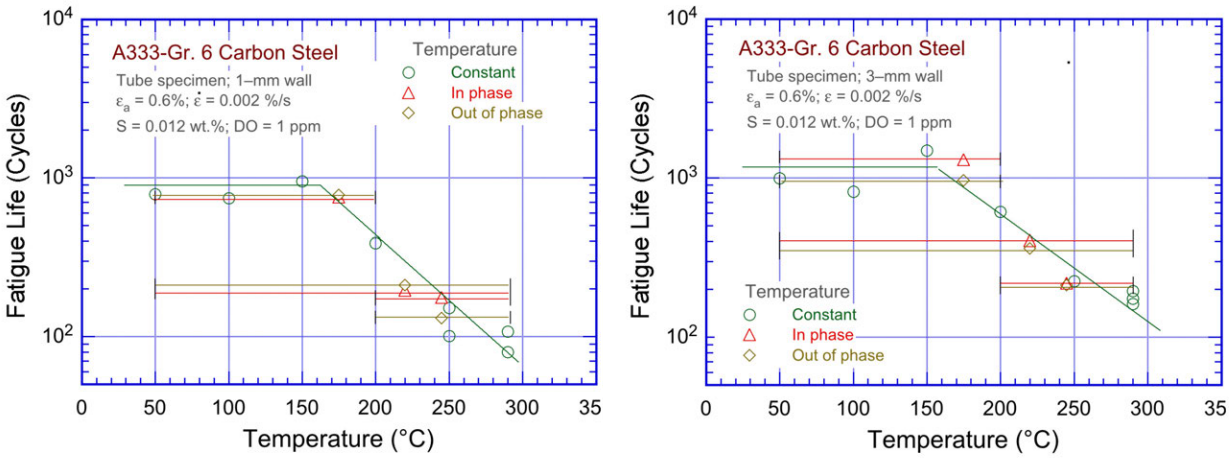


Figure 4-11 Fatigue lives of A333–Gr. 6 carbon steel tube specimens under varying temperature conditions, as indicated by horizontal bars (Ref. 21).

However, nearly identical fatigue lives were obtained from the in-phase and out-of-phase tests. Assuming that the tensile–load cycle was primarily responsible for the observed environmentally assisted reductions in fatigue lives, and that the applied strains and temperatures must be above a minimum threshold value for environmental effects to occur, the fatigue lives obtained from the out-of-phase tests were expected to be longer than those obtained from the in-phase tests. This expectation was based on the premise that the applied strains above the threshold strain occurred at temperatures above 150°C for the in-phase tests, whereas the applied strains above the threshold strain occurred at temperatures below 150°C for the out-of-phase tests. Under the assumption that

environmental effects on fatigue lives were considered to be minimal below the 150°C temperature and 0.28% strain threshold values, the average temperatures for the out-of-phase tests at 50–290°C, 50–200°C, and 200–290°C were 195, 160, and 236°C, respectively, instead of 220, 175, and 245°C, as plotted in Figure 4-11. Thus, the fatigue lives from out-of-phase tests were expected to be at least 50% higher than those from the in-phase tests. Such differences in environmental conditions were therefore assumed to be offset by the difference in the cyclic hardening behavior of the material for the out-of-phase and in-phase tests. From those observations, it was concluded that estimates of fatigue lives for actual nuclear power plant transients based on an average temperature may yield nonconservative estimates.

- *The effects of temperature on the fatigue lives of carbon and low-alloy steels in LWR environments were explicitly considered in F_{en} defined in Equation 34 (Section 4.1.11). For simple, linear transients, an average temperature that considers the threshold temperature of 150°C may be used to calculate F_{en} for a specific stress cycle or load set pair. Complex thermal transients that have multiple increasing and decreasing temperature excursions should be evaluated using the maximum temperature for the specific stress cycle or load set pair unless information is available to justify the use of an average temperature.*

4.1.5 Dissolved Oxygen

Figure 4-12 shows the dependence of fatigue lives of carbon and low-alloy steels on the DO content in water.[18,19,22] For the tests summarized in this figure, the temperatures, applied strain amplitudes, and sulfur contents in the steels tested were above, and the strain rates were below, the critical threshold values. The results indicated a minimum DO level of 0.04 ppm above which the environment decreased the fatigue lives of the steels tested. The effect of DO content on fatigue lives saturated at 0.5 ppm (i.e., increases in DO levels above 0.5 ppm did not cause further decreases in fatigue lives). In Figure 4-12, for DO levels between 0.04 and 0.5 ppm, fatigue lives decreased logarithmically with DO. Estimates of fatigue lives from the trained ANN also showed a similar effect of DO on the fatigue lives of carbon steels and low-alloy steels.

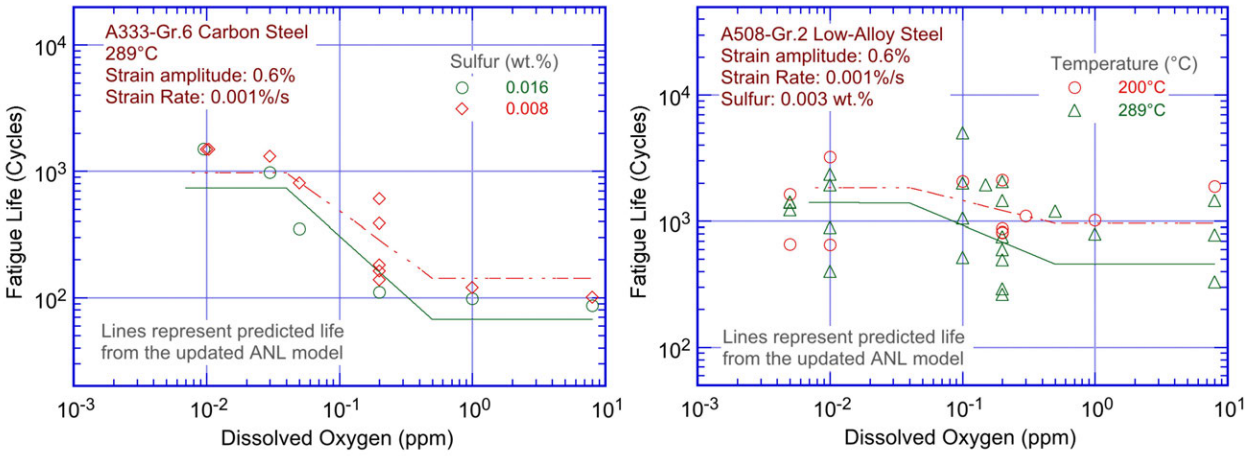


Figure 4-12 Dependence on DO of the fatigue lives of carbon and low-alloy steels in high-purity water (Refs. 18, 19, and 22).

Environmental effects on the fatigue lives of carbon and low-alloy steels were insignificant at DO levels of 0.04 ppm and strain rates greater than or equal to 1%/s; they increased with decreasing

strain rate (F_{en} was about 2 at 320°C, 0.010% S, 0.04 ppm DO, and 0.04%/s strain rate). In contrast, environmental enhancement of CGRs was observed in low-alloy steels even in low-DO water.[182] This apparent inconsistency of fatigue ε–N data with the CGR data was attributed to differences in the environmental conditions locally at the crack tip. As discussed earlier in Section 2.2.1.2, environmentally assisted enhancement of CGRs in low-alloy steels required a critical level of sulfides at the crack tip.[182] The development of this critical sulfide concentration required a minimum crack extension of 0.33 mm and CGRs in the range of 1.3×10^{-4} to 4.2×10^{-7} mm/s. These conditions were not achieved under the majority of the available fatigue ε–N tests. Thus, environmental effects on fatigue lives are expected to be insignificant in low-DO environments for carbon and low-alloy steels.

- *The effects of DO levels on the fatigue lives of carbon and low-alloy steels in LWR environments were explicitly considered in the F_{en}, defined in Equation 34 (Section 4.1.11).*

4.1.6 Water Conductivity

In most of the studies reviewed for this report, the DO level in water was considered as the key environmental parameter that affected the fatigue lives of materials in LWR environments. Studies on the effects of the concentration of anionic impurities in water (expressed as the overall conductivity of water) were limited. The limited data indicated that the fatigue lives of WB36 low-alloy steel at 177°C in water with approximately 8 ppm DO decreased by a factor of approximately 6 when the conductivity of the water was increased from 0.06 to 0.5 μS/cm.[78,227] Similar behavior was also observed in another study of the effects of conductivity on the initiation of short cracks.[228]

- *U.S. LWRs are unlikely to accumulate significant fatigue cycles during off–NWC conditions. Thus, the effects of water conductivity on fatigue lives were not considered in the determination of F_{en} for carbon and low-alloy steels.*

4.1.7 Sulfur Content in Steel

Sulfur content and morphology were the most important material-related parameters that determined susceptibility of low-alloy steels to environmentally enhanced fatigue CGRs.[184-188] A critical concentration of S^{2-} or HS^- ions was required at crack tips for environmental effects to occur. The corrosion fatigue CGRs and threshold stress intensity factor, ΔK_{th}, were both a function of the sulfur content in the range 0.003–0.019 wt.%.[187] The probability of environmental enhancement of fatigue CGRs in precracked specimens of low-alloy steels, diminished markedly for sulfur contents less than 0.005 wt.%.

The available fatigue ε–N data for carbon and low-alloy steels also indicated a dependence of fatigue lives on sulfur content. When all the threshold conditions were satisfied, the environmental effects on the fatigue lives of these materials increased with increased sulfur content. Figure 4-13 plots the fatigue lives of A508–Cl. 3 low-alloy steels with 0.003 and 0.008 wt.% sulfur and A333–Gr. 6 carbon steels with 0.008 and 0.016 wt.% sulfur as a function of strain rate,. The available datasets were too sparse to establish a functional form for dependence of fatigue lives on sulfur content and to define either a threshold for sulfur content below which environmental effects were unimportant or an upper limit above which the effects of sulfur on fatigue lives may saturate. A linear dependence of fatigue life vs. sulfur content was assumed in proposed correlations for estimating the fatigue lives of carbon steels and low-alloy steels in LWR environments.[10,118] The limited data indicated that, in high-purity water with

0.2 ppm DO at 289°C, the fatigue lives of carbon steels with 0.016 and 0.026 wt.% sulfur at 0.001%/s strain rate and 0.3% strain amplitude were comparable. Similar behavior was observed for low-alloy steels with greater than 0.0125 wt.% sulfur. Therefore, fatigue lives of carbon and low-alloy steels were assumed to saturate at sulfur contents above 0.015 wt.%.[10]

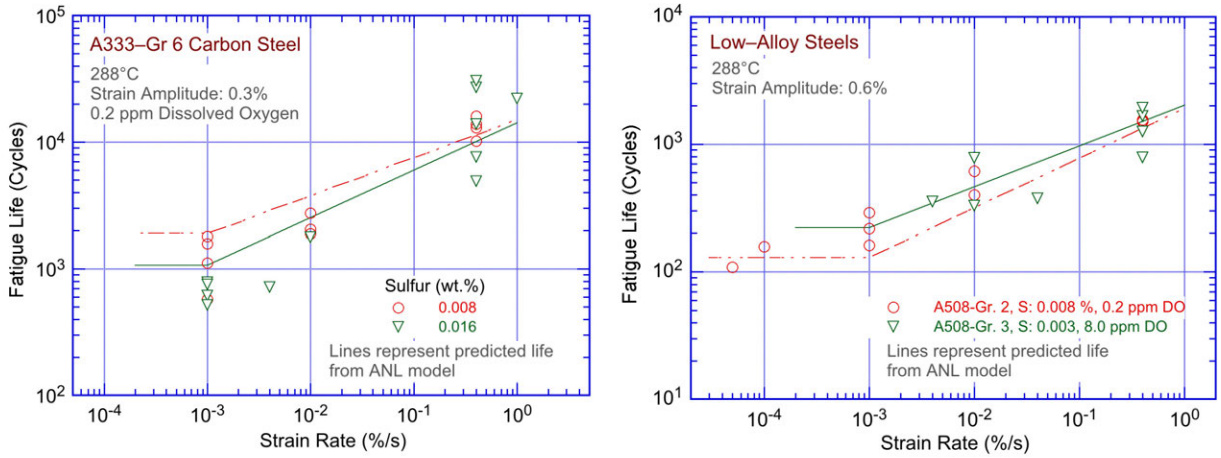


Figure 4-13 Effect of strain rate on fatigue life of low-alloy steels with different sulfur contents (Refs. 10 and 136).

The existing fatigue ε–N data also indicated significant reductions in fatigue lives for some heats of carbon steels with sulfur levels as low as 0.002 wt.%. Figure 4-14 plots the fatigue lives of several heats of A333–Gr. 6 carbon steels with sulfur contents of 0.002–0.016 wt.% in high-DO water at 288°C and 0.6% strain amplitude were plotted as a function of strain rate.[10] Environmental effects on the fatigue lives of these steels were independent of sulfur contents in the range of 0.002–0.015 wt.%. The fatigue lives of carbon steel in air-saturated water (approximately 8 ppm DO) were relatively insensitive to sulfur contents in very high-DO water. Under these conditions, the effects of DO dominated fatigue lives.

- *The effects of steel sulfur content on the fatigue lives of carbon and low-alloy steels in LWR environments were explicitly considered in the F_{en}, defined in Equation 34 (Section 4.1.11). Evaluation of experimental data on low-sulfur steels (less than 0.005 wt.% sulfur) in water with more than 1 ppm DO should be performed with caution because, in some cases, the effects of sulfur were observed to be larger than those predicted by Equation 34.*

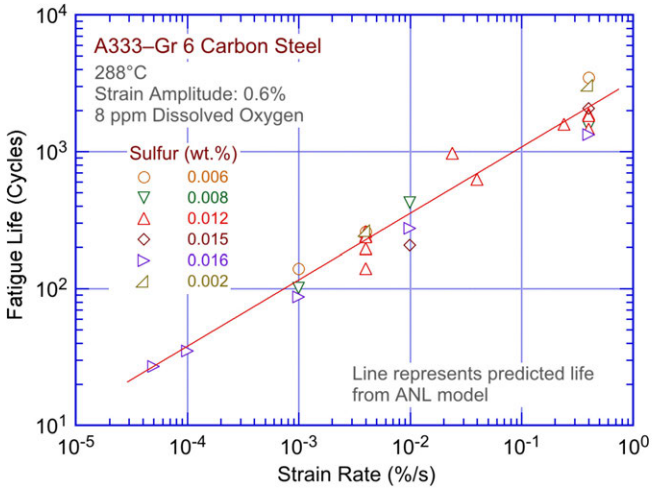
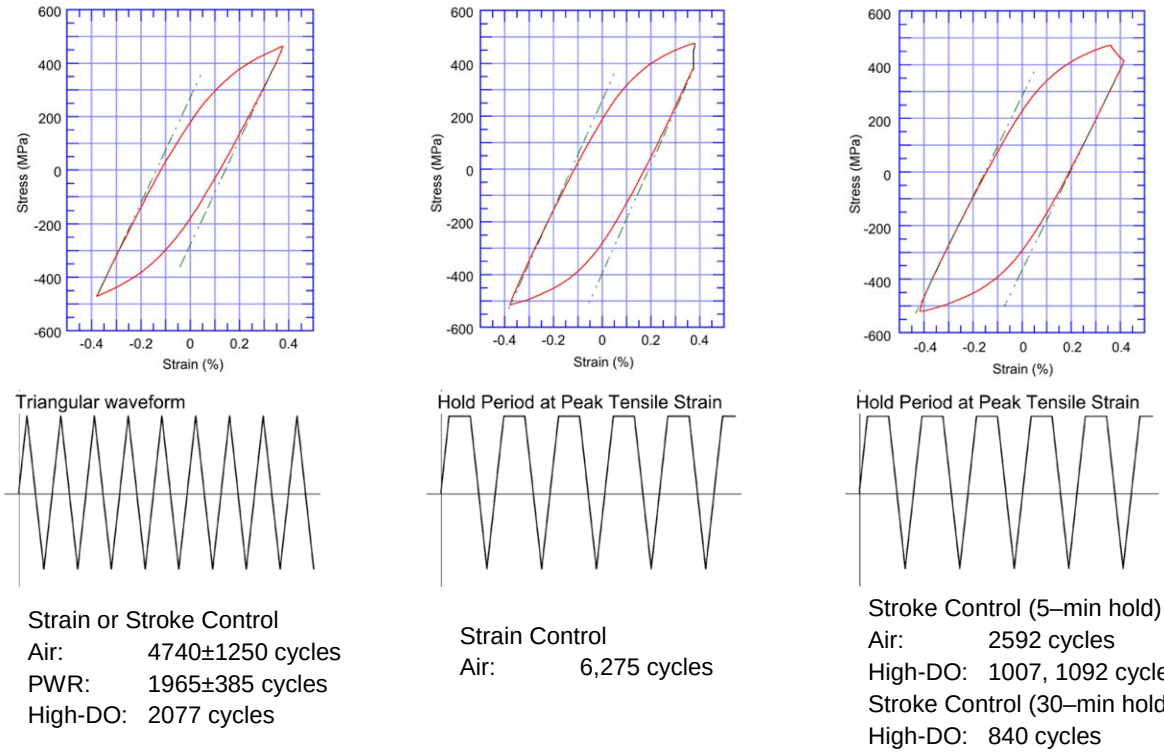


Figure 4-14 Effect of strain rate on the fatigue lives of A333–Gr. 6 carbon steels with different sulfur contents (Ref. 10).

4.1.8 Hold Periods

Fatigue tests conducted using trapezoidal loading waveforms indicated that hold periods at peak tensile strains decreased the fatigue lives of carbon steels in high-DO water at 289°C.[10,24] However, examination of the data indicated that these results were caused by limitations of the test procedures or by frequency effects. Figure 4-15 plots loading waveforms, hysteresis loops, and fatigue lives for the tests on A106–Gr B carbon steel in air and water environments.[10] A 300–s hold period was sufficient to reduce fatigue lives by approximately 50% (approximately 2,000 cycles without a hold period and approximately 1,000 cycles with a hold period); a longer hold period of 1800 s resulted in lower fatigue lives than those obtained with a 300–s hold period. For example, two 300–s hold tests at 288°C and approximately 0.78% strain range in oxygenated water with 0.7 ppm DO yielded fatigue lives of 1,007 and 1,092 cycles; the fatigue life from a 1,800–s hold test was 840 cycles. These tests were conducted in stroke–control mode and were different from conventional hold–time tests in a strain–controlled mode where the total strain in the sample was held constant during the hold period. However, a portion of the elastic strain was converted to plastic strain because of stress relaxation. In the stroke–controlled tests, the occurrence of additional plastic strains in the samples was due to relaxation of elastic strains from the load trains (Figure 4-15). Consequently, significant strain changes occurred during the hold periods; the measured plastic strains during the hold periods were approximately 0.028% from relaxation of the gauge and 0.05–0.06% from relaxation of the load trains. These conditions resulted in strain rates of 0.005–0.02%/s during the hold periods. The reductions in fatigue lives were attributed to slow strain rates during the hold periods. In addition, frequency effects decreased the fatigue lives obtained from hold time tests. For example, in air, the fatigue lives of stroke-controlled tests with hold periods were approximately 50% lower than those without the hold periods.



Strain or Stroke Control
Air: 4740±1250 cycles
PWR: 1965±385 cycles
High-DO: 2077 cycles

Strain Control
Air: 6,275 cycles

Stroke Control (5–min hold)
Air: 2592 cycles
High-DO: 1007, 1092 cycles
Stroke Control (30–min hold)
High-DO: 840 cycles

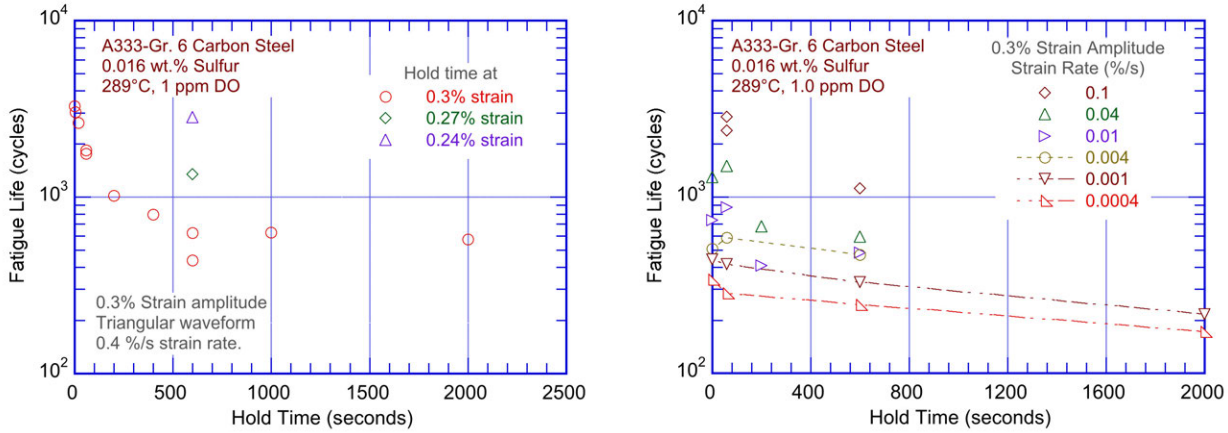
Figure 4-15 Fatigue lives of A106–Gr B steel in air and water environments at 288°C, 0.78% strain range, and hold periods at peak tensile strain (Ref. 10); (Hysteresis loops are for tests in air).

Hold time tests were also conducted on STS410 carbon steel at 289°C in water with 1 ppm DO (Figure 4-16).[24] The most significant observation was that, for strain hold periods at peak tensile strain, reduction in fatigue lives were significant in tests that were conducted at fast strain rates (e.g., 0.4%/s). The reduction in fatigue lives with hold periods decreased at lower strain rates with insignificant reductions in fatigue lives at 0.004%/s strain rate. The results also indicated that the decrease in fatigue lives with extended hold periods saturated at values that were comparable to fatigue lives at slow strain rates (e.g., 0.004%/s).

The most significant observation of these data was that little or no decreases in fatigue lives were observed when the hold periods were below the peak strain during the decreasing strain portions of the fatigue cycles (i.e., 0.06% below the peak strain of 0.24%). Based on these results, Higuchi et al.[24] concluded that the procedures for calculating F_{en} did not need revision.

The JNES report[136] investigated hold time effects and reported that, in the high-temperature water environments, the fatigue lives of carbon and low-alloy steels were reduced due to strain hold times at the peak (local maximum value). Fatigue life reductions caused by strain hold times at the peak were significant at higher strain rates; however, they were reduced as the strain rate decreased. There were little or no observed fatigue life reductions at strain rates of 0.004%/s or less. JNES concluded that the extent of fatigue life reduction depended on the length of the hold time, and that fatigue life reductions tended to be saturated as the hold time became longer. A threshold was observed at a strain rate of 0.004%/s. For carbon steels, the effects of strain hold times were negligible at strain rates of 0.004%/s or lower. Fatigue life reductions caused by strain hold times in low-alloy steels were smaller than those in carbon steels. Although fatigue lives were reduced due to strain hold times at the peak (local maximum

value), no reduction in fatigue lives was observed when strain was held at 0.06% below the peak strain after overshoot, although tensile stresses corresponding to the yield point still remained. From these results, JNES concluded that the effects of strain hold times in the actual components were not necessary because the peak thermal stress generated by actual operating thermal transients is not considered to exceed the monotonic yield stress significantly; however, for strain rates exceeding 0.004%/s, evaluations should be performed assuming a threshold strain rate of 0.004%/s while considering fatigue life reduction caused by strain holding when the strain is at the peak and held under the internal pressure condition that accompanies elastic followup.



(a) (b)

Figure 4-16 Effect of hold periods on the fatigue lives of A333–Gr. 6 carbon steel at 289°C in water with 1 ppm DO (Ref. 24).

As discussed in Section 4.1.11, the differences in fatigue lives observed in the JNES tests were generally within the data scatter for the fatigue ε–N data in LWR environments. Thus, the effects of hold time from available data are inconclusive and, until such time as sufficient data are available, the updated F_{en} methodology does not address these effects. Further research of these effects is recommended.

- *The available ε–N data investigated in this report were not fully conclusive with respect to the effects of hold time periods on the fatigue lives of carbon and low-alloy steels in LWR environments. Thus, the updated F_{en} methodology did not explicitly address hold time effects.*

4.1.9 Flow Rate

Nearly all of the laboratory fatigue ε–N data for LWR environments were obtained at very low water flow rates. Recent test data indicated that, under the environmental conditions typical for operating BWRs, environmental effects on the fatigue lives of carbon steels were lower at high flow rates (7 m/s) compared to the fatigue lives under very low flow rate conditions similar to those flow rates where most of the data were obtained.[25,26,55] Figure 4-17 shows the effects of water flow rate on the fatigue lives of high- and low-sulfur A333–Gr. 6 carbon steel and A533-Gr. B low-alloy steel in high-purity water at 289°C tested at different strain amplitudes and strain rates.

The results indicated that the effects of increased flow rates were modest. The benefits were greater for high-sulfur steels at high strain amplitudes and high strain rates (e.g., 0.4%/s).[25,26]

At 0.3% strain amplitude and 0.01%/s strain rate, for all DO levels, fatigue lives were increased by a factor of approximately 2 when the flow rate was increased from approximately 10^{-5} to 7 m/s. At 0.6% strain amplitude and 0.001%/s strain rate, fatigue lives were increased by a factor of approximately 6 in water with 0.2 ppm DO and by a factor of approximately 3 in water with 1.0 or 0.05 ppm DO.

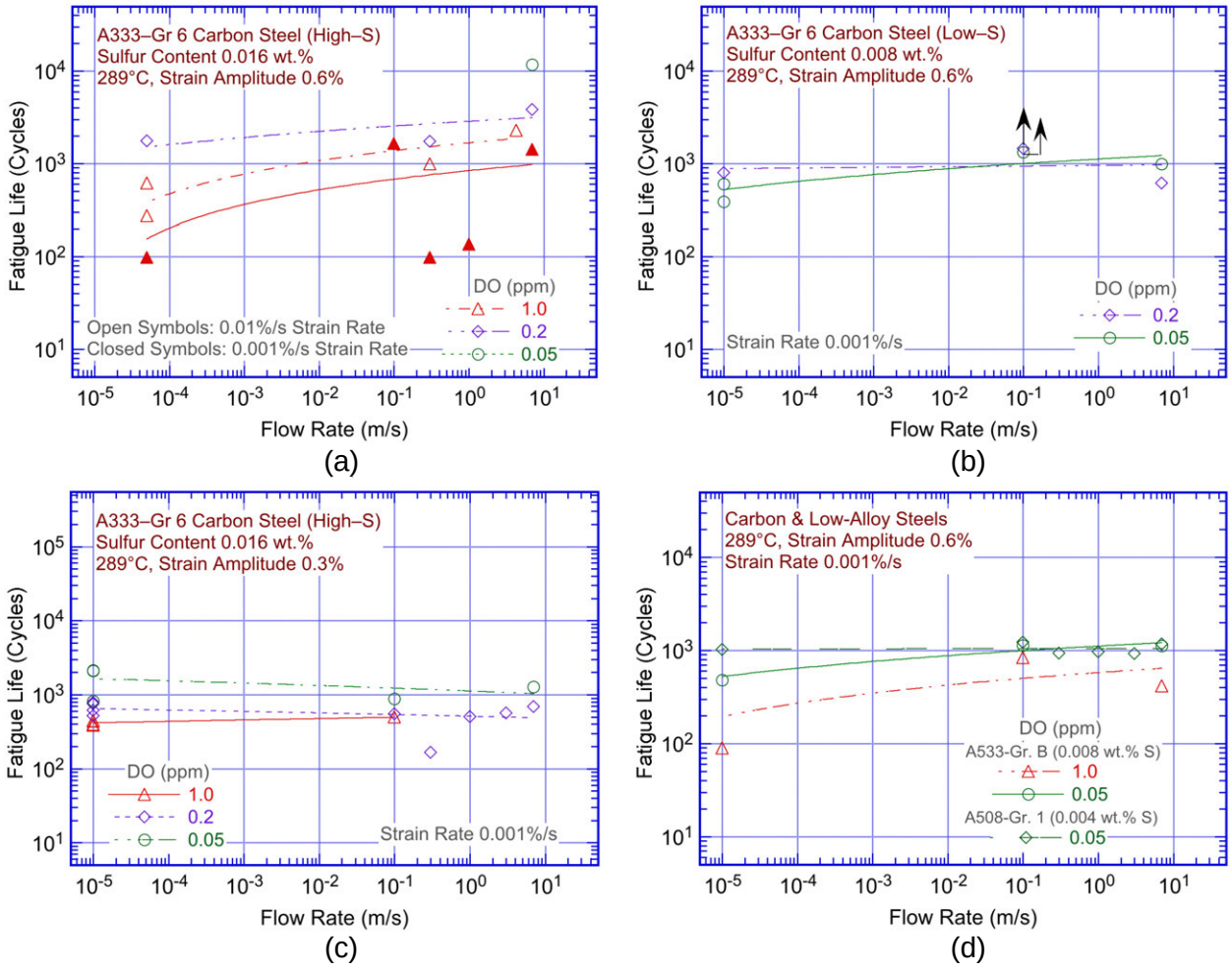


Figure 4-17 Effects of water flow rate on fatigue lives of A333–Gr. 6 and A508 Gr. 1 carbon steels and A533 Gr. B low-alloy steel at 289°C and 0.3 or 0.6% strain amplitudes and various strain rates (Refs. 25 and 26).

Under similar loading conditions (i.e., 0.6% strain amplitude and 0.001%/s strain rate), a low-sulfur (0.008 wt.%) heat of A333–Gr. 6 carbon steel showed a factor of approximately 2 increase in fatigue life with increased flow rates. Note that the beneficial effects of flow rate were determined from a single test on each material at very low flow rates; data scatter in LWR environments is typically a factor of approximately 2. A factor of 2 increase in fatigue lives was observed (Figure 4-18) at KWU during component tests with 180° bends of carbon steel tubing (0.025 wt.% sulfur) when internal flow rates of up to 0.6 m/s were established.[55] The tests were conducted at 240°C in water that contained 0.2 ppm DO.

- *Because of the uncertainties in the flow conditions at or near the locations of crack initiation, the updated F_{en} methodology did not explicitly consider the potentially beneficial effects of flow rates on the fatigue lives of carbon and low-alloy steels.*

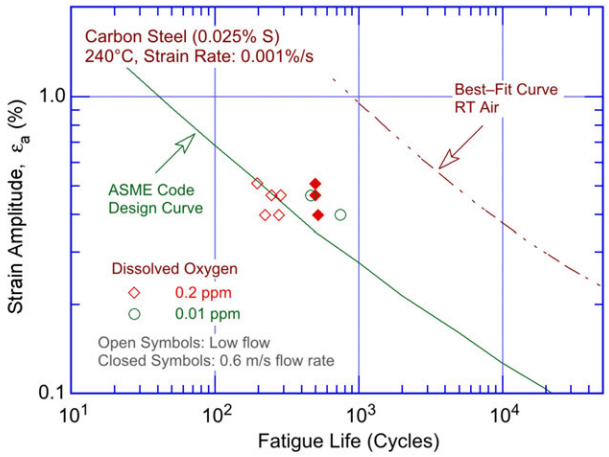


Figure 4-18 Effect of flow rate on low-cycle fatigue of carbon steel tube bends in high-purity water at 240°C (Ref. 55) (RT is room temperature).

4.1.10 Fatigue Life Model

As discussed in the beginning of Section 4.1, the fatigue life models for estimating the fatigue lives of carbon and low-alloy steels in LWR environments presented in the original version of NUREG/CR-6909 were based on an analysis of the updated PVRC database using an approach expressed by Equations 31-33. For this report, more recently available data were fit to a modified version of the Langer equation expressed by Equation 6, which included a term for environmental effects on fatigue lives. The environmental term included the effects of key parameters, such as temperature, strain rate, DO content in the water, and sulfur content in the steel on the fatigue lives of carbon and low-alloy steels, and considered revised constraints based on stakeholder comments and experience with implementation of the F_{en} methodology in industry analyses. However, a single F_{en} was determined for both carbon and low-alloy steels, from Equation 31 assuming that all three constants A, B, and C were the same as in air. The constant D and the functional forms of the dependencies and constraints of the transformed sulfur content, temperature, DO level, and strain rate were determined from the best fit of Equation 31 to the experimental data for carbon and low-alloy steels in LWR environments. The details are given in the next section.

- *The ANL fatigue life models for carbon and low-alloy steels represent the mean values of fatigue life as a function of applied strain amplitude, temperature, strain rate, DO level in the water, and sulfur content of the steel. The models did not include the effects of parameters (such as mean stress, surface finish, size and geometry, and loading history) known to influence fatigue lives; the effects of these parameters were considered in the development of the fatigue design curves, as discussed in Chapter 5.*

4.1.11 Environmental Fatigue Correction Factor

To incorporate environmental effects into ASME Code Section III fatigue evaluations, the original version of NUREG/CR-6909 specified that the fatigue usage for a specific stress cycle or load set pair based on the current ASME Code Section III fatigue design curves was multiplied by the F_{en} for carbon steels and low-alloy steels. Appendix A, "Incorporating Environmental Effects into Fatigue Evaluations," to the original version of NUREG/CR-6909 provides further details for incorporating environmental effects into fatigue evaluations.

The original F_{en} expressions for carbon and low-alloy steels have been updated in this report using the larger fatigue ε–N database described in Table 4-1 to remove some of the conservatism in the F_{en} methodology and to reflect the additional data available since the initial publication of NUREG/CR-6909. As discussed previously, an additional objective of the reevaluation was to investigate the significance of the constant terms in the previous expressions. The updated evaluation addressed stakeholders' concerns related to (1) the constants in the F_{en} expressions that result in F_{en} values of approximately 2 even when strain rate is very high or temperature is very low and (2) the temperature dependence of F_{en} for carbon and low-alloy steels.

The available fatigue ε–N data for carbon and low-alloy steels were reanalyzed using a different dependence of fatigue lives on strain rate, DO, and temperature such that F_{en} is equal to 1 at high strain rates (i.e., greater than 2.2%/s). A single F_{en} expression was developed for both carbon and low-alloy steels. The functional form of the new F_{en} expression and for the dependence of F_{en} on the sulfur content in the steel were comparable to the expressions proposed by JNES.[136] In addition, a maximum temperature limit was selected at 325°C as a reasonable extension to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions considering the use of average temperature (as discussed in Section 4.4 and shown in Figure 4-67). In addition, the limit for the saturation strain rate was decreased from 0.001 to 0.0004%/s. A best fit of the experimental data yielded the following expression for F_{en}, which was defined as the ratio of fatigue life in air at room temperature (25°C (77°F)) to that in water at the service temperature, for both carbon and low-alloy steels:

$$F_{en} = \exp((0.003 - 0.031\dot{\varepsilon}^*)\, S^* T^* O^*), \tag{34}$$

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

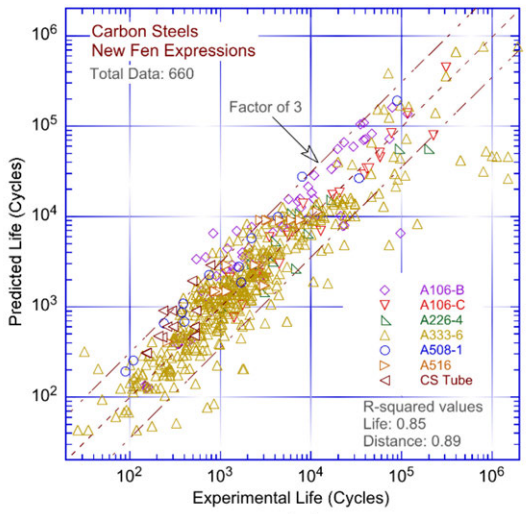
$$\begin{aligned} S^* &= 2.0 + 98\,S && (S \le 0.015 \text{ wt.\%}) \\ S^* &= 3.47 && (S > 0.015 \text{ wt.\%}) \end{aligned} \tag{35}$$

$$\begin{aligned} T^* &= 0.395 && (T < 150°C) \\ T^* &= (T - 75)/190 && (150°C \le T \le 325°C) \end{aligned} \tag{36}$$

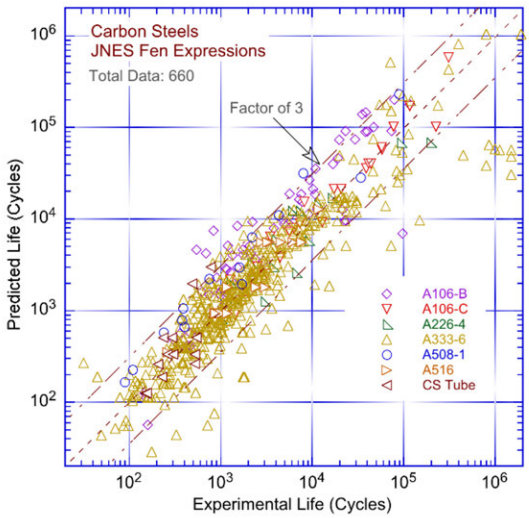
$$\begin{aligned} O^* &= 1.49 && (DO < 0.04 \text{ ppm}) \\ O^* &= \ln(DO/0.009) && (0.04 \text{ ppm} \le DO \le 0.5 \text{ ppm}) \\ O^* &= 4.02 && (DO > 0.5 \text{ ppm}) \end{aligned} \tag{37}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/2.2) && (0.0004\%/s \le \dot{\varepsilon} \le 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/2.2) && (\dot{\varepsilon} < 0.0004\%/s). \end{aligned} \tag{38}$$

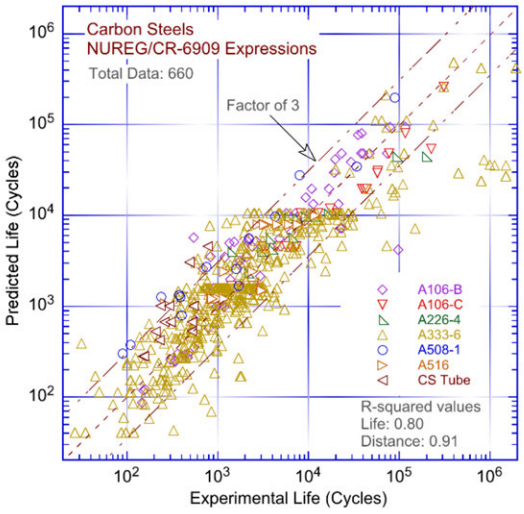
Figure 4-19 and Figure 4-20 plot the experimental values of fatigue lives compared to those predicted by Equation 34 and the expressions contained in the original version of NUREG/CR-6909 for carbon and low-alloy steels, respectively. The results indicate that the new F_{en} expressions represent a better fit of the experimental data relative to the fit for the expressions in the original version of NUREG/CR-6909; the regression (R-squared) values increased from 0.80 to 0.85 for carbon steels and from 0.83 to 0.84 for low-alloy steels. The new expressions typically underestimated environmental effects for operating conditions that resulted in very large F_{en} values (i.e., greater than 40) and in the high-cycle fatigue regime (i.e., fatigue lives above 50,000 cycles). However, such conditions are not typical of the thermal transients encountered during reactor operation or evaluated in most ASME Code CUF calculations. A threshold strain amplitude (one-half of $\Delta\varepsilon$) is also defined, below which LWR water environments have an insignificant effect on fatigue life. The threshold strain amplitude is specified as 0.07% or a 145 MPa (212 ksi) for both carbon and low-alloy steels.



(a)



(b)



(c)

Figure 4-19 Experimental fatigue lives of carbon steel in LWR environments vs. fatigue lives predicted from the (a) new expression, (b) JNES expression, and (c) the previous NUREG/CR-6909 expression.

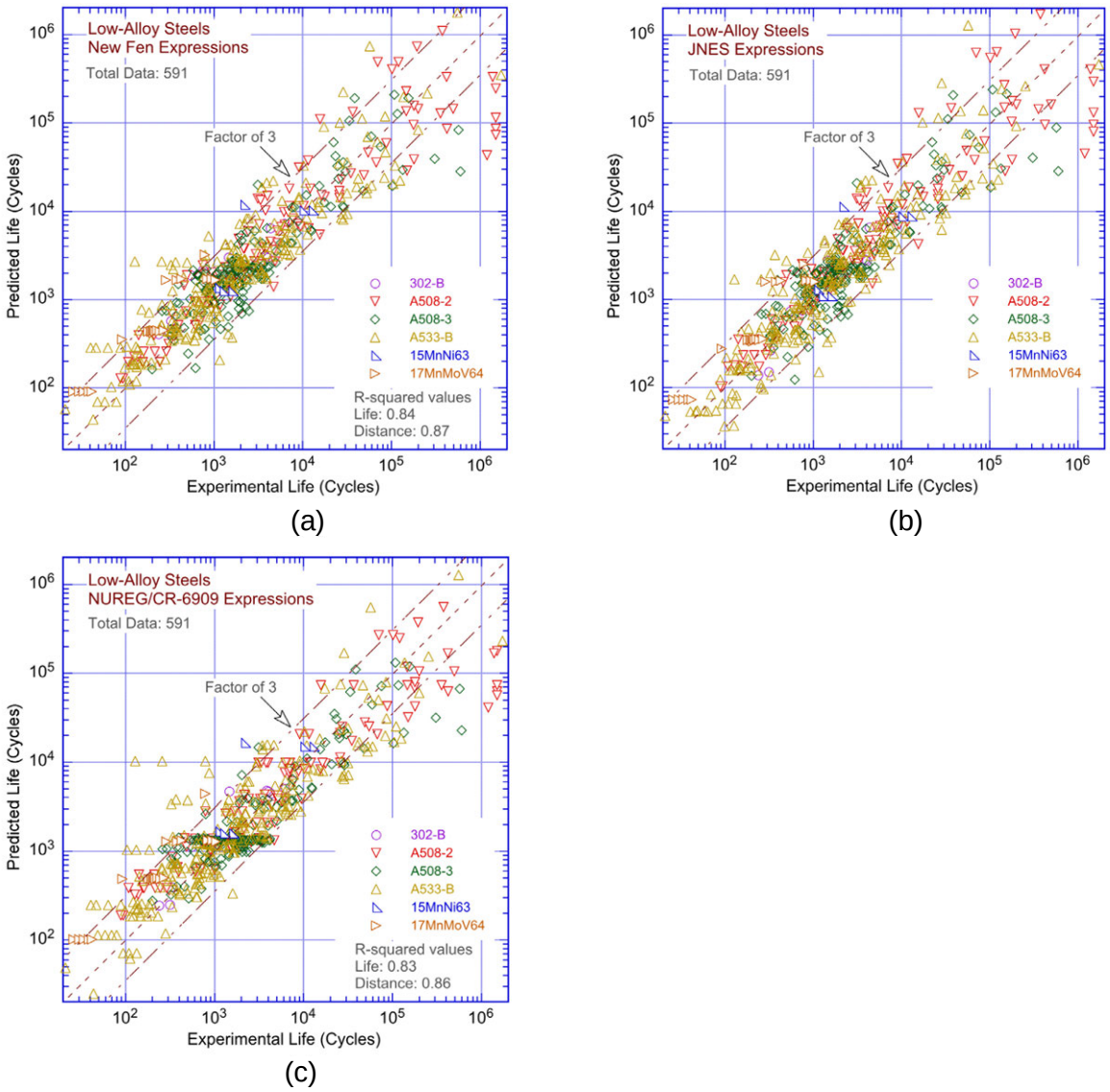


Figure 4-20 Experimental fatigue lives of low-alloy steels in LWR environments vs. fatigue lives predicted from the (a) new expression, (b) JNES expression, and (c) the previous NUREG/CR 6909 expression.

Figure 4-21 shows a comparison that was made of the fatigue lives predicted for carbon and low-alloy steels using the new F_{en} expressions and the JNES F_{en} expressions. In general, F_{en} values calculated from the new ANL expression were marginally lower than those obtained from the JNES expression in Reference 136; the fatigue lives predicted by the new ANL expressions were either comparable to or slightly longer than those predicted from the JNES expressions. However, there were a few data points for carbon steels and several data points for low-alloy steels for which the fatigue lives predicted by the JNES expression were significantly lower than those predicted by the new ANL expression (bottom left corner of the plots in Figure 4-21). As discussed previously, the new ANL F_{en} expression was optimized under environmental and loading conditions that are anticipated during reactor operation (i.e., conditions that yield F_{en} values less than 40). This optimization limitation explains the differences observed between the two expressions because the predicted F_{en} values for nearly all of these data points were above 60. The tests associated with these points were conducted in air-saturated water (8 ppm DO) at very low

strain rates. Considering this, the ANL and JNES expressions are in very good agreement, which is remarkable given that the development approaches used were different.

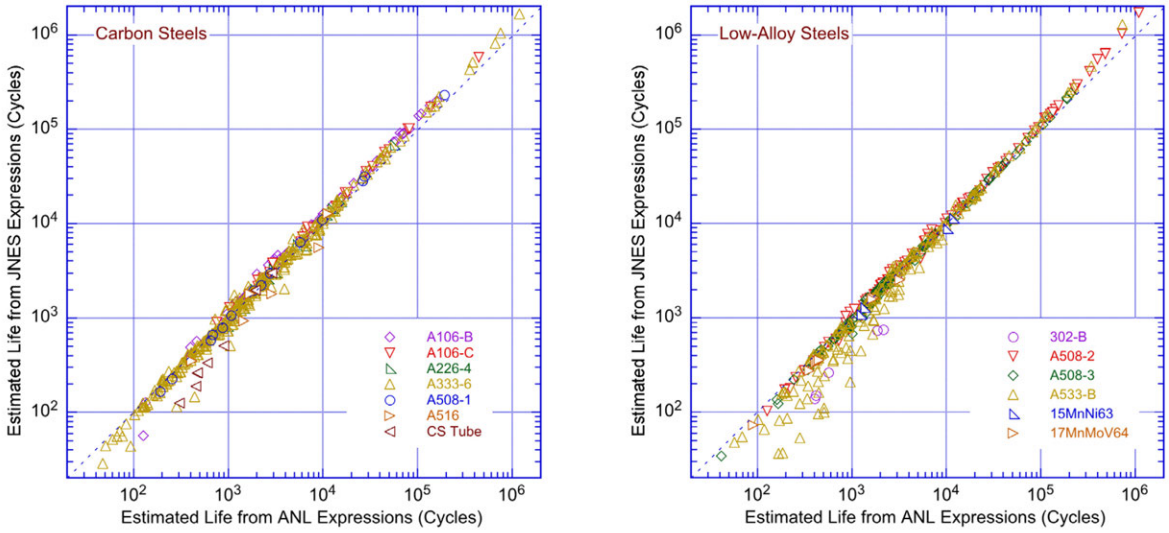


Figure 4-21 Comparison of the fatigue lives of carbon and low-alloy steels predicted from the new Fen expression and the JNES Fen expression.

Upon completion of the modeling phase, the residual errors (i.e., the Cartesian distance of each data point from the mean prediction curve) did not show significant patterns, such as heteroskedasticity (changing variance), or a nonzero slope. The residual errors for each variable, grouped by steel type, were plotted and are shown in Figure 4-22 and Figure 4-23 for carbon and low-alloy steels, respectively. The residuals were determined from the difference between the logarithms of the estimated lives and predicted lives. Thus, negative residual errors indicated conservative estimates of fatigue lives and positive residual errors indicated nonconservative estimates of fatigue lives (i.e., predicted lives were greater than the observed fatigue lives). However, if the residuals for a specific heat were not evenly distributed about zero, it did not necessarily indicate any deficiency in the predictive models. Such results indicated that the specific heat was either superior or inferior to the average behavior predicted by the model. For example, a positive residual indicated that the heat was inferior (i.e., the constant A from Equation 6 for the heat was smaller than the median value of A determined for the model) and a negative residual indicated that the heat was superior to the average behavior for the material. Section 4.1.13 discusses this behavior further.

The results presented in Figure 4-22 and Figure 4-23 did not show any unexplained patterns. In general, high variance tended to be associated with longer lives and lower strain amplitudes. Furthermore, biases were traceable to heat-to-heat variations. For example, the heats of A108-Gr. B, A508-Gr. 1, and A516-KC70 had inferior fatigue resistances and two heats of A333-Gr. 6 (ANL Material Identifications (IDs) 8 and 10 in Table 4-1) had superior fatigue resistances compared to the average behavior represented by the fatigue ε–N model (Equations 39 and 40).

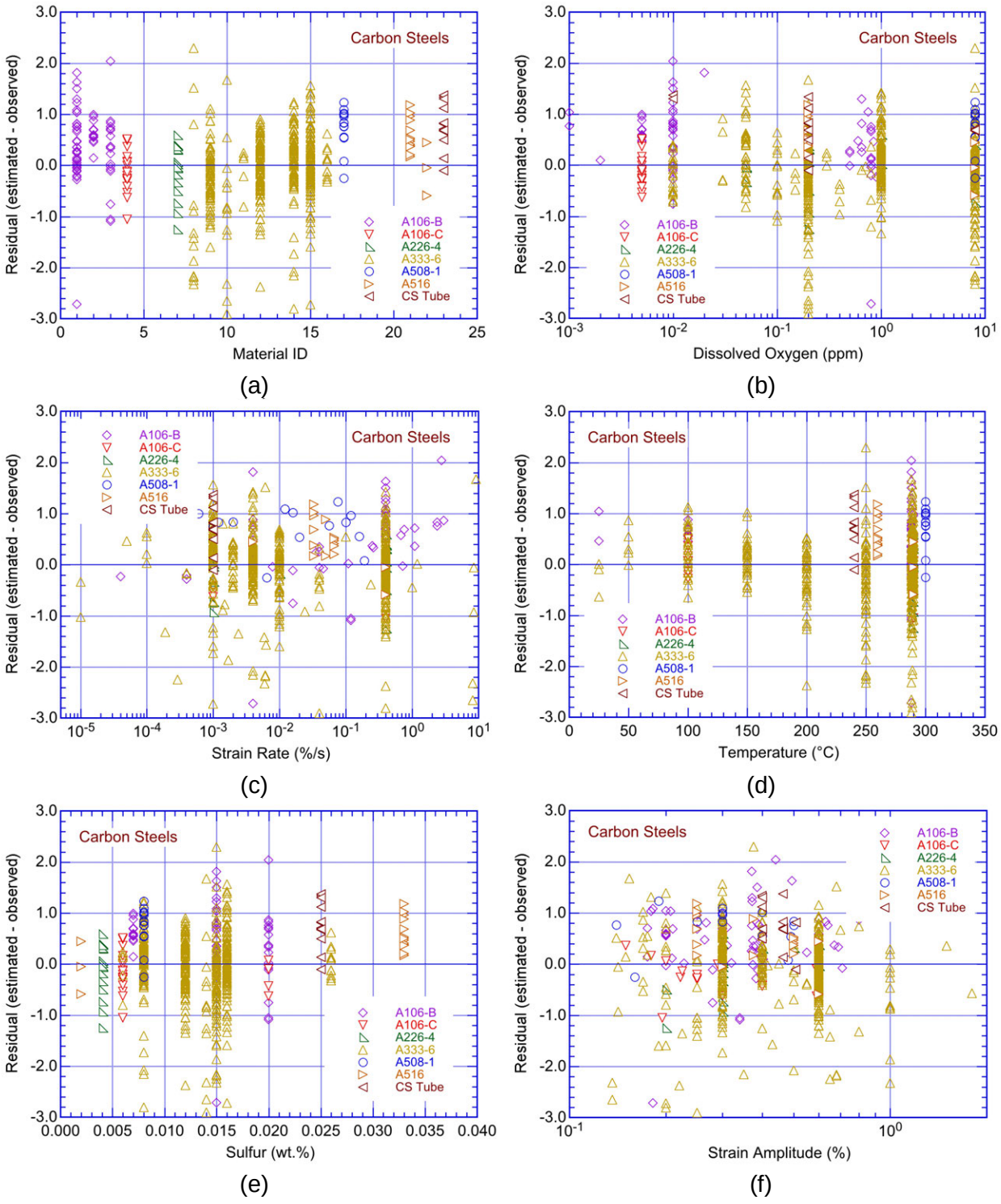


Figure 4-22 Residuals for predicted fatigue lives of carbon steels as a function of (a) Material ID, (b) water DO content, (c) strain rate, (d) temperature, (e) steel sulfur content, and (f) strain amplitude.

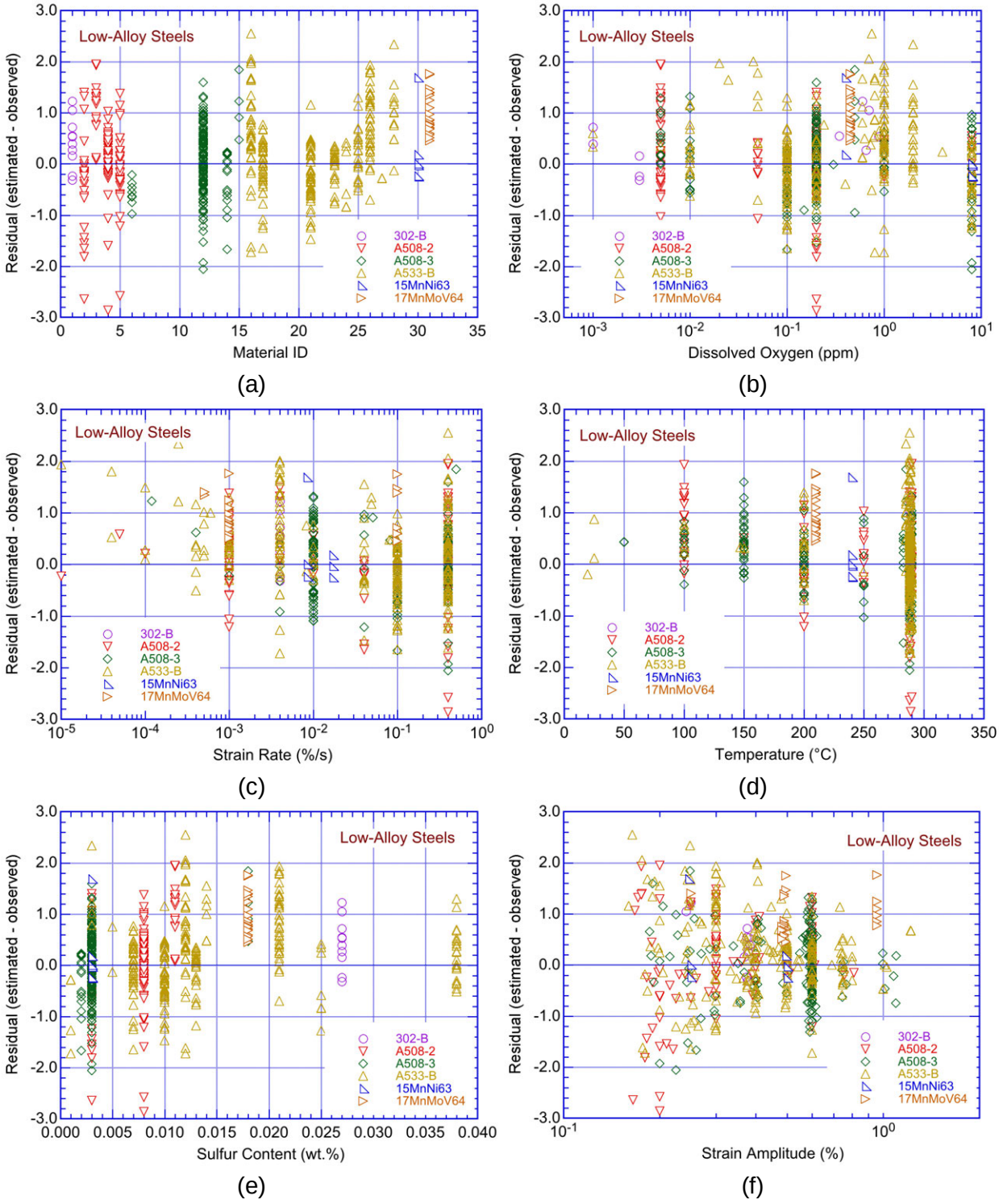


Figure 4-23 Residuals for predicted fatigue lives of low-alloy steels as a function of (a) Material ID, (b) water DO content, (c) strain rate, (d) temperature, (e) steel sulfur content, and (f) strain amplitude.

Some of the heats of carbon and low-alloy steels were also tested in air. The residual errors for the best fit of the fatigue ε–N data for carbon and low-alloy steels in air were plotted as a

function of the ANL Material ID, as shown in Figure 4-24. Most of the data subsets for fatigue tests in air followed the same trends observed in LWR environments; data subsets that yielded positive residuals in LWR environments also showed positive residuals in air, and vice versa.

The exception was ANL Material ID 21, which yielded a positive residual in an LWR environment but a negative residual in an air environment. However, the total data in air were quite limited for this heat of A516-KC70 carbon steel; therefore, quantitative conclusions were not made.

- *The F_{en} approach should be used to incorporate environmental effects into ASME Code, Section III fatigue evaluations for carbon and low-alloy steels. Appendix C of this report presents a sample application of F_{en} using the NB-3200 methodology.*

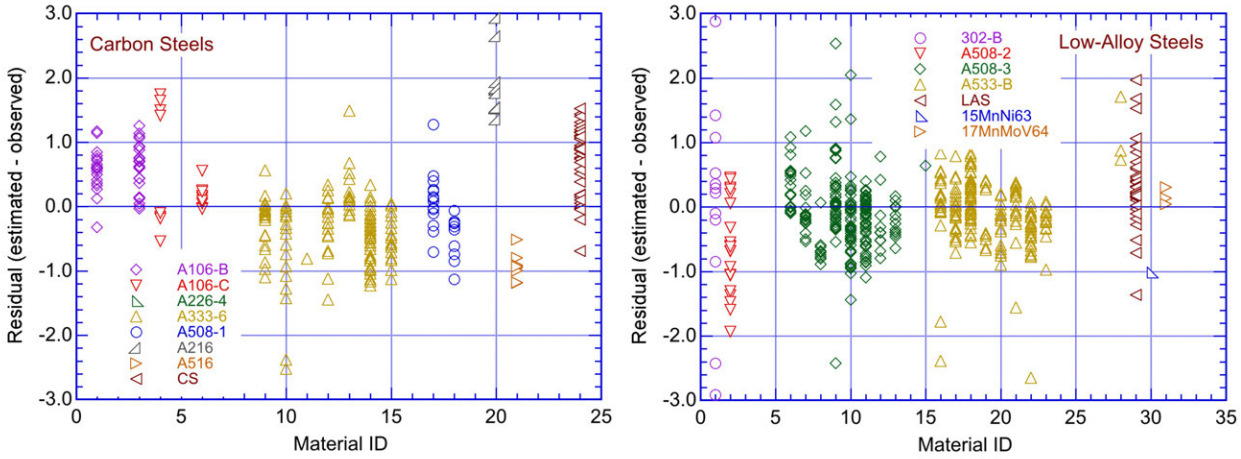


Figure 4-24 Residuals for predicted fatigue lives in air of carbon and low-alloy steels as a function of Material ID.

4.1.12 Surface Finish

Fatigue tests were conducted on specimens of carbon and low-alloy steels that were intentionally roughened in a lathe under controlled conditions with 50-grit sandpaper to produce circumferential scratches with an average surface roughness, R_a, of 1.2 μm and a root-mean-square surface roughness, R_q, of 1.6 μm (approximately 62 μin.).[46] Figure 4-25 shows the results for A106–Gr B carbon steel and A533–Gr B low-alloy steel. In air, the fatigue lives of rough A106–Gr B specimens were a factor of 3 lower than that of smooth specimens, and, in high-DO water, were the same as those of smooth specimens. In low-DO water, the fatigue lives of the roughened A106–Gr B specimen were slightly lower than those for smooth specimens. The effects of surface finish on the fatigue lives of A533–Gr B low-alloy steel were similar to those for A106–Gr B carbon steel; in high-DO water, the fatigue lives of both rough and smooth specimens were the same. The results in water were consistent with a mechanism of growth by a slip oxidation/dissolution process, which was not affected by surface finish. Surface roughness is expected to influence fatigue lives in LWR environments. However, additional data are needed to accurately establish the combined effects of surface finish and water environment on the fatigue life of carbon and low-alloy steels used in LWRs.

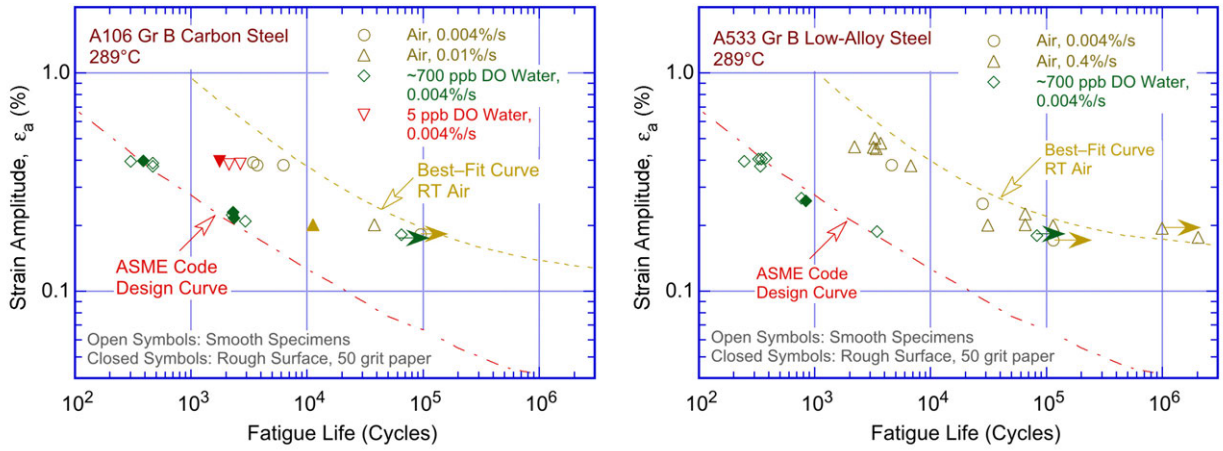


Figure 4-25 Effect of surface finish on the fatigue lives of (a) A106–Gr B carbon steel and (b) A533 low-alloy steel in air and high-purity water at 289°C (Ref. 46).

The potential additional impact of strain rate on the observed surface finish effects on the fatigue lives of low-alloy steels were also investigated (Figure 4-26).[144] The results showed a strong influence of strain rate on surface finish effects. At high strain rates, relative to smooth specimens, the fatigue lives of A533-Gr. B low-alloy steel decreased significantly even with slight increases in surface roughness, whereas at slow strain rates, because fatigue lives were already low, any further decrease in fatigue lives occurred only for very rough surfaces. The different behavior was attributed to the differences in the mechanism for corrosion fatigue of carbon and low-alloy steels in LWR environments. As discussed in Section 2.2.1.2, the corrosion fatigue mechanism changed from hydrogen-induced cracking to a slip-oxidation/dissolution mechanism with decreasing strain rates. During cyclic loading in high-temperature water, plastic deformation induced slip bands at the crack tip along the maximum shear directions or the preferred slip directions, which ruptured the protective oxide film at the crack tip. Furthermore, the slip bands were the favored paths for hydrogen transportation and the matrix/inclusion interfaces were the preferred traps for hydrogen. As a result, at high strain rates, fatigue cracking preferentially occurred along the slip bands and the matrix/inclusions interfaces, which resulted in macroscopically tortuous fatigue cracks and a rough fracture surface. However, at low strain rates, fatigue crack growth in high-temperature water was controlled by the film-rupture/oxidation-dissolution mechanism, which resulted in a macroscopically straight, relatively flat, featureless fracture surface.

The results in Figure 4-25 were also observed to be consistent with strain rate effects; the surface finish of the specimens that were tested at slow strain rates were not sufficiently rough to further decrease the fatigue lives.

- *The effects of surface finish were not explicitly included in the F_{en} for carbon and low-alloy steels; instead, they were included in the subfactor for "surface finish and environment" that was applied to the mean-data air curve to develop the fatigue design curve in air.*

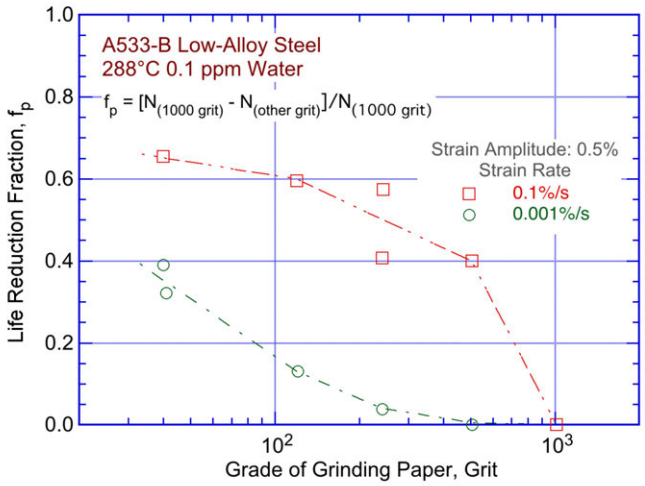


Figure 4-26 Relationship between surface finish and fatigue life reduction fraction for A533–Gr. B low-alloy steel in water at 288°C (Ref. 144).

4.1.13 Heat-to-heat Variability

The effects of material heat-to-heat variability and data scatter on the fatigue lives of carbon and low-alloy steels were evaluated for LWR environments. The fatigue behavior of each of the heats or loading conditions was characterized by the value of the constant A in the ANL models for carbon steels given by

$$\ln(N) = A - 1.975 \ln(\varepsilon_a - 0.113) - \ln(F_{en}), \quad (39)$$

and in the ANL model for low-alloy steels by

$$\ln(N) = A - 1.808 \ln(\varepsilon_a - 0.151) - \ln(F_{en}), \quad (40)$$

where F_{en} was determined from Equation 34. The values of A, determined from Equations 39 and 40 for the various datasets in the larger, updated fatigue ε–N database used in this report were ordered, and median ranks were used to estimate the cumulative distribution of A for the population. Figure 4-27 plots the estimated cumulative distribution of constant A for heats of carbon and low-alloy steels in water environments. The median value of constant A in water was slightly lower than that in air; the values of constant A in LWR and air environments were 6.503 and 6.583 for carbon steels and 6.358 and 6.449 for low-alloy steels, respectively. The results of the analysis of the larger, updated fatigue ε–N database indicated that an increase in the fatigue data of more than 60% had an insignificant impact on the parameters in the ANL models for the fatigue lives of carbon and low-alloy steels.

The results also demonstrated that the F_{en} expression given in Equation 34 adequately captured the effects of LWR environments on the fatigue lives of carbon and low-alloy steels. Because the actual heats of carbon and low-alloy steels that were tested in air and LWR environments were different, the location (percentile) of a specific heat on the distribution curve differed between the two environments. However, the estimated cumulative distribution of most of the heats of carbon steel and low-alloy steels that were tested in both air and LWR environments were comparable. However, a few exceptions showed significant differences. For example, for ANL heat designation A333-Gr. 6-3 (0.014 wt.% sulfur; ANL Material ID 10 in Table 3-1 and Table 4-1), the updated

ANL model underestimated environmental effects, and the material ranked in the 97th percentile in an LWR environment and in the 50th percentile in air. In contrast, for ANL heat designation A333-Gr. 6-7 (0.008 wt.% sulfur; ANL Material ID 14 in Table 3-1 and Table 4-1), the model overestimated environmental effects and the material ranked in the 40th percentile in an LWR environment and in the 55th percentile in air. A similar contrasting behavior was observed in two heats of low-alloy steels. For example, the environmental effects were overestimated for A302-Gr. B (0.027 wt.% sulfur; ANL Material ID 1 in Table 3-1 and Table 4-1) and underestimated for A508-Gr. 3-1 (0.003 wt.% sulfur; ANL Material ID 6 in Table 3-1 and Table 4-1).

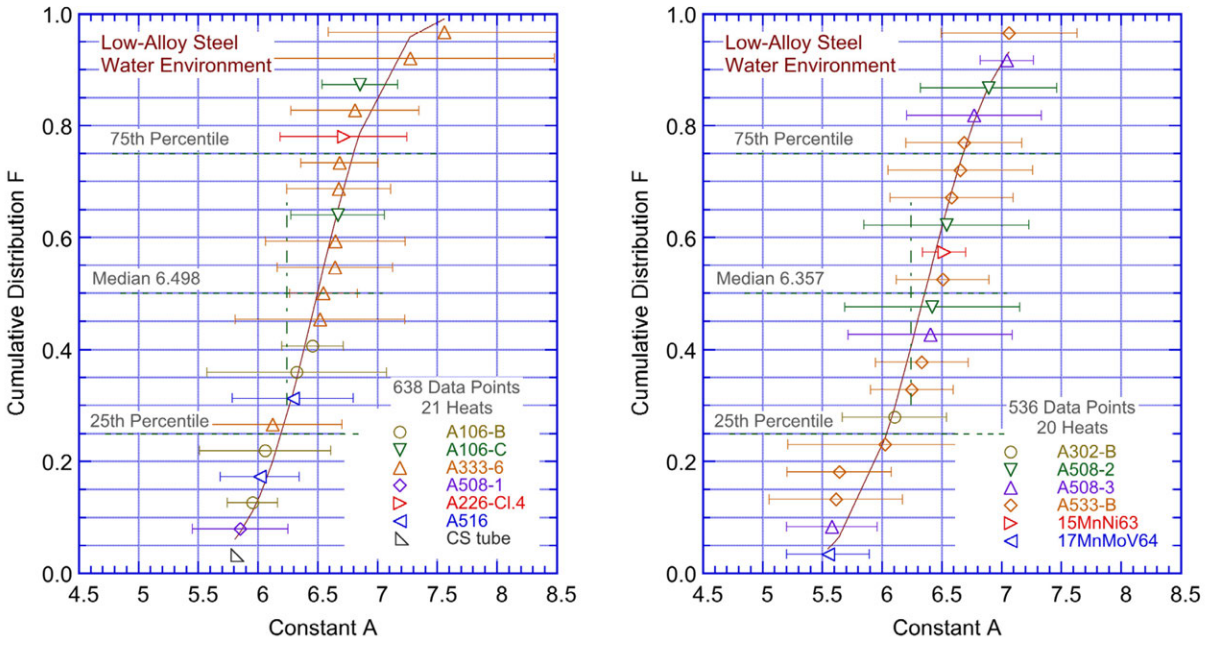


Figure 4-27 Estimated cumulative distribution of parameter A in the ANL model for fatigue lives for heats of carbon and low-alloy steels in LWR environments.

These results and evaluation indicated that, for carbon and low-alloy steels, the heat-to-heat variation in LWR environments were essentially the same as that established in air and presented in Section 3.1.7. Thus, the 95/95 values of the factors to account for material variability and data scatter were the same in air (i.e., presented in Table 3-2 and Table 3-3 for carbon and low-alloy steels, respectively). These factors were required to provide 95% confidence that the resultant lives were greater than those observed for 95% of the materials of interest.

- *The effects of heat-to-heat variability were not explicitly included in the F_{en} for carbon and low-alloy steels; instead, they were included in the subfactor for "data scatter and material variability" that was applied to the mean-data air curve to develop the fatigue design curve in air.*

4.2 Wrought and Cast Austenitic Stainless Steels

Fatigue life models for estimating the fatigue lives of wrought and cast austenitic SSs in LWR environments presented in the original version of NUREG/CR-6909 were based on the updated PVRC database available at that time. The correlations included the effects of key parameters, such as temperature, strain rate, and the DO content in water. The functional forms for the effects of these parameters were based on the observed data trends. For both wrought and cast

austenitic SSs, the model assumed threshold and saturation values of 0.4 and 0.0004%/s, respectively, for strain rate and a threshold value of 150°C for temperature. In addition, because of a lack of relevant fatigue data, the dependence of environmental effects on the DO level was not defined in the original version of NUREG/CR-6909. Lacking sufficient data to establish the effects of DO level on fatigue lives, those effects were assumed to be the same in low- and high-DO water for both wrought and cast austenitic SSs. The fatigue ε–N data for austenitic SSs in LWR environments were fitted to a modified version of Equation 6 and expressed as

$$\ln(N) = A - B \ln(\varepsilon_a - C) + T^* O^* \dot{\varepsilon}^*, \quad (41)$$

where T*, O*, and $\dot{\varepsilon}^*$ are the transformed temperature, water DO level, and strain rate, respectively. The least-squares fit of the experimental data in LWR environments yielded a steeper slope for the fatigue ε–N curve than the slope of the curve obtained in air.[45,121] These results indicated that, for austenitic SSs, environmental effects were less pronounced with increasing strain amplitudes above the threshold value of strain amplitude. Differing slopes for the fatigue ε–N curves in air and water environments added complexity to the determination of the F_{en}. Therefore, the slope, B, of the fatigue ε–N curve was assumed to be the same in LWR and air environments (i.e., the value of constant B was assumed to be 1.920 for both environments), and the constant C was also considered the same for both environments (i.e., constant C was assumed to be 0.112). A value of 6.891 for the constant A was determined from the best fit of the fatigue ε–N data in LWR environments. Note that this is the same fit value determined in Revision 0 of NUREG/CR-6909. However, the constant A in Revision 0 of NUREG/CR is 6.157 to reflect the subtraction of the Revision 0 water model constant, 0.734 (i.e., 6.891 – 0.734 = 6.157). Note also that the constant A in the ANL model for austenitic SSs presented in the original version of NUREG/CR-6909 differed from the values reported earlier in NUREG/CR–5704, "Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels," issued April 1999; NUREG/CR–6815; and NUREG/CR–6878, "Effect of Material Heat Treatment on Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments," issued July 2005, because relative to the earlier expressions, the F_{en}, determined in the original version of NUREG/CR-6909 was 45 to 60% lower. Equations E0.35 – E0.38 of Appendix E provide the F_{en} for wrought and cast austenitic SSs developed in the original version of NUREG/CR-6909.

Note that the F_{en} expression was based on the ANL model for austenitic SSs in air (Equation 29) and the analysis presented in Section 5.2.11 of the original version of NUREG/CR-6909. A single F_{en} expression was specified for Types 304, 304L, 316, 316L, and 316NG SSs. This expression was also applicable to cast austenitic SSs such as CF-3, CF-8, and CF-8M. The original version of NUREG/CR-6909 noted that, because the influence of DO level on the fatigue lives of austenitic SSs were influenced by the material composition and heat treatment, the ANL fatigue life model was somewhat conservative for some SSs in high-DO water.

Since the initial publication of NUREG/CR-6909, comments received from stakeholders focused on two areas. The first area concerned the constant in the F_{en} expression, which resulted in an F_{en} of approximately 2.5 even at very low temperatures (i.e., below the threshold temperature of 150°C) or at very high strain rates (e.g., during seismic or similar loadings). The other area concerned the absence of DO dependence on environmental effects. As a result, the F_{en} expression in the original version of NUREG/CR-6909 yielded conservative estimates of F_{en} for some materials (e.g., for low-carbon or nonsensitized high-carbon wrought SSs).

In this report, the F_{en} expressions for incorporating environmental effects on the fatigue life of wrought and cast austenitic SSs were updated to address the stakeholder comments and to

incorporate data from the much larger database described in Section 4.2.1. In addition, the dependence of environmental effects on the DO level in the water environment was included in the revised expression.

4.2.1 Experimental Data

The relevant fatigue ε–N data for wrought and cast austenitic SSs in LWR environments include the large JNES database;[136] tests performed by GE in a test loop at Dresden Nuclear Power Station, Unit 1;[14,15] work sponsored by the Electric Power Research Institute (EPRI) at GE;[58-60] and the data developed at ANL.[45] The data that were used in the evaluation consisted of 683 tests—193 tests on 11 heats of Type 304 SS, 255 tests on 8 heats of Type 316 SS, 115 tests on 7 heats of CF-8M cast austenitic SSs, and 120 tests on 6 compositions of SS weld metals. The database includes both low-carbon and high-carbon grades of Types 304 and 316 SSs. For all of the SS data, 15% of the tests were conducted at temperatures of 100–200°C, 39% at 250–290°C, 44% at 300–325°C, and 1% (10 tests) at 360°C. Table 4-2 summarizes the data sources for the updated database used in this report, as categorized by material type and test environment. Appendix B provides other material information such as chemical composition, heat treatment, and room temperature tensile properties of the various types and heats of materials.

The data indicated that the fatigue lives of austenitic SSs were decreased in LWR environments. Figure 4-28 provides an example of environmental effects on the fatigue lives of Types 304 and 316NG SSs in high-purity water at 288°C. This figure also includes the fatigue ε–N curves based on the ANL model The fatigue lives were decreased significantly when three threshold conditions were satisfied simultaneously (i.e., when both $\Delta\varepsilon$ and the service temperature were above minimum threshold levels and the loading strain rate was below a threshold value). The DO level in the water and, to some extent, the composition and heat treatment of the steel were important parameters for environmental effects on fatigue lives. For some steels, fatigue lives were longer in high-DO water than in low-DO PWR environments. Although the fatigue lives in air of Type 316NG SSs were slightly longer than those of Types 304 and 316 SSs, the effects of LWR environments were comparable for wrought Types 304, 316, and 316NG SSs. In addition, as discussed later in Section 4.2.13, available data indicated that the fatigue lives of cast austenitic SSs in both low-DO and high-DO environments were comparable to those of wrought SSs in low-DO environments.

Table 4-2 Sources of the Fatigue ε–N Data for Cast and Austenitic SSs in LWR Environments.

ANL Mat. ID[a]	Material Heat Designation[a]	Carbon Content (wt.%)	Dissolved Oxygen (ppm)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
Type 304 Stainless Steels							
1	304-1	0.050	0.02, 8.0	288	12, 5	JNES (Hasegawa, Fukakura)	136
3	304-3	0.060	0.2	288	7	JNES (Enomoto),	136
9	304-9T	0.070	8.0	300	22 (15 aged)	JNES (Endo)	136
20	304-G	0.070	0.2	260	7	GE	14,15
21	304-A2	0.060	0.003, 0.8	288	14, 5[b]	ANL	45
22	304-21T	0.060	0.005	100-360	58 (4 aged), 6	JNES (Kanasaki, Tsutsumi)	136
24	304-35	0.070	0.01-0.2	289	15 (4 aged)	JNES (Hirano)	136
25	304-36T	0.050	0.005	325	4	JNES (Nomura)	136
28	304L-E	0.039	0.09	150, 300	8, 20	Solomon	58-60
29	304L-1	0.017	0.01-0.2	289	6	JNES (Hirano)	136
30	304L-G	0.017	0.2	260	4	GE	14,15
Type 316 Stainless Steels							
42	316-12T	0.060	0.005, 8.0	100-325	45, 6	JNES (Kanasaki, Tsutsumi)	136
43	316-13T	0.070	0.005	325	4	JNES (Tsutsumi)	136
44	316-14T	0.060	0.005	325	8 (4 aged)	JNES (Tsutsumi)	136
45	316-15T	0.040	0.005	100-325	61[c]	JNES (EFT)	136
48	316N-1	0.010	0.01-0.2, 8.0	150-289, 288	65, 30	JNES (Nakao, Higuchi, Hirano, Fukakura)	136
49	316N-2	0.009	0.2	288	9	JNES (Asano)	136
51	316N-4	0.008	0.01, 8.0	290	11	JNES (Higuchi)	136
54	316N-A	0.013	0.004-0.75	288	16	ANL	45
Stainless Steel Weld Metals							
56a	308-WM-1	0.050	0.005	100, 200, 325	6, 6, 14	JNES (Tsutsumi)	136
56b	308-WM-2	0.034	0.005	325	9	JNES (Nomura)	136
57a	316 WM	0.039	0.005	100, 200, 325	4, 4, 24[d]	JNES (Tsutsumi)	136
57c	316TP-WM	0.070	0.005	100, 200, 325	3, 3, 11	JNES (Nomura)	136
58	316N-WM-1	0.018	0.01, 8.0	290	4, 8	JNES (Higuchi)	136
59	316N-WM-2	0.017	0.01-8.0	150-289	24	JNES (Hirano)	136
Cast Austenitic Stainless Steels							
61	CF–8M-1	0.050	0.01-1.0	289	26 (4 aged)	JNES (Hirano)	136
62	CF–8M-2T	0.050	0.005	325	36 (21 aged)	JNES (Tsutsumi)	136
63	CF–8M-3T	0.050	0.005	325	4	JNES (Tsutsumi	136
64	CF–8M-4T	0.050	0.005	325	4	JNES (Tsutsumi)	136
65	CF–8M-5T	0.050	0.005	325	38 (4 aged)	JNES (Nomura)	136
68	CF–8M-8	0.064	0.006-1.0	288	5	ANL	45
69	CF–8M-9	0.065	0.008-1.0	288	2	ANL	45

[a] T at the end of the number designates a tube specimen.

[b] Six specimens were sensitized.

[c] Twelve specimens had 2% mean strain.

[d] Six specimens were aged for 25,200 h at 465°C.

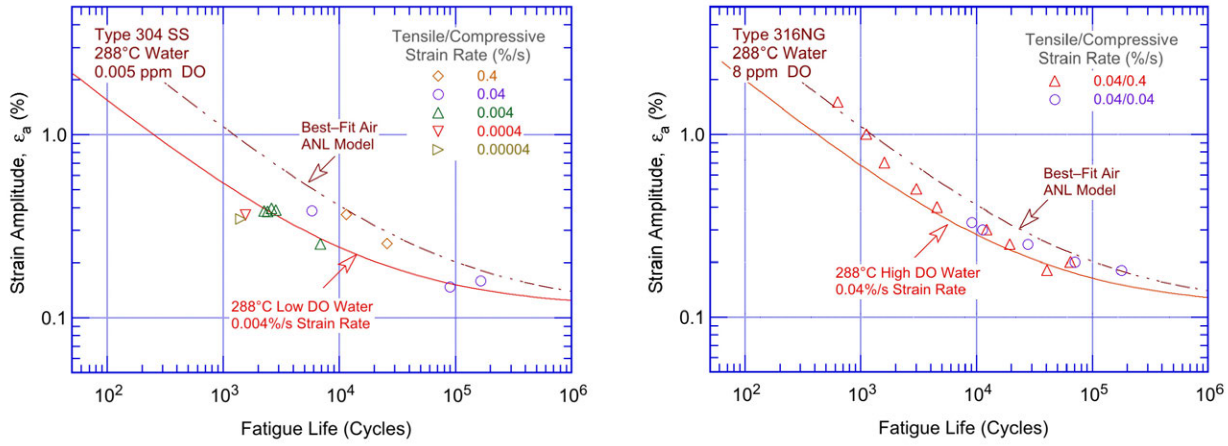


Figure 4-28 Strain amplitude vs. fatigue life data for (a) Type 304 and (b) Type 316NG SSs in water at 288°C (JNUFAD database; Refs. 13 and 45).

Furthermore, the existing fatigue data indicated that a slow strain rate applied during the tensile-loading cycle (i.e., up ramp with increasing strain) was primarily responsible for the environmentally assisted reduction in fatigue lives. Slow loading rates applied during both tensile- and compressive-loading cycles (i.e., up and down ramps) did not further decrease fatigue lives compared with those observed for tests with only slow tensile-loading cycles (Figure 4-28(b)). Consequently, loading and environmental conditions during the tensile-loading cycle (strain rate, temperature, and DO level) are important for environmentally assisted reduction of the fatigue lives of these steels.

Note that, for evaluation of experimental fatigue ε–N data, although most of the data were obtained from strain-controlled fatigue tests, some data, particularly at low strain amplitudes, were obtained from load-controlled fatigue tests. Caution should be exercised when comparing such data to the ASME Code fatigue design curve for austenitic SSs. For example, Figure 4-29 shows the applied stress amplitude vs. fatigue life data from load-controlled tests on Type 304L SSs, with or without a 100 MPa mean stress, in air and PWR primary water environments at 150 and 300°C. The results indicated that, for tests conducted at applied stress amplitudes of 80 to 170 MPa with 100 MPa mean stress, the fatigue lives in PWR water relative to fatigue lives in air were significantly decreased at 150°C, whereas the fatigue lives were increased at 300°C. Some investigators have incorrectly interpreted these results and indicated that a combination of mean stress and PWR environment decreased the 10^7 cycles fatigue limit of austenitic SSs at 150°C.

As discussed earlier, the ASME Code fatigue design curves were based on fully reversed (i.e., R ratio equal to -1) strain-controlled fatigue tests. The stress amplitude used to develop the stress-life (S–N) fatigue design curves was a pseudo-stress defined as $S_a = E\varepsilon_a$, where E is the elastic modulus. Therefore, for all fatigue tests conducted at strain amplitudes beyond the elastic limit (i.e., with some plastic strain), the experimental stress amplitudes were lower than the stress amplitudes plotted for use in developing the ASME Code fatigue design curves. Furthermore, as discussed earlier, at low strain amplitudes, based on the chemical composition of the material, the effects of DSA may affect the cyclic-hardening behavior of austenitic SSs. Therefore, depending on the temperature and strain rate, the cyclic stress amplitudes during strain-controlled tests or total

strain amplitudes during load-controlled tests, may vary significantly during tests. These differences have significant effects of the fatigue lives of SS materials.

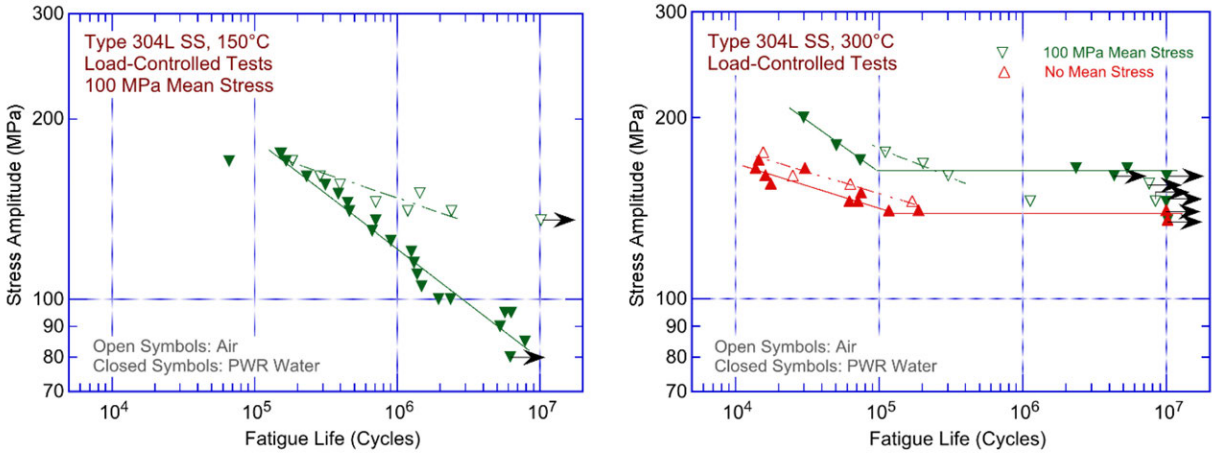


Figure 4-29 Fatigue stress-life data from load controlled tests on Type 304L SSs, with and without mean stress, in air and PWR water (Ref. 60).

Figure 4-30 plots the fatigue lives of some load-controlled tests as a function of total strain amplitude. Note that these results may also be plotted as stress amplitude, S_a vs. fatigue life, where S_a is obtained by multiplying the total strain amplitudes by the elastic modulus, E. The figure also shows the best-fit air curve and the mean-stress adjusted curve of the fatigue ε–N data and the ASME Code Section III fatigue design curve. Fatigue ε–N data from other strain-controlled tests performed by the same authors on Type 304L SSs are also included for comparison.[60] The results indicated that the load-controlled data show excellent agreement with the strain-controlled test results. Unfortunately, the comparison did not include data for the load-controlled tests that showed significant reductions in fatigue lives (i.e., tests with 100 MPa mean stress in PWR water at 150°C) because the actual strain amplitudes for these tests were not specified. In general, at a strain rate of 0.4%, environmental effects decreased fatigue lives at 300°C, and had insignificant effects at 150°C.

The results also indicated that, for Type 304L SSs, the slope of the fatigue ε–N curve was steeper than that of the best-fit air curve based on the ANL model for austenitic SSs. This behavior was consistent with the best-fit curves developed in NUREG/CR-5704 for Types 304, 316, and 316NG SSs. In general, the slope of the curve for low-carbon grades of austenitic SSs (e.g., Type 316NG or 304L) was steeper than the slope of the curve for high-carbon SSs (Types 304 or 316). For fatigue lives greater than 10^5 cycles, the fatigue data for Type 304L SSs were all below the best-fit air curve. The fatigue lives of tests in air at 150 or 300°C with 100 MPa mean stress were significantly below those predicted using the mean-stress-adjusted curve. However, all data were above the ASME Code Section III fatigue design curve without adjusting for environmental effects. Consequently, the potential effects of differences in the cyclic-hardening behavior of austenitic SSs, particularly at low strain amplitudes, should be considered while establishing the factors in the ASME Code Section III fatigue design curves to account for the effects of data scatter, heat-to-heat variability, component size and geometry, and surface roughness.

- *When interpreting load-controlled fatigue tests, care should be taken, particularly when comparing the experimental stress amplitudes from such tests to stress amplitudes from the ASME Code Section III fatigue design curve. In addition, the potential effects of differences in the cyclic-hardening behavior should be considered when establishing the factors in ASME Code Section III fatigue design curves.*

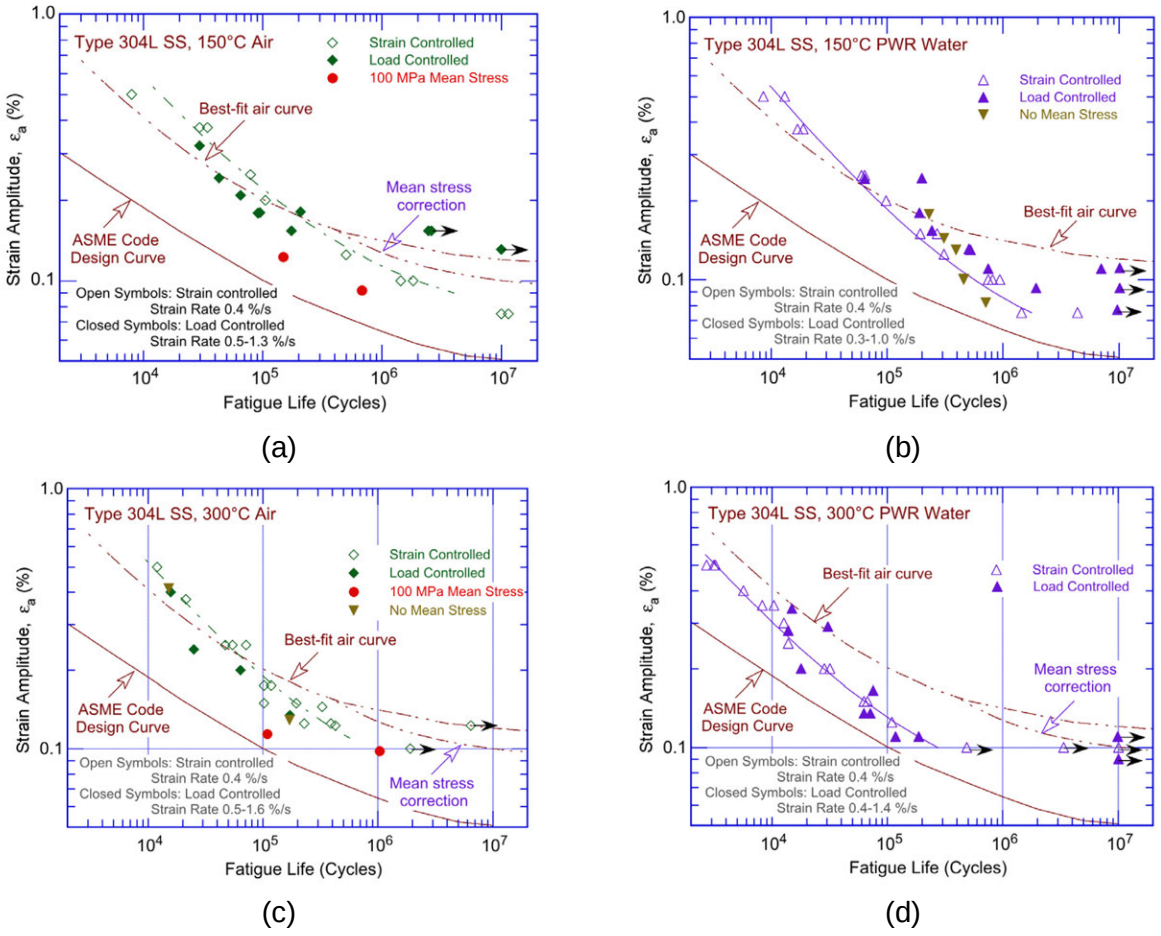


Figure 4-30 Fatigue strain-life data from load-controlled tests on Type 304L SSs, with and without mean stress, in air (a, c) and PWR water (b, d) (Refs. 58 and 60).

4.2.2 Strain Rate

Figure 4-31 plots the fatigue lives of Types 304L and 316 SSs in low-DO water as a function of tensile strain rate. The lines in the two plots of this figure were based on the best-fit air curve for austenitic SSs given by Equation 29 and the F_{en} expressions given in Equation 43 and Equations 44–46 (Section 4.2.13). The results of the reanalysis of the larger database indicated that, in low-DO PWR environments, the fatigue lives of austenitic SSs decreased with decreasing strain rates below approximately 7%/s; the effects of environment on fatigue lives saturated at approximately 0.0004%/s (Figure 4-31).[13,24,27-31,34,35,45-47] Environmental effects did not occur at strain rates greater than 7%/s (i.e., $F_{en} = 1$). Decreases in the strain rate from 7 to 0.0004%/s reduced the fatigue lives by more than a factor of 10.

In high-DO water at 288°C, the effects of strain rate were less pronounced than they were in low-DO water (Figure 4-32). For example, for Heat 30956 of Type 304 SS, the strain rate had no effect on the fatigue lives in high-DO water, whereas fatigue lives decreased linearly with strain rate in low-DO water (Figure 4-32(a)). For Heat D432804 of Type 316NG, some effect of strain rate was observed in high-DO water, although it was smaller than that in low-DO water (Figure 4-32(b)).

- *The effects of strain rate on the fatigue lives of austenitic SSs in LWR environments were explicitly considered in the F_{en} expression defined in Equation 43 (Section 4.2.13).*

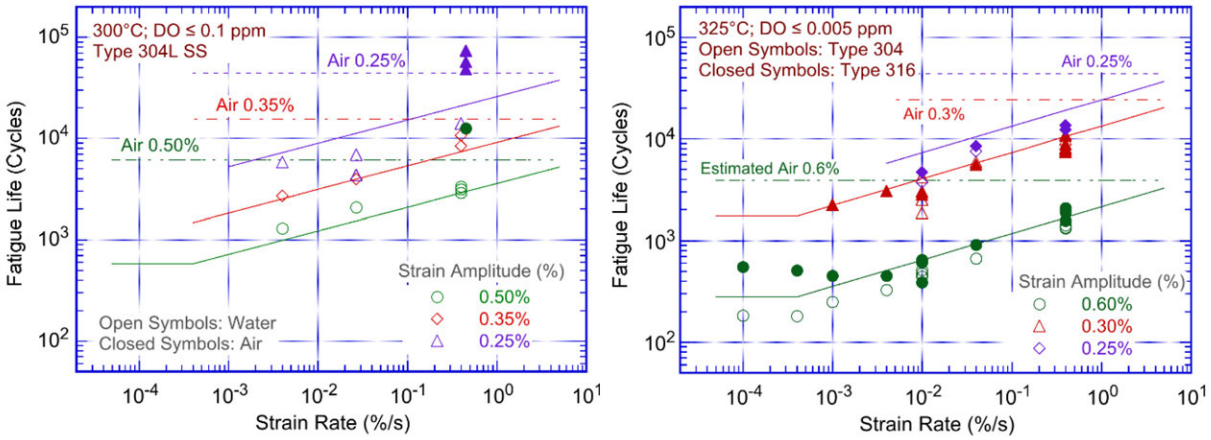


Figure 4-31 Dependence of fatigue lives of austenitic SSs on strain rate in low-DO water (Refs. 13, 45, 47, and 60).

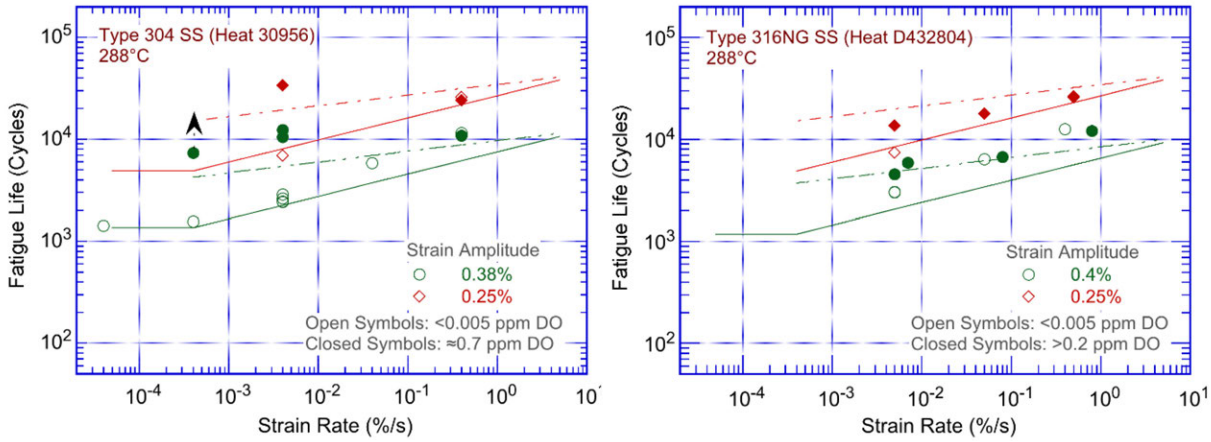


Figure 4-32 Dependence of fatigue lives of (a) Type 304 and (b) Type 316NG SSs on strain rate in high- and low-DO water at 288°C (Refs. 13, 45, and 47).

4.2.3 Strain Amplitude

As in the case of the carbon and low-alloy steels, a minimum $\Delta\varepsilon_{th}$ was required for the environmentally induced decrease in fatigue lives of SSs to occur. Exploratory fatigue tests were conducted on austenitic SSs to determine the $\Delta\varepsilon_{th}$ beyond which environmental effects were

significant during a fatigue cycle.[30,35] The tests were performed with loading waveforms in which the slow strain rate was applied during only a fraction of the tensile-loading cycle. The results indicated that a minimum threshold strain was necessary to produce an environmentally assisted decrease in the fatigue lives of SSs (Figure 4-33). The $\Delta\varepsilon_{th}$ was independent of material type (weld or base metal) and temperature in the range of 250–325°C, but it tended to decrease as the strain range was decreased.[30,35] The $\Delta\varepsilon_{th}$ was expressed in terms of $\Delta\varepsilon$ by the equation

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\,\Delta\varepsilon + 0.65. \quad (42)$$

The results suggested that the $\Delta\varepsilon_{th}$ was related to the elastic strain range of the test, and it did not correspond to the strain at which the crack closed. The threshold value was attributed to the rupture strain of the surface oxide film; limited data suggested that the threshold strain was between 0.32 and 0.36%. The above expression yields a value of 0.31% at a strain range of 0.6%.

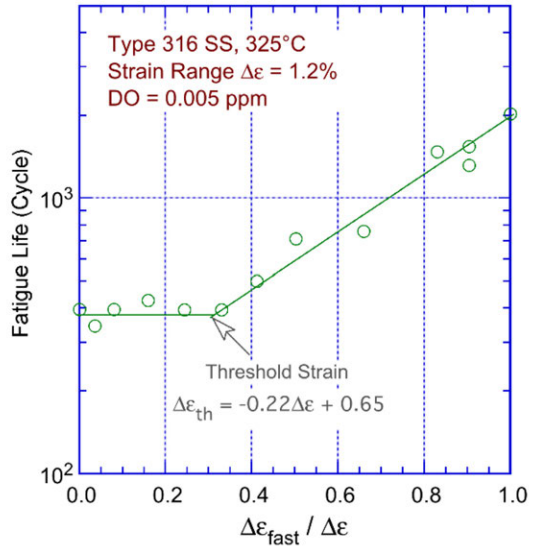


Figure 4-33 Results of strain rate change tests on Type 316 SSs in low-DO water at 325°C. Low strain rate was applied during only a fraction of the tensile loading cycle. Fatigue life is plotted as a function of fraction of strain at high strain rate (Refs. 30 and 35).

Because the contribution of strain threshold was relatively more significant at low strain amplitudes, a strain threshold value of 0.32% (or a strain amplitude of 0.16%) was identified in the original version of NUREG/CR-6909. This value was adjusted for the effects of mean stress and uncertainties due to material and loading variability. The threshold strain amplitude was decreased by approximately 10% (or a stress amplitude of 195 MPa {28.3 ksi}) to account for mean stress effects and by a factor of 1.5 to account for uncertainties in fatigue lives associated with material and loading variability. Thus, a threshold strain amplitude of 0.10% was selected, below which environmental effects on fatigue lives were considered insignificant.

Some stakeholders identified that the strain amplitude threshold of 0.10% was based on a factor of 1.7 on strain instead of the factor of 2 proposed in the criteria document for developing the ASME Code Section III fatigue design curves.[8] The PVRC Steering Committee for Cyclic Life

Environmental Effects (CLEE) endorsed the threshold value of 0.10%.[E] Based on experimental data, the CLEE proposed a strain threshold for environmental effects—a lower strain amplitude below which environmental effects were considered to be insignificant, a slightly higher strain amplitude above which environmental effects decreased fatigue lives, and a linear variation between these two values. The two strain amplitudes were 0.10 and 0.11% for both wrought and cast austenitic SSs. For simplicity, in the original version of NUREG/CR-6909, a single value of 0.10% was proposed for the strain amplitude threshold.

The same procedure is appropriate for defining a value of strain threshold that maintains the factor of 2 on strain proposed by ASME Code Section III. However, because the mean-stress adjustment to the best-fit mean-data curve using the modified Goodman relation accounts for the effects of mean stress on fatigue lives, only the effects of material and loading variability were addressed in defining the strain threshold for environmental effects to avoid the double counting of mean stress effects.

- *The procedure for calculating F_{en}, defined in Equation 43 (Section 4.2.13), includes a threshold strain amplitude of 0.10% (or a stress amplitude of 195 MPa {28.3 ksi}) below which LWR water environments do not affect fatigue lives (i.e., $F_{en} = 1$). However, this threshold strain amplitude should not be considered when the modified rate approach is used to determine F_{en} for a stress cycle or a load set pair.*

4.2.4 Temperature

Figure 4-34 plots the changes in fatigue lives of austenitic SSs with test temperatures at two strain amplitudes and two strain rates. The results indicated a threshold temperature of 100°C, above which the environment decreased fatigue lives in low-DO water if the strain rate was below the threshold value. In the range of 100–325°C, the logarithm of fatigue life decreased linearly with temperature. Environmental effects either did not occur or were insignificant at temperatures below the threshold value of 100°C. Note that the F_{en} expression in the original version of NUREG/CR-6909 included a temperature threshold of 150°C below which environmental effects were considered insignificant. In addition, the F_{en} expressions developed by JNES do not consider a temperature threshold. Therefore, to better represent the existing fatigue ε–N data, the temperature dependence relationships in the F_{en} expression were modified and the temperature threshold was decreased from 150°C to 100°C.

[E] See the Welding Research Council Progress Report, Volume LIX, Number 5/6, May/June 1999.

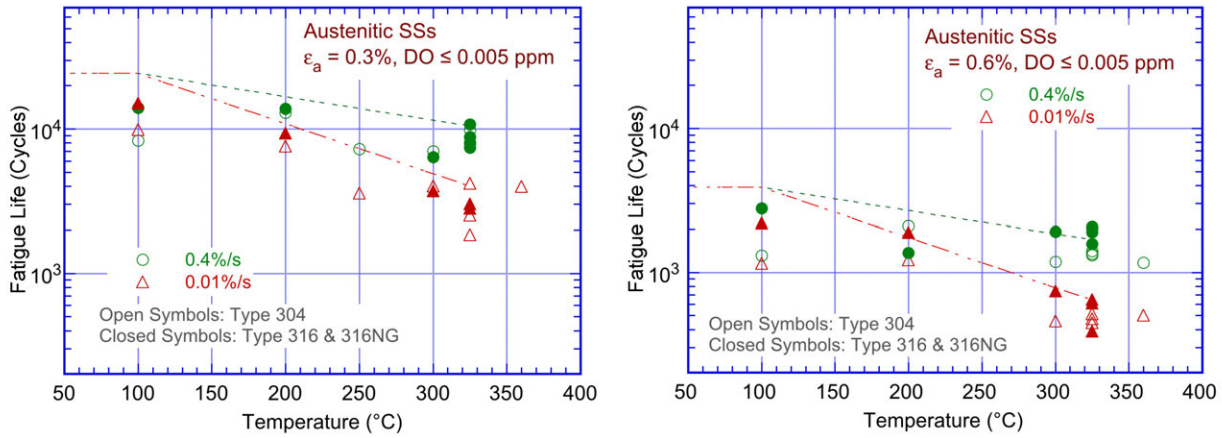


Figure 4-34 Change in fatigue lives of austenitic SSs in low-DO water with temperature (Refs. 13, 29–31, 34, and 45–47).

Fatigue tests were conducted at MHI in Japan on Type 316 SSs under combined mechanical and thermal cycling.[29,30] Triangular waveforms were used for both strain and temperature cycling. The strain rate for the tests was 0.002%/s. Two sequences were selected for temperature cycling: (1) an in-phase sequence, in which temperature cycling was synchronized with mechanical strain cycling and (2) 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. Figure 4-35 shows the results, along with data obtained from tests at constant temperature at a strain rate of 0.01%/s. An average temperature was used in Figure 4-35 for the thermal cycling tests. The average temperature was determined by considering that environmental effects were insignificant below threshold values of 100°C for temperature and 0.32% for strain. Thus, the average temperature for the thermal cycling tests was determined from the higher value between 100°C and the temperature at the threshold strain for the in-phase tests, and the lower value between the maximum temperature and the temperature at the threshold strain for the out-of-phase tests. The solid and chain-dash lines in the figure were based on the best-fit air curve (Equation 29) and the updated F_{en} expression for austenitic SSs (Equation 43).

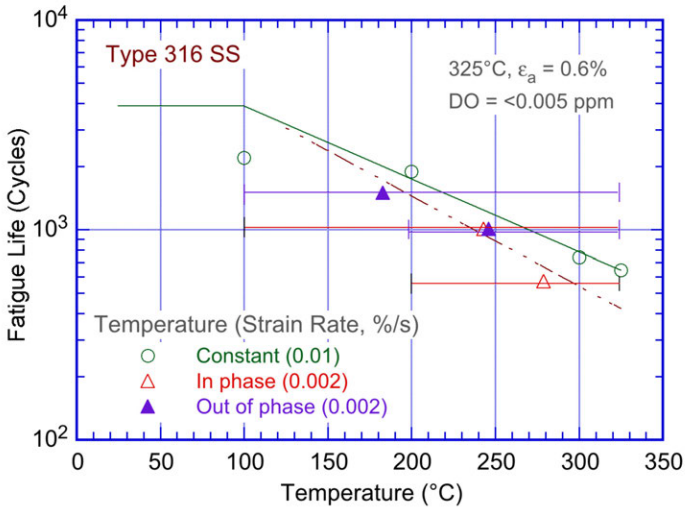


Figure 4-35 Fatigue lives of Type 316 SSs under constant and varying test temperatures (Refs. 29 and 30).

The results in Figure 4-35 indicated that for the variable temperature tests, fatigue lives estimated using an average temperature that was determined by taking into consideration the threshold values of temperature and strain showed good agreement with the experimental fatigue lives. As expected, the predicted fatigue lives of the in-phase tests were shorter than those for the out-of-phase tests. The reason fatigue lives were longer for out-of-phase tests compared to in-phase tests was that applied strains above the threshold strain occurred at higher temperatures for the in-phase tests, whereas they occurred at lower temperatures for the out-of-phase tests. The results from the thermal cycling tests (triangles) agreed well with the estimated values shown by the chain-dash line, and those from the constant-temperature tests (open circles) agreed well with the estimated values shown by the solid line.

Another study conducted by JNES on Type 316 SSs under combined mechanical and thermal cycling in PWR water showed similar results; the in-phase tests had lower fatigue lives than the out-of-phase tests.[36,38] These results indicated that load cycles involving simple linear temperature transients were represented by an average temperature that was determined by taking into consideration the threshold values of temperature and strain. However, the use of an average temperature for more complex temperature transients requires verification.

- *The effects of temperature on the fatigue lives of austenitic SSs in LWR environments were explicitly considered in the F_{en}, defined in Equation 43 (Section 4.2.13). In addition, guidance was developed to define the temperature used to calculate F_{en} for actual reactor transients.*

4.2.5 Dissolved Oxygen

In contrast to the behavior of carbon and low-alloy steels, the fatigue lives of austenitic SSs decreased significantly in low-DO water (i.e., less than 0.05 ppm DO). In low-DO water, the fatigue lives were not influenced by the material composition or heat treatment. The fatigue lives, however, continued to decrease with decreasing strain rate in the range of 10–0.0004%/s and increasing temperature in the range of 100–325°C.[13,24,29-31,34,35,45-47] As discussed in Sections 4.2.2 and 4.2.4, environmental effects saturated at a strain rate of 0.0004%/s and a temperature of 325°C.

In high-DO water, the fatigue lives of austenitic SSs were either comparable to[29,34] or, in some cases, higher[13,45,47] than those in low-DO water (i.e., for some SSs, environmental effects were lower in high-DO water compared to low-DO water). The results (Figure 4-32(a) and Figure 4-32(b)) indicated that, in high-DO water, environmental effects on the fatigue lives of austenitic SSs were influenced by the material composition and heat treatment. For example, for high-carbon Type 304 SS, environmental effects in high-DO water were insignificant for mill-annealed (MA) material (Figure 4-32(a)), whereas the effects of environment were the same for sensitized material in high- and low-DO water (see figure in section 4.2.7). For low-carbon Type 316NG SSs, some effects of strain rate were apparent in high-DO water, although they were smaller than those in low-DO water (Figure 4-32(b)). Section 4.2.7 further discusses the effects of material heat treatment on the fatigue lives of Type 304 SSs.

- *The effects of DO on the fatigue lives of austenitic SSs in LWR environments were explicitly considered in the F_{en}, defined in Equation 43 (Section 4.2.13). In high-DO water, the material composition and heat treatment affected the fatigue lives of austenitic SSs.*

4.2.6 Water Conductivity

The studies performed at ANL indicated that, for fatigue tests in high-DO water, the conductivity of water and the electrochemical potential (ECP) of steel were important parameters that must be held constant.[13,45,47] During laboratory tests, the time to reach stable environmental conditions depended on the autoclave volume, DO level, flow rate, and other such factors. In the ANL test facility, fatigue tests on austenitic SSs in high-DO water required a soaking period of 5 to 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 results shown in Figure 4-32(a) for Type 304 MA Heat 30956 SS in high-DO water (closed circular symbols) were obtained for specimens that were soaked for 5 to 6 days prior to testing. The same material tested in high-DO water after soaking for 24 h showed a significant reduction in fatigue life, as indicated by Figure 4-36. At conductivity values of 0.05 to 0.1 μS/cm, the fatigue lives of specimens that were soaked for 24 h (shown as solid symbols) were a factor of approximately 3 lower than those of specimens soaked for 120 h (shown as open symbols).

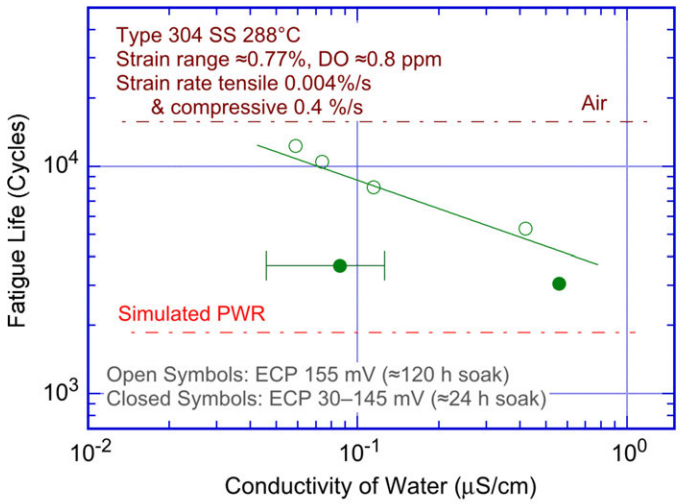


Figure 4-36 Effects of water conductivity and soaking period on fatigue lives of Type 304 SSs in high-DO water (Refs. 13 and 45).

The effects of water conductivity and the ECP of the steel on the fatigue lives of austenitic SSs were determined, as shown in Figure 4-36. In high-DO water, the fatigue lives were decreased by a factor of approximately 2 when the conductivity of the water was increased from approximately 0.05 to 0.4 μS/cm. Note that environmental effects appeared more significant for the specimens that were soaked for only 24 h. For these tests, the ECP of the steel was initially very low and increased during testing (i.e., the DO level in the test autoclave was lower than the target DO level of 0.7 ppm).

- *The determination of the F_{en} did not explicitly include the effects of water conductivity on the fatigue lives of austenitic SSs. Therefore, additional guidance was not included to address excursions from normal water chemistry conditions.*

4.2.7 Material Heat Treatment

Limited small-scale laboratory fatigue test data indicated that, although heat treatment had little or no effects on the fatigue lives of austenitic SSs in low-DO and air environments, fatigue lives in high-DO environments were longer for nonsensitized or slightly sensitized SSs.[47] Figure 4-37 shows the effects of heat treatment on the fatigue lives of Type 304 SSs in air, BWR, and PWR environments. Fatigue lives were plotted as a function of electrochemical potentiodynamic reactivation (EPR) values for various material conditions. The results indicated that heat treatment had little or no effects on the fatigue lives of Type 304 SSs in air and PWR environments. In a BWR environment, fatigue lives were lower for the sensitized SSs; fatigue lives decreased with increasing EPR values.

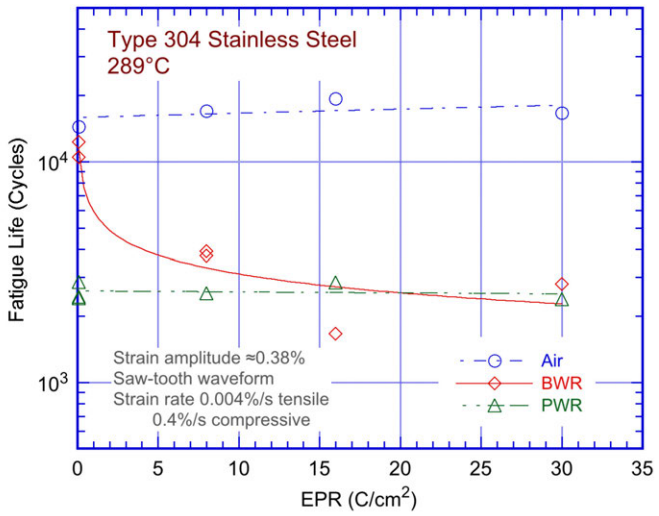


Figure 4-37 The effects of material heat treatment on fatigue lives of Type 304 SSs in air, BWR and PWR environments at 289°C, approximately 0.38% strain amplitude, sawtooth waveform loading, and 0.004%/s tensile strain rate (Ref. 47).

These results are consistent with the data obtained at MHI on solution-annealed and sensitized Types 304 and 316 SSs.[27,31] In low-DO water (less than 0.005 ppm DO) at 325°C, sensitization annealing had no effects on the fatigue lives of these steels. In high-DO (8 ppm) water at 300°C, the fatigue lives of sensitized Type 304 SSs were a factor of approximately 2 lower than those of solution–annealed steels. However, sensitization annealing had little or no effect on the

fatigue lives of low-carbon Type 316NG SSs in high-DO water at 288°C, and the fatigue lives of solution-annealed and sensitized Type 316NG SSs were comparable.

- *The effects of heat treatment were not explicitly included in the F_{en}. Therefore, estimates of F_{en} based on Equation 43 (Section 4.2.13) are conservative for some SSs in high-DO water.*

4.2.8 Cast Austenitic Stainless Steels

The fatigue lives of cast austenitic SSs were lower in LWR water environments. The available data also indicated that the fatigue lives of cast SSs in high-DO water were the same as those in low-DO water. Figure 4-38 plots the fatigue lives of CF-8M cast austenitic SSs in high-purity water at 289°C and 0.3 and 0.6% strain amplitudes as a function of DO. The results showed no fatigue life dependency on water DO levels. In both NWC and hydrogen water chemistry (HWC) BWR environments, the fatigue lives of cast austenitic SSs were well represented by the F_{en} expressions for wrought austenitic SSs in low-DO PWR environments.

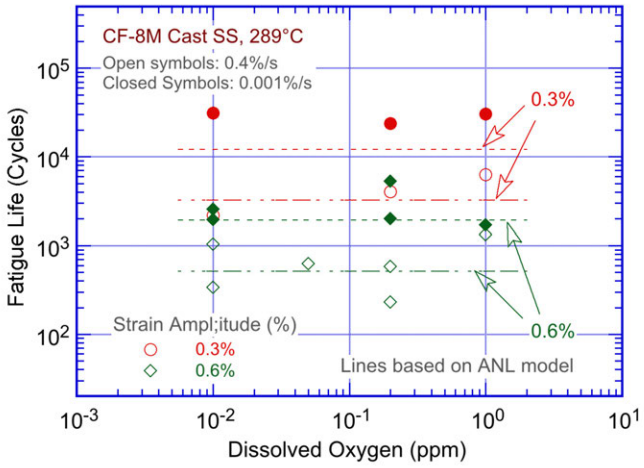


Figure 4-38 Fatigue lives of cast austenitic SSs in high-purity water at 289°C and 0.3% and 0.6% strain amplitude plotted as a function of DO content (Ref. 136).

In addition, the existing data indicated that the fatigue lives of cast austenitic SSs were relatively insensitive to changes in ferrite content in the range of 12–28%.[29,34] Figure 4-39 plots the fatigue ε–N data for a heat of CF-8M cast SS (with 19.7% ferrite) at 325°C in PWR water containing 0.005 ppm DO at various strain rates. The best-fit air curve at room temperature and the estimated fatigue lives for the tests at 0.4 and 0.01%/s strain rates were also included. The results showed a gradual decrease in fatigue lives with decreasing strain rates. The results also indicated that thermal aging for 25,200 h at 465°C had little or no effect on fatigue lives.

The experimental data showed good agreement with the estimated fatigue ε–N curves. However, the fatigue ε–N data for unaged and aged (for 10,000 h at 400°C) material from two heats of CF-8M cast SSs (shown in Figure 4-40(a)) indicated potential effects of thermal aging. Figure 4-40(a) plots some of the data shown in Figure 4-39 as a function of strain rate. The limited data for Heat CF8M-8 (shown as open and closed circular symbols in Figure 4-40(a)) indicated that, unlike the thermal aging effects of cast SSs aged at 450°C or higher, thermal aging for 10,000 h at 400°C decreased the fatigue lives of the material by a factor of 2.[45]

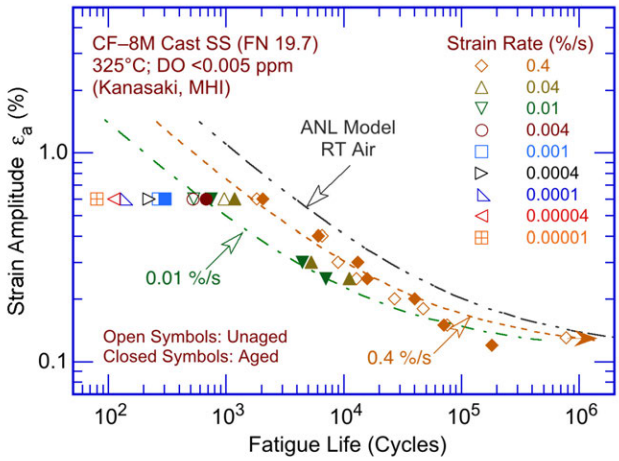


Figure 4-39 Strain amplitude vs. fatigue life data for cast austenitic SSs at 325°C and various strain rates in water with 0.005 ppm DO content (Refs. 29 and 34).

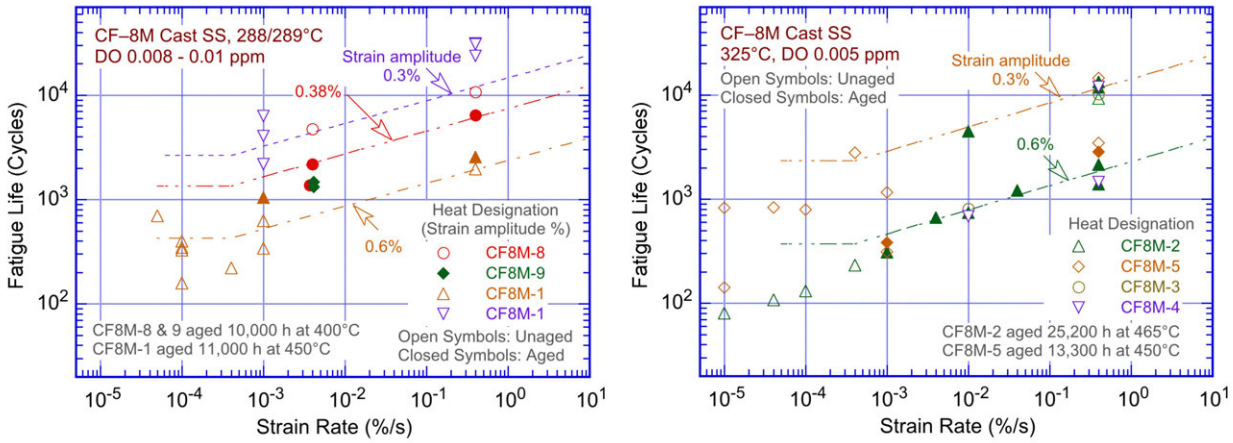


Figure 4-40 Dependence of fatigue lives of CF-8M cast SSs on strain rate in low-DO water at various strain amplitudes (Refs. 136, 43, and 45).

The different thermal aging effects for the cast austenitic SSs in Figure 4-40(a) and Figure 4-40(b) are attributed to differences in the microstructure produced after thermal aging at 400°C as opposed to 465°C. Available data indicated that thermal aging at temperatures between 300 and 400°C resulted in a spinodal decomposition of the ferrite phase which strengthened the ferrite phase and increased cyclic hardening.[229-232] In contrast, thermal aging at 465°C resulted in the nucleation and growth of large α' particles and other phases such as a sigma phase, which did not change the tensile or cyclic-hardening properties of the material.[230]

The results also showed that the effects of strain rate on the fatigue lives of cast SSs were similar to those for wrought SSs. However, for the cast SS unaged Heat CF8M-2, environmental effects on life did not appear to saturate even at strain rates as low as 0.00001%/s.[29,34] Similar results were also reported for unaged CF-8M steels in low-DO water at 325°C.[233] Based on these results, JNES[136] recommended a lower threshold value for the saturation strain rate for

cast austenitic SSs. The saturation strain rate of 0.0004%/s, recommended for wrought SSs, was decreased to 0.00004%/s for cast SSs.

As shown in Figure 4-40, the fatigue data obtained at 289°C were in good agreement with estimates based on the F_{en} expressions for wrought austenitic SSs. Even the data at 325°C for strain rates equal to or greater than 0.001%/s were in agreement with the estimated curves. However, the strain rate dependence of the data obtained on unaged material at low strain rates increased at strain rates below 0.0005%/s (i.e., the slope of the log-log plot of fatigue lives vs. strain rates was steeper). The reasons for this behavior of the unaged cast austenitic SSs were not determined. Until more data are available, the effects of strain rate on the fatigue lives of cast austenitic SSs were assumed similar to those for wrought SSs in low-DO PWR environments. Furthermore, strain rates less than 0.0004%/s are either not expected for typical reactor operation, or the total strain accumulated under these transients is expected to be insignificant.

Limited data indicated that the effects of temperature on the fatigue lives of cast austenitic SSs were also similar to those for wrought SSs in low-DO PWR environments, as shown in Figure 4-41. The data showed good agreement with the estimated values.

- *The effects of LWR environments on the fatigue lives of cast austenitic SSs were represented by the same F_{en} expression (i.e., Equation 43 in Section 4.2.13) developed for wrought SSs in low-DO PWR environments.*

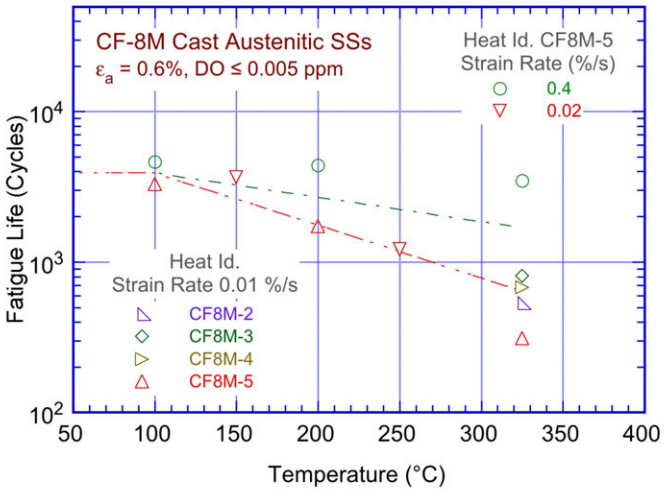


Figure 4-41 Change in fatigue lives of cast austenitic SSs in low-DO water with temperature (Ref. 136).

4.2.9 Stainless Steel Weld Metals

As discussed in Section 3.2.9, the available fatigue ε–N data indicated that the best-fit mean-data curve for wrought austenitic SSs in air may be used for the fatigue ε–N behavior of SS weld metals. In addition, the plots of the estimated cumulative distribution of constant A for the mean-data curve for wrought SSs in air (i.e., Figure 3-19) showed that the constant A for the few heats of SS weld metals for which fatigue data were available were evenly distributed about the median value of constant A. The available fatigue ε–N data for austenitic SS weld metals also indicated that environmental effects in LWR environments could be estimated from the F_{en}

expression given by Equation 43 in Section 4.2.13 for cast and wrought austenitic SSs. Figure 4-42 shows the fatigue ε–N data for Types 308 and 316TP SS weld metals at 325°C in PWR water containing 0.005 ppm DO at various strain rates. The fatigue lives estimated from Equations 29 (Section 3.2.6) and 43 (Section 4.2.13) for the tests at various strain rates are also shown in the figure. The experimental fatigue lives were in good agreement with the estimated ε–N curves; the fatigue lives decreased gradually with decreasing strain rates.

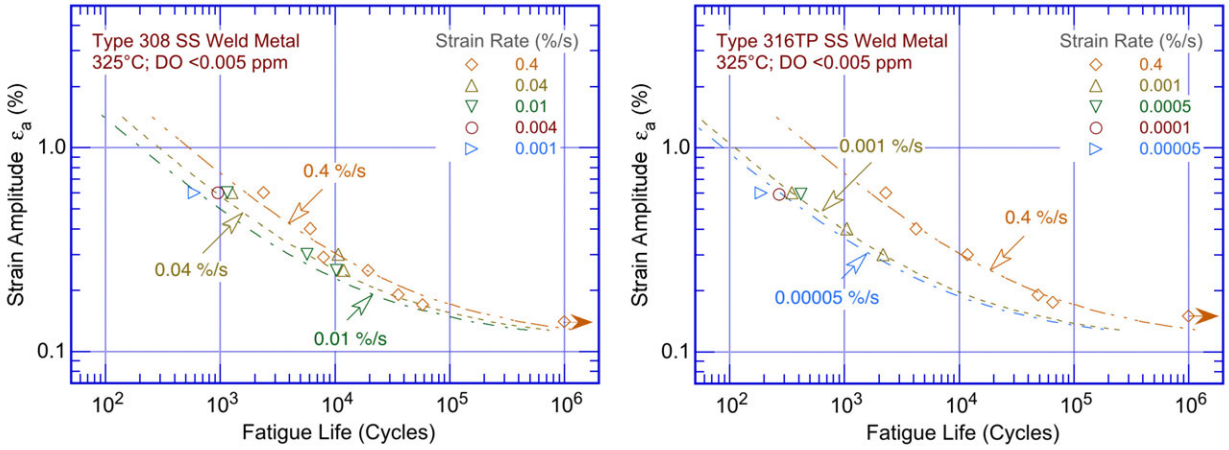


Figure 4-42 Strain amplitude vs. fatigue lives for Types 308 and 316TP SS weld metals at 325°C and various strain rates in water with 0.005 ppm DO content (Ref. 136).

The experimental fatigue lives of SS weld metals at 0.6% strain amplitude were compared with the estimated fatigue lives (using Equations 29 and 43) at various strain rates and temperatures, as shown in Figure 4-43. The results indicated that the estimates based on the expressions for wrought austenitic SSs yielded either comparable or slightly lower fatigue lives compared to the experimental values. The fatigue ε–N data also indicated that changes in the water DO content had little or no effects on fatigue lives; the fatigue lives in 8 or 0.2 ppm water were comparable to those in 0.005 ppm water.

- *The effects of LWR environments on the fatigue lives of austenitic SS weld metals were represented by the same F_{en} expression (i.e., Equation 43 in Section 4.2.13) developed for wrought SSs in low-DO PWR environments.*

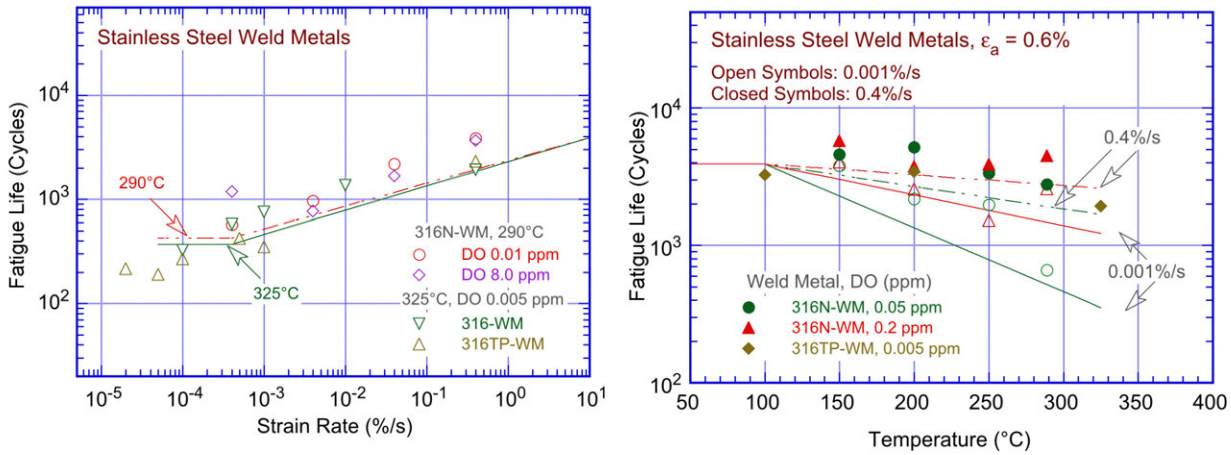


Figure 4-43 Change in fatigue lives of SS weld metals in LWR environments with strain rate and temperature (Ref. 136).

4.2.10 Hold Periods

Environmental effects on fatigue lives occurred primarily during tensile-loading cycles and at strain levels greater than the threshold strain value. Information on the effects of hold periods on the fatigue lives of austenitic SSs in water was limited. In high-DO water, the fatigue lives of Type 304 SSs tested with a trapezoidal waveform (i.e., hold periods at peak tensile and compressive strain)[14] were comparable to those tested with a triangular waveform,[31] as shown in Figure 4-44. As discussed in Section 4.1.8, a similar behavior was observed for carbon and low-alloy steels; the data showed little or no effects of hold periods on fatigue lives of the steels in high-DO water. Figure 4-45 shows the effects of hold periods as long as 2,000 s at peak tensile strains. The results indicated little or no effects of hold periods at peak tensile strains on the fatigue lives of austenitic SSs.

- *The available fatigue ε–N data did not demonstrate that hold periods at peak tensile strains affected the fatigue lives of austenitic SSs in LWR environments. Therefore, the effects of hold times were not explicitly included in the F_{en} expression (i.e., Equation 43 in Section 4.2.13) developed for austenitic SSs.*

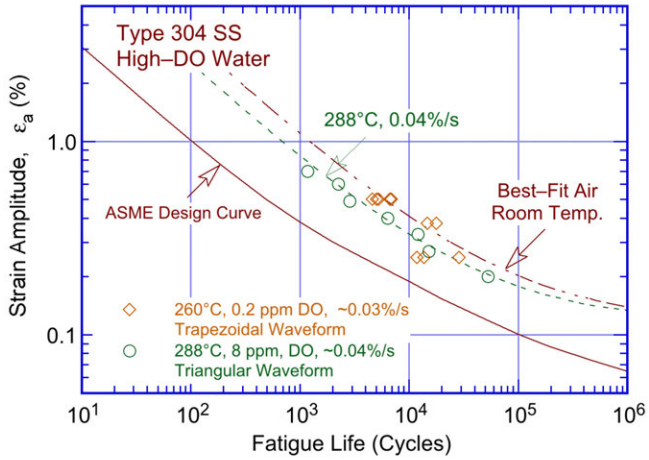


Figure 4-44 Fatigue lives of Type 304 SSs tested in high-DO water at 260–288°C with trapezoidal or triangular waveform loadings (Refs. 14 and 31).

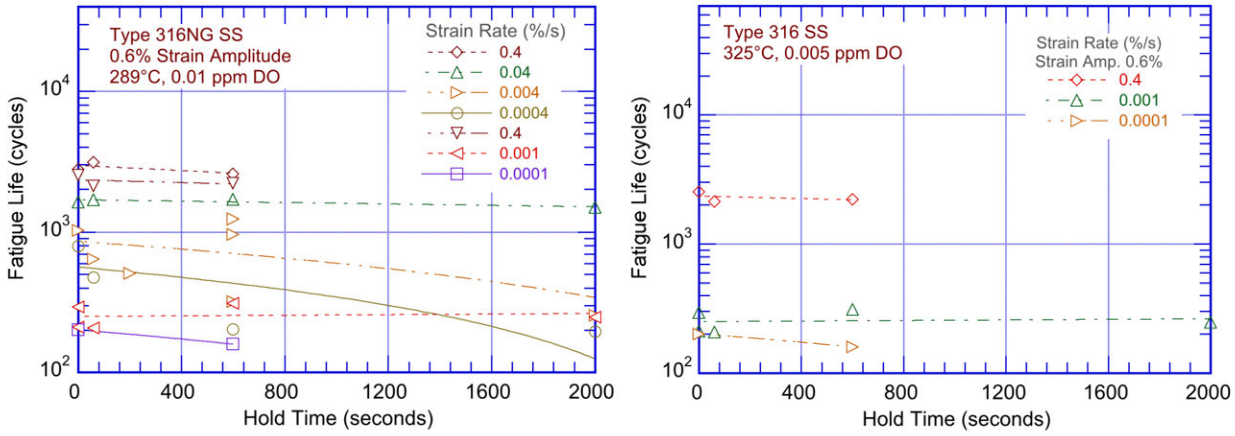


Figure 4-45 Effect of hold periods on the fatigue lives of Types 316NG and 316 SSs in LWR environments at various strain rates (Ref. 136).

4.2.11 Flow Rate

Flow rate affects the fatigue lives of LWR materials because it causes differences in local environmental conditions in the enclaves of the microcracks formed during the early stages of a fatigue ε–N test. As discussed in Section 4.1.9, data obtained under typical operating conditions for BWRs indicated that environmental effects on the fatigue lives of carbon steels were a factor of approximately 2 lower at high flow rates (7 m/s) compared to those at low flow rates (0.3 m/s or lower).[25,26] However, similar tests in both low-DO and high-DO environments indicated that increasing flow rates had either no effects or detrimental effects on the fatigue lives of austenitic SSs. Figure 4-46 plots the potential effects of water flow rate on the fatigue lives of Types 304, 304L, and 316NG wrought austenitic SSs and CF-8M cast austenitic SSs at 289°C in high-purity water containing 0.05 to 0.2 ppm DO. Similarly, Figure 4-47 plots the effects of flow rate on the fatigue lives of austenitic SSs in PWR primary water environment at 325°C. Under all test conditions, the fatigue lives of these steels were either the same or slightly lower at high flow rates compared to those at lower rates or semi-stagnant conditions.

Fatigue tests conducted on SS pipe bend specimens in simulated PWR primary water at 240°C also indicated that water flow rate had no effects on the fatigue lives of austenitic SSs.[131] Increasing the flow rate from 0.005 m/s to 2.2 m/s had no effects on fatigue crack initiation in approximately 26.5-mm-diameter tube specimens. These results were consistent with the notion that, in LWR environments, the mechanism of fatigue crack initiation in austenitic SSs differs from that in carbon and low-alloy steels.

- *Because of the uncertainties in the flow conditions at or near the locations of crack initiation and the observations of the insignificant effects of flow rate, flow rate effects were not explicitly included in the F_{en} expression (i.e., Equation 43 in Section 4.2.13) developed for austenitic SSs.*

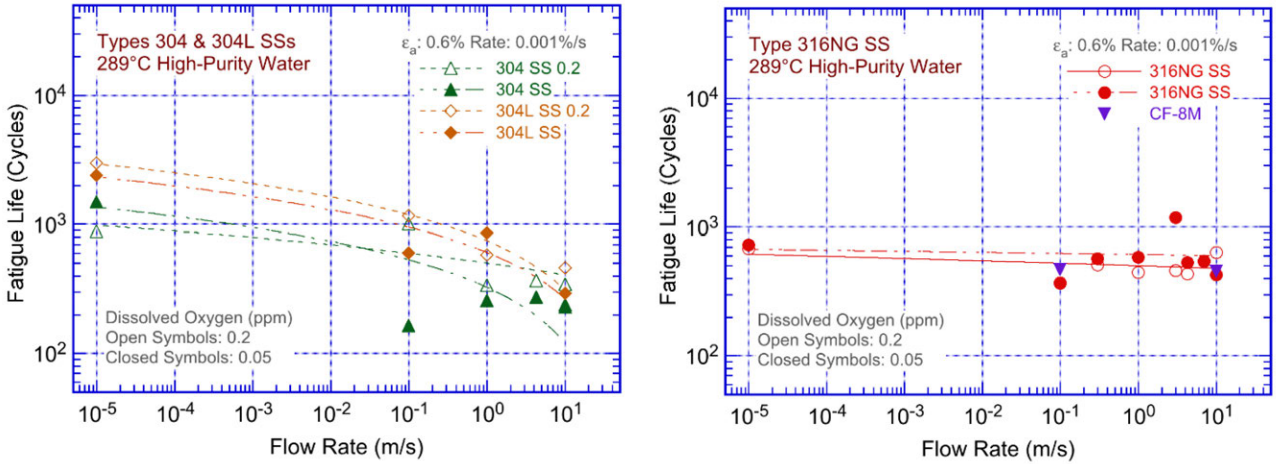


Figure 4-46 Effects of water flow rate on the fatigue lives of Types 304, 304L, 316NG and CF-8M cast SSs in high-purity water at 289°C (Ref. 136).

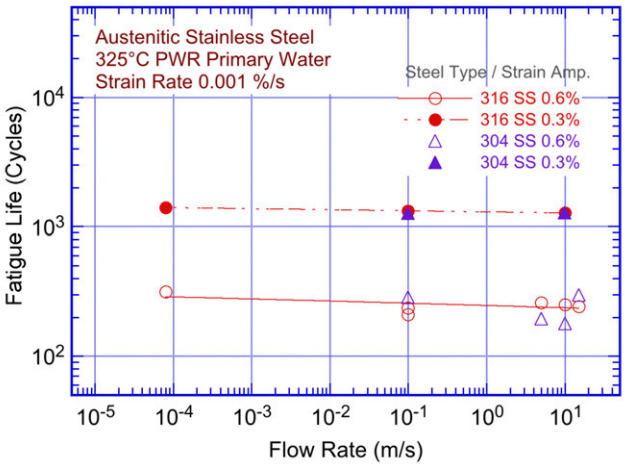


Figure 4-47 Effects of water flow rates on the fatigue lives of Types 304 and 316 austenitic SSs in PWR primary water at 325°C (Ref. 136).

4.2.12 Fatigue Life Model

The fatigue life models for estimating the fatigue lives of austenitic SSs in LWR environments were presented in the original version of NUREG/CR-6909 and were based on an analysis of the updated PVRC database. The data were fitted to a modified version of the Langer equation expressed by Equation 6, which included a term for environmental effects. The environmental term included the effects of key parameters, such as strain rate, water DO content, and temperature. The functional forms of these dependencies were based on the data trends. For both wrought and cast austenitic SSs, the model assumed threshold and saturation values of 0.4 and 0.0004%/s, respectively, for strain rate and a threshold value of 150°C for temperature. However, because of insufficient data, the dependencies of environmental effects on water DO content were not included. The experimental and predicted values differed by a factor of less than 3 for most heats of austenitic SSs. The experimental fatigue lives for a few tests on Type 304 SSs were up to a factor of approximately 4 lower than the predicted values; all of these tests were on tube specimens with 1 or 3 mm wall thicknesses. A threshold strain amplitude (one-half of $\Delta\varepsilon$) was defined, below which LWR water environments had insignificant effects on fatigue lives (i.e., $F_{en} = 1$). The threshold strain amplitude was specified as 0.10%, or as a 195 MPa (28.3 ksi) stress amplitude for wrought and cast austenitic SSs. A larger database was used to update the fatigue life model for wrought and cast austenitic SSs in LWR environments in this report. Section 4.2.13 provides the details.

- *The ANL model represented the mean values of fatigue lives as a function of applied strain amplitude, temperature, strain rate, and water DO content. The effects of parameters such as mean stress, surface finish, size and geometry, and loading history, which are known to influence fatigue lives, were not included in the model; the effects of these parameters were considered in the development of the fatigue design curve, as discussed in Chapter 5.*

4.2.13 Environmental Fatigue Correction Factor

As discussed at the beginning of Section 4.2, the ANL model for incorporating environmental effects on the fatigue lives of austenitic SSs resulted in approximately a factor of 2.5 decrease in fatigue lives relative to those in air, even when the environmental term of the expression is

neglected (i.e., when either the temperature was below the threshold value of 150°C or the strain rate was above the threshold strain rate value). In addition, the F_{en} expression did not consider the dependence of environmental effects on DO, and the temperature dependency was not consistent with the available fatigue ε–N data. As discussed in Section 4.2.5, the fatigue lives of austenitic SSs were decreased significantly in low-DO water, whereas, in high-DO water, they were either comparable or, for some steels, lower than those in low-DO water. In high-DO water, the material composition and heat treatment influenced the magnitude of environmental effects on austenitic SSs (see Section 4.2.7). Therefore, the F_{en} expression yielded very conservative estimates of F_{en} for some materials (e.g., for low-carbon or nonsensitized high-carbon wrought SSs).

The fatigue life model for incorporating environmental effects on the fatigue lives of wrought and cast austenitic SSs in LWR environments was updated in this report to address the foregoing concerns using a much larger database, which is described in Section 4.2.1. As discussed earlier, in the original version of NUREG/CR-6909, the least-squares fit of the experimental data for austenitic SSs in LWR environments yielded a steeper slope for the fatigue ε–N curve compared to the slope of the curve obtained in air.[45,121] These results indicated that environmental effects may be more pronounced at low strain amplitudes compared to high strain amplitudes. However, it is not clear whether the apparent increase in environmental effects with decreasing strain is a true strain dependence or just an artifact of the dataset being used to evaluate environmental effects. Most of the fatigue data on austenitic SSs in PWR environments is for low-C Type 304L or 316NG SSs. As mentioned in the report, the slope of the fatigue ε–N curve in air for these low-C SSs is steeper than that for the high-C SSs. Additional data are needed to investigate this topic more completely. Because of this uncertainty and because using different slopes for the fatigue ε–N curves in air and water environments would add complexity to the determination of the F_{en}, the ANL model slope of the fatigue ε–N curve was assumed to be the same in both LWR and air environments. Furthermore, the reevaluation of the fatigue ε–N data assumed that the constant A under environmental conditions was also the same as the value in air.

A review of the updated fatigue database indicated that the results from the EdF-sponsored study at GE on Type 304L SSs tested in PWR water at 150°C showed some environmental effects in the high-cycle regime (i.e., greater than 10^4 cycles). Therefore, as discussed earlier, to better represent the existing fatigue ε–N data, the temperature-dependent relationships in the F_{en} expression have been modified and the temperature threshold has been decreased from 150°C to 100°C. In addition, a maximum temperature limit was selected at 325°C to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions considering the use of average temperature (as discussed later in Section 4.4 and shown in Figure 4-67). The dependency of fatigue lives on strain rate was also modified, and the threshold strain rate below which environmental effects were significant was increased from 0.4 to 7%/s. In addition, the dependence of environmental effects on water DO content was also included; it was based on the material composition and heat treatment.

In this report, the effects of water environments on the fatigue lives of austenitic SSs, were expressed in terms of a fatigue life correction factor, F_{en}, which was defined as the ratio of fatigue life in air at room temperature (25°C (77°F)) to that in water at the service temperature, is given by

$$F_{en} = \exp(- T^* \dot{\varepsilon}^* O^*), \quad (43)$$

where the constants T*, ε̇*, and O* are the transformed parameters. Using Equation 41 and values of constants A, B, and C that are the same as those obtained for the best-fit air curve for austenitic SSs (i.e., Equation 29), a least-squares fit of the much larger fatigue ε–N database in LWR environments yielded the following expressions for the transformed parameters T*, ε̇*, and O*:

$$\begin{aligned} T^* &= 0 && (T < 100°C) \\ T^* &= (T - 100)/250 && (100°C \le T \le 325°C) \end{aligned} \quad (44)$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 7\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/7) && (0.0004\%/s \le \dot{\varepsilon} \le 7\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/7) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad (45)$$

For DO less than 0.1 ppm (i.e., PWR or BWR HWC water),

$O^* = 0.29$ (all wrought and cast SSs and heat treatments and SS weld metals)

For DO greater than or equal to 0.1 ppm (i.e., NWC BWR water),

$$\begin{aligned} O^* &= 0.29 && \text{(sensitized high-carbon wrought and cast SSs)} \\ O^* &= 0.14 && \text{(all wrought SSs except sensitized high-carbon SSs).} \end{aligned} \quad (46)$$

The reevaluation of the updated fatigue ε–N data for austenitic SSs using the updated expressions yielded a good fit of the data, particularly in the low-cycle regime. The R-squared values for the best fit of the data to minimize the error in the values of fatigue lives and the values of the shortest distance between the data points and the best-fit ε–N curve improved from 0.83 to 0.86 and 0.92 to 0.93, respectively. A single expression was used for Types 304, 304L, 316, 316L, and 316NG SSs, and Equations 43–46 also apply to cast austenitic SSs such as CF-3, CF-3M, CF-8, and CF-8M as well as SS weld metals. In addition, a threshold strain amplitude (one-half of $\Delta\varepsilon$) has been defined, below which LWR water environments have insignificant effects on fatigue lives (i.e., $F_{en} = 1$). The threshold strain amplitude is specified as a strain of 0.10% or as a stress amplitude of 195 MPa (28.3 ksi) for wrought and cast austenitic SSs.

To incorporate environmental effects into an ASME Code Section III fatigue evaluation, the fatigue usage in air for a specific stress cycle is multiplied by the F_{en}. Appendix A presents further details for incorporating environmental effects into fatigue evaluations.

Comparisons of the experimental fatigue lives of wrought and cast austenitic SSs, as well as their associated weld metals in LWR environments, were compared to those predicted by the updated F_{en} expression, the JNES expression,[136] and the expression in the original version of NUREG/CR-6909, as shown in Figure 4-48. The results indicated that the updated F_{en} expression represented a better fit to the larger experimental database relative to the fit for the expression in the original version of NUREG/CR-6909. Typically, for fatigue lives less than 3×10^4 cycles, the predicted values were within a factor of 3 to the experimental values. In addition, compared to the estimates based on the expressions in the original version of NUREG/CR-6909, the R-squared values for the best fit of the data were slightly higher.

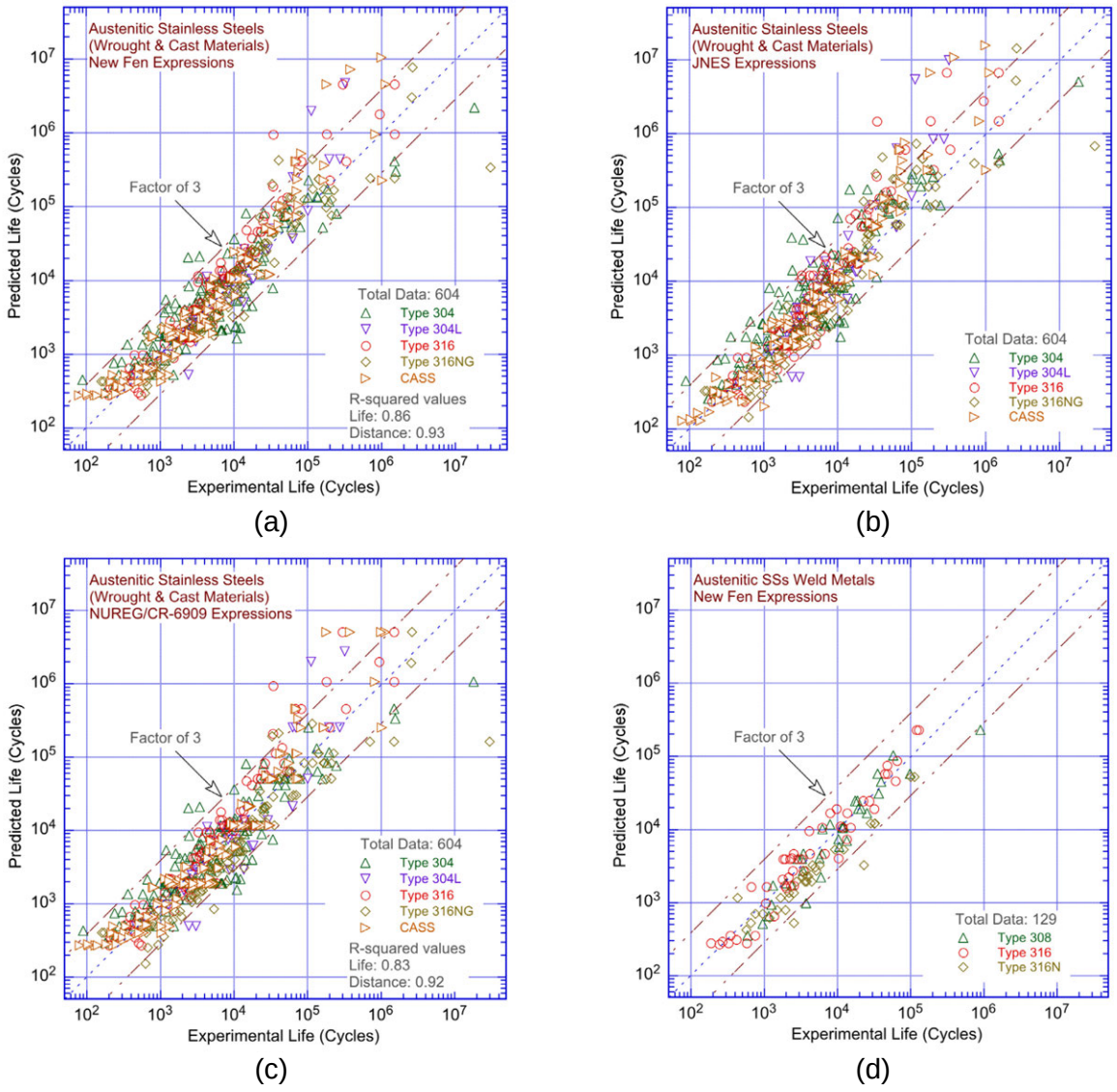


Figure 4-48 Experimental fatigue lives of wrought and cast austenitic SSs in LWR environments vs. fatigue lives predicted from (a) the updated ANL expression, (b) the JNES expression, (c) the previous NUREG/CR 6909 expression, and (d) fatigue lives of SS weld metal predicted from the updated ANL expression.

A comparison of the fatigue lives predicted using the updated F_{en} expression and the JNES F_{en} expression was also made, as shown in Figure 4-49. In general, the F_{en} values calculated from the updated expression were marginally lower for fatigue lives less than 10^4 cycles and slightly longer than those predicted from the JNES expression for fatigue lives greater than 10^4 cycles. Some significant differences remain in the predicted lives obtained from the updated F_{en} expression for SS compared to those obtained from the JNES expression for BWR environments. The reasons for these differences are not fully understood but appear to be predominantly associated with the DO and temperature relationships. Further investigation of these differences is recommended as a part of any future research activities.

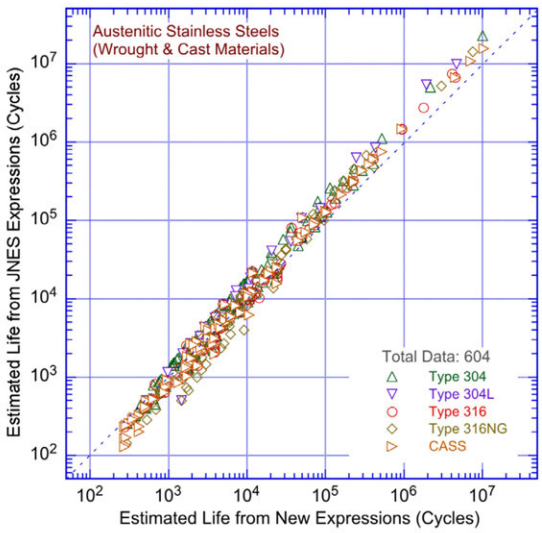


Figure 4-49 Fatigue lives of wrought and cast austenitic SSs in LWR environments estimated from the new F_{en} expressions vs. those estimated from the JNES expression.

The experimental fatigue lives were compared with the estimated values using the updated F_{en} expression and the JNES expression for a smaller dataset of Types 304L and 316N SSs and cast and wrought austenitic SSs in water containing greater than 0.1 ppm DO, as shown in Figure 4-50 and Figure 4-51, respectively. The results indicated that, in general, the estimates based on the updated expression were slightly better than those from the JNES expression. However, the data scatter for high-carbon Type 304 SSs in high-DO water (i.e., greater than 0.1 ppm DO in water) is larger than that for the other grades of SSs

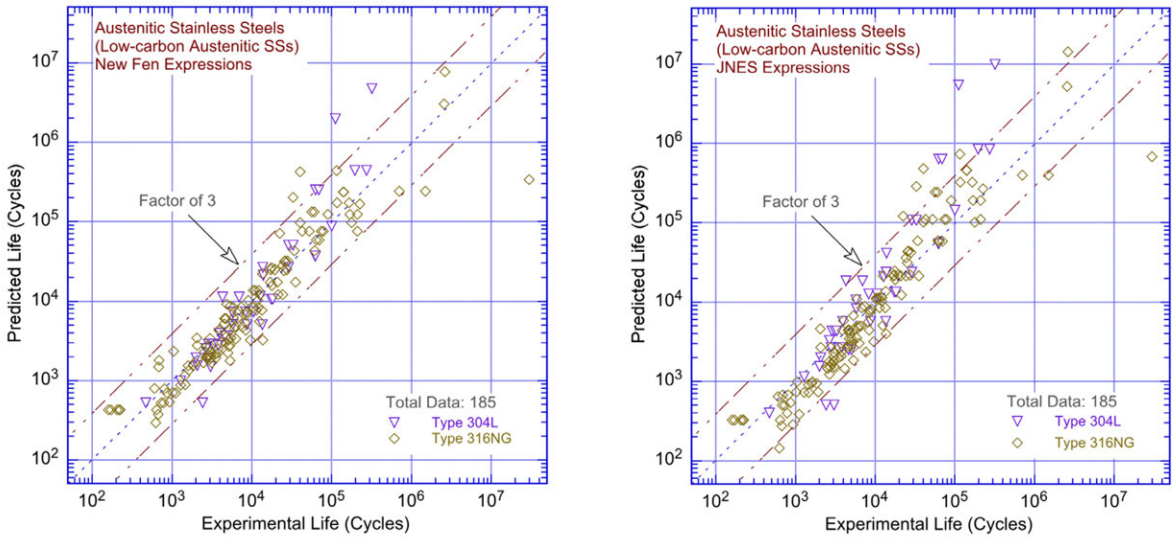


Figure 4-50 Experimental fatigue lives of Types 304L and 316N austenitic SSs in LWR environments vs. fatigue lives predicted from (a) the updated ANL expression and (b) the JNES expression.

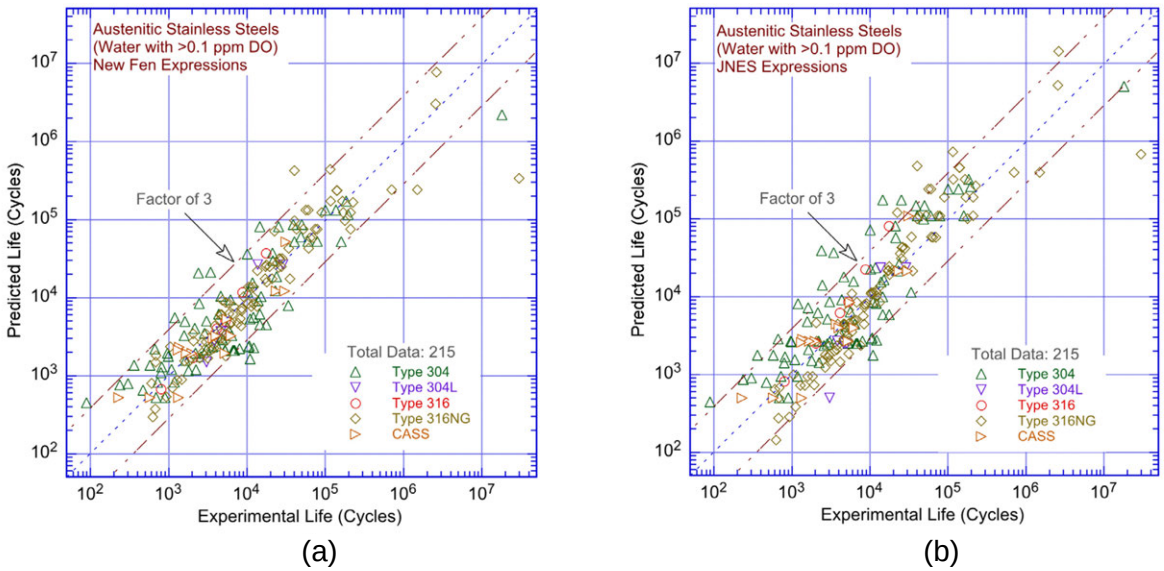


Figure 4-51 Experimental fatigue lives of wrought and cast austenitic SSs in water containing greater than 0.1 ppm DO vs. fatigue lives predicted from (a) the updated ANL expression and (b) the JNES expression.

As observed in Section 4.1.11 for carbon and low-alloy steels, upon completion of the modeling phase, the residual errors for austenitic SSs did not show significant patterns, such as changing variance or a nonzero slope. Figure 4-52 plots the residual errors for each variable, grouped by steel type, for wrought and cast austenitic SSs in LWR environments. The residuals were determined from the difference between the logarithms of the estimated lives and predicted lives. Thus, negative residual errors corresponded to conservative estimates of fatigue lives, and positive residual errors corresponded to nonconservative estimates of fatigue lives (i.e., predicted lives were greater than observed fatigue lives). However, predominantly positive or negative residuals did not necessarily indicate any deficiency in the predictive models. Such results indicated that the specific heat was either superior or inferior to the average behavior predicted by the model. For example, a positive residual indicated that the heat was inferior (i.e., the constant A for the heat was smaller than the median value of constant A in the model), and a negative residual indicated that the heat was superior to the average behavior for the material. Section 4.2.15 further discusses this behavior.

The results presented in Figure 4-52 did not reveal any unexplained patterns. In general, high observed variances tended to be associated with longer lives and lower strain amplitudes. Furthermore, any observed biases were traceable to heat-to-heat variations. For example, heats of Type 304 SSs with Material ID 9, Type 316 SSs with Material ID 49, and cast austenitic SSs with Material ID 61 had inferior fatigue resistance, and heats of Type 304 SSs with Material IDs 1 and 21 and Type 316 SSs with Material ID 51 had superior fatigue resistance than the average behavior represented by the fatigue ε–N model (Equations 43 and 29).

Some of the heats of austenitic SSs that were tested in LWR environments were also tested in air. Figure 4-53 plots the residual errors for the best fit of the fatigue ε–N data for austenitic SSs in air as a function of the ANL Material ID. Most of the data subsets for fatigue tests in air followed the same trends as those observed in LWR environments. For example, data subsets for Material IDs 21 and 51 yielded predominantly negative residuals in both environments and predominantly positive residuals for Material ID 61. The one exception was Material ID 9, which

yielded positive residuals in air and marginally negative residuals in LWR environments. These results indicated that environmental effects on fatigue lives in LWR environments were accurately estimated by the updated F_{en} expression.

- *The F_{en} approach should be used to incorporate environmental effects into ASME Code Section III fatigue evaluations for cast and wrought austenitic SSs and their associated weld metals. Appendix C to this report presents a sample application of the F_{en} approach using the methodology in Subarticle NB-3200, "Design by Analysis," of ASME Code Section III.*

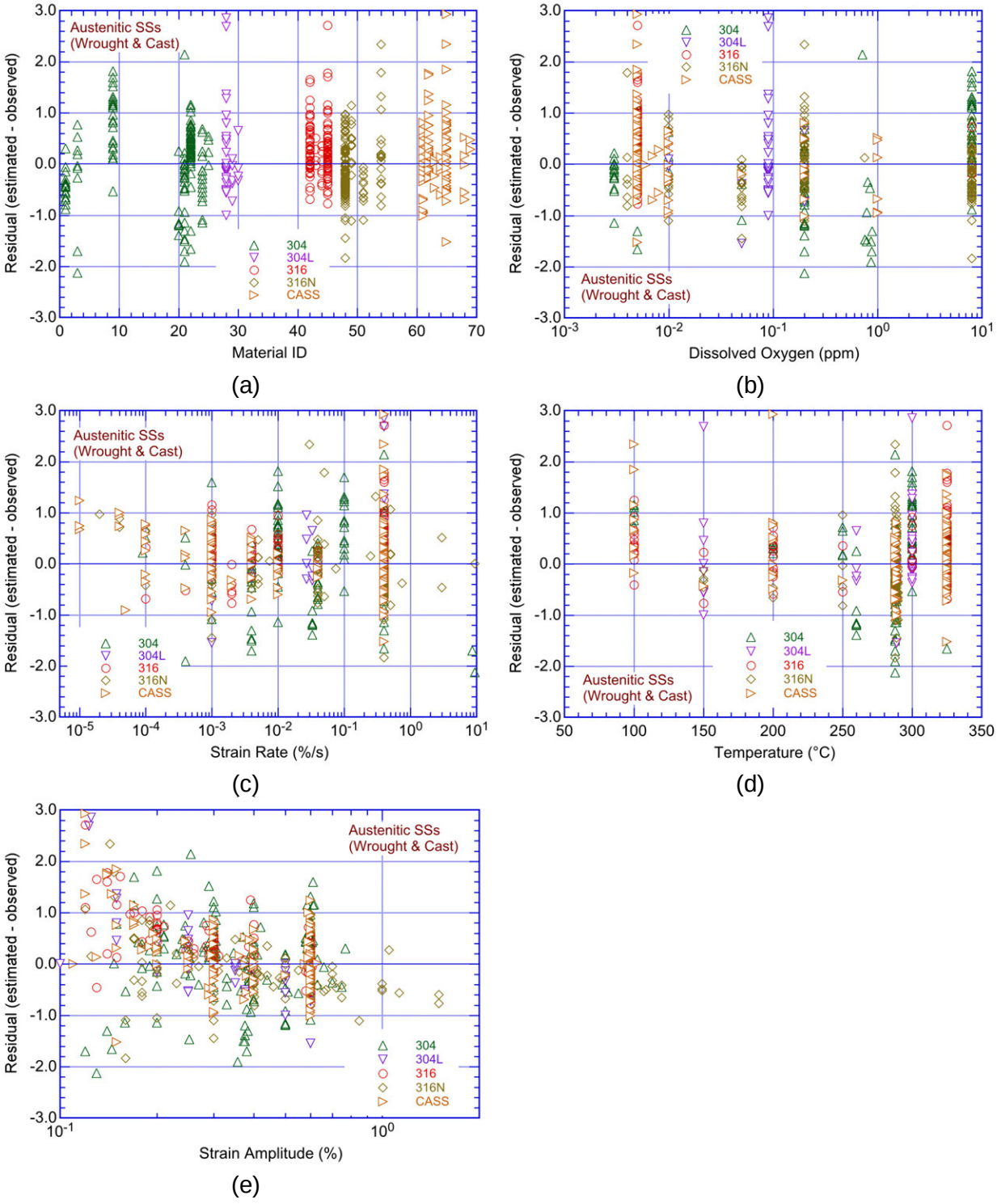


Figure 4-52 Residuals for predicted fatigue lives of wrought and cast austenitic SSs as a function of (a) ANL Material ID, (b) water DO content, (c) strain rate, (d) temperature, and (e) strain amplitude.

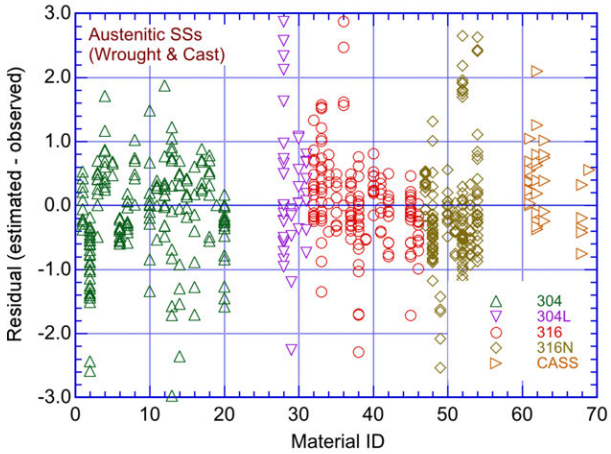


Figure 4-53 Residuals for predicted fatigue lives of wrought and cast austenitic SSs in air as a function of ANL Material ID.

4.2.14 Surface Finish

Fatigue tests were conducted on Types 304 and 316NG SSs that were intentionally roughened in a lathe under controlled conditions with 50-grit sandpaper to produce circumferential cracks with an average surface roughness of 1.2 μm. Figure 4-54 shows the results for Types 316NG and 304 SSs. For both steels, the fatigue lives of roughened specimens were up to a factor of 3 lower than those of the smooth specimens in both air and low-DO water environments. However, the results of a single test on Heat P91576 of Type 316NG in high-DO water (i.e., the BWR test in Figure 4-54(a)) did not show any effects of surface finish; the fatigue lives were the same for rough and smooth specimens (shown as open and closed diamond symbols in Figure 4-54(a)).

Similar tests conducted on Type 304L SSs in air and PWR water environments[155-157] also indicated a factor of approximately 2 decrease in fatigue lives of the ground specimens relative to those of the polished specimens, as shown in Figure 4-55. The tests were conducted with a triangular waveform loading with a strain rate of 0.4%/s and a complex waveform loading that simulated a PWR safety injection transient. The tests were conducted under strain control and the strain rates associated with the safety injection transient ranged from 0.08 to 0.00013%/s. In these tests, the F_{en} value for the portion of the transient at the slowest strain rates was high, but this was compensated by the small total accumulated strain during the same portion of the transient. Therefore, the slow strain rate portion of the transient did not significantly contribute to the overall F_{en} value for the entire transient.

Thus, the available small-scale laboratory fatigue ε–N data indicated a decrease in fatigue lives of up to a factor of 3 for the roughened specimens relative to the lives of polished specimens in both air and low-DO environments. Limited data also indicated that for some low-carbon heats of austenitic SSs, surface finish had little effect on the fatigue lives of SSs in high-DO water environments. However, the data were very limited; therefore, additional data are needed to validate this behavior.

- *The effects of surface finish were not included in F_{en}; instead, they were included in the subfactor for "surface finish and environment," which was applied to the mean-data air curve to develop the fatigue design curve in air.*

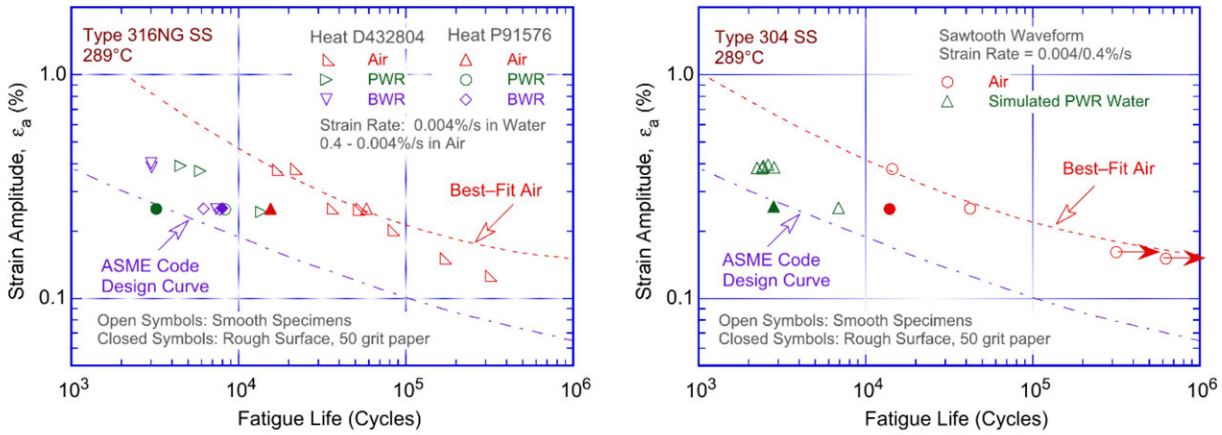


Figure 4-54 Effect of surface finish on fatigue life of (a) Type 316NG and (b) Type 304 SSs in air and high-purity water at 289°C.

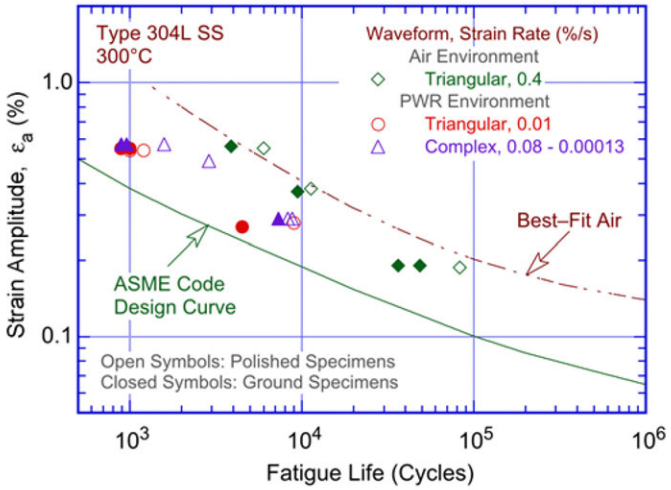


Figure 4-55 Effects of surface finish on the fatigue lives of Type 304L SSs in air and PWR primary water environments at 300°C (Refs. 155 and 157).

4.2.15 Heat-to-heat Variability

The effects of material variability and data scatter on the fatigue lives of austenitic SSs were evaluated for data in LWR environments. The fatigue behavior of each of the heats or loading conditions was characterized by the value of the constant A in the ANL model (e.g., Equation 6). The values of A were determined for the various datasets in the larger, updated fatigue ε–N database used in this report using Equation 41 with the values of constants B and C from Equation 29. The values of constant A were ordered, and median ranks were used to estimate the cumulative distribution of A for the population. If the F_{en} expression given in Equation 43 adequately captured the effects of LWR environments on the fatigue lives of wrought and cast austenitic SSs, the reanalysis should have yielded a median value of constant A that is the same as that in an air environment.

Figure 4-56 shows the estimated cumulative distribution of constant A. The results yielded a median value of A of 6.800 for all the datasets for cast and wrought austenitic SSs and their

associated weld metals and a value of 6.749 without the datasets for weld metals. These values of constant A are slightly lower than that in air (e.g., the difference is less than 10%). These results demonstrate that the F_{en} expressions for cast and wrought austenitic SSs adequately capture the environmental effects in LWR environments.

The heat-to-heat variation in LWR environments differed insignificantly from that in air and as presented in Section 3.2.7. The 95/95 values of the factors to account for material variability and data scatter were the same in air (i.e., as presented in Table 3-7 for austenitic SSs). These factors provide 95% confidence that the resultant lives are greater than those observed for 95% of the materials of interest.

- *Heat-to-heat variability was not explicitly included in the F_{en} for austenitic SSs; instead, it was included in the subfactor for "data scatter and material variability" that was applied to the room-temperature mean-data air curve to develop the fatigue design curve in air.*

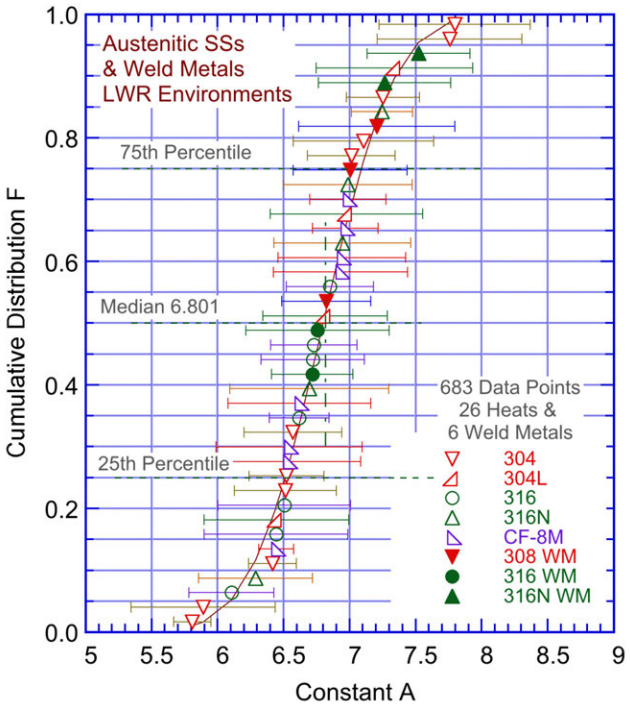


Figure 4-56 Estimated cumulative distribution of constant A in the ANL model for fatigue lives of heats of austenitic SSs in LWR environments.

4.3 Ni-Cr-Fe Alloys

The relevant fatigue ε–N data for Ni-Cr-Fe alloys and associated weld metals in LWR environments evaluated in this report included the data compiled in the JNES database from Japan[136] and the tests performed by Van Der Sluys et al.[75] The database was composed of 162 tests—87 tests on 5 heats of Alloy 600, 21 tests on 2 heats of Alloy 690, and 54 tests on 6 heats of Ni-Cr-Fe alloy weld metals that included Alloys 82, 182, 132, 152, and 690. Out of these, 7 tests were conducted at 100°C (one at 54°C), 10 tests at 200°C, 88 tests at 288/289°C, 10 tests at 315°C, and 47 tests at 325°C. Table 4-3 summarizes the data sources for the updated database used in this report as categorized by material type and test environment. Appendix B provides other material information such as chemical composition, heat treatment, and room temperature tensile properties for the Ni-Cr-Fe alloys and associated weld metals evaluated. Note that experimental data on environmental effects for Inconel 718 are not available. Therefore, the F_{en} expression for Ni-Cr-Fe alloys contained in this section is not applicable to Inconel 718.

Table 4-3 Sources of the Fatigue ε–N Data for Ni Cr Fe Alloys and their Weld Metals in LWR Environments.

ANL Mat. ID	Material Heat Designation	Carbon Content (wt.%)	Dissolved Oxygen (ppm)	Test Temperature (°C)	No. of Data Points	Source	Applicable Reference
Alloy 600							
1	Alloy 600-1	0.07	0.2	288	12	JNES (Higuchi)	39,136
2	Alloy 600-2	0.07	0.2	288	16	JNES (Nakao)	136
5	Alloy 600-3	0.01	0.01, 0.05, 0.2, 8.0	289 (4 at 200)	11, 1, 14, 4	JNES (Hirano)	136
3	Alloy 600-4	0.07	0.01, 0.2	289	2, 6	JNES (Hirano)	136
4	Alloy 600-5	0.03	0.005	100, 200, 325	6, 6, 9	JNES (Nomura)	136
Alloy 690							
9	Alloy 690-1	0.03	0.005	325	20	JNES (Nomura)	136
12	Alloy 690-3	0.02	0.01	315	1	PVP (Van der Sluys)	75
Ni-Cr-Fe Alloy Weld Metals							
10	Alloy 152 WM	0.037	0.005	325	9	JNES (Kanasaki)	136
6	Alloy 182-1	0.06	0.2	288	14	JNES (Higuchi)	136
7	Alloy 182-2	0.038	0.2	288	12	JNES (Nakao)	136
11	Alloy 82-5	0.04	0.01, 0.007	315	4,[a] 5	PVP (Van der Sluys)	75
8	Alloy 132	0.04	0.005	325	9	JNES (Nomura)	136
13	Alloy 152-2	0.032	0.01	315	1	PVP (Van der Sluys)	75

[a] One test in 0.01 ppm DO water was performed at 54°C.

4.3.1 Experimental Data

Similar to carbon, low-alloy and austenitic SSs, the fatigue lives of Ni-Cr-Fe alloys and their welds were also decreased in LWR environments. Figure 4-57 and Figure 4-58 show the fatigue ε–N data for various Ni-Cr-Fe alloys in simulated BWR water at approximately 289°C and PWR water at 315–325°C, respectively. The plots in these figures also include the fatigue ε–N air curve based on the ANL model for austenitic SSs (from Equation 29 in Section 3.2.6). The results indicated

that environmental effects on the fatigue lives of Ni-Cr-Fe alloys were also dependent on key parameters such as strain rate, temperature, and the DO level in the water. Similar to SSs, the effects of water environments on the fatigue lives of Ni-Cr-Fe alloys were greater in low-DO PWR environments than they were in the high-DO BWR environments. However, under similar loading and environmental conditions, the extent of the effects of environment was considerably less for the Ni-Cr-Fe alloys compared to that for austenitic SSs. In general, environmental effects on fatigue lives were the same for wrought and weld Ni-Cr-Fe alloys.

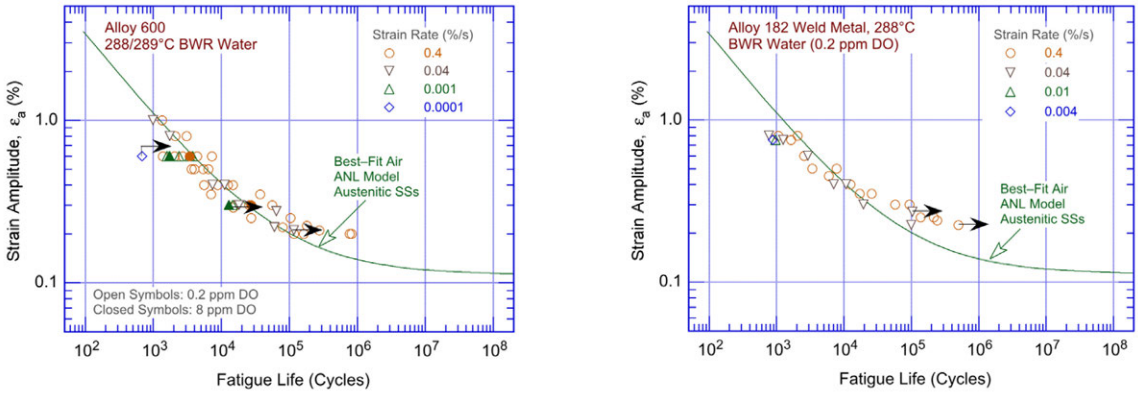


Figure 4-57 Fatigue ε–N behavior for Alloy 600 and its weld alloys in simulated BWR water at approximately 289°C (Refs. 136 and 39).

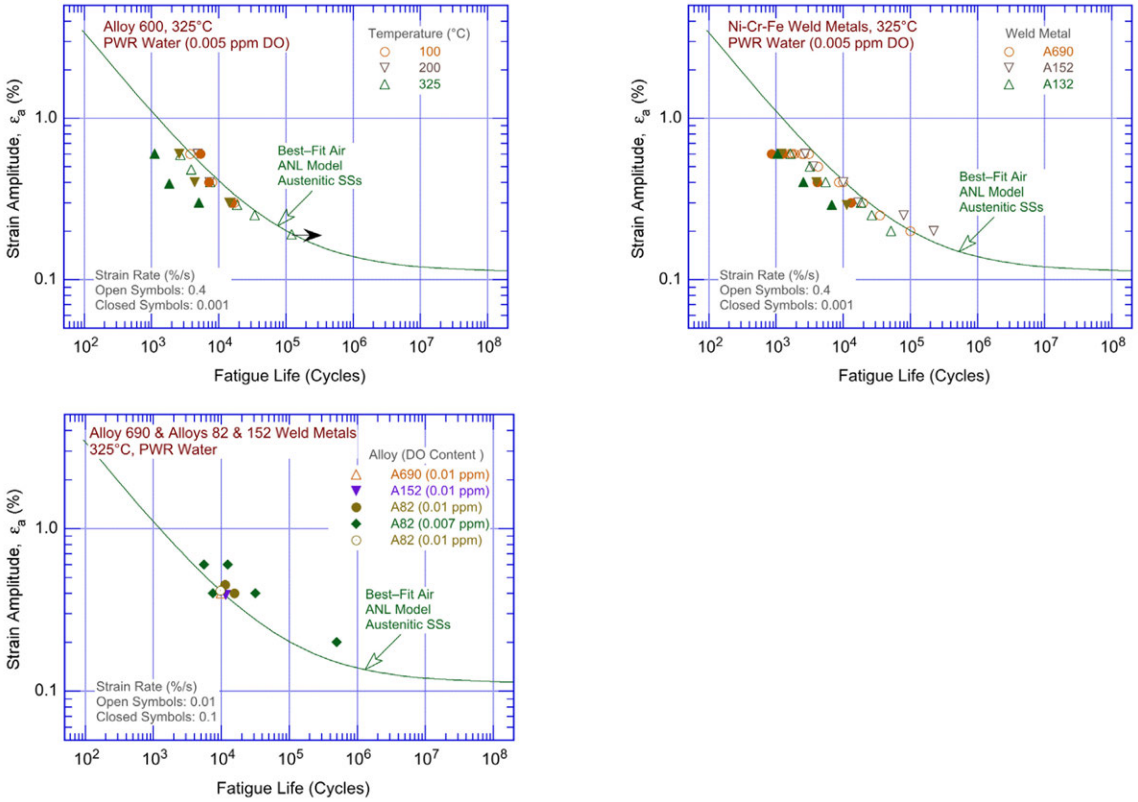


Figure 4-58 Fatigue ε–N behavior for Alloys 600 and 690 and associated weld metals in simulated PWR water at 325°C (Refs. 136 and 75).

4.3.2 Effects of Key Parameters

The effects of the key loading and environmental parameters (e.g., strain rate, temperature, and DO level) on the fatigue lives of Ni-Cr-Fe alloys in LWR environments were evaluated using the limited fatigue ε–N data that were available. Figure 4-59 plots the fatigue lives of Alloys 600 and 690 and their weld metals (e.g., Alloys 132 and 152) in simulated PWR and BWR water at different strain amplitudes as a function of strain rate. The fatigue lives of these alloys decreased logarithmically with decreasing strain rate. Because little or no data exist at strain rates below 0.001%/s, the effects of strain rate on Ni-Cr-Fe alloys were assumed to be similar to those for austenitic SSs. The effects were assumed to saturate at a strain rate of 0.0004%/s.

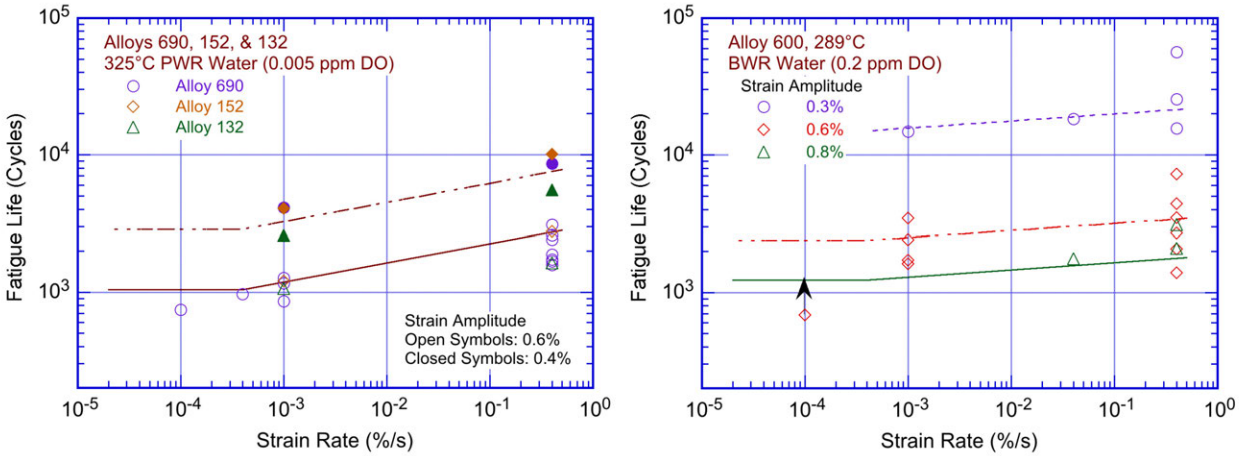


Figure 4-59 Dependence of fatigue lives of Alloys 690 and 600 and associated weld metals on strain rate in PWR and BWR environments (Refs. 39, 75, and 136).

Furthermore, the threshold strain rate below which environmental effects were insignificant could not be sufficiently determined from the available data. Higuchi et al.[39] defined a threshold strain rate of 1.8%/s in high-DO BWR water and 26.1%/s in low-DO PWR water. As discussed in Section 4.3.3, an average threshold value of 5%/s provided good estimates of fatigue lives of Ni-Cr-Fe alloys in LWR environments. The results also indicated that the effects of environment were greater in low-DO PWR water than in high-DO BWR water. For example, a decrease in strain rate by 3 orders of magnitude decreased the fatigue lives of these alloys by a factor of approximately 3 in PWR water and by a factor of approximately 2 in BWR water.

Figure 4-60 plots the fatigue lives of Alloy 600 in PWR environments at three different strain amplitudes as a function of temperature. The results indicated a decrease in fatigue lives with increasing temperature. Because of very limited fatigue data for Ni-Cr-Fe alloys, the effects of temperature on the fatigue lives of these materials were also assumed to be similar to those observed in austenitic SSs. Environmental effects on fatigue lives were considered to be insignificant below a threshold temperature of 50°C. In addition, it was assumed that a slow strain rate applied during the tensile-loading cycle (i.e., up ramp with increasing strain) was primarily responsible for the environmentally assisted reduction in fatigue lives. Slow rates applied during both tensile- and compressive-loading cycles (i.e., up and down ramps) did not further decrease fatigue lives compared with those observed for tests with only a slow tensile-loading cycle. Thus, loading and environmental conditions during the tensile-loading cycle were important for an environmentally assisted reduction in the fatigue lives of Ni-Cr-Fe alloys. The available fatigue ε–N

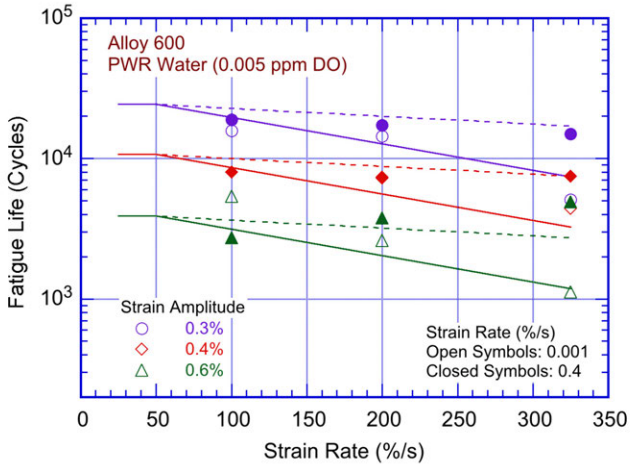


Figure 4-60 Dependence of fatigue lives of Alloy 600 on temperature in a PWR environment (Refs. 39, 75, and 136).

data for Ni-Cr-Fe alloys in LWR environments were inadequate to define the threshold strain amplitude below which environmental effects on fatigue lives did not occur.

As discussed in Section 4.2.13, some significant differences remain in the predicted lives obtained from the updated F_{en} expression for austenitic SSs compared to those obtained from the JNES expression for BWR environments. These differences may also impact the relations for Ni-Cr-Fe alloys. The reasons for these differences are not fully understood, but they appear to be predominantly associated with the DO and temperature relationships. Further investigation of these differences is recommended as a part of any future research activities.

4.3.3 Environmental Fatigue Correction Factor

The effects of water environments on the fatigue lives of Ni-Cr-Fe alloys were also expressed in terms of the F_{en}. The available fatigue data were too limited to develop a totally distinct fatigue life model for Ni-Cr-Fe alloys, including Inconel 718, in LWR environments. Additional data are needed to better define the F_{en} expressions in order to justify a totally unique model. However, as discussed in Section 4.3.2, the existing environmental effect data for these alloys showed the same trends as those observed for austenitic SSs. Environmental effects increased with increasing temperature and decreasing strain rate. Based on the available fatigue ε–N data, the effects of temperature on the fatigue lives were considered to be insignificant below 50°C and saturated at 325°C. A maximum temperature limit was selected at 325°C to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions considering the use of average temperature (as discussed later in Section 4.4 and shown in Figure 4-67). Similarly, the effects of strain rate were considered insignificant at strain rates above 5%/s and they saturated at 0.0004%/s. Thus, the F_{en} relationship for Ni-Cr-Fe alloys was expressed as the ratio of fatigue life in air at room temperature (25°C (77°F)) to that in water at the service temperature as

$$F_{en} = \exp(-T^* \dot{\varepsilon}^* O^*), \quad (47)$$

where T^*, $\dot{\varepsilon}^*$, and O^* are transformed temperature, strain rate, and DO, respectively. The functional forms for these transformed parameters were obtained from the best fit of the experimental data and were defined as follows:

$$\begin{aligned} T^* &= 0 && (T < 50°C) \\ T^* &= (T-50)/275 && (50°C \le T \le 325°C) \end{aligned} \quad (48)$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/5.0) && (0.0004\%/s \le \dot{\varepsilon} \le 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/5.0) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad (49)$$

$$\begin{aligned} O^* &= 0.06 && (\text{NWC BWR water (i.e., } \ge 0.1 \text{ ppm DO)}) \\ O^* &= 0.14 && (\text{PWR or HWC BWR water (i.e., } < 0.1 \text{ ppm DO)} \end{aligned} \quad (50)$$

These expressions are essentially the same as those in the original version of NUREG/CR-6909, but the dependences of temperature and DO have been updated. Note that the methodology used for developing the F_{en} for Ni-Cr-Fe alloys also assumes that the constant A in Equation 41 was also the same as the value in air. A threshold strain amplitude (one-half of $\Delta\varepsilon$) has also been defined, below which LWR water environments have insignificant effects on fatigue lives (i.e., $F_{en} = 1$). The threshold value for strain amplitude was assumed to be the same as that for austenitic SSs, which is a strain of 0.10% or a stress amplitude of 195 MPa (28.3 ksi). Appendix A provides further details for incorporating environmental effects into fatigue evaluations for Ni-Cr-Fe materials.

The fatigue lives of Ni-Cr-Fe alloys in LWR environments were estimated from Equation 29 and Equations 47–50. Figure 4-61-Figure 4-63 plot the experimental fatigue lives of various Ni-Cr-Fe alloys in BWR NWC (i.e., ≥ 0.1 ppm DO) and PWR or HWC BWR (i.e., < 0.1 ppm DO) environments using either the updated F_{en} expression, the original NUREG/CR-6909 expression, or the JNES expression, respectively, to estimate the fatigue life. The results indicated that the updated expression represented a better fit to the larger database compared to the expression in the original version of NUREG/CR-6909. The R-squared values for the best fit of the data were slightly higher for the updated expression compared to those obtained from the original NUREG/CR-6909 F_{en} expression. In general, the estimated values were either comparable (within a factor of 2) or longer (conservative) than those observed experimentally.

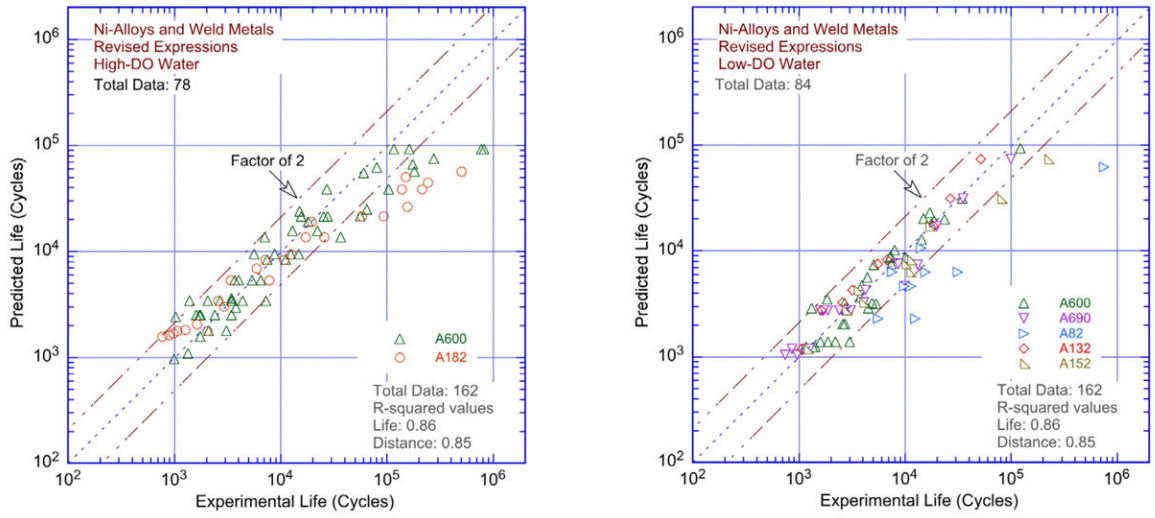


Figure 4-61 Experimental fatigue lives vs. fatigue lives predicted from the updated F_{en} expression for Ni Cr Fe alloys and weld metals in simulated (a) BWR and (b) PWR environments.

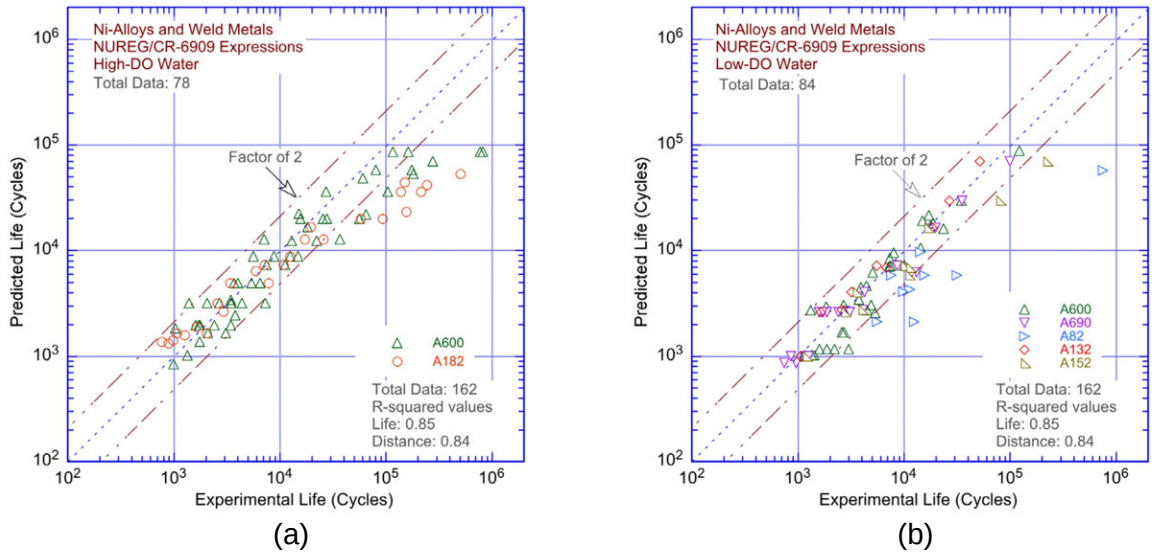


Figure 4-62 Experimental fatigue lives vs. fatigue lives predicted from the F_{en} expression in the original version of NUREG/CR 6909 for Ni Cr Fe alloys and weld metals in simulated (a) BWR and (b) PWR environments.

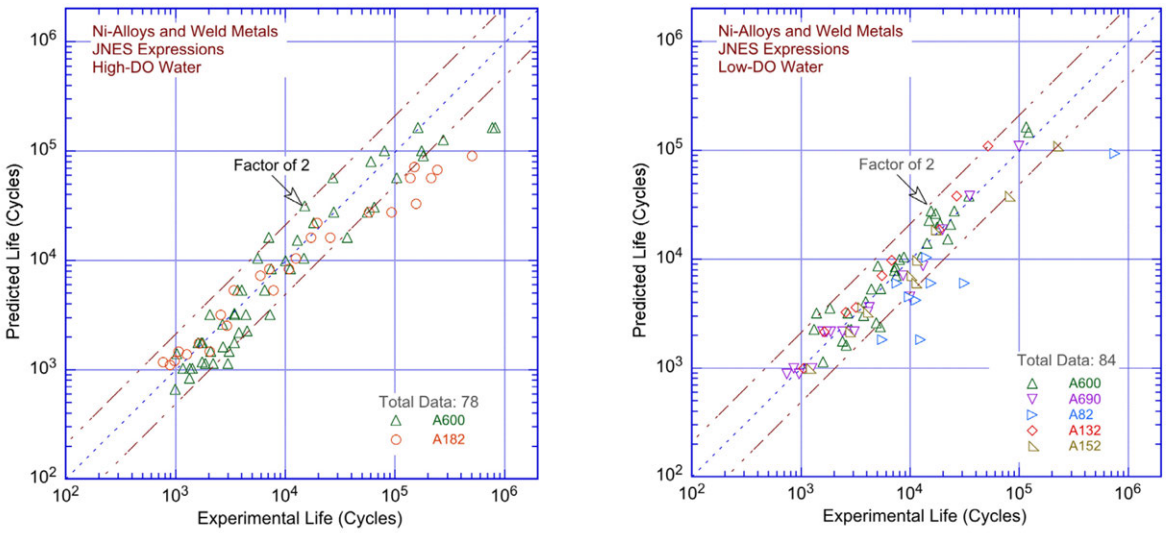


Figure 4-63 Experimental fatigue lives vs. fatigue lives predicted from the JNES F_{en} expression for Ni Cr Fe alloys and associated weld metals in simulated (a) BWR and (b) PWR environments.

For Ni-Cr-Fe alloys, the residual errors did not show significant patterns such as changing variances or nonzero slopes. Figure 4-64 plots the residual errors for each variable, grouped by steel type, for Ni-Cr-Fe wrought and weld alloys in LWR environments. The residuals were determined from the difference between the logarithms of the estimated lives and the predicted lives. Therefore, negative residual errors corresponded to conservative estimates of fatigue lives and positive residual errors corresponded to nonconservative estimates of fatigue lives. The results did not reveal any unexplained patterns. In general, high observed variances tended to be associated with longer lives and lower strain amplitudes. Furthermore, any observed biases were traceable to heat-to-heat variations.

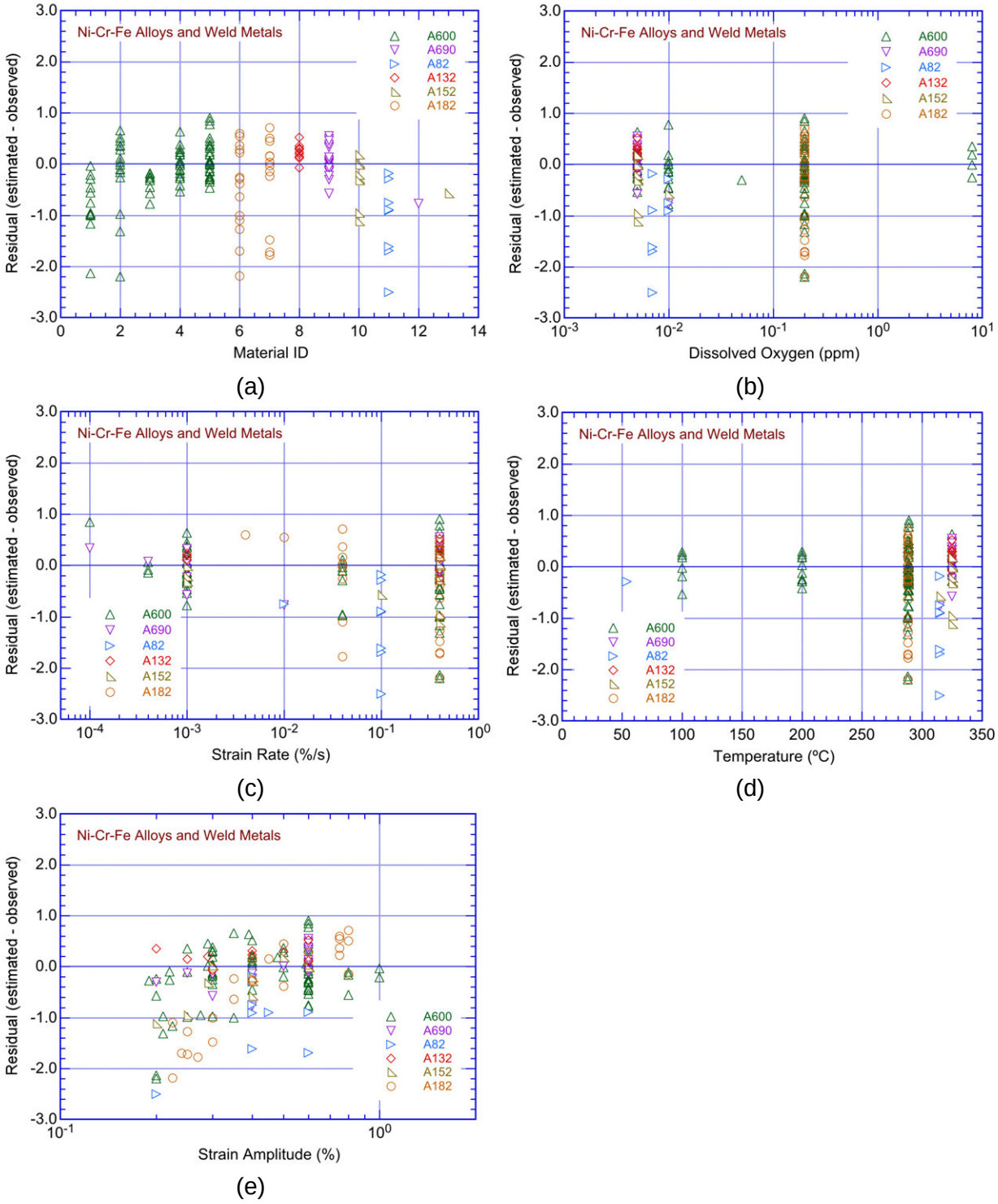


Figure 4-64 Residuals for predicted fatigue lives of Ni Cr Fe alloys and associated weld metals as a function of (a) Material ID, (b) water DO content, (c) strain rate, (d) temperature, and (e) strain amplitude.

For example, the negative residuals for Alloy 82 weld metal were likely due to superior fatigue properties of the material relative to that of Alloy 600. Most of the compositions of Ni-Cr-Fe

alloys that were tested in LWR environments were also tested in air. Figure 4-65 plots the residual errors for the best fit of the fatigue ε–N data for Ni-Cr-Fe alloys in air as a function of the Material ID. Most of the data subsets for fatigue tests in air followed the same trends as those observed in LWR environments. For example, except for the data subset associated with Material ID 42, the other four data subsets for Alloy 82, including Material ID 51, yielded predominantly negative residuals in air. These results indicated that environmental effects on the fatigue lives of Ni-Cr-Fe alloys in LWR environments were reasonably estimated by the updated F_{en} expression.

- *The updated Ni-Cr-Fe F_{en} expression should be used along with the SS design fatigue curve to incorporate environmental effects into ASME Code Section III fatigue evaluations for all Ni-Cr-Fe materials except Inconel 718. Because of insufficient experimental data on environmental effects for Inconel 718, the F_{en} expression for Ni-Cr-Fe alloys contained in this section is not applicable to Inconel 718. The modified rate approach discussed in Section 4.4 also applies to Ni-Cr-Fe materials. Appendix C of this report presents a sample application of the F_{en} approach using the methodology in Subarticle NB-3200 of ASME Code Section III.*

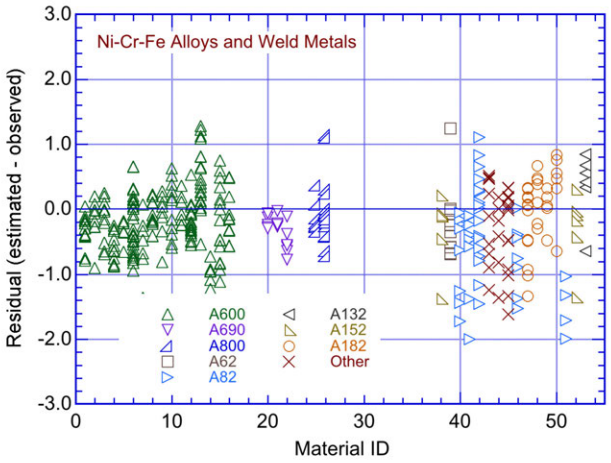


Figure 4-65 Residuals for predicted fatigue lives of Ni Cr Fe alloys and associated weld metals in air as a function of ANL Material ID.

4.4 Modified Rate Approach

Most of the available fatigue ε–N data evaluated in this report were obtained under loading histories with constant strain rate, temperature, and strain amplitude. The actual loading histories encountered during service of nuclear power plants are far more complex. Exploratory fatigue tests were conducted with loading waveforms in which the test temperature and strain rate were varied.[10,21,24] The results of such tests provided limited guidance for developing procedures and rules for fatigue evaluation of components under complex loading histories.

The modified rate approach was proposed to predict fatigue lives under changing test conditions.[37,38] This approach provided methods for calculating F_{en} under conditions where temperature and strain rate were varied. In this approach, the environmental fatigue correction factor, $F_{en}(\dot{\varepsilon}, T)$, is assumed to increase linearly from a minimum value of 1.0 with increments of

strain from a minimum value, ε_{min} (%), to a maximum value, ε_{max} (%). Increments of F_{en}, dF_{en}, during increments of increasing strain, $d\varepsilon$, are calculated from

$$dF_{en} = (F_{en} - 1)\, d\varepsilon / (\varepsilon_{max} - \varepsilon_{min}). \tag{51}$$

Integration of Equation 51 from ε_{min} to ε_{max} (i.e., the portion of loading where strain is increasing) provides the F_{en} under changing temperature and strain rate. Figure 4-66 illustrates the application of the modified rate approach to an increasing strain transient. At each strain increment, $d\varepsilon$, the associated $F_{en}(\dot{\varepsilon},T)$ value for carbon and low-alloy steels is determined from Equation 34. Thus, F_{en} for the total increasing strain transient is given by

$$F_{en} = \sum_{k=1}^{n} F_{en,k}\,(\dot{\varepsilon}_k, T_k)\, \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min})}\ , \tag{52}$$

where n is the total number of strain increments, and k is the subscript for the kth incremental segment.

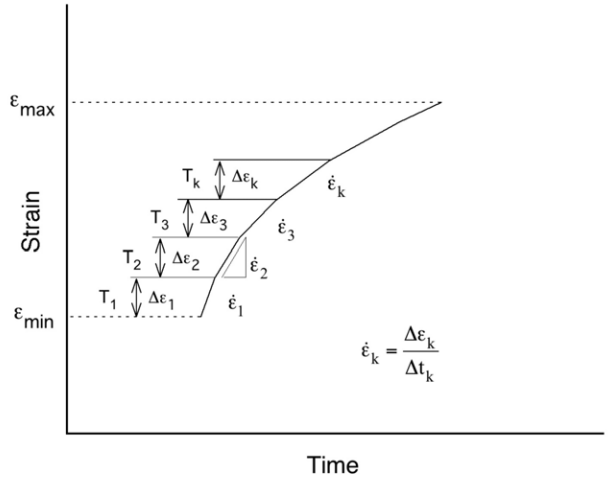


Figure 4-66 Application of the modified rate approach to determine the F_{en} during the increasing strain portion of a transient.

As discussed in Section 4.1.3, a minimum threshold strain, ε_{th} (one-half of the strain threshold of 0.14% strain for carbon and low-alloy steels considering a factor of 2 for data scatter), was required for an environmentally assisted decrease in fatigue life. Consideration of a strain threshold assumes that during a strain cycle, environmental effects are significant only after the applied strain level exceeds the threshold value. In application of the modified rate approach when a threshold strain, ε_{th}, is considered, the following equation can be used to calculate F_{en} for the total strain transient:

$$F_{en} = \sum_{k=1}^{n} F_{en,k}\,(\dot{\varepsilon}_k, T_k)\, \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min}) - \varepsilon_{th}}\ . \tag{53}$$

The modified rate approach defined by both Equations 52 and 53 was used to evaluate fatigue lives under cyclic loading conditions where both temperature and strain rate were varied during the test.[24,37,38] The studies demonstrated the applicability of the modified rate approach to variable loading conditions such as those that are typically present during actual plant transients. The following significant conclusions were made from those studies:

(1) The use of a strain threshold, ε_{th}, for calculating F_{en} by the modified rate approach (i.e., Equation 53) was not necessary because it did not improve the accuracy of estimation.[38] As discussed in Section 4.1.3, application of the modified rate approach, without the consideration of a strain threshold (i.e., Equation 52), gave the best estimates of fatigue lives.

(2) Under load cycles that involved variable strain rates, estimates of F_{en} based on an average strain rate (i.e., in Figure 4-66, total strain ($\varepsilon_{max} - \varepsilon_{min}$) divided by the total time between ε_{min} and ε_{max}) were the most conservative when the maximum transient temperature was used.[24] Thus, calculations of F_{en} based on an average strain rate for the transient are expected to yield conservative estimates of fatigue lives as long as the calculations use appropriate temperatures (either maximum temperatures or appropriate average temperatures in accordance with Item 3 below).

(3) For the modified rate approach, the difference in F_{en} results is insignificant when either average or maximum temperatures are used if the integration time step is sufficiently small. However, as shown in Figure 4-67, use of an average temperature with the average strain rate approach does not always yield a conservative F_{en} estimate when compared to the results obtained from an integrated F_{en} using the modified rate approach. Therefore, an average temperature should only be used if it is demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach. If an average temperature is justified for the average strain rate approach, the temperature can be calculated to estimate F_{en} during a load cycle using one of the following procedures:

   a) as the average of the maximum temperature for the transient and the higher of the threshold temperature for the material under consideration (i.e., 150°C) or the minimum temperature for the transient

   b) as the average of the transient maximum temperature and the F_{en} threshold temperature

(4) The calculated strain rate is dependent on the selected value of Young's modulus, E. In turn, E is dependent upon temperature. Typically, the value of E decreases with increasing temperature; therefore, using maximum temperatures leads to higher calculated strain rates compared to using average temperatures, which in turn will lead to lower calculated F_{en} values based on the transformed strain rate term in the F_{en} expressions. However, the use of higher temperatures also increases the F_{en} values based on the transformed temperature term in the F_{en} expressions. The change in E is typically less than 10% over the range of normal LWR operating temperatures. The change in the calculated F_{en} value for a 10% change in strain rate is significantly less than the change in the calculated F_{en} value over the same temperature range. Therefore, the selection of the temperature used to calculate E generally has a small effect on the calculation of F_{en}. The sample problem in Appendix C used the maximum metal temperature to determine E for calculating strain rate. If the integration time step is sufficiently small, the difference in calculated strain rates for the

modified rate approach is insignificant when either average or maximum temperatures are used for selecting E

- *Where information is available regarding the transients associated with a specific stress cycle or load set pair, the modified rate approach may be used to determine F_{en} using Equation 52*

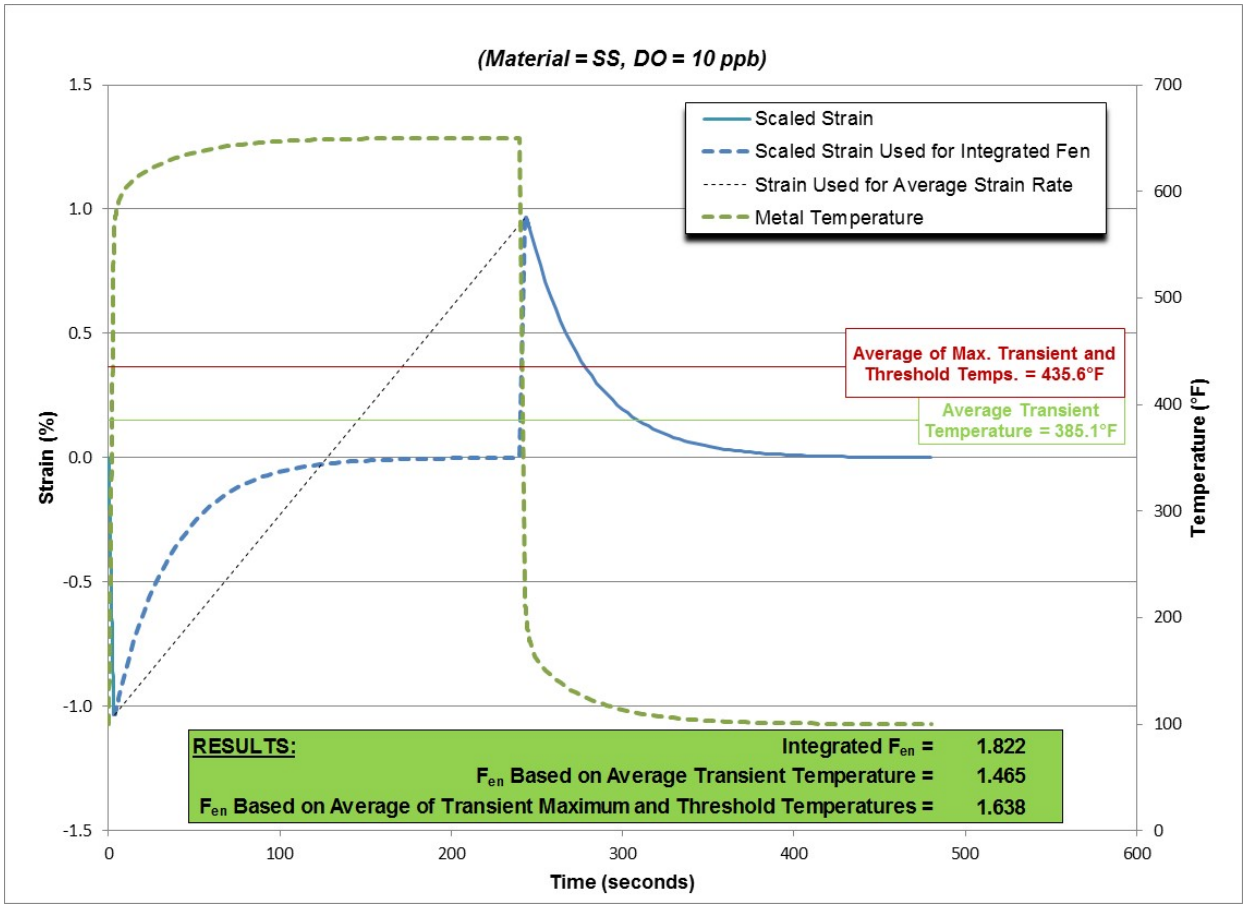


Figure 4-67 Example showing F_{en} values computed using average temperatures compared to the F_{en} computed using an integrated (modified rate) approach.

5 ADJUSTMENT FACTORS IN ASME CODE FATIGUE DESIGN CURVES

Conservatisms in fatigue evaluations in Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) typically arise from the fatigue evaluation procedures and assumptions implemented by the analyst or the fatigue design curves, or both. The overall conservatisms in ASME Code Section III fatigue evaluations were demonstrated in fatigue tests on components.[234,235] Mayfield et al.[234] showed that, in air, the factors on the number of cycles to failure for elbows and tees ranged from 40 to 310 and 104 to 510, respectively, for austenitic stainless steels (SSs) and 118 to 2,500 and 123 to 1,700, respectively, for carbon steels. The factors for girth butt welds were significantly lower, ranging from 6 to 77 for SSs and from 14 to 128 for carbon steels. Data obtained by Heald and Kiss[235] on 26 piping components at room temperature and 288°C showed that the adjustment factors for cracking exceeded a factor of 20; for most of the components, it was greater than a factor of 100. In these tests, fatigue lives were expressed as the number of cycles for the crack to penetrate through the wall thickness of the test specimens, which ranged in thicknesses from 6 to 18 mm. Consequently, depending on the wall thickness, the actual factors to initiate a finite crack (e.g., to form a 3-mm-deep crack) were estimated to be a factor of 2 to 3 lower.

Deardorff and Smith[236] discussed the types and extent of conservatisms present in ASME Code Section III fatigue evaluation procedures and the effects of LWR environments on fatigue adjustment factors. The sources of conservatisms in the procedures included (1) the use of design transients that were significantly more severe than those experienced in service, (2) conservative grouping of transients, and (3) the use of simplified elastic-plastic analyses that led to higher stresses. The authors estimated that the ratio of the cumulative usage factors (CUFs) computed with the mean experimental air fatigue curve for test specimen data in air to those obtained using more accurate values of the stresses and calculated CUFs using the ASME Code Section III air fatigue design curve was approximately 60 and 90, respectively, for pressurized-water reactor (PWR) and boiling-water reactor (BWR) nozzles. The reductions in these factors caused by environmental effects were estimated to be factors of 5.2 and 4.6 for PWR and BWR nozzles, respectively. Thus, Deardorff and Smith[236] argued that, after accounting for environmental effects, factors of 12 and 20 on life for PWR and BWR nozzles, respectively, were available to account for uncertainties due to material variability, surface finish, size, mean stress, and loading sequence.

However, other studies on piping and components indicated that the ASME Code Section III fatigue design procedures do not always contain large conservatisms.[237,238] The Southwest Research Institute performed fatigue tests in room-temperature water on 0.91 m (36 in) diameter carbon and low-alloy steel vessels.[237] In the low-cycle regime, approximately 5-mm-deep (0.2-in-deep) cracks were initiated slightly above the number of cycles predicted by the ASME Code Section III fatigue design curve (Figure 5-1(a)). Battelle Columbus Laboratories conducted tests on 203 mm (8.0 in) and 914 mm (36.0 in) carbon steel pipe welds at room temperature in an inert environment, and Oak Ridge National Laboratory (ORNL) performed four-point bend tests on a 406 mm (16.0 in) diameter Type 304 SS pipe removed from the C-reactor at the Savannah River Site.[238] The results showed that the number of cycles to produce leaks was lower than predicted from calculations using the ASME Code Section III fatigue design curves (Figure 5-1). In the case of the ORNL "tie-in" and flawed "test" welds, the specimens cracked completely through the 12.7 mm (0.5 in) wall thickness, and the number of cycles to initiate a 3-mm crack was slightly lower than the cycles predicted using the ASME

Code Section III fatigue design curve. These and other similar tests indicate that other factors, such as environmental effects, may eliminate much of the conservatism that may be present in ASME Code calculations.

Much of the margin in ASME Code Section III fatigue evaluations arises from design procedures (e.g., stress analysis rules and assumptions) that, as discussed by Deardorff and Smith,[236] are quite conservative. However, ASME Code Section III is not fully prescriptive; therefore, the specific procedures that different analysts apply to fatigue evaluations vary widely. For example, modern computer capabilities, particularly modern finite element methods, fatigue monitoring, and improved K_e factors, allow for evaluation refinements that significantly decrease the conservatisms traditionally applied in past fatigue evaluation procedures.

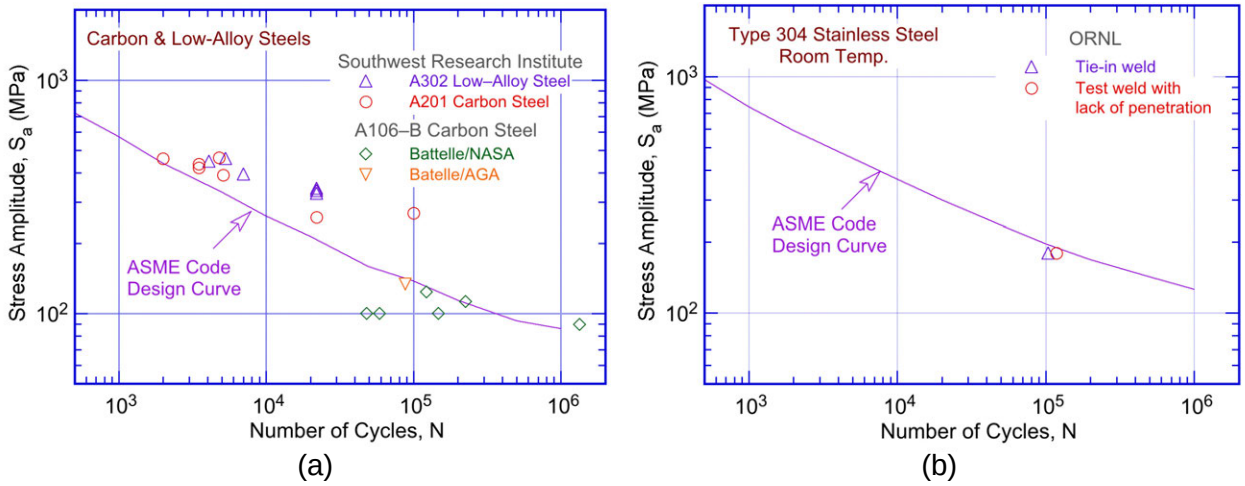


Figure 5-1 Fatigue data for (a) carbon and low-alloy steel and (b) Type 304 SS components (Refs. 237 and 238).

The factors of 2 on stress and 20 on cycles used in the ASME Code Section III air fatigue design curves were intended to cover the effects of variables that influence fatigue lives but were not investigated in the laboratory tests that provided the data for the curves. Therefore, it is not clear how much conservatism is embedded in the particular values of 2 and 20. A study sponsored by the PVRC to assess the factors of 2 and 20 used in the development of the ASME Code Section III air fatigue design curves concluded that these factors should not be changed because there were too many unknowns.[239]

The variables that can affect fatigue lives in air and LWR environments are broadly classified into three groups:

(a) material

- (i) composition
- (ii) metallurgy (grain size, inclusions, and orientation within a forging or plate)
- (iii) processing (cold work and heat treatment)
- (iv) size and geometry
- (v) surface finish (fabrication surface condition)
- (vi) surface preparation (surface work hardening)

(b) loading

(i) strain rate (rise time)
(ii) sequence (cycle counting and linear damage summation or Miner's rule)
(iii) mean stress
(iv) biaxial effects (constraints)

(c) environment

(i) water chemistry (dissolved oxygen (DO), lithium hydroxide, and boric acid concentrations)
(ii) temperature
(iii) flow rate

The existing fatigue strain vs. life (ε–N) database covers an adequate range of material parameters ((a)(i–iii)), one loading parameter ((b)(i)), and environmental parameters ((c)(i–ii)); therefore, the revised Argonne National Laboratory (ANL) models described in Chapter 4 incorporate the variability and uncertainty in fatigue lives resulting from these parameters. The existing data are conservative with respect to the effects of surface preparation because the fatigue ε–N data were obtained for specimens that were free of surface cold work, which tends to improve fatigue performance due to the introduction of favorable compressive surface residual stresses. Fabrication procedures for fatigue test specimens generally followed American Society for Testing and Materials (ASTM) guidelines requiring the avoidance of surface work-hardening during the final polishing of the specimens. Biaxial effects were covered by design procedures and were not considered in the ASME Code Section III fatigue design curves.

As discussed in Sections 4.1.9 and 4.2.11, under conditions that were typical of operating BWRs, environmental effects on the fatigue lives were a factor of approximately 2 lower at high flow rates (7 m/s) compared to those at very low flow rates (0.3 m/s or lower) for carbon and low-alloy steels and were independent of flow rate for austenitic SSs.[25,26] However, because of the uncertainties in the flow conditions at or near the locations of crack initiation, the revised ANL models described in Chapter 4 did not include beneficial effects of flow rate on the fatigue lives of carbon and low-alloy steels.

Thus, the ANL investigations considered the contributions of four groups of variables (i.e., material variability and data scatter, specimen size and geometry, surface finish, and loading sequence (Miner's rule)) for developing revised fatigue design curves applicable to components.

5.1 Material Variability and Data Scatter

The ANL investigations included effects of material variability and data scatter to ensure that the design curves encompass the available test data well and adequately describe the fatigue lives of the much larger number of heats of material that are found in the field. The effects of material variability and data scatter were evaluated for various materials by considering the best-fit curves determined from tests on individual heats of materials or loading conditions as samples of the much larger population of heats of materials and service conditions of interest. The fatigue behaviors of each of the heats or loading conditions were characterized by the values of the constant A in Equation 6. The values of A for the various datasets were ordered, and median ranks were used to estimate the cumulative distribution of A for the entire population. The distributions were fit to lognormal curves. Further details of heat-to-heat variability of fatigue

lives in air and LWR environments are discussed, respectively, in Sections 3.1.7 and 4.1.13 for carbon and low-alloy steels and in Sections 3.2.7 and 4.2.15 for cast and wrought austenitic SSs. The results indicated that the revised environmental fatigue correction factor (F_{en}) expressions presented in this report adequately capture the effects of LWR environments on the fatigue lives of carbon and low-alloy steels and austenitic SSs. After accounting for the environmental effects from the experimental fatigue lives in LWR environments, the resultant fatigue lives showed good agreement with the fatigue lives that are expected for the materials in air. The results also indicated that the statistical data presented in the original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials," issued February 2007, remain valid and, therefore, were not updated.

Table 5-1 lists the median values of A and the standard deviations for the sample of data available for each material that were presented in the original version of NUREG/CR-6909. Because these values did not change significantly based on the reevaluation of the larger database used for this report, they were not changed. The 95/95 values of the factors on the median values to account for material variability and data scatter for the samples of heats of materials used in the present evaluation were determined as 2.8, 2.1, and 2.3 for carbon steels, low-alloy steels, and austenitic SSs, respectively. These factors applied to the mean values of fatigue lives determined from the ANL models provide 95% confidence that the fatigue lives of the 95th percentile of the materials of interest were greater than the resultant values estimated from the ANL model.

Table 5-1 Statistical Information for the Constant A used to Evaluate Material Variability and Data Scatter.

	Air Environment		
	Median Value of A	Standard Deviation	Number of Datasets
Carbon Steel	6.583	0.477	17
Low-alloy Steel	6.449	0.375	32
Stainless Steel	6.891	0.417	51

5.2 Size and Geometry

The effect of specimen size on fatigue lives were reviewed in earlier reports.[12,46] Various studies concluded that "size effects" are not significant in the design curve factors when the fatigue curves were based on data from axial strain-controlled specimens rather than bending test specimens. No intrinsic size effects were observed for smooth specimens tested in axial loading or plain bending. However, size effects did occur in rotating bending test specimens; the fatigue endurance limits decreased by approximately 25% if the specimen sizes were increased from 2 to 16 mm, but the limits did not decrease further with larger sizes. In addition, some effects of size and geometry were observed on small-scale-vessel tests conducted at the Ecole Polytechnique in conjunction with the large-size-pressure-vessel tests carried out by the Southwest Research Institute.[237] The tests at the Ecole Polytechnique were conducted in room-temperature water on 19 mm (0.75 in) thick shells with a 305 mm (12.0 in) inner diameter that contained nozzles made of machined bar stock. The results indicated that the fatigue lives determined from tests on the small-scale vessels were 30 to 50% lower than those obtained from tests on small, smooth fatigue specimens. However, the differences in fatigue lives in these tests were not attributed to specimen size alone; instead, they were attributed to the effects of both size and surface finish.

During cyclic loading, cracks generally form at surface irregularities that already exist or were produced by slip bands, grain boundaries, second-phase particles, and other such features. In smooth specimens, the specimen size affects the formation of surface cracks; crack initiation is easier in larger specimens because of their increased surface area and, therefore, an increased number of crack initiation sites. However, specimen sizes are not likely to have a significant effect on crack initiation in specimens with rough surfaces because cracks would initiate at existing irregularities on the rough surface. As discussed in Section 5.3, surface roughness has large effects on fatigue lives. Consequently, for rough surfaces, the effects of specimen sizes are not appropriate for consideration in the factor of 12 applied to the fatigue design curves developed in this report. Therefore, considering all of the foregoing, a factor ranging from 1.0 to 1.4 on fatigue lives was used to incorporate size effects on fatigue lives in the low-cycle regime. This range is slightly improved over the range used in the original version of NUREG/CR-6909 (1.2 to 1.4) to account for the fact that, in some cases, size effects were observed to be negligible.

5.3 Surface Finish

The effects of surface finish were considered to account for the differences in fatigue lives expected in actual components with industrial-grade surface finishes compared to the smooth polished surfaces of test specimens. Fatigue lives are sensitive to surface finish; cracks are more likely to initiate at surface irregularities that act as stress risers. The height, spacing, shape, and distribution of surface irregularities are important for crack initiation. The effects of surface finish on crack initiation are expressed by Equation 26 in terms of the root-mean-square (RMS) value of surface roughness (R_q).

The roughness of machined surfaces or natural finishes typically ranges from approximately 0.8 to 6.0 μm.[219] Typical surface finishes for various machining processes are in the range of 0.2 to 1.6 μm for cylindrical grinding, 0.4 to 3.0 μm for surface grinding, 0.8 to 3.0 μm for finish turning and drilling, and 1.6 to 4.0 μm for milling. For fabrication processes, the roughness ranges from 0.8 to 3.0 μm for extrusion and 1.6 to 4.0 μm for cold rolling. Thus, from Equation 26, the fatigue lives of components with finishes within these ranges of surface roughness can be a factor of 1.5 to 3.5 lower than those of smooth specimens.

Limited data in LWR environments on specimens that were intentionally roughened indicated that the effects of surface roughness on fatigue lives were the same in air and water environments for austenitic SSs, but were insignificant in water for carbon and low-alloy steels, particularly in normal water chemistry (NWC) BWR environments. However, the results for surface finish effects on carbon and low-alloy steels were limited. Therefore, additional data are needed to better define surface finish effects for carbon and low-alloy steels in LWR environments. Because additional data are not available to verify that surface finish effects for carbon and low-alloy steels are insignificant in LWR environments, the ANL investigations used a range of 1.5 to 3.5 to account for the effects of surface finish on the fatigue lives of carbon and low-alloy steels and wrought and cast austenitic SSs. This range is slightly improved over the range used in the original version of NUREG/CR-6909 (2.0 to 3.5) to account for the fact that, in some cases, surface finish effects as low as a factor of 1.5 have been observed.

5.4 Loading Sequence

The effects of variable amplitude loading of smooth specimens were also reviewed in an earlier report.[46] A few cycles at high strain amplitude loading introduced into a small strain amplitude

load history resulted in significantly lower fatigue lives compared to constant-amplitude loading, (i.e., the fatigue limits of the materials were lower under variable loading histories).

As discussed in Section 2.1, fatigue life is conventionally divided into two stages: (1) initiation, which is expressed as the number of cycles required to form microstructurally small cracks (MSCs) on the surface, and (2) initial propagation, expressed as the number of cycles required to propagate the MSCs to engineering size (approximately 3 mm)—the depth at which most crack propagation analyses take over and crack initiation is considered complete. The transition from the initiation stage to the propagation stage strongly depends on the applied stress amplitude; at stress levels above the fatigue limit of the material, tests showed that the transition from the initiation stage to the propagation stage occurred at crack depths in the range of 150 to 250 μm. However, under constant loading at stress levels below the fatigue endurance limit of the material ($\Delta\sigma_1$ in Figure 2-4), although approximately 10 μm microcracks formed early in life, they did not grow to an engineering size. Under the variable loading conditions typically encountered during the operation of nuclear power plants, cracks created by growth of MSCs at high stresses ($\Delta\sigma_3$ in Figure 2-4) with depths larger than the transition crack depth grew to an engineering size even at continued stress levels below the fatigue limit of the material tested. Therefore, because the fatigue ε–N data used to develop the ASME Code Section III fatigue design curves were obtained from fatigue tests at constant strain amplitudes, the effects of loading sequence on the fatigue lives and the fatigue limits of materials were incorporated into the adjustment factor of 12 on the number of cycles when developing the ASME Code fatigue design curves from the best-fit curves of the data. These effects were also included in the development of the ANL air design curves.

Studies on fatigue damage in Type 304 SS under complex loading histories[240] indicated that the loading sequences for decreasing strain levels (i.e., high strain levels followed by low strain levels) were more damaging than those of increasing strain levels. The fatigue lives of the steels at low strain levels decreased by factors of 2 to 4 under decreasing strain sequences. In another study, the fatigue endurance limits of medium carbon steels were lowered even after low-stress, high-cycle fatigue; higher applied stresses caused greater decreases in the fatigue thresholds.[241] A study on Type 316NG and titanium-stabilized Type 316 SS on strain-controlled tests in air and PWR environments with constant or variable strain amplitudes reported factors of 3 or more decreases in fatigue lives under variable amplitude loading compared with constant amplitude loading.[158] Although the strain spectrum used in the study was not intended to be representative of actual operating plant transients, it represented a generic loading case and demonstrated the effects of variable strain amplitudes on the fatigue lives of materials.

Because variable loading histories primarily influence fatigue lives at low strain levels, the mean fatigue ε–N curves were lowered to account for damaging cycles that occur below the constant-amplitude fatigue limits of the materials tested. Factors ranging from 1.0 to 2.0 were used to incorporate the possible effects of variable strain amplitudes on fatigue lives in the low-cycle regime. This range is slightly improved over the range used in the original version of NUREG/CR-6909 (1.2 to 2.0) to account for the fact that, in some cases, loading sequence effects were observed to be negligible.

5.5 Summary of Air Fatigue Design Curve Adjustment Factors

The ASME Code Section III air fatigue design curves were obtained from the mean-data curves by first adjusting for the effects of mean stress using the modified Goodman relationship and then by reducing the life at each point of the adjusted curve by a factor of 2 on strain or a factor

of 20 on life, whichever was more conservative. The factors on strain were needed to account for the variation in the fatigue limit of the material caused by material variability and data scatter, component size, surface finish, and load history. At present, the adjustment factor of 2 on strain is used to account not only for data scatter, size, surface finish, and loading sequence but also for the potential effects of a combination of temperature and strain rate on secondary hardening and dynamic strain aging. These effects are not cumulative within the high-cycle fatigue region and only the most dominant of these effects controls the net adjustment factor. However, these parameters principally affect the growth of MSCs and their significance depends on the operating conditions, environment, material, and fabrication process. Therefore, the effect that dominates is a function of material and environmental conditions. The factor of 2 on strain is sufficient to account for the dominant effect within the high-cycle fatigue region. In addition, when comparing the fatigue lives of laboratory test specimens to those of actual reactor components, the factor of 2 on strain used to develop the ASME Code Section III air design curves was adequate to account for the uncertainties associated with material variability, component size, surface finish, and load history.

The factors on life are needed to account for variations in fatigue lives in the low-cycle regime. Based on the previous discussions, the effects of various material, loading, and environmental parameters on fatigue lives may be summarized as follows:

- The results presented in Table 5-1 were used to determine the factors that were applied to the mean value of fatigue life to ensure that the resultant value of fatigue life bounded the 95th percentile of the materials and loading conditions of interest.

- For rough surfaces, specimen size does not significantly influence fatigue lives. However, specimen size does, in some cases, significantly affect fatigue lives for smooth specimens. Absent additional test data that indicate otherwise, factors ranging from 1.0 to 1.4 on fatigue lives were used in the reanalysis of the larger fatigue database to incorporate size effects on fatigue lives.

- Factors ranging from 1.5 to 3.5 were used to incorporate the effects of surface finish on fatigue lives in air. Because additional data are not available to verify that the surface finish effects are lower or insignificant in LWR environments, this investigation used a range of 1.5 to 3.5 to account for the effects of surface finish on the fatigue lives of carbon and low-alloy steels and wrought and cast austenitic SSs both in air and LWR environments.

- Because variable loading histories primarily influence fatigue lives at low strain levels (i.e., in the high-cycle regime), the mean air fatigue ε–N curves were adjusted by a factor of 2.0 on strain to account for damaging cycles that occur below the constant-strain fatigue limit of the material. Factors ranging from 1.0 to 2.0 were used to incorporate the possible effects of load histories on fatigue lives in the low-cycle regime.

Table 5-2 summarizes the subfactors needed to account for the effects of the various material, loading, and environmental parameters on fatigue lives. The total adjustment on life varies from 4.7 to 27.4. However, because the maximum value represents relatively poor heats of materials and assumes the maximum effects of size, surface finish, and loading history, the maximum value of 27.4 is overly conservative to apply unless very high confidence bounds are desired. Therefore, to avoid overly conservative estimates, the maximum values of the individual parameters are not used in defining the total adjustment factor to account for the combined effect of these parameters.

Table 5-2 Factors on Life Applied to the Mean Fatigue ε–N Air Curve to Account for the Effects of Various Material, Loading, and Environmental Parameters.

Parameter	ASME Code Section III Criterion Document	Present Report
Material Variability and Data Scatter (minimum to mean)	2.0	2.1–2.8
Size Effect	2.5	1.0–1.4
Surface Finish and Other Factors	4.0	1.5–3.5
Loading History	–	1.0–2.0
Total Adjustment	20	3.15–27.4

To determine the most appropriate value for the adjustment factor on fatigue life, Monte Carlo simulations were performed using the material variability and data scatter results given in Table 5-1 and the factors needed to account for the effects of size, surface finish, and loading history listed in Table 5-2. In this analysis, these effects are conservatively considered to be independent even though some effects, as discussed previously, may be correlated. However, current data are insufficient to develop quantitative correlation factors needed for a more rigorous analysis. A lognormal distribution was assumed for the effects of size, surface finish, and loading history, and 5th and 95th percentile values were assumed to represent the minimum and maximum values of the adjustment factors (i.e., 1.0 to 1.4 for size; 1.5 to 3.5 for surface finish; and 1.0 to 2.0 for loading history, respectively). A total of 25,000 simulations were performed for each material. The median value, standard deviation, and 95th percentile values for the factor were 5.037, 3.159, and 10.233 for carbon steels; 4.830, 2.558, and 9.037 for low-alloy steels; and 4.932, 2.864, and 9.643 for austenitic SSs, respectively. Table 5-3 lists the 95th percentile values for the factors that were applied to the best-fit mean air curves to obtain the design fatigue ε–N air curves. The factor that was applied to the mean-data curves for test specimens to obtain component curves that bounded 95% of the population ranged from 9.0 to 10.2 for carbon, low-alloy, and austenitic SSs, respectively, as shown in Table 5-3. Figure 5-2 plots the cumulative distribution of the values of constant A for best-fit mean-data air curves and for the adjusted design air curves for carbon, low-alloy, and austenitic SSs.

Table 5-3 Factors Applied to the Mean Values of Fatigue Life to Bound 95% of the Data Population.

Material	Air Environment
Carbon Steels	10.2
Low-alloy Steels	9.0
Austenitic Stainless Steels	9.6

The average value for the factor for application to the best-fit mean air curves for the three materials to obtain air fatigue design curves that apply to reactor components is 9.6. Note that selection of the 95th percentile value for the factor was arbitrary but is consistent with current practice. As a comparison, the corresponding 98th percentile values for the factors are 11.5, 10.1, and 10.8, respectively, for carbon, low-alloy, and austenitic SSs (or an average value of 10.8).

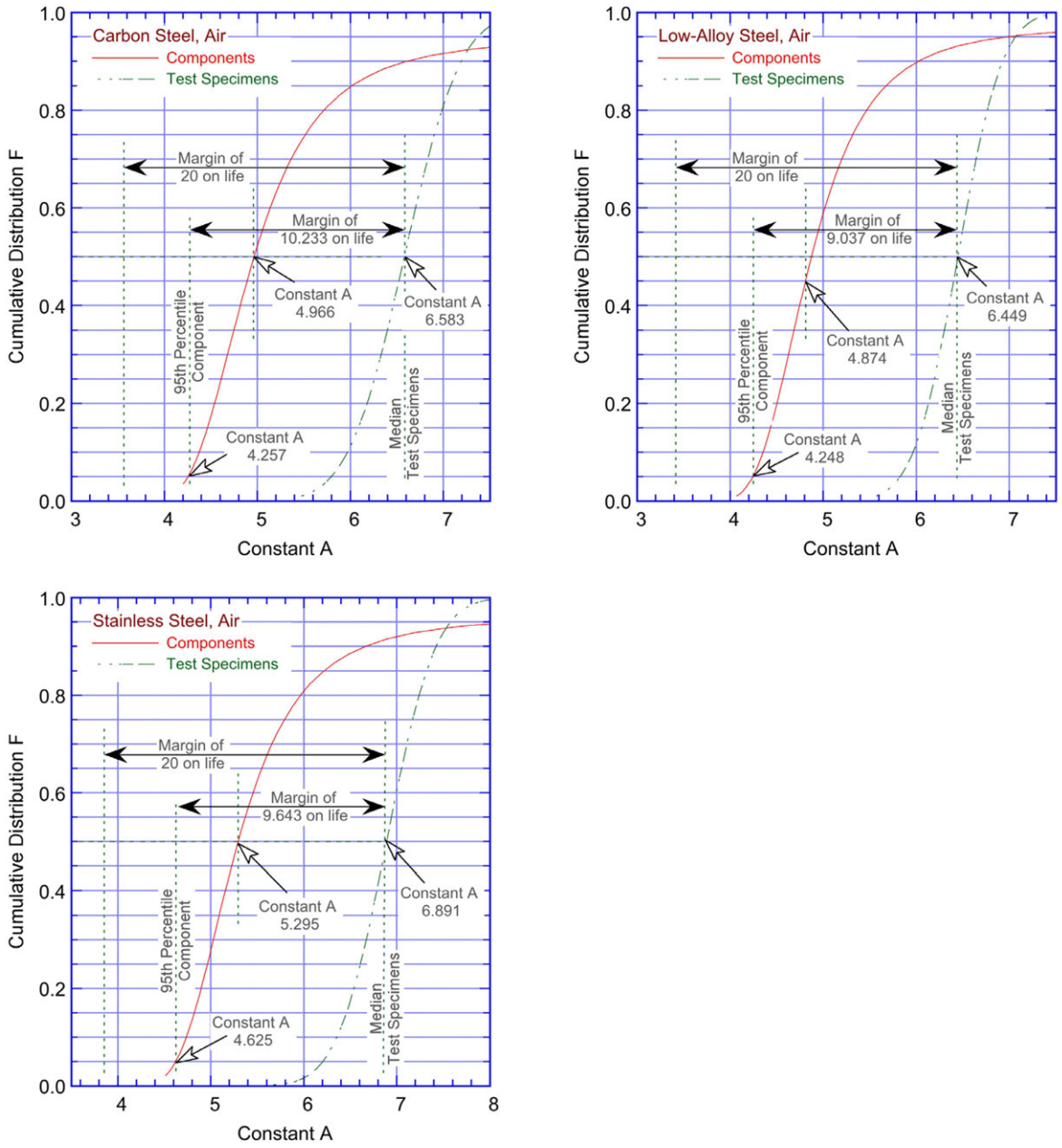


Figure 5-2 Estimated cumulative distribution of parameter A in the ANL models that represent the fatigue lives of test specimens and actual components in air.

The results of the reanalysis of the fatigue adjustment factors indicate that, for all materials, the current ASME Code Section III use of a factor of 20 on cycles to account for the effects of material variability and data scatter, specimen size, surface finish, and loading history may contain as much as a factor of 2.0 conservatism (i.e., 20/10 considering the average factor of 9.6 obtained from Table 5-3). To reduce this conservatism, fatigue design air curves were derived from the mean-data curves first by correcting for mean stress effects using the modified Goodman relationship and then by reducing the mean–stress adjusted curve by a factor of 2 on stress and 12 on cycles, whichever was more conservative. Although the Monte Carlo analysis justifies a value of 10 for the combined factor on life, a value of 12 was used for the adjustment on cycles to be consistent with the factor used in the ASME Code fatigue design curves.

Sections 3.1.11 and 3.2.11 present the fatigue design curves, which were developed from the ANL fatigue life models using this procedure, for carbon and low-alloy steels and wrought and cast austenitic SSs, respectively. The selection of bounding the 95th percentile of the population for a design curve was made under the presumption that the design curve controls fatigue initiation, not failure. The choice also recognized that there were conservatisms implied in the choice of log normal distributions, which have infinite tails, and in the identification of values of the effects as 95th percentile values. Finally, the results of the present analysis indicate that the conservatism in the ASME Code Section III fatigue design air curves may be further reduced by using a factor of 10 on life instead of the factor of 12 on life used in the fatigue design air curves in this report for carbon, low-alloy, and wrought and cast austenitic SSs.

6 VALIDATION OF ENVIRONMENTAL FATIGUE CORRECTION FACTOR EXPRESSIONS

The updated environmental fatigue correction factor (F_{en}) expressions were validated by comparing calculated results from six experimental datasets with estimates of fatigue lives based on the updated F_{en} expressions. The intent of the calculations was only to validate the accuracy of the revised F_{en} expressions. The experimental datasets evaluated included the following:

1. tests with changing strain rates within each strain cycle.[136]

2. tests performed by Valtion Teknillinen Tutkimuskeskus (VTT), the Technical Research Center of Finland, on small specimens with either constant or spectrum strain cycling (i.e., an amplitude sequence of a narrow-band randomized block of 50 strain cycles that was repeated until specimen failure).[158,159]

3. tests performed by Areva on small specimens with triangular and complex strain cycles of cold and hot thermal shock associated with a simulated safety injection transient.[155-157]

4. Electric Power Research Institute (EPRI) U-bend tests in inert (dry nitrogen) and pressurized-water reactor (PWR) environments.[97-99]

5. tests with changing strain rates and temperatures within each strain cycle.[154]

6. Bettis Atomic Power Laboratory thermal fatigue tests of a stepped pipe of differing thicknesses exposed to temperature cycles between 38 and 343°C (100 and 650°F).[160]

Because the experimental datasets were tested to crack initiation (i.e., a cumulative usage factor (CUF) greater than unity), the goal of these evaluations was to benchmark the F_{en} methodology against the predictions of failures and, if warranted, make appropriate adjustments to the F_{en} expressions. In the tests evaluated, fatigue failure was defined as the number of cycles to (1) form a finite crack or (2) decrease the cyclic tensile stress by 25% from its peak (steady-state) value. The three methods described below were used to calculate the F_{en} which was applied to the number of loading cycles in air to estimate the number of loading cycles in the environment.

Strain-Integrated Method

In this method, the applied strain cycle was divided into small time intervals, and the F_{en} was determined at each time interval using the modified rate approach and the updated F_{en} expressions. In addition, the F_{en} was calculated using expressions presented in the initial version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials," issued February 2007, for comparative purposes. In these calculations, the overall integrated F_{en} was expressed as

$$F_{en} = \frac{\sum F_{en,i} \, (\varepsilon_i - \varepsilon_{i-1})}{(\varepsilon_{max} - \varepsilon_{min})} \, , \tag{54}$$

where ε_{min} and ε_{max}, respectively, are the minimum and maximum values of strain, and ε_i and $F_{en,i}$ are the strain and F_{en} at the ith increment of strain. The summation was only applied when the strain increment was positive. In addition, a threshold strain, ε_{th}, was also considered to compute the overall F_{en}. Consideration of a threshold strain assumes that, during a strain cycle, environmental effects are significant only after the applied strain exceeds the threshold value. Thus,

$$F_{en} = \frac{\sum F_{en,i} (\varepsilon_i - \varepsilon_{i-1})}{\varepsilon_{max} - (\varepsilon_{min} + \varepsilon_{th})}. \quad (55)$$

Simplified Method

In this method the overall F_{en} was determined for the entire period of the strain cycle where the strain rate was greater than zero (i.e., increasing strain) and used the average temperature and average strain rate for the interval. The average values were determined using an average (i.e., straight line) from the valley to the adjacent peak strain. As before, the overall F_{en} was computed from both the updated F_{en} expressions and the expressions in the initial version of NUREG/CR-6909.

Multilinear Strain-Based Method

This method is a modified version of the simplified method. Depending on the strain-time profile, the applied strain cycle was divided into two or more linear ramps within which the strain rate was positive. The overall F_{en} was determined for each ramp using the updated and the original NUREG/CR-6909 F_{en} expressions. In addition, average values of temperature and strain rate were used in the F_{en} calculations for each ramp. The overall F_{en} was defined as

$$F_{en} = \frac{(F_{en,1}\Delta\varepsilon_1 + F_{en,2}\Delta\varepsilon_2 + ..)}{(\Delta\varepsilon_1 + \Delta\varepsilon_2 + ..)}, \quad (56)$$

where $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ are the first and second strain increments and $F_{en,1}$ and $F_{en,2}$ are the F_{en} values for the first and second strain increments. Overall F_{en} values were calculated for each dataset using the foregoing three methods. The results were compared with the experimental values to benchmark the revised F_{en} methodology and to provide insights as to which computational methods yielded the most consistent and reliable results. Section 4.1.3 presents the results associated with the changing strain rates within each cycle as a part of the discussion on the threshold strain amplitude; therefore, this section does not duplicated them. In addition, the assessments to estimate the overall F_{en} for the thermal fatigue tests of a stepped pipe indicated that the reported estimates of the total applied strain (elastic and plastic) were not reliable. Therefore, additional finite element analyses are needed to provide meaningful thermal strain values for use in the evaluation. As a result, the dataset for the stepped pipe thermal fatigue tests was not considered further, and this report does not include those results. The next sections discuss the results of the remaining four datasets.

Note that some of the validation performed in this section, particularly those associated with component testing (as opposed to small-scale test specimens), the F_{en} approach yielded more conservative estimates (i.e., lower life) compared to the experimental values. This was most likely due to the presence of through-wall thermal stress gradients, which are not considered in the development of the design air fatigue curves. Item vii in Section 1.5 addresses this potential

conservatism. At the time of publication of this report, American Society of Mechanical Engineers (ASME) committees and EPRI were investigating gradient effects in fatigue calculations.

6.1 Spectrum Straining

Low-cycle, strain-controlled, completely reversed fatigue tests were conducted on Type 316NG and titanium (Ti)-stabilized 316 (O8X8H10T steel) austenitic stainless steels (SSs) in air and simulated PWR environments using cylindrical specimens with a 4 mm diameter and a 10 mm gauge length.[158] Test specimens were fabricated from a 12 mm diameter round bar of Type 316NG SS. A 300 mm diameter, 16 mm thick pipe was fabricated from the Ti-stabilized 316 material. The test specimens were smooth, but not polished. Table 6-1 provides the chemical composition and tensile properties of the two materials. Pneumatic bellows, designed and developed by VTT, were used for accurate control of strain. Fatigue tests were conducted on the Type 316NG SS specimens in a simulated PWR environment at 320°C. For the Ti-stabilized 316 SS specimens, fatigue tests were conducted in a simulated Voda-Vodyanoi Energetichesky Reaktor (VVER) Russian reactor environment at 293°C. Both steels were also tested in air at room temperature (25°C). Table 6-2 provides further details of the environmental conditions.

Table 6-1 Chemical Composition and Tensile Strength of Test Materials for the Constant and Spectrum Strain Amplitude Fatigue Tests.

Material	Chemical Composition (wt.%)									Min. YS (MPa)	Min. UTS (MPa)	Min. Elong. (%)
	C	Si	Mn	Ni	Cr	Mo	V	Cu	Ti			
316NG	0.01	0.60	1.40	11.2	16.9	2.60	-	-	-	250	570	-
Ti-stab.	0.08	0.39	1.36	10.5	18.2	0.17	0.05	0.18	0.62	330	595	-

Table 6-2 Environmental Conditions for the Constant and Spectrum Strain Amplitude Fatigue Tests.

Test Condition	For Type 316NG SS	For Ti-Stabilized 316 SS
Temperature	320°C	293°C
Pressure	125 bar	100 bar
pH at RT	5.1	7.2
Conductivity	2 to 40 μmho/cm	80 to 90 μmho/cm
Dissolved Oxygen (DO)	< 0.01 ppm	< 0.01 ppm
Chlorides	< 0.15 ppm	< 0.05 ppm
Fluorides	< 0.15 ppm	< 0.01 ppm
Dissolved Hydrogen	25 to 35 cm^3/kg	30 to 35 cm^3/kg
Boric Acid	2500 ppm	2750 ppm
To Adjust pH 7.0	Lithium	Kalium

Constant and variable strain amplitude fatigue tests were performed using a sinusoidal waveform. For spectrum loading, an amplitude sequence of a narrow-band, randomized block of 50 strain cycles, as shown in Figure 6-1, was repeated until specimen failure occurred, which

was defined as a 25% decrease in load from the steady-state value. The spectrum straining data were transformed to equivalent constant-amplitude fatigue ε–N data as follows:

$$\varepsilon_{a,eq}=\frac{\sum\{n_i D_i(\varepsilon_{a,i})\}}{\sum\{n_i D_i\}}, \quad N_{eq}=\sum\left\{n_i\left(\frac{D_i}{D_i(\varepsilon_{a,eq})}\right)\right\}, \tag{57}$$

where N_{eq} and $\varepsilon_{a,eq}$ are the equivalent number of cycles and strain amplitude, respectively, under constant strain loading; n_i is the number of cycles at strain amplitude $\varepsilon_{a,i}$ under spectrum loading; and D_i is an arbitrary damage function associated with that fatigue loading and is given by

$$D_i=\frac{1}{N_f}=f(\varepsilon_a). \tag{58}$$

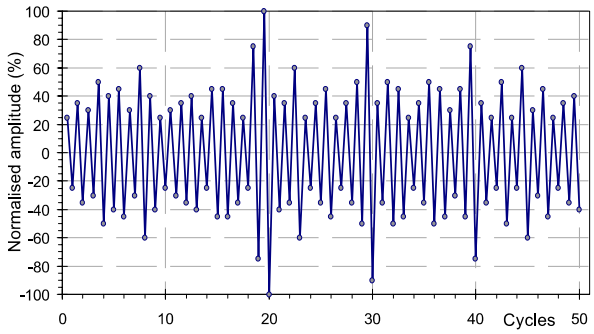


Figure 6-1 Schematic of the repeated sequence of randomized block of 50 strain cycles (Ref. 158).

The results yielded an equivalent strain amplitude at the mean damage level representative of the spectrum straining and the number of equivalent cycles that provided an identical damage sum (i.e., usage factor) for the equivalent straining and the original spectrum straining. Thus, the results were directly comparable and, therefore, were plotted on common graphs. Table 6-3 provides the test conditions and summarizes the results. Figure 6-2 shows the fatigue ε–N data for Type 316NG and Ti-stabilized 316 SSs in air and PWR environments using constant and spectrum strain amplitude loading.

The results indicated that, for the two heats of Type 316NG and Ti-stabilized 316 SSs tested, the slope of the fatigue ε–N data obtained under the constant strain amplitude loading was less steep than that of the Argonne National Laboratory (ANL) best-fit mean-data curve. For fatigue lives greater than 10^4 cycles, the experimental fatigue lives were greater than those estimated from the ANL best-fit air curve. For the Ti-stabilized steel, the experimental fatigue life was a factor of 6 greater than the fatigue life estimated using the best-fit mean-data curve. For both steels, the measured fatigue lives at strain amplitudes between 0.3 and 0.5% were approximately 60% greater than the estimated values. Thus, a subfactor of 1.6 was used to account for heat-to-heat variability. Note that, because all tests were conducted on smooth rather than polished specimens, this subfactor included some effects of surface finish.

Table 6-3 The Conditions and Results of Fatigue Tests on Austenitic SSs Obtained under Constant and Spectrum Strain Amplitude Loading.

Environment	Strain Rate (%/s)	ε_a (%)	Equiv. ε_a (%)	N_f	N_{eq}	Estimated[a] N_{air}	Estimated F_{en}	Predicted[b] N_f
Type 316NG SS								
Air 25°C	1.020	0.510	0.510	6,120	6,120	5,767	-	9,227
Air 25°C	0.620	0.310	0.310	47,000	47,000	22,036	-	35,257
Air 100°C	0.170	0.420	0.420	15,600	15,600	9,434	-	15,095
Air 25°C	0.800	0.20-0.80	0.535	9,650	3,260	5,130	-	4,104
PWR 320°C	0.020	0.508	0.508	1,400	1,400	5,823	4.88	1,908
PWR 320°C	0.016	0.040	0.400	2,650	2,650	10,732	5.17	3,321
PWR 320°C	0.013	0.315	0.315	6,660	6,660	21,005	5.45	6,165
PWR 320°C	0.013	0.315	0.315	7,800	7,800	21,005	5.45	6,165
PWR 320°C	0.065	0.19-0.78	0.529	1,250	384	5,273	3.62	1,167
PWR 320°C	0.039	0.11-0.48	0.359	4,600	883	14,413	4.12	2,799
Ti-Stabilized 316 SS								
Air 25°C	1.000	0.500	0.500	4,590	4,590	6,056	-	9,689
Air 25°C	0.980	0.350	0.350	26,700	26,700	15,477	-	24,764
Air 25°C	0.920	0.230	0.230	362,900	362,900	59,526	-	95,242
Air 25°C	1.000	0.20-0.80	0.536	6,900	2,282	5,107	-	4,086
Air 25°C	1.000	0.12-0.50	0.359	21,900	4,367	14,413	-	11,530
Air 25°C	1.000	0.12-0.50	0.372	36,350	7,250	13,061	-	10,449
Air 25°C	1.000	0.072-0.30	0.238	450,000	84,437	52,482	-	41,986
VVER 293°C	0.020	0.500	0.500	1,734	1,734	6,056	4.02	2,410
VVER 293°C	0.011	0.283	0.283	12,256	12,256	29,199	4.60	10,165
VVER 293°C	0.060	0.18-0.77	0.523	2,150	641	5,422	3.14	1,380
VVER 293°C	0.030	0.09-0.39	0.302	14,400	2,492	23,852	3.67	5,197
VVER 293°C	0.024	0.08-0.31	0.247	95,500	17,847	45,971	3.86	9,529

a The fatigue lives were estimated using Equation 29.

b For constant strain amplitude loading, the fatigue lives were determined from the estimated lives in air by multiplying by a factor of 1.6 to account for heat-to-heat variability. For fatigue lives in a PWR environment, the adjusted values were divided by F_{en}. For spectrum loading, the effects of loading sequence were also included by dividing the values determined for the constant strain amplitude loading by a factor of 2.

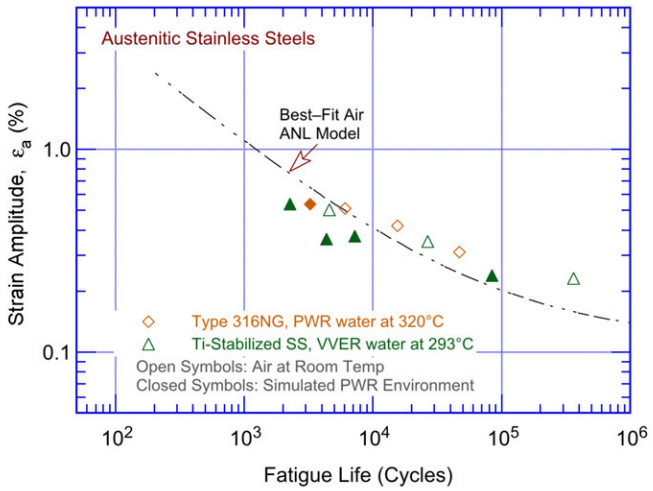


Figure 6-2 Fatigue strain-life data for Type 316NG SS in PWR water at 320°C and for Ti-stabilized 316 SS in VVER water at 293°C (Refs. 158 and 159).

The results also indicated that the fatigue ε–N data obtained under spectrum strain amplitude loading were up to a factor of 5 lower than those obtained under constant strain amplitude loading. The actual differences between spectrum and constant strain amplitude loading in air and PWR environments, respectively, were factors of 2.4 and 4.4 for Type 316NG and 3.4 and 5.2 for Ti-stabilized 316 SS. The differences were greater for a PWR environment, most likely because these tests were conducted using a sine-wave loading and the estimated values were based on average strain rates. Therefore, the environmental effects were likely underestimated. However, these results demonstrated the potential effects of loading sequence, which are discussed in Section 5.4.

The last column of Table 6-3 lists the predicted fatigue lives for the constant and spectrum strain loading fatigue tests. These values were determined from the fatigue lives in air (N_{air}) estimated from Equation 29 (seventh column of Table 6-3). Because these tests were conducted at constant strain rate and temperature, the predicted fatigues lives were determined by multiplying N_{air} by a factor of 1.6 to account for heat-to-heat variability (and potential effects of surface finish), and by dividing the adjusted values by F_{en} to account for environmental effects. Furthermore, for spectrum loading, the effects of loading sequence were included by dividing the values determined for the constant strain amplitude loading by a factor of 2, which is the maximum subfactor proposed in Table 5-2 (Section 5.5) to account for the effects of loading sequence. A subfactor of 2 was used instead of the values of 3.4–5.2 measured in these tests because these tests were conducted using a sinusoidal waveform instead of a triangular waveform. Therefore, the experimental environmental effects were greater because of differences in strain rates. The subfactor to account for the effects of surface finish was not used to determine the fatigue lives, even though the test specimens were “smooth” but not polished, because the effects of surface finish were already included in the heat-to-heat adjustment factor of 1.6 used to determine the predicted fatigue lives from the best-fit mean-data curve.

Figure 6-3 plots the measured fatigue lives, N_{eq}, and the predicted fatigue lives for the constant and spectrum strain loading tests. The results for the constant strain amplitude loading showed very good agreement with the experimental values; the predicted fatigue lives were within a factor of 2 (i.e., within the factor for data scatter). The predicted fatigue lives for the spectrum

strain amplitude loading were generally greater than the measured values because of differences in the loading waveform (sinusoidal or triangular waveforms).

- *The predicted fatigue lives showed very good agreement with the experimental values. The loading sequence effects observed in the spectrum loading tests were greater than those proposed in this study; the differences were attributed to differences in the loading waveform (e.g., sinusoidal or triangular waveforms) and the methods used to determine equivalent strain amplitude and fatigue lives.*

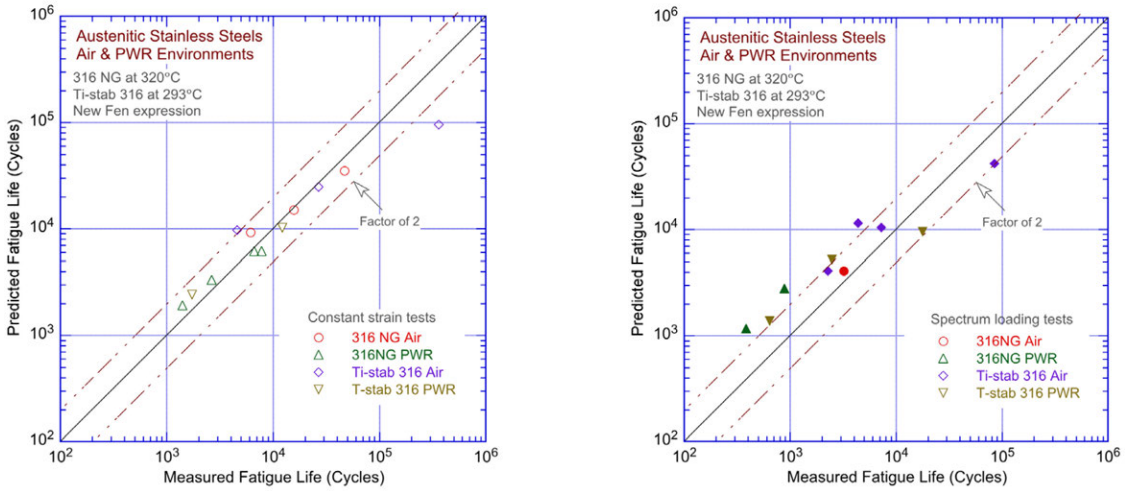


Figure 6-3 Experimental and estimated fatigue lives for Type 316NG and Ti-stabilized 316 SS tested with constant and spectrum strain loading (Refs. 158 and 159).

6.2 Complex Loading—Safety Injection Transient

Low-cycle, strain-controlled, completely reversed fatigue tests were conducted on Type 304L austenitic SSs in a simulated PWR environment using cylindrical specimens with a 9 mm diameter and a 13.5 mm gauge length.[155-157] The test specimens were fabricated from a 590 by 450 by 103 mm rolled plate that was water quenched. Table 6-4 lists the chemical composition and tensile properties of the Type 304L SS. Fatigue tests were conducted on both polished and ground specimens in air and the simulated PWR environment at 300°C using a triangular loading waveform and a waveform that simulated the typical strain history of cold and hot thermal shocks associated with a PWR safety injection transient. Figure 6-4 shows the actual strain cycle used in this study. The specimen surface finish was specified as R_t = 40 μm. This value corresponds to the material surface height between the maximum peak and minimum valley measured over a length of 4 mm. The authors noted that the machining process induced a superficial hardened layer the polishing process did not totally remove. Table 6-5 provides the environmental conditions for the tests in the PWR environment.

Table 6-4 Chemical Composition and Tensile Strength of Type 304L SS.

Material	Chemical Composition (wt.%)									Min. YS (MPa)	Min. UTS (MPa)	Min. Elong. (%)
	C	Si	Mn	Ni	Cr	Mo	V	Cu	Ti			
304L	0.025	0.37	1.687	9.12	18.3	0.38	-	0.217	-	255	573	64

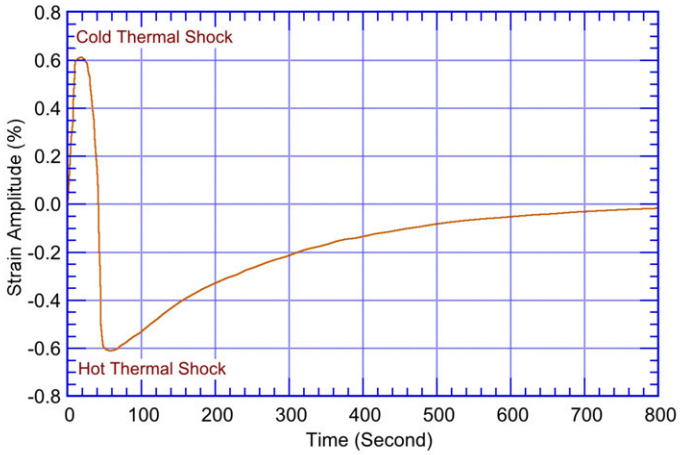


Figure 6-4 Typical strain cycle of cold and hot thermal shocks corresponding to a PWR safety injection transient (Ref. 155).

Table 6-5 Environmental Conditions for Fatigue Tests in Simulated PWR Environment.

Test Condition	Value
Temperature	300°C
Pressure	140 bar
Conductivity	2 to 40 μS/cm
Dissolved Oxygen (DO)	< 0.1 ppm
Chlorides, Fluorides	< 0.15 ppm
Dissolved Hydrogen	25 to 35 cm^3/kg
Boron	1,000 ppm (adjusted by boric acid)
Lithium	~ 2 ppm (adjustment for pH)

Strain-controlled fatigue tests were conducted in both air and the PWR environment at 300°C using a triangular waveform to obtain the baseline data for the Type 304L SS material.[155-157] Figure 6-5 shows the results. The tests in air were used to establish the heat-to-heat variation of the material and surface finish effects, and the tests in the PWR environment were used to validate the estimates of fatigue lives calculated using the updated F_{en} expressions. The results indicated a small heat-to-heat variation; the fatigue lives for the heat of Type 304L SS used for these tests were 12% lower than those predicted by the best-fit mean-data curve. The results also indicated that in air, fatigue lives of the ground specimens relative to those of polished specimens were decreased by a factor of 1.7.

In addition, the effects of the PWR environment on the fatigue lives of Type 304L SS at 300°C and a strain rate of 0.01%/s were determined from a comparison of the measured fatigue ε–N behavior of the polished specimens in air vs. those in the PWR environment. The experimental data yielded a ratio of 3.62 (i.e., the fatigue lives in the PWR environment were decreased by a factor of 3.62 relative to those in air). The experimental data also indicated that surface finish effects were smaller in the PWR environment than those in air. For example, the measured reductions in the fatigue lives of the ground specimens in a PWR environment compared to

those in an air environment were a factor of 2.90 instead of the factor of 3.62 obtained for the polished specimens.

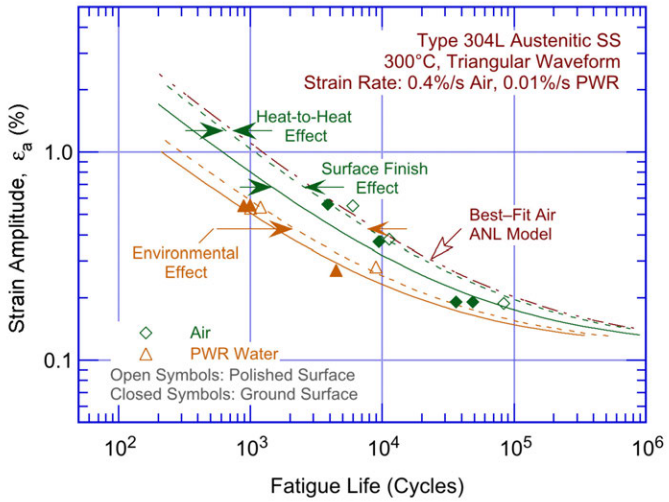


Figure 6-5 Fatigue strain-life data for Type 304L SS in air and PWR environments at 300°C (Refs. 155–157).

For the tests performed with a complex strain loading cycle, F_{en} values were determined using the three methods and the modified rate approach as described previously. Table 6-6 lists the test conditions and results for these tests. The predicted fatigue lives were determined from the estimated fatigue lives in air (using Equation 29) by multiplying the values by 0.88 to account for the effects of heat-to-heat variability, dividing by 1.7 to account for the effects of surface finish, and dividing by F_{en} to account for environmental effects. The overall F_{en} values were computed using the strain-integrated method (i.e., Equations 54 and 55 for the values without and with a strain threshold of 0.32%, respectively).

Figure 6-6 plots the measured fatigue lives and the predicted fatigue lives for the triangular and complex loading tests. The results indicated that the predicted fatigue lives from the tests with a triangular loading waveform were in good agreement with the experimental values. The differences were within a factor of 2 (i.e., within data scatter). The predicted fatigue lives for the tests with the complex strain loading cycle were approximately a factor of 2.5 lower than the experimental values; this difference was less than a factor of 2 when the strain threshold was included in the computation of F_{en}. This behavior is considered unique to this specific strain loading cycle. For example, the calculations assumed that the surface oxide film forms during the decreasing strain portion of the cycle and does not re-form until the peak strain. The protective oxide film is likely to re-form at the end of the transient when strain rates are very low and strain accumulation is negligible. Therefore, an additional threshold strain would be needed to rupture the surface oxide film for environmental effects to occur. Fatigue tests with other strain loading cycle profiles should be conducted to provide a better understanding of possible effects of complex loading patterns on the fatigue lives of materials. However, although the predicted lives were generally lower, the estimated values were within the range of data scatter.

For the PWR safety injection transient, the predicted fatigue lives estimated using the simplified method were 25% lower than those obtained from the modified rate approach. The predicted lives estimated using the multilinear method (using three ramps) were marginally (3%) lower.

- *The predicted fatigue lives were generally lower than the experimental values; however, the values were within the range of data scatter.*

Table 6-6 The Conditions and Results of Fatigue Tests on Type 304L Austenitic SS at 300°C in Air and PWR Environments using a Triangular or Complex Strain Cycle.

Environment / Surface Finish	Strain Rate (%/s)	ε_a (%)	Measured N_f	Estimated[a] N_{air}	Without Strain Threshold		With Strain Threshold	
					Estimated F_{en}	Predicted[b] N_f	Estimated F_{en}	Predicted N_f
Triangular Waveform								
Air, Polished	0.40	0.550	6,798	4,798	1.00	4,223	-	-
Air, Polished	0.40	0.380	11,325	12,323	1.00	10,844	-	-
Air, Polished	0.40	0.187	83,500	142,104	1.00	125.051	-	-
Air, Ground	0.40	0.560	4,667	4,595	1.00	2,379	-	-
Air, Ground	0.40	0.370	10,314	13,256	1.00	6,862	-	-
Air, Ground	0.40	0.190	37,469	131,796	1.00	68,224	-	-
Air, Ground	0.40	0.190	55,000	131,796	1.00	68,224	-	-
PWR, Polished	0.01	0.540	1,002	5,016	4.97	889	-	-
PWR, Polished	0.01	0.560	1,200	4,594	4.97	889	-	-
PWR, Polished	0.01	0.280	9,000	30,209	4.97	5,353	-	-
PWR, Ground	0.01	0.550	890	4,798	4.97	500	-	-
PWR, Ground	0.01	0.550	1,000	4,798	4.97	500	-	-
PWR, Ground	0.01	0.272	4,506	33,175	4.97	3,543	-	-
Complex Strain Cycle								
PWR, Polished	variable	0.590	1,588	4,057	5.70	655	5.37	722
PWR, Polished	variable	0.575	1,936	4,313	5.80	655	5.37	722
PWR, Polished	variable	0.490	2,900	6,367	5.80	919	5.37	1,047
PWR, Polished	variable	0.288	8,318	27,627	5.70	3,535	5.37	5,469
PWR, Polished	variable	0.288	8,810	27,627	5.70	3,535	5.37	5,469
PWR, Ground	variable	0.570	895	4,404	5.80	385	5.37	425
PWR, Ground	variable	0.570	960	4,404	5.80	385	5.37	425
PWR, Ground	variable	0.290	8,000	27,034	5.70	2,079	5.37	3,217
PWR, Ground	variable	0.290	6,665	27,034	5.70	2,079	5.37	3,217

[a] Fatigue lives were estimated using Equation 29.

[b] The predicted fatigue lives were obtained from the estimated lives in air by multiplying by a factor of 0.88 to account for heat-to-heat variability, dividing by 1.7 to account for surface finish effects, and dividing by F_{en} to include environmental effects. The differences between the F_{en} values in the sixth and eighth columns are due to the consideration of a threshold strain value of 0.32% as part of the calculation of the F_{en} values shown in the eighth column.

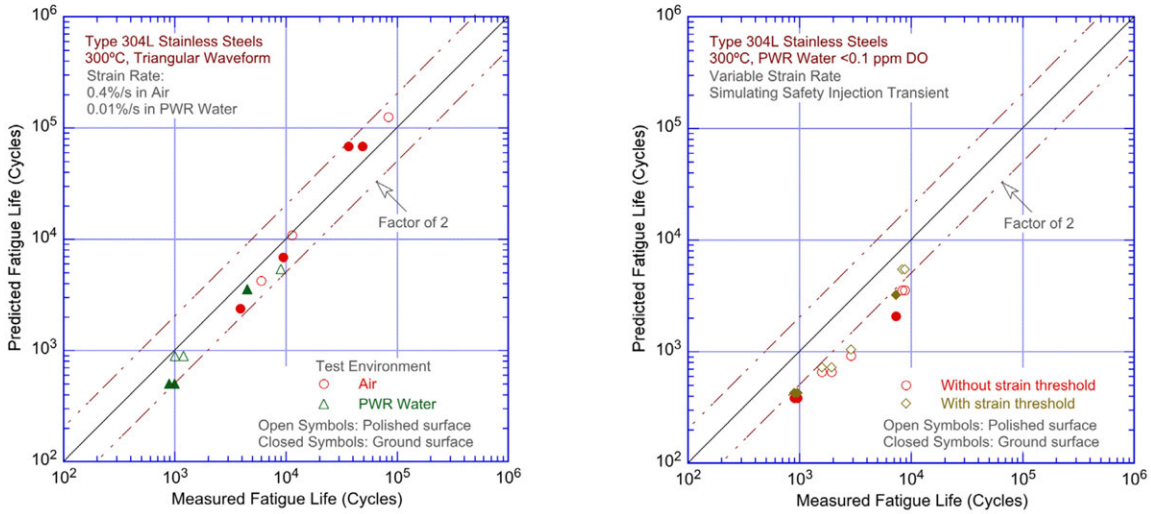


Figure 6-6 The experimental and estimated fatigue lives for Type 304L SS tested at 300°C in air and a PWR environment using triangular and complex loading that simulated a PWR safety injection transient (Refs. 155–157).

6.3 U-Bend Tests in Inert and PWR Water Environments

Low-cycle, corrosion-fatigue tests were conducted on Type 304L SS tube U-bend specimens in an inert (pressurized nitrogen) environment and a simulated PWR primary water environment at 240°C.[97-99] The primary focus of the tests was to study the effects of flow rate on fatigue crack initiation. Initially straight tubing of nominal 33.4 mm outer diameter (OD) and 3.38 mm wall thickness was used for the tests. The tubing was manufactured by cold rolling followed by solution annealing at 1,100°C and water quenching. The tubing was subsequently subjected to a pickling and passivation process. The tubing material was procured from Tubacex, Spain, meeting the compositional and mechanical property requirements of SA 312 Grade Type 304L low-carbon austenitic SS. A qualified, reproducible bending procedure was used by Babcock and Wilcox, Canada, to deform the tubing into a 180° U-bend using a cold die bend with an internal mandrel. A total of 10 U-bend test specimens were fabricated. Figure 6-7 shows a typical, as-received U-bend test specimen and the nomenclature adopted for the orientation around the circumference at the apex of the bend. The monotonic tensile yield strength, ultimate tensile strength, and total elongation of the material were, respectively, 245 MPa, 607 MPa, and 76.5% at room temperature and 168 MPa, 476 MPa, and 41.5% at 240°C.

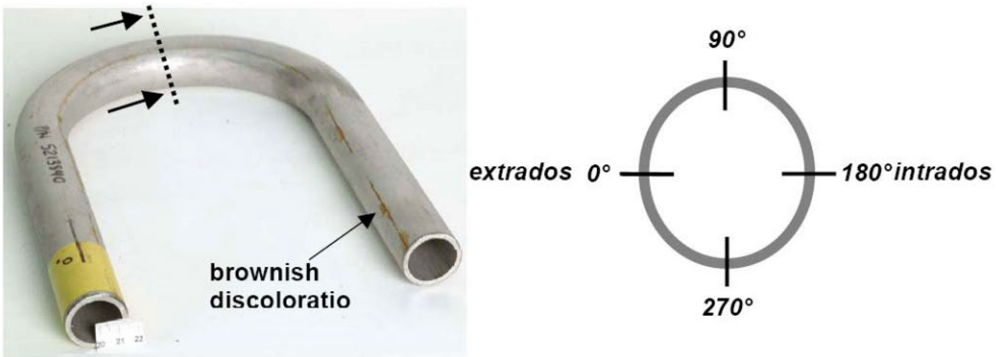


Figure 6-7 U-bend test specimen and nomenclature (Ref. 97).

Measurements made to characterize the as-received condition indicated that, as expected, the U-bend specimens exhibited a nonuniform wall thickness that was thinner at the extrados (0° circumferential position) and thicker at the intrados (180° position) in the apex region. The "neutral" bend positions (90° and 270°) retained the original wall thickness of the tubing. Furthermore, the stress states at all locations along the outer surface of the bend were predominantly tensile in nature with the exception of the circumferential stress at the intrados, which was compressive throughout most of the evaluation depth. This stress state implied tensile residual stress for this location at the water-wetted, internal surface. The macroscopic external and internal surface condition of the bends was generally good, except for some shallow linear indications. Both the outer and internal surfaces exhibited mild pickling attack. For some tests, the outer surface was mechanically polished and the inside surface was electropolished. All U-bend specimens were preconditioned by lengthy exposure to simulated PWR primary water before testing.

Low-cycle fatigue tests were carried out using fully reversed cycling (R = -1) and a triangular loading waveform. Both load and axial strain gauge response at the 0, 90, and 180° positions were continuously monitored during the cycling. All fatigue tests were allowed to continue until failure, which is defined as a through-wall crack leading to a loss of internal pressure within the U-bend specimens. Strain control was used for the first 12 loading cycles to allow for shakedown, with the remainder of the test performed under displacement control. An axial strain gauge at the bend intrados was used as the leading strain gauge to establish the desired strain amplitudes of either 0.6% or 0.4%. A series of baseline tests involving U-bends instrumented with numerous strain gauges were carried out in an inert environment at both room temperature and 240°C to establish both the basic fatigue behavior of the bend specimens and the appropriate load control sequence for subsequent testing in a simulated PWR primary water environment.

The simulated PWR primary water environment consisted of high-purity water with less than 10 ppb DO, 1,200 ppm boron as boric acid, and 2 ppm lithium (Li) as lithium hydroxide (LiOH). The combined chloride, fluoride, and sulfate impurities in water were less than 100 ppb. The tests were performed with either a low flow rate of 0.005 m/s (10 L/h) or a high flow rate of 2.2 m/s (4,400 L/h) for the 26.5 mm internal diameter (ID) tube. To facilitate proper evaluation of interim fatigue results, the following loading considerations were originally expected to be appropriate for the U-bend tests:

- The bend test was effectively strain controlled, with the axial strain at the outside surface of the bend intrados (180° position) acting as the control strain.

- Despite the reduced wall thickness from fabrication at the bend extrados (0° position), axial strains at the outer surface of that location were anticipated to be considerably smaller than at the intrados because of bend radius effects.

- Under the push-pull of the bend legs, compressive/tensile, cyclic, and axial strains were also created at the inside surface of the intrados, but their maximum values were expected to be about 35% lower than the control strain at the outer surface.

- As a result of ovalization at the apex of the bend during cycling, the circumferential strains expected at the inside surface in the 90° and 270° locations were estimated to be approximately 75% of the axial control strain, and slightly higher than the circumferential strains at the outer surface.

- The strains resulting from cyclic loading at the various locations around the bend apex were not expected to be entirely symmetrical because of factors such as "out-of-roundness" and wall-thickness variations caused by the tube manufacturing and bending processes and by the bend residual stress.

From these considerations, mechanically dominated fatigue was expected to lead to circumferential cracking, starting at the outside surface of the intrados, whereas environmental effects were expected to manifest themselves primarily as axial cracking at the inside surface in the "neutral" bend positions (i.e., 90° and 270°) at the apex of the test specimens. Table 6-7 summarizes the key conditions and results of the U-bend tests. All tests were conducted at a strain rate of 0.01%/s, except Tests 3a and 3b, which were performed at a strain rate of 0.0005%/s. The dominant failures were through-wall cracks that led to a loss of internal pressure in the U-bend tube specimens. The results also showed that fatigue cracks were typically circumferential on the outer surfaces and were axial on the inner surfaces. Figure 6-8 and Figure 6-9 present an overview of the extent and location of the fatigue cracking in the U-bend tests at strain amplitudes of 0.6 and 0.4%, respectively.

Table 6-7 Summary of the Key Conditions and Results of the U-Bend Tests at 240°C.

Test	Strain Amplitude (%)	Displace-ments (mm)	Surface Condition		Flow Rate	N_f	Failure Location & Mechanism	Striation Spacing Mid Fracture Area		Crack Depth 180° Position	Crack Depth 90° Position
			Outer	Internal				Env.	Mech.(1)		
BLT2	0.60	+6.90 -4.70	As pickled		Stag-nant N_2	1705	180° OD mechanical	- (2)	2.0 μm	- (2)	- (2)
2a	0.60	+6.50 -4.85	As pickled		Low	1520	180° OD mechanical	1 μm	5.0 μm	>1000 μm	N/A(3)
2b	0.60	+7.15 -5.40	As pickled		High	1238 at notch	180° OD mechanical	1 μm	2.5 μm	400 μm	N/A(3)
BLT3	0.40	+4.90 -4.92	Mech. polished	As pickled	Stag-nant N_2	4995	180° OD mechanical	- (2)	3.0 μm	- (2)	- (2)
4a	0.40	+4.82 -5.25	As pickled		Low	3609	270° ID environ.	3 μm	1 μm (180°)	580 μm	1700 μm
4a'	0.40	+4.91 -5.07	Mech. polished	As pickled	Low	3437	270° ID environ.	1 μm	N/A(3) (180°)	500 μm	1050 μm
4b	0.40	+5.07 -5.08	Mech. polished	As pickled	High	3616	270° ID environ.	1 μm	- (2)	1000 μm	750 μm
4d	0.40	+4.83 -5.03	Mech. polished	electro polished	High	3835	270° ID environ.	1 μm	N/A(3) (180°)	680 μm	2600 μm
3a	0.40	+4.88 -5.07	Mech. polished	As pickled	Low	1939	270° ID environ.	2 μm	- (2)	200 μm	2900 μm
3b	0.40	+4.67 -4.71	Mech. polished	As pickled	High	1517	270° ID environ.	2 μm	- (2)	210 μm	Through wall

1 OD crack initiation.
2 Crack did not exist.
3 Crack existed but was not examined.

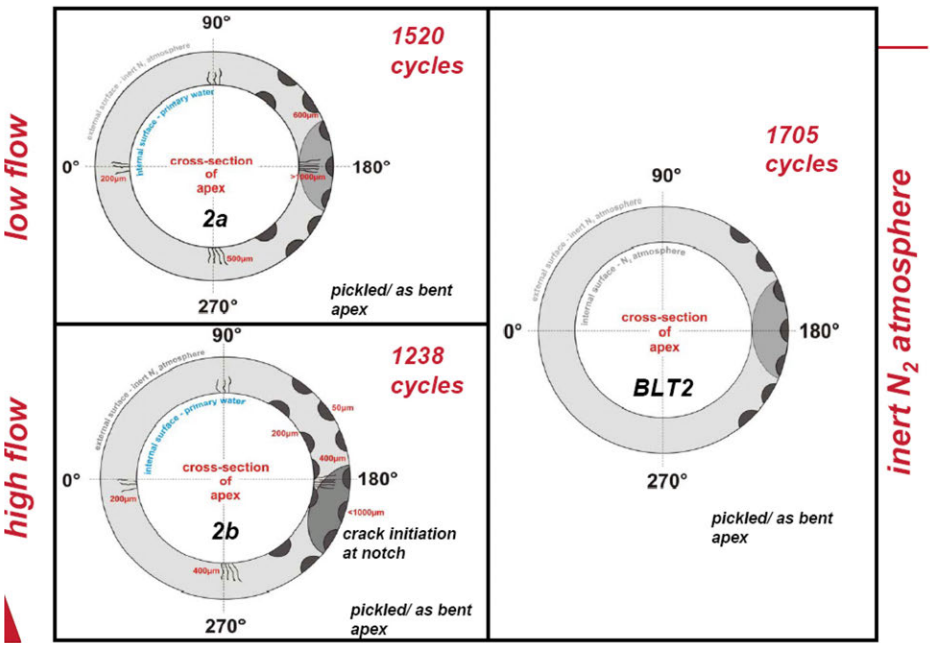


Figure 6-8 Overview of the extent and location of fatigue cracking in U bend tests at a strain amplitude of 0.6% (Ref. 97).

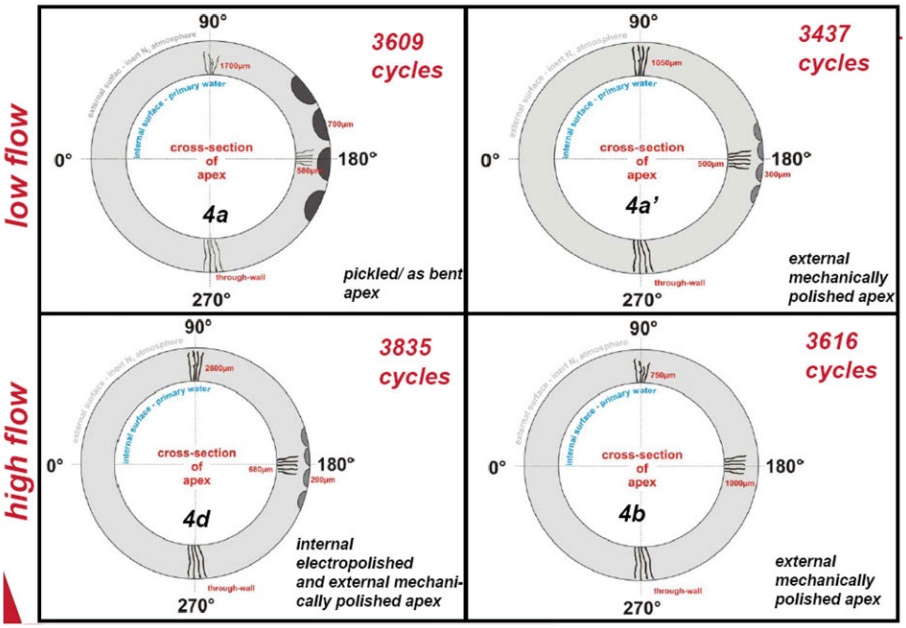


Figure 6-9 Overview of the extent and location of fatigue cracking in U bend tests at a strain amplitude of 0.4% (Ref. 97).

The predicted fatigue lives for the U-bend tests were obtained by dividing the estimated fatigue lives in air, N_{air} (determined from Equation 29), by F_{en} to account for environmental effects. Furthermore, because the tests were conducted using constant strain rate and temperature, the modified rate approach was not considered, and the F_{en} was determined using the simplified method. However, because the estimates of fatigue lives based on Equation 29 represent small, polished test specimens, and the U-bend test results were obtained on larger U-bend tube

specimens with a mechanically polished or pickled surface, the U-bend test results were adjusted for the effects of surface finish, size, and heat-to-heat variability. An adjustment for loading sequence was not included because all tests were conducted at constant strain amplitude. A value of 1.4 was used for the combined adjustment factor to account for the effects of surface finish, size, and heat-to-heat variability. This factor was determined by comparing the predicted fatigue lives with the results of the two tests in the inert environment (i.e., tests BLT2 and BLT3). The fatigue lives estimated from the small, smooth test specimen data were adjusted by dividing by a factor of 1.4 to obtain the fatigue lives for the U-bend tests.

Figure 6-10 plots the experimental and predicted fatigue lives for the Type 304L SS U-bend specimens at 240°C in inert and simulated PWR primary water environments. As mentioned before, the data in an inert environment (stagnant N_2) were used to determine the adjustment factor to account for the effects of surface finish, size, and heat-to-heat variability on fatigue life. Consequently, the data in the inert environment (solid circles in Figure 6-10) lie on the diagonal line, as expected. The results indicate that the predicted fatigue lives for the axial cracks that initiated at the 270° neutral bend position in the PWR environment fall within a factor of ±1.7 compared to the experimental values. These results are quite reasonable considering that several sources of uncertainties are associated with the actual strain and surface conditions of the test specimens. Sources of uncertainties include the following:

- the adjustment factor to account for the effects of surface finish, size, and heat-to-heat variability
- the ratio of the inside surface strain to the axial control strain
- the presence of a through-wall thermal stress gradient, which is not accounted for in the analysis
- the magnitude and distribution of residual stresses produced during the fabrication process
- the extent to which these stresses may relax during the pretest exposure to the primary water environment
- the contributions of surface flaws and the circumferential cracks that initiated at the OD extrados position on the strain magnitude produced during the test.

The implications of some of these uncertainties is apparent in the test results and may also contribute to some unexpected trends. In all tests, failure occurred by axial cracking at the 270° location, whereas the extent of cracking at the 90° location is significantly less even though the strain is nominally identical in both locations. The average depth of the axial cracks at the 90° location for three of the four tests are only 1.7, 1.05, and 0.75 mm instead of 3 mm, which is the value used for fatigue crack initiation. In addition, the U-bend test results surprisingly indicate that, in contrast to the results for carbon steels, higher flow rates have no beneficial effects on the fatigue lives of Type 304L austenitic SSs. In addition, the fatigue lives for either electropolished or pickled surface finishes are not significantly different, which is contrary to expectations.

- *The predicted fatigue lives were within a factor of ±1.7 of the experimental values (i.e., within the range of data scatter). The results did not indicate any beneficial effects of higher flow rates on the fatigue lives of austenitic SSs.*

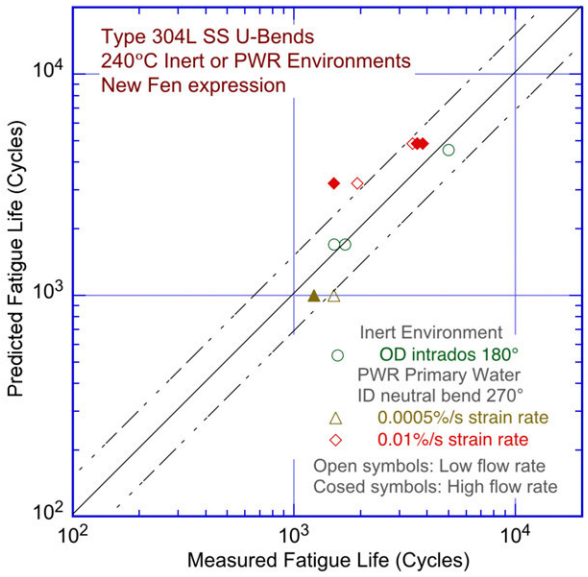


Figure 6-10 The experimental and predicted fatigue lives for Type 304L SS U-bend specimens at 240°C in inert and PWR environments (Refs. 97–99).

6.4 Simulation of Actual Plant Conditions

As discussed in Section 4.4, a modified rate approach was proposed for estimating fatigue lives of materials in LWR environments under varying temperature and strain rate conditions. The applicability of the modified rate approach was validated using fatigue ε–N data obtained under varying temperature and strain rate conditions. However, actual operating plant transients involve not only varying temperatures and strain rates, but also varying strain amplitudes. Therefore, to validate the applicability of the modified rate approach together with CUF evaluations that account for varying strain amplitudes, fatigue tests were conducted in a simulated PWR environment by combining loading cycle blocks of different strain amplitudes, which included changes in both temperature and strain rate.

Tests were conducted on Type 316 austenitic SS hollow, cylindrical specimens with a 12 mm OD, a 3 mm wall thickness, and a 24 mm gauge length. The material was obtained from a Type 316 SS pipe with a 355.7 mm OD and a 35.7 mm wall thickness. The material was heat treated for 30 minutes at 1,055°C followed by water quenching. Table 6-8 lists the chemical composition and mechanical properties.

Table 6-8 Chemical Composition and Tensile Strength of Type 316 SS Material.

Material	Chemical Composition (wt.%)									Min. YS (MPa)	Min. UTS (MPa)	Min. Elong. (%)
	C	Si	Mn	Ni	Cr	Mo	V	Cu	Ti			
316 SS	0.04	0.37	1.55	12.55	16.5	2.10	-	-	-	247	531	54

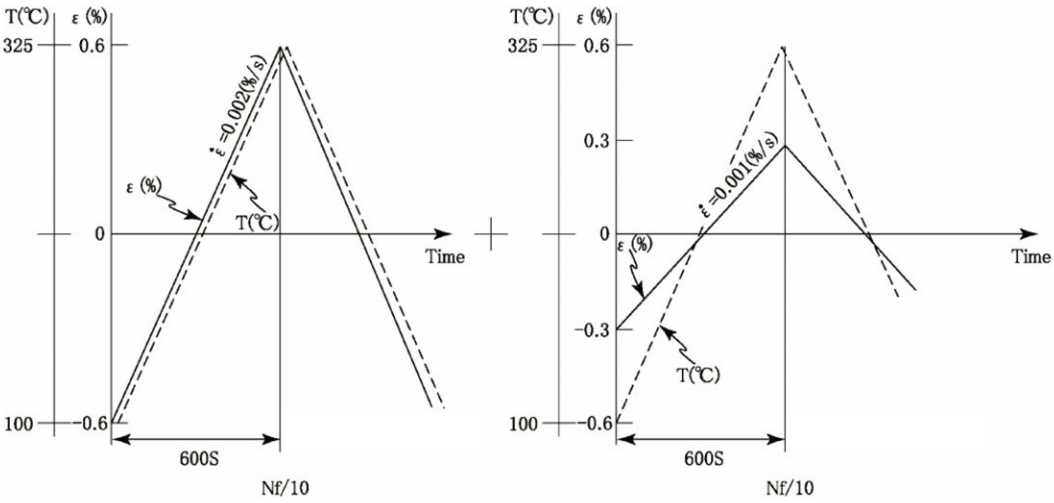
The tubular specimens were machined from the piping material such that the specimen gauge lengths were in the axial direction of the pipe. The outer and inner surfaces of the specimens were polished in the axial direction using emery papers up to 800 grit to remove machining scratches. All fatigue tests were conducted in a simulated PWR primary water environment under axial strain control using an extensometer attached to the outer surface of the specimens.

The test environment consisted of 500 ppm boron added as boric acid, 2 ppm Li added as LiOH, less than 0.005 ppm DO, and dissolved hydrogen was maintained at 30 cc/kg of water. The fatigue loading consisted of two blocks of differing strain amplitude and temperature ranges, in which either the strain rate changed in response to the temperature or the temperature was changed in response to strain rate (in phase or out of phase). Figure 6-11 provides examples of the loading cycles. Table 6-9 presents the test matrix for the combined two-block cumulative fatigue damage test. Fatigue life was defined as the number of cycles at which a fatigue crack penetrated through the wall thickness of the specimen, N_{leak}.

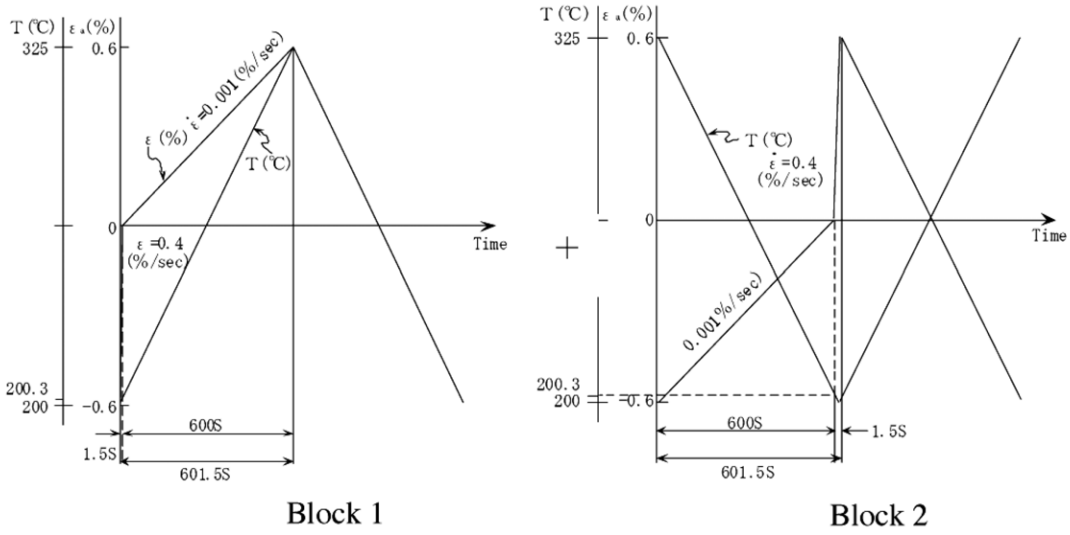
Figure 6-12 plots the measured fatigue lives and the predicted fatigue lives for the simulated actual plant conditions tests. The predicted fatigue lives for these tests were obtained by dividing the estimated fatigue lives in air, N_{air} (determined from Equation 29), by F_{en} to account for environmental effects. In addition, because the tests were conducted using linear changes in strain rate and temperature, the multilinear method was used to determine the F_{en}. Table 6-10 lists the predicted and experimental fatigue lives and the associated number of blocks and F_{en} values. The fatigue usage per block was determined from the ratio of cycles per block and the predicted fatigue life for the loading and environmental conditions for that block.

The results show good agreement between the predicted and experimental fatigue lives for all tests; the difference is within a factor of ±2 (i.e., within the range of material variability and data scatter).

- *The predicted fatigue lives for all block loading tests were within a factor of ±2.0 of the experimental values (i.e., within the range of material variability and data scatter).*



Test No. 1



Test No. 7

Figure 6-11 Loading waveforms for Fatigue Test Nos. 1 and 7 (Ref. 154).

Table 6-9 Test Matrix for the Two Block Fatigue Damage Tests.

Test No.	Block 1					Block 2				
	ε_a (%)	Pattern	Temp. (°C)	Strain Rate (%/s)	Cycles /Block	ε_a (%)	Pattern	Temp. (°C)	Strain Rate (%/s)	Cycles /Block
1	0.6	In phase	100-325	0.002	275	0.3	In phase	100-325	0.001	379[a]
2	0.6	In phase	100-325	0.002	27	0.3	In phase	100-325	0.001	379
3	0.6	Out of phase	100-325	0.002	311	0.6	In phase	200-325	0.002	152
4	0.6	Out of phase	100-325	0.002	311	0.6	In phase	200-325	0.002	15
5	0.6	In phase	200-325	0.4-0.001	77	0.6	In phase	200-325	0.001-0.4	70
6	0.6	Out of phase	200-325	0.4-0.001	70	0.6	Out of phase	200-325	0.001-0.4	77
7	0.6	In phase	200-325	0.4-0.001	77	0.6	Out of phase	200-325	0.001-0.4	77

[a] The second block stopped after 129 cycles.

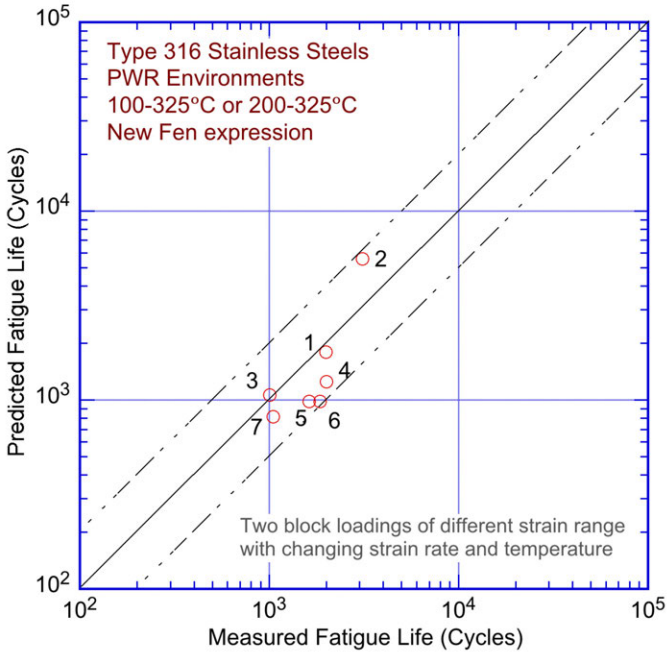


Figure 6-12 The experimental and predicted fatigue lives of Type 316 SS tested in PWR primary water using two blocks of fatigue cycles of different strain amplitudes and varying temperature and strain rate (Ref. 154).

Table 6-10 Results of the Two Block Fatigue Damage Tests.

Test No.	ε_a (%)	Temp. (°C)	Strain Rate (%/s)	Cycles /Block	N_{leak} (cycles)		N_{air} (cycles)	F_{en}	Usage /Block	Predicted Blocks	N_{estd} (cycles)	
					Partial	Total					Partial	Total
1	0.6	100-325	0.002	275	1,108	1,995	3,899	3.039	0.214	3.302	908	1,795
	0.3	100-325	0.001	379	887		24,341	3.327	0.052		887	
2	0.6	100-325	0.002	27	216	3,100	3,899	3.039	0.021	13.729	378	5,574
	0.3	100-325	0.001	379	2,884		24,341	3.327	0.052		5,196	
3	0.6	100-325	0.002	311	699	1,003	3,899	3.039	0.242	2.291	757	1,061
	0.6	200-325	0.002	152	304		3,899	4.980	0.194		304	
4	0.6	100-325	0.002	311	1,915	2,005	3,899	3.039	0.242	3.823	1,201	1,246
	0.6	200-325	0.002	15	90		3,899	4.980	0.019		45	
5	0.6	200-325	0.4-0.001	77	1,001	1,857	3,899	4.779	0.094	6.695	539	984
	0.6	200-325	0.001-0.4	70	856		3,899	3.063	0.055		445	
6	0.6	200-325	0.4-0.001	70	777	1,624	3,899	3.063	0.055	6.695	490	984
	0.6	200-325	0.001-0.4	77	847		3,899	4.779	0.094		494	
7	0.6	200-325	0.4-0.001	77	539	1,046	3,899	4.779	0.094	5.298	431	816
	0.6	200-325	0.001-0.4	77	507		3,899	4.779	0.094		385	

7 SUMMARY

The comprehensive review of the available fatigue strain vs. life (ε–N) data for nuclear power plant piping and pressure vessel steels presented in the original version of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," issued February 2007, was reevaluated using a much larger database, and the results were updated to address feedback from interested stakeholders regarding the environmental fatigue correction factor (F_{en}) methodology for incorporating environmental effects into the fatigue cumulative usage factor (CUF) evaluations in Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code). Note that the F_{en} approach has been developed only for use as part of an ASME Code fatigue evaluation. Further, this report does not address any conservatisms associated with the ASME Code fatigue evaluation procedures.

This report describes fatigue life as the number of cycles of a specified strain amplitude that a specimen can sustain before the formation of a 3-mm-deep crack (i.e., an "engineering crack"). This equates to a 25% load drop in test specimens and is assumed to equate to crack initiation in an actual component. Using this definition, a calculated fatigue CUF less than unity provides reasonable assurance that a fatigue crack has not formed in a component, and indicates that the probability of forming a crack in the component is low.

In the original version of NUREG/CR-6909, the existing fatigue ε–N data for carbon and low-alloy steels, wrought and cast austenitic stainless steels (SSs), and nickel-chromium-iron (Ni-Cr-Fe) alloys were evaluated to identify the various material, environmental, and loading parameters that influenced fatigue crack initiation and to establish the effects of key parameters on the fatigue lives of these steels. The fatigue lives of these materials were decreased in light-water reactor (LWR) environments; the magnitude of the reduction depended on temperature; strain rate; dissolved oxygen (DO) level in the water; and, for carbon and low-alloy steels, the sulfur content of the steel. For all steels, environmental effects on fatigue lives were significant only when critical parameters (temperature, strain rate, DO level, and strain amplitude) met certain threshold values. Environmental effects were moderate (e.g., less than a factor of 2 decrease in lives) when any one of the threshold conditions was not satisfied. The threshold values of the critical parameters and the effects of other parameters (such as water conductivity, water flow rate, and material heat treatment) on the fatigue lives of the steels were also discussed. This report updates and reevaluates all of these evaluations; the results are summarized below.

Carbon and Low-Alloy Steels

In air, the fatigue lives of carbon and low-alloy steels depended on steel type, temperature, specimen orientation, and strain rate. The fatigue lives of carbon steels were a factor of approximately 1.5 lower than those of low-alloy steels. For both steels, fatigue lives decreased with an increase in temperature. Some heats of carbon and low-alloy steels exhibited effects of strain rate and specimen orientation. For these heats, fatigue lives decreased with decreasing strain rate. In addition, the data indicated significant heat-to-heat variation; the distribution and morphology of sulfides had a significant effect on the fatigue lives of these materials. The results also indicated that, in room temperature air, the ASME Code Section III mean curve for low-alloy steels was in good agreement with the available experimental data, and the mean curve for carbon steels was somewhat conservative in the high-cycle regime (i.e., fatigue lives greater than 10^4 cycles. Revised fatigue design curves based on the Argonne National

Laboratory (ANL) models were developed in the initial version of NUREG/CR-6909. Those curves extended up to 10^{11} cycles. In the present report, the extension of the fatigue design curves beyond 10^6 cycles was modified to be consistent with the current ASME Code Section III fatigue design air curve to better accommodate the field vibration data.

The fatigue lives of both carbon and low-alloy steels were decreased in LWR environments; the amount of reduction depended on temperature, strain rate, DO level in the water, and sulfur content of the steel. The results indicated that a minimum threshold strain was required for an environmentally assisted decrease in the fatigue lives of these steels. In addition, environmental effects occurred primarily during the tensile-loading cycles and at strain levels greater than a threshold value. The fatigue lives were decreased significantly when all four conditions were satisfied simultaneously (i.e., when the strain amplitude, temperature, and DO in the water were above minimum levels and the strain rate was below a threshold value). The sulfur content in the steel was also important; its effect on fatigue lives depended on the DO level in the water.

Although the microstructures and cyclic–hardening behavior of carbon and low-alloy steels differed significantly, environmental degradation of the fatigue lives of these steels was very similar. The available fatigue ε–N data were reviewed to establish the critical parameters that influenced fatigue lives and updated definitions were developed for their threshold and limiting values within which environmental effects were significant. In the original version of NUREG/CR-6909, the F_{en} expressions for both steels predicted a moderate decrease in fatigue lives (i.e., by about a factor of 2) when any one of the threshold conditions was not satisfied, (e.g., a low-DO boiling-water reactor (BWR) hydrogen water chemistry (HWC) or a pressurized-water reactor (PWR) environment, temperatures less than 150°C, or vibratory fatigue. In the present report, the F_{en} expressions for carbon and low-alloy steels were revised so that the F_{en} value is 1.0 (i.e., no environmental effects) when the strain rates are very high (i.e., greater than 2.2%/s), the DO level is less than 0.04 ppm, and the temperature is less than 150°C. The impact of this revision on fatigue CUF values relative to the F_{en} expressions in the original version of NUREG/CR-6909 is that the updated F_{en} values are generally lower under certain environmental and loading conditions compared to the previous expressions.

Austenitic Stainless Steels

In air, the fatigue lives of Types 304 and 316 SS were comparable; those of Type 316NG were superior to those of Types 304 and 316 SS at high strain amplitudes (i.e., the slope of the fatigue ε–N curve was steeper). The fatigue lives of austenitic SSs in air were independent of temperature in the range from room temperature to 427°C. In addition, variations in strain rate in the range of 0.4–0.008%/s had no effect on the fatigue lives of SSs at temperatures up to 400°C. The fatigue ε–N behavior of cast SSs was similar to that of wrought austenitic SSs. The results indicated that the experimental data at strain amplitudes less than 0.5% or 975 MPa (141 ksi) were not consistent with the mean-data curve for SSs corresponding to the fatigue design curves in editions of ASME Code Section III prior to the 2009 Addenda; the ASME Code Section III mean air curve predicted significantly longer lives than those observed experimentally. The fatigue design air curve in editions of ASME Code Section III later than the 2009 Addenda was based on the ANL model and is consistent with the available fatigue ε–N data. Please note that the fatigue test data used in developing the ASME Code fatigue design curve did not consider grades of austenitic steels, such as the titanium- or niobium-modified SSs that have improved fatigue resistance compared to the other austenitic materials evaluated in this report. Therefore, fatigue lives based on the proposed fatigue design curve are expected to be conservative for such materials as the titanium- or niobium-modified steels.

The fatigue lives of cast and wrought austenitic SSs decreased in LWR environments compared to those in air. The decrease depended on the strain rate, the DO level in the water, and temperature. Similar to the behavior of carbon and low-alloy steels, a minimum threshold strain was required for environmental effects on fatigue lives of SSs to occur, and this strain was independent of material types (weld or base metal) and temperatures in the range of 250–325°C. Furthermore, environmental effects were significant only during the tensile-loading cycles. Strain rates and temperatures had strong effects on fatigue lives in LWR environments. Fatigue lives decreased with decreasing strain rates below 0.4%/s; the effects saturated at 0.0004%/s. In the original version of NUREG/CR-6909, a threshold temperature of 150°C was defined below which environmental effects were insignificant; in the range of 150–325°C, the logarithm of fatigue lives decreased linearly with temperature. However, to better represent all of the more recently available fatigue ε–N data, the temperature dependence relationships in the F_{en} expressions were modified and the temperature threshold decreased from 150°C to 100°C. The dependency of fatigue lives on strain rate was also modified, and the threshold strain rate above which environmental effects were considered insignificant was increased from 0.4%/s to 7%/s. The impact of these revisions on fatigue CUF values relative to the F_{en} expressions in the original version of NUREG/CR-6909 was that F_{en} values using the updated expressions are lower under many environmental and loading conditions, but are marginally higher for some conditions.

The effects of DO levels were different for different steels. In low-DO water (i.e., less than 0.01 ppm DO), the fatigue lives for all wrought and cast austenitic SSs were decreased significantly; compositions or heat treatments of the steels had little or no effects on fatigue lives. However, in high-DO water, the environmental effects on fatigue lives were influenced by the composition and heat treatment of the steels. For example, for high-C Type 304 SSs, environmental effects were significant only for sensitized steels. For low-C Type 316NG SSs, some effects of environment were observed even for mill-annealed (nonsensitized) steels in high-DO water, although the effects were smaller than those observed in low-DO water. Limited fatigue ε–N data indicated that the fatigue lives of cast SSs were approximately the same in low- and high-DO water and were comparable to those observed for wrought SSs in low-DO water. As such, in the initial version of NUREG/CR-6909, environmental effects on the fatigue lives of wrought and cast austenitic SSs were considered to be identical in high-DO and low-DO environments. However, based on the more recently available fatigue ε–N data, the dependency of environmental effects on water DO content was included in this report; that dependency was based on the material composition and heat treatment.

Ni-Cr-Fe Alloy Steels

The available fatigue ε–N data for Ni-Cr-Fe alloys indicated that, although the data for Alloys 690 and 800 were very limited, the fatigue lives of these alloys were comparable to those of Alloy 600. In addition, the fatigue lives of the Ni-Cr-Fe alloy weld metals were comparable to those of the wrought Alloy 600 and 690 materials in the low-cycle regime (i.e., less than 10^5 cycles), and were slightly superior in the high-cycle regime. The data for Ni-Cr-Fe alloys also indicated that the fatigue resistance of Inconel 718 was superior to that of Alloy 600, 690, and 800 materials. For Inconel 718, the slope of the fatigue ε–N curve was flatter and the fatigue limit (i.e., fatigue life at 10^6 cycles) was higher than those for austenitic SSs. Therefore, the current ASME Code fatigue air design curve for austenitic SSs curve is conservative for representing the fatigue ε–N behavior of Inconel 718.

The available laboratory fatigue data for Ni-Cr-Fe alloys in LWR environments were very limited. However, the available data indicated that the effects of key loading and environmental

parameters on fatigue lives are similar to those for austenitic SSs. For example, the fatigue lives of these steels decreased logarithmically with decreasing strain rates. In addition, the effects of environment were greater in low-DO PWR water compared to those in high-DO environment were greater in low-DO PWR water compared to those in high-DO BWR water. However, environmental effects on the fatigue lives of Ni-Cr-Fe alloys were lower than those for austenitic SSs. Therefore, in this report, the temperature dependency of the F_{en} expression for Ni-Cr-Fe alloys was revised; the effects of temperature on fatigue lives of these materials were considered to be insignificant below 50°C and they saturated at temperatures above 325°C. The impact of this revision on fatigue evaluations is that updated F_{en} values are typically lower relative to those based on F_{en} expressions in the initial version of NUREG/CR-6909. Because experimental data on environmental effects for Inconel 718 are not available, the F_{en} expressions for Ni-Cr-Fe alloys do not apply to Inconel 718.

Model Validation

The updated F_{en} methodology proposed in this revised report was validated by comparing the evaluation of the results of several experimental datasets obtained from fatigue tests that simulated actual plant conditions with estimates of fatigue usage using the updated F_{en} expressions. The datasets represented fatigue tests with changing strain rates or temperatures; complex loadings that simulated a PWR safety injection transient; spectrum loadings (i.e., random strain amplitudes); and pipe U-bend tests. In all cases, the results indicated that the predicted fatigue lives were in good agreement with the experimental values; the differences between the experimental and predicted fatigue lives were within a factor of 2, which is within data scatter. However, the predicted fatigue lives for the tests with the complex strain loading cycles were all lower than the experimental values by a factor of about 2. The reason for this one exception was not clear. This behavior may have been unique to the specific strain loading cycles used in the test. For example, the calculations assumed that the surface oxide film forms during the decreasing strain portion of the cycle and does not re-form until the peak strain. The protective oxide film is likely to re-form at the end of the transient when strain rates are very low and strain accumulation is negligible. Therefore, an additional threshold strain would be needed to rupture the surface oxide film for environmental effects to occur. Fatigue tests with other strain loading cycle profiles are recommended to provide further understanding of possible effects of complex loading patterns on the fatigue lives of materials. Nonetheless, although the predicted lives were lower, the estimated values were within the range of data scatter.

Fatigue Design Curve Adjustment Factors

This updated report also presents a critical review of the ASME Code Section III fatigue adjustment factors of 2 on stress and 20 on life and assesses the possible conservatisms in the choice of these adjustment factors. These factors covered the effects of variables that influence fatigue lives but were not investigated in the tests that provided the data for the ASME Code Section III air design curves. These variables included material variability and data scatter, size, surface finish, and loading sequence. Although the factors of 2 and 20 used by ASME were intended to be conservative, they are not considered to be safety margins because they were intended to account for variables that are known to affect fatigue lives. Data available in the literature were reviewed to evaluate the factors on cycles and stress that are needed to account for the differences and uncertainties caused by the four parameters that were not considered in the fatigue test data. Monte Carlo simulations were performed to determine the factor on cycles needed to obtain fatigue design air curves that provide conservative estimates of the number of cycles to initiate a fatigue crack in reactor components.

The results presented in the initial version of NUREG/CR-6909 indicated that, for carbon and low-alloy steels and austenitic SSs, the current ASME Code Section III requirements for a factor of 20 on cycles to account for the effects of material variability and data scatter, size, surface finish, and loading history were conservative by at least a factor of 1.7. Thus, to reduce this conservatism, fatigue design curves were developed from the ANL model by first correcting for mean stress effects and then by reducing the mean-stress adjusted curve by a factor of 2 on stress and 12 on cycles, whichever was more conservative. In this updated report, the range of the subfactors for material variability and data scatter, size, surface finish, and loading sequence were examined and modified, and Monte Carlo simulations were performed to determine the factor on cycles needed to obtain fatigue design air curves with 95% confidence bounds. The results indicated that for these materials, factors of 2 on stress and 10 on cycles were adequate to develop the fatigue design curves from the best-fit mean air curves. Although this report justifies an adjustment factor of 10 on life, a value of 12 was used to develop the air design curves from mean-data curves for each material to be consistent with the adjustment factor used in the ASME Code fatigue design curves.

Evaluation Procedure

Appendix A presents a detailed procedure for incorporating environmental effects into ASME Code Section III fatigue evaluations. The methodology is identical to that presented in the initial version of NUREG/CR-6909; however, the F_{en} expressions were updated based on the analyses presented in this report. In addition, the updated methodology described in this report applies to any component exposed to the LWR environment that requires an ASME CUF calculation as part of its design or if it is required by the safety basis for the component or by the plant current licensing basis, unless otherwise justified. Appendix C of this report presents a sample application of F_{en} using the methodology in Subarticle NB-3200, “Design by Analysis,” in ASME Code Section III. The procedure allows evaluation using either a modified rate or an average rate approach. F_{en} calculations based on an average strain rate for the transient are expected to yield conservative estimates of fatigue lives as long as the calculations use appropriate temperatures selected in accordance with the recommended procedures in Section 4.4. Using an average transient temperature within the average strain rate approach does not always yield a conservative estimate of F_{en}. Therefore, an average temperature should only be used if it has been demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach.

Applicability of Method and Future Work

The ASME Code Section III fatigue design curves for carbon and low-alloy steels and austenitic SSs are applicable to various grades and compositions of materials having a wide range of tensile strength. Furthermore, the criterion used in establishing the fatigue design curve ensures that the proposed curve bounds 95% of the available fatigue data with 95% confidence. In addition, the mean stress correction for the design curves is based on a conservative value of mean stress at room temperature. Finally, the fatigue loading in laboratory specimens is uniformly tensile which is more severe than in many applications where the loading decreases through the thickness. Therefore, the design curves should be conservative for most materials and applications, particularly at reactor operating temperatures where mean stresses are likely to be lower.

The criteria used for establishing the adjustment factors to account for the parameters that influence fatigue life but were not considered in the experimental data used to develop the fatigue design curves (Section 5) also yield conservative values of fatigue life in applications.

These adjustment factors may be further optimized. It should be stressed that other factors (e.g., component size) may lead to decreases in fatigue life in applications compared to laboratory testing. Therefore, any modifications of the design curves or adjustment factors should be performed holistically to develop a technical basis that addresses all the sources of conservatism and uncertainty mentioned above.

It is recommended that guidance should be provided for using the high-cycle portion of the curves for mechanical loading. This guidance is necessary because strain-controlled fatigue test data are used to develop the ASME Code ε–N fatigue design curves, and these must be converted to pseudo-stress vs. life curves in most applications.

8 REFERENCES

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APPENDIX A
INCORPORATING ENVIRONMENTAL EFFECTS INTO FATIGUE EVALUATIONS

A.1 Scope

This appendix provides the environmental fatigue correction factor (F_{en}) methodology that is considered acceptable for incorporating the effects of water environments in fatigue usage factor evaluations of metal components. It describes the methodology used to perform fatigue evaluations for the four major categories of structural materials (e.g., carbon steels, low-alloy steels, wrought and cast austenitic stainless steels (SSs), and nickel-chromium-iron (Ni-Cr-Fe) alloys).

A.2 Environmental Fatigue Correction Factor

The effects of water environments on the fatigue lives of structural materials are expressed in terms of an environmental fatigue correction factor, F_{en}, which is defined as the ratio of fatigue life in air at room temperature ($N_{air,RT}$) (25°C (77°F)) to that in water at the service temperature to that in water at the service temperature (N_{water}) as follows:

$$F_{en} = N_{air,RT}/N_{water} \tag{A.1}$$

The F_{en} for both carbon and low-alloy steels is expressed as

$$F_{en} = \exp((0.003 - 0.031\dot{\varepsilon}^*)\, S^* T^* O^*), \tag{A.2}$$

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

$$\begin{aligned} S^* &= 2.0 + 98\,S && (S \le 0.015 \text{ wt.\%}) \\ S^* &= 3.47 && (S > 0.015 \text{ wt.\%}) \end{aligned} \tag{A.3}$$

$$\begin{aligned} T^* &= 0.395 && (T < 150°C) \\ T^* &= (T - 75)/190 && (150°C \le T \le 325°C) \end{aligned} \tag{A.4}$$

$$\begin{aligned} O^* &= 1.49 && (DO < 0.04 \text{ ppm}) \\ O^* &= \ln(DO/0.009) && (0.04 \text{ ppm} \le DO \le 0.5 \text{ ppm}) \\ O^* &= 4.02 && (DO > 0.5 \text{ ppm}) \end{aligned} \tag{A.5}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/2.2) && (0.0004\%/s \le \dot{\varepsilon} \le 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/2.2) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \tag{A.6}$$

For carbon and low-alloy steels, a threshold value of either 0.07% for strain amplitude (one-half the strain range for the cycle) or a stress amplitude of 145 MPa (21.0 ksi) is defined, below which environmental effects on the fatigue lives of these steels may not occur. Thus,

$$F_{en} = 1 \qquad (\varepsilon_a \le 0.07\% \text{ or } 145 \text{ MPa } \{21.0 \text{ ksi}\} \text{ stress amplitude}) \tag{A.7}$$

Note that the strain amplitude threshold should not be applied when using a modified rate approach because it may yield nonconservative results.

For wrought and cast austenitic SSs,

$$F_{en} = \exp(- T^* \dot{\varepsilon}^* O^*) \quad \text{(A.8)}$$

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

$$\begin{aligned} T^* &= 0 && (T \le 100°C) \\ T^* &= (T - 100)/250 && (100°C \le T \le 325°C) \end{aligned} \quad \text{(A.9)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 7\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/7) && (0.0004\%/s \le \dot{\varepsilon} \le 7\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/7) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad \text{(A.10)}$$

For DO less than 0.1 ppm (i.e., for pressurized-water reactor (PWR) or boiling-water reactor (BWR) hydrogen water chemistry (HWC) water),

$$O^* = 0.29 \quad \text{(all wrought and cast SSs and heat treatments and SS weld metals)} \quad \text{(A.11)}$$

For DO greater than or equal to 0.1 ppm (i.e., for BWR normal water chemistry (NWC) water),

$$\begin{aligned} O^* &= 0.29 && \text{(sensitized high-carbon wrought and cast SSs)} \\ O^* &= 0.14 && \text{(all wrought SSs except sensitized high-carbon SSs)} \end{aligned} \quad \text{(A.12)}$$

For wrought and cast austenitic SSs, a threshold value of either 0.10% for strain amplitude (one-half the strain range for the cycle) or a 195 MPa (28.3 ksi) stress amplitude is defined, below which environmental effects on the fatigue lives of these steels do not occur. Thus,

$$F_{en} = 1 \quad (\varepsilon_a \le 0.10\% \text{ or a 195 MPa \{28.3 ksi\} stress amplitude}) \quad \text{(A.13)}$$

Note that the strain amplitude threshold should not be applied when using a modified rate approach because it may yield nonconservative results.

For all Ni-Cr-Fe alloys except Inconel 718,

$$F_{en} = \exp(- T^* \dot{\varepsilon}^* O^*) \quad \text{(A.14)}$$

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

$$\begin{aligned} T^* &= 0 && (T < 50°C) \\ T^* &= (T - 50)/275 && (50°C \le T \le 325°C) \end{aligned} \quad \text{(A.15)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/5.0) && (0.0004\%/s \le \dot{\varepsilon} \le 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/5.0) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad \text{(A.16)}$$

$O^* = 0.06$ (NWC BWR water (i.e., ≥ 0.1 ppm DO)))
$O^* = 0.14$ (PWR or HWC BWR water (i.e., < 0.1 ppm DO)) (A.17)

For Ni-Cr-Fe alloys except Inconel 718, a threshold value of either 0.10% for strain amplitude (one-half the strain range for the cycle) or a 195 MPa (28.3 ksi) stress amplitude is defined, below which environmental effects on the fatigue lives of these alloys do not occur. Thus,

$F_{en} = 1$ ($\varepsilon_a \leq 0.10\%$ or a 195 MPa {28.3 ksi} stress amplitude) (A.18)

Note that the strain amplitude threshold should not be applied when using a modified rate approach because it may yield nonconservative results. Also, because of the lack of environmental effect data, these F_{en} expressions are not applicable for Inconel 718.

For all materials, a maximum temperature limit was selected at 325°C as a reasonable bound to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions, especially when considering the use of average temperature. If the applicable average temperature for the transient exceeds 325°C, the user should thoroughly document this exceedance and justify the rationale for it as part of the analysis.

A.2.1 Fatigue Evaluation Procedure

The environmental fatigue evaluation method uses as its input the partial fatigue usage factors U_1, U_2, U_3, …U_n, determined in fatigue evaluations. To incorporate environmental effects into the fatigue evaluation, the partial fatigue usage factor for a specific stress cycle or load set pair, based on the fatigue design curves, is multiplied by the environmental fatigue correction factor, F_{en}, as follows:

$$U_{en,1} = U_1 \cdot F_{en,1} \quad (A.19)$$

In the methods in Subarticle NB-3200, “Design by Analysis,” of Section III, “Rules for Construction of Nuclear Facility Components,” of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), the partial fatigue usage factors are calculated for each type of stress cycle in Subparagraph NB-3222.4(e)(5). For piping products designed using the methods in Subarticle NB-3600, “Piping Design,” of ASME Code Section III, Paragraph NB-3653 provides the procedures for the calculation of partial fatigue usage factors for each of the load set pairs. The partial usage factors are obtained from the fatigue design curves in the ASME Code Section III editions as of the 2009 Addenda. Note that the ASME Code fatigue design curves for austenitic SS developed in the 1960s (i.e., before publication of the 2009 Addenda) were not consistent with the fatigue database used to develop the environmental fatigue correction factors in this report and, therefore, may give nonconservative estimates of environmental fatigue usage factors for most heats of austenitic SSs used in the construction of nuclear reactor components. Examples of methods used to calculate partial usage factors are as follows:

- For carbon and low-alloy steels with ultimate tensile strengths less than 552 MPa (80 ksi), the partial fatigue usage factors are obtained from the ASME Code fatigue design curve (i.e., Figure I-9.1 of Mandatory Appendix I to ASME Code Section III). As an alternative, to reduce conservatism in the current ASME Code fatigue design curve for carbon steel and the ASME Code requirement of a factor of 20 on life, partial usage factors may be determined from the fatigue design curves developed from the Argonne National Laboratory (ANL) fatigue life model (i.e., Figure A-1 and Figure A-2 and Table A-1).

- For wrought or cast austenitic SSs and Ni-Cr-Fe alloys (except Inconel 718), the partial fatigue usage factors are obtained from the fatigue design curve in the 2009 Addenda or later editions of the ASME Code (i.e., Figure I-9.2 of Mandatory Appendix I to ASME Code Section III), which is the same as the ANL fatigue design curve. The ANL fatigue design curve is based on the ANL fatigue life model and was developed using a factor of 12 on life (i.e., Figure A-3 and Table A-2).

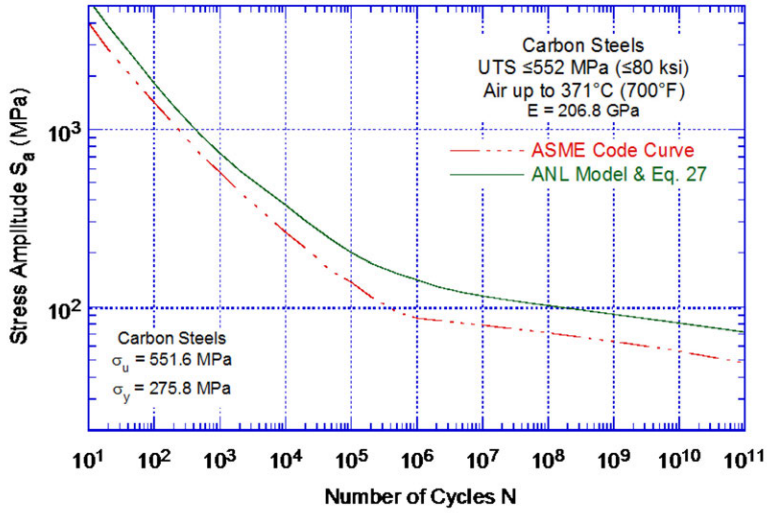


Figure A-1 Fatigue design curves for carbon steels in air (The curve developed from the ANL model is based on factors of 12 on life and 2 on stress.)

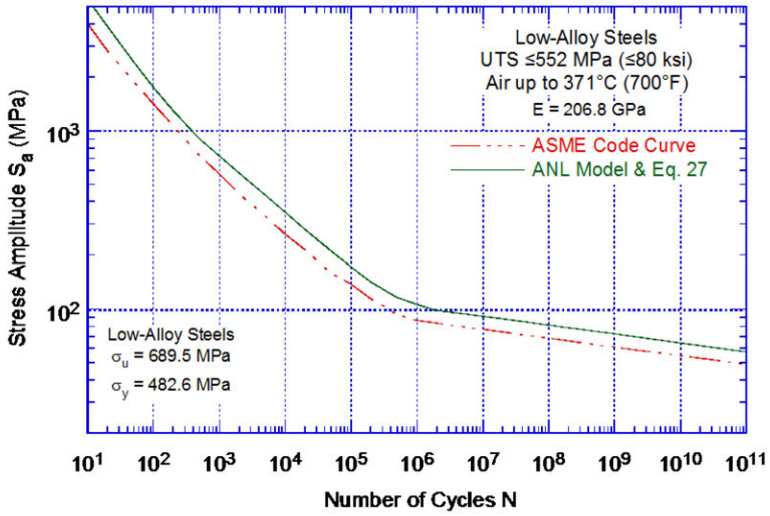


Figure A-2 Fatigue design curves for low-alloy steels in air (The curve developed from the ANL model is based on factors of 12 on life and 2 on stress).

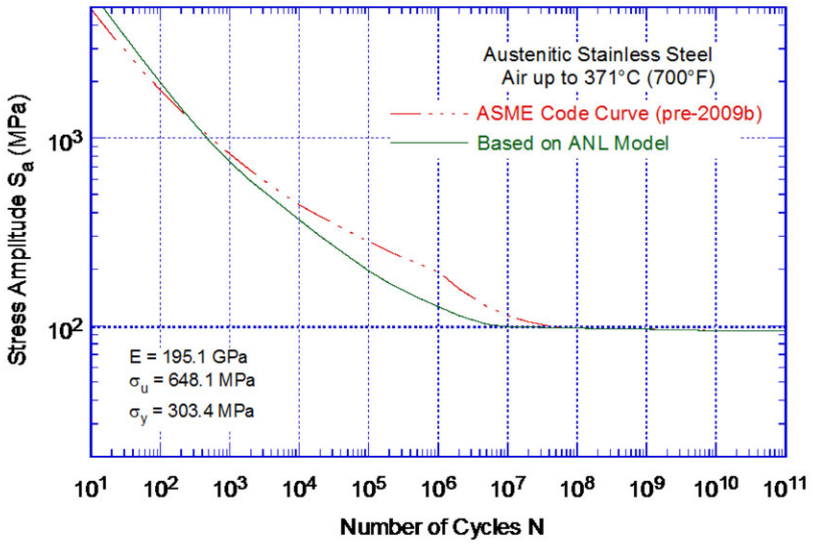


Figure A-3 Fatigue design curve for austenitic SSs in air (The curve developed from the ANL model is based on factors of 12 on life and 2 on stress).

Table A-1 Fatigue Design Curves for Carbon and Low Alloy Steels in Air.

Cycles	Stress Amplitude, MPa (ksi)		
	ASME Code Curve	Carbon Steel	Low-alloy Steel
1E+01	3999 (580)	5355 (777)	5467 (793)
2E+01	2827 (410)	3830 (556)	3880 (563)
5E+01	1896 (275)	2510 (364)	2438 (354)
1E+02	1413 (205)	1820 (264)	1760 (255)
2E+02	1069 (155)	1355 (197)	1300 (189)
5E+02	724 (105)	935 (136)	900 (131)
1E+03	572 (83)	733 (106)	720 (104)
2E+03	441 (64)	584 (84.7)	576 (83.5)
5E+03	331 (48)	451 (65.4)	432 (62.7)
1E+04	262 (38)	373 (54.1)	342 (49.6)
2E+04	214 (31)	305 (44.2)	276 (40.0)
5E+04	159 (23)	238 (34.5)	210 (30.5)
1E+05	138 (20.0)	201 (29.2)	172 (24.9)
2E+05	114 (16.5)	176 (25.5)	141 (20.5)
5E+05	93.1 (13.5)	154 (22.3)	116 (16.8)
1E+06	86.2 (12.5)	142 (20.6)	106 (15.4)
2E+06		130 (18.9)	98 (14.2)
5E+06		120 (17.4)	94 (13.6)
1E+07	76.8 (11.1)	115 (16.7)	91 (13.2)
2E+07		110 (16.0)	88 (12.7)
5E+07		105 (15.2)	84 (12.2)
1E+08	68.5 (9.9)	101 (14.7)	81 (11.8)
1E+09	61.1 (8.8)	90 (13.1)	72.3 (10.5)
1E+010	54.4 (7.9)	81 (11.7)	64.4 (9.3)
1E+011	48.5 (7.0)	72 (10.4)	57.4 (8.3)

Table A-2 Fatigue Design Curves for Austenitic SSs in Air.

	Stress Amplitude, MPa (ksi)		Stress Amplitude, MPa (ksi)
Cycles	ASME Code Design Curve	Cycles	ASME Code Design Curve
1E+01	6000 (870)	2E+05	168 (24.4)
2E+01	4300 (624)	5E+05	142 (20.6)
5E+01	2748 (399)	1E+06	126 (18.3)
1E+02	1978 (287)	2E+06	113 (16.4)
2E+02	1440 (209)	5E+06	102 (14.8)
5E+02	974 (141)	1E+07	99 (14.4)
1E+03	745 (108)	1E+08	97.1 (14.1)
2E+03	590 (85.6)	1E+09	95.8 (13.9)
5E+03	450 (65.3)	1E+10	94.4 (13.7)
1E+04	368 (53.4)	1E+11	93.7 (13.6)
2E+04	300 (43.5)		
5E+04	235 (34.1)		
1E+05	196 (28.4)		

The cumulative fatigue usage factor, U_{en}, considering the effects of water environments is then calculated as follows:

$$U_{en} = U_1 \cdot F_{en,1} + U_2 \cdot F_{en,2} + U_3 \cdot F_{en,3} + U_i \cdot F_{en,i} \ldots + U_n \cdot F_{en,n} \quad \text{(A.20)}$$

where $F_{en,i}$ is the F_{en} for the "i^{th}" stress cycle (Subarticle NB-3200) or load set pair (Subarticle NB-3600). Because environmental effects on fatigue lives occur primarily during the tensile-loading cycle (i.e., up ramp with increasing strain or stress), this calculation is performed only for the increasing strain or stress portion of the loading cycle constituting a load pair. In addition, the values for key parameters such as strain rate, material temperature, and DO in the

water and for carbon- and low-alloy-steel S content are needed to calculate F_{en} for each stress cycle or load set pair. As discussed in Section 4 of this report, the following guidance may be used to determine these parameters:

- An average strain rate for the transient typically yields a conservative estimate of F_{en}. For complex loading conditions, the strain rates used in the calculations should produce results that are consistent with the results that would be obtained using the modified rate approach described in Section 4.4 of this report. The lower bound or saturation strain rate of 0.0004%/s can be used to perform the most conservative evaluation. The Young's modulus, E, used to calculate the strain rate may be determined using a temperature that is consistent with the discussion in Section 4.4.

- For the case of a constant strain rate and a linear temperature response, an average temperature (i.e., average of the maximum temperature for the transient and the higher of the threshold temperature for the material under consideration and the minimum temperature for the transient) may be used to calculate F_{en}. Using the average temperature in fatigue evaluations should produce results that are consistent with the results that would be obtained using the modified rate approach described in Section 4.4 of this report. The maximum temperature can be used to perform the most conservative evaluation.

- The DO value is obtained from each transient constituting the stress cycle. For carbon and low-alloy steels, the DO content associated with a stress cycle is the highest oxygen level in the transient, and for austenitic SSs, it is the lowest DO level in the transient. A value of 0.5 ppm for carbon and low-alloy steels and 0.05 ppm for austenitic SSs and Ni-Cr-Fe alloys can be used for the DO content to perform a conservative evaluation.

- The S content in terms of weight percent might be obtained from the certified material test report or an equivalent source. If the S content is unknown, then its value shall be assumed as the maximum value specified in the procurement specification or the applicable construction ASME Code.

The detailed procedures for incorporating environmental effects into the ASME Code fatigue evaluations have been presented in several articles and reports. The following are just two examples of such documents that may be used for guidance:

(1) Mehta, H.S., "An Update on the Consideration of Reactor Water Effects in Code Fatigue Initiation Evaluations for Pressure Vessels and Piping," in *Assessment Methodologies for Preventing Failure: Service Experience and Environmental Considerations*, PVP Volume 410-2, R. Mohan (ed.), American Society of Mechanical Engineers, New York, pp. 45–51, 2000.

(2) Nakamura, T., M. Higuchi, T. Kusunoki, and Y. Sugie, "JSME Codes on Environmental Fatigue Evaluation," in *Proceedings of the 2006 ASME Pressure Vessels and Piping Conference*, July 23–27, 2006, Vancouver, BC, Canada, Paper No. PVP2006-ICPVT11-93305.

In addition, Appendix C to this report presents a sample application of F_{en} using the methodology in Subarticle NB-3200 of ASME Code Section III.

APPENDIX B
MATERIAL INFORMATION

The various grades, heat treatment, chemical composition, and mechanical properties of the carbon and low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloy steels used in this report are provided in this appendix.

B.1 Carbon and Low-Alloy Steels Included in the Fatigue Database

The various grades, heat treatment, chemical composition, and mechanical properties of the carbon and low-alloy steels used in this report are listed in the following table.

Table B-1 Carbon and Low Alloy Steels in Fatigue Database.

Mat. ID	Heat Designation	Heat Treatment	Chemical Composition (wt.%)								YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Refer-ence
			C	Si	Mn	P	S	Ni	Cr	Mo					
Carbon Steels															
1	A106-Gr.B-A	-	0.29	0.25	0.88	0.013	0.015	0.09	0.19	0.05	301	572	23.5	44.0	10
2	A106-Gr.B-H	-	0.24	0.29	0.91	0.01	0.007	-	-	-	333	559	34.0	-	136
3	A106-Gr.B-T	-	0.26	0.28	0.92	0.008	0.020	0.002	0.015	0.003	300	523	36.3	66.3	45
4	A106-Gr.C-1	-	0.24	0.27	1.27	0.022	0.006	-	-	-	340	520	37.0	-	136
5	A106-Gr.C-2	-	0.21	0.24	1.25	0.003	0.020	-	-	-	390	533	34.0	72.0	136
6	A106-Gr.C-3	-	0.27	0.29	0.87	0.012	0.007	-	-	-	323	519	35.0	-	136
7	A226-Cl.4	650°C×1.5hr	0.19	0.23	1.24	0.005	0.004	-	-	-	347	501	36.0	77.0	136
8	A333-Gr.6-1	900°C×10hxA	0.16	0.14	1.2	0.026	0.015	-	-	-	353	539	36.0	-	136
9	A333-Gr.6-2	900°C×0.5hxAC	0.20	0.31	0.93	0.020	0.015	-	-	-	302	490	41.0	80.0	136
10	A333-Gr.6-3	900°C ×2hxA	0.16	0.29	1.26	0.02	0.014	-	-	-	297	426	36.4	77.0	136
11	A333-Gr.6-4	-	0.15	0.2	1.25	0.019	0.006				314	490	41.0	-	136
12	A333-Gr.6-5	-	0.21	0.31	1.14	0.016	0.012				383	549	35.0	-	136
13	A333-Gr.6-GE	-	0.12	0.23	1.05	0.010	0.030	-	-	-	309	427	-	-	17
14	A333-Gr.6-7	As received	0.21	0.27	1.29	0.01	0.008	-	-	-	310	531	34.0	74.0	136
15	A333-Gr.6-8	900°C×0.5hxAC	0.20	0.26	1.14	0.01	0.016	-	-	-	348	509	36.0	76.0	136
16	A333-Gr.6-9	650℃×1.5hr	0.21	0.27	1.29	0.011	0.026	-	-	-	278	524	36.0	73.0	136

Mat. ID	Heat Designation	Heat Treatment	Chemical Composition (wt.%)								YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Refer-ence
			C	Si	Mn	P	S	Ni	Cr	Mo					
17	A508-Gr.1-1	870℃×6.0h×W, 620℃×1.0h×AC, 635℃×46.0h×FC	0.20	0.26	1.31	0.008	0.008	0.35	0.06	0.02	335	503	38.5	72.1	136
18	A508-Gr.1-2	-	0.19	0.23	1.24	0.005	0.004	0.32	0.21	0.02	347	501	36.0	77.0	136
19	A508-Gr.1-3	-	0.21	0.30	1.25	0.011	0.008	-	-	-	350	540	34.8	72.1	136
20	A216-Gr.WCC	-	0.22	0.40	0.90	0.013	0.015	0.14	0.20	0.17	316	500	31.6	58.0	136
21	A516-KC70-	-	0.26	0.28	0.95	0.017	0.033	-	-	-	331	514	31.0	-	14
22	A516-G70	As received	0.23	0.24	1.11	0.012	0.002	-	0.05	-	330	526	30.0	-	136
23	CS Tube	-	-	-	-	-	-	-	-	-	-	-	-	-	
24	CS	-	-	-	-	-	-	-	-	-	-	-	-	-	
Low-alloy Steels															
1	A302-Gr.B	899-927°Cx4hxWQ to 538°CxA:649-tempered @ 677°C:621-649°Cx6hxA	0.21	0.22	1.34	0.021	0.027	0.23	0.14	0.51	389	552	-	-	10
2	A508-Gr.2	880℃X4.5hXWC+665℃X4.3hXAC+620℃X46.2hXFC	0.21	0.25	0.88	0.007	0.003	0.86	0.42	0.66	521	673	22.9	72.5	136
3	A508-Gr.2	-	0.21	0.25	0.68	0.01	0.011	0.84	0.36	0.65	469	629	28	-	136
4	A508-Gr.2	880℃X6hXWC+660℃X10hXAC+620℃X45hXFC	0.18	0.31	0.77	0.008	0.008	0.74	0.36	0.6	510	637	27	74	136
5	A508-Gr.2	880℃XWC+660℃XAC+620℃XFC	0.20	0.26	0.94	0.006	0.008	0.78	0.36	0.6	583	655	24	76	136
6	A508-Gr.3	880℃X7hXWC+654℃X8hXWC	0.17	0.28	1.38	0.003	0.003	0.74	0.15	0.48	447	598	29.1	73	136
7	A508-Gr.3	900℃×16.7hxA:650℃×16.5hxF:890℃×9.1hxW:660℃×9.0hxA	0.20	0.26	1.42	0.004	0.002	0.74	0.11	0.5	453	605	30	69	136
8	A508-Gr.3	900℃×8.3hxA:650℃×8.0hx:880℃×4.8hxW:660℃×4.1hxA	0.23	0.27	1.5	0.004	0.003	0.77	0.13	0.52	503	637	26	69	141

Mat. ID	Heat Designation	Heat Treatment	Chemical Composition (wt.%)								YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Refer-ence
			C	Si	Mn	P	S	Ni	Cr	Mo					
9	A508-Gr.3	910℃×8hxA:660℃×7.0 hxA:890℃×8.0hxW:650 ℃×8.0hxA	0.18	0.22	1.46	0.003	0.005	0.69	0.15	0.57	476	602	30.9	74.7	55,56
10	A508-Gr.3	910℃X8.0hXAC+660℃ X7.0hXAC+890℃X8.0h XWC+650℃X8.0hXAC	0.20	0.29	1.45	0.003	0.003	0.68	0.12	0.55	476	611	29.9	74.4	10
11	A508-Gr.3	930℃×8hxA:660℃×5.0 hxA:890℃×6.0hxW:660 ℃×8.0hxA	0.19	0.2	1.46	0.003	0.003	0.76	0.15	0.48	456	596	24.5	75.5	136,141
12	A508-Gr.3	910℃×8hxA:660℃×7.0 hxA:890℃×8.0hxW:650 ℃×8.0hxA	0.20	0.29	1.45	0.003	0.003	0.68	0.12	0.55	476	611	29.9	74.4	136
13	A508-Gr.3	-	0.20	0.26	0.94	0.006	0.008	0.78	0.36	0.6	533	655	24	76	136
14	A508-Gr.3	880°C x 7h water quenching, 655°C x 9h air cooling	0.21	0.25	1.24	0.007	0.002	0.88	0.21	0.47	461	593	29	74	136
15	A508-Gr.3	-	-	-	-	-	0.018	-	-	-	-	-	-	-	136
16	A533-Gr.B	871-899°Cx5.5hxBQ:649-663°Cx5.5hxBQ:607°Cx 23.8hxA	0.22	0.19	1.3	0.01	0.012	0.51	0.18	0.48	431	602	27.8	66.6	136
17	A533-Gr.B	880℃X0.0hXWC+660℃ X5.0hXFC	0.19	0.24	1.28	0.008	0.007	0.64	0.19	0.45	454	601	29	68	136
18		900℃×5.0hxA:640℃×5.0hxA:880℃×4.0hxW:660℃×4.0hxA	0.17	0.27	1.32	0.004	0.001	0.65	0.13	0.55	518	647	26.8	72.8	136
19	A533-Gr.B	900℃×8.0hxA:635℃×12.3hxA:880℃×8.0hxW:655℃×6.2hxA	0.18	0.27	1.39	0.008	0.003	0.61	0.15	0.54	580	647	27	73	55,56
20	A533-Gr.B	900℃×3.3hxA:880℃×3.3hxW::655℃×3.3hxA	0.18	0.22	1.42	0.004	0.002	0.69	0.09	0.49	443	597	31	74	55,56
21	A533-Gr.B	880℃X5.6hXWC+660℃ X4.9hXAC+615℃X45.9 hXFC	0.19	0.27	1.45	0.02	0.010	0.60	0.13	0.52	488	630	27.7	65.2	55,56

Mat. ID	Heat Designation	Heat Treatment	Chemical Composition (wt.%)								YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Refer-ence
			C	Si	Mn	P	S	Ni	Cr	Mo					
22	A533-Gr.B	880℃×5.6hxW:660℃×4.9hxA:615℃×45.9hxF:375℃×480.0hxF	0.18	0.31	0.77	0.008	0.008	0.74	0.36	0.6	510	637	27	74.0	136
23	A533-Gr.B	900°C x 3h water quenching, 660°C x 3h air cooling, then 600°C x 25h to relieve stress	0.17	0.25	1.39	0.003	0.013	0.59	0.004	0.46	483	584	23.5	58	136
24	A533-Gr.B	900°C x 3h water quenching, 660°C x 3h air cooling, then 600°C x 25h to relieve stress	0.17	0.24	1.38	0.003	0.025	0.60	0.004	0.47	488	582	21.5	52	55,56
25	A533-Gr.B	-	0.17	0.24	0.36	0.003	0.038	0.59	0.009	0.47	-	-	-	-	55,56
26	A533- Gr. B (SQV2A)	-	0.22	0.28	1.43	0.021	0.021	0.51	0.1	0.49	481	617	-	-	55,56
27	A533-Gr.B Cl.2	-	0.18	0.24	1.43	0.003	<0.001	0.66	-	0.57	548	679	26	75	136
28	A533-Gr.B	-	-	-	-	-	0.014	-	-	-	-	-	-	-	136
29	LAS	-	-	-	-	-	-	-	-	-	-	-	-	-	136
30	15MnNi63	-	-	-	-	-	-	-	-	-	-	-	-	-	136
31	17MNMoV64	-	-	-	-	-	-	-	-	-	-	-	-	-	136

B.2 Wrought and Cast Austenitic Stainless Steels and Welds

The various grades, heat treatment, chemical composition, and mechanical properties of the wrought and cast austenitic stainless steels and associated weld metals used in this report are listed in the following table.

Table B-2 Wrought and Cast Austenitic Stainless Steels and Welds in Fatigue Database.

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Mo	N					
Type 304 Stainless Steel															
1	304-1	0.050	0.50	1.52	0.028	0.001	9.45	18.35	-	-	253	570	66.3	78.6	136
2	304-2H	0.050	0.26	0.74	0.032	0.022	8.21	18.14	0.15	-	252	605	78.8	80.7	
3	304-3, 3H	0.060	0.50	1.55	0.023	0.001	9.35	18.35	-	-	260	573	59.7	81.7	136
4	304-4B	0.050	0.51	0.15	0.035	0.004	9.04	18.52	-	-	-	-	-	-	136
5	304-5B	0.060	0.54	0.11	0.027	0.008	8.87	18.51	-	-	-	-	-	-	136
6	304-6B	0.060	0.56	0.16	0.040	0.005	9.20	18.35	-	-	-	-	-	-	136
7	304-7B	0.059	0.69	0.08	0.025	0.005	8.89	18.28	-	-	-	-	-	-	136
8	304-8B	0.060	0.54	0.09	0.025	0.007	8.69	18.15	-	-	-	-	-	-	136
9	304-9T	0.070	0.27	1.69	0.033	0.009	8.15	18.16			223	602	63.0	79.8	136
10	304-10	0.060	0.50	0.80	0.032	0.010	8.82	18.35	0.19	0.019	222	667	72.9	77.6	136
11	304-11H	0.070	0.56	1.60	0.023	0.007	9.40	18.30	-	-	237	628	53.0	80.0	136
12	304-12	-	-	-	-	-	-	-	-	-	-	600	-	-	136
13	304-13	0.026	0.40	0.45	0.030	0.014	8.50	18.67	0.02	-	255	745	-	74.3	64
14	304-14	0.026	0.40	0.45	0.030	0.014	8.50	18.67	0.02	-	745	951	-	68.8	64
15	304-15	-	-	-	-	-	-	-	-	-	-	-	-	-	63
16	304-16	0.060	0.31	1.89	0.026	0.025	9.96	19.92	0.15	-	305	632	60.9	69.1	68
17	304-17	-	-	-	-	-	-	-	-	-	-	-	-	-	65
18	304-18	0.020	0.49	1.78	0.014	0.011	9.78	18.50	-	-	276.5	572.2	-	-	71
19	304-19	-	-	-	-	-	-	-	-	-	-	-	-	-	61

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Mo	N					
20	304-G	0.070	0.54	1.63	0.016	0.013	9.50	18.57	-	-	251	561	64.0	-	14,15
21	304-A2	0.060	0.48	1.54	0.019	0.007	8.00	18.99	0.44	-	-	-	-	-	45
22	304-21T	0.060	0.59	0.83	0.023	0.002	9.17	18.89	-	0.040	246	604	57.4	70.4	136
23	304-32	0.070	0.27	1.69	0.033	0.009	8.15	18.16	-	-	221	616	62.0	77.4	136
24	304-35	0.070	0.65	0.91	0.022	0.002	8.09	18.48	-	-	245	682	59.0	73.0	136
25	304-xxT	0.050	0.48	1.72	0.027	0.003	9.23	18.12	-	-	274	580	60.0	78.0	136,10
26	304HP-1	0.050	0.54	0.88	0.029	0.010	9.10	18.53	0.12	-	242	666	68.0	82.0	136
27	304HP-2	0.060	0.45	0.82	0.029	0.006	8.61	18.38	-	0.052	275	618	68.0	82.0	136
28	304L-E	0.039	0.36	1.82	0.030	0.006	10.38	18.50	0.06	0.055	-	-	-	-	58-60
29	304L-1	0.017	0.29	1.19	0.024	0.002	9.15	18.05	-	-	245	574	61.0	84.0	136
30	304L-G	0.017	0.51	1.72	0.018	0.013	10.16	19.09	-	-	259	339	63.3	65.2	14,15
31	304L	0.013	0.61	0.90	0.020	0.080	9.30	18.50	-	0.090	235	588	65.0	75.0	136
Type 316 Stainless Steel															
32	316-1H	0.055	0.52	1.51	0.027	0.005	13.20	16.25	2.12	-	177	465	43.5	75.5	210
33	316-2	0.050	0.70	1.10	0.034	0.003	12.60	17.05	2.24	0.017	257	606	67	79	136
34	316-3H	0.040	0.76	1.63	0.030	0.007	11.57	17.44	2.47	-	-	-	58	63.6	136
35	316-4	0.060	0.40	1.72	0.012	0.007	13.30	17.30	2.33	-	-	-	-	-	63
36	316-5	-	-	-	-	-	-	-	-	-	-	-	-	-	61
37	316-6	-	-	-	-	-	-	-	-	-	-	-	-	-	61
38	316-7	-	-	-	-	-	-	-	-	-	-	-	-	-	61
39	316-8	-	-	-	-	-	-	-	-	-	-	-	-	-	61
40	316-9	-	-	-	-	-	-	-	-	-	-	-	-	-	61
41	316-10	-	-	-	-	-	-	-	-	-	-	-	-	-	61
42	316-12T	0.060	0.61	1.69	0.025	0.010	13.06	16.55	2.08		234	550	63	81.1	136
43	316-13T	0.070	0.50	1.50	0.031	0.010	11.10	17.60	2.30	-	264	569	58.5	81.5	136
44	316-14T	0.060	0.60	1.60	0.026	0.010	13.00	16.50	2.07	-	250	555	50.5	67.6	136

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Mo	N					
45	316-15T, 27T	0.040	0.37	1.55	0.025	0.001	12.55	16.50	2.10	-	247	531	54	-	136
46	316-26T	0.057	0.64	1.64	0.026	0.005	13.02	16.48	2.07	-	250	555	50	68	136
47	316L-1H	0.040	0.37	1.55	0.025	0.001	12.55	16.50	2.10	-	154	406	43	80	136
48	316N-1	0.015	0.39	1.66	0.025	0.003	14.90	17.25	2.32	-	259	555	60.7	81.2	136
49	316N-2	0.010	0.51	1.67	0.027	0.001	13.25	17.50	2.50	0.106	264	574	63.9	82.9	136
50	316N-3H	0.009	0.65	1.55	0.023	0.002	12.70	17.60	2.74	-	168	454	43.7	77	136
51	316N-6	0.012	0.45	1.58	0.024	0.004	12.60	17.15	2.46	0.102	310	710	44.2	-	136
52	316N-7	0.007	0.36	0.51	0.002	0.001	74.95	16.01		-	300	588	55	-	136
53	316N-8	0.008	0.56	1.46	0.028	0.001	12.11	17.73	2.60	0.090	252	558	62	85	136
54	316N-A	0.011	0.61	0.91	0.017	0.004	11.18	16.26	2.17	-	-	-	-	-	45
Stainless Steel Welds															
55	304HP-WM-1	0.058	0.68	1.78	0.026	0.005	9.62	19.98	0.06	0.039	-	-	-	-	136
56a	308-WM-1	0.050	0.56	1.39	0.022	0.004	10.30	19.90	-	-	-	-	-	-	136
56b	308-WM-2	0.034	0.71	1.93	0.022	0.007	9.78	19.60	0.08	-	414	578	38.0	52.0	136
57a	316 WM	0.039	0.39	1.31	0.011	0.005	11.60	19.60	2.20	-	-	-	-	-	136
57b	316TP WM-1	0.020	0.41	1.90	0.013	0.006	12.20	18.80	2.20	-	-	-	-	-	136
57c	316TP WM-2	0.070	0.40	1.82	0.011	0.006	12.50	18.50	2.19	-	-	-	-	-	136
57	316N-WM-1	0.018	0.39	1.70	0.010	0.007	11.47	19.75	2.27	0.075	-	-	-	-	136
59	316N-WM-2	0.017	0.43	1.86	0.011	0.006	12.01	19.49	2.39	-	489	615	30.0	67.0	136
60	316N-WM-3	0.002	0.44	1.46	0.026	0.001	13.14	17.21	2.43	0.078	254	548	57.0	-	136
Cast Austenitic Stainless Steel															
61	CF–8M-1	0.053	0.95	0.80	0.030	0.005	9.52	20.52	2.20	0.045	300	611	45.3	74.6	136
62	CF–8M-2	0.050	1.17	0.86	0.021	0.006	10.03	20.59	2.28	-	308	619	51.0	76.0	136
63	CF–8M-3	0.050	0.79	0.74	0.026	0.009	9.66	18.86	2.23	-	232	561	49.0	62.0	136
64	CF–8M-4	0.050	1.00	0.80	0.030	0.010	9.52	20.50	2.20	-	300	611	45.3	74.6	136
65	CF–8M-5	0.050	1.30	0.80	0.280	0.020	9.32	20.80	2.30	-	352	644	43.3	69.0	136

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Mo	N					
66	CF–8M-6	0.050	0.60	0.80	0.280	0.010	10.50	20.20	2.16	-	259	521	48.6	77.6	136
67	CF–8M-7	0.050	0.79	0.74	0.026	0.009	9.66	18.86	2.23	-	252	498	50.0	72.0	136
68	CF–8M-8	0.064	0.73	0.54	0.022	0.016	9.03	19.11	2.51	0.048	273	537	63.0	66.8	45
69	CF–8M-9	0.065	0.67	0.53	0.022	0.012	9.12	20.86	2.58	0.0523	322	601	43.6	71.4	45

B.3 Ni-Cr-Fe Alloys and Welds

The various grades, heat treatment, chemical composition, and mechanical properties of the Ni-Cr-Fe Alloys and associated weld metals used in this report are listed in the following table.

Table B-3 Ni Cr Fe Alloys and Welds in Fatigue Database.

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Fe	Other					
1	Alloy 600-1	0.070	0.32	0.51	0.002	0.001	74.86	15.95	8.13	-	310	710	44.2	-	136
2	Alloy 600-2	0.070	0.29	0.37	0.006	0.001	76.07	15.46	7.12	0.01 Cu	294	686	42.0	-	136
3	Alloy 600-3	0.010	0.17	0.21	0.007	0	73.33	16.60	6.95	2.56 Nb+Ta	279	677	54.0	63.0	136
4	Alloy 600-4	0.010	0.17	0.21	0.007	0	73.33	16.60	6.95	2.56 Nb+Ta	289	693	63.0	57.0	136
5	Alloy 600-5	0.070	0.34	0.37	0.007	0.001	73.56	15.64	9.46	0.16 Nb, 0.01 Ta, 0.27 Ti	303	696	39.0	62.0	136
6	Alloy 600-6	0.030	0.05	0.49	0.004	0.001	74.50	16.00	8.37	-	264	635	55.0	74.0	136
7	Alloy 600-7	0.020	0.17	0.13	0.017	0.010	75.85	15.54	6.81	0.06 Cu, 0.01 Co, 0.18 Al, 0.11 Ti, 0.096 Cb	253	612	50.0	70.0	67
8	Alloy 600-8	0.080	0.19	0.13	-	0.007	77.31	15.70	6.52	0.04 Cu, 0.23 Ti, 0.05 Co, 0.14 Al	567	745	-	51.4	68

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Fe	Other					
9	Alloy 600-9	0.060	0.25	0.20	-	0.007	76.67	15.45	7.24	0.06 Cu, 0.21 Ti, 0.09 Co, 0.13 Al	256	651	-	57.9	68
10	Alloy 600-10	0.080	0.48	0.46	0.010	0.008	73.63	15.72	9.40	0.08 Cu, 0.12 Ti, 0.05 Co, 0.02 Al	267	656	-	49.9	68
11	Alloy 600-11	0.030	1.20	0.99	-	0.012	73.76	15.52	7.58	0.12 Cu, 0.05 Ti, 0.08 Co, 0.009 Al, 0.65 Cb+Ta	253	538	-	55.0	68
12	Alloy 600-12	0.070	0.73	0.78	-	0.005	74.40	16.00	7.70	0.01 Cu, 0.01 Ti, 0.11 Co, 0.01 Al	170	374	-	45.1	68
13	Alloy 600-13	0.051	0.31	0.25	0.010	0.0012	73.72	15.80	8.86	0.021 Cu, 0.24 Ti, 0.05 Co, 0.21 Al, 0.0010 B	237	654	45.5	65.8	66
14	Alloy 600-14	0.050	0.20	0.20	-	0.007	78.04	15.37	6.03	0.08 Cu	312	685	45.5	58.7	70
15	Alloy 600-15	-	-	0.24	-	0.008	74.21	-	-	0.13 Cu	403	721	43.0	53.0	14
16	Alloy 600-16	0.050	0.20	0.20	-	0.007	78.04	15.37	6.03	0.08 Cu	312	685	45.5	58.7	61
16	Alloy 600-16	0.060	0.25	0.20	-	0.007	76.67	15.45	7.24	0.06 Cu, 0.21 Ti, 0.09 Co, 0.13 Al	256	651	-	57.9	61
17	Alloy 600-17	0.020	0.17	0.13	0.017	0.010	75.85	15.54	6.81	0.06 Cu, 0.11 Ti, 0.01 Co,	245	595	48.4	67.8	61

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Fe	Other					
										0.18 Al, 0.096 Cb					
20	Alloy 690-1	0.030	0.11	0.27	0.007	0.001	60.1	29.50	9.44	-	280	691	46.0	60.0	136
21	Alloy 690-2	-	-	-	-	-	-	-	-	-	-	-	-	-	39
22	Alloy 690-3	0.020	0.09	0.15	-	<0.001	61.58	29.15	9.00	<0.01 Cu, 0.007 Co	247	643	52.0	64.0	75
25	Alloy 800-1	0.060	0.38	0.90	-	0.007	32.11	20.35	45.17	0.25 Cu, 0.39 Ti, 0.36 Al	190	546	-	75.0	69
26	Alloy 800-2	0.060	0.38	0.90	-	0.007	32.11	20.35	45.17	0.25 Cu, 0.39 Ti, 0.36 Al	158	499	-	51.0	69
26	Alloy 800-2	-	-	-	-	-	-	-	-	-	212	515	-	57.5	71
30	Inconel 718-1	-	-	-	-	-	-	-	-	-	-	-	-	-	210
31	Inconel 718-2	-	-	-	-	-	-	-	-	-	1200	1515	-	30.5	72
32	Inconel 718-3	-	-	-	-	-	-	-	-	-	-	-	-	-	61
33	Inconel 718-4	-	-	-	-	-	-	-	-	-	-	-	-	-	61
34	Inconel 718-5	-	-	-	-	-	-	-	-	-	-	-	-	-	61
35	Inconel 718-6	0.030	0.35	0.18	-	0.007	52.64	18.59	18.94	0.36 Al, 0.03 Cu, 2.96 Mo, 0.91 Ti 4.98 Cb+Ta	1110	1304	-	-	61, 73
36	Inconel 718-7	-	-	-	-	-	-	-	-	-	-	-	-	-	61
38	Alloy 690 WM	0.037	0.32	4.47	<0.005	0.001	55.60	29.20	8.71	-	431	656	39.0	49.0	136
39	Alloy 62 *	0.070	0.175	0.325	-	0.006	73.50	17.75	6.90	1.0 Cb, 0.01 Cu, 0.05 Co	-	-	-	-	68
40	Alloy 82-1	0.040	0.10	2.80	-	0.017	63.50	17.28	13.56	0.02 Co, 0.004 Al,	353	606	-	55.3	68

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Fe	Other					
										0.01 Cu, 0.044 Mo, 0.08 Ti 1.92 Cb+Ta					
41	Alloy 82-2	0.040	0.86	2.54	-	0.014	65.05	20.00	8.60	0.10 Co, 1.75 Mo, 0.03 Ti 1.46 Cb+Ta	322	633	-	53.7	68
42	Alloy 82-3	0.070	0.30	2.48	0.005	0.015	54.70	13.95	25.70	0.02 Co, 0.05 Al, 0.02 Cu, 0.01 Mo, 0.25 Ti 1.77 Cb+Ta 0.01 V, 0.01 W, 0.002 Mg	355	573	-	47.5	68
43	NiCrFe WM-1	-	-	-	-	-	-	-	-	-	-	-	-	-	SGFS 1988
44	Arcaloy 8N12	-	-	-	-	-	-	-	-	-	-	-	-	-	68
45	NiCrFe WM-2	-	-	-	-	-	-	-	-	-	-	-	-	-	210
46	Alloy 82-4	0.040	0.10	2.80	-	0.017	63.50	17.28	13.56	0.02 Co, 0.004 Al, 0.01 Cu, 0.044 Mo, 0.08 Ti 1.92 Cb+Ta	353	606	-	55.3	68
47	Alloy 182-1	0.060	0.61	5.56	0.004	0.006	68.20	15.50	7.25	0.14 Cu, 0.52 Ti	456	698	35.3	43.5	136
48	Alloy 182-2	0.060	0.61	5.56	0.004	0.006	68.20	15.50	7.25	0.14 Cu, 0.52 Ti	456	698	35.3	43.5	136
49	Alloy 182-3	0.038	0.25	2.50	0.004	0.005	73.00	15.10	7.20	-	405	667	38.1	50.2	136

Mat. ID	Heat Designation	Chemical Composition (wt.%)									YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)	Reference
		C	Si	Mn	P	S	Ni	Cr	Fe	Other					
50	Alloy 182-4	0.040	0.21	2.76	<0.005	0.004	72.50	15.00	7.99	-	409	623	34.0	44.0	136
51	Alloy 82-5	0.040	0.12	2.92	0.003	0.001	72.85	20.64	0.65	0.03 Cu, 0.04 Co, 0.27 Ti	339	565	56.0	72.0	75
52	Alloy 152	-	-	-	-	-	-	-	-	-	-	-	-	-	39
53	Alloy 132	0.040	0.21	2.76	<0.005	0.004	72.50	15.0	7.99	<0.01 Cu	409	623	34.4	43.9	39,136

* Average composition of first and second layers.

APPENDIX C
SAMPLE PROBLEM

C.1 Background

Appendix C provides the cumulative usage factor (CUF), environmental fatigue correction factor (F_{en}), and environmentally assisted fatigue cumulative usage factor (CUF_{en}) solution for a sample problem. The sample problem was obtained from Appendix B to Reference C-1. The purpose of this sample problem solution is to demonstrate one example of the use of the methodology described in this report to calculate the F_{en} and CUF_{en} for a relatively simple problem. The sample problem is not intended to be an exhaustive treatment of more comprehensive component assessments that may be present in operating nuclear power plants.

The sample problem selected for solution in this appendix was the second example problem developed and solved by several industry participants. The purpose of the industry's sample problem efforts was to evaluate the effectiveness of some American Society of Mechanical Engineers Boiler and Pressure Vessel Code, (ASME Code) Code Cases in providing sufficient guidance for environmentally assisted fatigue (EAF) evaluations and to identify any related guidelines that may be useful for industry applications. The main intentions of the second sample problem were to ensure that transient pairs occurred between peaks and valleys from different transients, include a complex transient with multiple peaks and valleys, to incorporate a dynamic load event, and include dissolved oxygen (DO) variations between transients and during at least one transient.

During the industry's solution of its first sample problem (documented in Appendix A to Reference C-1), considerable time was spent standardizing input parameters and stresses for the fatigue evaluation that preceded the environmental calculations. Those iterations yielded insight into the impact of certain modeling and analysis choices and the resulting differences in the fatigue results, which could be further magnified in the environmental fatigue analysis. Based on that insight, and to minimize differences in the stress and fatigue portions of the analysis, a standard set of stress histories for all transients was provided for all participants to use in the second sample problem. Those stress histories were used as the starting point for the calculations in this appendix. As a result, this appendix includes only minimal portions of the content for the sample problem statement and finite element modeling details used to derive the stresses for the sample problem. The reader is referred to Appendix B to Reference C-1 for those details.

C.2 Problem Description

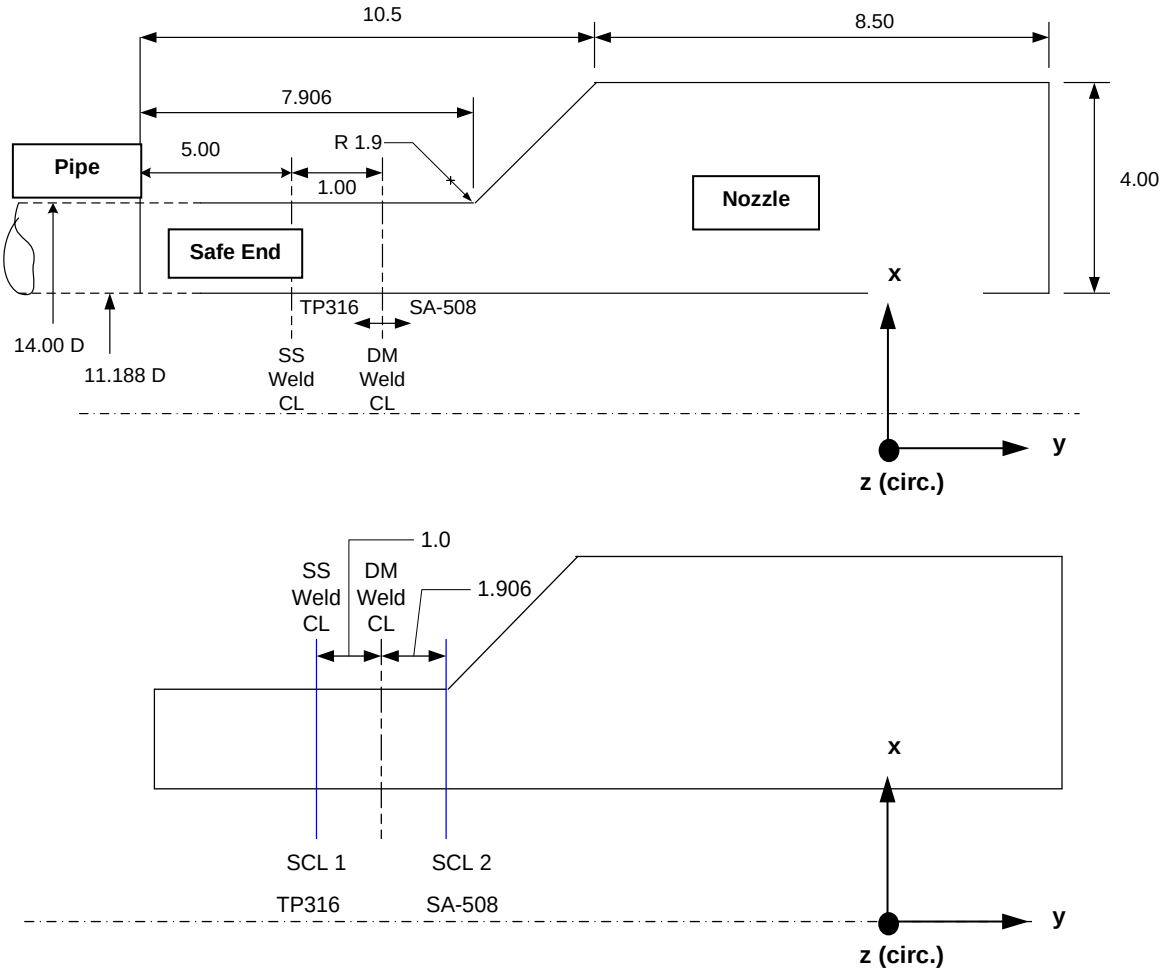
Appendix B to Reference C-1 provides the full problem statement and definitions for the sample problem.

Figure C-1 shows the geometry evaluated in the sample problem. The geometry represents a typical vessel nozzle with attached piping.

The temperature-dependent material properties assumed for Stress Cut Line (SCL) 2 are provided in Table C-1 and are the same as those provided in Appendix B to Reference C-1 for SA-508 Class 2 material.

Table C-2 lists the transients evaluated in the sample problem while Figure C-2 plots the transient temperature, pressure, and DO time histories.

The transient stress component histories and metal surface temperatures that were obtained from finite element analysis were provided for the sample problem for both SCLs shown in Figure C-1. Figure C-3 and Figure C-4 plot the SCL 2 stresses are plotted in. Only the stresses for SCL 2 were evaluated in this appendix; calculations for SCL 1 would be performed in a similar manner with consideration given to the different material and a stress concentration factor of 2 applied to the linearized stresses. For the purposes of this example, the transients were arbitrarily linked in sequential order to obtain the overall stress histories used in the F_{en} evaluation, as shown in Figure C-5. In the general case, the transient order would be defined by the stress history, as required by Subparagraph NB-3216.2, "Varying Principal Stress Direction," of Section III, "Rules for Construction of Nuclear Facility Components," of the ASME Code (see Section C.3(A) below). Peak cycle counting as specified in the ASME Code was used to calculate CUF in the analysis. The operating-basis earthquake (OBE) stresses were assumed to occur coincident with the peak stresses associated with Transient No. 2, which had the highest total stress intensity of any of the four thermal transients evaluated.



(Note: All dimensions are in inches. Sketches are not to scale.)

Figure C-1 Sample problem geometry.

Table C-1 Material Properties for SCL 2 (SA 508 Class 2.)

Temperature (°F)	S_m (psi)	E (psi)
70	30,000	27.8×10^6
100	30,000	27.6×10^6
200	30,000	27.1×10^6
300	30,000	26.7×10^6
400	30,000	26.2×10^6
500	30,000	25.7×10^6
600	30,000	25.1×10^6
700	30,000	24.9×10^6

Notes: 1. The sulfur content, S, for this material was assumed to be 0.025 weight percent for the purposes of the sample problem.

2. The low-alloy steel fatigue curve from Table A-1 in Appendix A was used to calculate CUF using a fatigue curve Young's modulus value of 30.0×10^6 psi.

Table C-2 Sample Problem Transient Definitions.

Transient No.	Time (sec)	Fluid Temperature (°F)	Heat Transfer Coefficient, h (BTU/s-in^2-°F)	Pressure (psi)	Resultant Moment (in-kips)	DO (ppm)
1 (20 cycles)	0	450	0.003	2,250	-3,000	0.150
	100	450	0.003	2,250	-3,000	0.150
	450	100	0.003	1,000	1,000	0.150
	1,510	100	0.003	1,000	1,000	0.150
	1,710	600	0.003	2,250	-3,000	0.150
	3,210	600	0.003	2,250	-3,000	0.150
2 (50 cycles)	0	500	0.003	1,500	-2,500	0.550
	100	500	0.003	1,500	-2,500	0.550
	260	100	0.003	2,250	1,000	0.550
	1,290	100	0.003	2,250	1,000	0.550
	1,540	350	0.003	2,000	-2,500	0.550
	3,240	350	0.003	2,000	-2,500	0.550
3 (20 cycles)	0	300	0.003	1,600	0	0.050
	50	650	0.003	1,600	0	0.050
	250	650	0.003	1,600	0	0.050
	275	400	0.003	1,600	0	0.050
	400	400	0.003	1,600	0	0.050
	600	550	0.003	1,600	0	0.050
	700	550	0.003	1,600	0	0.050
	900	350	0.003	1,600	0	0.050
	1,000	350	0.003	1,600	0	0.050
	1,200	400	0.003	1,600	0	0.050
	1,300	400	0.003	1,600	0	0.050
	1,500	70	0.003	1,600	0	0.050
	1,600	70	0.003	1,600	0	0.050
	2,000	300	0.003	1,600	0	0.050
	3,800	300	0.003	1,600	0	0.050
4 (100 cycles)	0	70	0.003	400	-3000	0.55
	100	70	0.003	400	-3000	0.55
	3,700	170	0.003	400	-2100	0.442
	7,300	270	0.003	400	-1200	0.334
	8,272	297	0.003	580.32	-957	0.30484
	10,072	347	0.003	914.26	-507	0.25084
	13,672	447	0.003	1582.13	393	0.14284
	17,272	547	0.003	2250	1293	0.3484
	18,100	547	0.003	2250	1500	0.01
	26,000	547	0.003	2250	1500	0.01
5 (5 cycles*)	Operating Basis Earthquake (OBE) Transient OBE loading was defined by resultant moment loads. The resultant moment load was specified as +/- 2,000 in-kips. Each OBE event was assumed to occur at any time during any of the transients. DO= 0.100 ppm. (* Note that the sample problem statement assumed five events with 10 cycles per event; for this analysis, 5 peak cycles during Transient No. 2 were evaluated and the remaining 45 cycles were assumed to self-pair and not contribute to CUF.)					

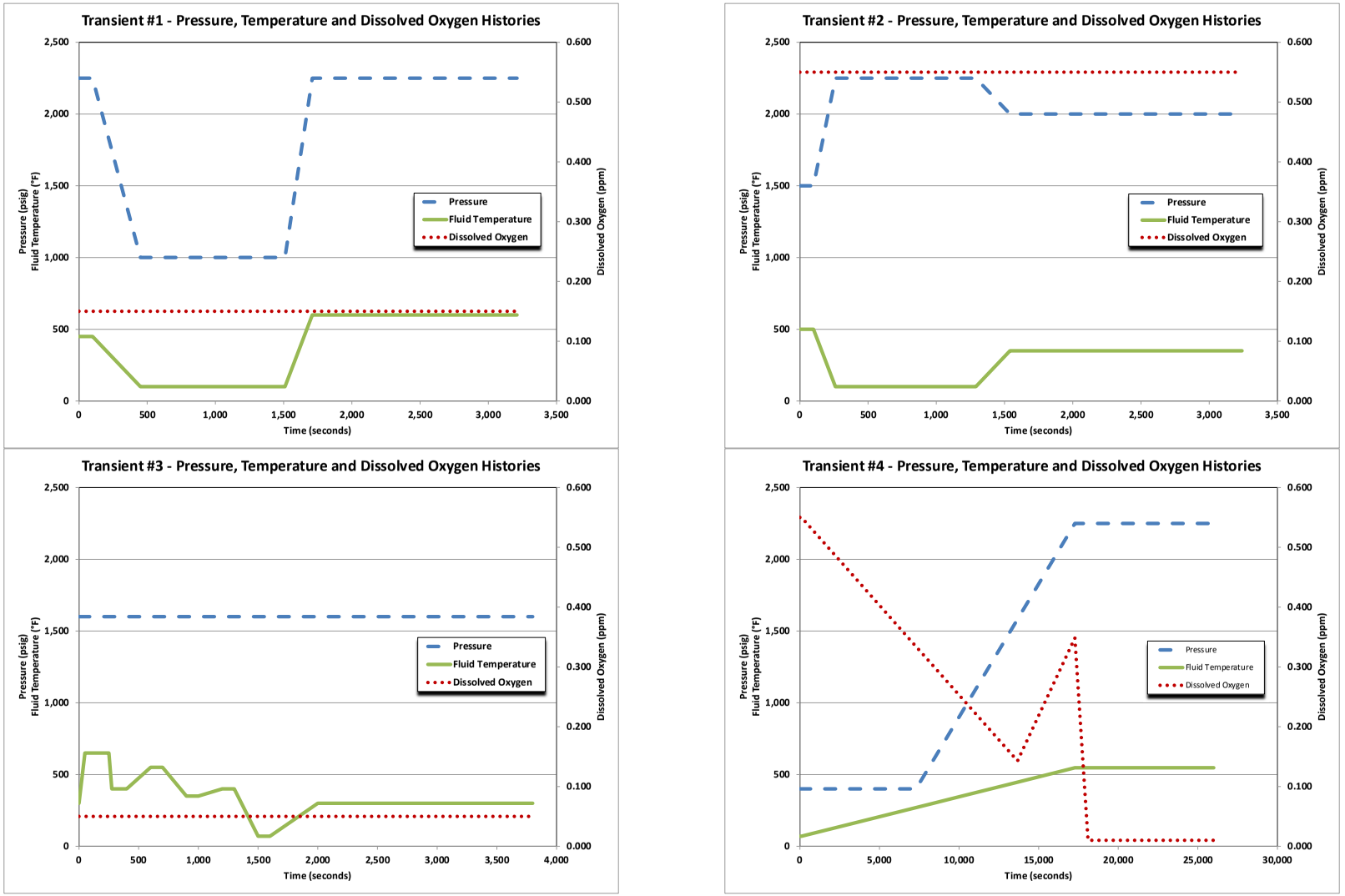
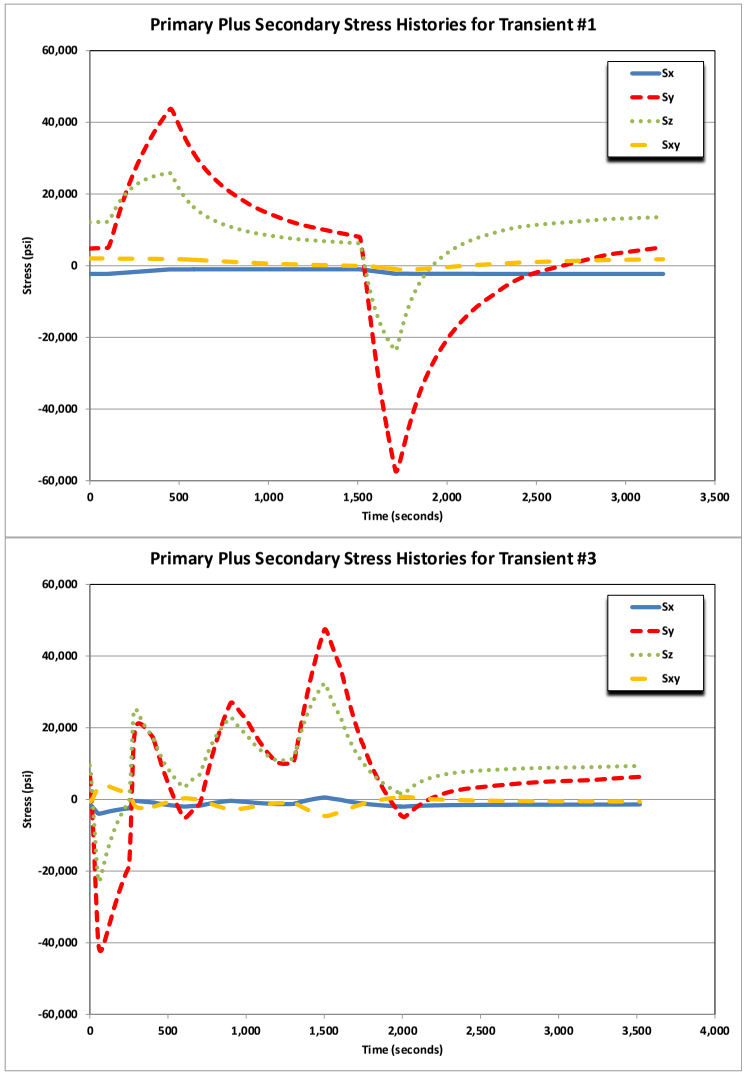


Figure C-2 Sample problem transient time histories.



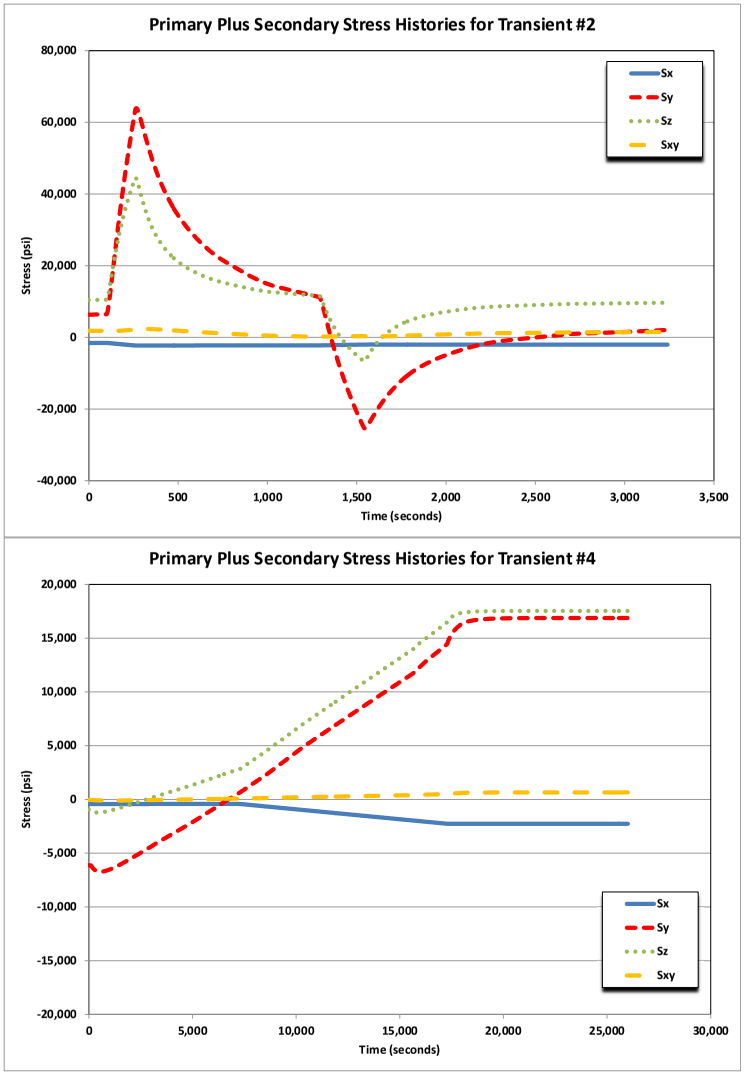


Figure C-3 Sample problem transient membrane plus bending stress histories for SCL 2.

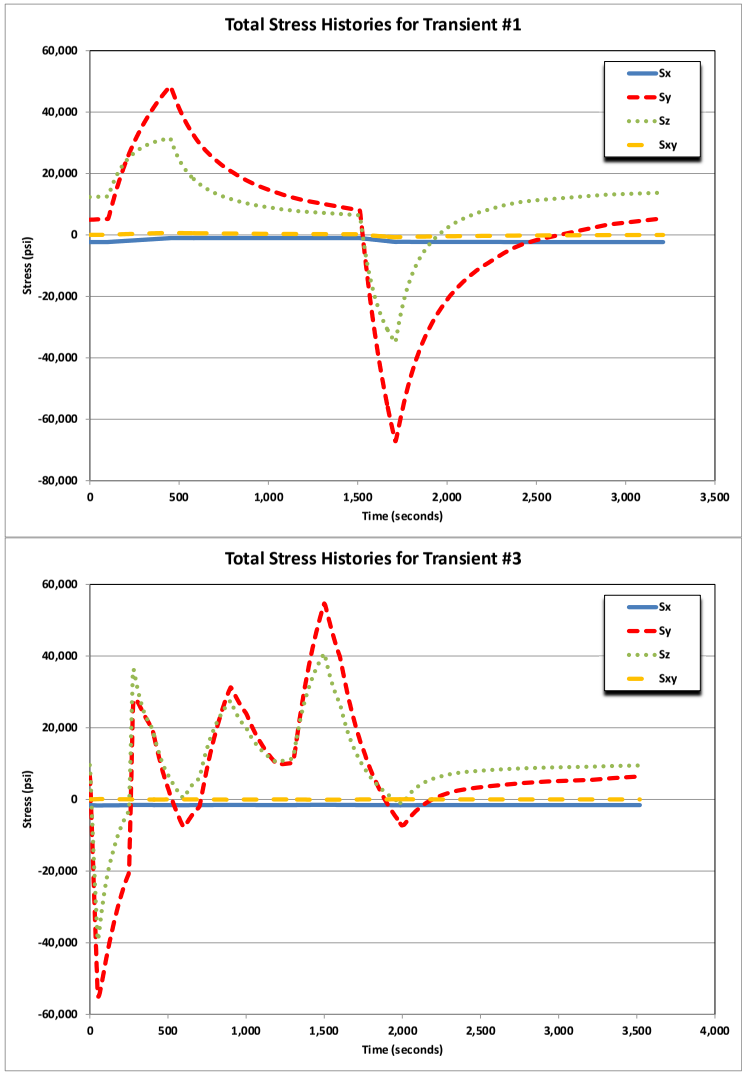


Figure C-4 Sample problem transient total stress histories for SCL 2.

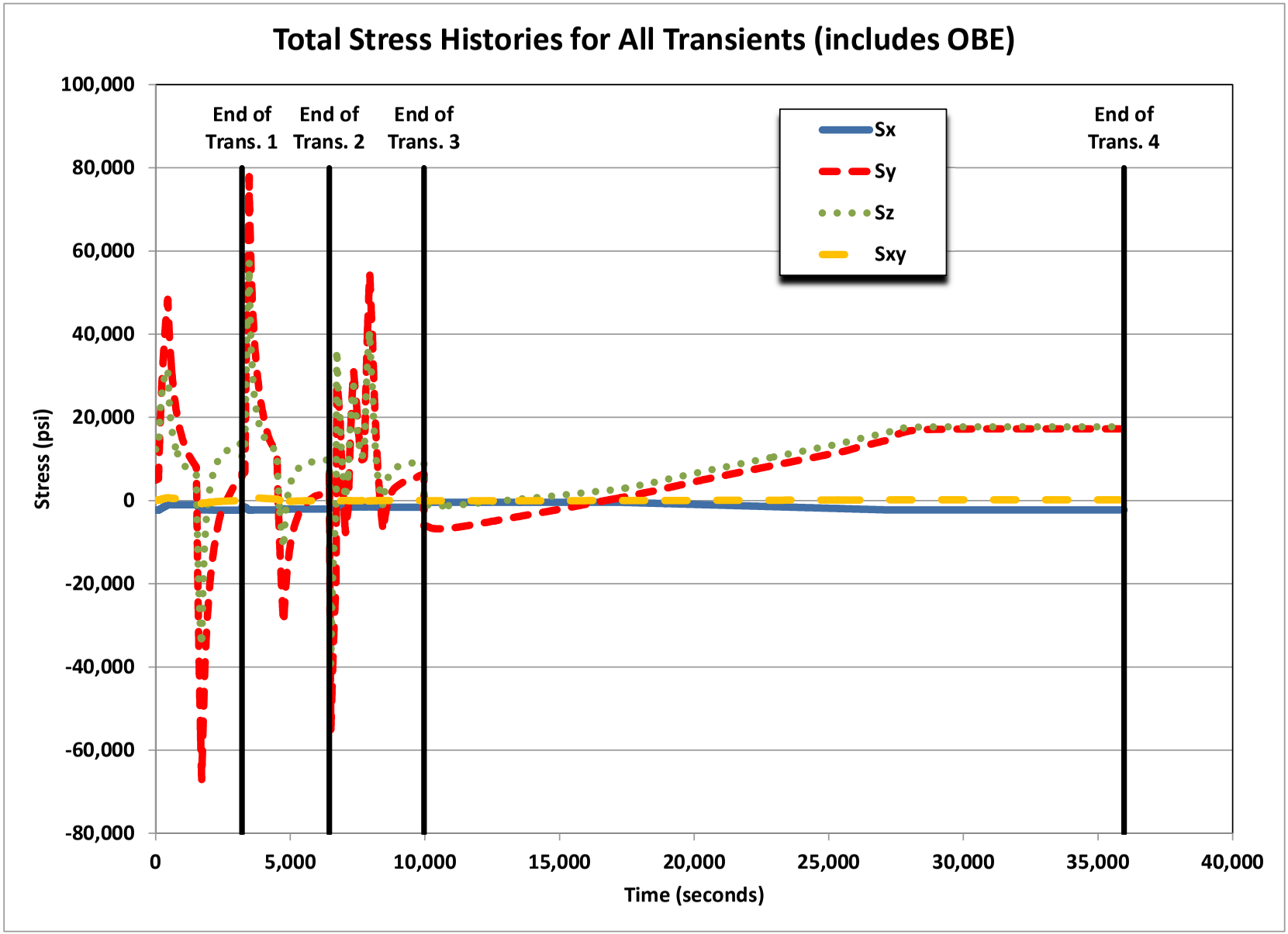


Figure C-5 Sample problem combined transient stress history for SCL 2.

C.3 Evaluation

The CUF for the sample problem was calculated in accordance with Subsection NB, "Class 1 Components," of ASME Code Section III (Ref. C-2) using the provisions of Subarticle NB-3200, "Design by Analysis." In the evaluation, the metal surface temperatures supplied in the finite element analysis results were used. The following information summarizes the steps used to calculate the CUF:

A. The alternating stress intensities, S_{alt}, were calculated for the input stress history (Figures. C-3 through C-5) using the following steps (i.e., these steps follow the methodology in Subparagraph NB-3216.2 of ASME Code Section III for varying principal stress direction[F]):

   a. Subparagraph NB-3216.2(a) requires that six components of stress be considered taking into account both gross and local structural discontinuities and the thermal effects that vary during the cycle. The membrane plus bending stresses shown in Figure C-3 and the total stresses shown in Figure C-4 satisfy this requirement and were used as input to the calculation.

   b. Subparagraph NB-3216.2(b) requires selection of a point in time when conditions are at an extreme (either maximum or minimum algebraically). As described in Step h, six cases were evaluated (each of three stresses for both membrane plus bending and total stress histories). The maximum stress values for each of the six stress components were found for each case and identified as SX_i, SY_i, SZ_i, and so on.

   c. Subparagraph NB-3216.2(c) requires calculation of the stress differences for the entire stress history for every point in time. These differences were computed as

      $$S'X = (SX - SX_i),\ S'Y = (SY - SY_i),\ S'Z = (SZ - SZ_i),\ \text{and so on.}$$

   d. Subparagraph NB-3216.2(d) requires calculation of the principal stresses for the entire stress history for every point in time from the stress differences calculated in Step c. These differences were computed as S'_1, S'_2, and S'_3 using the six stress differences (i.e., S′X, S′Y, S′Z, and so on.) and were ordered as $S'_1 > S'_2 > S'_3$.

   e. Principal stresses were calculated for the entire stress history by solving a cubic equation for the six component stress differences from Step d.

   f. Subparagraph NB-3216.2(e) requires calculating the principal stress differences for the entire stress history for every point in time as $S'_{12} = (S'_1 - S'_2)$, $S'_{23} = (S'_2 - S'_3)$, and $S'_{31} = (S'_3 - S'_1)$ and finding the largest absolute magnitudes of these three differences based on their variations throughout the stress history. S_{alt} values were calculated as one-half of all of these largest stress amplitudes based on range-pair cycle counting for the entire stress intensity history to

[F] Note that stress differences other than those described and shown in this appendix were used by some problem solvers based on their unique interpretations of Subparagraph NB-3216.1, "Constant Principal Stress Direction," and Subparagraph NB-3216.2, "Varying Principal Stress Direction," in ASME Code Section III. These differences led to relatively small changes in the computed CUF.

identify stress “peaks” (points of local stress maxima) and “valleys” (points of local stress minima)[G].

g. The S_{alt} values were adjusted for the effects of Young’s modulus (in accordance with Subparagraph NB-3222.4(e)(4) in ASME Code Section III) and for the effects of simplified elastic-plastic analysis (i.e., K_e, in accordance with Subparagraph NB-3228.5).

h. Because it was not obvious which case led to the highest S_{alt} values, all six of the following cases were evaluated[H]:

   i. based on maximum total SX_i stress
   ii. based on maximum total SY_i stress
   iii. based on maximum total SZ_i stress
   iv. based on maximum membrane plus bending SX_i stress
   v. based on maximum membrane plus bending SY_i stress
   vi. based on maximum membrane plus bending SZ_i stress

   Two subcases were evaluated for each case: (1) S_{alt} values based on peak and valleys for the membrane plus bending principal stress S'_{31} difference history, and (2) S_{alt} values based on peak and valleys for the total principal stress S'_{31} difference history.

i. The S_{alt} values counted for each subcase in Step h were designated as $S_{alt\,1}$, $S_{alt\,2}$, $S_{alt\,3}$, …, $S_{alt\,n}$. The number of times that each S_{alt} value occurred during the entire principal stress difference history was determined, and these were designated as n_1, n_2, n_3, …, n_n, respectively.

j. From the $S_{alt\,1}$, $S_{alt\,2}$, $S_{alt\,3}$, …, $S_{alt\,n}$ values calculated for each case in Step h, the applicable design fatigue curve from Appendix A was used to determine the maximum number of allowable cycles, N_1, N_2, N_3, …, N_n.

k. Partial usage factors, U_1, U_2, U_3, …, U_n, were calculated as $U_1 = n_1/N_1$, $U_2 = n_2/N_2$, $U_3 = n_3/N_3$, …, $U_n = n_n/N_n$.

l. The total CUF was calculated as $U_1 + U_2 + U_3 + \ldots + U_n$ for each subcase. Thus, 2 CUF values were calculated for the two subcases for each of the six cases, for a total of 12 CUF values.

m. The highest of the 12 CUF values resulting from all of the six cases/two subcases was used as the final reported CUF value.

[G] The software used to perform the calculations searches the local extrema in the S'_{31} principal stress difference using a stress “filter” of 100 psi to search for the peaks and valleys to eliminate small anomalies in the stress histories caused by round off in the as-reported stress values. Thus, stress variations between adjacent points of less than 100 psi were ignored and were not counted as a peak or a valley. In some cases, this may have led to the exact peak or valley not being selected but rather a point adjacent to the true peak or valley. Sensitivity studies indicated that any differences introduced by this approximation were insignificant.

[H] Because the shear stress components (SXY, SYZ, and SZX) have significantly lower values compared to the stress components (SX, SY, and SZ), they do not lead to a maximum S_{alt} situation. As a result, they were not considered in the maximum S_{alt} selection process. For each case (i) through (vi), the subscript “i” represents the time where the selected stress component peaked, and the remaining stress components were also selected at the same time.

Only CUF and F_{en} calculations were performed for the sample problem. Therefore, this appendix does not include the results of stress limit checks required as a part of ASME Code design calculations.

Calculations for CUF_{en} were performed for the limiting CUF value. Strain rates were calculated based on the total S'_{31} history, which was expected to produce the limiting CUF case because the principal stress differences were algebraically sorted ($S'_{12} > S'_{23} > S'_{31}$). The following two approaches were used to compute F_{en} using the equations in Appendix A of this report:

A. Average Strain Rate Approach: In this approach, the F_{en} for each peak and valley resulting from the S_{alt} calculation process was computed as follows:

i. The strain rate was based on the total stress component principal stress difference, S'_{31}, which was used to compute CUF. For simplicity, K_e was conservatively not included in the calculation of strain rate.

ii. The strain rate was calculated between each adjacent valley and peak with increasing stress as follows:

$$\dot{\varepsilon} = \frac{(S'_{31\text{-peak}} - S'_{31\text{-valley}})}{\Delta t\, E} \text{ x } 100$$

where:
$\dot{\varepsilon}$ = strain rate (%/s)
$S'_{31\text{-peak}}$ = S'_{31} stress intensity value at the peak (psi)
$S'_{31\text{-valley}}$ = S'_{31} stress intensity value at the valley (psi)
Δt = time increment between the valley and peak (seconds)
E = the Young's modulus.

For this sample problem, E was determined at the maximum metal temperature of the peak and valley (psi). Refer to the discussion in Section 4.4 on the selection of temperature for determining E.

iii. To neglect compressive loading in the determination of F_{en} caused by small fluctuations in the finite element stress histories, the F_{en} value was set to 1.0 for any valley-to-peak interval where $\dot{\varepsilon}$ was less than zero.

iv. The F_{en} was calculated between each adjacent valley and peak using the appropriate equation from Appendix A for the material evaluated and using the maximum metal surface temperature of the peak and valley.

v. The F_{en} computed over each range in Step A(ii) was assigned to both the valley and peak associated with that range. When peaks and valleys were subsequently paired for CUF calculation, the maximum of the two F_{en} values assigned to the paired peak and valley was used in the CUF_{en} calculation.

vi. The above steps were repeated for all valley-peak intervals for the entire principal stress intensity history.

vii. The total CUF_{en} was calculated as $F_{en\text{-}1}\,U_1 + F_{en\text{-}2}\,U_2 + F_{en\text{-}3}\,U_3 + \ldots + F_{en\text{-}n}\,U_n$

B. Modified Strain Rate Approach: In this approach, the modified rate approach described in Section 4.4 was used to compute the F_{en} for each peak and valley resulting from the S_{alt} calculation process as follows:

i. The strain rate was based on the total stress component principal stress difference, S'_{31}, which was used to compute CUF. For simplicity, K_e was conservatively not included in the calculation of strain rate.

ii. The F_{en} integration was performed between each valley and peak with increasing stress, as follows (refer to Figure 4-66):

$$\dot{\varepsilon}_i = \frac{S'_{31\,i+1} - S'_{31\,i}}{\Delta t\ E} \times 100$$

where:
- $\dot{\varepsilon}_i$ = strain rate at any point, i, between the valley and peak (%/s)
- $S'_{31\,i+1}$ = S'_{31} stress intensity value at point i+1 (psi)
- $S'_{31\,i}$ = S'_{31} stress intensity value at point i (psi)
- Δt = time increment between points i and i+1 (seconds)
- E = the Young's modulus determined at the maximum metal temperature of points i and i+1 (psi)

iii. To neglect compressive loading in the determination of F_{en} caused by small fluctuations in the finite element stress histories, the F_{en} value was set to 1.0 for any point interval where $\dot{\varepsilon}$ was less than zero.[l]

iv. The $F_{en,i}$ was calculated between point i and i+1 using the appropriate equation from Appendix A for the material evaluated, and using the maximum metal temperature of points i and i+1.

v. The integrated $F_{en\text{-}n}$ for the valley-peak load pair was calculated as

$$F_{en-n} = \sum_{i=1}^{k} F_{en,i}\ \frac{(\varepsilon_{i+1} - \varepsilon_i)}{(\varepsilon_{max} - \varepsilon_{min})}$$

where:
- $F_{en\text{-}n}$ = integrated F_{en} for valley-peak load pair n
- k = number of integration points between valley and peak
- ε_i = strain at any point, i, between the valley and peak computed as $S'_{31\,i}$ divided by E
- ε_{i+1} = strain at any point, i+1, between the valley and peak computed as $S'_{31\,i}$ divided by E
- ε_{max} = maximum strain at the peak computed as $S'_{31\text{-peak}}$ divided by E evaluated at the metal temperature of the peak
- ε_{min} = minimum strain at the valley computed as $S'_{31\text{-valley}}$ divided by E evaluated at the metal temperature of the valley
- E = the Young's modulus determined at the maximum metal temperature of points i and i+1 (psi).
  Refer to the discussion in Section 4.4 on the selection of temperature for determining E.

[l] Note that this implementation may lead to small subtraction terms in the summation equation in Step B(v). A casual reader may find this logic odd because only positive ("traction") terms are generally expected. The effect of this implementation is negligible.

vi. The F_{en} computed over each range in Step B(v) was assigned to both the valley and peak associated with that range. When peaks and valleys were subsequently paired for CUF calculation, the maximum of the two F_{en} values assigned to the paired peak and valley was used in the CUF_{en} calculation.

vii. The above steps were repeated for all valley-peak intervals for the entire principal stress intensity history.

viii. The total CUF_{en} was calculated as $F_{en-1}\,U_1 + F_{en-2}\,U_2 + F_{en-3}\,U_3 + \ldots + F_{en-n}\,U_n$.

For both of the above approaches, the transient times assigned to the peaks and valleys represented the time of stress reversal for the S'_{31} principal stress difference for each of the six cases evaluated in Step A(h). For example, for Case A(h)(i) (based on maximum **total** SY_i stress), the times for the peaks and valleys were based on when the **total** S'_{31} principal stress difference reversed direction; the corresponding membrane plus bending values at the same peak and valley times were used in the calculation of CUF.

C.4 Results

Table C-3 shows the highest CUF calculated for the sample problem from Step A(m) in Section C.3. The highest CUF resulted from the using the membrane plus bending and total stresses from the S'_{31} membrane plus bending principal stress difference case (Case (v) for maximum membrane plus bending SY_i stress in Step A(h) in Section C.3). Figure C-6 illustrates the entire principal stress difference time history for this case. The plot in Figure C-6 also indicates the peaks and valleys listed in the Table C-3 CUF calculation.

Table C-4 shows the CUF_{en} calculated for the sample problem using the average strain rate approach. Table C-5 shows the CUF_{en} calculated for the sample problem using the modified strain rate approach. It is noted that the F_{en} and corresponding CUF_{en} results calculated using the average strain rate approach are actually less than the results calculated using the modified strain rate approach. This example illustrates the situation noted in Section 4.4, Item (3) and associated Figure 4-67, where the average strain rate approach does not necessarily provide a more conservative F_{en} estimate than the modified rate approach.

Table C-6 lists the entire principal stress difference time history for this case, as calculated in Step A(f) in Section C.3.

Table C-3 Limiting CUF Results for the Sample Problem for SCL 2 (Case ii, Subcase 1.)

Point No. for Load A[(1)]	Point No. for Load B[(1)]	Applied Cycles for Load A	Applied Cycles for Load B	M+B Stress (psi)	K_e	Total Stress (psi)	S_{alt} (psi)	N_n	n_n	U_n	Maximum Metal Temp. (°F)	DO (ppm)
694	447	5	20	125542.9	2.580	144164.4	220490.4	140.005	5	0.0357	566.6	0.150
699	447	50	15	121622.8	2.405	139047.0	198300.6	178.958	15	0.0838	566.6	0.550
699	1021	35	20	104691.5	1.653	126037.5	124507.0	582.468	20	0.0343	600.4	0.550
699	899	15	50	89695.4	1.000	102302.8	57864.5	6339.47	15	0.0024	336.1	0.550
695	899	5	35	84993.9	1.000	98798.6	55882.4	7027.83	5	0.0007	336.1	0.550
185	899	20	30	68222.2	1.000	76465.1	43250.2	15549.1	20	0.0013	336.1	0.550
1432	899	20	10	66665.7	1.000	83098.8	47002.3	11892.7	10	0.0008	336.1	0.550
1432	1653	10	100	49437.0	1.000	61950.9	33687.5	35734.8	10	0.0003	103.0	0.522
1296	1653	20	90	32478.6	1.000	38719.1	22025.4	154852	20	0.0001	366.2	0.522
1136	1653	20	70	27045.6	1.000	33751.1	19388.7	258499	20	0.0001	417.7	0.522
2215	1653	100	50	25255.9	1.000	25668.1	15147.6	1.15E+06	50	0.0000	547.0	0.522
2215	1213	50	20	22343.7	1.000	25298.3	14929.4	1.30E+06	20	0.0000	547.0	0.050
2215	1562	30	20	22047.7	1.000	24970.1	14735.7	1.46E+06	20	0.0000	547.0	0.050
2215	1	10	20	11956.0	1.000	12255.6	7232.5	1.00E+11	10	0.0000	547.0	0.150
1347	1	20	10	3786.5	1.000	4173.0	2412.1	1.00E+11	10	0.0000	450.0	0.150
1347	1595	10	20	3408.0	1.000	3430.2	1963.3	1.00E+11	10	0.0000	398.7	0.050
960	1595	20	10	241.8	1.000	259.9	146.0	1.00E+11	10	0.0000	299.5	0.050

TOTAL CUF = 0.1596

Note: 1. For the transient times associated with each point number, refer to Table C-4 and Table C-5.

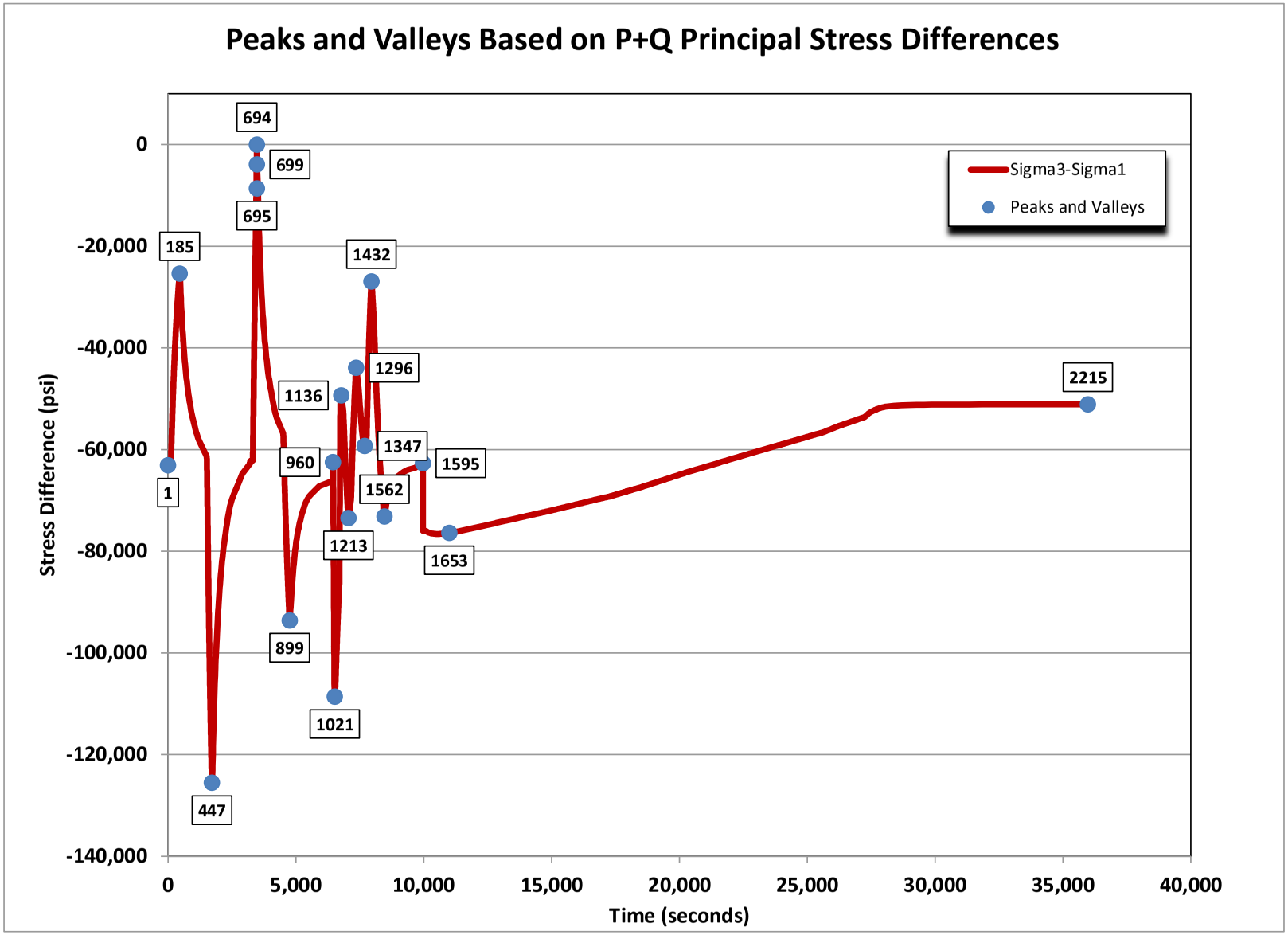


Figure C-6 **Principal stress intensity histories and peaks and valleys used in limiting CUF calculation for sample problem for SCL 2.**

Table C-4 CUF_{en} Results Based on the Sample Problem for SCL 2 using Average Strain Rate Approach.

Point No. for Load A	Time for Load A (seconds)	Point No. for Load B	Time for Load B (seconds)	F_{en-n}	U_n	CUF_{en-n}
694	3471.40	447	1716.00	21.753	0.0357	0.7769
699	3476.00	447	1716.00	3.156	0.0838	0.2645
699	3476.00	1021	6520.00	3.156	0.0343	0.1084
699	3476.00	899	4754.00	3.156	0.0024	0.0075
695	3471.60	899	4754.00	1.000	0.0007	0.0007
185	454.00	899	4754.00	8.856	0.0013	0.0114
1432	7955.00	899	4754.00	2.802	0.0008	0.0024
1432	7955.00	1653	10999.00	2.802	0.0003	0.0008
1296	7356.00	1653	10999.00	5.418	0.0001	0.0007
1136	6770.00	1653	10999.00	5.865	0.0001	0.0005
2215	35971.00	1653	10999.00	65.669	0.0000	0.0029
2215	35971.00	1213	7059.00	65.669	0.0000	0.0010
2215	35971.00	1562	8461.00	65.669	0.0000	0.0009
2215	35971.00	1	0.00	65.669	0.0000	0.0000
1347	7689.00	1	0.00	1.000	0.0000	0.0000
1347	7689.00	1595	9969.00	1.886	0.0000	0.0000
960	6450.00	1595	9969.00	6.437	0.0000	0.0000
960	6450.00	960	6450.00	6.437	0.0000	0.0000

TOTAL CUF_{en} = 1.1784

(Overall F_{en} = 7.3818)

Table C-5 CUF_{en} Results Based on the Sample Problem for SCL 2 using Modified Strain Rate Approach.

Point No. for Load A	Time for Load A (seconds)	Point No. for Load B	Time for Load B (seconds)	$F_{en\text{-}nA}$	$F_{en\text{-}nB}$	U_n	$F_{en\text{-}n}$	$CUF_{en\text{-}n}$
694	3471.40	447	1716.00	15.520	15.520	0.0357	15.520	0.5543
699	3476.00	447	1716.00	1.517	15.520	0.0838	15.520	1.3009
699	3476.00	1021	6520.00	1.517	5.065	0.0343	5.065	0.1739
699	3476.00	899	4754.00	1.517	6.429	0.0024	6.429	0.0152
695	3471.60	899	4754.00	1.517	6.429	0.0007	6.429	0.0046
185	454.00	899	4754.00	4.298	6.429	0.0013	6.429	0.0083
1432	7955.00	899	4754.00	2.009	6.429	0.0008	6.429	0.0054
1432	7955.00	1653	10999.00	2.009	11.465	0.0003	11.465	0.0032
1296	7356.00	1653	10999.00	4.184	11.465	0.0001	11.465	0.0015
1136	6770.00	1653	10999.00	5.065	11.465	0.0001	11.465	0.0009
2215	35971.00	1653	10999.00	11.465	11.465	0.0000	11.465	0.0005
2215	35971.00	1213	7059.00	11.465	4.184	0.0000	11.465	0.0002
2215	35971.00	1562	8461.00	11.465	1.886	0.0000	11.465	0.0002
2215	35971.00	1	0.00	11.465	4.298	0.0000	11.465	0.0000
1347	7689.00	1	0.00	2.009	4.298	0.0000	4.298	0.0000
1347	7689.00	1595	9969.00	2.009	1.886	0.0000	2.009	0.0000
960	6450.00	1595	9969.00	6.429	1.886	0.0000	6.429	0.0000
960	6450.00	960	6450.00	6.429	6.429	0.0000	6.429	0.0000
					TOTALS	**0.1596**	**---**	**2.0691**

(Overall F_{en} = 12.9607)

Table C-6 Principal Stress Intensity Histories Used in the Limiting CUF Calculation for the Sample Problem for SCL 2 (Case ii).

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1	0.00	34007.5	29079.5	-63087.0	45032.0	27828.0	-72859.9	450.0	20	0.150
2	10.00	33994.5	29077.5	-63072.0	45002.0	27826.0	-72827.9	449.9	20	0.150
3	20.00	33977.5	29071.5	-63049.0	44976.0	27821.0	-72796.9	449.7	20	0.150
4	30.00	33961.5	29064.5	-63025.9	44954.0	27814.0	-72767.9	449.6	20	0.150
5	40.00	33946.5	29057.5	-63003.9	44934.0	27807.0	-72740.9	449.5	20	0.150
6	60.00	33920.5	29040.5	-62960.9	44899.9	27792.0	-72691.9	449.2	20	0.150
7	80.00	33898.4	29023.4	-62921.9	44873.0	27776.0	-72648.9	448.9	20	0.150
8	100.00	33880.4	29005.4	-62885.9	44850.9	27758.9	-72609.9	448.6	20	0.150
9	103.00	33902.5	28926.5	-62829.1	44871.9	27678.9	-72550.8	448.6	20	0.150
10	105.00	33857.6	28864.6	-62722.2	44605.8	27617.8	-72223.6	447.2	20	0.150
11	107.00	33752.7	28792.7	-62545.3	44275.7	27545.7	-71821.4	445.7	20	0.150
12	109.00	33614.7	28711.7	-62326.4	43940.6	27466.6	-71407.2	444.1	20	0.150
13	111.00	33454.8	28622.8	-62077.5	43606.5	27380.5	-70987.0	442.4	20	0.150
14	113.00	33282.8	28526.8	-61809.6	43276.4	27289.4	-70565.8	440.8	20	0.150
15	115.00	33096.9	28424.9	-61521.7	42952.3	27191.3	-70143.6	439.1	20	0.150
16	117.00	32906.9	28317.9	-61224.8	42634.2	27087.2	-69721.4	437.3	20	0.150
17	119.00	32712.9	28203.9	-60916.9	42321.1	26979.1	-69300.2	435.6	20	0.150
18	121.00	32518.0	28085.0	-60602.9	42015.1	26866.1	-68881.1	433.9	20	0.150
19	123.00	32319.0	27962.0	-60281.0	41715.0	26747.0	-68461.9	432.1	20	0.150
20	125.00	32121.0	27835.0	-59956.1	41421.9	26624.9	-68046.8	430.3	20	0.150
21	127.00	31924.1	27703.1	-59627.1	41132.8	26499.8	-67632.7	428.5	20	0.150
22	129.00	31728.1	27568.1	-59296.2	40850.8	26370.8	-67221.6	426.7	20	0.150
23	131.00	31534.1	27429.1	-58963.2	40576.7	26237.7	-66814.5	424.9	20	0.150
24	133.00	31341.1	27287.1	-58628.3	40306.7	26101.7	-66408.3	423.1	20	0.150
25	135.00	31151.2	27142.1	-58293.3	40042.6	25962.6	-66005.2	421.3	20	0.150
26	137.00	30964.2	26994.2	-57958.3	39783.5	25821.5	-65605.1	419.5	20	0.150
27	139.00	30780.2	26845.2	-57625.4	39531.5	25677.5	-65209.0	417.7	20	0.150
28	141.00	30598.2	26693.2	-57291.4	39283.4	25532.4	-64815.9	415.8	20	0.150
29	143.00	30419.2	26539.2	-56958.5	39041.4	25384.4	-64425.8	414.0	20	0.150
30	145.00	30243.2	26382.2	-56625.5	38804.3	25234.3	-64038.7	412.2	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
31	147.00	30071.3	26224.3	-56295.5	38573.3	25082.3	-63655.6	410.3	20	0.150
32	149.00	29901.3	26065.3	-55966.5	38346.3	24929.3	-63275.5	408.5	20	0.150
33	151.00	29734.3	25904.3	-55638.6	38123.2	24775.2	-62898.4	406.6	20	0.150
34	153.00	29570.3	25742.3	-55312.6	37904.1	24620.2	-62524.3	404.8	20	0.150
35	155.00	29409.3	25580.3	-54989.6	37691.1	24464.1	-62155.2	402.9	20	0.150
36	157.00	29251.3	25416.3	-54667.6	37481.1	24306.1	-61787.1	401.1	20	0.150
37	159.00	29096.3	25251.3	-54347.7	37276.0	24148.0	-61424.0	399.2	20	0.150
38	161.00	28943.3	25085.3	-54028.7	37075.0	23988.0	-61062.9	397.3	20	0.150
39	163.00	28794.4	24918.4	-53712.7	36877.9	23827.9	-60705.8	395.5	20	0.150
40	165.00	28648.4	24751.4	-53399.7	36685.9	23667.9	-60353.7	393.6	20	0.150
41	167.00	28503.4	24584.4	-53087.7	36495.8	23506.8	-60002.6	391.7	20	0.150
42	169.00	28362.4	24415.4	-52777.8	36309.8	23344.8	-59654.6	389.8	20	0.150
43	171.00	28222.4	24247.4	-52469.8	36127.7	23182.7	-59310.5	388.0	20	0.150
44	173.00	28085.4	24078.4	-52163.8	35948.7	23019.7	-58968.4	386.1	20	0.150
45	175.00	27952.4	23909.4	-51861.8	35773.6	22857.6	-58631.3	384.2	20	0.150
46	177.00	27820.4	23739.4	-51559.8	35601.6	22694.6	-58296.2	382.3	20	0.150
47	179.00	27691.4	23569.4	-51260.8	35433.5	22530.6	-57964.1	380.4	20	0.150
48	181.00	27564.4	23399.4	-50963.8	35267.5	22367.5	-57635.0	378.5	20	0.150
49	183.00	27440.4	23229.4	-50669.9	35106.5	22203.5	-57309.9	376.6	20	0.150
50	185.00	27319.4	23058.4	-50377.9	34948.4	22039.4	-56987.8	374.7	20	0.150
51	187.00	27199.4	22888.4	-50087.9	34792.4	21875.4	-56667.7	372.9	20	0.150
52	189.00	27081.4	22718.5	-49799.9	34639.3	21711.3	-56350.6	371.0	20	0.150
53	191.00	26965.5	22549.4	-49514.9	34489.3	21547.2	-56036.5	369.1	20	0.150
54	193.00	26851.5	22379.5	-49230.9	34341.2	21384.2	-55725.4	367.2	20	0.150
55	195.00	26741.5	22208.5	-48949.9	34198.2	21220.1	-55418.3	365.3	20	0.150
56	197.00	26631.5	22039.5	-48671.0	34056.1	21056.1	-55112.2	363.4	20	0.150
57	199.00	26524.5	21869.5	-48393.9	33917.1	20892.1	-54809.1	361.4	20	0.150
58	201.00	26418.5	21700.5	-48119.0	33780.0	20730.0	-54510.0	359.5	20	0.150
59	203.00	26315.5	21530.5	-47846.0	33647.0	20566.0	-54212.9	357.6	20	0.150
60	205.00	26215.5	21361.5	-47577.0	33515.9	20402.9	-53918.8	355.7	20	0.150
61	207.00	26115.5	21192.5	-47308.0	33386.9	20240.9	-53627.8	353.8	20	0.150
62	209.00	26017.5	21024.5	-47042.0	33260.8	20076.8	-53337.7	351.9	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
63	211.00	25921.5	20855.5	-46777.0	33135.8	19915.8	-53051.5	350.0	20	0.150
64	213.00	25828.5	20687.5	-46516.0	33014.7	19753.7	-52768.4	348.1	20	0.150
65	215.00	25735.5	20519.5	-46255.0	32895.7	19590.7	-52486.4	346.1	20	0.150
66	217.00	25644.5	20352.5	-45997.1	32778.6	19429.6	-52208.3	344.2	20	0.150
67	219.00	25555.5	20185.5	-45741.1	32663.6	19268.6	-51932.1	342.3	20	0.150
68	221.00	25468.5	20018.5	-45487.1	32551.5	19106.5	-51658.0	340.4	20	0.150
69	223.00	25384.5	19851.5	-45236.1	32441.5	18946.5	-51388.0	338.5	20	0.150
70	225.00	25300.6	19685.5	-44986.1	32333.4	18786.4	-51119.9	336.6	20	0.150
71	227.00	25218.5	19519.5	-44738.1	32227.4	18626.4	-50853.7	334.6	20	0.150
72	229.00	25137.6	19354.6	-44492.1	32122.3	18467.3	-50589.7	332.7	20	0.150
73	231.00	25057.6	19190.6	-44248.1	32019.3	18308.3	-50327.5	330.8	20	0.150
74	233.00	24980.6	19025.6	-44006.1	31919.2	18149.2	-50068.4	328.9	20	0.150
75	235.00	24903.6	18861.6	-43765.2	31819.2	17991.2	-49810.3	326.9	20	0.150
76	237.00	24827.6	18698.6	-43526.2	31722.1	17832.1	-49554.2	325.0	20	0.150
77	239.00	24753.6	18535.6	-43289.2	31626.1	17675.1	-49301.1	323.1	20	0.150
78	241.00	24681.6	18372.6	-43054.2	31532.0	17518.0	-49050.0	321.1	20	0.150
79	243.00	24610.6	18210.6	-42821.2	31439.0	17362.0	-48800.9	319.2	20	0.150
80	245.00	24540.6	18048.6	-42589.2	31347.9	17204.9	-48552.8	317.3	20	0.150
81	247.00	24471.6	17886.6	-42358.2	31258.9	17048.9	-48307.7	315.4	20	0.150
82	249.00	24403.6	17726.6	-42130.3	31170.8	16893.8	-48064.6	313.4	20	0.150
83	251.00	24338.6	17565.6	-41904.3	31085.8	16738.8	-47824.5	311.5	20	0.150
84	253.00	24273.6	17405.7	-41679.3	31000.7	16584.7	-47585.4	309.6	20	0.150
85	255.00	24209.7	17246.7	-41456.3	30917.7	16430.6	-47348.3	307.6	20	0.150
86	257.00	24147.7	17086.7	-41234.3	30836.6	16276.6	-47113.2	305.7	20	0.150
87	259.00	24087.7	16928.7	-41016.3	30758.5	16122.5	-46881.1	303.7	20	0.150
88	261.00	24027.7	16770.7	-40798.4	30680.5	15970.5	-46651.0	301.8	20	0.150
89	263.00	23969.7	16612.7	-40582.4	30604.4	15817.4	-46421.9	299.9	20	0.150
90	265.00	23912.7	16455.7	-40368.4	30529.4	15666.4	-46195.8	297.9	20	0.150
91	267.00	23856.7	16298.7	-40155.4	30456.3	15514.3	-45970.7	296.0	20	0.150
92	269.00	23801.7	16143.7	-39945.5	30384.3	15364.3	-45748.5	294.0	20	0.150
93	271.00	23747.7	15987.7	-39735.5	30313.2	15213.2	-45526.5	292.1	20	0.150
94	273.00	23693.7	15832.8	-39526.5	30243.2	15063.2	-45306.3	290.1	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
95	275.00	23640.8	15677.8	-39318.5	30173.1	14914.1	-45087.2	288.2	20	0.150
96	277.00	23589.8	15523.8	-39113.6	30106.1	14765.1	-44871.1	286.2	20	0.150
97	279.00	23538.8	15369.8	-38908.6	30039.0	14616.0	-44655.0	284.3	20	0.150
98	281.00	23488.8	15215.8	-38704.6	29971.9	14467.9	-44439.9	282.4	20	0.150
99	283.00	23438.8	15063.8	-38502.6	29906.9	14319.9	-44226.8	280.4	20	0.150
100	285.00	23390.8	14911.8	-38302.7	29842.8	14172.8	-44015.7	278.5	20	0.150
101	287.00	23342.8	14759.8	-38102.7	29779.8	14025.8	-43805.6	276.5	20	0.150
102	289.00	23295.9	14607.9	-37903.7	29716.7	13879.7	-43596.5	274.6	20	0.150
103	291.00	23248.9	14456.9	-37705.8	29655.7	13732.7	-43388.4	272.6	20	0.150
104	293.00	23203.9	14306.9	-37510.8	29595.6	13587.6	-43183.3	270.6	20	0.150
105	295.00	23159.9	14155.9	-37315.8	29535.6	13442.6	-42978.1	268.7	20	0.150
106	297.00	23114.9	14006.9	-37121.9	29477.5	13297.5	-42775.0	266.7	20	0.150
107	299.00	23071.9	13857.9	-36929.9	29419.5	13153.5	-42572.9	264.8	20	0.150
108	301.00	23030.0	13709.0	-36738.9	29363.4	13010.4	-42373.8	262.8	20	0.150
109	303.00	22989.0	13560.0	-36549.0	29307.4	12866.3	-42173.7	260.9	20	0.150
110	305.00	22948.0	13412.0	-36360.0	29252.3	12724.3	-41976.6	258.9	20	0.150
111	307.00	22907.0	13266.0	-36173.1	29198.2	12581.2	-41779.5	257.0	20	0.150
112	309.00	22869.1	13118.1	-35987.1	29146.2	12439.2	-41585.4	255.0	20	0.150
113	311.00	22830.1	12972.1	-35802.1	29094.1	12298.1	-41392.2	253.0	20	0.150
114	313.00	22792.1	12826.1	-35618.2	29043.1	12157.1	-41200.2	251.1	20	0.150
115	315.00	22756.1	12681.1	-35437.2	28994.0	12016.0	-41010.1	249.1	20	0.150
116	317.00	22720.1	12535.1	-35255.3	28945.0	11874.9	-40819.9	247.2	20	0.150
117	319.00	22684.2	12391.2	-35075.3	28895.9	11734.9	-40630.8	245.2	20	0.150
118	321.00	22649.2	12247.2	-34896.4	28846.9	11595.9	-40442.7	243.2	20	0.150
119	323.00	22615.2	12103.2	-34718.4	28800.8	11456.8	-40257.6	241.3	20	0.150
120	325.00	22581.2	11960.2	-34541.5	28753.8	11318.7	-40072.5	239.3	20	0.150
121	327.00	22548.3	11817.3	-34365.5	28708.7	11179.7	-39888.4	237.3	20	0.150
122	329.00	22516.3	11675.3	-34191.6	28663.6	11042.6	-39706.3	235.4	20	0.150
123	331.00	22485.3	11533.3	-34018.6	28621.6	10904.6	-39526.2	233.4	20	0.150
124	333.00	22455.3	11391.3	-33846.7	28578.5	10768.5	-39347.1	231.4	20	0.150
125	335.00	22425.4	11250.4	-33675.8	28536.5	10631.5	-39168.0	229.4	20	0.150
126	337.00	22396.4	11110.4	-33506.8	28497.4	10495.4	-38992.8	227.5	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
127	339.00	22368.4	10970.4	-33338.9	28457.4	10360.4	-38817.7	225.5	20	0.150
128	341.00	22340.5	10830.5	-33170.9	28418.3	10225.3	-38643.6	223.5	20	0.150
129	343.00	22313.5	10691.5	-33005.0	28380.3	10090.3	-38470.5	221.5	20	0.150
130	345.00	22287.5	10553.5	-32841.1	28343.2	9956.2	-38299.4	219.6	20	0.150
131	347.00	22261.6	10414.6	-32676.1	28306.1	9822.1	-38128.3	217.6	20	0.150
132	349.00	22235.6	10276.6	-32512.2	28269.1	9689.1	-37958.2	215.6	20	0.150
133	351.00	22210.6	10139.6	-32350.3	28234.1	9556.0	-37790.1	213.6	20	0.150
134	353.00	22185.7	10002.7	-32188.3	28199.0	9423.0	-37622.0	211.7	20	0.150
135	355.00	22161.7	9865.7	-32027.4	28163.9	9289.9	-37453.9	209.7	20	0.150
136	357.00	22137.8	9728.7	-31866.5	28128.9	9158.9	-37287.8	207.7	20	0.150
137	359.00	22114.8	9593.8	-31708.6	28096.8	9026.8	-37123.7	205.7	20	0.150
138	361.00	22091.8	9457.8	-31549.7	28062.8	8895.8	-36958.5	203.7	20	0.150
139	363.00	22069.9	9321.9	-31391.7	28030.7	8764.7	-36795.5	201.8	20	0.150
140	365.00	22047.9	9187.9	-31235.8	27999.6	8633.7	-36633.3	199.8	20	0.150
141	367.00	22027.0	9053.0	-31079.9	27968.6	8503.6	-36472.2	197.8	20	0.150
142	369.00	22006.0	8919.0	-30925.0	27938.6	8374.5	-36313.1	195.8	20	0.150
143	371.00	21986.0	8786.0	-30772.1	27909.5	8244.5	-36154.0	193.9	20	0.150
144	373.00	21967.1	8653.1	-30620.2	27881.5	8116.4	-35997.9	191.9	20	0.150
145	375.00	21948.2	8520.2	-30468.3	27853.4	7988.4	-35841.8	189.9	20	0.150
146	377.00	21930.2	8387.2	-30317.4	27826.3	7859.4	-35685.7	187.9	20	0.150
147	379.00	21913.2	8255.2	-30168.5	27800.3	7732.3	-35532.6	185.9	20	0.150
148	381.00	21895.3	8125.3	-30020.6	27774.2	7605.2	-35379.5	184.0	20	0.150
149	383.00	21878.4	7993.4	-29871.7	27749.2	7477.2	-35226.4	182.0	20	0.150
150	385.00	21862.4	7862.4	-29724.8	27724.1	7351.1	-35075.3	180.0	20	0.150
151	387.00	21847.5	7732.5	-29579.9	27700.1	7225.1	-34925.2	178.0	20	0.150
152	389.00	21831.5	7603.5	-29435.0	27676.0	7099.0	-34775.0	176.1	20	0.150
153	391.00	21816.6	7473.6	-29290.2	27653.0	6974.0	-34627.0	174.1	20	0.150
154	393.00	21803.6	7344.6	-29148.3	27630.9	6848.9	-34479.8	172.1	20	0.150
155	395.00	21789.7	7215.7	-29005.4	27608.9	6723.9	-34332.7	170.1	20	0.150
156	397.00	21775.8	7087.8	-28863.5	27586.8	6599.8	-34186.6	168.1	20	0.150
157	399.00	21763.8	6959.8	-28723.7	27566.8	6476.8	-34043.5	166.1	20	0.150
158	401.00	21750.9	6832.9	-28583.8	27546.7	6352.7	-33899.4	164.2	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
159	403.00	21739.0	6706.0	-28444.9	27526.7	6229.7	-33756.3	162.2	20	0.150
160	405.00	21729.0	6579.0	-28308.1	27507.6	6107.6	-33615.2	160.2	20	0.150
161	407.00	21717.1	6454.1	-28171.2	27488.6	5985.6	-33474.1	158.2	20	0.150
162	409.00	21707.2	6327.2	-28034.4	27470.5	5863.5	-33334.0	156.2	20	0.150
163	411.00	21696.3	6203.3	-27899.5	27452.5	5742.5	-33194.9	154.3	20	0.150
164	413.00	21688.3	6077.3	-27765.7	27436.4	5620.4	-33056.8	152.3	20	0.150
165	415.00	21678.4	5953.4	-27631.8	27419.4	5500.4	-32919.7	150.3	20	0.150
166	417.00	21669.5	5829.5	-27499.0	27403.3	5380.3	-32783.6	148.3	20	0.150
167	419.00	21662.6	5705.6	-27368.2	27388.3	5259.3	-32647.5	146.3	20	0.150
168	421.00	21653.7	5582.7	-27236.3	27372.2	5140.2	-32512.4	144.3	20	0.150
169	423.00	21645.8	5459.8	-27105.5	27356.2	5021.2	-32377.3	142.3	20	0.150
170	425.00	21639.8	5336.8	-26976.7	27342.1	4902.1	-32244.2	140.3	20	0.150
171	427.00	21632.9	5214.9	-26847.9	27327.1	4785.1	-32112.1	138.4	20	0.150
172	429.00	21626.0	5094.0	-26720.0	27313.0	4667.0	-31980.0	136.4	20	0.150
173	431.00	21620.1	4973.1	-26593.2	27300.0	4549.0	-31848.9	134.4	20	0.150
174	433.00	21614.2	4852.2	-26466.4	27286.9	4431.9	-31718.8	132.4	20	0.150
175	435.00	21608.3	4731.3	-26339.6	27273.9	4314.8	-31588.7	130.4	20	0.150
176	437.00	21603.4	4611.4	-26214.8	27261.8	4197.8	-31459.6	128.4	20	0.150
177	439.00	21598.5	4490.5	-26089.0	27248.8	4081.8	-31330.5	126.4	20	0.150
178	441.00	21593.6	4370.6	-25964.2	27236.7	3965.7	-31202.4	124.4	20	0.150
179	443.00	21589.7	4250.7	-25840.5	27226.7	3848.6	-31075.3	122.4	20	0.150
180	445.00	21584.9	4131.9	-25716.7	27214.6	3733.6	-30948.2	120.4	20	0.150
181	447.00	21580.9	4012.9	-25593.9	27203.6	3618.6	-30822.2	118.4	20	0.150
182	449.00	21577.1	3895.1	-25472.1	27193.5	3503.5	-30697.0	116.4	20	0.150
183	450.00	21579.1	3836.1	-25415.3	27212.5	3446.5	-30659.0	115.6	20	0.150
184	451.00	21580.0	3804.0	-25384.0	27243.5	3416.5	-30660.0	114.8	20	0.150
185	454.00	21670.7	3722.7	-25393.3	27615.6	3339.5	-30955.1	113.6	20	0.150
186	459.00	22014.3	3631.3	-25645.6	28424.7	3253.7	-31678.4	112.6	20	0.150
187	467.00	22762.9	3581.9	-26344.8	29713.8	3201.9	-32915.7	111.6	20	0.150
188	477.00	23772.8	3644.8	-27417.6	31199.0	3252.9	-34451.9	110.6	20	0.150
189	478.00	23872.8	3655.8	-27528.5	31335.9	3264.0	-34599.9	110.5	20	0.150
190	488.00	24847.8	3823.8	-28671.7	32661.0	3418.0	-36079.0	109.8	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
191	492.00	25216.9	3910.9	-29127.8	33146.0	3498.0	-36644.0	109.5	20	0.150
192	502.00	26098.1	4160.1	-30258.2	34294.0	3731.0	-38025.1	108.9	20	0.150
193	509.00	26670.3	4355.3	-31025.5	35023.1	3915.0	-38938.1	108.5	20	0.150
194	519.00	27434.6	4657.6	-32092.2	35994.1	4200.0	-40194.1	108.0	20	0.150
195	529.00	28137.0	4974.0	-33111.0	36871.1	4500.1	-41371.2	107.5	20	0.150
196	539.00	28786.4	5302.4	-34088.8	37681.1	4811.1	-42492.2	107.0	20	0.150
197	549.00	29385.9	5634.9	-35020.8	38419.2	5127.1	-43546.3	106.6	20	0.150
198	553.00	29611.1	5769.1	-35380.2	38694.2	5255.1	-43949.3	106.4	20	0.150
199	563.00	30151.6	6103.6	-36255.3	39358.2	5574.2	-44932.3	106.1	20	0.150
200	573.00	30653.2	6437.2	-37090.4	39966.2	5892.2	-45858.4	105.7	20	0.150
201	582.00	31073.7	6734.7	-37808.5	40473.2	6176.3	-46649.5	105.4	20	0.150
202	592.00	31518.4	7062.4	-38580.7	41012.3	6488.3	-47500.6	105.1	20	0.150
203	602.00	31935.0	7386.0	-39321.1	41510.3	6798.3	-48308.7	104.8	20	0.150
204	612.00	32318.7	7702.7	-40021.4	41965.3	7100.4	-49065.7	104.5	20	0.150
205	617.00	32498.1	7858.1	-40356.1	42178.4	7248.4	-49426.8	104.4	20	0.150
206	627.00	32850.8	8161.8	-41012.6	42600.4	7539.4	-50139.8	104.2	20	0.150
207	637.00	33184.5	8459.5	-41644.0	42995.5	7823.5	-50819.0	103.9	20	0.150
208	647.00	33501.3	8750.3	-42251.6	43367.5	8101.5	-51469.0	103.7	20	0.150
209	657.00	33799.1	9033.1	-42832.1	43716.6	8371.6	-52088.1	103.5	20	0.150
210	661.00	33912.4	9144.4	-43056.8	43849.6	8477.6	-52327.2	103.4	20	0.150
211	671.00	34190.2	9417.2	-43607.3	44180.6	8737.6	-52918.3	103.2	20	0.150
212	681.00	34451.0	9683.0	-44134.0	44485.7	8991.7	-53477.4	103.1	20	0.150
213	691.00	34695.8	9939.8	-44635.7	44768.7	9237.7	-54006.5	102.9	20	0.150
214	701.00	34927.7	10191.7	-45119.4	45037.8	9477.8	-54515.6	102.7	20	0.150
215	721.00	35360.4	10675.4	-46035.8	45536.9	9938.9	-55475.8	102.4	20	0.150
216	731.00	35567.3	10908.3	-46475.6	45782.0	10161.0	-55942.9	102.3	20	0.150
217	741.00	35767.2	11137.2	-46904.4	46013.0	10380.0	-56393.1	102.2	20	0.150
218	751.00	35956.1	11360.1	-47316.3	46231.1	10592.1	-56823.2	102.1	20	0.150
219	761.00	36136.0	11578.0	-47714.1	46437.1	10800.1	-57237.3	102.0	20	0.150
220	781.00	36464.9	11994.9	-48459.8	46812.2	11196.3	-58008.5	101.7	20	0.150
221	801.00	36770.8	12391.8	-49162.6	47159.4	11575.4	-58734.7	101.5	20	0.150
222	815.00	36973.2	12664.2	-49637.3	47388.4	11834.4	-59222.9	101.4	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
223	825.00	37119.1	12855.1	-49974.2	47561.5	12016.5	-59578.0	101.3	20	0.150
224	835.00	37263.1	13044.1	-50307.2	47726.6	12196.6	-59923.2	101.3	20	0.150
225	845.00	37403.1	13232.1	-50635.2	47886.6	12374.6	-60261.3	101.2	20	0.150
226	855.00	37538.1	13416.1	-50954.1	48040.7	12549.7	-60590.4	101.2	20	0.150
227	875.00	37797.1	13776.1	-51573.1	48333.8	12891.8	-61225.6	101.1	20	0.150
228	895.00	38039.1	14124.1	-52163.2	48605.9	13223.9	-61829.9	101.0	20	0.150
229	915.00	38260.2	14456.2	-52716.3	48855.0	13539.0	-62394.1	100.9	20	0.150
230	955.00	38632.2	15058.2	-53690.3	49270.3	14111.3	-63381.6	100.7	20	0.150
231	995.00	38959.0	15602.0	-54561.0	49634.5	14627.5	-64262.0	100.6	20	0.150
232	1039.00	39281.1	16152.1	-55433.1	49992.7	15149.8	-65142.5	100.4	20	0.150
233	1049.00	39357.0	16272.0	-55628.9	50086.8	15263.8	-65350.6	100.4	20	0.150
234	1059.00	39432.9	16390.9	-55823.8	50174.8	15375.8	-65550.7	100.4	20	0.150
235	1069.00	39505.8	16508.8	-56014.6	50258.9	15487.9	-65746.8	100.5	20	0.150
236	1079.00	39576.7	16624.7	-56201.4	50340.0	15596.9	-65936.9	100.5	20	0.150
237	1099.00	39711.4	16848.4	-56559.9	50492.0	15809.1	-66301.1	100.6	20	0.150
238	1119.00	39835.1	17063.1	-56898.2	50630.1	16014.2	-66644.3	100.7	20	0.150
239	1139.00	39949.8	17268.8	-57218.6	50758.2	16208.2	-66966.5	100.8	20	0.150
240	1179.00	40151.9	17646.9	-57798.9	50983.4	16566.4	-67549.8	100.9	20	0.150
241	1219.00	40318.0	17985.0	-58302.9	51167.6	16887.6	-68055.1	101.1	20	0.150
242	1299.00	40594.3	18570.3	-59164.6	51472.9	17441.9	-68914.7	101.4	20	0.150
243	1379.00	40860.5	19134.5	-59995.0	51767.1	17977.1	-69744.3	101.7	20	0.150
244	1510.00	41284.2	20042.2	-61326.4	52234.6	18835.6	-71070.2	102.2	20	0.150
245	1512.00	41259.6	20143.6	-61403.3	52213.6	18938.6	-71152.3	102.2	20	0.150
246	1513.00	41289.9	20199.9	-61489.7	52432.7	18996.7	-71429.4	103.8	20	0.150
247	1514.00	41380.1	20266.1	-61646.3	52866.9	19063.8	-71930.7	105.5	20	0.150
248	1515.00	41505.4	20338.4	-61843.9	53291.0	19135.0	-72426.0	107.4	20	0.150
249	1516.00	41656.8	20416.8	-62073.6	53724.1	19212.1	-72936.3	109.3	20	0.150
250	1517.00	41830.2	20501.2	-62331.3	54160.3	19294.3	-73454.5	111.3	20	0.150
251	1518.00	42020.5	20590.5	-62611.1	54598.4	19381.4	-73979.8	113.3	20	0.150
252	1519.00	42227.0	20684.0	-62911.0	55036.5	19471.5	-74508.0	115.4	20	0.150
253	1520.00	42441.4	20783.4	-63224.8	55471.6	19566.6	-75038.3	117.4	20	0.150
254	1521.00	42664.9	20886.9	-63551.8	55903.8	19665.8	-75569.5	119.5	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
255	1522.00	42898.4	20993.4	-63891.8	56333.9	19768.9	-76102.8	121.7	20	0.150
256	1523.00	43137.9	21104.9	-64242.8	56759.0	19875.0	-76634.0	123.8	20	0.150
257	1524.00	43384.5	21221.5	-64606.0	57179.1	19986.1	-77165.2	126.0	20	0.150
258	1525.00	43635.0	21341.1	-64976.1	57596.2	20100.2	-77696.4	128.1	20	0.150
259	1526.00	43885.6	21465.6	-65351.2	58008.3	20218.3	-78226.6	130.3	20	0.150
260	1527.00	44140.2	21591.3	-65731.5	58418.4	20338.4	-78756.8	132.5	20	0.150
261	1528.00	44395.8	21720.8	-66116.6	58822.5	20462.5	-79285.0	134.7	20	0.150
262	1529.00	44653.4	21853.4	-66506.9	59224.6	20587.6	-79812.2	136.9	20	0.150
263	1530.00	44911.1	21990.1	-66901.3	59619.7	20718.7	-80338.4	139.1	20	0.150
264	1531.00	45171.8	22129.8	-67301.6	60011.8	20850.8	-80862.5	141.3	20	0.150
265	1532.00	45431.5	22272.5	-67704.0	60398.8	20985.9	-81384.7	143.5	20	0.150
266	1533.00	45692.2	22418.2	-68110.3	60781.9	21124.9	-81906.9	145.7	20	0.150
267	1534.00	45950.9	22565.9	-68516.8	61160.0	21265.0	-82425.0	147.9	20	0.150
268	1535.00	46209.6	22716.6	-68926.3	61536.1	21408.1	-82944.2	150.2	20	0.150
269	1536.00	46467.3	22868.3	-69335.7	61906.2	21553.2	-83459.4	152.4	20	0.150
270	1537.00	46725.1	23024.1	-69749.2	62273.2	21701.3	-83974.5	154.7	20	0.150
271	1538.00	46981.9	23180.9	-70162.8	62637.3	21850.3	-84487.6	156.9	20	0.150
272	1539.00	47236.7	23340.7	-70577.3	62996.4	22002.4	-84998.8	159.2	20	0.150
273	1540.00	47490.4	23503.4	-70993.9	63352.5	22156.5	-85508.9	161.4	20	0.150
274	1541.00	47744.2	23667.2	-71411.4	63703.5	22313.5	-86017.1	163.7	20	0.150
275	1542.00	47994.1	23834.0	-71828.1	64050.6	22471.6	-86522.2	165.9	20	0.150
276	1543.00	48243.9	24001.9	-72245.8	64395.7	22631.7	-87027.3	168.2	20	0.150
277	1544.00	48492.7	24170.7	-72663.3	64736.8	22792.7	-87529.5	170.5	20	0.150
278	1545.00	48737.5	24342.5	-73080.0	65072.8	22955.8	-88028.6	172.8	20	0.150
279	1546.00	48982.4	24514.4	-73496.7	65406.9	23119.9	-88526.8	175.0	20	0.150
280	1547.00	49225.2	24688.2	-73913.4	65737.9	23285.0	-89022.9	177.3	20	0.150
281	1548.00	49466.1	24863.1	-74329.2	66064.0	23452.0	-89516.0	179.6	20	0.150
282	1549.00	49704.9	25039.9	-74744.9	66387.1	23621.1	-90008.1	181.9	20	0.150
283	1550.00	49942.9	25217.9	-75160.7	66706.1	23791.1	-90497.3	184.2	20	0.150
284	1551.00	50177.7	25397.7	-75575.4	67021.2	23963.2	-90984.4	186.5	20	0.150
285	1552.00	50410.7	25579.6	-75990.3	67334.2	24135.3	-91469.5	188.8	20	0.150
286	1553.00	50642.5	25762.5	-76405.0	67643.3	24309.3	-91952.6	191.1	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
287	1554.00	50872.4	25946.4	-76818.9	67948.4	24485.4	-92433.7	193.4	20	0.150
288	1555.00	51099.4	26130.4	-77229.8	68249.4	24661.4	-92910.9	195.7	20	0.150
289	1556.00	51324.3	26317.2	-77641.5	68548.5	24838.5	-93387.0	198.0	20	0.150
290	1557.00	51548.2	26503.2	-78051.4	68844.5	25016.5	-93861.1	200.3	20	0.150
291	1558.00	51769.1	26690.1	-78459.2	69137.6	25194.6	-94332.2	202.6	20	0.150
292	1559.00	51989.1	26878.1	-78867.1	69426.7	25374.7	-94801.4	204.9	20	0.150
293	1560.00	52207.0	27066.0	-79273.0	69713.7	25554.7	-95268.5	207.2	20	0.150
294	1561.00	52423.0	27256.0	-79678.9	69996.8	25735.8	-95732.5	209.5	20	0.150
295	1562.00	52634.9	27445.9	-80080.8	70275.8	25916.8	-96192.7	211.8	20	0.150
296	1563.00	52846.9	27636.9	-80483.7	70552.9	26098.9	-96651.8	214.1	20	0.150
297	1564.00	53056.9	27827.9	-80884.8	70827.9	26281.0	-97108.9	216.4	20	0.150
298	1565.00	53264.8	28018.8	-81283.7	71099.0	26464.0	-97563.0	218.7	20	0.150
299	1566.00	53468.8	28211.8	-81680.6	71366.1	26648.1	-98014.2	221.0	20	0.150
300	1567.00	53672.7	28404.8	-82077.5	71632.1	26832.1	-98464.3	223.3	20	0.150
301	1568.00	53874.8	28598.8	-82473.5	71894.2	27018.2	-98912.4	225.6	20	0.150
302	1569.00	54074.7	28792.7	-82867.5	72154.2	27203.2	-99357.5	227.9	20	0.150
303	1570.00	54272.7	28986.7	-83259.4	72411.3	27389.3	-99800.6	230.2	20	0.150
304	1571.00	54467.7	29182.7	-83650.4	72664.4	27576.3	-100240.7	232.5	20	0.150
305	1572.00	54660.7	29379.7	-84040.4	72915.4	27763.4	-100678.8	234.9	20	0.150
306	1573.00	54852.7	29575.7	-84428.4	73163.4	27951.4	-101114.9	237.2	20	0.150
307	1574.00	55043.8	29770.7	-84814.5	73409.5	28139.5	-101549.0	239.5	20	0.150
308	1575.00	55230.7	29968.7	-85199.4	73652.6	28327.5	-101980.1	241.8	20	0.150
309	1576.00	55417.7	30164.8	-85582.5	73894.6	28515.6	-102410.2	244.1	20	0.150
310	1577.00	55602.7	30361.7	-85964.5	74133.7	28704.7	-102838.4	246.4	20	0.150
311	1578.00	55786.8	30558.8	-86345.5	74370.7	28892.8	-103263.5	248.8	20	0.150
312	1579.00	55968.8	30755.8	-86724.6	74604.8	29082.8	-103687.6	251.1	20	0.150
313	1580.00	56147.8	30953.8	-87101.6	74836.9	29270.9	-104107.7	253.4	20	0.150
314	1581.00	56326.8	31151.8	-87478.7	75067.9	29460.9	-104528.8	255.7	20	0.150
315	1582.00	56503.9	31349.9	-87853.8	75298.0	29648.9	-104946.9	258.1	20	0.150
316	1583.00	56679.9	31547.9	-88227.7	75525.0	29839.0	-105364.0	260.4	20	0.150
317	1584.00	56853.9	31745.9	-88599.8	75750.1	30029.1	-105779.1	262.7	20	0.150
318	1585.00	57027.0	31944.0	-88970.9	75973.1	30219.1	-106192.3	265.1	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
319	1586.00	57198.0	32143.0	-89341.0	76194.2	30409.2	-106603.4	267.4	20	0.150
320	1587.00	57368.1	32341.1	-89709.1	76413.2	30599.2	-107012.5	269.7	20	0.150
321	1588.00	57536.1	32540.0	-90076.1	76630.3	30789.3	-107419.6	272.1	20	0.150
322	1589.00	57702.1	32739.1	-90441.2	76843.4	30980.4	-107823.7	274.4	20	0.150
323	1590.00	57867.2	32938.2	-90805.3	77056.4	31170.4	-108226.8	276.7	20	0.150
324	1591.00	58030.2	33138.2	-91168.4	77266.5	31361.5	-108628.0	279.1	20	0.150
325	1592.00	58192.3	33337.3	-91529.5	77473.5	31553.5	-109027.0	281.4	20	0.150
326	1593.00	58352.3	33536.3	-91888.7	77678.6	31744.6	-109423.2	283.8	20	0.150
327	1594.00	58511.4	33736.4	-92247.8	77883.6	31934.6	-109818.3	286.1	20	0.150
328	1595.00	58669.5	33935.5	-92604.9	78085.7	32125.7	-110211.4	288.4	20	0.150
329	1596.00	58825.5	34134.5	-92960.1	78285.7	32317.8	-110603.5	290.8	20	0.150
330	1597.00	58980.6	34333.6	-93314.2	78484.8	32507.8	-110992.6	293.1	20	0.150
331	1598.00	59133.7	34532.7	-93666.3	78680.9	32698.9	-111379.8	295.5	20	0.150
332	1599.00	59286.7	34731.7	-94018.4	78875.9	32889.9	-111765.8	297.8	20	0.150
333	1600.00	59437.7	34930.7	-94368.5	79070.0	33079.9	-112149.9	300.2	20	0.150
334	1601.00	59587.8	35128.8	-94716.6	79261.0	33271.1	-112532.1	302.5	20	0.150
335	1602.00	59734.9	35328.9	-95063.8	79450.1	33461.1	-112911.2	304.9	20	0.150
336	1603.00	59882.0	35527.0	-95408.9	79638.1	33652.2	-113290.3	307.2	20	0.150
337	1604.00	60027.0	35726.0	-95753.0	79823.2	33842.2	-113665.4	309.5	20	0.150
338	1605.00	60171.1	35923.1	-96094.2	80007.2	34031.3	-114038.5	311.9	20	0.150
339	1606.00	60314.2	36120.2	-96434.4	80189.3	34221.3	-114410.7	314.2	20	0.150
340	1607.00	60454.3	36318.3	-96772.5	80368.4	34410.4	-114778.7	316.6	20	0.150
341	1608.00	60594.3	36515.3	-97109.7	80547.4	34599.4	-115146.9	318.9	20	0.150
342	1609.00	60732.4	36713.4	-97445.7	80723.5	34788.5	-115511.9	321.3	20	0.150
343	1610.00	60869.4	36910.5	-97779.9	80898.5	34977.6	-115876.1	323.7	20	0.150
344	1611.00	61004.5	37106.5	-98111.1	81070.6	35166.6	-116237.2	326.0	20	0.150
345	1612.00	61138.6	37304.6	-98443.2	81241.7	35355.7	-116597.3	328.4	20	0.150
346	1613.00	61272.7	37499.7	-98772.4	81411.7	35543.7	-116955.4	330.7	20	0.150
347	1614.00	61404.7	37696.7	-99101.5	81579.8	35732.8	-117312.5	333.1	20	0.150
348	1615.00	61533.8	37893.8	-99427.7	81744.8	35921.8	-117666.7	335.4	20	0.150
349	1616.00	61663.9	38089.9	-99753.8	81910.9	36108.9	-118019.8	337.8	20	0.150
350	1617.00	61793.0	38285.0	-100078.0	82074.9	36297.0	-118371.9	340.1	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
351	1618.00	61920.1	38481.1	-100401.2	82237.0	36485.0	-118722.0	342.5	20	0.150
352	1619.00	62047.1	38676.1	-100723.3	82398.0	36672.1	-119070.1	344.8	20	0.150
353	1620.00	62171.2	38871.2	-101042.5	82556.1	36860.1	-119416.2	347.2	20	0.150
354	1621.00	62295.3	39066.3	-101361.7	82714.1	37047.2	-119761.3	349.6	20	0.150
355	1622.00	62419.4	39260.4	-101679.8	82871.2	37234.2	-120105.5	351.9	20	0.150
356	1623.00	62540.5	39456.5	-101996.9	83026.3	37420.3	-120446.6	354.3	20	0.150
357	1624.00	62660.6	39649.6	-102310.1	83177.4	37607.3	-120784.7	356.6	20	0.150
358	1625.00	62779.7	39844.7	-102624.3	83328.4	37793.4	-121121.8	359.0	20	0.150
359	1626.00	62898.8	40036.8	-102935.5	83477.5	37979.5	-121456.9	361.3	20	0.150
360	1627.00	63014.8	40231.8	-103246.6	83624.5	38165.5	-121790.0	363.7	20	0.150
361	1628.00	63129.9	40423.9	-103553.8	83769.6	38350.5	-122120.1	366.0	20	0.150
362	1629.00	63244.0	40618.0	-103862.0	83914.6	38535.6	-122450.3	368.4	20	0.150
363	1630.00	63358.1	40809.1	-104167.1	84057.7	38720.7	-122778.4	370.8	20	0.150
364	1631.00	63470.2	41002.2	-104472.4	84198.7	38905.7	-123104.5	373.1	20	0.150
365	1632.00	63580.2	41194.2	-104774.5	84338.8	39089.8	-123428.6	375.5	20	0.150
366	1633.00	63689.3	41386.3	-105075.7	84476.9	39273.9	-123750.7	377.8	20	0.150
367	1634.00	63798.5	41578.4	-105376.9	84614.9	39457.9	-124072.8	380.2	20	0.150
368	1635.00	63906.5	41769.5	-105676.0	84751.0	39642.0	-124392.9	382.5	20	0.150
369	1636.00	64013.6	41959.6	-105973.2	84886.0	39826.0	-124712.1	384.9	20	0.150
370	1637.00	64118.7	42150.7	-106269.4	85020.1	40008.1	-125028.2	387.2	20	0.150
371	1638.00	64223.8	42340.8	-106564.6	85153.1	40191.1	-125344.3	389.6	20	0.150
372	1639.00	64327.9	42531.8	-106859.7	85285.2	40373.2	-125658.4	391.9	20	0.150
373	1640.00	64432.0	42721.0	-107152.9	85416.3	40555.2	-125971.5	394.3	20	0.150
374	1641.00	64533.0	42910.0	-107443.1	85545.3	40737.3	-126282.7	396.7	20	0.150
375	1642.00	64635.1	43099.1	-107734.3	85673.4	40919.4	-126592.8	399.0	20	0.150
376	1643.00	64736.2	43288.2	-108024.4	85801.4	41100.4	-126901.9	401.4	20	0.150
377	1644.00	64836.3	43476.3	-108312.7	85928.5	41281.5	-127210.0	403.7	20	0.150
378	1645.00	64934.4	43664.4	-108598.8	86054.6	41462.5	-127517.1	406.1	20	0.150
379	1646.00	65033.5	43852.5	-108886.0	86180.6	41643.6	-127824.2	408.5	20	0.150
380	1647.00	65131.6	44039.6	-109171.2	86306.6	41822.7	-128129.3	410.8	20	0.150
381	1648.00	65228.7	44227.7	-109456.4	86430.7	42003.7	-128434.5	413.2	20	0.150
382	1649.00	65324.8	44414.8	-109739.5	86553.8	42183.8	-128737.6	415.6	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
383	1650.00	65419.8	44601.9	-110021.7	86676.8	42362.8	-129039.7	418.0	20	0.150
384	1651.00	65516.0	44788.0	-110303.9	86798.9	42541.9	-129340.8	420.3	20	0.150
385	1652.00	65610.0	44974.0	-110584.1	86920.0	42719.9	-129639.9	422.7	20	0.150
386	1653.00	65702.1	45161.1	-110863.2	87038.0	42900.0	-129938.0	425.1	20	0.150
387	1654.00	65795.2	45346.2	-111141.5	87157.1	43078.1	-130235.1	427.4	20	0.150
388	1655.00	65887.3	45531.3	-111418.6	87275.1	43255.1	-130530.2	429.8	20	0.150
389	1656.00	65978.4	45716.4	-111694.8	87390.2	43434.2	-130824.4	432.2	20	0.150
390	1657.00	66068.5	45901.5	-111970.0	87506.2	43611.2	-131117.5	434.6	20	0.150
391	1658.00	66158.6	46085.6	-112244.2	87620.3	43789.3	-131409.6	436.9	20	0.150
392	1659.00	66246.7	46270.7	-112517.3	87734.4	43965.4	-131699.7	439.3	20	0.150
393	1660.00	66333.7	46454.8	-112788.5	87845.4	44142.4	-131987.9	441.7	20	0.150
394	1661.00	66421.9	46637.9	-113059.8	87956.5	44319.5	-132276.0	444.1	20	0.150
395	1662.00	66508.0	46820.9	-113328.9	88067.5	44494.5	-132562.1	446.5	20	0.150
396	1663.00	66594.0	47004.0	-113598.1	88176.6	44670.6	-132847.2	448.8	20	0.150
397	1664.00	66677.1	47187.1	-113864.2	88283.7	44846.7	-133130.3	451.2	20	0.150
398	1665.00	66761.2	47369.2	-114130.5	88390.7	45022.8	-133413.5	453.6	20	0.150
399	1666.00	66844.3	47552.3	-114396.7	88497.8	45196.8	-133694.6	456.0	20	0.150
400	1667.00	66927.4	47733.4	-114660.8	88602.9	45371.8	-133974.7	458.4	20	0.150
401	1668.00	67007.5	47915.5	-114923.0	88705.9	45546.9	-134252.8	460.7	20	0.150
402	1669.00	67088.6	48096.6	-115185.1	88809.0	45721.0	-134529.9	463.1	20	0.150
403	1670.00	67168.7	48276.7	-115445.3	88911.0	45895.0	-134806.0	465.5	20	0.150
404	1671.00	67246.7	48457.8	-115704.5	89011.1	46069.1	-135080.2	467.9	20	0.150
405	1672.00	67324.9	48638.9	-115963.8	89111.2	46242.1	-135353.3	470.3	20	0.150
406	1673.00	67402.0	48819.0	-116221.0	89210.2	46414.2	-135624.4	472.7	20	0.150
407	1674.00	67479.1	48998.1	-116477.1	89308.3	46587.2	-135895.5	475.1	20	0.150
408	1675.00	67554.2	49177.2	-116731.3	89405.3	46759.3	-136164.6	477.4	20	0.150
409	1676.00	67630.2	49355.3	-116985.5	89502.4	46930.4	-136432.8	479.8	20	0.150
410	1677.00	67705.3	49534.3	-117239.7	89598.4	47102.4	-136700.9	482.2	20	0.150
411	1678.00	67780.4	49711.4	-117491.9	89693.5	47274.5	-136968.0	484.6	20	0.150
412	1679.00	67853.5	49889.5	-117743.1	89787.6	47444.6	-137232.1	487.0	20	0.150
413	1680.00	67927.6	50066.6	-117994.2	89881.6	47615.6	-137497.3	489.4	20	0.150
414	1681.00	68000.7	50243.7	-118244.4	89975.7	47785.7	-137761.4	491.8	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
415	1682.00	68071.8	50421.8	-118493.6	90067.7	47955.8	-138023.5	494.2	20	0.150
416	1683.00	68143.8	50597.8	-118741.7	90160.8	48124.8	-138285.6	496.5	20	0.150
417	1684.00	68215.9	50773.9	-118989.9	90251.9	48295.9	-138547.8	498.9	20	0.150
418	1685.00	68287.0	50950.0	-119237.1	90342.9	48464.9	-138807.8	501.3	20	0.150
419	1686.00	68356.1	51126.1	-119482.2	90433.0	48633.0	-139066.0	503.7	20	0.150
420	1687.00	68426.2	51301.2	-119727.4	90521.0	48802.0	-139323.1	506.1	20	0.150
421	1688.00	68495.3	51476.3	-119971.6	90608.1	48970.1	-139578.2	508.5	20	0.150
422	1689.00	68562.4	51651.4	-120213.8	90693.2	49138.2	-139831.3	510.9	20	0.150
423	1690.00	68630.5	51825.5	-120455.9	90778.2	49306.2	-140084.5	513.2	20	0.150
424	1691.00	68697.6	51999.6	-120697.1	90863.3	49473.3	-140336.6	515.6	20	0.150
425	1692.00	68763.6	52173.6	-120937.2	90947.3	49640.3	-140587.7	518.0	20	0.150
426	1693.00	68828.7	52346.7	-121175.4	91029.4	49807.4	-140836.8	520.4	20	0.150
427	1694.00	68893.8	52519.8	-121413.6	91112.5	49973.5	-141085.9	522.8	20	0.150
428	1695.00	68958.9	52691.9	-121650.7	91194.5	50139.5	-141334.1	525.1	20	0.150
429	1696.00	69022.0	52865.0	-121886.9	91274.6	50305.6	-141580.2	527.5	20	0.150
430	1697.00	69085.1	53037.1	-122122.2	91355.6	50471.6	-141827.3	529.9	20	0.150
431	1698.00	69148.1	53209.1	-122357.2	91436.7	50635.7	-142072.4	532.3	20	0.150
432	1699.00	69210.2	53381.2	-122591.5	91515.8	50801.7	-142317.5	534.7	20	0.150
433	1700.00	69271.3	53551.3	-122822.6	91594.8	50964.8	-142559.7	537.0	20	0.150
434	1701.00	69333.4	53721.4	-123054.8	91672.9	51129.9	-142802.8	539.4	20	0.150
435	1702.00	69394.4	53892.5	-123286.9	91751.0	51294.0	-143044.9	541.8	20	0.150
436	1703.00	69453.5	54062.6	-123516.1	91828.0	51457.0	-143285.0	544.2	20	0.150
437	1704.00	69513.6	54232.6	-123746.2	91904.1	51621.1	-143525.2	546.6	20	0.150
438	1705.00	69572.7	54401.7	-123974.3	91981.1	51783.1	-143764.3	549.0	20	0.150
439	1706.00	69631.8	54570.8	-124202.5	92056.2	51946.2	-144002.4	551.3	20	0.150
440	1707.00	69689.8	54739.8	-124429.7	92131.2	52108.2	-144239.5	553.7	20	0.150
441	1708.00	69747.9	54907.9	-124655.8	92207.3	52271.3	-144478.6	556.1	20	0.150
442	1709.00	69806.0	55076.0	-124882.0	92283.4	52433.4	-144716.7	558.5	20	0.150
443	1710.00	69862.0	55245.0	-125107.1	92358.4	52594.4	-144952.8	560.9	20	0.150
444	1711.00	69914.7	55365.7	-125280.4	92335.4	52707.4	-145042.8	562.5	20	0.150
445	1712.00	69926.3	55479.3	-125405.7	92153.4	52815.4	-144968.8	563.7	20	0.150
446	1714.00	69845.4	55689.5	-125534.9	91603.3	53012.3	-144615.6	565.4	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
447	1716.00	69666.5	55876.5	-125542.9	90974.2	53190.2	-144164.4	566.6	20	0.150
448	1719.00	69272.9	56118.9	-125391.8	89974.0	53422.0	-143396.0	568.0	20	0.150
449	1722.00	68784.2	56320.2	-125104.3	88968.9	53615.9	-142584.8	569.2	20	0.150
450	1726.00	68049.7	56529.7	-124579.4	87653.7	53821.7	-141475.4	570.5	20	0.150
451	1730.00	67269.1	56682.1	-123951.1	86381.6	53973.6	-140355.2	571.6	20	0.150
452	1735.00	66266.5	56801.6	-123068.1	84861.5	54095.5	-138957.1	572.8	20	0.150
453	1740.00	65265.8	56853.8	-122119.7	83417.5	54153.5	-137571.0	573.9	20	0.150
454	1746.00	64091.2	56845.2	-120936.4	81779.5	54154.5	-135933.9	575.0	20	0.150
455	1752.00	62958.4	56770.4	-119728.7	80241.5	54091.5	-134333.0	576.1	20	0.150
456	1759.00	61707.4	56618.5	-118325.9	78575.6	53954.5	-132530.1	577.2	20	0.150
457	1766.00	60527.3	56418.3	-116945.6	77026.6	53770.6	-130797.2	578.3	20	0.150
458	1774.00	59270.1	56136.1	-115406.3	75397.7	53507.7	-128905.4	579.4	20	0.150
459	1782.00	58098.7	55819.7	-113918.5	73893.8	53210.8	-127104.6	580.4	20	0.150
460	1791.00	56877.2	55428.2	-112305.3	72340.9	52841.9	-125182.8	581.5	20	0.150
461	1800.00	55746.4	55011.5	-110757.9	70915.0	52447.0	-123361.9	582.5	20	0.150
462	1810.00	54585.5	54528.5	-109114.1	69462.1	51990.1	-121452.2	583.6	20	0.150
463	1820.00	53516.4	54030.4	-107546.7	68133.2	51516.2	-119649.3	584.6	20	0.150
464	1830.00	52524.1	53524.1	-106048.2	66907.2	51034.2	-117941.5	585.6	20	0.150
465	1831.00	52429.1	53474.1	-105903.1	66791.2	50985.3	-117776.5	585.6	20	0.150
466	1841.00	51509.6	52960.5	-104470.1	65663.3	50496.3	-116159.7	586.5	20	0.150
467	1843.00	51334.4	52858.4	-104192.9	65449.3	50399.3	-115848.7	586.7	20	0.150
468	1853.00	50493.8	52350.8	-102844.6	64423.4	49914.4	-114337.8	587.5	20	0.150
469	1856.00	50254.6	52199.6	-102454.2	64132.4	49770.4	-113902.8	587.8	20	0.150
470	1866.00	49496.8	51702.8	-101199.5	63213.5	49295.5	-112508.9	588.5	20	0.150
471	1870.00	49213.4	51505.4	-100718.8	62872.5	49107.5	-111980.0	588.8	20	0.150
472	1880.00	48536.4	51023.4	-99559.8	62055.5	48646.5	-110702.0	589.5	20	0.150
473	1885.00	48212.9	50785.9	-98998.8	61668.5	48419.5	-110088.0	589.8	20	0.150
474	1895.00	47586.8	50317.8	-97904.7	60915.6	47972.6	-108888.1	590.4	20	0.150
475	1902.00	47169.0	49995.0	-97164.0	60418.5	47663.6	-108082.1	590.9	20	0.150
476	1912.00	46596.8	49540.8	-96137.7	59732.5	47230.6	-106963.1	591.4	20	0.150
477	1921.00	46110.6	49140.6	-95251.3	59156.6	46847.6	-106004.1	591.9	20	0.150
478	1931.00	45598.3	48703.3	-94301.7	58545.5	46430.6	-104976.1	592.4	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
479	1941.00	45118.9	48276.9	-93395.8	57981.5	46022.5	-104004.1	592.9	20	0.150
480	1942.00	45072.8	48234.8	-93307.5	57927.5	45982.5	-103910.0	593.0	20	0.150
481	1952.00	44626.3	47818.3	-92444.6	57399.5	45585.5	-102985.0	593.4	20	0.150
482	1962.00	44200.8	47418.8	-91619.7	56900.5	45204.5	-102104.9	593.8	20	0.150
483	1966.00	44035.3	47261.3	-91296.6	56707.4	45053.4	-101760.9	594.0	20	0.150
484	1976.00	43628.8	46871.8	-90500.6	56227.4	44681.4	-100908.8	594.3	20	0.150
485	1986.00	43236.3	46488.3	-89724.7	55770.4	44315.4	-100085.8	594.7	20	0.150
486	1994.00	42936.1	46186.1	-89122.3	55421.3	44027.4	-99448.7	595.0	20	0.150
487	2004.00	42567.6	45814.6	-88382.2	54988.3	43672.3	-98660.6	595.3	20	0.150
488	2014.00	42215.1	45450.1	-87665.2	54578.2	43324.2	-97902.5	595.6	20	0.150
489	2024.00	41889.5	45096.5	-86986.1	54202.2	42988.2	-97190.4	595.9	20	0.150
490	2028.00	41765.9	44959.9	-86725.8	54061.2	42856.2	-96917.3	596.0	20	0.150
491	2038.00	41467.3	44628.3	-86095.7	53711.1	42541.1	-96252.2	596.2	20	0.150
492	2048.00	41181.8	44305.8	-85487.6	53382.0	42233.0	-95615.0	596.4	20	0.150
493	2058.00	40907.2	43990.2	-84897.4	53066.9	41932.9	-94999.9	596.7	20	0.150
494	2068.00	40645.7	43681.7	-84327.4	52766.9	41638.9	-94405.8	596.9	20	0.150
495	2072.00	40542.1	43561.1	-84103.2	52648.8	41523.8	-94172.7	597.0	20	0.150
496	2082.00	40288.6	43260.6	-83549.3	52351.8	41238.8	-93590.5	597.2	20	0.150
497	2092.00	40041.1	42968.1	-83009.2	52066.7	40959.7	-93026.4	597.3	20	0.150
498	2102.00	39804.7	42679.7	-82484.3	51795.6	40686.6	-92482.2	597.5	20	0.150
499	2112.00	39578.2	42400.2	-81978.4	51537.5	40419.5	-91957.1	597.6	20	0.150
500	2132.00	39153.4	41861.4	-81014.7	51055.4	39906.4	-90961.7	598.0	20	0.150
501	2134.00	39114.0	41808.1	-80922.1	51010.4	39855.4	-90865.7	598.0	20	0.150
502	2144.00	38912.7	41549.7	-80462.4	50774.3	39610.3	-90384.5	598.1	20	0.150
503	2154.00	38717.3	41297.3	-80014.7	50551.2	39369.2	-89920.4	598.2	20	0.150
504	2164.00	38531.0	41051.0	-79581.9	50339.1	39135.1	-89474.1	598.3	20	0.150
505	2174.00	38356.6	40811.6	-79168.2	50141.0	38907.0	-89048.0	598.4	20	0.150
506	2194.00	38033.0	40355.1	-78388.1	49776.8	38472.8	-88249.6	598.6	20	0.150
507	2214.00	37744.5	39925.5	-77670.1	49452.6	38064.6	-87517.2	598.8	20	0.150
508	2234.00	37463.2	39505.2	-76968.3	49135.4	37666.4	-86801.9	599.0	20	0.150
509	2239.00	37393.5	39401.5	-76795.1	49057.4	37567.4	-86624.8	599.0	20	0.150
510	2249.00	37246.4	39192.4	-76438.8	48883.3	37368.3	-86251.6	599.0	20	0.150

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
511	2259.00	37098.2	38982.2	-76080.5	48713.2	37168.2	-85881.4	599.0	20	0.150
512	2269.00	36951.1	38771.1	-75722.2	48546.1	36967.1	-85513.3	599.0	20	0.150
513	2279.00	36807.0	38559.9	-75366.9	48382.0	36766.0	-85148.1	599.0	20	0.150
514	2299.00	36520.7	38138.7	-74659.4	48058.8	36365.8	-84424.7	599.1	20	0.150
515	2319.00	36247.5	37721.5	-73968.9	47750.7	35970.7	-83721.3	599.1	20	0.150
516	2339.00	36002.4	37330.4	-73332.7	47476.5	35597.5	-83074.0	599.1	20	0.150
517	2379.00	35574.6	36617.6	-72192.2	46997.1	34920.1	-81917.2	599.1	20	0.150
518	2419.00	35224.4	36002.4	-71226.8	46606.8	34334.8	-80941.6	599.2	20	0.150
519	2499.00	34744.6	35060.5	-69805.1	46073.2	33439.2	-79512.4	599.3	20	0.150
520	2579.00	34401.2	34352.2	-68753.4	45689.8	32766.8	-78456.6	599.4	20	0.150
521	2739.00	33740.6	33000.6	-66741.1	44955.0	31477.0	-76432.0	599.5	20	0.150
522	2899.00	33104.1	31683.1	-64787.2	44244.2	30222.2	-74466.5	599.7	20	0.150
523	3210.00	32518.4	30204.4	-62722.8	43589.3	28808.3	-72397.6	600.0	20	0.150
524	3210.00	36431.2	25862.2	-62293.4	47466.4	24528.4	-71994.8	500.0	50	0.550
525	3220.00	36424.2	25861.2	-62285.4	47449.4	24527.4	-71976.8	499.9	50	0.550
526	3230.00	36414.2	25858.2	-62272.4	47435.4	24524.4	-71959.8	499.8	50	0.550
527	3240.00	36405.2	25854.2	-62259.4	47422.4	24520.4	-71942.8	499.8	50	0.550
528	3250.00	36396.2	25850.2	-62246.4	47411.4	24516.4	-71927.8	499.7	50	0.550
529	3270.00	36381.2	25841.2	-62222.3	47392.4	24507.4	-71899.8	499.5	50	0.550
530	3290.00	36369.2	25831.2	-62200.3	47376.4	24498.4	-71874.8	499.4	50	0.550
531	3310.00	36359.2	25821.2	-62180.3	47364.4	24488.4	-71852.8	499.2	50	0.550
532	3311.00	36318.3	25804.3	-62122.6	47322.4	24473.4	-71795.7	499.2	50	0.550
533	3312.00	36245.5	25784.5	-62029.9	47102.3	24452.3	-71554.5	498.0	50	0.550
534	3313.00	36122.6	25754.6	-61877.2	46695.1	24424.1	-71119.2	496.5	50	0.550
535	3314.00	35964.7	25720.7	-61685.4	46267.0	24391.0	-70658.0	494.8	50	0.550
536	3315.00	35780.8	25679.8	-61460.7	45817.8	24352.8	-70170.7	493.0	50	0.550
537	3316.00	35572.9	25634.0	-61206.9	45356.7	24309.7	-69666.4	491.2	50	0.550
538	3317.00	35347.1	25583.0	-60930.1	44888.5	24262.5	-69151.1	489.2	50	0.550
539	3318.00	35104.1	25527.1	-60631.3	44416.4	24210.4	-68626.8	487.3	50	0.550
540	3319.00	34851.3	25465.3	-60316.5	43943.2	24155.2	-68098.5	485.3	50	0.550
541	3320.00	34587.3	25401.3	-59988.7	43471.1	24095.1	-67566.2	483.2	50	0.550
542	3321.00	34315.4	25331.4	-59646.9	43001.0	24030.0	-67031.0	481.2	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
543	3322.00	34034.5	25258.5	-59293.0	42532.8	23962.8	-66495.7	479.1	50	0.550
544	3323.00	33745.6	25180.6	-58926.2	42067.7	23890.7	-65958.4	477.0	50	0.550
545	3324.00	33452.6	25098.6	-58551.3	41604.6	23815.6	-65420.1	474.9	50	0.550
546	3325.00	33156.7	25013.7	-58170.4	41144.5	23737.5	-64881.9	472.7	50	0.550
547	3326.00	32857.8	24924.8	-57782.5	40688.3	23655.3	-64343.7	470.6	50	0.550
548	3327.00	32556.8	24833.8	-57390.7	40235.2	23571.3	-63806.5	468.4	50	0.550
549	3328.00	32252.9	24737.9	-56990.8	39785.1	23482.1	-63267.3	466.2	50	0.550
550	3329.00	31947.9	24639.9	-56587.9	39339.0	23392.0	-62731.0	464.1	50	0.550
551	3330.00	31641.0	24538.0	-56179.0	38895.9	23297.9	-62193.8	461.9	50	0.550
552	3331.00	31333.0	24434.0	-55767.1	38457.8	23201.8	-61659.6	459.7	50	0.550
553	3332.00	31025.1	24326.1	-55351.2	38023.7	23101.7	-61125.4	457.5	50	0.550
554	3333.00	30717.1	24215.1	-54932.2	37592.6	22998.6	-60591.2	455.3	50	0.550
555	3334.00	30409.2	24103.2	-54512.3	37165.5	22894.5	-60060.0	453.1	50	0.550
556	3335.00	30101.2	23988.2	-54089.4	36741.4	22787.4	-59528.9	450.8	50	0.550
557	3336.00	29795.2	23870.2	-53665.5	36322.3	22678.3	-59000.7	448.6	50	0.550
558	3337.00	29489.3	23750.3	-53239.5	35906.2	22566.2	-58472.5	446.4	50	0.550
559	3338.00	29183.3	23627.3	-52810.6	35493.2	22453.2	-57946.3	444.1	50	0.550
560	3339.00	28879.3	23502.3	-52381.6	35085.1	22337.1	-57422.1	441.9	50	0.550
561	3340.00	28575.3	23375.3	-51950.7	34680.0	22218.0	-56897.9	439.6	50	0.550
562	3341.00	28273.4	23247.4	-51520.7	34278.9	22097.9	-56376.8	437.4	50	0.550
563	3342.00	27972.4	23116.4	-51088.8	33880.8	21975.8	-55856.6	435.1	50	0.550
564	3343.00	27673.4	22984.4	-50657.8	33486.7	21852.7	-55339.5	432.8	50	0.550
565	3344.00	27375.4	22850.4	-50225.8	33094.6	21727.6	-54822.3	430.6	50	0.550
566	3345.00	27079.4	22714.4	-49793.9	32707.6	21600.6	-54308.1	428.3	50	0.550
567	3346.00	26784.5	22577.5	-49361.9	32322.5	21472.5	-53795.0	426.0	50	0.550
568	3347.00	26492.5	22438.5	-48930.9	31941.4	21343.4	-53284.8	423.7	50	0.550
569	3348.00	26200.5	22298.5	-48499.0	31563.3	21212.3	-52775.7	421.4	50	0.550
570	3349.00	25911.5	22156.5	-48068.0	31189.3	21080.3	-52269.5	419.2	50	0.550
571	3350.00	25623.5	22013.5	-47637.0	30818.2	20945.2	-51763.3	416.9	50	0.550
572	3351.00	25336.5	21869.5	-47206.0	30450.1	20810.1	-51260.2	414.6	50	0.550
573	3352.00	25053.5	21722.5	-46776.0	30087.0	20673.0	-50760.1	412.3	50	0.550
574	3353.00	24770.5	21574.5	-46345.0	29726.0	20534.0	-50259.9	410.0	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
575	3354.00	24490.5	21426.5	-45917.0	29368.9	20394.9	-49763.8	407.7	50	0.550
576	3355.00	24211.5	21277.5	-45489.0	29013.8	20254.8	-49268.6	405.4	50	0.550
577	3356.00	23935.5	21126.5	-45062.0	28662.7	20113.7	-48776.5	403.1	50	0.550
578	3357.00	23660.5	20975.5	-44636.0	28312.7	19971.7	-48284.3	400.7	50	0.550
579	3358.00	23386.5	20823.5	-44210.0	27966.6	19828.6	-47795.2	398.4	50	0.550
580	3359.00	23115.5	20670.5	-43786.0	27623.5	19685.5	-47309.0	396.1	50	0.550
581	3360.00	22845.5	20517.5	-43362.9	27281.4	19541.5	-46822.9	393.8	50	0.550
582	3361.00	22577.5	20363.5	-42940.9	26942.4	19397.4	-46339.8	391.5	50	0.550
583	3362.00	22311.5	20207.4	-42518.9	26606.3	19250.3	-45856.6	389.1	50	0.550
584	3363.00	22045.4	20052.4	-42097.9	26272.2	19104.3	-45376.5	386.8	50	0.550
585	3364.00	21783.4	19895.4	-41678.9	25941.2	18957.2	-44898.4	384.5	50	0.550
586	3365.00	21521.4	19738.4	-41259.8	25612.1	18810.1	-44422.2	382.1	50	0.550
587	3366.00	21263.4	19580.4	-40843.8	25287.0	18661.0	-43948.1	379.8	50	0.550
588	3367.00	21005.4	19421.4	-40426.8	24964.0	18512.0	-43475.9	377.5	50	0.550
589	3368.00	20748.4	19262.4	-40010.7	24643.9	18360.9	-43004.8	375.1	50	0.550
590	3369.00	20495.3	19102.3	-39597.7	24326.8	18210.8	-42537.7	372.8	50	0.550
591	3370.00	20242.3	18942.3	-39184.7	24011.8	18059.8	-42071.5	370.4	50	0.550
592	3371.00	19992.3	18781.3	-38773.6	23700.7	17907.7	-41608.4	368.1	50	0.550
593	3372.00	19743.3	18619.3	-38362.6	23390.6	17755.6	-41146.2	365.7	50	0.550
594	3373.00	19496.3	18457.3	-37953.6	23083.5	17602.6	-40686.1	363.4	50	0.550
595	3374.00	19251.2	18295.2	-37546.5	22779.5	17449.5	-40228.9	361.0	50	0.550
596	3375.00	19007.2	18132.2	-37139.4	22476.4	17296.4	-39772.8	358.6	50	0.550
597	3376.00	18764.2	17969.2	-36733.4	22175.3	17143.3	-39318.7	356.3	50	0.550
598	3377.00	18524.2	17806.2	-36330.4	21877.3	16990.3	-38867.5	353.9	50	0.550
599	3378.00	18285.1	17642.2	-35927.3	21581.2	16835.2	-38416.4	351.6	50	0.550
600	3379.00	18048.1	17479.1	-35527.3	21288.1	16681.1	-37969.2	349.2	50	0.550
601	3380.00	17811.1	17315.1	-35126.2	20996.0	16527.0	-37523.1	346.8	50	0.550
602	3381.00	17577.1	17150.1	-34727.1	20707.0	16372.0	-37079.0	344.5	50	0.550
603	3382.00	17345.1	16986.1	-34331.1	20421.9	16216.9	-36638.8	342.1	50	0.550
604	3383.00	17113.0	16822.0	-33935.1	20137.8	16061.9	-36199.7	339.7	50	0.550
605	3384.00	16885.0	16657.0	-33542.0	19856.8	15906.8	-35763.5	337.4	50	0.550
606	3385.00	16657.0	16492.0	-33149.0	19577.7	15750.7	-35328.4	335.0	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
607	3386.00	16429.9	16327.9	-32757.9	19300.6	15594.6	-34895.3	332.7	50	0.550
608	3387.00	16206.9	16161.9	-32368.8	19026.5	15438.5	-34465.1	330.3	50	0.550
609	3388.00	15983.9	15996.9	-31980.7	18753.5	15282.5	-34036.0	327.9	50	0.550
610	3389.00	15761.9	15831.9	-31593.7	18483.4	15126.4	-33609.8	325.5	50	0.550
611	3390.00	15542.8	15665.8	-31208.6	18216.3	14969.3	-33185.7	323.2	50	0.550
612	3391.00	15324.8	15499.8	-30824.6	17950.3	14812.3	-32762.5	320.8	50	0.550
613	3392.00	15108.8	15332.8	-30441.5	17686.2	14655.2	-32341.4	318.4	50	0.550
614	3393.00	14893.7	15167.7	-30061.4	17424.1	14499.1	-31923.3	316.0	50	0.550
615	3394.00	14679.7	15001.7	-29681.4	17164.1	14342.1	-31506.1	313.7	50	0.550
616	3395.00	14468.7	14835.6	-29304.3	16906.0	14186.0	-31092.0	311.3	50	0.550
617	3396.00	14257.6	14669.6	-28927.3	16648.9	14028.9	-30677.8	308.9	50	0.550
618	3397.00	14047.6	14503.6	-28551.2	16393.9	13872.9	-30266.7	306.5	50	0.550
619	3398.00	13839.5	14338.5	-28178.1	16141.8	13715.8	-29857.5	304.2	50	0.550
620	3399.00	13632.5	14172.5	-27805.0	15889.7	13558.7	-29448.4	301.8	50	0.550
621	3400.00	13426.5	14006.5	-27433.0	15639.6	13402.6	-29042.3	299.4	50	0.550
622	3401.00	13222.5	13841.5	-27063.9	15392.6	13245.6	-28638.1	297.0	50	0.550
623	3402.00	13019.4	13675.4	-26694.8	15146.5	13088.5	-28235.0	294.6	50	0.550
624	3403.00	12818.4	13510.4	-26328.7	14902.4	12932.4	-27834.8	292.2	50	0.550
625	3404.00	12618.4	13344.4	-25962.7	14660.3	12775.3	-27435.7	289.8	50	0.550
626	3405.00	12419.3	13178.3	-25597.6	14419.3	12619.3	-27038.6	287.5	50	0.550
627	3406.00	12222.3	13013.3	-25235.5	14180.2	12463.2	-26643.4	285.1	50	0.550
628	3407.00	12025.2	12848.2	-24873.5	13943.1	12307.1	-26250.3	282.7	50	0.550
629	3408.00	11830.2	12683.2	-24513.4	13707.1	12151.1	-25858.1	280.3	50	0.550
630	3409.00	11637.2	12518.2	-24155.3	13474.0	11994.0	-25468.0	277.9	50	0.550
631	3410.00	11444.1	12353.1	-23797.2	13241.9	11837.9	-25079.8	275.5	50	0.550
632	3411.00	11254.1	12188.1	-23442.2	13012.8	11681.8	-24694.7	273.1	50	0.550
633	3412.00	11064.0	12023.0	-23087.1	12783.8	11525.8	-24309.6	270.7	50	0.550
634	3413.00	10875.0	11858.0	-22733.0	12555.7	11369.7	-23925.4	268.3	50	0.550
635	3414.00	10688.0	11694.0	-22381.9	12330.6	11214.6	-23545.3	265.9	50	0.550
636	3415.00	10500.9	11529.9	-22030.9	12106.6	11058.6	-23165.1	263.5	50	0.550
637	3416.00	10315.9	11364.9	-21680.8	11883.5	10902.5	-22785.9	261.1	50	0.550
638	3417.00	10131.9	11200.9	-21332.7	11662.4	10747.4	-22409.8	258.7	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
639	3418.00	9948.8	11036.8	-20985.6	11442.3	10592.3	-22034.7	256.3	50	0.550
640	3419.00	9767.8	10872.8	-20640.5	11224.3	10437.3	-21661.5	253.9	50	0.550
641	3420.00	9585.7	10709.7	-20295.5	11006.2	10283.2	-21289.3	251.5	50	0.550
642	3421.00	9405.7	10546.7	-19952.4	10790.1	10129.1	-20919.2	249.1	50	0.550
643	3422.00	9227.7	10382.7	-19610.3	10577.0	9973.0	-20550.1	246.7	50	0.550
644	3423.00	9049.6	10219.6	-19269.2	10362.0	9820.0	-20181.9	244.3	50	0.550
645	3424.00	8873.6	10056.6	-18930.2	10149.9	9664.9	-19814.7	241.9	50	0.550
646	3425.00	8696.5	9894.5	-18591.1	9936.8	9510.8	-19447.6	239.4	50	0.550
647	3426.00	8521.5	9731.5	-18253.0	9724.7	9357.7	-19082.5	237.0	50	0.550
648	3427.00	8347.5	9569.5	-17916.9	9515.7	9203.7	-18719.3	234.6	50	0.550
649	3428.00	8173.4	9407.4	-17580.8	9306.6	9049.6	-18356.1	232.2	50	0.550
650	3429.00	8000.4	9245.4	-17245.7	9099.5	8895.5	-17995.0	229.7	50	0.550
651	3430.00	7830.3	9082.3	-16912.7	8893.4	8743.4	-17636.9	227.3	50	0.550
652	3431.00	7659.3	8921.3	-16580.6	8688.4	8590.4	-17278.7	224.9	50	0.550
653	3432.00	7490.2	8759.2	-16249.5	8486.3	8437.3	-16923.6	222.5	50	0.550
654	3433.00	7321.2	8598.2	-15919.4	8284.2	8284.2	-16568.4	220.0	50	0.550
655	3434.00	7153.2	8437.2	-15590.3	8083.1	8131.1	-16214.2	217.6	50	0.550
656	3435.00	6987.1	8276.1	-15263.2	7884.1	7979.1	-15863.1	215.2	50	0.550
657	3436.00	6821.1	8115.1	-14936.1	7685.0	7827.0	-15512.0	212.7	50	0.550
658	3437.00	6656.0	7955.0	-14611.1	7487.9	7674.9	-15162.8	210.3	50	0.550
659	3438.00	6492.0	7794.0	-14286.0	7290.8	7523.8	-14814.6	207.9	50	0.550
660	3439.00	6328.0	7634.0	-13961.9	7095.7	7371.7	-14467.5	205.4	50	0.550
661	3440.00	6165.9	7474.9	-13640.8	6901.7	7220.7	-14122.3	203.0	50	0.550
662	3441.00	6003.9	7314.9	-13318.8	6708.6	7069.6	-13778.2	200.6	50	0.550
663	3442.00	5842.8	7155.8	-12998.6	6517.5	6917.5	-13435.0	198.1	50	0.550
664	3443.00	5682.8	6996.8	-12679.6	6326.4	6767.4	-13093.9	195.7	50	0.550
665	3444.00	5523.7	6837.7	-12361.5	6138.3	6617.3	-12755.7	193.3	50	0.550
666	3445.00	5365.7	6679.7	-12045.4	5952.3	6467.3	-12419.5	190.8	50	0.550
667	3446.00	5208.7	6521.7	-11730.3	5766.2	6318.2	-12084.4	188.4	50	0.550
668	3447.00	5053.6	6363.6	-11417.2	5583.1	6168.1	-11751.2	186.0	50	0.550
669	3448.00	4898.6	6205.6	-11104.2	5400.0	6019.1	-11419.1	183.5	50	0.550
670	3449.00	4744.5	6047.5	-10792.1	5219.0	5869.0	-11088.0	181.1	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
671	3450.00	4592.5	5890.5	-10483.0	5038.9	5719.9	-10758.8	178.7	50	0.550
672	3451.00	4439.5	5734.5	-10173.9	4858.8	5571.8	-10430.7	176.2	50	0.550
673	3452.00	4289.4	5577.4	-9866.9	4681.8	5423.8	-10105.5	173.8	50	0.550
674	3453.00	4138.4	5421.4	-9559.8	4503.7	5275.7	-9779.4	171.4	50	0.550
675	3454.00	3989.4	5265.4	-9254.7	4327.6	5127.6	-9455.2	168.9	50	0.550
676	3455.00	3841.3	5109.3	-8950.6	4153.5	4980.5	-9134.1	166.5	50	0.550
677	3456.00	3693.3	4954.3	-8647.5	3978.4	4833.4	-8811.9	164.1	50	0.550
678	3457.00	3547.2	4799.2	-8346.4	3806.4	4686.4	-8492.7	161.6	50	0.550
679	3458.00	3401.2	4644.2	-8045.4	3634.3	4539.3	-8173.6	159.2	50	0.550
680	3459.00	3256.2	4489.2	-7745.3	3463.2	4393.2	-7856.4	156.8	50	0.550
681	3460.00	3112.1	4335.1	-7447.2	3294.1	4247.1	-7541.3	154.3	50	0.550
682	3461.00	2969.1	4181.1	-7150.2	3125.1	4101.1	-7226.1	151.9	50	0.550
683	3462.00	2827.0	4027.0	-6854.1	2958.0	3956.0	-6914.0	149.5	50	0.550
684	3463.00	2685.0	3874.0	-6559.0	2790.9	3809.9	-6600.8	147.0	50	0.550
685	3464.00	2544.0	3721.0	-6264.9	2623.8	3664.8	-6288.7	144.6	50	0.550
686	3465.00	2403.9	3567.9	-5971.8	2457.8	3519.8	-5977.5	142.1	50	0.550
687	3466.00	2263.9	3414.9	-5678.8	2291.7	3374.7	-5666.4	139.7	50	0.550
688	3467.00	2124.8	3263.8	-5388.7	2126.6	3230.6	-5357.3	137.2	50	0.550
689	3468.00	1986.8	3110.8	-5097.6	1961.6	3087.6	-5049.1	134.7	50	0.550
690	3469.00	1848.8	2958.8	-4807.5	1798.5	2942.5	-4741.0	132.3	50	0.550
691	3470.00	1711.7	2806.7	-4518.4	1636.4	2799.4	-4435.8	129.8	50	0.550
692	3471.00	1636.4	2674.4	-4310.8	1636.4	2674.4	-4310.8	128.2	50	0.550
693	3471.20	1636.4	2674.4	-4310.8	1636.4	2674.4	-4310.8	128.2	5	0.100
694	3471.40	0.0	0.0	0.0	0.0	0.0	0.0	128.2	5	0.100
695	3471.60	3272.8	5348.8	-8621.6	3272.8	5348.8	-8621.6	128.2	5	0.100
696	3471.80	1636.4	2674.4	-4310.8	1636.4	2674.4	-4310.8	128.2	5	0.100
697	3472.00	1605.2	2549.2	-4154.4	1808.4	2555.4	-4363.9	127.0	50	0.550
698	3474.00	1655.0	2318.0	-3973.0	2351.6	2337.6	-4689.1	125.5	50	0.550
699	3476.00	1809.1	2111.1	-3920.2	2976.7	2140.7	-5117.4	124.4	50	0.550
700	3479.00	2175.5	1842.5	-4018.0	3971.9	1881.9	-5853.8	123.2	50	0.550
701	3483.00	2810.2	1552.2	-4362.3	5293.1	1598.1	-6891.2	121.9	50	0.550
702	3487.00	3528.7	1326.7	-4855.5	6575.3	1374.3	-7949.5	120.9	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
703	3492.00	4479.2	1126.2	-5605.4	8103.4	1172.4	-9275.8	119.8	50	0.550
704	3498.00	5631.4	985.4	-6616.9	9825.5	1024.5	-10850.0	118.8	50	0.550
705	3505.00	6945.4	930.4	-7875.8	11686.6	958.5	-12645.1	117.7	50	0.550
706	3513.00	8371.2	980.2	-9351.4	13634.6	994.6	-14629.2	116.6	50	0.550
707	3522.00	9866.8	1139.8	-11006.7	15627.6	1135.6	-16763.2	115.6	50	0.550
708	3532.00	11393.4	1413.4	-12806.8	17626.6	1384.6	-19011.2	114.5	50	0.550
709	3542.00	12793.0	1754.0	-14547.0	19432.6	1702.6	-21135.2	113.6	50	0.550
710	3543.00	12927.0	1790.0	-14716.9	19602.6	1737.6	-21340.2	113.5	50	0.550
711	3553.00	14199.6	2184.6	-16384.3	21226.6	2106.6	-23333.3	112.7	50	0.550
712	3555.00	14439.6	2266.6	-16706.2	21528.6	2185.6	-23714.3	112.5	50	0.550
713	3565.00	15578.3	2692.3	-18270.7	22966.7	2586.6	-25553.3	111.8	50	0.550
714	3569.00	16004.2	2867.2	-18871.5	23497.7	2753.7	-26251.3	111.5	50	0.550
715	3579.00	17003.1	3313.1	-20316.2	24746.7	3177.7	-27924.4	110.8	50	0.550
716	3584.00	17470.0	3539.1	-21009.1	25324.7	3391.7	-28716.4	110.4	50	0.550
717	3594.00	18349.0	3992.0	-22341.0	26412.7	3823.7	-30236.4	109.8	50	0.550
718	3601.00	18921.0	4310.0	-23231.0	27113.8	4126.7	-31240.5	109.4	50	0.550
719	3611.00	19694.1	4761.1	-24455.1	28063.8	4556.8	-32620.6	108.9	50	0.550
720	3620.00	20340.2	5165.2	-25505.3	28848.8	4943.8	-33792.6	108.4	50	0.550
721	3630.00	21009.4	5610.3	-26619.7	29661.9	5369.9	-35031.7	107.9	50	0.550
722	3640.00	21629.6	6050.6	-27680.2	30407.9	5790.9	-36198.8	107.4	50	0.550
723	3641.00	21689.6	6094.6	-27784.2	30479.9	5832.9	-36312.8	107.4	50	0.550
724	3651.00	22275.9	6522.9	-28798.8	31187.9	6242.9	-37430.9	107.0	50	0.550
725	3661.00	22827.2	6942.2	-29769.5	31847.0	6645.0	-38492.0	106.6	50	0.550
726	3666.00	23088.4	7147.4	-30235.8	32159.0	6841.0	-39000.0	106.4	50	0.550
727	3676.00	23590.8	7549.8	-31140.6	32763.1	7225.0	-39988.1	106.0	50	0.550
728	3686.00	24060.3	7940.3	-32000.5	33320.1	7599.1	-40919.2	105.7	50	0.550
729	3695.00	24451.7	8280.7	-32732.4	33782.1	7925.2	-41707.3	105.3	50	0.550
730	3705.00	24858.2	8647.2	-33505.5	34265.2	8277.2	-42542.4	105.1	50	0.550
731	3715.00	25234.8	9003.8	-34238.6	34708.2	8617.2	-43325.5	104.8	50	0.550
732	3725.00	25596.4	9349.4	-34945.8	35131.3	8948.3	-44079.6	104.5	50	0.550
733	3730.00	25770.7	9519.7	-35290.4	35334.3	9112.3	-44446.6	104.3	50	0.550
734	3740.00	26113.4	9855.4	-35968.8	35740.4	9432.4	-45172.8	104.1	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
735	3750.00	26442.1	10185.1	-36627.1	36124.4	9747.4	-45871.9	103.9	50	0.550
736	3760.00	26753.8	10506.8	-37260.6	36487.5	10055.5	-46543.0	103.7	50	0.550
737	3770.00	27050.6	10821.6	-37872.1	36831.6	10355.6	-47187.1	103.4	50	0.550
738	3775.00	27193.9	10975.9	-38169.8	36996.6	10503.6	-47500.2	103.3	50	0.550
739	3785.00	27471.7	11279.7	-38751.5	37323.6	10793.6	-48117.3	103.2	50	0.550
740	3795.00	27736.6	11574.6	-39311.2	37630.7	11074.7	-48705.4	103.0	50	0.550
741	3805.00	27992.4	11862.4	-39854.9	37924.8	11350.8	-49275.5	102.8	50	0.550
742	3815.00	28240.3	12150.3	-40390.6	38210.8	11624.8	-49835.6	102.7	50	0.550
743	3835.00	28705.2	12703.2	-41408.4	38741.9	12153.9	-50895.9	102.3	50	0.550
744	3836.00	28727.3	12730.3	-41457.6	38767.0	12180.0	-50946.9	102.3	50	0.550
745	3846.00	28948.3	12998.2	-41946.5	39027.0	12434.0	-51461.0	102.2	50	0.550
746	3856.00	29164.2	13259.2	-42423.5	39275.1	12683.1	-51958.2	102.1	50	0.550
747	3866.00	29370.2	13514.2	-42884.5	39511.1	12926.1	-52437.3	102.0	50	0.550
748	3876.00	29566.2	13762.2	-43328.5	39735.2	13162.2	-52897.4	101.9	50	0.550
749	3896.00	29932.3	14236.3	-44168.6	40150.3	13615.3	-53765.7	101.7	50	0.550
750	3916.00	30260.4	14682.4	-44942.8	40523.4	14039.5	-54562.9	101.5	50	0.550
751	3933.00	30512.2	15039.2	-45551.3	40806.6	14378.6	-55185.1	101.3	50	0.550
752	3943.00	30655.2	15239.2	-45894.4	40973.6	14569.6	-55543.2	101.3	50	0.550
753	3953.00	30789.3	15434.3	-46223.6	41127.7	14754.7	-55882.4	101.2	50	0.550
754	3963.00	30915.4	15621.3	-46536.7	41270.7	14932.8	-56203.5	101.2	50	0.550
755	3973.00	31034.4	15803.4	-46837.8	41404.8	15104.8	-56509.6	101.2	50	0.550
756	3993.00	31273.5	16162.5	-47436.0	41673.9	15446.9	-57120.9	101.1	50	0.550
757	4013.00	31507.7	16520.7	-48028.3	41937.1	15787.1	-57724.1	101.0	50	0.550
758	4033.00	31736.9	16876.9	-48613.8	42194.2	16126.2	-58320.4	100.9	50	0.550
759	4073.00	32189.5	17585.5	-49774.9	42701.4	16798.4	-59499.9	100.7	50	0.550
760	4113.00	32633.2	18288.2	-50921.5	43196.7	17466.7	-60663.4	100.6	50	0.550
761	4178.00	33196.8	19276.8	-52473.6	43822.1	18404.1	-62226.2	100.3	50	0.550
762	4188.00	33272.9	19408.9	-52681.8	43916.1	18529.1	-62445.3	100.4	50	0.550
763	4198.00	33347.9	19535.9	-52883.8	44002.2	18650.2	-62652.4	100.4	50	0.550
764	4208.00	33418.9	19657.9	-53076.9	44082.2	18766.3	-62848.5	100.4	50	0.550
765	4218.00	33483.0	19775.0	-53257.9	44155.3	18876.3	-63031.6	100.5	50	0.550
766	4238.00	33596.8	19989.8	-53586.6	44283.4	19080.4	-63363.8	100.5	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
767	4258.00	33689.6	20182.6	-53872.2	44387.5	19262.5	-63650.0	100.6	50	0.550
768	4278.00	33769.2	20354.2	-54123.4	44475.6	19424.6	-63900.1	100.7	50	0.550
769	4318.00	33939.1	20692.1	-54631.3	44664.7	19744.7	-64409.4	100.8	50	0.550
770	4358.00	34102.1	21025.1	-55127.2	44845.9	20059.9	-64905.7	101.0	50	0.550
771	4438.00	34414.2	21675.2	-56089.4	45190.2	20677.2	-65867.3	101.3	50	0.550
772	4500.00	34647.9	22171.9	-56819.8	45448.4	21147.4	-66595.8	101.5	50	0.550
773	4503.00	34705.3	22242.3	-56947.5	45510.4	21216.5	-66726.9	101.5	50	0.550
774	4505.00	34807.3	22297.3	-57104.5	45846.5	21273.6	-67120.1	103.0	50	0.550
775	4507.00	34971.2	22364.3	-57335.5	46249.7	21337.7	-67587.4	104.6	50	0.550
776	4509.00	35168.3	22441.3	-57609.7	46653.8	21411.8	-68065.6	106.2	50	0.550
777	4511.00	35388.4	22525.4	-57913.8	47054.9	21491.9	-68546.8	107.9	50	0.550
778	4513.00	35620.6	22616.6	-58237.1	47450.0	21579.0	-69029.1	109.6	50	0.550
779	4515.00	35865.7	22714.7	-58580.5	47839.1	21672.2	-69511.3	111.3	50	0.550
780	4517.00	36116.0	22819.0	-58935.0	48221.2	21771.2	-69992.5	113.1	50	0.550
781	4519.00	36368.2	22928.2	-59296.4	48596.3	21875.4	-70471.7	114.8	50	0.550
782	4521.00	36623.5	23042.5	-59666.0	48965.5	21983.4	-70948.9	116.6	50	0.550
783	4523.00	36879.8	23161.8	-60041.7	49325.6	22097.5	-71423.1	118.4	50	0.550
784	4525.00	37136.1	23286.1	-60422.3	49680.6	22214.6	-71895.3	120.2	50	0.550
785	4527.00	37391.5	23413.5	-60805.1	50028.7	22335.7	-72364.4	122.0	50	0.550
786	4529.00	37644.9	23545.9	-61190.8	50370.8	22460.8	-72831.6	123.8	50	0.550
787	4531.00	37896.3	23680.3	-61576.6	50704.9	22588.9	-73293.8	125.6	50	0.550
788	4533.00	38145.7	23819.7	-61965.4	51033.0	22720.9	-73753.9	127.4	50	0.550
789	4535.00	38392.2	23961.2	-62353.4	51356.1	22855.0	-74211.1	129.2	50	0.550
790	4537.00	38636.7	24104.7	-62741.3	51673.1	22992.1	-74665.2	131.1	50	0.550
791	4539.00	38877.2	24251.2	-63128.3	51985.2	23130.2	-75115.4	132.9	50	0.550
792	4541.00	39114.7	24399.7	-63514.3	52290.3	23271.3	-75561.6	134.7	50	0.550
793	4543.00	39349.2	24550.2	-63899.3	52589.4	23415.4	-76004.7	136.6	50	0.550
794	4545.00	39581.7	24702.7	-64284.4	52883.4	23561.4	-76444.8	138.4	50	0.550
795	4547.00	39810.3	24857.2	-64667.5	53173.5	23707.5	-76881.0	140.3	50	0.550
796	4549.00	40034.8	25013.8	-65048.6	53457.6	23855.6	-77313.1	142.1	50	0.550
797	4551.00	40257.4	25170.4	-65427.7	53737.6	24004.7	-77742.3	144.0	50	0.550
798	4553.00	40476.0	25329.0	-65804.9	54011.7	24155.7	-78167.4	145.8	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
799	4555.00	40692.5	25487.5	-66180.0	54282.8	24306.8	-78589.6	147.7	50	0.550
800	4557.00	40906.1	25647.1	-66553.2	54548.9	24458.9	-79007.7	149.5	50	0.550
801	4559.00	41115.7	25808.8	-66924.5	54809.9	24612.9	-79422.9	151.4	50	0.550
802	4561.00	41323.4	25970.4	-67293.7	55068.0	24767.0	-79835.0	153.3	50	0.550
803	4563.00	41527.0	26134.0	-67661.0	55320.1	24923.1	-80243.1	155.1	50	0.550
804	4565.00	41728.6	26297.6	-68026.3	55569.1	25079.1	-80648.3	157.0	50	0.550
805	4567.00	41926.3	26461.3	-68387.6	55814.2	25234.2	-81048.4	158.9	50	0.550
806	4569.00	42123.0	26625.0	-68748.0	56055.3	25391.3	-81446.6	160.7	50	0.550
807	4571.00	42316.6	26789.6	-69106.3	56293.3	25548.4	-81841.7	162.6	50	0.550
808	4573.00	42507.3	26954.3	-69461.6	56528.4	25705.4	-82233.9	164.5	50	0.550
809	4575.00	42696.0	27119.9	-69815.9	56759.5	25862.5	-82622.0	166.4	50	0.550
810	4577.00	42882.7	27284.7	-70167.4	56986.6	26021.6	-83008.1	168.3	50	0.550
811	4579.00	43065.4	27450.3	-70515.7	57210.6	26178.7	-83389.3	170.1	50	0.550
812	4581.00	43246.0	27616.0	-70862.1	57430.7	26337.7	-83768.4	172.0	50	0.550
813	4583.00	43423.8	27781.8	-71205.5	57646.8	26495.8	-84142.6	173.9	50	0.550
814	4585.00	43599.5	27948.5	-71547.9	57860.9	26653.9	-84514.7	175.8	50	0.550
815	4587.00	43773.2	28114.2	-71887.4	58071.9	26811.9	-84883.9	177.7	50	0.550
816	4589.00	43944.9	28279.9	-72224.8	58280.0	26971.0	-85251.0	179.6	50	0.550
817	4591.00	44114.6	28445.6	-72560.2	58485.1	27129.1	-85614.2	181.5	50	0.550
818	4593.00	44281.4	28611.4	-72892.7	58687.1	27287.1	-85974.3	183.3	50	0.550
819	4595.00	44447.1	28776.1	-73223.2	58886.2	27446.2	-86332.4	185.2	50	0.550
820	4597.00	44608.8	28941.8	-73550.7	59082.3	27603.3	-86685.6	187.1	50	0.550
821	4599.00	44769.6	29107.6	-73877.1	59275.4	27762.4	-87037.7	189.0	50	0.550
822	4601.00	44928.3	29272.3	-74200.7	59466.4	27919.4	-87385.9	190.9	50	0.550
823	4603.00	45085.1	29437.1	-74522.1	59654.5	28077.5	-87732.0	192.8	50	0.550
824	4605.00	45239.8	29601.8	-74841.6	59840.6	28234.6	-88075.2	194.7	50	0.550
825	4607.00	45392.6	29766.6	-75159.1	60023.7	28391.7	-88415.3	196.6	50	0.550
826	4609.00	45544.3	29930.3	-75474.6	60204.7	28548.7	-88753.5	198.5	50	0.550
827	4611.00	45693.1	30094.1	-75787.2	60383.8	28704.8	-89088.6	200.4	50	0.550
828	4613.00	45839.9	30257.8	-76097.7	60558.9	28860.9	-89419.8	202.3	50	0.550
829	4615.00	45985.6	30420.6	-76406.3	60732.9	29016.0	-89748.9	204.2	50	0.550
830	4617.00	46129.4	30583.4	-76712.8	60904.0	29172.0	-90076.0	206.1	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
831	4619.00	46272.2	30745.1	-77017.3	61072.1	29328.1	-90400.2	208.0	50	0.550
832	4621.00	46412.0	30907.0	-77318.9	61239.2	29482.2	-90721.3	209.9	50	0.550
833	4623.00	46550.7	31068.7	-77619.4	61403.2	29637.2	-91040.5	211.8	50	0.550
834	4625.00	46687.5	31229.5	-77917.0	61565.3	29791.3	-91356.6	213.7	50	0.550
835	4627.00	46821.3	31391.3	-78212.6	61725.4	29944.4	-91669.8	215.6	50	0.550
836	4629.00	46956.1	31550.1	-78506.1	61883.5	30098.5	-91981.9	217.5	50	0.550
837	4631.00	47087.8	31710.8	-78798.7	62040.5	30250.5	-92291.1	219.4	50	0.550
838	4633.00	47219.7	31869.7	-79089.3	62195.6	30403.6	-92599.2	221.4	50	0.550
839	4635.00	47349.4	32028.4	-79377.9	62348.7	30555.7	-92904.4	223.3	50	0.550
840	4637.00	47477.2	32187.2	-79664.4	62500.8	30706.8	-93207.5	225.2	50	0.550
841	4639.00	47605.0	32345.0	-79950.0	62650.8	30858.8	-93509.7	227.1	50	0.550
842	4641.00	47729.8	32502.8	-80232.6	62798.9	31008.9	-93807.8	229.0	50	0.550
843	4643.00	47853.6	32659.6	-80513.2	62945.0	31159.0	-94104.0	230.9	50	0.550
844	4645.00	47977.4	32815.4	-80792.8	63090.1	31309.1	-94399.1	232.8	50	0.550
845	4647.00	48099.2	32972.2	-81071.4	63233.1	31459.1	-94692.3	234.7	50	0.550
846	4649.00	48219.0	33128.0	-81347.0	63375.2	31607.2	-94982.4	236.6	50	0.550
847	4651.00	48338.8	33282.8	-81621.6	63515.3	31756.3	-95271.6	238.5	50	0.550
848	4653.00	48455.6	33437.6	-81893.2	63652.3	31904.3	-95556.7	240.5	50	0.550
849	4655.00	48571.4	33592.4	-82163.8	63789.4	32051.4	-95840.8	242.4	50	0.550
850	4657.00	48687.2	33745.2	-82432.4	63924.5	32198.5	-96123.0	244.3	50	0.550
851	4659.00	48800.0	33900.0	-82700.0	64057.6	32345.6	-96403.1	246.2	50	0.550
852	4661.00	48912.8	34051.8	-82964.7	64188.6	32492.7	-96681.3	248.1	50	0.550
853	4663.00	49023.6	34204.6	-83228.3	64318.7	32637.7	-96956.5	250.0	50	0.550
854	4665.00	49133.5	34356.5	-83489.9	64447.8	32782.8	-97230.6	252.0	50	0.550
855	4667.00	49242.3	34506.3	-83748.5	64574.9	32926.9	-97501.8	253.9	50	0.550
856	4669.00	49350.1	34658.1	-84008.2	64702.0	33071.0	-97772.9	255.8	50	0.550
857	4671.00	49457.9	34807.9	-84265.8	64828.0	33215.1	-98043.1	257.7	50	0.550
858	4673.00	49565.7	34956.7	-84522.5	64954.1	33358.1	-98312.2	259.7	50	0.550
859	4675.00	49671.5	35106.5	-84778.0	65078.2	33501.2	-98579.4	261.6	50	0.550
860	4677.00	49776.3	35255.3	-85031.7	65200.3	33644.3	-98844.5	263.5	50	0.550
861	4679.00	49881.2	35403.2	-85284.3	65323.3	33785.4	-99108.7	265.4	50	0.550
862	4681.00	49985.0	35552.0	-85537.0	65444.4	33927.4	-99371.8	267.4	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
863	4683.00	50087.8	35699.8	-85787.5	65565.5	34068.5	-99634.0	269.3	50	0.550
864	4685.00	50190.6	35846.6	-86037.2	65684.6	34209.6	-99894.1	271.2	50	0.550
865	4687.00	50292.4	35992.4	-86284.9	65803.6	34349.6	-100153.3	273.2	50	0.550
866	4689.00	50392.2	36139.2	-86531.5	65919.7	34489.7	-100409.5	275.1	50	0.550
867	4691.00	50492.1	36285.1	-86777.1	66036.8	34628.8	-100665.6	277.0	50	0.550
868	4693.00	50591.9	36429.9	-87021.8	66152.9	34767.9	-100920.8	279.0	50	0.550
869	4695.00	50690.7	36574.7	-87265.4	66267.0	34907.0	-101174.0	280.9	50	0.550
870	4697.00	50788.5	36718.5	-87507.1	66381.0	35045.0	-101426.1	282.8	50	0.550
871	4699.00	50884.3	36862.3	-87746.7	66493.1	35182.1	-101675.2	284.8	50	0.550
872	4701.00	50981.2	37005.2	-87986.4	66605.2	35320.2	-101925.4	286.7	50	0.550
873	4703.00	51076.0	37149.0	-88225.0	66716.3	35456.3	-102172.6	288.6	50	0.550
874	4705.00	51170.8	37291.8	-88462.7	66826.4	35593.3	-102419.7	290.6	50	0.550
875	4707.00	51264.6	37433.6	-88698.3	66935.4	35729.4	-102664.9	292.5	50	0.550
876	4709.00	51358.4	37574.4	-88932.9	67043.5	35864.5	-102908.0	294.4	50	0.550
877	4711.00	51449.3	37716.3	-89165.6	67150.6	35998.6	-103149.2	296.4	50	0.550
878	4713.00	51541.1	37857.1	-89398.2	67256.7	36133.7	-103390.3	298.3	50	0.550
879	4715.00	51631.9	37996.9	-89628.8	67361.8	36268.7	-103630.5	300.3	50	0.550
880	4717.00	51722.8	38136.8	-89859.5	67466.8	36401.8	-103868.7	302.2	50	0.550
881	4719.00	51811.6	38275.6	-90087.2	67569.9	36534.9	-104104.8	304.1	50	0.550
882	4721.00	51899.4	38414.4	-90313.8	67672.0	36667.0	-104338.9	306.1	50	0.550
883	4723.00	51987.2	38552.2	-90539.4	67773.1	36800.1	-104573.1	308.0	50	0.550
884	4725.00	52074.0	38691.0	-90765.1	67874.1	36932.1	-104806.2	310.0	50	0.550
885	4727.00	52160.9	38827.9	-90988.7	67973.2	37064.2	-105037.4	311.9	50	0.550
886	4729.00	52245.7	38964.7	-91210.4	68072.3	37194.3	-105266.6	313.9	50	0.550
887	4731.00	52329.6	39101.5	-91431.1	68169.4	37324.4	-105493.7	315.8	50	0.550
888	4733.00	52413.4	39237.4	-91650.8	68265.5	37455.4	-105720.9	317.7	50	0.550
889	4735.00	52497.2	39372.2	-91869.4	68361.5	37585.5	-105947.1	319.7	50	0.550
890	4737.00	52579.0	39507.0	-92086.1	68456.6	37714.6	-106171.2	321.6	50	0.550
891	4739.00	52660.9	39641.9	-92302.7	68550.7	37842.7	-106393.4	323.6	50	0.550
892	4741.00	52740.7	39775.6	-92516.3	68642.8	37971.8	-106614.6	325.5	50	0.550
893	4743.00	52820.5	39909.5	-92730.0	68734.9	38098.9	-106833.7	327.5	50	0.550
894	4745.00	52900.3	40043.3	-92943.6	68827.9	38225.9	-107053.9	329.4	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
895	4747.00	52980.1	40175.2	-93155.3	68919.0	38353.0	-107272.0	331.4	50	0.550
896	4749.00	53059.0	40307.0	-93366.0	69009.1	38480.1	-107489.2	333.3	50	0.550
897	4750.00	53093.9	40372.9	-93466.8	69031.1	38542.1	-107573.3	334.1	50	0.550
898	4751.00	53108.1	40421.1	-93529.2	69018.1	38588.1	-107606.2	335.0	50	0.550
899	4754.00	53061.8	40553.8	-93615.5	68708.1	38712.1	-107420.2	336.1	50	0.550
900	4759.00	52798.7	40727.7	-93526.4	68005.0	38878.0	-106883.0	337.1	50	0.550
901	4767.00	52178.8	40912.8	-93091.7	66874.9	39058.9	-105933.8	338.2	50	0.550
902	4777.00	51324.0	41021.0	-92345.0	65574.8	39169.8	-104744.7	339.2	50	0.550
903	4778.00	51239.1	41026.1	-92265.1	65455.8	39173.8	-104629.7	339.2	50	0.550
904	4788.00	50409.9	41026.9	-91436.8	64299.9	39181.9	-103481.7	340.0	50	0.550
905	4792.00	50095.2	41008.2	-91103.5	63880.9	39164.9	-103045.8	340.3	50	0.550
906	4802.00	49349.8	40922.8	-90272.7	62888.9	39090.0	-101978.9	340.9	50	0.550
907	4809.00	48865.2	40842.2	-89707.4	62262.0	39015.0	-101277.0	341.3	50	0.550
908	4819.00	48211.5	40684.5	-88896.1	61418.1	38868.0	-100286.1	341.8	50	0.550
909	4829.00	47604.7	40495.7	-88100.4	60652.1	38689.1	-99341.3	342.4	50	0.550
910	4839.00	47043.8	40291.8	-87335.6	59944.2	38496.2	-98440.4	342.8	50	0.550
911	4849.00	46529.7	40076.8	-86606.5	59305.2	38292.2	-97597.5	343.2	50	0.550
912	4852.00	46384.7	40010.7	-86395.4	59126.3	38230.3	-97356.5	343.4	50	0.550
913	4862.00	45921.6	39789.6	-85711.1	58551.3	38019.3	-96570.6	343.7	50	0.550
914	4872.00	45493.4	39564.4	-85057.8	58027.3	37804.3	-95831.7	344.1	50	0.550
915	4879.00	45214.2	39406.2	-84620.4	57688.3	37653.3	-95341.7	344.4	50	0.550
916	4889.00	44833.9	39178.9	-84012.8	57221.4	37437.4	-94658.8	344.7	50	0.550
917	4899.00	44479.6	38951.6	-83431.1	56793.4	37221.4	-94014.8	345.0	50	0.550
918	4909.00	44151.1	38726.1	-82877.2	56401.4	37004.4	-93405.8	345.3	50	0.550
919	4912.00	44058.0	38659.0	-82717.0	56290.4	36940.4	-93230.8	345.4	50	0.550
920	4922.00	43753.5	38434.5	-82188.1	55922.4	36725.4	-92647.8	345.6	50	0.550
921	4932.00	43462.0	38210.0	-81672.0	55575.4	36511.4	-92086.8	345.9	50	0.550
922	4942.00	43183.5	37986.5	-81169.9	55244.4	36298.4	-91542.8	346.1	50	0.550
923	4952.00	42918.9	37763.9	-80682.7	54933.4	36085.4	-91018.8	346.4	50	0.550
924	4953.00	42892.8	37741.8	-80634.6	54902.4	36065.4	-90967.8	346.4	50	0.550
925	4963.00	42636.2	37519.2	-80155.4	54594.4	35852.4	-90446.8	346.6	50	0.550
926	4973.00	42392.5	37301.5	-79694.1	54307.4	35645.4	-89952.7	346.8	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
927	4983.00	42176.0	37106.0	-79282.0	54054.3	35457.3	-89511.7	347.0	50	0.550
928	4993.00	41975.4	36917.4	-78892.9	53820.3	35277.3	-89097.7	347.2	50	0.550
929	5007.00	41707.7	36659.7	-78367.4	53509.3	35031.3	-88540.6	347.4	50	0.550
930	5017.00	41524.1	36481.1	-78005.2	53289.3	34861.3	-88150.6	347.6	50	0.550
931	5027.00	41347.5	36308.5	-77656.1	53083.2	34695.2	-87778.5	347.7	50	0.550
932	5037.00	41182.0	36140.0	-77321.9	52891.2	34534.2	-87425.5	347.8	50	0.550
933	5047.00	41025.4	35976.4	-77001.9	52709.2	34379.2	-87088.4	347.9	50	0.550
934	5067.00	40742.3	35668.3	-76410.6	52384.1	34085.1	-86469.3	348.2	50	0.550
935	5087.00	40494.3	35384.2	-75878.5	52100.1	33814.1	-85914.1	348.4	50	0.550
936	5097.00	40372.7	35246.7	-75619.4	51954.1	33683.0	-85637.1	348.5	50	0.550
937	5107.00	40252.2	35110.2	-75362.3	51814.0	33553.0	-85367.0	348.6	50	0.550
938	5117.00	40135.7	34977.6	-75113.3	51681.0	33426.0	-85107.0	348.6	50	0.550
939	5127.00	40025.1	34846.1	-74871.2	51552.9	33300.9	-84853.9	348.7	50	0.550
940	5147.00	39815.1	34591.1	-74406.2	51312.9	33058.9	-84371.7	348.8	50	0.550
941	5167.00	39621.1	34349.1	-73970.2	51091.8	32827.8	-83919.6	348.9	50	0.550
942	5187.00	39443.1	34119.1	-73562.2	50890.7	32608.7	-83499.4	349.0	50	0.550
943	5227.00	39132.3	33692.3	-72824.6	50540.5	32201.5	-82742.1	349.3	50	0.550
944	5251.00	38972.2	33460.2	-72432.5	50361.5	31980.5	-82341.9	349.4	50	0.550
945	5261.00	38902.8	33364.8	-72267.7	50277.4	31890.4	-82167.8	349.4	50	0.550
946	5271.00	38832.4	33269.4	-72101.8	50194.4	31800.4	-81994.8	349.4	50	0.550
947	5281.00	38762.0	33173.0	-71934.9	50114.3	31708.3	-81822.7	349.4	50	0.550
948	5291.00	38691.5	33077.6	-71769.1	50034.3	31616.3	-81650.6	349.5	50	0.550
949	5311.00	38558.7	32886.7	-71445.5	49883.2	31436.2	-81319.4	349.5	50	0.550
950	5331.00	38437.9	32706.9	-71144.8	49748.1	31263.1	-81011.2	349.5	50	0.550
951	5351.00	38326.2	32535.2	-70861.3	49621.0	31101.0	-80722.1	349.5	50	0.550
952	5391.00	38127.8	32222.8	-70350.6	49398.9	30803.9	-80202.9	349.5	50	0.550
953	5431.00	37963.6	31948.6	-69912.2	49214.8	30543.8	-79758.6	349.5	50	0.550
954	5511.00	37723.7	31520.7	-69244.4	48947.6	30135.6	-79083.1	349.6	50	0.550
955	5591.00	37575.4	31224.4	-68799.8	48782.4	29854.4	-78636.8	349.6	50	0.550
956	5751.00	37296.2	30686.2	-67982.4	48471.1	29342.1	-77813.1	349.7	50	0.550
957	5911.00	37029.2	30166.2	-67195.4	48174.8	28845.8	-77020.6	349.7	50	0.550
958	6231.00	36851.6	29750.7	-66602.3	47976.5	28449.5	-76426.1	349.9	50	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
959	6450.00	36709.4	29379.4	-66088.8	47818.3	28094.3	-75912.6	350.0	50	0.550
960	6450.00	37709.4	24757.4	-62466.7	48508.8	23348.4	-71857.3	299.5	20	0.050
961	6452.00	37934.9	24819.7	-62754.6	49589.4	23397.6	-72987.0	304.2	20	0.050
962	6453.00	38192.5	24886.6	-63079.0	50514.4	23450.2	-73964.7	308.1	20	0.050
963	6454.00	38522.3	24971.4	-63493.7	51524.1	23517.9	-75042.0	312.4	20	0.050
964	6455.00	38905.6	25071.6	-63977.2	52575.9	23599.1	-76175.1	316.9	20	0.050
965	6456.00	39331.8	25185.6	-64517.3	53651.2	23693.3	-77344.5	321.6	20	0.050
966	6457.00	39797.6	25313.0	-65110.7	54746.4	23799.9	-78546.3	326.5	20	0.050
967	6458.00	40293.4	25452.8	-65746.2	55850.1	23918.3	-79768.4	331.4	20	0.050
968	6459.00	40817.6	25604.6	-66422.2	56960.9	24048.3	-81009.2	336.5	20	0.050
969	6460.00	41359.4	25767.0	-67126.4	58070.8	24188.8	-82259.6	341.7	20	0.050
970	6461.00	41915.6	25939.4	-67855.0	59177.7	24339.3	-83517.0	346.9	20	0.050
971	6462.00	42486.3	26122.0	-68608.3	60281.4	24499.9	-84781.4	352.1	20	0.050
972	6463.00	43071.6	26314.7	-69386.3	61382.1	24670.7	-86052.8	357.5	20	0.050
973	6464.00	43670.7	26517.6	-70188.3	62479.4	24851.2	-87330.7	362.9	20	0.050
974	6465.00	44277.8	26729.3	-71007.0	63570.3	25040.9	-88611.2	368.3	20	0.050
975	6466.00	44891.1	26949.6	-71840.8	64654.3	25239.0	-89893.3	373.8	20	0.050
976	6467.00	45510.8	27178.6	-72689.4	65731.2	25445.9	-91177.1	379.3	20	0.050
977	6468.00	46136.9	27416.2	-73553.1	66801.1	25661.2	-92462.2	384.9	20	0.050
978	6469.00	46768.7	27662.3	-74431.0	67863.8	25885.0	-93748.7	390.5	20	0.050
979	6470.00	47401.2	27915.0	-75316.2	68918.1	26115.3	-95033.4	396.1	20	0.050
980	6471.00	48033.4	28173.7	-76207.1	69964.1	26351.5	-96315.6	401.7	20	0.050
981	6472.00	48665.1	28438.6	-77103.7	71001.3	26593.9	-97595.2	407.4	20	0.050
982	6473.00	49296.4	28709.5	-78006.0	72030.1	26842.3	-98872.4	413.1	20	0.050
983	6474.00	49927.4	28986.6	-78914.0	73050.4	27096.6	-100147.0	418.8	20	0.050
984	6475.00	50557.9	29269.9	-79827.7	74062.1	27357.1	-101419.2	424.5	20	0.050
985	6476.00	51187.9	29559.2	-80747.1	75065.3	27623.6	-102688.9	430.3	20	0.050
986	6477.00	51817.6	29854.7	-81672.3	76059.9	27896.1	-103956.1	436.1	20	0.050
987	6478.00	52446.9	30156.2	-82603.0	77046.1	28174.6	-105220.7	441.9	20	0.050
988	6479.00	53075.7	30463.9	-83539.6	78023.5	28459.3	-106482.9	447.7	20	0.050
989	6480.00	53703.6	30777.3	-84480.9	78992.7	28749.4	-107742.1	453.6	20	0.050
990	6481.00	54328.9	31094.9	-85423.7	79953.5	29043.9	-108997.4	459.4	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
991	6482.00	54951.2	31416.8	-86368.0	80906.1	29342.3	-110248.4	465.3	20	0.050
992	6483.00	55570.6	31742.8	-87313.4	81850.5	29644.7	-111495.2	471.2	20	0.050
993	6484.00	56187.1	32072.9	-88260.0	82786.6	29951.2	-112737.8	477.1	20	0.050
994	6485.00	56800.7	32407.2	-89207.9	83714.4	30261.9	-113976.3	483.1	20	0.050
995	6486.00	57411.4	32745.6	-90157.0	84634.1	30576.4	-115210.6	489.0	20	0.050
996	6487.00	58019.1	33088.1	-91107.2	85545.4	30895.2	-116440.6	494.9	20	0.050
997	6488.00	58623.9	33434.8	-92058.7	86448.6	31217.9	-117666.6	500.9	20	0.050
998	6489.00	59225.8	33785.7	-93011.4	87343.6	31544.7	-118888.3	506.9	20	0.050
999	6490.00	59824.8	34140.6	-93965.4	88230.3	31875.6	-120105.8	512.9	20	0.050
1000	6491.00	60420.5	34498.7	-94919.3	89109.3	32209.6	-121318.9	518.9	20	0.050
1001	6492.00	61012.8	34858.6	-95871.3	89981.9	32545.1	-122527.0	524.9	20	0.050
1002	6493.00	61601.5	35220.0	-96821.5	90847.9	32882.1	-123730.0	531.0	20	0.050
1003	6494.00	62186.7	35583.2	-97769.8	91707.4	33220.8	-124928.2	537.0	20	0.050
1004	6495.00	62768.2	35947.9	-98716.1	92560.3	33561.0	-126121.4	543.0	20	0.050
1005	6496.00	63346.1	36314.4	-99660.5	93406.9	33902.6	-127309.5	549.1	20	0.050
1006	6497.00	63920.6	36682.2	-100602.9	94246.8	34245.9	-128492.7	555.2	20	0.050
1007	6498.00	64491.4	37051.9	-101543.3	95080.1	34590.9	-129671.0	561.2	20	0.050
1008	6499.00	65058.7	37423.1	-102481.8	95907.1	34937.2	-130844.3	567.3	20	0.050
1009	6500.00	65622.3	37795.9	-103418.2	96727.5	35285.2	-132012.7	573.4	20	0.050
1010	6501.00	66123.3	38152.8	-104276.0	97218.6	35621.3	-132840.0	578.1	20	0.050
1011	6502.00	66510.5	38481.5	-104992.0	97268.0	35936.4	-133204.4	580.9	20	0.050
1012	6503.00	66802.9	38789.3	-105592.2	97143.6	36236.2	-133379.8	583.1	20	0.050
1013	6504.00	67018.5	39079.7	-106098.2	96928.0	36522.4	-133450.4	585.0	20	0.050
1014	6506.00	67286.8	39618.9	-106905.8	96369.6	37059.7	-133429.3	588.0	20	0.050
1015	6508.00	67386.1	40109.1	-107495.2	95713.4	37553.5	-133266.9	590.5	20	0.050
1016	6510.00	67365.0	40556.9	-107921.9	95009.3	38007.8	-133017.1	592.6	20	0.050
1017	6512.00	67267.1	40969.0	-108236.1	94289.1	38428.0	-132717.1	594.5	20	0.050
1018	6514.00	67096.5	41346.0	-108442.4	93555.6	38814.0	-132369.6	596.2	20	0.050
1019	6516.00	66874.8	41692.0	-108566.8	92819.1	39169.9	-131989.0	597.8	20	0.050
1020	6518.00	66614.0	42006.5	-108620.5	92088.4	39494.2	-131582.6	599.2	20	0.050
1021	6520.00	66321.8	42289.9	-108611.7	91367.1	39787.8	-131154.8	600.4	20	0.050
1022	6522.00	66017.6	42549.9	-108567.5	90659.3	40057.9	-130717.2	601.6	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1023	6524.00	65702.5	42787.1	-108489.6	89965.4	40305.1	-130270.5	602.8	20	0.050
1024	6526.00	65376.7	43001.2	-108377.9	89285.4	40529.1	-129814.5	603.9	20	0.050
1025	6528.00	65040.0	43192.5	-108232.5	88619.2	40730.2	-129349.4	604.9	20	0.050
1026	6530.00	64693.1	43361.1	-108054.2	87966.9	40908.6	-128875.5	605.8	20	0.050
1027	6532.00	64343.0	43512.9	-107856.0	87327.5	41070.0	-128397.5	606.7	20	0.050
1028	6534.00	63992.2	43649.8	-107642.0	86700.8	41216.4	-127917.1	607.5	20	0.050
1029	6536.00	63640.7	43771.8	-107412.5	86086.7	41347.7	-127434.3	608.4	20	0.050
1030	6538.00	63288.5	43878.7	-107167.2	85485.3	41463.8	-126949.1	609.2	20	0.050
1031	6540.00	62935.6	43970.8	-106906.3	84896.5	41564.9	-126461.4	609.9	20	0.050
1032	6542.00	62583.2	44051.8	-106635.0	84317.9	41655.0	-125972.9	610.6	20	0.050
1033	6544.00	62236.0	44125.3	-106361.3	83751.0	41737.2	-125488.2	611.3	20	0.050
1034	6546.00	61894.9	44190.2	-106085.1	83197.4	41811.0	-125008.4	612.0	20	0.050
1035	6548.00	61559.7	44246.9	-105806.6	82657.1	41876.1	-124533.2	612.7	20	0.050
1036	6550.00	61230.5	44295.3	-105525.9	82130.1	41932.8	-124062.9	613.3	20	0.050
1037	6552.00	60907.4	44335.2	-105242.6	81616.3	41980.9	-123597.2	613.9	20	0.050
1038	6554.00	60590.2	44366.9	-104957.1	81115.8	42020.5	-123136.3	614.5	20	0.050
1039	6556.00	60279.1	44390.2	-104669.3	80628.5	42051.6	-122680.2	615.1	20	0.050
1040	6558.00	59974.0	44405.1	-104379.1	80154.6	42074.2	-122228.8	615.6	20	0.050
1041	6560.00	59674.8	44411.8	-104086.5	79693.9	42088.2	-121782.1	616.2	20	0.050
1042	6562.00	59381.7	44410.0	-103791.7	79246.4	42093.8	-121340.2	616.7	20	0.050
1043	6564.00	59094.7	44399.9	-103494.5	78812.3	42090.7	-120903.0	617.1	20	0.050
1044	6566.00	58813.5	44381.5	-103195.0	78391.3	42079.4	-120470.6	617.6	20	0.050
1045	6568.00	58537.4	44358.0	-102895.4	77979.9	42062.6	-120042.6	618.1	20	0.050
1046	6570.00	58265.4	44331.1	-102596.5	77576.1	42042.4	-119618.5	618.5	20	0.050
1047	6572.00	57997.7	44300.8	-102298.5	77179.8	42018.7	-119198.5	618.9	20	0.050
1048	6574.00	57734.2	44267.4	-102001.6	76790.9	41991.6	-118782.5	619.3	20	0.050
1049	6576.00	57474.9	44230.7	-101705.6	76409.4	41961.3	-118370.7	619.7	20	0.050
1050	6578.00	57219.9	44190.5	-101410.4	76035.6	41927.4	-117963.0	620.1	20	0.050
1051	6580.00	56969.2	44147.0	-101116.2	75669.2	41890.0	-117559.2	620.5	20	0.050
1052	6582.00	56722.6	44100.4	-100823.0	75310.3	41849.3	-117159.5	620.9	20	0.050
1053	6584.00	56480.3	44050.3	-100530.6	74958.8	41805.1	-116763.9	621.3	20	0.050
1054	6586.00	56242.2	43997.0	-100239.2	74614.9	41757.6	-116372.5	621.6	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1055	6588.00	56008.4	43940.3	-99948.7	74278.3	41706.6	-115985.0	622.0	20	0.050
1056	6590.00	55778.8	43880.3	-99659.1	73949.4	41652.1	-115601.5	622.3	20	0.050
1057	6593.00	55440.9	43785.4	-99226.2	73467.2	41565.4	-115032.6	622.8	20	0.050
1058	6596.00	55103.8	43689.8	-98793.5	72986.6	41477.9	-114464.5	623.3	20	0.050
1059	6599.00	54766.7	43594.3	-98361.1	72506.0	41390.3	-113896.3	623.8	20	0.050
1060	6602.00	54432.5	43498.1	-97930.6	72029.7	41302.1	-113331.8	624.2	20	0.050
1061	6605.00	54104.7	43400.4	-97505.1	71563.1	41212.1	-112775.2	624.7	20	0.050
1062	6608.00	53783.2	43301.0	-97084.2	71106.3	41120.4	-112226.6	625.2	20	0.050
1063	6611.00	53468.1	43200.2	-96668.3	70659.3	41026.9	-111686.2	625.6	20	0.050
1064	6614.00	53159.4	43097.7	-96257.0	70222.2	40931.6	-111153.7	626.0	20	0.050
1065	6617.00	52857.0	42993.7	-95850.7	69794.7	40834.6	-110629.3	626.5	20	0.050
1066	6620.00	52561.0	42888.0	-95449.1	69377.1	40735.8	-110112.9	626.9	20	0.050
1067	6623.00	52271.4	42780.9	-95052.2	68969.2	40635.4	-109604.6	627.3	20	0.050
1068	6626.00	51988.1	42672.2	-94660.3	68571.1	40533.1	-109104.2	627.7	20	0.050
1069	6629.00	51711.2	42561.8	-94273.0	68182.8	40429.2	-108611.9	628.0	20	0.050
1070	6632.00	51440.6	42449.9	-93890.6	67804.2	40323.4	-108127.6	628.4	20	0.050
1071	6635.00	51176.5	42336.5	-93513.0	67435.5	40215.9	-107651.4	628.8	20	0.050
1072	6638.00	50918.6	42221.5	-93140.1	67076.5	40106.7	-107183.2	629.1	20	0.050
1073	6641.00	50667.2	42104.9	-92772.1	66727.3	39995.7	-106723.0	629.4	20	0.050
1074	6644.00	50422.1	41986.8	-92408.8	66387.9	39883.0	-106270.9	629.7	20	0.050
1075	6647.00	50183.3	41866.9	-92050.2	66058.2	39768.6	-105826.8	630.0	20	0.050
1076	6650.00	49950.7	41745.7	-91696.4	65738.0	39652.4	-105390.4	630.3	20	0.050
1077	6653.00	49719.8	41624.1	-91343.8	65420.3	39535.9	-104956.2	630.6	20	0.050
1078	6656.00	49488.9	41502.4	-90991.3	65102.6	39419.2	-104521.9	630.9	20	0.050
1079	6659.00	49259.3	41381.1	-90640.4	64786.8	39302.9	-104089.7	631.2	20	0.050
1080	6662.00	49035.5	41260.9	-90296.4	64479.3	39187.4	-103666.6	631.5	20	0.050
1081	6665.00	48817.9	41141.7	-89959.6	64180.5	39072.9	-103253.4	631.8	20	0.050
1082	6669.00	48537.4	40984.6	-89522.0	63796.0	38921.7	-102717.7	632.1	20	0.050
1083	6673.00	48267.9	40829.4	-89097.3	63427.1	38772.2	-102199.4	632.5	20	0.050
1084	6677.00	48009.3	40676.3	-88685.6	63074.0	38624.6	-101698.5	632.8	20	0.050
1085	6681.00	47761.7	40525.1	-88286.8	62736.6	38478.5	-101215.1	633.1	20	0.050
1086	6685.00	47525.1	40375.9	-87901.0	62414.9	38334.3	-100749.2	633.4	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1087	6689.00	47299.4	40228.7	-87528.1	62108.9	38191.8	-100300.7	633.6	20	0.050
1088	6693.00	47084.7	40083.5	-87168.2	61818.6	38051.0	-99869.5	633.9	20	0.050
1089	6698.00	46831.7	39904.7	-86736.4	61477.8	37877.4	-99355.2	634.2	20	0.050
1090	6701.00	46603.9	39774.0	-86377.9	60824.2	37755.5	-98579.7	632.3	20	0.050
1091	6702.00	46316.5	39672.0	-85988.5	59679.0	37670.2	-97349.2	627.7	20	0.050
1092	6703.00	45899.6	39538.3	-85437.9	58296.1	37560.9	-95857.0	622.2	20	0.050
1093	6704.00	45379.4	39378.4	-84757.7	56793.2	37430.3	-94223.5	616.1	20	0.050
1094	6705.00	44782.7	39196.1	-83978.9	55231.2	37280.3	-92511.5	609.7	20	0.050
1095	6706.00	44125.2	38993.7	-83119.0	53636.6	37112.2	-90748.9	603.0	20	0.050
1096	6707.00	43411.4	38772.0	-82183.4	52014.7	36926.2	-88940.9	596.1	20	0.050
1097	6708.00	42655.0	38532.6	-81187.6	50381.1	36723.5	-87104.6	589.1	20	0.050
1098	6709.00	41858.1	38276.0	-80134.1	48737.4	36504.2	-85241.6	581.9	20	0.050
1099	6710.00	41036.3	38004.5	-79040.8	47094.9	36270.1	-83365.0	574.6	20	0.050
1100	6711.00	40194.2	37718.9	-77913.1	45457.0	36021.5	-81478.5	567.2	20	0.050
1101	6712.00	39331.7	37419.3	-76750.9	43823.4	35758.7	-79582.0	559.7	20	0.050
1102	6713.00	38448.9	37105.6	-75554.5	42194.3	35481.4	-77675.7	552.1	20	0.050
1103	6714.00	37546.9	36778.1	-74325.0	40570.0	35189.9	-75759.9	544.5	20	0.050
1104	6715.00	36634.3	36438.6	-73073.0	38954.8	34885.8	-73840.6	536.8	20	0.050
1105	6716.00	35713.6	36087.7	-71801.3	37349.6	34569.4	-71919.0	529.0	20	0.050
1106	6717.00	34784.7	35725.3	-70510.1	35754.5	34240.7	-69995.3	521.1	20	0.050
1107	6718.00	33847.8	35351.7	-69199.5	34169.6	33899.7	-68069.3	513.3	20	0.050
1108	6719.00	32903.9	34967.0	-67870.9	32594.9	33546.8	-66141.8	505.3	20	0.050
1109	6720.00	31960.1	34574.3	-66534.4	31032.1	33184.8	-64216.9	497.3	20	0.050
1110	6721.00	31018.1	34174.2	-65192.3	29481.5	32814.0	-62295.5	489.3	20	0.050
1111	6722.00	30078.2	33766.8	-63845.0	27943.2	32434.7	-60378.0	481.2	20	0.050
1112	6723.00	29140.5	33352.0	-62492.5	26417.1	32046.9	-58464.0	473.2	20	0.050
1113	6724.00	28204.8	32930.2	-61135.0	24903.3	31650.4	-56553.8	465.0	20	0.050
1114	6725.00	27271.5	32501.4	-59772.9	23401.7	31245.5	-54647.2	456.9	20	0.050
1115	6726.00	26424.0	32089.6	-58513.6	22373.1	30850.9	-53224.1	450.7	20	0.050
1116	6727.00	25733.8	31711.5	-57445.3	21978.7	30479.7	-52458.4	447.2	20	0.050
1117	6728.00	25174.6	31356.3	-56530.9	21835.1	30123.8	-51958.9	444.5	20	0.050
1118	6729.00	24720.2	31019.1	-55739.3	21824.4	29780.9	-51605.4	442.4	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1119	6730.00	24344.3	30696.3	-55040.6	21886.1	29449.2	-51335.4	440.6	20	0.050
1120	6731.00	24034.0	30387.8	-54421.8	21993.1	29129.9	-51123.0	438.9	20	0.050
1121	6732.00	23784.9	30092.9	-53877.7	22140.4	28822.5	-50962.9	437.5	20	0.050
1122	6733.00	23583.0	29809.8	-53392.8	22311.4	28526.5	-50837.9	436.2	20	0.050
1123	6734.00	23425.9	29538.2	-52964.1	22504.4	28241.1	-50745.4	435.1	20	0.050
1124	6736.00	23195.2	29021.8	-52217.0	22918.7	27697.1	-50615.9	433.0	20	0.050
1125	6738.00	23063.5	28539.3	-51602.8	23362.5	27187.6	-50550.0	431.2	20	0.050
1126	6740.00	23019.4	28088.2	-51107.5	23830.2	26710.4	-50540.5	429.7	20	0.050
1127	6743.00	23056.6	27472.0	-50528.6	24536.0	26058.7	-50594.6	427.7	20	0.050
1128	6746.00	23188.5	26931.0	-50119.5	25228.8	25486.9	-50715.7	426.0	20	0.050
1129	6749.00	23358.9	26444.5	-49803.4	25896.0	24973.4	-50869.4	424.5	20	0.050
1130	6752.00	23566.0	26011.6	-49577.6	26537.2	24517.4	-51054.6	423.2	20	0.050
1131	6755.00	23808.7	25631.7	-49440.4	27152.4	24118.6	-51271.0	422.1	20	0.050
1132	6758.00	24067.0	25289.0	-49356.1	27744.4	23759.7	-51504.2	421.0	20	0.050
1133	6761.00	24331.4	24976.4	-49307.8	28314.2	23433.0	-51747.2	420.1	20	0.050
1134	6764.00	24602.0	24693.7	-49295.6	28861.9	23138.4	-52000.4	419.2	20	0.050
1135	6767.00	24876.7	24436.6	-49313.3	29390.1	22871.2	-52261.3	418.5	20	0.050
1136	6770.00	25146.7	24194.6	-49341.2	29901.1	22620.2	-52521.3	417.7	20	0.050
1137	6773.00	25410.3	23968.2	-49378.4	30393.4	22385.6	-52779.0	417.0	20	0.050
1138	6776.00	25667.5	23757.4	-49424.9	30867.2	22167.3	-53034.5	416.3	20	0.050
1139	6779.00	25919.3	23562.7	-49482.1	31324.0	21965.8	-53289.8	415.7	20	0.050
1140	6782.00	26167.8	23384.8	-49552.5	31766.3	21782.3	-53548.6	415.1	20	0.050
1141	6785.00	26412.8	23223.6	-49636.4	32194.3	21616.5	-53810.8	414.5	20	0.050
1142	6789.00	26734.1	23035.1	-49769.2	32742.7	21423.1	-54165.8	413.8	20	0.050
1143	6793.00	27048.9	22873.9	-49922.8	33267.0	21258.5	-54525.4	413.1	20	0.050
1144	6797.00	27347.7	22733.4	-50081.1	33759.9	21115.4	-54875.3	412.5	20	0.050
1145	6801.00	27627.6	22614.2	-50241.8	34217.7	20994.4	-55212.1	411.9	20	0.050
1146	6805.00	27888.5	22516.3	-50404.8	34640.2	20895.4	-55535.6	411.4	20	0.050
1147	6810.00	28188.1	22423.9	-50612.0	35118.8	20802.8	-55921.6	410.8	20	0.050
1148	6815.00	28458.0	22364.8	-50822.7	35542.2	20744.8	-56286.9	410.4	20	0.050
1149	6820.00	28708.7	22331.0	-51039.7	35929.0	20712.7	-56641.7	409.9	20	0.050
1150	6825.00	28966.5	22301.9	-51268.4	36325.4	20685.5	-57010.9	409.5	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1151	6830.00	29230.5	22275.5	-51506.0	36730.5	20661.5	-57391.9	409.0	20	0.050
1152	6835.00	29494.9	22249.5	-51744.4	37136.2	20637.4	-57773.6	408.6	20	0.050
1153	6840.00	29759.4	22223.6	-51983.0	37541.8	20613.3	-58155.1	408.2	20	0.050
1154	6845.00	30024.0	22197.8	-52221.8	37947.4	20589.3	-58536.8	407.7	20	0.050
1155	6850.00	30288.4	22172.2	-52460.6	38352.6	20565.4	-58918.0	407.3	20	0.050
1156	6853.00	30491.5	22172.0	-52663.5	38800.0	20563.9	-59363.9	407.9	20	0.050
1157	6855.00	30663.5	22183.2	-52846.7	39168.1	20572.9	-59741.0	408.7	20	0.050
1158	6857.00	30850.3	22201.5	-53051.8	39541.7	20588.6	-60130.3	409.6	20	0.050
1159	6859.00	31046.7	22225.8	-53272.6	39913.8	20610.4	-60524.3	410.5	20	0.050
1160	6861.00	31247.3	22255.7	-53502.9	40280.0	20638.0	-60918.0	411.5	20	0.050
1161	6863.00	31449.9	22290.8	-53740.7	40638.6	20670.9	-61309.6	412.5	20	0.050
1162	6865.00	31653.8	22331.0	-53984.8	40989.3	20709.1	-61698.4	413.5	20	0.050
1163	6867.00	31856.4	22376.0	-54232.3	41330.8	20752.3	-62083.1	414.6	20	0.050
1164	6869.00	32057.6	22425.4	-54483.0	41663.1	20800.0	-62463.2	415.7	20	0.050
1165	6872.00	32352.7	22506.8	-54859.5	42143.4	20879.2	-63022.7	417.3	20	0.050
1166	6875.00	32638.6	22596.3	-55234.8	42601.9	20966.8	-63568.7	419.0	20	0.050
1167	6878.00	32921.6	22692.0	-55613.5	43048.6	21060.7	-64109.3	420.8	20	0.050
1168	6881.00	33203.6	22793.1	-55996.7	43487.1	21160.2	-64647.2	422.5	20	0.050
1169	6884.00	33482.9	22898.3	-56381.2	43917.5	21263.8	-65181.3	424.3	20	0.050
1170	6887.00	33759.2	23007.4	-56766.6	44340.1	21371.3	-65711.4	426.1	20	0.050
1171	6890.00	34032.6	23120.4	-57153.0	44754.7	21482.6	-66237.3	427.9	20	0.050
1172	6893.00	34303.0	23236.1	-57539.1	45162.1	21596.7	-66758.8	429.7	20	0.050
1173	6896.00	34569.9	23353.6	-57923.5	45563.2	21712.5	-67275.7	431.5	20	0.050
1174	6899.00	34834.6	23473.5	-58308.0	45959.7	21830.6	-67790.3	433.3	20	0.050
1175	6902.00	35097.9	23596.5	-58694.4	46352.8	21951.8	-68304.6	435.1	20	0.050
1176	6905.00	35360.0	23722.8	-59082.8	46742.6	22076.1	-68818.7	437.0	20	0.050
1177	6908.00	35620.4	23852.1	-59472.5	47128.3	22203.5	-69331.8	438.8	20	0.050
1178	6911.00	35872.9	23983.7	-59856.5	47501.1	22333.0	-69834.1	440.6	20	0.050
1179	6914.00	36115.5	24116.9	-60232.5	47857.9	22464.2	-70322.1	442.5	20	0.050
1180	6917.00	36348.3	24252.0	-60600.2	48198.9	22596.9	-70795.9	444.4	20	0.050
1181	6920.00	36571.5	24387.7	-60959.2	48525.1	22730.4	-71255.5	446.3	20	0.050
1182	6923.00	36785.3	24524.0	-61309.3	48836.6	22864.5	-71701.1	448.2	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1183	6926.00	36989.6	24661.0	-61650.5	49133.6	22999.0	-72132.6	450.2	20	0.050
1184	6929.00	37184.4	24798.4	-61982.8	49416.0	23134.0	-72550.0	452.1	20	0.050
1185	6933.00	37429.7	24982.6	-62412.3	49770.4	23314.9	-73085.3	454.8	20	0.050
1186	6937.00	37669.0	25169.5	-62838.5	50114.7	23498.4	-73613.2	457.4	20	0.050
1187	6941.00	37906.6	25359.9	-63266.5	50455.5	23685.3	-74140.9	460.1	20	0.050
1188	6945.00	38143.5	25553.0	-63696.5	50794.2	23875.0	-74669.2	462.7	20	0.050
1189	6949.00	38379.3	25747.3	-64126.7	51131.0	24065.6	-75196.6	465.4	20	0.050
1190	6953.00	38611.6	25940.8	-64552.5	51462.4	24255.2	-75717.6	468.0	20	0.050
1191	6957.00	38840.3	26133.5	-64973.8	51788.3	24443.9	-76232.2	470.7	20	0.050
1192	6961.00	39065.4	26325.2	-65390.6	52108.7	24631.6	-76740.3	473.4	20	0.050
1193	6965.00	39286.7	26516.1	-65802.8	52423.6	24818.3	-77241.9	476.1	20	0.050
1194	6969.00	39504.5	26706.0	-66210.5	52733.0	25003.9	-77737.0	478.8	20	0.050
1195	6973.00	39718.6	26895.1	-66613.7	53037.0	25188.6	-78225.6	481.4	20	0.050
1196	6977.00	39929.0	27083.2	-67012.3	53335.4	25372.3	-78707.7	484.1	20	0.050
1197	6981.00	40135.8	27270.5	-67406.3	53628.4	25555.0	-79183.3	486.8	20	0.050
1198	6985.00	40338.9	27456.9	-67795.7	53915.8	25736.7	-79652.5	489.6	20	0.050
1199	6989.00	40538.2	27642.3	-68180.5	54197.8	25917.4	-80115.2	492.3	20	0.050
1200	6993.00	40734.0	27826.8	-68560.7	54474.3	26097.0	-80571.3	495.0	20	0.050
1201	6997.00	40926.0	28010.3	-68936.3	54745.2	26275.8	-81021.0	497.7	20	0.050
1202	7001.00	41114.4	28192.9	-69307.3	55010.9	26453.5	-81464.4	500.4	20	0.050
1203	7005.00	41300.1	28374.3	-69674.4	55272.7	26629.8	-81902.5	503.2	20	0.050
1204	7009.00	41483.4	28554.4	-70037.8	55530.9	26804.8	-82335.7	505.9	20	0.050
1205	7014.00	41708.9	28777.7	-70486.6	55848.5	27021.8	-82870.3	509.3	20	0.050
1206	7019.00	41930.4	28999.1	-70929.5	56160.4	27236.6	-83397.0	512.8	20	0.050
1207	7024.00	42148.1	29218.4	-71366.5	56466.7	27449.4	-83916.1	516.2	20	0.050
1208	7029.00	42360.1	29435.0	-71795.2	56765.1	27659.4	-84424.4	519.6	20	0.050
1209	7034.00	42557.7	29644.6	-72202.3	57043.0	27862.3	-84905.3	523.1	20	0.050
1210	7039.00	42739.1	29846.5	-72585.6	57298.5	28057.6	-85356.1	526.6	20	0.050
1211	7045.00	42935.7	30078.6	-73014.3	57575.4	28281.8	-85857.2	530.8	20	0.050
1212	7053.00	43110.4	30356.8	-73467.2	57680.2	28552.8	-86233.0	535.5	20	0.050
1213	7059.00	42983.8	30490.9	-73474.7	57209.4	28693.2	-85902.6	536.7	20	0.050
1214	7064.00	42804.1	30567.0	-73371.1	56797.4	28775.5	-85572.9	537.5	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1215	7069.00	42596.5	30616.9	-73213.4	56396.7	28831.3	-85228.0	538.1	20	0.050
1216	7074.00	42380.8	30646.6	-73027.4	56014.1	28866.2	-84880.4	538.6	20	0.050
1217	7079.00	42164.8	30658.9	-72823.7	55651.4	28883.3	-84534.7	539.0	20	0.050
1218	7085.00	41909.3	30654.0	-72563.3	55241.8	28883.4	-84125.2	539.5	20	0.050
1219	7091.00	41662.9	30631.6	-72294.4	54859.6	28865.4	-83725.0	540.0	20	0.050
1220	7097.00	41426.8	30597.5	-72024.3	54500.6	28835.3	-83335.9	540.4	20	0.050
1221	7103.00	41201.9	30555.2	-71757.1	54162.3	28796.7	-82959.0	540.7	20	0.050
1222	7110.00	40956.1	30497.9	-71454.0	53797.1	28743.2	-82540.3	541.1	20	0.050
1223	7117.00	40731.1	30434.8	-71165.9	53467.3	28683.5	-82150.8	541.5	20	0.050
1224	7125.00	40497.3	30361.2	-70858.5	53127.5	28613.2	-81740.7	541.8	20	0.050
1225	7134.00	40262.9	30279.5	-70542.4	52788.7	28534.9	-81323.6	542.2	20	0.050
1226	7144.00	40037.5	30190.3	-70227.9	52465.7	28448.8	-80914.5	542.5	20	0.050
1227	7152.00	39839.5	30110.6	-69950.1	52074.9	28373.4	-80448.2	542.0	20	0.050
1228	7154.00	39713.2	30069.5	-69782.7	51738.6	28337.6	-80076.1	540.9	20	0.050
1229	7156.00	39554.4	30018.5	-69572.9	51374.0	28293.0	-79666.9	539.7	20	0.050
1230	7158.00	39373.1	29958.9	-69331.9	50998.2	28240.1	-79238.3	538.3	20	0.050
1231	7160.00	39176.2	29891.5	-69067.7	50618.3	28179.8	-78798.1	536.9	20	0.050
1232	7162.00	38969.9	29817.4	-68787.3	50238.8	28112.6	-78351.4	535.5	20	0.050
1233	7164.00	38754.8	29736.6	-68491.4	49860.3	28038.6	-77898.9	534.0	20	0.050
1234	7166.00	38533.9	29649.8	-68183.7	49484.0	27958.3	-77442.3	532.5	20	0.050
1235	7168.00	38308.9	29557.1	-67866.0	49110.8	27872.0	-76982.8	531.0	20	0.050
1236	7170.00	38080.7	29459.1	-67539.7	48740.9	27780.1	-76521.0	529.5	20	0.050
1237	7172.00	37852.2	29356.8	-67209.0	48375.2	27683.9	-76059.0	527.9	20	0.050
1238	7174.00	37624.6	29251.2	-66875.8	48015.0	27584.0	-75599.0	526.3	20	0.050
1239	7176.00	37398.2	29142.3	-66540.5	47660.7	27480.6	-75141.3	524.8	20	0.050
1240	7178.00	37172.9	29030.2	-66203.0	47312.2	27373.8	-74686.0	523.2	20	0.050
1241	7180.00	36948.8	28914.9	-65863.7	46969.6	27263.6	-74233.2	521.6	20	0.050
1242	7182.00	36727.2	28797.2	-65524.3	46632.8	27151.0	-73783.8	519.9	20	0.050
1243	7184.00	36508.0	28677.5	-65185.5	46302.0	27035.9	-73337.9	518.3	20	0.050
1244	7186.00	36291.5	28555.6	-64847.2	45976.8	26918.7	-72895.5	516.7	20	0.050
1245	7188.00	36077.7	28431.7	-64509.4	45657.5	26799.1	-72456.6	515.0	20	0.050
1246	7190.00	35866.4	28305.7	-64172.1	45343.9	26677.3	-72021.3	513.4	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1247	7192.00	35657.9	28178.1	-63836.1	45035.8	26553.8	-71589.6	511.7	20	0.050
1248	7194.00	35452.5	28049.8	-63502.3	44732.4	26429.5	-71161.9	510.0	20	0.050
1249	7196.00	35249.9	27920.8	-63170.7	44433.9	26304.2	-70738.1	508.3	20	0.050
1250	7198.00	35050.3	27791.1	-62841.4	44140.2	26178.2	-70318.4	506.7	20	0.050
1251	7200.00	34853.6	27660.7	-62514.3	43851.2	26051.3	-69902.5	505.0	20	0.050
1252	7202.00	34659.6	27529.6	-62189.2	43566.7	25923.6	-69490.3	503.3	20	0.050
1253	7205.00	34373.5	27331.8	-61705.4	43148.1	25730.6	-68878.7	500.7	20	0.050
1254	7208.00	34093.4	27132.6	-61226.0	42739.3	25535.9	-68275.2	498.1	20	0.050
1255	7211.00	33819.3	26931.9	-60751.2	42340.3	25339.5	-67679.8	495.6	20	0.050
1256	7214.00	33551.2	26729.7	-60280.9	41951.1	25141.3	-67092.3	493.0	20	0.050
1257	7217.00	33288.9	26526.3	-59815.2	41571.4	24941.4	-66512.9	490.4	20	0.050
1258	7220.00	33032.1	26322.8	-59354.9	41200.0	24741.4	-65941.4	487.8	20	0.050
1259	7223.00	32780.7	26119.3	-58900.0	40836.5	24541.2	-65377.7	485.1	20	0.050
1260	7226.00	32534.6	25916.0	-58450.6	40481.0	24340.9	-64821.9	482.5	20	0.050
1261	7229.00	32293.9	25712.8	-58006.7	40133.4	24140.5	-64273.9	479.9	20	0.050
1262	7232.00	32058.4	25509.9	-57568.3	39793.7	23939.9	-63733.7	477.2	20	0.050
1263	7235.00	31828.4	25306.9	-57135.3	39461.9	23739.4	-63201.3	474.5	20	0.050
1264	7238.00	31603.6	25104.2	-56707.8	39138.1	23538.7	-62676.8	471.9	20	0.050
1265	7241.00	31384.2	24901.6	-56285.7	38822.2	23338.0	-62160.1	469.2	20	0.050
1266	7244.00	31169.6	24699.4	-55869.0	38513.2	23137.4	-61650.7	466.5	20	0.050
1267	7247.00	30958.8	24498.6	-55457.5	38209.8	22938.1	-61147.9	463.8	20	0.050
1268	7250.00	30752.2	24298.9	-55051.1	37911.8	22739.7	-60651.5	461.1	20	0.050
1269	7253.00	30549.4	24100.3	-54649.8	37619.5	22542.3	-60161.8	458.4	20	0.050
1270	7256.00	30350.7	23902.9	-54253.6	37332.6	22346.0	-59678.5	455.7	20	0.050
1271	7259.00	30155.7	23706.8	-53862.5	37051.1	22150.4	-59201.5	453.0	20	0.050
1272	7262.00	29964.0	23511.7	-53475.7	36774.2	21955.9	-58730.1	450.3	20	0.050
1273	7265.00	29775.8	23317.5	-53093.3	36501.9	21762.3	-58264.2	447.6	20	0.050
1274	7268.00	29590.8	23124.5	-52715.3	36234.1	21569.7	-57803.8	444.8	20	0.050
1275	7271.00	29409.1	22932.6	-52341.7	35971.0	21377.9	-57348.8	442.1	20	0.050
1276	7274.00	29230.7	22741.7	-51972.4	35712.3	21187.0	-56899.3	439.4	20	0.050
1277	7277.00	29055.7	22551.9	-51607.6	35458.3	20997.1	-56455.3	436.6	20	0.050
1278	7280.00	28883.9	22363.1	-51246.9	35208.8	20807.9	-56016.8	433.9	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1279	7284.00	28659.9	22113.1	-50773.0	34883.4	20557.2	-55440.5	430.2	20	0.050
1280	7288.00	28441.8	21864.9	-50306.7	34566.0	20308.1	-54874.1	426.6	20	0.050
1281	7292.00	28229.6	21618.6	-49848.1	34256.8	20060.6	-54317.3	422.9	20	0.050
1282	7296.00	28023.2	21374.0	-49397.2	33955.6	19814.7	-53770.4	419.2	20	0.050
1283	7300.00	27822.8	21131.5	-48954.3	33662.9	19570.6	-53233.5	415.5	20	0.050
1284	7304.00	27627.6	20891.5	-48519.1	33377.1	19328.8	-52705.9	411.8	20	0.050
1285	7308.00	27436.9	20653.9	-48090.9	33097.7	19089.1	-52186.8	408.1	20	0.050
1286	7312.00	27250.9	20419.1	-47670.0	32824.4	18852.0	-51676.3	404.4	20	0.050
1287	7316.00	27070.2	20187.5	-47257.7	32558.1	18618.1	-51176.2	400.6	20	0.050
1288	7320.00	26895.0	19959.6	-46854.5	32299.4	18387.4	-50686.8	396.9	20	0.050
1289	7324.00	26725.3	19735.0	-46460.3	32048.0	18160.4	-50208.3	393.2	20	0.050
1290	7328.00	26561.0	19514.1	-46075.1	31804.0	17936.6	-49740.6	389.4	20	0.050
1291	7332.00	26402.2	19296.8	-45699.0	31567.4	17716.5	-49283.9	385.7	20	0.050
1292	7336.00	26248.8	19083.0	-45331.8	31338.3	17499.7	-48838.0	381.9	20	0.050
1293	7341.00	26064.6	18820.6	-44885.2	31062.2	17233.6	-48295.8	377.2	20	0.050
1294	7346.00	25889.0	18563.7	-44452.7	30797.8	16972.9	-47770.7	372.5	20	0.050
1295	7351.00	25729.8	18314.4	-44044.2	30590.9	16719.5	-47310.5	368.0	20	0.050
1296	7356.00	25787.7	18120.5	-43908.2	31037.2	16516.1	-47553.2	366.2	20	0.050
1297	7360.00	25944.0	17998.7	-43942.8	31479.1	16387.6	-47866.8	365.3	20	0.050
1298	7364.00	26139.4	17899.0	-44038.3	31921.0	16283.4	-48204.4	364.5	20	0.050
1299	7368.00	26355.0	17817.9	-44172.9	32351.0	16199.9	-48550.8	363.9	20	0.050
1300	7372.00	26578.0	17752.3	-44330.4	32764.3	16133.4	-48897.7	363.3	20	0.050
1301	7376.00	26799.5	17699.1	-44498.6	33158.7	16080.4	-49239.1	362.8	20	0.050
1302	7380.00	27019.0	17658.2	-44677.2	33534.1	16040.9	-49575.0	362.3	20	0.050
1303	7385.00	27287.8	17623.3	-44911.1	33980.2	16008.5	-49988.7	361.8	20	0.050
1304	7390.00	27548.6	17604.7	-45153.3	34401.9	15993.5	-50395.4	361.3	20	0.050
1305	7395.00	27800.7	17598.6	-45399.3	34801.9	15991.5	-50793.4	360.8	20	0.050
1306	7400.00	28043.1	17600.8	-45643.8	35183.6	15998.0	-51181.6	360.4	20	0.050
1307	7405.00	28276.0	17611.1	-45887.0	35546.9	16012.9	-51559.8	360.0	20	0.050
1308	7410.00	28499.2	17629.7	-46128.9	35891.9	16036.2	-51928.2	359.6	20	0.050
1309	7416.00	28754.5	17662.9	-46417.4	36281.7	16075.2	-52356.9	359.2	20	0.050
1310	7422.00	28997.4	17704.5	-46701.9	36649.0	16122.8	-52771.8	358.8	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1311	7428.00	29229.0	17751.8	-46980.7	36997.4	16176.0	-53173.4	358.5	20	0.050
1312	7434.00	29449.3	17804.7	-47254.0	37326.8	16234.6	-53561.4	358.2	20	0.050
1313	7441.00	29692.1	17873.6	-47565.7	37687.1	16310.1	-53997.1	357.8	20	0.050
1314	7448.00	29922.9	17947.5	-47870.4	38027.5	16390.3	-54417.8	357.5	20	0.050
1315	7454.00	30143.1	18019.2	-48162.2	38416.7	16466.4	-54883.1	357.7	20	0.050
1316	7458.00	30329.6	18079.1	-48408.6	38753.7	16528.0	-55281.7	358.2	20	0.050
1317	7462.00	30528.0	18145.9	-48673.9	39090.4	16596.5	-55686.9	358.8	20	0.050
1318	7466.00	30731.1	18218.5	-48949.6	39420.6	16671.4	-56092.0	359.4	20	0.050
1319	7470.00	30935.0	18296.2	-49231.2	39742.9	16751.5	-56494.4	360.0	20	0.050
1320	7474.00	31136.8	18378.1	-49514.9	40056.3	16835.7	-56892.1	360.7	20	0.050
1321	7479.00	31384.3	18485.9	-49870.3	40435.0	16946.7	-57381.8	361.5	20	0.050
1322	7484.00	31625.3	18598.7	-50224.0	40798.4	17062.6	-57861.0	362.4	20	0.050
1323	7489.00	31858.3	18715.3	-50573.6	41146.2	17182.4	-58328.5	363.3	20	0.050
1324	7494.00	32083.0	18835.3	-50918.3	41478.8	17305.2	-58784.0	364.2	20	0.050
1325	7499.00	32299.3	18956.9	-51256.2	41797.2	17429.8	-59227.0	365.1	20	0.050
1326	7504.00	32507.5	19079.6	-51587.2	42102.7	17555.1	-59657.8	366.1	20	0.050
1327	7509.00	32709.4	19203.1	-51912.5	42397.4	17681.1	-60078.4	367.0	20	0.050
1328	7514.00	32904.8	19327.6	-52232.4	42681.4	17807.8	-60489.2	368.0	20	0.050
1329	7520.00	33131.1	19477.6	-52608.7	43008.8	17960.3	-60969.1	369.2	20	0.050
1330	7526.00	33349.5	19628.7	-52978.2	43323.7	18113.6	-61437.3	370.4	20	0.050
1331	7532.00	33560.5	19781.0	-53341.4	43626.7	18268.0	-61894.7	371.6	20	0.050
1332	7538.00	33764.0	19934.5	-53698.5	43917.9	18423.3	-62341.2	372.8	20	0.050
1333	7544.00	33960.1	20089.2	-54049.3	44197.5	18579.4	-62776.9	374.0	20	0.050
1334	7550.00	34149.9	20244.2	-54394.0	44467.1	18735.8	-63202.9	375.3	20	0.050
1335	7557.00	34363.6	20425.1	-54788.7	44769.7	18918.2	-63687.9	376.7	20	0.050
1336	7564.00	34570.6	20606.3	-55176.9	45062.2	19100.3	-64162.5	378.2	20	0.050
1337	7571.00	34770.6	20784.2	-55554.8	45344.1	19279.0	-64623.1	379.7	20	0.050
1338	7578.00	34961.5	20956.5	-55918.0	45613.1	19451.8	-65064.9	381.2	20	0.050
1339	7586.00	35168.1	21146.1	-56314.2	45904.3	19641.6	-65545.8	382.9	20	0.050
1340	7594.00	35365.1	21330.7	-56695.8	46181.2	19826.2	-66007.4	384.7	20	0.050
1341	7602.00	35554.4	21513.0	-57067.5	46446.9	20008.2	-66455.1	386.4	20	0.050
1342	7610.00	35735.8	21691.6	-57427.4	46701.0	20186.4	-66887.5	388.2	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1343	7619.00	35930.5	21888.0	-57818.5	46973.7	20381.9	-67355.6	390.2	20	0.050
1344	7628.00	36115.5	22079.3	-58194.8	47232.3	20572.1	-67804.4	392.2	20	0.050
1345	7638.00	36309.6	22286.0	-58595.6	47503.1	20777.5	-68280.6	394.4	20	0.050
1346	7648.00	36491.5	22486.6	-58978.1	47756.6	20976.4	-68733.0	396.7	20	0.050
1347	7689.00	36366.2	22934.3	-59300.5	47251.0	21436.0	-68687.0	398.7	20	0.050
1348	7738.00	36108.9	23096.6	-59205.5	46820.0	21602.6	-68422.7	399.2	20	0.050
1349	7753.00	35949.2	23097.3	-59046.5	46272.3	21609.9	-67882.1	397.3	20	0.050
1350	7755.00	35776.3	23058.5	-58834.7	45777.5	21579.1	-67356.5	395.2	20	0.050
1351	7757.00	35561.6	23006.8	-58568.4	45257.2	21536.2	-66793.4	393.0	20	0.050
1352	7759.00	35317.3	22943.6	-58260.9	44726.8	21482.1	-66208.9	390.7	20	0.050
1353	7761.00	35055.1	22870.7	-57925.8	44196.2	21417.9	-65614.0	388.2	20	0.050
1354	7763.00	34780.0	22788.8	-57568.8	43668.7	21344.4	-65013.0	385.7	20	0.050
1355	7765.00	34493.7	22698.2	-57191.9	43145.2	21261.6	-64406.9	383.2	20	0.050
1356	7767.00	34201.7	22599.9	-56801.6	42628.5	21170.8	-63799.3	380.6	20	0.050
1357	7769.00	33904.7	22494.2	-56398.9	42118.8	21071.9	-63190.6	378.0	20	0.050
1358	7771.00	33606.6	22382.3	-55989.0	41616.6	20966.6	-62583.2	375.3	20	0.050
1359	7773.00	33309.4	22265.0	-55574.5	41122.6	20855.1	-61977.7	372.7	20	0.050
1360	7775.00	33013.1	22142.4	-55155.4	40636.6	20737.9	-61374.5	370.0	20	0.050
1361	7777.00	32717.7	22014.2	-54731.9	40158.7	20614.7	-60773.4	367.3	20	0.050
1362	7779.00	32423.3	21880.4	-54303.7	39688.8	20485.5	-60174.3	364.5	20	0.050
1363	7781.00	32130.4	21741.9	-53872.3	39226.8	20351.0	-59577.8	361.8	20	0.050
1364	7783.00	31840.8	21599.6	-53440.4	38772.6	20212.4	-58984.9	359.0	20	0.050
1365	7785.00	31554.4	21453.3	-53007.7	38326.1	20069.4	-58395.6	356.2	20	0.050
1366	7787.00	31271.1	21303.7	-52574.8	37887.4	19922.5	-57809.9	353.4	20	0.050
1367	7789.00	30991.1	21150.1	-52141.2	37456.4	19771.5	-57227.9	350.6	20	0.050
1368	7791.00	30714.3	20993.1	-51707.4	37033.0	19616.5	-56649.5	347.8	20	0.050
1369	7793.00	30441.2	20834.3	-51275.5	36616.0	19459.3	-56075.3	345.0	20	0.050
1370	7795.00	30171.7	20674.1	-50845.8	36205.1	19300.4	-55505.5	342.1	20	0.050
1371	7797.00	29906.3	20512.7	-50419.0	35800.6	19140.1	-54940.7	339.3	20	0.050
1372	7799.00	29644.7	20350.2	-49995.0	35402.8	18978.2	-54381.0	336.4	20	0.050
1373	7801.00	29387.3	20186.6	-49573.9	35011.3	18815.0	-53826.2	333.6	20	0.050
1374	7803.00	29133.7	20022.0	-49155.7	34626.3	18650.3	-53276.6	330.7	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1375	7805.00	28884.1	19856.2	-48740.4	34247.6	18484.4	-52732.0	327.8	20	0.050
1376	7807.00	28638.4	19689.3	-48327.7	33875.2	18316.9	-52192.1	324.9	20	0.050
1377	7809.00	28396.6	19521.3	-47917.9	33509.2	18147.9	-51657.1	322.0	20	0.050
1378	7811.00	28158.7	19352.2	-47510.9	33149.4	17977.6	-51126.9	319.1	20	0.050
1379	7813.00	27924.6	19182.0	-47106.6	32795.9	17805.7	-50601.7	316.2	20	0.050
1380	7815.00	27694.5	19010.7	-46705.2	32448.8	17632.5	-50081.3	313.3	20	0.050
1381	7817.00	27468.1	18838.7	-46306.7	32107.7	17458.0	-49565.7	310.3	20	0.050
1382	7819.00	27245.3	18666.4	-45911.6	31771.6	17283.1	-49054.8	307.4	20	0.050
1383	7821.00	27025.8	18494.3	-45520.0	31440.5	17108.1	-48548.6	304.4	20	0.050
1384	7823.00	26809.8	18322.2	-45132.0	31114.2	16932.9	-48047.2	301.5	20	0.050
1385	7825.00	26597.3	18150.1	-44747.4	30793.0	16757.3	-47550.3	298.5	20	0.050
1386	7827.00	26388.1	17978.2	-44366.3	30476.7	16581.5	-47058.2	295.6	20	0.050
1387	7829.00	26182.5	17806.2	-43988.7	30165.4	16405.5	-46570.8	292.6	20	0.050
1388	7831.00	25980.4	17634.3	-43614.6	29858.9	16229.3	-46088.2	289.6	20	0.050
1389	7833.00	25781.5	17462.5	-43244.0	29557.4	16052.7	-45610.1	286.7	20	0.050
1390	7835.00	25586.2	17290.6	-42876.8	29260.9	15875.9	-45136.8	283.7	20	0.050
1391	7837.00	25394.4	17118.9	-42513.3	28969.4	15698.8	-44668.2	280.7	20	0.050
1392	7839.00	25206.0	16947.2	-42153.2	28682.8	15521.5	-44204.3	277.7	20	0.050
1393	7841.00	25021.0	16775.5	-41796.6	28401.1	15344.0	-43745.1	274.7	20	0.050
1394	7843.00	24839.2	16604.2	-41443.5	28123.7	15166.5	-43290.2	271.7	20	0.050
1395	7845.00	24659.8	16433.9	-41093.6	27849.5	14989.6	-42839.0	268.7	20	0.050
1396	7847.00	24482.9	16264.1	-40747.0	27578.5	14813.2	-42391.7	265.7	20	0.050
1397	7849.00	24308.4	16095.4	-40403.8	27310.7	14637.3	-41948.0	262.7	20	0.050
1398	7851.00	24136.4	15927.5	-40063.9	27046.0	14462.2	-41508.1	259.6	20	0.050
1399	7853.00	23966.9	15760.4	-39727.2	26784.6	14287.4	-41072.0	256.6	20	0.050
1400	7855.00	23799.7	15594.2	-39393.9	26526.3	14113.3	-40639.6	253.6	20	0.050
1401	7857.00	23635.1	15428.7	-39063.8	26271.2	13939.8	-40210.9	250.6	20	0.050
1402	7860.00	23392.6	15182.3	-38574.9	25894.3	13680.4	-39574.7	246.0	20	0.050
1403	7863.00	23155.5	14937.6	-38093.1	25524.3	13422.2	-38946.6	241.5	20	0.050
1404	7866.00	22923.7	14694.8	-37618.5	25161.2	13165.4	-38326.6	236.9	20	0.050
1405	7869.00	22697.3	14453.8	-37151.2	24804.9	12909.7	-37714.6	232.3	20	0.050
1406	7872.00	22476.2	14214.9	-36691.0	24455.3	12655.3	-37110.6	227.8	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1407	7875.00	22260.5	13977.6	-36238.1	24112.7	12402.1	-36514.8	223.2	20	0.050
1408	7878.00	22050.0	13742.4	-35792.4	23777.0	12150.1	-35927.0	218.6	20	0.050
1409	7881.00	21845.0	13508.9	-35353.9	23448.0	11899.3	-35347.3	214.0	20	0.050
1410	7884.00	21645.2	13277.4	-34922.6	23125.9	11649.8	-34775.7	209.4	20	0.050
1411	7887.00	21450.8	13047.9	-34498.6	22810.6	11401.5	-34212.2	204.8	20	0.050
1412	7890.00	21261.7	12820.1	-34081.8	22502.3	11154.3	-33656.7	200.2	20	0.050
1413	7893.00	21077.9	12594.1	-33672.1	22200.7	10908.6	-33109.3	195.6	20	0.050
1414	7896.00	20899.5	12370.1	-33269.6	21906.0	10663.9	-32569.9	190.9	20	0.050
1415	7899.00	20726.4	12148.0	-32874.4	21618.2	10420.5	-32038.7	186.3	20	0.050
1416	7902.00	20558.1	11927.8	-32485.9	21336.3	10178.6	-31514.9	181.6	20	0.050
1417	7905.00	20393.7	11710.2	-32103.9	21059.1	9938.4	-30997.5	177.0	20	0.050
1418	7908.00	20233.3	11494.9	-31728.3	20786.4	9699.9	-30486.4	172.3	20	0.050
1419	7911.00	20077.0	11281.9	-31358.9	20518.5	9463.0	-29981.5	167.7	20	0.050
1420	7914.00	19924.5	11071.3	-30995.8	20255.2	9227.9	-29483.1	163.0	20	0.050
1421	7917.00	19776.0	10862.9	-30638.9	19996.4	8994.4	-28990.8	158.4	20	0.050
1422	7920.00	19631.4	10656.9	-30288.2	19742.2	8762.5	-28504.8	153.7	20	0.050
1423	7923.00	19490.7	10453.1	-29943.8	19492.6	8532.4	-28025.0	149.0	20	0.050
1424	7926.00	19353.9	10251.8	-29605.7	19247.7	8303.8	-27551.5	144.4	20	0.050
1425	7929.00	19221.1	10052.8	-29273.8	19007.4	8077.0	-27084.4	139.7	20	0.050
1426	7932.00	19092.1	9856.0	-28948.1	18771.6	7851.8	-26623.4	135.0	20	0.050
1427	7935.00	18967.2	9661.5	-28628.7	18540.5	7628.3	-26168.9	130.3	20	0.050
1428	7938.00	18846.1	9469.7	-28315.8	18314.2	7406.7	-25720.9	125.6	20	0.050
1429	7942.00	18691.0	9217.5	-27908.5	18019.8	7114.1	-25133.9	119.3	20	0.050
1430	7946.00	18542.9	8969.6	-27512.5	17733.9	6824.8	-24558.7	113.1	20	0.050
1431	7950.00	18401.8	8726.2	-27128.0	17456.4	6538.9	-23995.3	106.8	20	0.050
1432	7955.00	18482.6	8467.2	-26949.8	18078.2	6243.2	-24321.4	103.0	20	0.050
1433	7958.00	18671.8	8338.2	-27010.0	18653.6	6107.5	-24761.1	101.7	20	0.050
1434	7960.00	18826.6	8261.3	-27087.9	19047.7	6031.7	-25079.4	101.0	20	0.050
1435	7962.00	18993.3	8191.4	-27184.8	19440.8	5966.0	-25406.8	100.3	20	0.050
1436	7964.00	19171.1	8128.7	-27299.9	19832.0	5910.6	-25742.6	99.7	20	0.050
1437	7966.00	19355.9	8072.7	-27428.6	20219.1	5864.4	-26083.5	99.1	20	0.050
1438	7968.00	19545.2	8023.5	-27568.7	20600.6	5827.1	-26427.7	98.6	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1439	7970.00	19738.0	7980.7	-27718.7	20976.3	5798.1	-26774.5	98.1	20	0.050
1440	7972.00	19930.5	7943.4	-27873.9	21345.3	5775.5	-27120.8	97.6	20	0.050
1441	7974.00	20122.6	7911.7	-28034.3	21707.4	5759.5	-27466.9	97.1	20	0.050
1442	7977.00	20409.8	7874.5	-28284.2	22237.7	5747.3	-27985.0	96.4	20	0.050
1443	7980.00	20695.8	7849.7	-28545.4	22752.1	5749.2	-28501.4	95.8	20	0.050
1444	7983.00	20978.0	7835.1	-28813.1	23251.2	5762.2	-29013.4	95.2	20	0.050
1445	7986.00	21255.0	7830.0	-29085.0	23734.9	5785.0	-29520.0	94.7	20	0.050
1446	7989.00	21527.0	7834.2	-29361.2	24203.3	5817.4	-30020.7	94.2	20	0.050
1447	7992.00	21793.7	7847.0	-29640.7	24656.9	5858.3	-30515.2	93.7	20	0.050
1448	7995.00	22055.1	7865.1	-29920.1	25098.5	5903.9	-31002.4	93.2	20	0.050
1449	7998.00	22310.8	7888.2	-30199.1	25528.3	5953.8	-31482.1	92.7	20	0.050
1450	8001.00	22561.1	7916.3	-30477.4	25946.4	6008.0	-31954.4	92.3	20	0.050
1451	8004.00	22805.8	7949.5	-30755.3	26352.8	6066.7	-32419.6	91.8	20	0.050
1452	8007.00	23045.2	7988.1	-31033.2	26748.0	6130.2	-32878.1	91.4	20	0.050
1453	8010.00	23279.3	8031.9	-31311.2	27131.8	6198.4	-33330.3	91.0	20	0.050
1454	8013.00	23508.1	8081.1	-31589.1	27504.4	6271.6	-33776.0	90.7	20	0.050
1455	8016.00	23731.4	8135.5	-31866.9	27865.6	6349.5	-34215.1	90.3	20	0.050
1456	8019.00	23950.0	8193.7	-32143.7	28217.3	6430.4	-34647.7	89.9	20	0.050
1457	8022.00	24164.2	8254.8	-32419.1	28560.7	6513.4	-35074.1	89.6	20	0.050
1458	8025.00	24374.2	8318.5	-32692.8	28895.9	6598.3	-35494.2	89.3	20	0.050
1459	8028.00	24579.9	8384.8	-32964.7	29222.7	6685.5	-35908.2	89.0	20	0.050
1460	8031.00	24781.1	8454.0	-33235.1	29541.2	6774.6	-36315.8	88.6	20	0.050
1461	8034.00	24978.0	8525.7	-33503.7	29851.4	6865.7	-36717.1	88.3	20	0.050
1462	8038.00	25233.6	8625.3	-33858.9	30252.2	6990.3	-37242.5	88.0	20	0.050
1463	8042.00	25481.3	8729.5	-34210.9	30638.3	7118.4	-37756.8	87.6	20	0.050
1464	8046.00	25723.7	8836.1	-34559.8	31014.4	7248.1	-38262.5	87.2	20	0.050
1465	8050.00	25961.9	8944.3	-34906.2	31382.7	7378.1	-38760.8	86.9	20	0.050
1466	8053.00	26175.7	9034.5	-35210.2	31818.5	7484.2	-39302.7	87.4	20	0.050
1467	8055.00	26347.3	9101.8	-35449.1	32166.1	7561.6	-39727.7	87.9	20	0.050
1468	8057.00	26531.8	9173.0	-35704.8	32520.8	7643.3	-40164.1	88.5	20	0.050
1469	8059.00	26725.1	9248.2	-35973.3	32877.0	7729.2	-40606.2	89.2	20	0.050
1470	8061.00	26923.5	9326.7	-36250.2	33231.7	7818.5	-41050.2	89.9	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1471	8063.00	27125.1	9408.6	-36533.7	33583.4	7911.2	-41494.6	90.6	20	0.050
1472	8065.00	27329.5	9493.8	-36823.3	33931.8	8007.3	-41939.1	91.3	20	0.050
1473	8067.00	27535.0	9581.8	-37116.8	34276.0	8106.2	-42382.3	92.1	20	0.050
1474	8069.00	27741.3	9672.8	-37414.1	34616.0	8208.1	-42824.1	92.9	20	0.050
1475	8071.00	27946.9	9766.4	-37713.3	34951.5	8312.3	-43263.7	93.6	20	0.050
1476	8073.00	28151.4	9862.2	-38013.5	35282.1	8418.6	-43700.8	94.4	20	0.050
1477	8075.00	28354.6	9960.3	-38314.9	35608.1	8527.0	-44135.1	95.2	20	0.050
1478	8077.00	28556.6	10060.6	-38617.2	35929.3	8637.5	-44566.8	96.0	20	0.050
1479	8079.00	28757.2	10163.1	-38920.3	36245.4	8749.9	-44995.3	96.8	20	0.050
1480	8081.00	28956.0	10267.7	-39223.6	36556.5	8864.1	-45420.5	97.7	20	0.050
1481	8083.00	29152.6	10373.7	-39526.2	36862.4	8979.4	-45841.9	98.5	20	0.050
1482	8085.00	29346.8	10481.4	-39828.2	37163.3	9096.2	-46259.5	99.3	20	0.050
1483	8087.00	29538.9	10590.4	-40129.2	37459.1	9214.1	-46673.2	100.2	20	0.050
1484	8089.00	29728.5	10701.2	-40429.7	37749.9	9333.3	-47083.2	101.0	20	0.050
1485	8092.00	30008.7	10869.8	-40878.4	38176.6	9514.2	-47690.9	102.3	20	0.050
1486	8095.00	30283.3	11040.3	-41323.6	38593.2	9696.3	-48289.5	103.6	20	0.050
1487	8098.00	30552.4	11212.4	-41764.8	38999.7	9879.3	-48879.0	105.0	20	0.050
1488	8101.00	30816.0	11386.2	-42202.1	39396.2	10063.3	-49459.6	106.3	20	0.050
1489	8104.00	31075.2	11561.1	-42636.3	39784.7	10247.8	-50032.5	107.6	20	0.050
1490	8107.00	31330.2	11737.0	-43067.3	40165.2	10432.9	-50598.1	109.0	20	0.050
1491	8110.00	31580.9	11914.2	-43495.1	40538.0	10618.5	-51156.5	110.3	20	0.050
1492	8113.00	31827.4	12092.3	-43919.7	40902.6	10804.9	-51707.5	111.7	20	0.050
1493	8116.00	32069.4	12271.7	-44341.1	41259.5	10991.7	-52251.2	113.1	20	0.050
1494	8119.00	32307.3	12451.5	-44758.8	41609.1	11178.6	-52787.6	114.5	20	0.050
1495	8122.00	32541.1	12631.4	-45172.5	41951.8	11365.0	-53316.8	115.9	20	0.050
1496	8125.00	32770.8	12811.4	-45582.2	42287.7	11551.0	-53838.7	117.3	20	0.050
1497	8128.00	32996.6	12991.3	-45987.9	42616.6	11736.8	-54353.4	118.7	20	0.050
1498	8131.00	33218.1	13171.4	-46389.5	42938.8	11922.0	-54860.8	120.1	20	0.050
1499	8134.00	33435.5	13351.5	-46787.0	43254.0	12107.0	-55361.0	121.5	20	0.050
1500	8137.00	33648.7	13531.5	-47180.2	43562.4	12291.4	-55853.8	122.9	20	0.050
1501	8140.00	33857.8	13711.6	-47569.4	43864.1	12475.5	-56339.6	124.4	20	0.050
1502	8143.00	34062.9	13891.4	-47954.3	44159.0	12659.2	-56818.3	125.8	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1503	8146.00	34264.4	14070.8	-48335.2	44448.4	12842.1	-57290.4	127.3	20	0.050
1504	8149.00	34462.6	14249.6	-48712.2	44732.4	13023.9	-57756.3	128.7	20	0.050
1505	8152.00	34657.4	14427.7	-49085.1	45011.0	13204.9	-58215.9	130.2	20	0.050
1506	8155.00	34848.6	14605.3	-49453.9	45284.1	13385.0	-58669.1	131.7	20	0.050
1507	8158.00	35036.6	14782.2	-49818.8	45552.0	13564.0	-59116.1	133.1	20	0.050
1508	8161.00	35222.2	14958.6	-50180.8	45816.1	13742.4	-59558.5	134.6	20	0.050
1509	8164.00	35405.6	15134.6	-50540.2	46076.8	13920.1	-59996.8	136.1	20	0.050
1510	8167.00	35587.1	15310.0	-50897.1	46334.1	14097.1	-60431.2	137.6	20	0.050
1511	8170.00	35766.5	15485.0	-51251.5	46588.2	14273.3	-60861.5	139.1	20	0.050
1512	8174.00	36002.3	15717.5	-51719.9	46921.8	14507.2	-61429.0	141.0	20	0.050
1513	8178.00	36234.4	15949.3	-52183.7	47249.4	14739.9	-61989.4	143.0	20	0.050
1514	8182.00	36462.8	16180.0	-52642.8	47571.1	14971.4	-62542.5	145.0	20	0.050
1515	8186.00	36687.4	16409.7	-53097.1	47886.9	15201.4	-63088.3	147.0	20	0.050
1516	8190.00	36907.9	16638.2	-53546.1	48196.4	15429.8	-63626.2	149.1	20	0.050
1517	8196.00	37147.9	16791.1	-53938.9	48540.5	15584.7	-64125.2	152.2	20	0.050
1518	8200.00	37361.6	17024.4	-54386.0	48839.0	15817.4	-64656.4	154.2	20	0.050
1519	8204.00	37570.9	17255.5	-54826.3	49130.8	16047.5	-65178.2	156.2	20	0.050
1520	8208.00	37775.9	17483.8	-55259.7	49416.4	16274.7	-65691.0	158.2	20	0.050
1521	8212.00	37976.9	17709.7	-55686.6	49695.9	16499.2	-66195.1	160.3	20	0.050
1522	8216.00	38173.9	17933.7	-56107.6	49969.8	16721.5	-66691.3	162.3	20	0.050
1523	8220.00	38367.2	18155.8	-56522.9	50237.9	16941.7	-67179.6	164.4	20	0.050
1524	8224.00	38556.5	18375.7	-56932.2	50500.4	17159.5	-67659.9	166.4	20	0.050
1525	8228.00	38741.9	18593.6	-57335.5	50757.1	17375.1	-68132.2	168.5	20	0.050
1526	8232.00	38923.3	18809.4	-57732.7	51008.1	17588.4	-68596.5	170.6	20	0.050
1527	8236.00	39100.8	19023.0	-58123.9	51253.3	17799.5	-69052.7	172.6	20	0.050
1528	8240.00	39274.4	19234.6	-58509.0	51492.8	18008.2	-69500.9	174.7	20	0.050
1529	8245.00	39485.7	19496.0	-58981.6	51784.0	18265.9	-70049.9	177.3	20	0.050
1530	8250.00	39690.8	19754.1	-59444.9	52066.3	18520.1	-70586.3	179.9	20	0.050
1531	8255.00	39889.6	20008.8	-59898.4	52339.6	18770.6	-71110.2	182.5	20	0.050
1532	8260.00	40082.4	20260.2	-60342.5	52604.2	19017.7	-71621.9	185.1	20	0.050
1533	8265.00	40270.2	20508.3	-60778.5	52861.7	19261.4	-72123.1	187.8	20	0.050
1534	8270.00	40453.0	20753.4	-61206.4	53112.2	19501.8	-72614.0	190.4	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1535	8275.00	40630.9	20995.1	-61626.1	53355.8	19738.8	-73094.6	193.0	20	0.050
1536	8280.00	40804.4	21234.0	-62038.4	53593.1	19972.7	-73565.8	195.7	20	0.050
1537	8285.00	40974.8	21470.5	-62445.3	53826.1	20204.2	-74030.3	198.3	20	0.050
1538	8290.00	41142.2	21704.6	-62846.9	54054.8	20433.2	-74488.1	201.0	20	0.050
1539	8295.00	41306.7	21936.5	-63243.2	54279.4	20659.9	-74939.3	203.7	20	0.050
1540	8301.00	41500.0	22211.7	-63711.7	54543.4	20928.6	-75472.0	206.9	20	0.050
1541	8307.00	41689.0	22483.5	-64172.5	54801.3	21193.9	-75995.2	210.1	20	0.050
1542	8313.00	41873.5	22751.8	-64625.3	55053.0	21455.5	-76508.5	213.3	20	0.050
1543	8319.00	42053.6	23016.6	-65070.3	55298.5	21713.6	-77012.1	216.5	20	0.050
1544	8325.00	42229.3	23278.0	-65507.3	55537.9	21968.2	-77506.1	219.7	20	0.050
1545	8331.00	42400.5	23536.0	-65936.5	55771.1	22219.2	-77990.2	222.9	20	0.050
1546	8337.00	42567.1	23790.4	-66357.5	55998.1	22466.5	-78464.6	226.1	20	0.050
1547	8343.00	42729.3	24041.2	-66770.5	56218.9	22710.3	-78929.2	229.4	20	0.050
1548	8349.00	42886.9	24288.6	-67175.5	56433.6	22950.4	-79383.9	232.6	20	0.050
1549	8356.00	43065.2	24572.7	-67637.9	56676.1	23226.2	-79902.3	236.4	20	0.050
1550	8363.00	43237.3	24852.1	-68089.3	56910.3	23497.1	-80407.4	240.2	20	0.050
1551	8370.00	43403.2	25126.5	-68529.8	57136.1	23763.1	-80899.2	243.9	20	0.050
1552	8377.00	43563.0	25396.3	-68959.2	57353.5	24024.2	-81377.7	247.7	20	0.050
1553	8384.00	43717.3	25661.5	-69378.8	57563.6	24280.8	-81844.4	251.6	20	0.050
1554	8391.00	43866.9	25922.6	-69789.5	57767.2	24533.2	-82300.4	255.4	20	0.050
1555	8399.00	44031.9	26215.6	-70247.5	57992.0	24816.3	-82808.3	259.7	20	0.050
1556	8407.00	44193.0	26504.2	-70697.2	58211.5	25095.1	-83306.5	264.1	20	0.050
1557	8415.00	44349.5	26787.9	-71137.3	58424.8	25368.8	-83793.6	268.5	20	0.050
1558	8419.00	44498.4	27087.9	-71586.3	58620.7	25659.7	-84280.4	270.6	20	0.050
1559	8428.00	44659.6	27383.5	-72043.0	58841.5	25944.4	-84785.9	275.5	20	0.050
1560	8437.00	44815.4	27673.6	-72489.0	59055.2	26223.8	-85279.1	280.5	20	0.050
1561	8446.00	44965.9	27958.3	-72924.2	59261.8	26497.8	-85759.6	285.4	20	0.050
1562	8461.00	44857.1	28321.6	-73178.7	58713.7	26860.7	-85574.4	289.8	20	0.050
1563	8467.00	44651.9	28399.4	-73051.2	58301.1	26943.3	-85244.4	290.4	20	0.050
1564	8473.00	44429.2	28451.4	-72880.6	57906.2	26999.7	-84906.0	290.9	20	0.050
1565	8479.00	44205.6	28483.4	-72689.0	57533.2	27035.6	-84568.9	291.4	20	0.050
1566	8486.00	43948.5	28499.4	-72448.0	57125.5	27055.4	-84180.9	291.9	20	0.050

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1567	8493.00	43701.2	28497.2	-72198.4	56746.0	27056.5	-83802.5	292.3	20	0.050
1568	8500.00	43465.3	28484.2	-71949.5	56389.9	27046.4	-83436.3	292.7	20	0.050
1569	8508.00	43211.3	28459.0	-71670.3	56011.1	27024.0	-83035.1	293.1	20	0.050
1570	8516.00	42973.9	28422.7	-71396.5	55662.7	26990.1	-82652.7	293.4	20	0.050
1571	8525.00	42724.9	28372.8	-71097.8	55301.6	26942.5	-82244.1	293.8	20	0.050
1572	8534.00	42493.9	28317.2	-70811.1	54969.3	26888.7	-81858.0	294.1	20	0.050
1573	8544.00	42257.8	28248.8	-70506.6	54632.9	26822.0	-81454.9	294.5	20	0.050
1574	8555.00	42016.1	28170.9	-70187.0	54290.3	26745.7	-81036.0	294.8	20	0.050
1575	8566.00	41790.5	28092.5	-69882.9	53971.9	26668.6	-80640.4	295.1	20	0.050
1576	8578.00	41562.8	28006.2	-69569.0	53651.9	26583.4	-80235.3	295.4	20	0.050
1577	8591.00	41337.8	27912.0	-69249.8	53337.6	26490.1	-79827.7	295.7	20	0.050
1578	8605.00	41119.7	27809.9	-68929.6	53035.3	26388.6	-79424.0	295.9	20	0.050
1579	8621.00	40894.2	27698.1	-68592.3	52724.0	26277.3	-79001.3	296.2	20	0.050
1580	8638.00	40679.8	27585.5	-68265.3	52429.3	26164.9	-78594.2	296.5	20	0.050
1581	8658.00	40460.9	27461.0	-67921.9	52130.3	26040.4	-78170.7	296.7	20	0.050
1582	8680.00	40247.7	27333.2	-67580.9	51840.6	25912.3	-77752.9	296.9	20	0.050
1583	8704.00	40035.1	27202.8	-67237.9	51552.3	25781.5	-77333.9	297.2	20	0.050
1584	8731.00	39824.2	27070.7	-66894.9	51267.3	25648.8	-76916.1	297.4	20	0.050
1585	8761.00	39618.8	26924.6	-66543.4	50991.7	25502.3	-76494.0	297.6	20	0.050
1586	8803.00	39407.8	26794.4	-66202.3	50709.6	25370.4	-76080.0	297.8	20	0.050
1587	8854.00	39197.5	26660.4	-65857.9	50429.9	25234.4	-75664.3	298.1	20	0.050
1588	8926.00	38986.2	26522.5	-65508.7	50151.5	25094.2	-75245.6	298.3	20	0.050
1589	9012.00	38780.3	26372.3	-65152.6	49882.2	24942.2	-74824.4	298.5	20	0.050
1590	9114.00	38585.3	26191.0	-64776.3	49629.6	24760.5	-74390.1	298.6	20	0.050
1591	9223.00	38406.7	25975.1	-64381.8	49400.1	24546.2	-73946.3	298.8	20	0.050
1592	9377.00	38233.1	25747.8	-63980.9	49178.1	24321.2	-73499.3	299.0	20	0.050
1593	9668.00	38063.5	25510.6	-63574.1	48962.3	24087.0	-73049.2	299.1	20	0.050
1594	9796.00	37922.9	25219.4	-63142.2	48782.4	23801.4	-72583.8	299.3	20	0.050
1595	9969.00	37784.9	24923.6	-62708.5	48605.8	23511.4	-72117.1	299.4	20	0.050
1596	9971.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1597	9973.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1598	9974.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1599	9976.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1600	9979.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1601	9983.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1602	9986.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1603	9989.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1604	9993.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1605	9996.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1606	9999.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1607	10003.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1608	10006.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1609	10009.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1610	10013.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1611	10016.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1612	10018.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1613	10021.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1614	10023.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1615	10024.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1616	10026.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1617	10029.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1618	10033.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1619	10036.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1620	10039.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1621	10043.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1622	10046.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1623	10049.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1624	10053.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1625	10056.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1626	10059.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1627	10063.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1628	10066.33	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1629	10068.67	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550
1630	10071.00	48988.8	27018.6	-76007.5	60187.0	25621.8	-85808.9	70.0	100	0.550

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1631	10119.00	49078.2	27061.5	-76139.7	60322.2	25661.0	-85983.2	71.1	100	0.549
1632	10159.00	49140.3	27107.2	-76247.5	60404.9	25703.4	-86108.3	72.1	100	0.547
1633	10199.00	49186.1	27152.1	-76338.2	60463.9	25745.2	-86209.1	73.1	100	0.546
1634	10239.00	49219.0	27192.5	-76411.5	60506.2	25782.8	-86288.9	74.2	100	0.545
1635	10279.00	49242.0	27227.4	-76469.5	60536.2	25814.9	-86351.0	75.3	100	0.544
1636	10319.00	49257.4	27256.9	-76514.3	60556.9	25841.8	-86398.8	76.3	100	0.543
1637	10359.00	49266.9	27281.2	-76548.1	60570.6	25863.9	-86434.4	77.4	100	0.541
1638	10399.00	49271.5	27301.0	-76572.5	60578.6	25881.6	-86460.2	78.5	100	0.540
1639	10439.00	49272.2	27316.8	-76589.0	60582.2	25895.3	-86477.5	79.6	100	0.539
1640	10479.00	49269.8	27328.9	-76598.7	60582.0	25905.7	-86487.7	80.7	100	0.538
1641	10519.00	49264.6	27337.8	-76602.5	60578.9	25912.9	-86491.8	81.8	100	0.537
1642	10559.00	49257.3	27344.1	-76601.3	60573.3	25917.4	-86490.7	82.9	100	0.535
1643	10599.00	49248.0	27347.7	-76595.7	60565.5	25919.6	-86485.1	84.0	100	0.534
1644	10639.00	49237.2	27349.2	-76586.3	60555.9	25919.7	-86475.5	85.1	100	0.533
1645	10679.00	49224.9	27348.6	-76573.5	60544.6	25917.9	-86462.5	86.2	100	0.532
1646	10719.00	49211.4	27346.4	-76557.8	60532.1	25914.3	-86446.4	87.3	100	0.531
1647	10759.00	49196.9	27342.4	-76539.3	60518.4	25909.2	-86427.6	88.4	100	0.529
1648	10799.00	49181.4	27337.1	-76518.5	60503.7	25902.7	-86406.4	89.5	100	0.528
1649	10839.00	49165.2	27330.4	-76495.6	60488.1	25895.0	-86383.1	90.6	100	0.527
1650	10879.00	49148.2	27322.6	-76470.8	60471.6	25886.2	-86357.8	91.7	100	0.526
1651	10919.00	49130.7	27313.6	-76444.3	60454.5	25876.3	-86330.8	92.8	100	0.525
1652	10959.00	49112.5	27303.8	-76416.3	60436.7	25865.6	-86302.3	93.9	100	0.523
1653	10999.00	49093.9	27293.0	-76386.8	60418.4	25853.9	-86272.4	95.0	100	0.522
1654	11039.00	49074.8	27281.3	-76356.1	60399.6	25841.5	-86241.2	96.1	100	0.521
1655	11079.00	49055.3	27269.0	-76324.3	60380.4	25828.4	-86208.8	97.2	100	0.520
1656	11119.00	49035.5	27256.0	-76291.5	60360.8	25814.6	-86175.4	98.3	100	0.519
1657	11159.00	49015.3	27242.4	-76257.7	60340.8	25800.3	-86141.1	99.4	100	0.517
1658	11199.00	48994.7	27228.2	-76222.9	60319.6	25785.5	-86105.1	100.5	100	0.516
1659	11235.00	48975.3	27215.2	-76190.5	60299.5	25771.9	-86071.4	101.5	100	0.515
1660	11271.00	48955.1	27201.9	-76157.0	60279.2	25758.0	-86037.2	102.5	100	0.514
1661	11319.00	48927.7	27183.6	-76111.2	60252.2	25738.9	-85991.1	103.9	100	0.513
1662	11359.00	48904.9	27167.3	-76072.2	60229.5	25722.2	-85951.6	105.0	100	0.511

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1663	11399.00	48882.1	27150.3	-76032.5	60206.7	25704.7	-85911.3	106.1	100	0.510
1664	11439.00	48859.3	27132.8	-75992.1	60183.7	25686.7	-85870.4	107.2	100	0.509
1665	11479.00	48836.3	27114.8	-75951.1	60160.6	25668.2	-85828.8	108.3	100	0.508
1666	11519.00	48813.3	27096.4	-75909.7	60137.5	25649.3	-85786.8	109.4	100	0.507
1667	11559.00	48790.2	27077.6	-75867.8	60114.3	25630.0	-85744.3	110.5	100	0.505
1668	11599.00	48767.0	27058.5	-75825.5	60091.0	25610.4	-85701.3	111.6	100	0.504
1669	11639.00	48743.8	27039.1	-75782.9	60067.5	25590.6	-85658.1	112.7	100	0.503
1670	11679.00	48720.4	27019.6	-75740.0	60044.0	25570.7	-85614.7	113.8	100	0.502
1671	11719.00	48696.9	27000.3	-75697.1	60020.3	25550.9	-85571.2	114.9	100	0.501
1672	11759.00	48673.1	26980.9	-75654.0	59996.3	25531.1	-85527.5	116.1	100	0.499
1673	11799.00	48649.3	26961.3	-75610.6	59972.3	25511.1	-85483.4	117.2	100	0.498
1674	11839.00	48625.4	26941.5	-75567.0	59948.2	25490.9	-85439.1	118.3	100	0.497
1675	11879.00	48601.4	26921.7	-75523.1	59924.0	25470.6	-85394.6	119.4	100	0.496
1676	11919.00	48577.3	26901.6	-75479.0	59899.7	25450.1	-85349.9	120.5	100	0.495
1677	11959.00	48553.2	26881.5	-75434.7	59875.3	25429.6	-85304.9	121.6	100	0.493
1678	11999.00	48529.0	26861.2	-75390.1	59850.9	25408.9	-85259.8	122.7	100	0.492
1679	12039.00	48504.6	26840.8	-75345.5	59826.3	25388.2	-85214.5	123.8	100	0.491
1680	12079.00	48480.3	26820.3	-75300.6	59801.7	25367.2	-85169.0	124.9	100	0.490
1681	12119.00	48455.9	26799.8	-75255.6	59777.1	25346.3	-85123.4	126.0	100	0.489
1682	12159.00	48431.4	26779.0	-75210.4	59752.3	25325.2	-85077.6	127.2	100	0.487
1683	12199.00	48406.8	26758.3	-75165.1	59727.5	25304.1	-85031.6	128.3	100	0.486
1684	12239.00	48382.2	26737.5	-75119.7	59702.7	25282.8	-84985.5	129.4	100	0.485
1685	12279.00	48357.6	26716.5	-75074.1	59677.8	25261.6	-84939.3	130.5	100	0.484
1686	12319.00	48332.9	26695.5	-75028.4	59652.8	25240.2	-84893.0	131.6	100	0.483
1687	12359.00	48308.2	26674.5	-74982.7	59627.8	25218.8	-84846.6	132.7	100	0.481
1688	12399.00	48283.3	26653.4	-74936.8	59602.7	25197.4	-84800.1	133.8	100	0.480
1689	12435.00	48261.0	26634.4	-74895.4	59580.1	25178.0	-84758.1	134.8	100	0.479
1690	12471.00	48238.6	26615.3	-74854.0	59557.5	25158.6	-84716.1	135.8	100	0.478
1691	12519.00	48208.7	26589.8	-74798.5	59527.3	25132.6	-84659.9	137.2	100	0.477
1692	12559.00	48183.8	26568.5	-74752.3	59502.0	25111.0	-84613.0	138.3	100	0.475
1693	12599.00	48158.8	26547.1	-74705.9	59476.8	25089.3	-84566.1	139.4	100	0.474
1694	12639.00	48133.7	26525.7	-74659.5	59451.5	25067.5	-84518.9	140.5	100	0.473

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1695	12679.00	48108.7	26504.3	-74613.0	59426.1	25045.8	-84471.8	141.6	100	0.472
1696	12719.00	48083.6	26482.9	-74566.4	59400.7	25023.9	-84424.6	142.7	100	0.471
1697	12759.00	48058.4	26461.4	-74519.8	59375.3	25002.1	-84377.3	143.8	100	0.469
1698	12799.00	48033.2	26439.8	-74473.1	59349.8	24980.1	-84329.9	144.9	100	0.468
1699	12839.00	48008.0	26418.3	-74426.3	59324.3	24958.2	-84282.5	146.0	100	0.467
1700	12879.00	47982.8	26396.7	-74379.4	59298.8	24936.3	-84235.0	147.1	100	0.466
1701	12919.00	47957.5	26375.0	-74332.5	59273.2	24914.3	-84187.5	148.3	100	0.465
1702	12959.00	47932.2	26353.4	-74285.6	59247.6	24892.3	-84139.9	149.4	100	0.463
1703	12999.00	47906.9	26331.6	-74238.5	59222.0	24870.1	-84092.1	150.5	100	0.462
1704	13039.00	47881.8	26309.5	-74191.3	59196.5	24847.7	-84044.2	151.6	100	0.461
1705	13079.00	47856.8	26287.1	-74144.0	59171.3	24824.9	-83996.2	152.7	100	0.460
1706	13119.00	47832.3	26264.8	-74097.1	59146.4	24802.2	-83948.6	153.8	100	0.459
1707	13159.00	47808.1	26243.2	-74051.3	59121.9	24780.3	-83902.2	154.9	100	0.457
1708	13199.00	47783.9	26222.1	-74006.0	59097.5	24758.8	-83856.3	156.0	100	0.456
1709	13239.00	47759.7	26200.9	-73960.6	59073.0	24737.3	-83810.3	157.1	100	0.455
1710	13279.00	47735.5	26179.7	-73915.2	59048.5	24715.8	-83764.3	158.3	100	0.454
1711	13319.00	47711.3	26158.5	-73869.8	59024.1	24694.2	-83718.3	159.4	100	0.453
1712	13359.00	47687.1	26137.2	-73824.4	58999.6	24672.7	-83672.3	160.5	100	0.451
1713	13399.00	47662.9	26116.0	-73778.9	58975.1	24651.1	-83626.2	161.6	100	0.450
1714	13439.00	47638.7	26094.8	-73733.5	58950.7	24629.5	-83580.2	162.7	100	0.449
1715	13479.00	47614.6	26073.5	-73688.1	58926.3	24607.9	-83534.1	163.8	100	0.448
1716	13519.00	47590.4	26052.2	-73642.6	58901.8	24586.3	-83488.1	164.9	100	0.447
1717	13559.00	47566.3	26030.9	-73597.2	58877.4	24564.7	-83442.1	166.0	100	0.445
1718	13599.00	47542.1	26009.6	-73551.8	58853.0	24543.1	-83396.1	167.1	100	0.444
1719	13635.00	47520.4	25990.5	-73510.9	58831.0	24523.6	-83354.7	168.1	100	0.443
1720	13671.00	47498.7	25971.4	-73470.0	58809.1	24504.2	-83313.3	169.1	100	0.442
1721	13707.00	47477.0	25952.2	-73429.2	58787.1	24484.8	-83271.9	170.1	100	0.441
1722	13737.00	47458.9	25936.3	-73395.2	58768.9	24468.5	-83237.4	171.0	100	0.440
1723	13767.00	47440.8	25920.3	-73361.2	58750.6	24452.4	-83203.0	171.8	100	0.439
1724	13797.00	47422.8	25904.4	-73327.2	58732.3	24436.1	-83168.5	172.6	100	0.438
1725	13827.00	47404.7	25888.5	-73293.2	58714.1	24420.0	-83134.0	173.5	100	0.437
1726	13857.00	47386.6	25872.5	-73259.2	58695.8	24403.8	-83099.6	174.3	100	0.436

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1727	13887.00	47368.6	25856.6	-73225.2	58677.5	24387.7	-83065.2	175.1	100	0.436
1728	13917.00	47350.5	25840.7	-73191.2	58659.3	24371.5	-83030.8	176.0	100	0.435
1729	13947.00	47332.5	25824.8	-73157.3	58641.1	24355.3	-82996.3	176.8	100	0.434
1730	13977.00	47314.5	25808.8	-73123.3	58622.8	24339.2	-82962.0	177.6	100	0.433
1731	14007.00	47296.4	25792.9	-73089.3	58604.6	24322.9	-82927.5	178.5	100	0.432
1732	14037.00	47278.4	25777.0	-73055.4	58586.3	24306.8	-82893.1	179.3	100	0.431
1733	14067.00	47260.4	25761.1	-73021.5	58568.1	24290.6	-82858.7	180.1	100	0.430
1734	14097.00	47242.3	25745.2	-72987.5	58549.8	24274.6	-82824.4	181.0	100	0.429
1735	14127.00	47224.3	25729.3	-72953.6	58531.6	24258.4	-82790.0	181.8	100	0.428
1736	14157.00	47206.3	25713.4	-72919.7	58513.4	24242.2	-82755.6	182.6	100	0.427
1737	14187.00	47188.3	25697.5	-72885.8	58495.2	24226.0	-82721.3	183.5	100	0.427
1738	14217.00	47170.3	25681.6	-72851.9	58477.0	24209.9	-82686.9	184.3	100	0.426
1739	14247.00	47152.3	25665.7	-72818.0	58458.8	24193.7	-82652.6	185.1	100	0.425
1740	14277.00	47134.3	25649.8	-72784.1	58440.6	24177.6	-82618.2	186.0	100	0.424
1741	14307.00	47116.3	25633.9	-72750.2	58422.5	24161.5	-82583.9	186.8	100	0.423
1742	14337.00	47098.3	25618.0	-72716.3	58404.2	24145.3	-82549.6	187.6	100	0.422
1743	14367.00	47080.3	25602.2	-72682.5	58386.1	24129.2	-82515.3	188.5	100	0.421
1744	14397.00	47062.4	25586.2	-72648.6	58367.9	24113.1	-82481.0	189.3	100	0.420
1745	14427.00	47044.3	25570.4	-72614.7	58349.7	24097.0	-82446.7	190.1	100	0.419
1746	14457.00	47026.3	25554.5	-72580.9	58331.6	24080.8	-82412.3	191.0	100	0.418
1747	14487.00	47008.4	25538.6	-72547.0	58313.4	24064.7	-82378.1	191.8	100	0.418
1748	14517.00	46990.5	25522.7	-72513.2	58295.2	24048.6	-82343.8	192.6	100	0.417
1749	14544.00	46974.3	25508.5	-72482.8	58278.9	24034.0	-82313.0	193.4	100	0.416
1750	14571.00	46958.1	25494.2	-72452.3	58262.5	24019.6	-82282.1	194.1	100	0.415
1751	14607.00	46936.5	25475.2	-72411.7	58240.7	24000.3	-82241.0	195.1	100	0.414
1752	14637.00	46918.6	25459.3	-72377.9	58222.7	23984.0	-82206.7	196.0	100	0.413
1753	14667.00	46900.7	25443.3	-72344.1	58204.5	23968.0	-82172.5	196.8	100	0.412
1754	14697.00	46882.8	25427.5	-72310.3	58186.4	23951.9	-82138.2	197.6	100	0.411
1755	14727.00	46864.9	25411.7	-72276.5	58168.3	23935.8	-82104.0	198.5	100	0.410
1756	14757.00	46846.9	25395.9	-72242.8	58150.1	23919.7	-82069.8	199.3	100	0.409
1757	14787.00	46828.9	25380.0	-72209.0	58132.0	23903.6	-82035.6	200.1	100	0.409
1758	14817.00	46810.8	25364.6	-72175.4	58113.6	23888.0	-82001.6	201.0	100	0.408

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1759	14847.00	46792.6	25349.2	-72141.8	58095.2	23872.4	-81967.6	201.8	100	0.407
1760	14877.00	46774.1	25334.2	-72108.3	58076.5	23857.1	-81933.6	202.6	100	0.406
1761	14907.00	46755.1	25319.2	-72074.3	58057.4	23841.9	-81899.3	203.5	100	0.405
1762	14937.00	46735.8	25303.5	-72039.3	58037.8	23826.0	-81863.8	204.3	100	0.404
1763	14967.00	46716.3	25287.0	-72003.3	58018.1	23809.2	-81827.3	205.1	100	0.403
1764	14997.00	46696.7	25270.5	-71967.2	57998.4	23792.3	-81790.7	206.0	100	0.402
1765	15027.00	46677.3	25253.9	-71931.1	57978.7	23775.4	-81754.1	206.8	100	0.401
1766	15057.00	46657.8	25237.2	-71895.0	57958.9	23758.6	-81717.5	207.6	100	0.400
1767	15087.00	46638.2	25220.6	-71858.9	57939.2	23741.6	-81680.8	208.4	100	0.400
1768	15117.00	46618.7	25204.0	-71822.7	57919.4	23724.7	-81644.2	209.3	100	0.399
1769	15147.00	46599.2	25187.3	-71786.5	57899.6	23707.9	-81607.5	210.1	100	0.398
1770	15177.00	46579.5	25170.8	-71750.3	57879.8	23691.0	-81570.8	210.9	100	0.397
1771	15207.00	46560.0	25154.1	-71714.1	57860.0	23674.1	-81534.1	211.8	100	0.396
1772	15237.00	46540.4	25137.5	-71677.9	57840.2	23657.1	-81497.3	212.6	100	0.395
1773	15267.00	46520.9	25120.8	-71641.6	57820.4	23640.2	-81460.6	213.4	100	0.394
1774	15297.00	46501.2	25104.2	-71605.5	57800.5	23623.3	-81423.8	214.3	100	0.393
1775	15327.00	46481.5	25087.7	-71569.2	57780.6	23606.5	-81387.1	215.1	100	0.392
1776	15357.00	46461.9	25070.9	-71532.8	57760.8	23589.4	-81350.2	215.9	100	0.391
1777	15387.00	46442.2	25054.3	-71496.5	57740.8	23572.6	-81313.4	216.8	100	0.391
1778	15417.00	46422.5	25037.6	-71460.1	57720.9	23555.5	-81276.4	217.6	100	0.390
1779	15444.00	46404.8	25022.6	-71427.4	57702.9	23540.3	-81243.2	218.4	100	0.389
1780	15471.00	46387.0	25007.7	-71394.7	57685.0	23525.1	-81210.1	219.1	100	0.388
1781	15507.00	46363.3	24987.6	-71350.9	57661.0	23504.8	-81165.8	220.1	100	0.387
1782	15537.00	46343.6	24970.9	-71314.4	57641.0	23487.8	-81128.8	220.9	100	0.386
1783	15567.00	46323.8	24954.2	-71278.0	57621.0	23470.7	-81091.7	221.8	100	0.385
1784	15597.00	46304.0	24937.5	-71241.5	57601.0	23453.7	-81054.7	222.6	100	0.384
1785	15627.00	46284.2	24920.7	-71204.9	57581.0	23436.7	-81017.6	223.4	100	0.383
1786	15657.00	46264.4	24903.9	-71168.3	57560.9	23419.7	-80980.6	224.3	100	0.382
1787	15687.00	46244.5	24887.2	-71131.7	57540.8	23402.7	-80943.5	225.1	100	0.382
1788	15717.00	46224.7	24870.4	-71095.1	57520.7	23385.7	-80906.3	225.9	100	0.381
1789	15747.00	46204.9	24853.6	-71058.5	57500.6	23368.6	-80869.1	226.8	100	0.380
1790	15777.00	46184.9	24836.9	-71021.8	57480.4	23351.5	-80832.0	227.6	100	0.379

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1791	15807.00	46165.0	24820.1	-70985.1	57460.3	23334.4	-80794.8	228.4	100	0.378
1792	15837.00	46145.2	24803.2	-70948.4	57440.1	23317.4	-80757.5	229.3	100	0.377
1793	15867.00	46125.2	24786.4	-70911.7	57419.9	23300.4	-80720.3	230.1	100	0.376
1794	15897.00	46105.2	24769.7	-70874.9	57399.7	23283.2	-80683.0	230.9	100	0.375
1795	15927.00	46085.3	24752.8	-70838.0	57379.5	23266.1	-80645.6	231.8	100	0.374
1796	15957.00	46065.3	24735.9	-70801.3	57359.3	23249.0	-80608.3	232.6	100	0.373
1797	15987.00	46045.3	24719.2	-70764.5	57339.1	23231.8	-80571.0	233.4	100	0.373
1798	16017.00	46025.3	24702.3	-70727.6	57318.8	23214.7	-80533.5	234.3	100	0.372
1799	16047.00	46005.2	24685.5	-70690.7	57298.6	23197.5	-80496.1	235.1	100	0.371
1800	16077.00	45985.2	24668.6	-70653.8	57278.3	23180.3	-80458.6	235.9	100	0.370
1801	16107.00	45965.2	24651.6	-70616.8	57258.0	23163.2	-80421.2	236.8	100	0.369
1802	16137.00	45945.1	24634.8	-70579.9	57237.7	23145.9	-80383.7	237.6	100	0.368
1803	16167.00	45925.0	24617.9	-70542.9	57217.4	23128.8	-80346.3	238.4	100	0.367
1804	16197.00	45905.0	24601.0	-70505.9	57197.0	23111.7	-80308.7	239.3	100	0.366
1805	16227.00	45884.8	24584.0	-70468.9	57176.7	23094.3	-80271.1	240.1	100	0.365
1806	16257.00	45864.7	24567.1	-70431.9	57156.3	23077.2	-80233.5	240.9	100	0.364
1807	16287.00	45844.6	24550.2	-70394.8	57135.9	23060.0	-80195.9	241.8	100	0.364
1808	16317.00	45824.3	24533.3	-70357.7	57115.5	23042.8	-80158.3	242.6	100	0.363
1809	16344.00	45806.2	24518.0	-70324.2	57097.1	23027.2	-80124.4	243.4	100	0.362
1810	16371.00	45788.0	24502.8	-70290.8	57078.7	23011.8	-80090.5	244.1	100	0.361
1811	16407.00	45763.8	24482.4	-70246.2	57054.2	22991.1	-80045.3	245.1	100	0.360
1812	16437.00	45743.6	24465.4	-70209.0	57033.7	22973.8	-80007.5	245.9	100	0.359
1813	16467.00	45723.4	24448.4	-70171.8	57013.2	22956.5	-79969.7	246.8	100	0.358
1814	16497.00	45703.1	24431.4	-70134.5	56992.7	22939.3	-79932.0	247.6	100	0.357
1815	16527.00	45682.8	24414.5	-70097.3	56972.2	22922.0	-79894.2	248.4	100	0.356
1816	16557.00	45662.6	24397.4	-70060.0	56951.7	22904.7	-79856.3	249.3	100	0.355
1817	16587.00	45642.3	24380.3	-70022.6	56931.1	22887.3	-79818.5	250.1	100	0.355
1818	16617.00	45622.2	24362.8	-69985.0	56910.9	22869.5	-79780.3	250.9	100	0.354
1819	16647.00	45602.4	24345.0	-69947.4	56890.6	22851.4	-79742.0	251.8	100	0.353
1820	16677.00	45582.9	24326.9	-69909.7	56870.9	22832.9	-79703.8	252.6	100	0.352
1821	16707.00	45563.8	24308.8	-69872.6	56851.6	22814.5	-79666.1	253.4	100	0.351
1822	16737.00	45545.4	24291.5	-69836.9	56832.9	22797.0	-79629.9	254.3	100	0.350

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1823	16767.00	45527.1	24275.4	-69802.5	56814.4	22780.6	-79594.9	255.1	100	0.349
1824	16797.00	45508.8	24259.5	-69768.3	56795.9	22764.3	-79560.2	255.9	100	0.348
1825	16827.00	45490.5	24243.4	-69733.9	56777.4	22748.0	-79525.4	256.8	100	0.347
1826	16857.00	45472.2	24227.5	-69699.6	56758.8	22731.8	-79490.6	257.6	100	0.346
1827	16887.00	45453.8	24211.5	-69665.4	56740.3	22715.7	-79455.9	258.4	100	0.346
1828	16917.00	45435.5	24195.5	-69631.0	56721.8	22699.3	-79421.1	259.3	100	0.345
1829	16947.00	45417.2	24179.5	-69596.7	56703.3	22683.1	-79386.4	260.1	100	0.344
1830	16977.00	45399.0	24163.4	-69562.4	56684.8	22666.8	-79351.6	260.9	100	0.343
1831	17007.00	45380.7	24147.4	-69528.1	56666.3	22650.5	-79316.8	261.8	100	0.342
1832	17037.00	45362.4	24131.4	-69493.8	56647.8	22634.2	-79282.0	262.6	100	0.341
1833	17067.00	45344.0	24115.4	-69459.4	56629.3	22617.9	-79247.3	263.4	100	0.340
1834	17097.00	45325.8	24099.3	-69425.2	56610.8	22601.6	-79212.5	264.3	100	0.339
1835	17127.00	45307.5	24083.4	-69390.9	56592.3	22585.4	-79177.7	265.1	100	0.338
1836	17157.00	45289.3	24067.2	-69356.5	56573.8	22569.1	-79142.9	265.9	100	0.337
1837	17187.00	45271.0	24051.3	-69322.2	56555.3	22552.9	-79108.2	266.8	100	0.337
1838	17217.00	45252.8	24035.2	-69288.0	56536.8	22536.5	-79073.4	267.6	100	0.336
1839	17244.00	45236.2	24020.8	-69257.0	56520.3	22521.9	-79042.2	268.3	100	0.335
1840	17271.00	45219.8	24006.3	-69226.2	56503.6	22507.3	-79010.9	269.1	100	0.334
1841	17283.96	45200.3	24006.5	-69206.8	56484.0	22507.2	-78991.3	269.5	100	0.334
1842	17296.92	45180.7	24006.6	-69187.3	56464.4	22507.3	-78971.6	269.8	100	0.333
1843	17316.58	45151.0	24006.9	-69157.9	56434.5	22507.4	-78941.9	270.4	100	0.333
1844	17336.25	45121.3	24007.1	-69128.5	56404.7	22507.4	-78912.1	270.9	100	0.332
1845	17355.93	45091.6	24007.4	-69099.0	56374.9	22507.5	-78882.4	271.4	100	0.331
1846	17375.61	45062.0	24007.6	-69069.6	56345.0	22507.6	-78852.6	272.0	100	0.331
1847	17395.30	45032.3	24007.9	-69040.1	56315.2	22507.7	-78822.9	272.5	100	0.330
1848	17414.99	45002.5	24008.2	-69010.7	56285.3	22507.9	-78793.2	273.1	100	0.330
1849	17434.69	44972.8	24008.4	-68981.2	56255.5	22507.9	-78763.3	273.6	100	0.329
1850	17454.39	44943.1	24008.7	-68951.8	56225.6	22508.0	-78733.6	274.2	100	0.328
1851	17474.09	44913.3	24009.0	-68922.3	56195.7	22508.1	-78703.8	274.7	100	0.328
1852	17493.80	44883.6	24009.2	-68892.8	56165.9	22508.2	-78674.0	275.3	100	0.327
1853	17513.52	44853.8	24009.5	-68863.3	56135.9	22508.2	-78644.2	275.8	100	0.327
1854	17533.24	44824.0	24009.7	-68833.8	56106.1	22508.3	-78614.4	276.4	100	0.326

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1855	17552.96	44794.3	24010.0	-68804.3	56076.1	22508.5	-78584.7	276.9	100	0.326
1856	17572.70	44764.5	24010.2	-68774.8	56046.3	22508.5	-78554.8	277.5	100	0.325
1857	17583.85	44747.7	24010.3	-68758.1	56029.3	22508.6	-78537.9	277.8	100	0.325
1858	17595.00	44730.9	24010.6	-68741.5	56012.5	22508.7	-78521.1	278.1	100	0.324
1859	17607.96	44711.3	24010.7	-68722.0	55992.8	22508.7	-78501.5	278.4	100	0.324
1860	17620.92	44691.8	24010.9	-68702.7	55973.1	22508.8	-78481.9	278.8	100	0.324
1861	17640.67	44662.1	24011.1	-68673.1	55943.3	22508.9	-78452.2	279.4	100	0.323
1862	17660.42	44632.3	24011.4	-68643.6	55913.4	22508.9	-78422.3	279.9	100	0.322
1863	17680.18	44602.5	24011.6	-68614.1	55883.4	22509.1	-78392.5	280.5	100	0.322
1864	17699.94	44572.6	24011.9	-68584.6	55853.5	22509.1	-78362.6	281.0	100	0.321
1865	17719.71	44542.8	24012.2	-68555.0	55823.5	22509.3	-78332.8	281.5	100	0.321
1866	17739.48	44513.0	24012.4	-68525.4	55793.6	22509.3	-78302.9	282.1	100	0.320
1867	17759.26	44483.2	24012.7	-68495.9	55763.6	22509.5	-78273.1	282.6	100	0.319
1868	17779.04	44453.4	24013.0	-68466.4	55733.7	22509.6	-78243.2	283.2	100	0.319
1869	17798.82	44423.5	24013.3	-68436.8	55703.7	22509.6	-78213.3	283.7	100	0.318
1870	17818.62	44393.7	24013.5	-68407.2	55673.7	22509.7	-78183.5	284.3	100	0.318
1871	17838.41	44363.8	24013.8	-68377.6	55643.7	22509.8	-78153.5	284.8	100	0.317
1872	17858.21	44334.0	24014.1	-68348.1	55613.8	22509.9	-78123.7	285.4	100	0.316
1873	17878.02	44304.1	24014.4	-68318.5	55583.7	22510.1	-78093.8	285.9	100	0.316
1874	17897.83	44274.3	24014.6	-68288.9	55553.7	22510.2	-78063.8	286.5	100	0.315
1875	17908.42	44258.3	24014.7	-68273.1	55537.8	22510.2	-78048.0	286.8	100	0.315
1876	17919.00	44242.3	24015.0	-68257.3	55521.7	22510.3	-78032.0	287.1	100	0.315
1877	17931.96	44222.8	24015.1	-68237.9	55502.1	22510.3	-78012.4	287.4	100	0.314
1878	17944.92	44203.3	24015.3	-68218.5	55482.4	22510.5	-77992.9	287.8	100	0.314
1879	17964.75	44173.4	24015.6	-68189.0	55452.4	22510.5	-77963.0	288.4	100	0.313
1880	17984.58	44143.5	24015.9	-68159.4	55422.4	22510.7	-77933.0	288.9	100	0.313
1881	18004.42	44113.6	24016.1	-68129.7	55392.4	22510.8	-77903.1	289.5	100	0.312
1882	18024.26	44083.7	24016.4	-68100.1	55362.3	22510.9	-77873.2	290.0	100	0.311
1883	18044.11	44053.8	24016.7	-68070.5	55332.3	22510.9	-77843.2	290.6	100	0.311
1884	18063.96	44023.9	24016.9	-68040.8	55302.2	22511.1	-77813.4	291.1	100	0.310
1885	18083.82	43994.0	24017.2	-68011.2	55272.1	22511.3	-77783.4	291.7	100	0.310
1886	18103.68	43964.1	24017.5	-67981.6	55242.1	22511.3	-77753.4	292.2	100	0.309

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1887	18123.55	43934.1	24017.7	-67951.9	55212.0	22511.5	-77723.5	292.8	100	0.308
1888	18143.42	43904.2	24018.1	-67922.3	55182.0	22511.5	-77693.5	293.3	100	0.308
1889	18163.30	43874.2	24018.5	-67892.6	55151.9	22511.6	-77663.5	293.9	100	0.307
1890	18183.18	43844.2	24018.7	-67862.9	55121.8	22511.8	-77633.5	294.4	100	0.307
1891	18203.07	43814.3	24019.0	-67833.3	55091.7	22511.9	-77603.6	295.0	100	0.306
1892	18222.96	43784.3	24019.2	-67803.5	55061.6	22512.1	-77573.6	295.5	100	0.305
1893	18243.00	43754.2	24019.4	-67773.7	55031.3	22512.1	-77543.4	296.1	100	0.305
1894	18279.00	43699.9	24020.1	-67720.0	54976.8	22512.4	-77489.2	297.1	100	0.304
1895	18309.00	43654.8	24020.5	-67675.2	54931.5	22512.6	-77444.0	297.9	100	0.303
1896	18339.00	43609.6	24020.9	-67630.5	54886.0	22512.7	-77398.8	298.7	100	0.302
1897	18369.00	43564.4	24021.4	-67585.8	54840.7	22512.9	-77353.6	299.6	100	0.301
1898	18399.00	43519.2	24022.0	-67541.2	54795.3	22513.3	-77308.5	300.4	100	0.300
1899	18429.00	43473.6	24023.3	-67496.9	54749.5	22514.4	-77263.9	301.2	100	0.299
1900	18459.00	43427.7	24024.8	-67452.5	54703.5	22515.8	-77219.3	302.1	100	0.298
1901	18489.00	43381.5	24026.6	-67408.1	54657.2	22517.4	-77174.6	302.9	100	0.297
1902	18519.00	43334.4	24028.0	-67362.4	54609.9	22518.6	-77128.5	303.7	100	0.297
1903	18549.00	43286.7	24028.0	-67314.7	54561.9	22518.3	-77080.2	304.6	100	0.296
1904	18579.00	43239.0	24027.1	-67266.0	54514.0	22517.2	-77031.2	305.4	100	0.295
1905	18609.00	43191.3	24026.1	-67217.4	54466.0	22516.0	-76982.0	306.2	100	0.294
1906	18639.00	43143.6	24025.2	-67168.8	54418.1	22514.7	-76932.8	307.1	100	0.293
1907	18669.00	43096.0	24024.2	-67120.2	54370.2	22513.5	-76883.7	307.9	100	0.292
1908	18699.00	43048.2	24023.4	-67071.5	54322.1	22512.3	-76834.4	308.7	100	0.291
1909	18729.00	43000.5	24022.4	-67022.9	54274.2	22511.1	-76785.2	309.6	100	0.290
1910	18759.00	42952.7	24021.5	-66974.2	54226.2	22509.9	-76736.1	310.4	100	0.289
1911	18789.00	42905.1	24020.5	-66925.6	54178.2	22508.6	-76686.8	311.2	100	0.288
1912	18819.00	42857.3	24019.6	-66876.8	54130.1	22507.4	-76637.5	312.1	100	0.288
1913	18849.00	42809.5	24018.7	-66828.2	54082.1	22506.2	-76588.3	312.9	100	0.287
1914	18879.00	42761.7	24017.8	-66779.5	54034.0	22505.0	-76539.0	313.7	100	0.286
1915	18909.00	42713.9	24016.9	-66730.8	53986.0	22503.7	-76489.7	314.6	100	0.285
1916	18939.00	42666.1	24016.0	-66682.0	53937.8	22502.6	-76440.5	315.4	100	0.284
1917	18969.00	42618.2	24015.0	-66633.2	53889.8	22501.3	-76391.1	316.2	100	0.283
1918	18999.00	42570.3	24014.2	-66584.5	53841.6	22500.2	-76341.8	317.1	100	0.282

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1919	19029.00	42522.5	24013.1	-66535.6	53793.5	22499.0	-76292.5	317.9	100	0.281
1920	19059.00	42474.7	24012.2	-66486.8	53745.4	22497.8	-76243.1	318.7	100	0.280
1921	19089.00	42426.7	24011.3	-66438.0	53697.2	22496.5	-76193.6	319.6	100	0.279
1922	19116.00	42383.6	24010.4	-66394.1	53653.9	22495.3	-76149.2	320.3	100	0.279
1923	19143.00	42340.5	24009.6	-66350.1	53610.6	22494.1	-76104.7	321.1	100	0.278
1924	19179.00	42282.9	24008.5	-66291.4	53552.7	22492.7	-76045.3	322.1	100	0.277
1925	19209.00	42235.0	24007.5	-66242.5	53504.4	22491.5	-75995.9	322.9	100	0.276
1926	19239.00	42187.1	24006.5	-66193.6	53456.3	22490.1	-75946.4	323.7	100	0.275
1927	19269.00	42139.1	24005.5	-66144.6	53408.0	22488.9	-75896.9	324.6	100	0.274
1928	19299.00	42091.1	24004.6	-66095.7	53359.8	22487.6	-75847.4	325.4	100	0.273
1929	19329.00	42043.1	24003.6	-66046.7	53311.5	22486.3	-75797.8	326.2	100	0.272
1930	19359.00	41995.1	24002.6	-65997.6	53263.2	22485.1	-75748.2	327.1	100	0.271
1931	19389.00	41947.1	24001.5	-65948.6	53214.9	22483.7	-75698.7	327.9	100	0.270
1932	19419.00	41899.0	24000.6	-65899.6	53166.6	22482.4	-75649.0	328.7	100	0.270
1933	19449.00	41850.9	23999.6	-65850.5	53118.2	22481.2	-75599.4	329.6	100	0.269
1934	19479.00	41803.0	23998.5	-65801.4	53070.0	22479.8	-75549.8	330.4	100	0.268
1935	19509.00	41754.9	23997.4	-65752.3	53021.6	22478.5	-75500.1	331.2	100	0.267
1936	19539.00	41706.7	23996.6	-65703.3	52973.3	22477.0	-75450.3	332.1	100	0.266
1937	19569.00	41658.6	23995.4	-65654.0	52924.8	22475.8	-75400.7	332.9	100	0.265
1938	19599.00	41610.5	23994.4	-65604.9	52876.5	22474.4	-75350.9	333.7	100	0.264
1939	19629.00	41562.4	23993.4	-65555.8	52828.0	22473.2	-75301.2	334.6	100	0.263
1940	19659.00	41514.3	23992.2	-65506.5	52779.7	22471.7	-75251.3	335.4	100	0.262
1941	19689.00	41466.1	23991.2	-65457.3	52731.2	22470.3	-75201.6	336.2	100	0.261
1942	19719.00	41417.9	23990.2	-65408.1	52682.8	22469.0	-75151.8	337.1	100	0.261
1943	19749.00	41369.8	23989.0	-65358.8	52634.3	22467.6	-75101.9	337.9	100	0.260
1944	19779.00	41321.6	23988.0	-65309.5	52585.9	22466.2	-75052.1	338.7	100	0.259
1945	19809.00	41273.4	23986.8	-65260.2	52537.4	22464.8	-75002.2	339.6	100	0.258
1946	19839.00	41225.1	23985.8	-65210.9	52488.9	22463.5	-74952.3	340.4	100	0.257
1947	19869.00	41176.9	23984.6	-65161.5	52440.4	22461.9	-74902.4	341.2	100	0.256
1948	19899.00	41128.6	23983.6	-65112.2	52391.9	22460.6	-74852.5	342.1	100	0.255
1949	19929.00	41080.4	23982.4	-65062.8	52343.3	22459.2	-74802.5	342.9	100	0.254
1950	19959.00	41032.2	23981.3	-65013.5	52294.8	22457.8	-74752.6	343.7	100	0.253

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1951	19989.00	40983.9	23980.1	-64964.0	52246.2	22456.3	-74702.5	344.6	100	0.252
1952	20016.00	40940.4	23979.1	-64919.5	52202.5	22455.0	-74657.5	345.3	100	0.252
1953	20043.00	40896.9	23978.1	-64875.0	52158.8	22453.8	-74612.5	346.1	100	0.251
1954	20079.00	40839.0	23976.7	-64815.6	52100.5	22451.9	-74552.4	347.1	100	0.250
1955	20109.00	40790.6	23975.5	-64766.1	52051.8	22450.5	-74502.3	347.9	100	0.249
1956	20139.00	40742.2	23974.4	-64716.6	52003.3	22449.0	-74452.3	348.7	100	0.248
1957	20169.00	40693.9	23973.1	-64667.0	51954.6	22447.4	-74402.1	349.6	100	0.247
1958	20199.00	40645.6	23971.7	-64617.3	51906.1	22445.7	-74351.8	350.4	100	0.246
1959	20229.00	40597.8	23969.5	-64567.3	51857.9	22443.2	-74301.2	351.2	100	0.245
1960	20259.00	40550.3	23966.9	-64517.2	51810.1	22440.3	-74250.4	352.1	100	0.244
1961	20289.00	40503.3	23964.1	-64467.4	51762.9	22437.0	-74199.8	352.9	100	0.243
1962	20319.00	40457.3	23961.7	-64418.9	51716.5	22434.2	-74150.8	353.7	100	0.243
1963	20349.00	40412.0	23961.3	-64373.3	51671.1	22433.4	-74104.5	354.6	100	0.242
1964	20379.00	40366.7	23961.6	-64328.3	51625.6	22433.6	-74059.2	355.4	100	0.241
1965	20409.00	40321.5	23962.0	-64283.5	51580.1	22433.7	-74013.8	356.2	100	0.240
1966	20439.00	40276.2	23962.3	-64238.6	51534.7	22433.8	-73968.5	357.1	100	0.239
1967	20469.00	40231.0	23962.7	-64193.7	51489.2	22433.9	-73923.1	357.9	100	0.238
1968	20499.00	40185.7	23963.0	-64148.8	51443.8	22433.9	-73877.8	358.7	100	0.237
1969	20529.00	40140.6	23963.3	-64103.9	51398.4	22434.1	-73832.5	359.6	100	0.236
1970	20559.00	40095.3	23963.8	-64059.1	51352.9	22434.2	-73787.2	360.4	100	0.235
1971	20589.00	40050.1	23964.1	-64014.2	51307.5	22434.3	-73741.8	361.2	100	0.234
1972	20619.00	40004.8	23964.6	-63969.4	51262.1	22434.5	-73696.5	362.1	100	0.234
1973	20649.00	39959.6	23964.8	-63924.5	51216.6	22434.7	-73651.3	362.9	100	0.233
1974	20679.00	39914.4	23965.3	-63879.7	51171.2	22434.7	-73605.9	363.7	100	0.232
1975	20709.00	39869.2	23965.7	-63834.9	51125.8	22434.9	-73560.7	364.6	100	0.231
1976	20739.00	39824.0	23966.1	-63790.1	51080.3	22435.1	-73515.4	365.4	100	0.230
1977	20769.00	39778.7	23966.6	-63745.3	51035.0	22435.2	-73470.2	366.2	100	0.229
1978	20799.00	39733.6	23967.0	-63700.5	50989.6	22435.4	-73424.9	367.1	100	0.228
1979	20829.00	39688.3	23967.4	-63655.7	50944.1	22435.5	-73379.7	367.9	100	0.227
1980	20859.00	39643.1	23967.8	-63610.9	50898.8	22435.6	-73334.4	368.7	100	0.226
1981	20889.00	39598.0	23968.1	-63566.1	50853.4	22435.8	-73289.2	369.5	100	0.225
1982	20916.00	39557.3	23968.5	-63525.8	50812.6	22435.9	-73248.5	370.3	100	0.225

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
1983	20943.00	39516.6	23969.0	-63485.6	50771.8	22436.1	-73207.8	371.0	100	0.224
1984	20979.00	39462.4	23969.4	-63431.8	50717.3	22436.2	-73153.5	372.0	100	0.223
1985	21009.00	39417.3	23969.9	-63387.1	50671.8	22436.5	-73108.3	372.9	100	0.222
1986	21039.00	39372.0	23970.3	-63342.3	50626.5	22436.7	-73063.2	373.7	100	0.221
1987	21069.00	39326.9	23970.8	-63297.6	50581.2	22436.8	-73017.9	374.5	100	0.220
1988	21099.00	39281.7	23971.1	-63252.8	50535.7	22437.1	-72972.8	375.4	100	0.219
1989	21129.00	39236.6	23971.6	-63208.2	50490.4	22437.2	-72927.6	376.2	100	0.218
1990	21159.00	39191.4	23972.0	-63163.4	50445.1	22437.3	-72882.4	377.0	100	0.217
1991	21189.00	39146.2	23972.5	-63118.8	50399.7	22437.5	-72837.2	377.9	100	0.216
1992	21219.00	39101.2	23972.9	-63074.1	50354.4	22437.7	-72792.1	378.7	100	0.216
1993	21249.00	39056.0	23973.4	-63029.4	50309.1	22437.9	-72746.9	379.5	100	0.215
1994	21279.00	39010.9	23973.8	-62984.7	50263.7	22438.0	-72701.8	380.4	100	0.214
1995	21309.00	38965.7	23974.3	-62940.0	50218.4	22438.3	-72656.6	381.2	100	0.213
1996	21339.00	38920.6	23974.7	-62895.3	50173.0	22438.5	-72611.6	382.0	100	0.212
1997	21369.00	38875.5	23975.1	-62850.6	50127.7	22438.7	-72566.4	382.9	100	0.211
1998	21399.00	38830.4	23975.6	-62805.9	50082.4	22438.9	-72521.3	383.7	100	0.210
1999	21429.00	38785.3	23976.0	-62761.3	50037.0	22439.2	-72476.2	384.5	100	0.209
2000	21459.00	38740.1	23976.5	-62716.6	49991.8	22439.2	-72431.0	385.4	100	0.208
2001	21489.00	38695.1	23976.9	-62672.0	49946.5	22439.5	-72386.0	386.2	100	0.207
2002	21519.00	38649.9	23977.4	-62627.3	49901.1	22439.7	-72340.8	387.0	100	0.207
2003	21549.00	38604.9	23977.8	-62582.7	49855.9	22439.9	-72295.8	387.9	100	0.206
2004	21579.00	38559.7	23978.3	-62538.0	49810.6	22440.2	-72250.7	388.7	100	0.205
2005	21609.00	38514.7	23978.8	-62493.4	49765.3	22440.2	-72205.6	389.5	100	0.204
2006	21639.00	38469.6	23979.2	-62448.8	49720.0	22440.5	-72160.5	390.4	100	0.203
2007	21669.00	38424.6	23979.7	-62404.2	49674.8	22440.7	-72115.5	391.2	100	0.202
2008	21699.00	38379.4	23980.2	-62359.6	49629.5	22440.9	-72070.4	392.0	100	0.201
2009	21729.00	38334.4	23980.7	-62315.1	49584.2	22441.2	-72025.4	392.9	100	0.200
2010	21759.00	38289.3	23981.2	-62270.5	49539.0	22441.4	-71980.4	393.7	100	0.199
2011	21789.00	38244.2	23981.6	-62225.9	49493.7	22441.6	-71935.4	394.5	100	0.198
2012	21816.00	38203.7	23982.0	-62185.8	49453.0	22441.8	-71894.8	395.3	100	0.198
2013	21843.00	38163.2	23982.5	-62145.7	49412.3	22442.0	-71854.3	396.0	100	0.197
2014	21879.00	38109.1	23983.1	-62092.2	49358.0	22442.3	-71800.3	397.0	100	0.196

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2015	21909.00	38064.0	23983.6	-62047.6	49312.8	22442.5	-71755.3	397.9	100	0.195
2016	21939.00	38019.1	23984.0	-62003.1	49267.6	22442.8	-71710.3	398.7	100	0.194
2017	21969.00	37974.0	23984.5	-61958.5	49222.3	22443.0	-71665.4	399.5	100	0.193
2018	21999.00	37929.0	23985.1	-61914.0	49177.1	22443.2	-71620.3	400.4	100	0.192
2019	22029.00	37883.9	23985.6	-61869.5	49131.9	22443.5	-71575.4	401.2	100	0.191
2020	22059.00	37839.0	23986.0	-61824.9	49086.6	22443.8	-71530.4	402.0	100	0.190
2021	22089.00	37793.9	23986.5	-61780.4	49041.4	22444.0	-71485.4	402.9	100	0.189
2022	22119.00	37748.8	23987.1	-61735.9	48996.2	22444.2	-71440.4	403.7	100	0.189
2023	22149.00	37703.8	23987.7	-61691.5	48950.9	22444.5	-71395.4	404.5	100	0.188
2024	22179.00	37658.7	23988.2	-61646.9	48905.7	22444.8	-71350.5	405.4	100	0.187
2025	22209.00	37613.7	23988.8	-61602.5	48860.4	22445.3	-71305.6	406.2	100	0.186
2026	22239.00	37568.6	23989.3	-61558.0	48815.1	22445.5	-71260.7	407.0	100	0.185
2027	22269.00	37523.6	23989.9	-61513.5	48769.9	22445.8	-71215.7	407.9	100	0.184
2028	22299.00	37478.5	23990.5	-61469.0	48724.7	22446.2	-71170.9	408.7	100	0.183
2029	22329.00	37433.6	23990.9	-61424.5	48679.5	22446.4	-71125.9	409.5	100	0.182
2030	22359.00	37388.5	23991.6	-61380.1	48634.3	22446.8	-71081.1	410.4	100	0.181
2031	22389.00	37343.5	23992.1	-61335.6	48589.1	22447.0	-71036.1	411.2	100	0.180
2032	22419.00	37298.5	23992.7	-61291.2	48543.8	22447.5	-70991.3	412.0	100	0.180
2033	22449.00	37253.4	23993.2	-61246.7	48498.7	22447.7	-70946.4	412.9	100	0.179
2034	22479.00	37208.4	23993.9	-61202.3	48453.5	22448.0	-70901.5	413.7	100	0.178
2035	22509.00	37163.4	23994.5	-61157.9	48408.2	22448.4	-70856.6	414.5	100	0.177
2036	22539.00	37118.5	23994.9	-61113.4	48363.1	22448.6	-70811.7	415.4	100	0.176
2037	22569.00	37073.4	23995.6	-61069.0	48318.0	22448.9	-70766.9	416.2	100	0.175
2038	22599.00	37028.5	23996.2	-61024.6	48272.7	22449.3	-70722.0	417.0	100	0.174
2039	22629.00	36983.5	23996.7	-60980.2	48227.6	22449.6	-70677.2	417.9	100	0.173
2040	22659.00	36938.6	23997.3	-60935.8	48182.4	22450.0	-70632.4	418.7	100	0.172
2041	22689.00	36893.6	23997.8	-60891.4	48137.3	22450.3	-70587.6	419.5	100	0.171
2042	22716.00	36853.1	23998.5	-60851.5	48096.6	22450.6	-70547.2	420.3	100	0.171
2043	22743.00	36812.6	23999.0	-60811.6	48056.0	22450.9	-70506.9	421.0	100	0.170
2044	22779.00	36758.7	23999.6	-60758.4	48001.8	22451.4	-70453.2	422.0	100	0.169
2045	22809.00	36713.8	24000.3	-60714.1	47956.8	22451.6	-70408.4	422.9	100	0.168
2046	22839.00	36668.8	24000.9	-60669.7	47911.7	22452.0	-70363.6	423.7	100	0.167

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2047	22869.00	36623.9	24001.5	-60625.4	47866.5	22452.3	-70318.9	424.5	100	0.166
2048	22899.00	36579.0	24002.1	-60581.1	47821.4	22452.7	-70274.1	425.4	100	0.165
2049	22929.00	36534.1	24002.7	-60536.8	47776.3	22453.1	-70229.4	426.2	100	0.164
2050	22959.00	36489.1	24003.4	-60492.5	47731.2	22453.5	-70184.7	427.0	100	0.163
2051	22989.00	36444.3	24003.9	-60448.2	47686.1	22453.8	-70139.9	427.9	100	0.162
2052	23019.00	36399.3	24004.6	-60403.9	47640.9	22454.3	-70095.2	428.7	100	0.162
2053	23049.00	36354.5	24005.2	-60359.6	47595.9	22454.6	-70050.6	429.5	100	0.161
2054	23079.00	36309.5	24005.8	-60315.3	47550.8	22455.0	-70005.8	430.4	100	0.160
2055	23109.00	36264.6	24006.5	-60271.1	47505.8	22455.4	-69961.1	431.2	100	0.159
2056	23139.00	36219.8	24007.0	-60226.8	47460.7	22455.8	-69916.5	432.0	100	0.158
2057	23169.00	36174.8	24007.8	-60182.6	47415.6	22456.1	-69871.7	432.9	100	0.157
2058	23199.00	36130.0	24008.4	-60138.4	47370.6	22456.5	-69827.1	433.7	100	0.156
2059	23229.00	36085.1	24009.0	-60094.1	47325.5	22456.9	-69782.4	434.5	100	0.155
2060	23259.00	36040.3	24009.7	-60050.0	47280.5	22457.3	-69737.8	435.4	100	0.154
2061	23289.00	35995.4	24010.3	-60005.8	47235.5	22457.7	-69693.1	436.2	100	0.153
2062	23319.00	35950.6	24011.0	-59961.6	47190.4	22458.2	-69648.6	437.0	100	0.153
2063	23349.00	35905.7	24011.7	-59917.4	47145.3	22458.6	-69603.9	437.9	100	0.152
2064	23379.00	35860.9	24012.3	-59873.2	47100.4	22458.9	-69559.3	438.7	100	0.151
2065	23409.00	35816.0	24013.0	-59829.0	47055.3	22459.4	-69514.7	439.5	100	0.150
2066	23439.00	35771.2	24013.6	-59784.8	47010.3	22459.8	-69470.1	440.4	100	0.149
2067	23469.00	35726.3	24014.4	-59740.7	46965.3	22460.3	-69425.5	441.2	100	0.148
2068	23499.00	35681.4	24015.1	-59696.5	46920.2	22460.7	-69381.0	442.0	100	0.147
2069	23529.00	35636.6	24015.7	-59652.3	46875.2	22461.1	-69336.3	442.9	100	0.146
2070	23559.00	35591.8	24016.4	-59608.2	46830.3	22461.5	-69291.8	443.7	100	0.145
2071	23589.00	35547.0	24017.2	-59564.1	46785.2	22462.0	-69247.2	444.5	100	0.144
2072	23616.00	35506.6	24017.7	-59524.3	46744.7	22462.4	-69207.2	445.3	100	0.144
2073	23643.00	35466.3	24018.3	-59484.6	46704.2	22462.8	-69167.0	446.0	100	0.143
2074	23691.00	35394.6	24019.5	-59414.1	46632.2	22463.5	-69095.7	447.4	100	0.146
2075	23731.00	35334.9	24020.4	-59355.2	46572.2	22464.1	-69036.3	448.5	100	0.148
2076	23771.00	35275.1	24021.4	-59296.5	46512.3	22464.7	-68977.0	449.6	100	0.150
2077	23811.00	35215.4	24022.2	-59237.6	46452.3	22465.3	-68917.6	450.7	100	0.152
2078	23851.00	35155.7	24023.2	-59178.9	46392.4	22465.9	-68858.3	451.8	100	0.155

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2079	23891.00	35096.0	24024.1	-59120.1	46332.5	22466.5	-68799.0	452.9	100	0.157
2080	23931.00	35036.3	24025.1	-59061.4	46272.6	22467.2	-68739.7	454.0	100	0.159
2081	23971.00	34976.7	24025.9	-59002.6	46212.7	22467.7	-68680.4	455.1	100	0.162
2082	24011.00	34917.0	24026.8	-58943.9	46152.8	22468.2	-68621.1	456.2	100	0.164
2083	24051.00	34857.4	24027.7	-58885.1	46092.9	22468.9	-68561.8	457.3	100	0.166
2084	24091.00	34797.7	24028.6	-58826.3	46033.1	22469.4	-68502.5	458.5	100	0.168
2085	24131.00	34738.1	24029.6	-58767.7	45973.3	22469.9	-68443.2	459.6	100	0.171
2086	24171.00	34678.6	24030.4	-58708.9	45913.5	22470.4	-68383.9	460.7	100	0.173
2087	24211.00	34618.9	24031.3	-58650.3	45853.7	22471.0	-68324.7	461.8	100	0.175
2088	24251.00	34559.4	24032.2	-58591.6	45793.9	22471.6	-68265.5	462.9	100	0.178
2089	24291.00	34499.8	24033.2	-58533.0	45734.1	22472.2	-68206.3	464.0	100	0.180
2090	24331.00	34440.2	24034.2	-58474.4	45674.3	22472.8	-68147.1	465.1	100	0.182
2091	24371.00	34380.7	24035.1	-58415.8	45614.4	22473.5	-68088.0	466.2	100	0.184
2092	24411.00	34321.1	24036.1	-58357.2	45554.6	22474.2	-68028.9	467.3	100	0.187
2093	24451.00	34261.5	24037.1	-58298.7	45494.8	22474.9	-67969.7	468.5	100	0.189
2094	24491.00	34202.0	24038.1	-58240.1	45435.0	22475.6	-67910.6	469.6	100	0.191
2095	24531.00	34142.4	24039.3	-58181.7	45375.2	22476.3	-67851.6	470.7	100	0.194
2096	24571.00	34082.8	24040.3	-58123.1	45315.5	22477.0	-67792.5	471.8	100	0.196
2097	24611.00	34023.3	24041.4	-58064.6	45255.7	22477.7	-67733.4	472.9	100	0.198
2098	24651.00	33963.8	24042.3	-58006.1	45195.9	22478.5	-67674.4	474.0	100	0.200
2099	24691.00	33904.2	24043.4	-57947.7	45136.2	22479.1	-67615.3	475.1	100	0.203
2100	24731.00	33844.7	24044.5	-57889.2	45076.4	22479.9	-67556.3	476.2	100	0.205
2101	24771.00	33785.1	24045.6	-57830.7	45016.7	22480.6	-67497.3	477.3	100	0.207
2102	24807.00	33731.6	24046.4	-57778.1	44962.9	22481.3	-67444.2	478.3	100	0.209
2103	24843.00	33678.0	24047.5	-57725.5	44909.1	22481.9	-67391.0	479.3	100	0.211
2104	24891.00	33606.6	24048.7	-57655.4	44837.4	22482.8	-67320.2	480.7	100	0.214
2105	24931.00	33547.1	24049.8	-57596.9	44777.7	22483.5	-67261.3	481.8	100	0.216
2106	24971.00	33487.7	24050.9	-57538.6	44718.0	22484.3	-67202.4	482.9	100	0.219
2107	25011.00	33428.2	24052.0	-57480.2	44658.3	22485.1	-67143.4	484.0	100	0.221
2108	25051.00	33368.7	24053.1	-57421.8	44598.6	22485.9	-67084.5	485.1	100	0.223
2109	25091.00	33309.3	24054.2	-57363.4	44539.0	22486.5	-67025.4	486.2	100	0.226
2110	25131.00	33249.8	24055.2	-57305.1	44479.3	22487.3	-66966.6	487.3	100	0.228

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2111	25171.00	33190.4	24056.3	-57246.7	44419.6	22488.1	-66907.7	488.5	100	0.230
2112	25211.00	33131.0	24057.4	-57188.4	44360.0	22488.8	-66848.8	489.6	100	0.232
2113	25251.00	33071.5	24058.6	-57130.1	44300.2	22489.6	-66789.9	490.7	100	0.235
2114	25291.00	33012.1	24059.7	-57071.8	44240.6	22490.4	-66731.1	491.8	100	0.237
2115	25331.00	32952.7	24060.7	-57013.4	44181.0	22491.1	-66672.1	492.9	100	0.239
2116	25371.00	32893.2	24061.9	-56955.2	44121.3	22492.0	-66613.4	494.0	100	0.242
2117	25411.00	32833.9	24063.0	-56896.9	44061.7	22492.8	-66554.5	495.1	100	0.244
2118	25451.00	32774.5	24064.2	-56838.7	44002.1	22493.5	-66495.6	496.2	100	0.246
2119	25491.00	32715.0	24065.4	-56780.4	43942.5	22494.4	-66436.9	497.3	100	0.248
2120	25531.00	32655.7	24066.5	-56722.2	43882.9	22495.2	-66378.0	498.4	100	0.251
2121	25571.00	32596.4	24067.6	-56663.9	43823.3	22496.0	-66319.2	499.6	100	0.253
2122	25611.00	32534.2	24069.3	-56603.5	43742.9	22497.4	-66240.3	500.7	100	0.255
2123	25651.00	32459.3	24073.8	-56533.2	43650.2	22501.8	-66151.9	501.8	100	0.257
2124	25691.00	32374.4	24079.5	-56454.0	43560.9	22507.6	-66068.6	502.9	100	0.260
2125	25731.00	32286.5	24087.6	-56374.2	43478.9	22514.7	-65993.6	504.0	100	0.262
2126	25771.00	32200.7	24093.8	-56294.5	43401.1	22518.0	-65919.1	505.1	100	0.264
2127	25811.00	32124.2	24089.1	-56213.4	43325.5	22515.9	-65841.5	506.2	100	0.267
2128	25851.00	32050.2	24081.4	-56131.6	43251.9	22509.5	-65761.4	507.3	100	0.269
2129	25891.00	31978.4	24070.7	-56049.1	43180.0	22499.7	-65679.7	508.4	100	0.271
2130	25931.00	31908.4	24058.1	-55966.5	43109.7	22487.3	-65597.0	509.6	100	0.273
2131	25971.00	31840.0	24043.6	-55883.6	43041.0	22472.9	-65513.9	510.7	100	0.276
2132	26007.00	31779.7	24029.3	-55809.0	42980.3	22458.7	-65439.0	511.7	100	0.278
2133	26043.00	31720.5	24014.0	-55734.6	42920.8	22443.4	-65364.2	512.7	100	0.280
2134	26091.00	31643.0	23992.8	-55635.8	42842.7	22422.2	-65264.9	514.0	100	0.283
2135	26131.00	31579.5	23974.8	-55554.3	42778.8	22404.2	-65183.1	515.1	100	0.285
2136	26171.00	31516.6	23957.4	-55474.0	42715.7	22386.8	-65102.5	516.2	100	0.287
2137	26211.00	31454.2	23941.7	-55395.9	42652.9	22371.2	-65024.1	517.3	100	0.289
2138	26251.00	31390.8	23931.2	-55322.1	42589.3	22360.5	-64949.8	518.4	100	0.292
2139	26291.00	31325.2	23927.1	-55252.4	42523.1	22356.2	-64879.3	519.5	100	0.294
2140	26331.00	31259.1	23924.4	-55183.5	42456.5	22353.0	-64809.5	520.7	100	0.296
2141	26371.00	31192.9	23921.7	-55114.5	42389.7	22349.8	-64739.6	521.8	100	0.299
2142	26411.00	31126.6	23918.9	-55045.5	42323.0	22346.6	-64669.6	522.9	100	0.301

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2143	26451.00	31060.4	23916.0	-54976.4	42256.3	22343.5	-64599.7	524.0	100	0.303
2144	26491.00	30994.1	23913.3	-54907.3	42189.4	22340.4	-64529.8	525.1	100	0.305
2145	26531.00	30927.8	23910.4	-54838.2	42122.7	22337.1	-64459.8	526.2	100	0.308
2146	26571.00	30861.5	23907.6	-54769.1	42055.8	22333.9	-64389.7	527.3	100	0.310
2147	26611.00	30795.1	23904.8	-54699.9	41989.0	22330.7	-64319.7	528.4	100	0.312
2148	26651.00	30728.8	23901.9	-54630.7	41922.2	22327.4	-64249.6	529.5	100	0.315
2149	26691.00	30662.4	23899.0	-54561.5	41855.2	22324.2	-64179.4	530.7	100	0.317
2150	26731.00	30596.1	23896.1	-54492.1	41788.4	22320.8	-64109.2	531.8	100	0.319
2151	26771.00	30529.7	23893.3	-54422.9	41721.4	22317.6	-64039.0	532.9	100	0.321
2152	26811.00	30463.3	23890.3	-54353.6	41654.5	22314.3	-63968.8	534.0	100	0.324
2153	26851.00	30396.8	23887.4	-54284.2	41587.6	22311.0	-63898.6	535.1	100	0.326
2154	26891.00	30330.3	23884.5	-54214.8	41520.6	22307.6	-63828.3	536.2	100	0.328
2155	26931.00	30263.8	23881.6	-54145.4	41453.6	22304.4	-63757.9	537.3	100	0.331
2156	26971.00	30197.3	23878.6	-54075.9	41386.5	22301.1	-63687.6	538.4	100	0.333
2157	27011.00	30130.8	23875.6	-54006.4	41319.5	22297.7	-63617.2	539.5	100	0.335
2158	27051.00	30064.2	23872.7	-53936.9	41252.4	22294.3	-63546.7	540.7	100	0.337
2159	27091.00	29997.7	23869.7	-53867.4	41185.4	22290.9	-63476.3	541.8	100	0.340
2160	27131.00	29931.1	23866.7	-53797.8	41118.3	22287.6	-63405.9	542.9	100	0.342
2161	27171.00	29864.5	23863.7	-53728.2	41051.1	22284.2	-63335.3	544.0	100	0.344
2162	27207.00	29804.6	23860.9	-53665.5	40990.7	22281.2	-63271.9	545.0	100	0.346
2163	27243.00	29744.6	23858.2	-53602.9	40930.3	22278.0	-63208.3	546.0	100	0.348
2164	27259.56	29696.7	23835.0	-53531.7	40853.4	22255.3	-63108.7	546.1	100	0.342
2165	27276.12	29643.4	23805.1	-53448.5	40779.9	22226.4	-63006.4	546.2	100	0.335
2166	27303.72	29561.3	23748.7	-53309.9	40676.1	22171.9	-62848.0	546.3	100	0.324
2167	27331.32	29489.0	23690.2	-53179.2	40588.0	22115.0	-62703.0	546.4	100	0.312
2168	27358.92	29425.7	23632.0	-53057.8	40512.5	22059.4	-62572.0	546.4	100	0.301
2169	27386.52	29370.0	23576.4	-52946.4	40447.1	22005.9	-62452.9	546.5	100	0.290
2170	27414.12	29320.4	23523.5	-52844.0	40389.6	21954.3	-62343.9	546.5	100	0.278
2171	27441.72	29276.1	23472.5	-52748.6	40338.7	21905.3	-62244.0	546.6	100	0.267
2172	27469.32	29236.0	23424.2	-52660.2	40293.0	21859.0	-62152.0	546.6	100	0.256
2173	27496.92	29199.6	23378.3	-52577.8	40251.9	21814.1	-62066.0	546.6	100	0.245
2174	27524.52	29166.2	23334.2	-52500.4	40214.4	21772.6	-61987.0	546.6	100	0.233

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2175	27552.12	29135.5	23292.6	-52428.1	40180.2	21731.9	-61912.0	546.7	100	0.222
2176	27579.72	29107.1	23252.7	-52359.8	40148.5	21693.5	-61842.1	546.7	100	0.211
2177	27607.32	29080.6	23214.8	-52295.5	40119.3	21656.8	-61776.1	546.7	100	0.200
2178	27634.92	29055.8	23178.3	-52234.2	40092.1	21622.0	-61714.1	546.7	100	0.188
2179	27657.00	29037.0	23149.9	-52186.9	40071.4	21594.8	-61666.2	546.7	100	0.179
2180	27673.56	29023.4	23129.4	-52152.8	40056.5	21574.7	-61631.2	546.7	100	0.172
2181	27690.12	29010.3	23109.3	-52119.6	40042.2	21555.1	-61597.2	546.7	100	0.166
2182	27717.72	28989.6	23076.8	-52066.3	40019.7	21524.6	-61544.3	546.8	100	0.154
2183	27745.32	28969.9	23046.2	-52016.1	39998.4	21494.0	-61492.3	546.8	100	0.143
2184	27772.92	28951.3	23015.6	-51966.9	39978.2	21465.2	-61443.4	546.8	100	0.132
2185	27800.52	28933.5	22987.1	-51920.7	39959.0	21437.5	-61396.5	546.8	100	0.121
2186	27828.12	28916.5	22958.9	-51875.5	39940.5	21410.0	-61350.5	546.8	100	0.109
2187	27855.72	28900.2	22931.1	-51831.3	39923.1	21383.6	-61306.6	546.8	100	0.098
2188	27883.32	28884.6	22904.5	-51789.1	39906.3	21358.4	-61264.7	546.8	100	0.087
2189	27910.92	28869.6	22879.4	-51748.9	39890.2	21333.6	-61223.8	546.8	100	0.075
2190	27938.52	28855.1	22854.7	-51709.8	39874.7	21309.1	-61183.8	546.8	100	0.064
2191	27966.12	28841.1	22830.6	-51671.6	39859.7	21285.2	-61144.9	546.8	100	0.053
2192	27993.72	28827.6	22806.9	-51634.5	39845.3	21262.7	-61108.0	546.9	100	0.042
2193	28021.32	28814.6	22783.8	-51598.4	39831.4	21240.7	-61072.1	546.9	100	0.030
2194	28048.92	28801.9	22761.4	-51563.3	39818.0	21219.1	-61037.2	546.9	100	0.019
2195	28071.00	28792.1	22744.1	-51536.2	39807.6	21201.6	-61009.2	546.9	100	0.010
2196	28387.00	28745.0	22648.4	-51393.4	39755.2	21111.7	-60866.9	546.9	100	0.010
2197	28681.03	28716.7	22589.5	-51306.3	39724.0	21054.7	-60778.7	546.9	100	0.010
2198	28975.06	28698.5	22549.0	-51247.5	39703.7	21016.9	-60720.6	547.0	100	0.010
2199	29269.59	28686.5	22522.4	-51209.0	39690.4	20991.1	-60681.5	547.0	100	0.010
2200	29564.22	28678.7	22504.0	-51182.6	39681.6	20973.8	-60655.4	547.0	100	0.010
2201	29858.93	28673.4	22492.0	-51165.4	39675.9	20962.5	-60638.4	547.0	100	0.010
2202	30153.68	28670.0	22484.2	-51154.2	39672.1	20955.3	-60627.4	547.0	100	0.010
2203	30448.45	28667.8	22478.3	-51146.1	39669.6	20949.8	-60619.3	547.0	100	0.010
2204	30743.24	28666.2	22474.8	-51141.1	39667.9	20946.4	-60614.3	547.0	100	0.010
2205	31038.05	28665.2	22472.8	-51138.0	39666.8	20944.6	-60611.3	547.0	100	0.010
2206	31332.86	28664.6	22471.4	-51136.0	39666.1	20942.2	-60608.3	547.0	100	0.010

Point No.	Time (s)	Membrane Plus Bending Stresses			Total Stresses			Metal Temp. (°F)	No. of Cycles	DO (ppm)
		S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)	S'_{12} (psi)	S'_{23} (psi)	S'_{31} (psi)			
2207	31859.52	28664.0	22470.0	-51134.0	39665.4	20941.0	-60606.3	547.0	100	0.010
2208	32386.19	28663.6	22468.4	-51132.0	39664.9	20940.4	-60605.3	547.0	100	0.010
2209	32912.86	28663.5	22468.5	-51131.9	39664.8	20939.5	-60604.3	547.0	100	0.010
2210	33439.52	28663.4	22468.6	-51131.9	39664.6	20939.7	-60604.3	547.0	100	0.010
2211	33966.19	28663.3	22467.7	-51130.9	39664.5	20939.8	-60604.3	547.0	100	0.010
2212	34492.86	28663.3	22467.7	-51130.9	39664.5	20939.8	-60604.3	547.0	100	0.010
2213	35019.52	28663.3	22467.7	-51130.9	39664.5	20939.8	-60604.3	547.0	100	0.010
2214	35546.19	28663.3	22467.7	-51130.9	39664.5	20939.8	-60604.3	547.0	100	0.010
2215	35971.00	28663.3	22467.7	-51130.9	39664.5	20939.8	-60604.3	547.0	100	0.010

C.5 References

C-1. EPRI Report No. 1025823, “Guidelines for Addressing Environmental Effects in Fatigue Usage Calculations,” Electric Power Research Institute, Palo Alto, CA, December 2012.

C-2. ASME Boiler and Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Facility Components,” Division 1, Subsection NB, “Class 1 Components,” American Society of Mechanical Engineers, New York, NY, 2013.

APPENDIX D
COMPENDIUM OF FIGURES

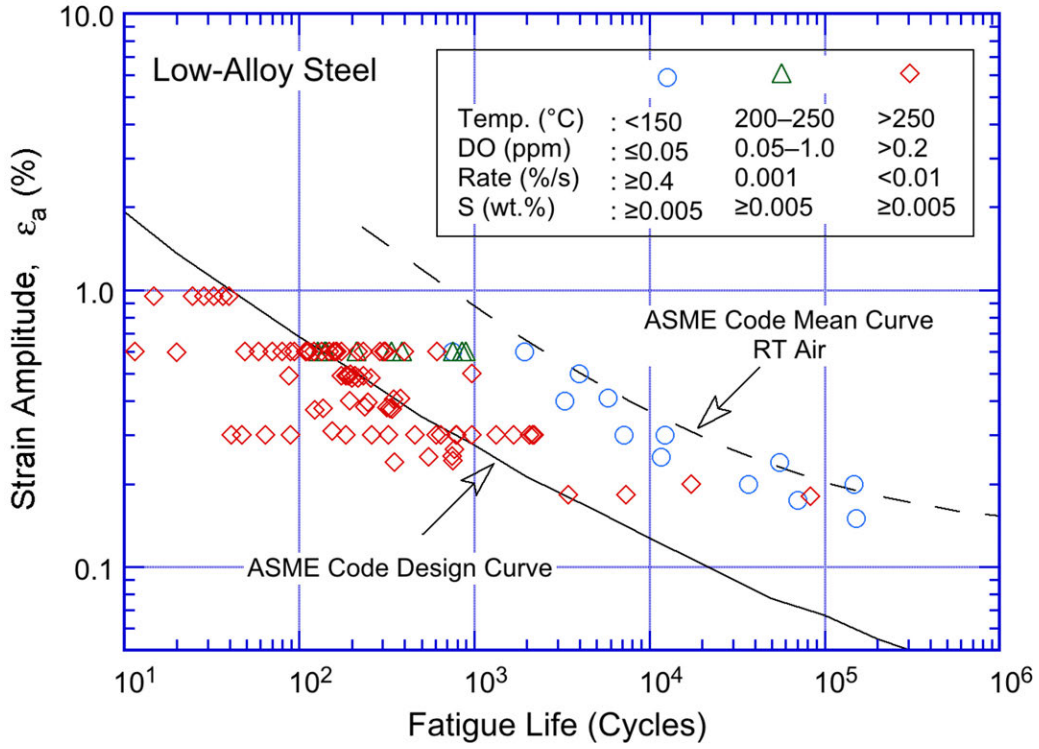


Figure 1-1(a)

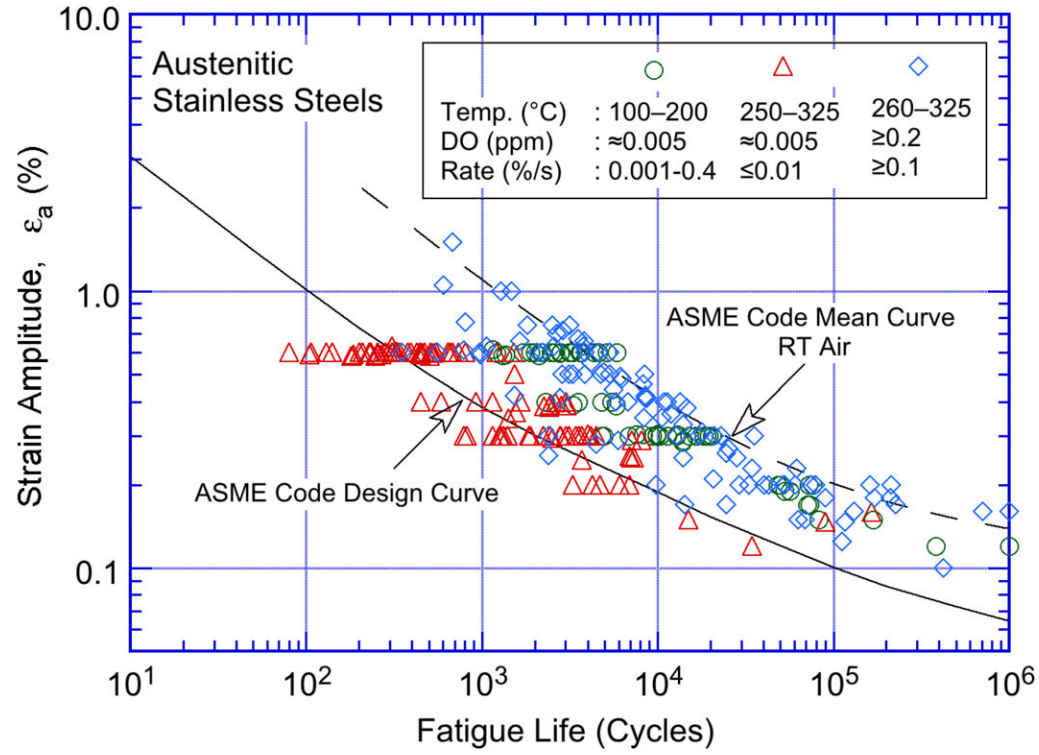


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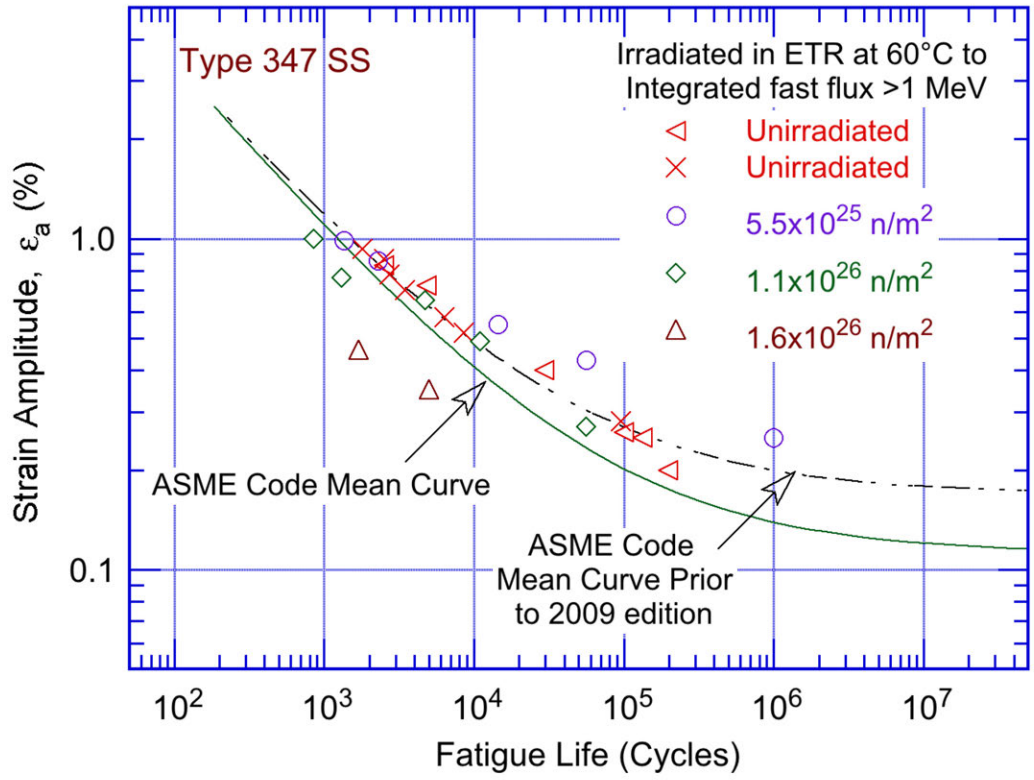


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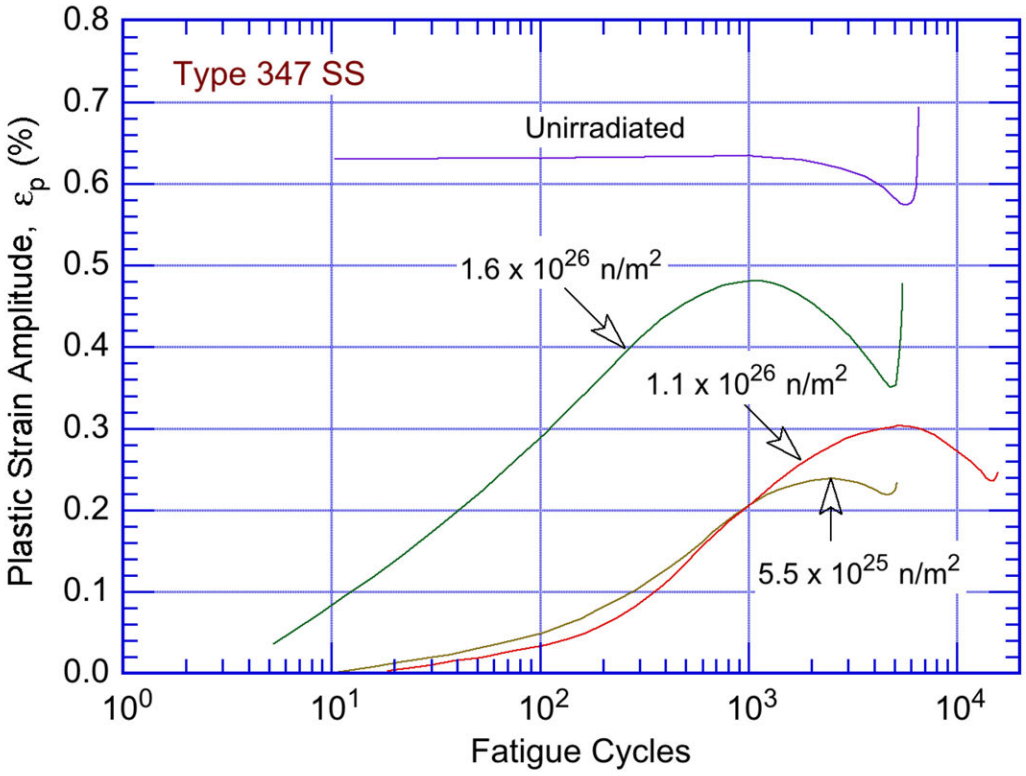


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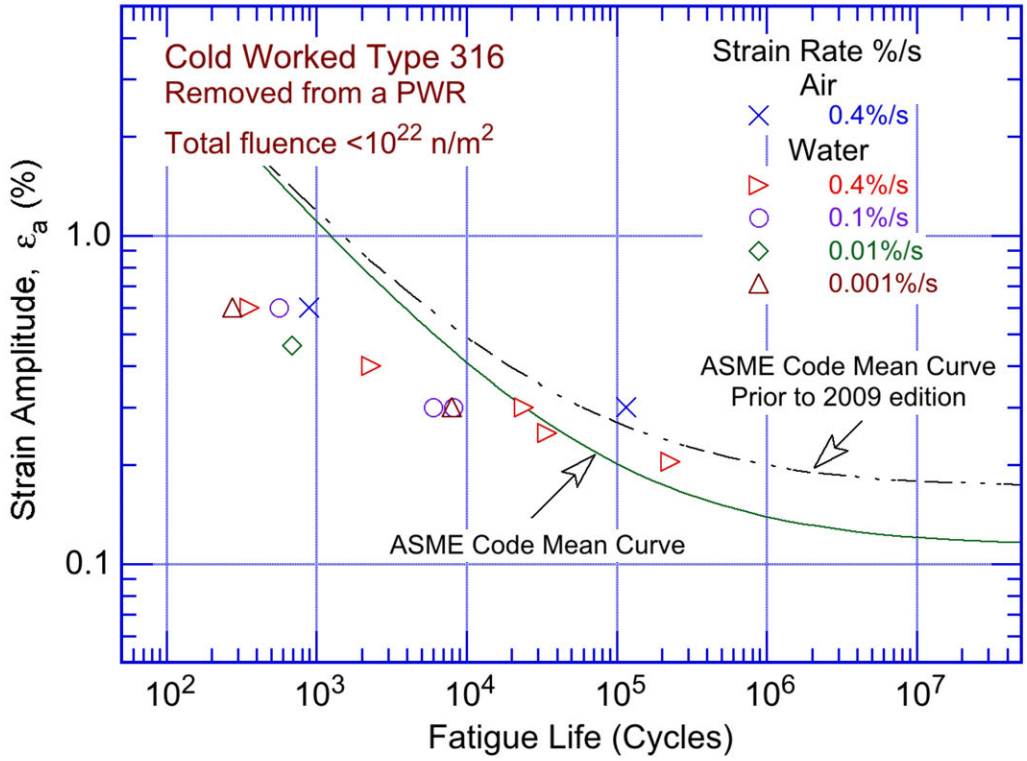


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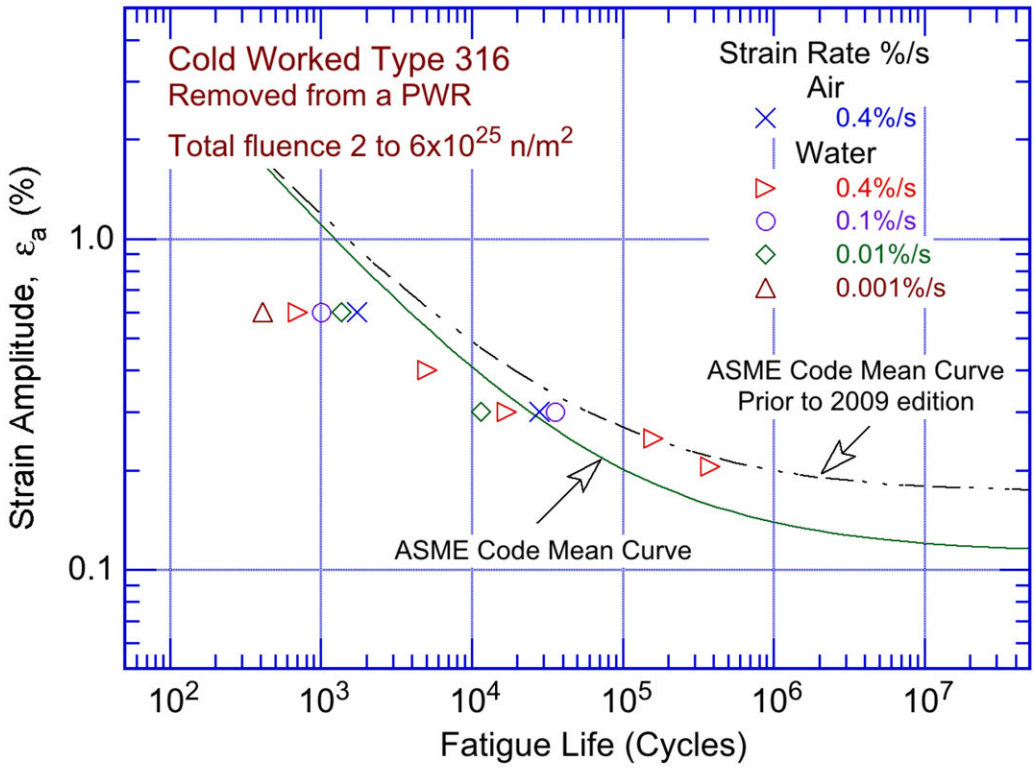


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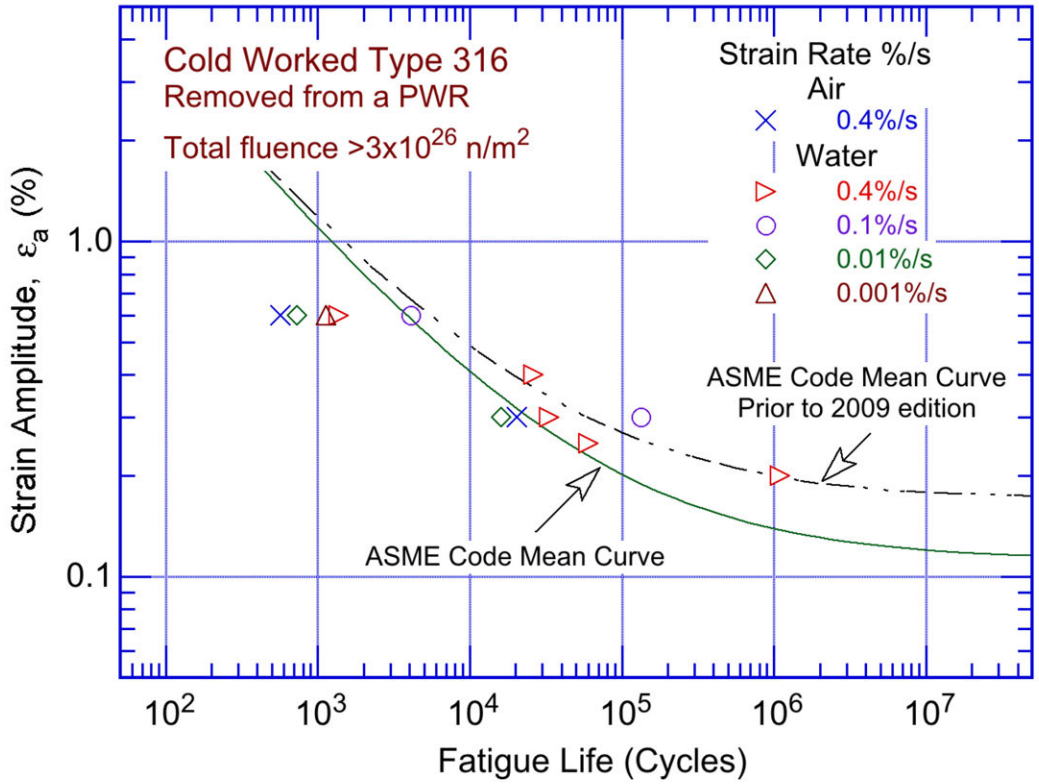


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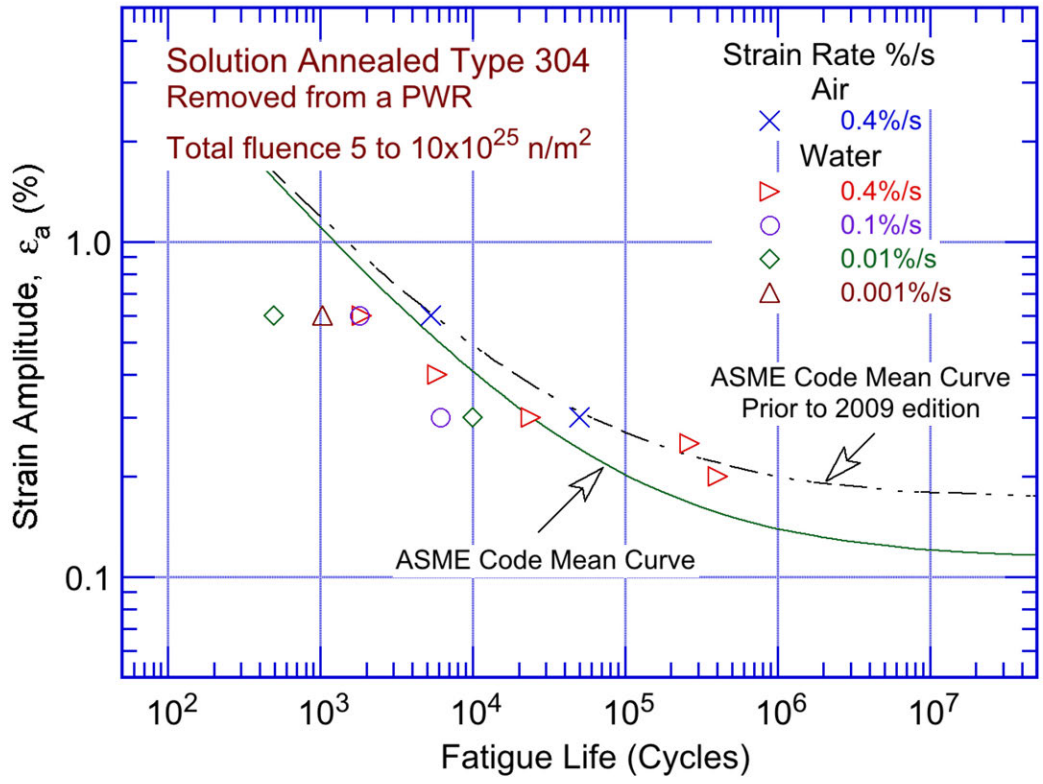


Figure 1-4

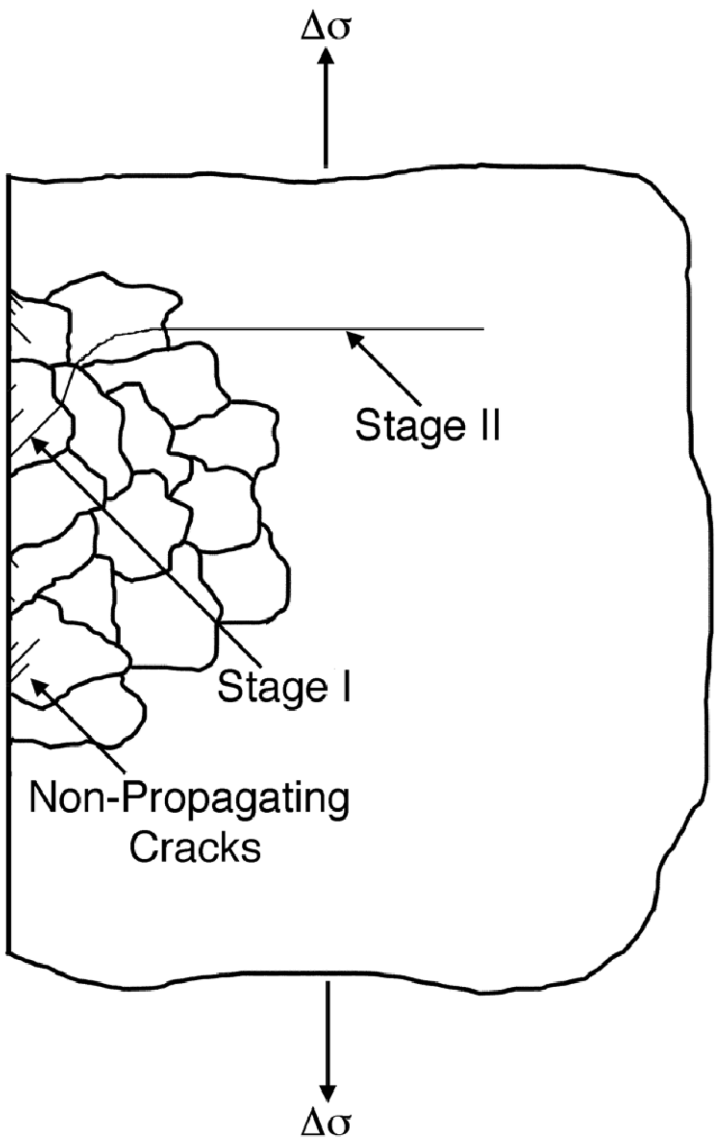


Figure 2-1(a)

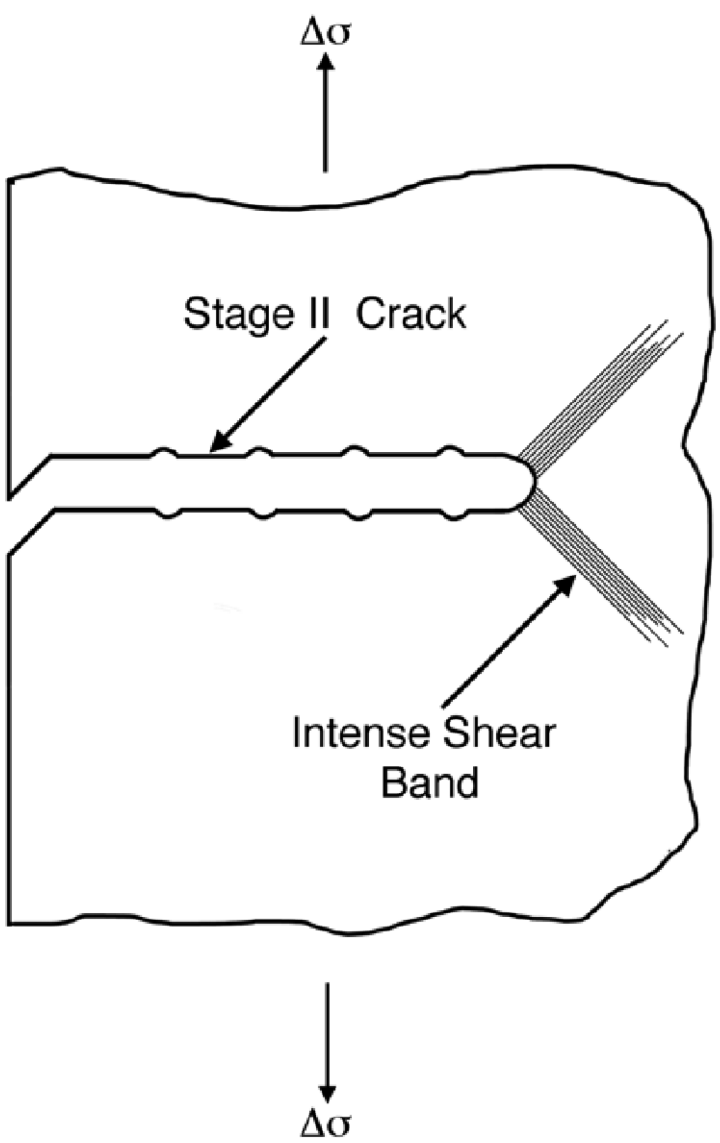


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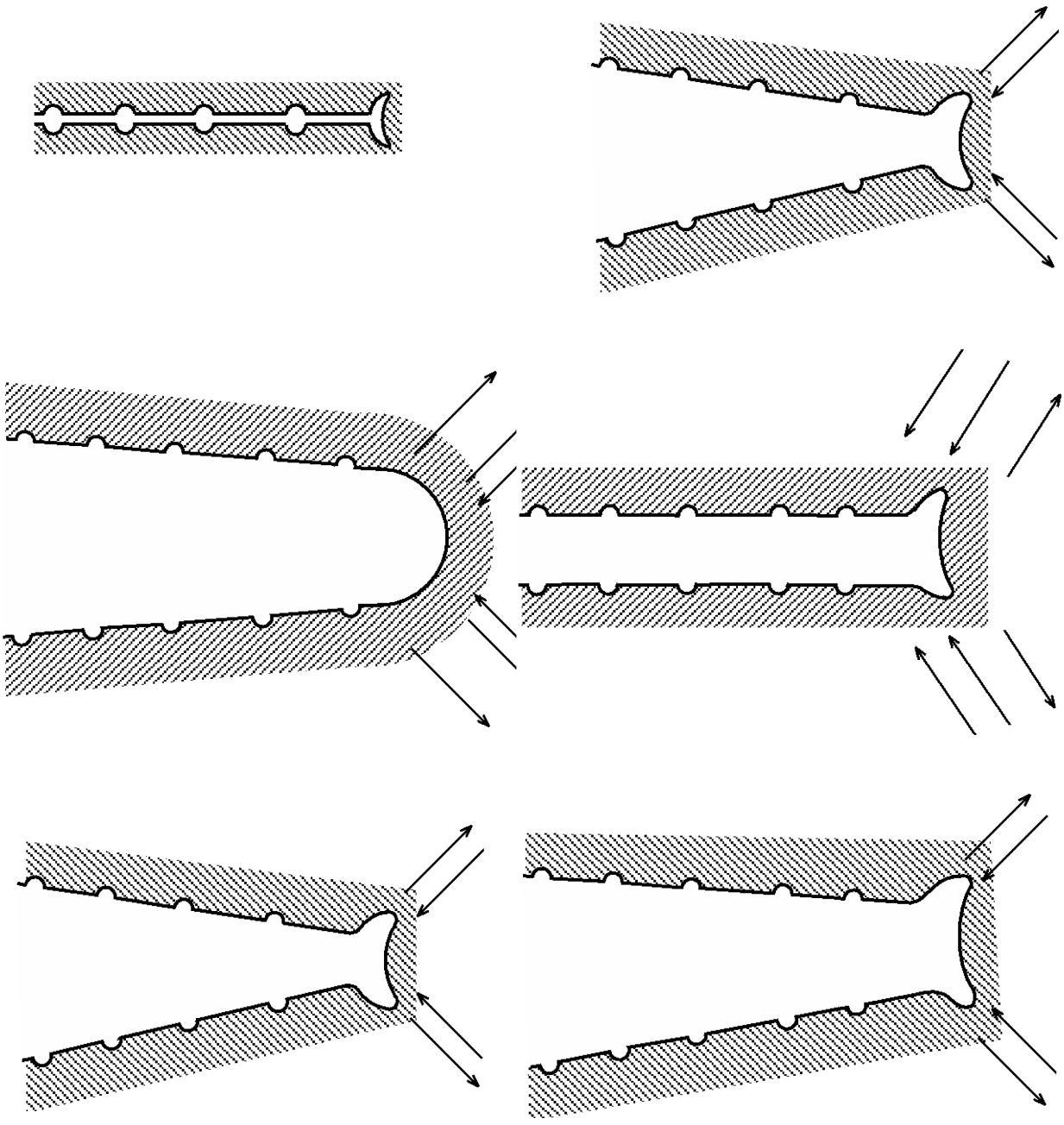


Figure 2-2(a) – 2-2(f)

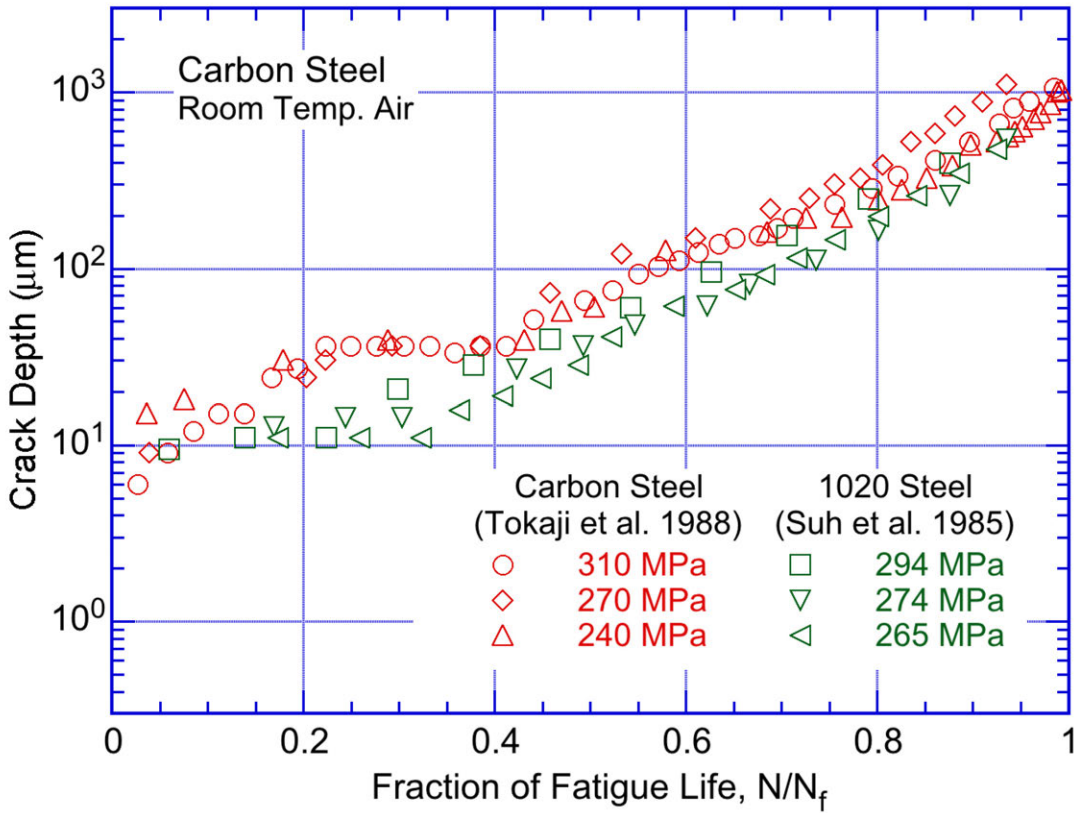


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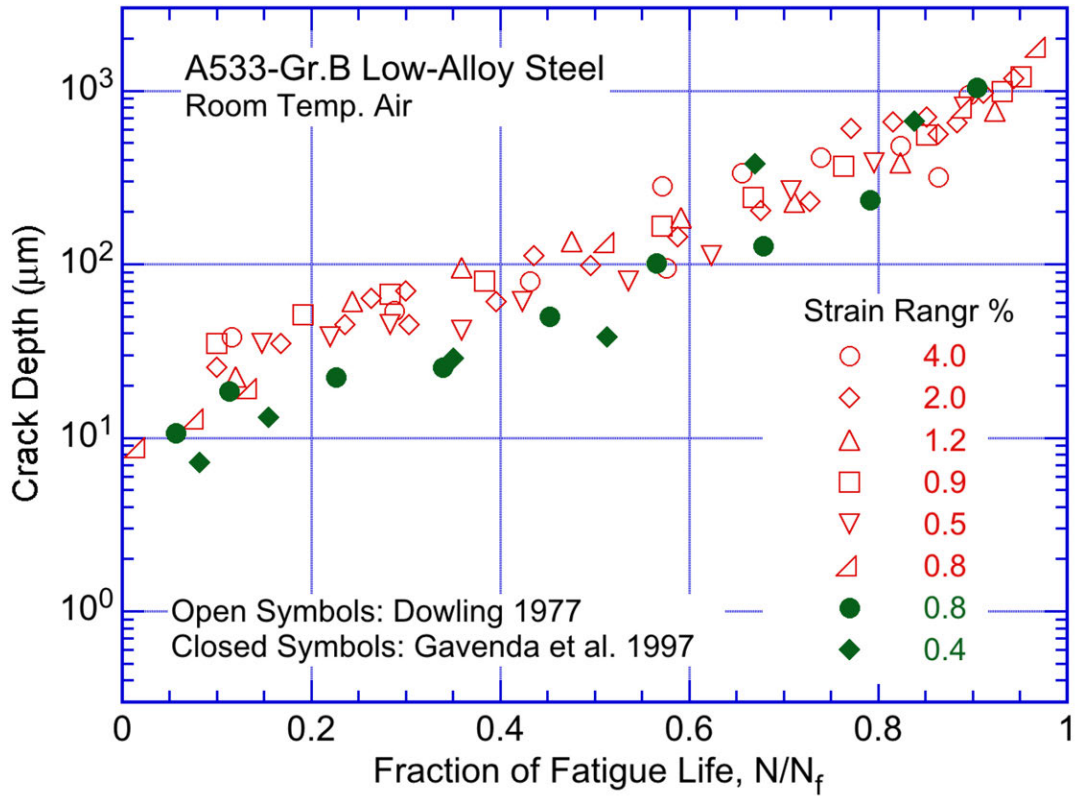


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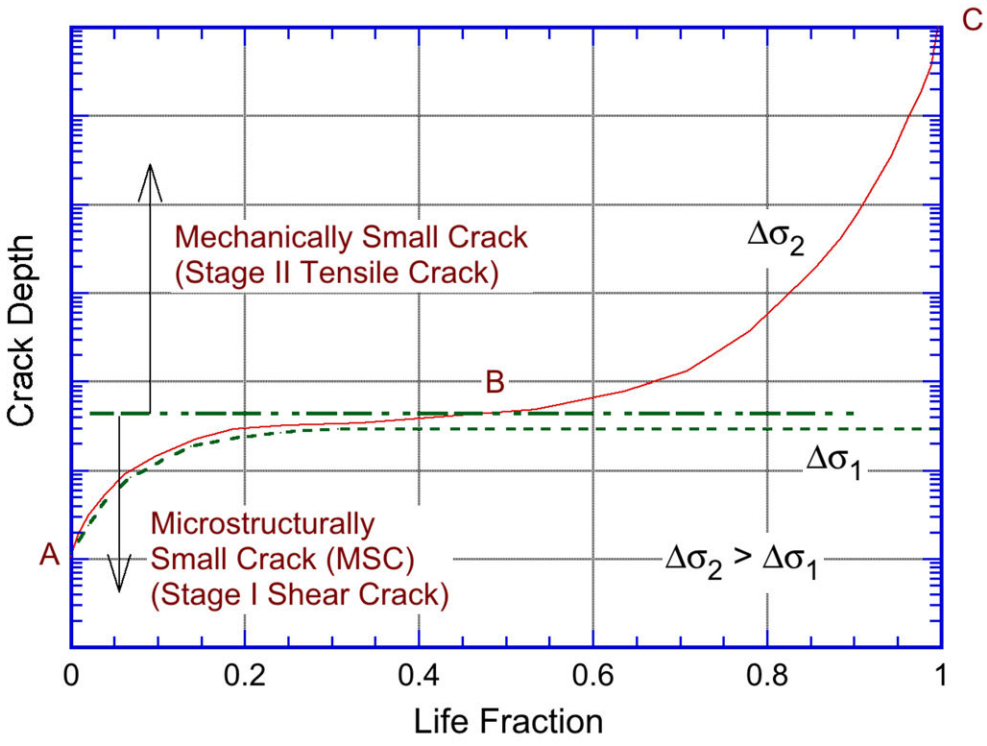


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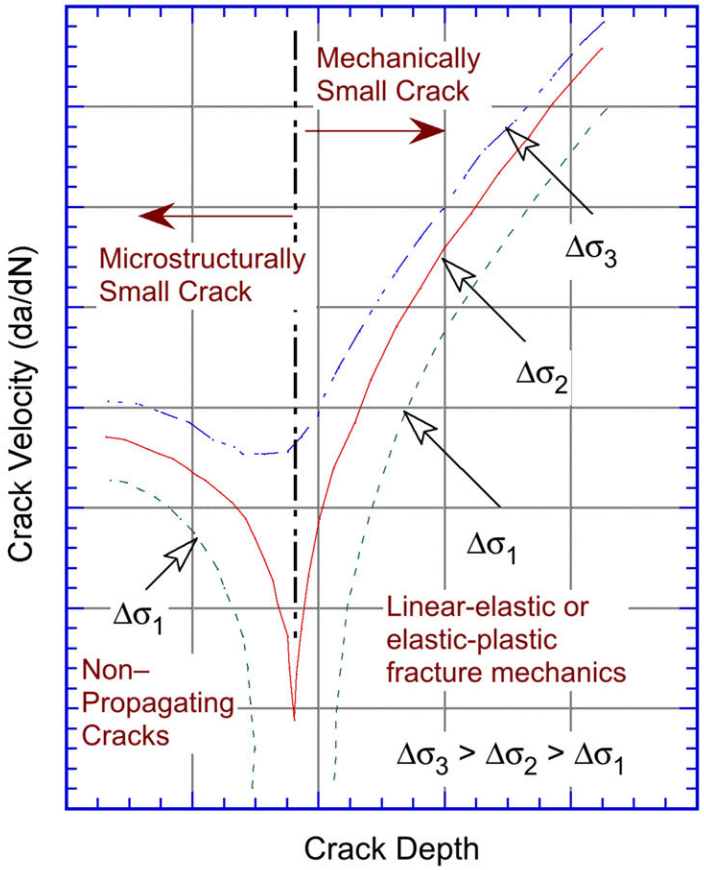


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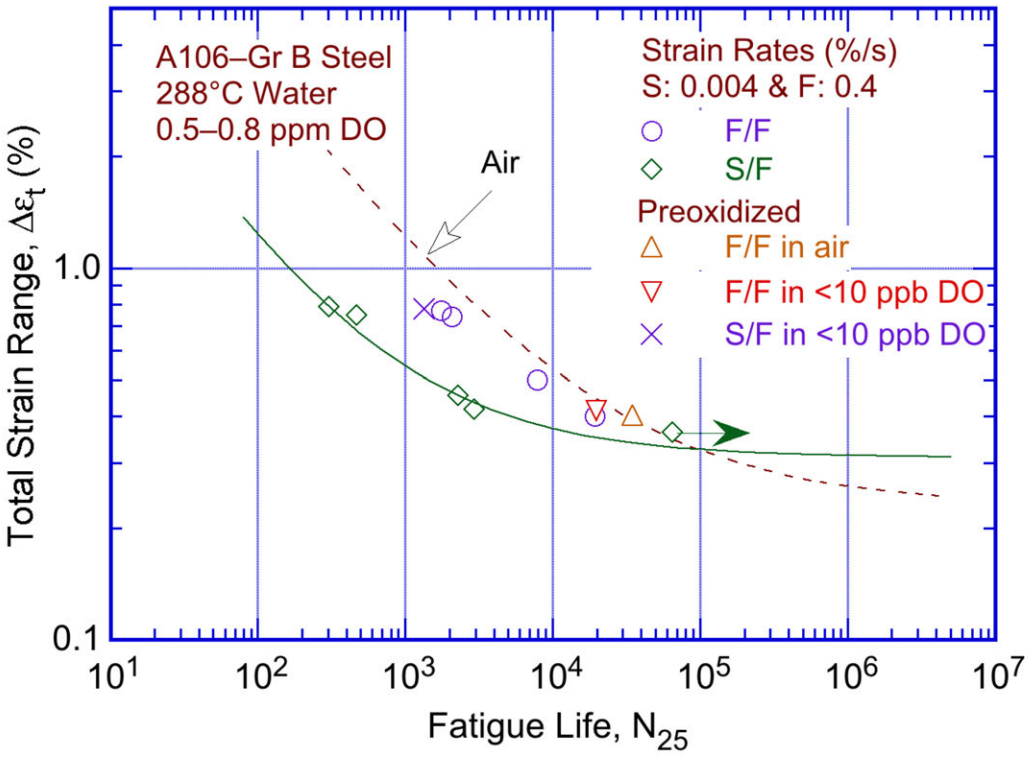


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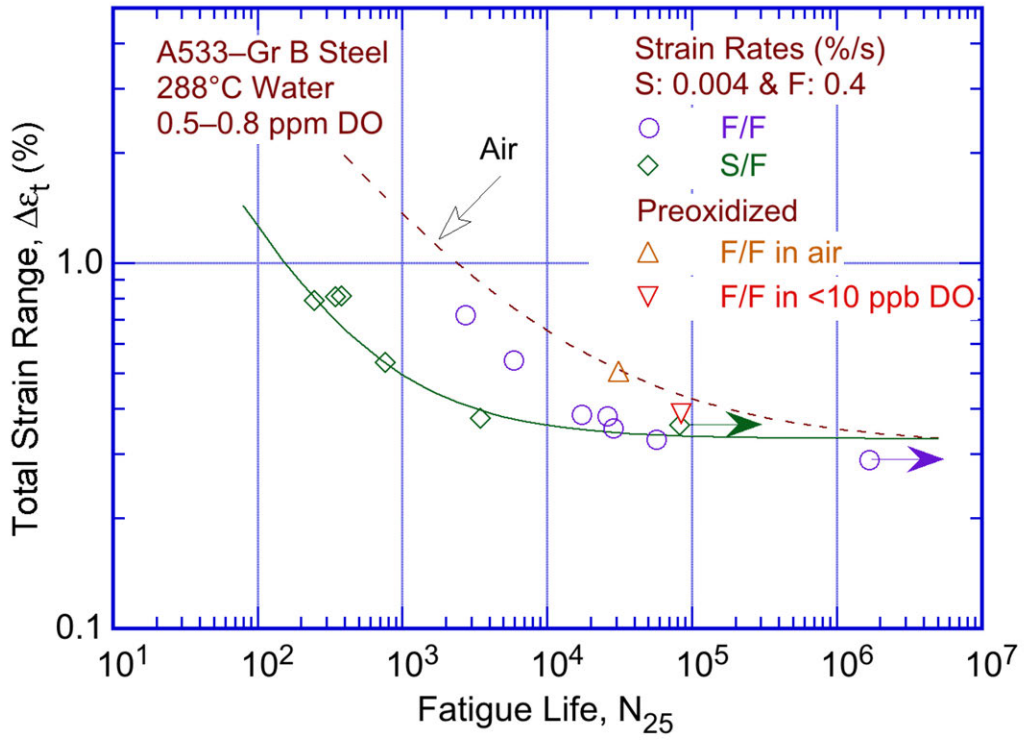


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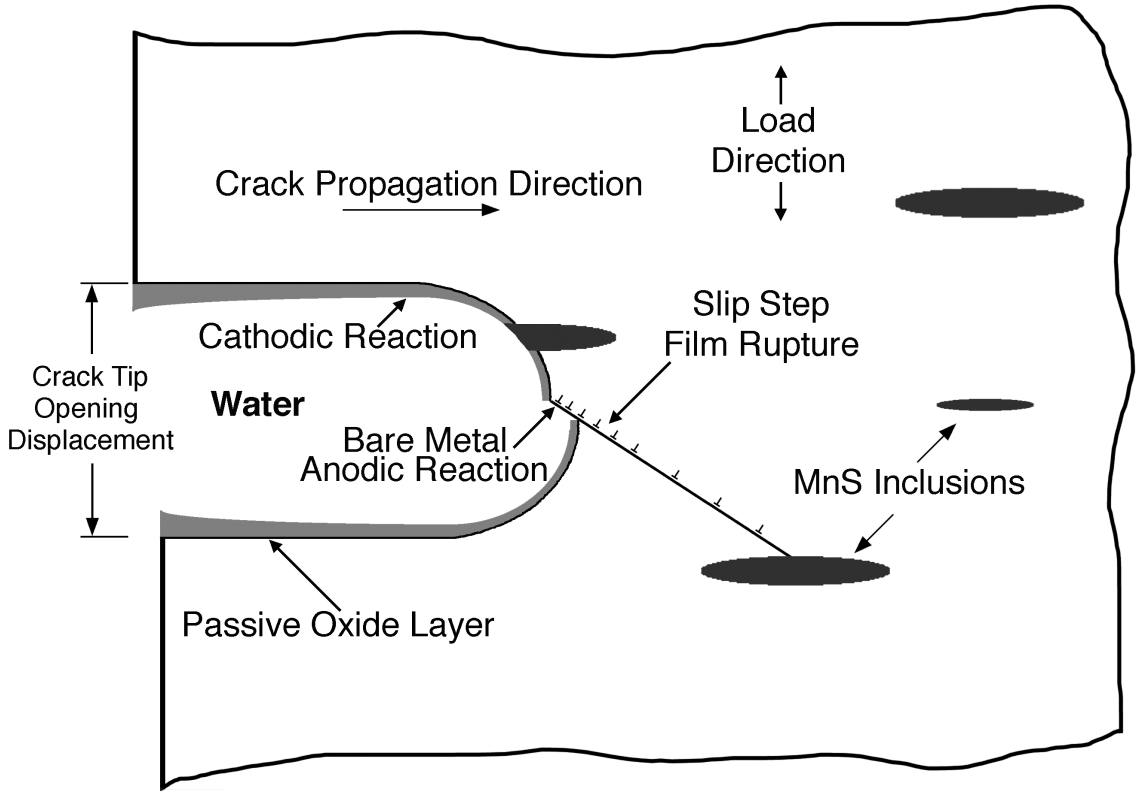


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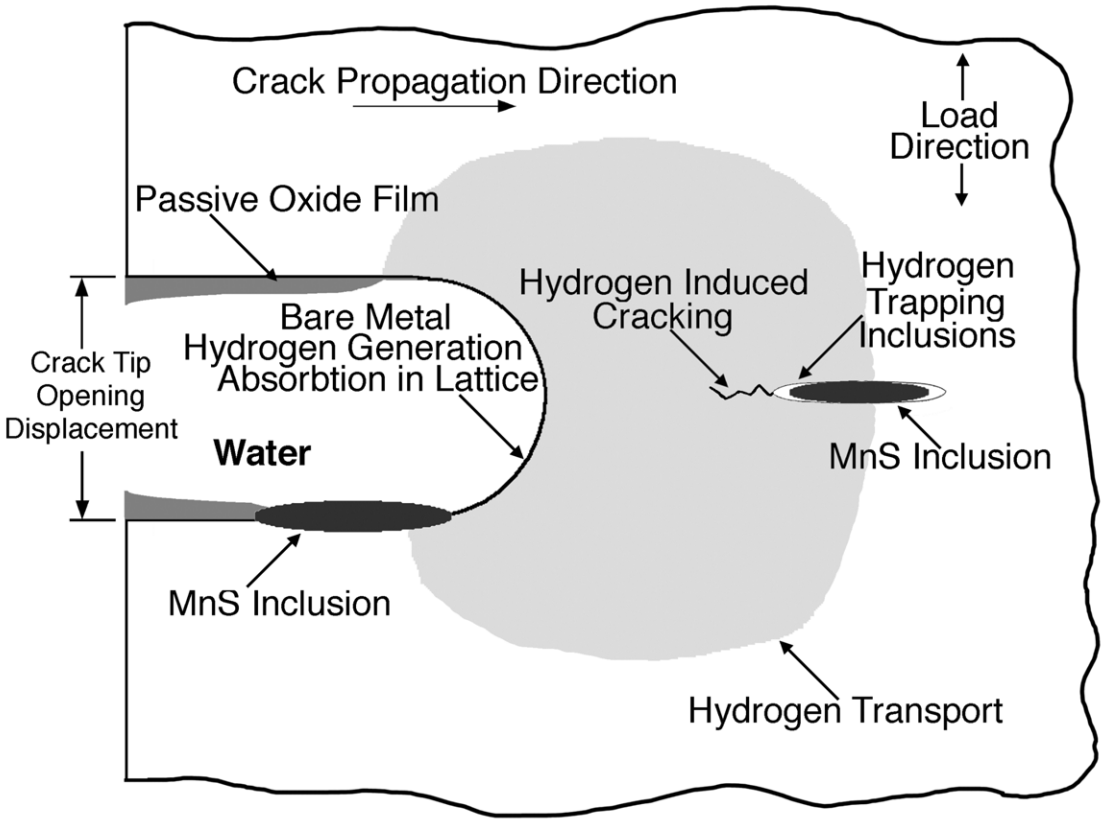


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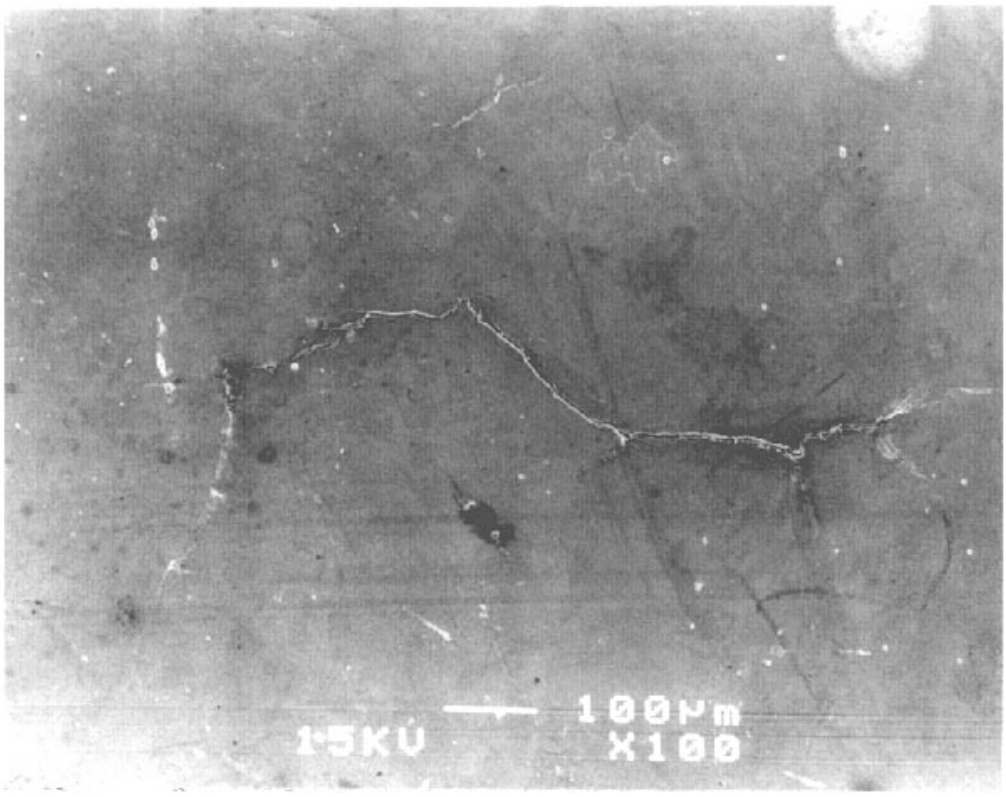


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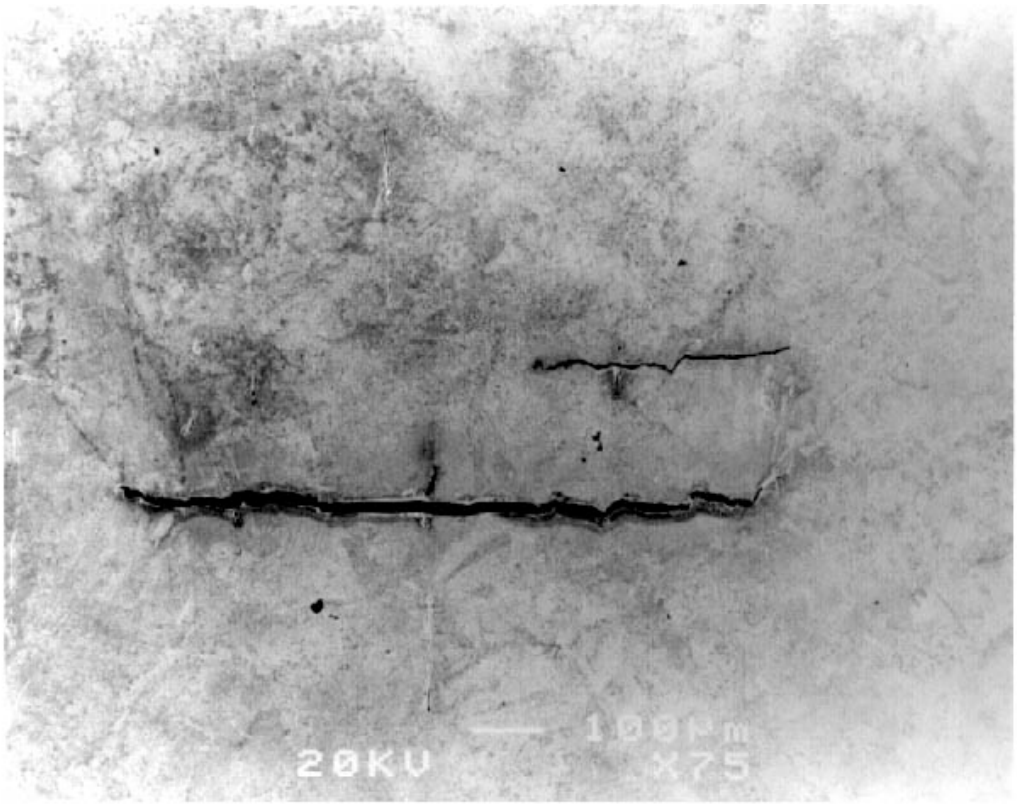


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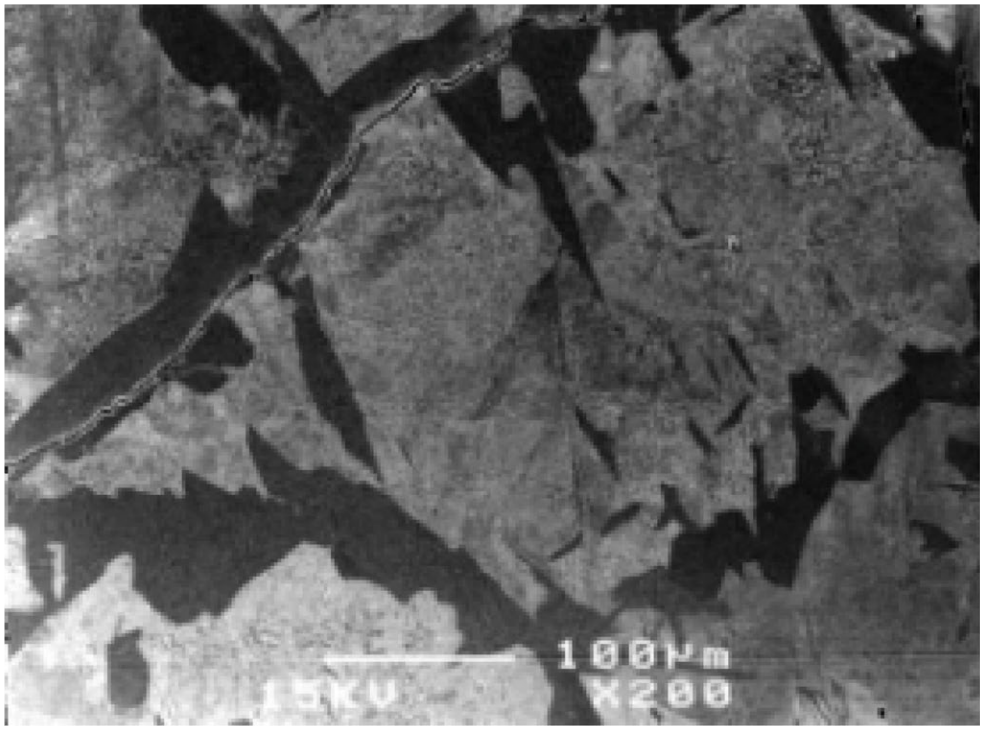


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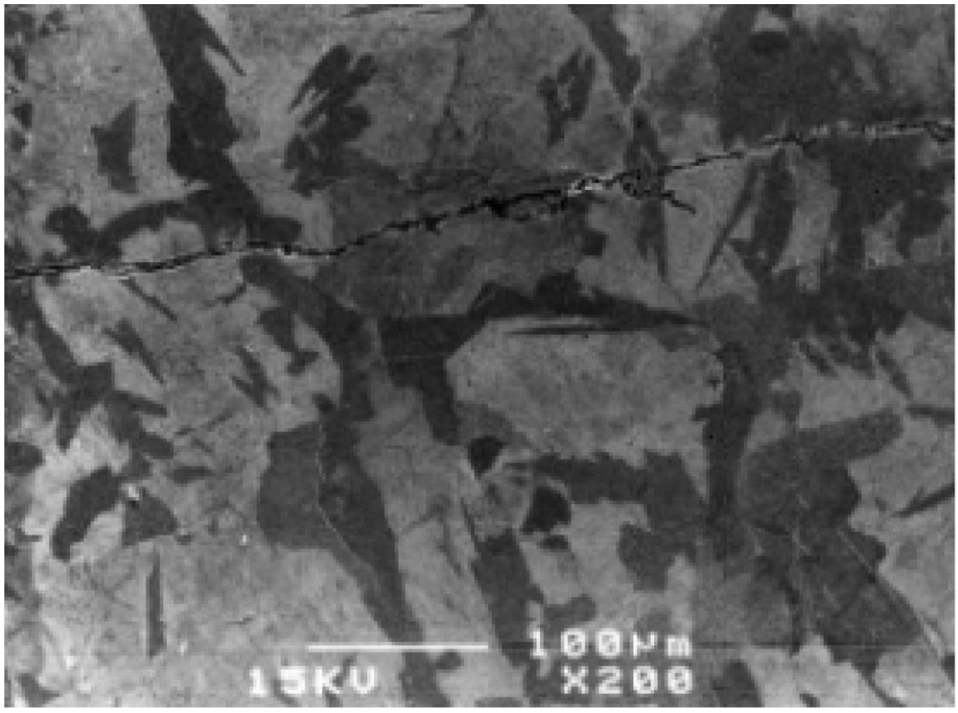


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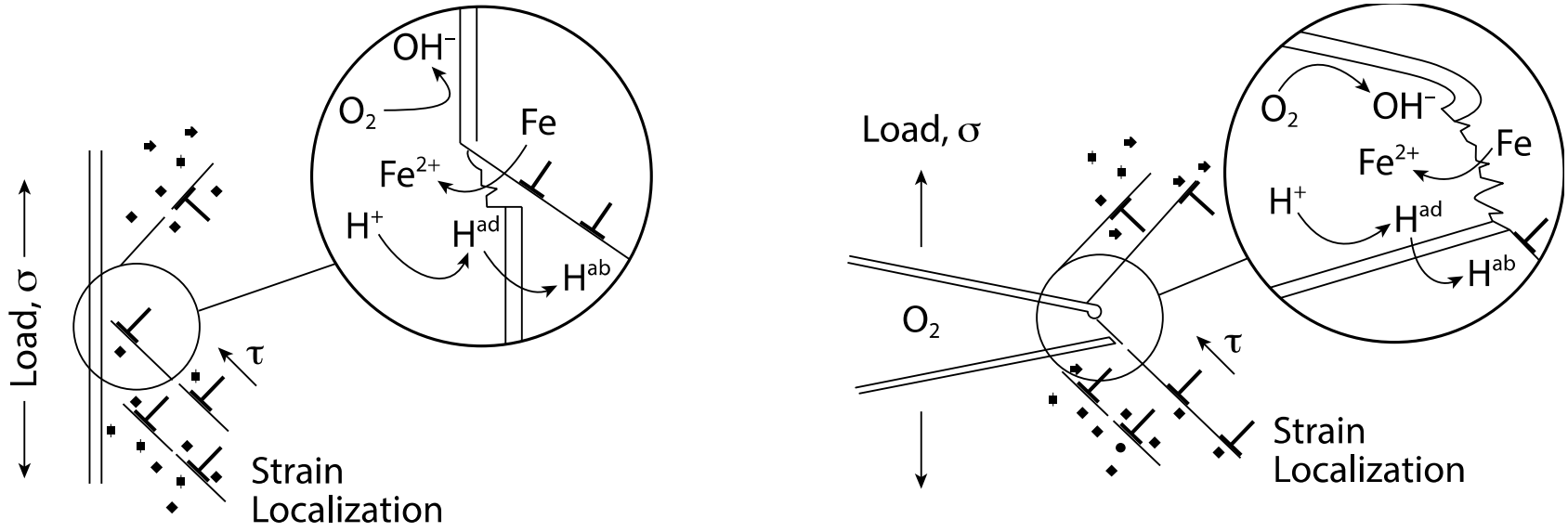

Load, σ
OH⁻
O₂
Fe
Fe²⁺
H⁺
Hᵃᵈ
Hᵃᵇ
τ
Strain
Localization
Load, σ
O₂
O₂
OH⁻
Fe
Fe²⁺
H⁺
Hᵃᵈ
Hᵃᵇ
τ
Strain
Localization

Figure 2-10

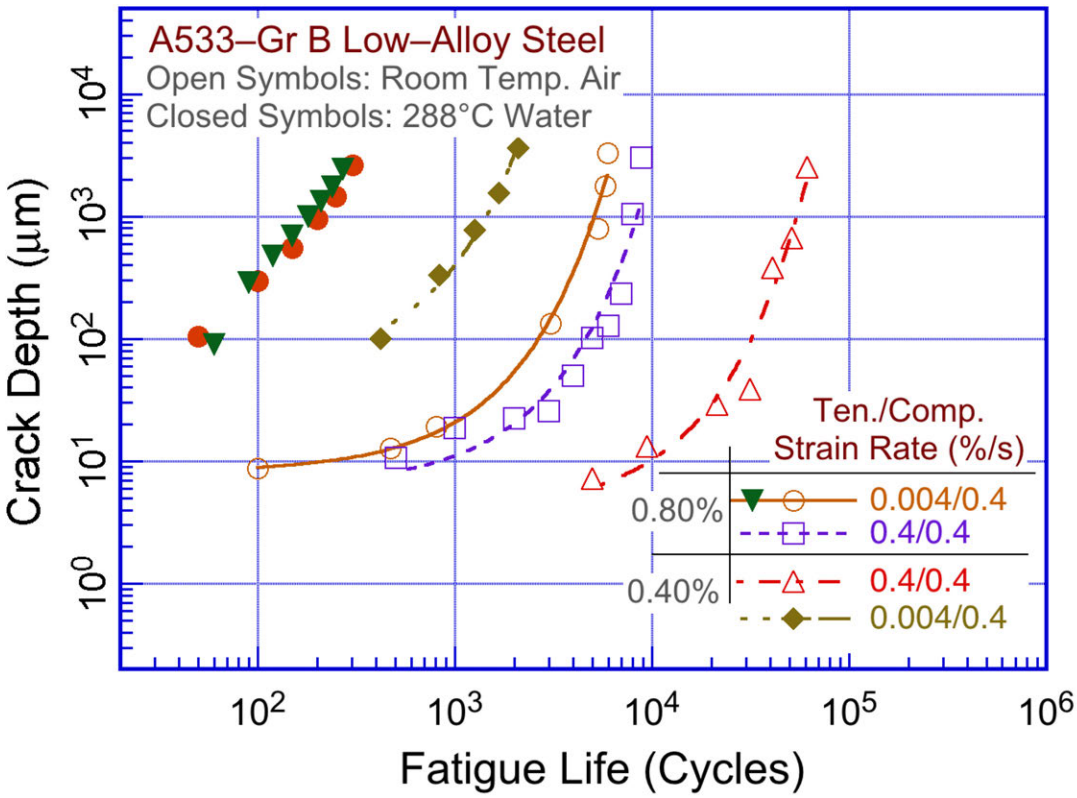


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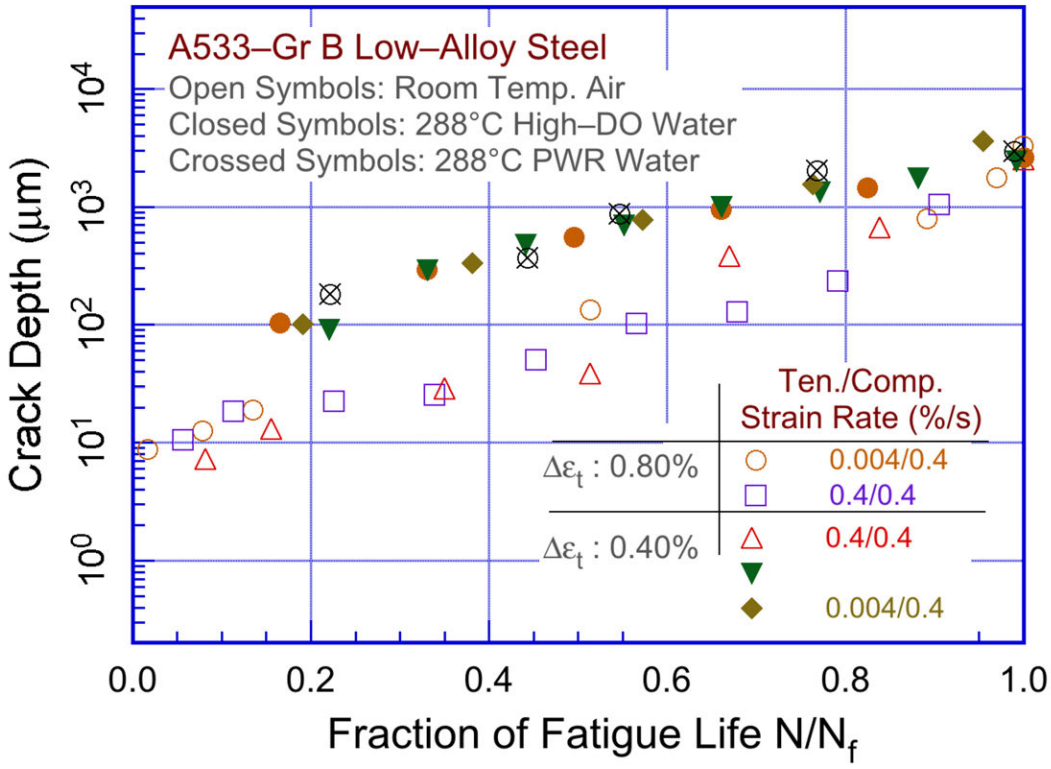


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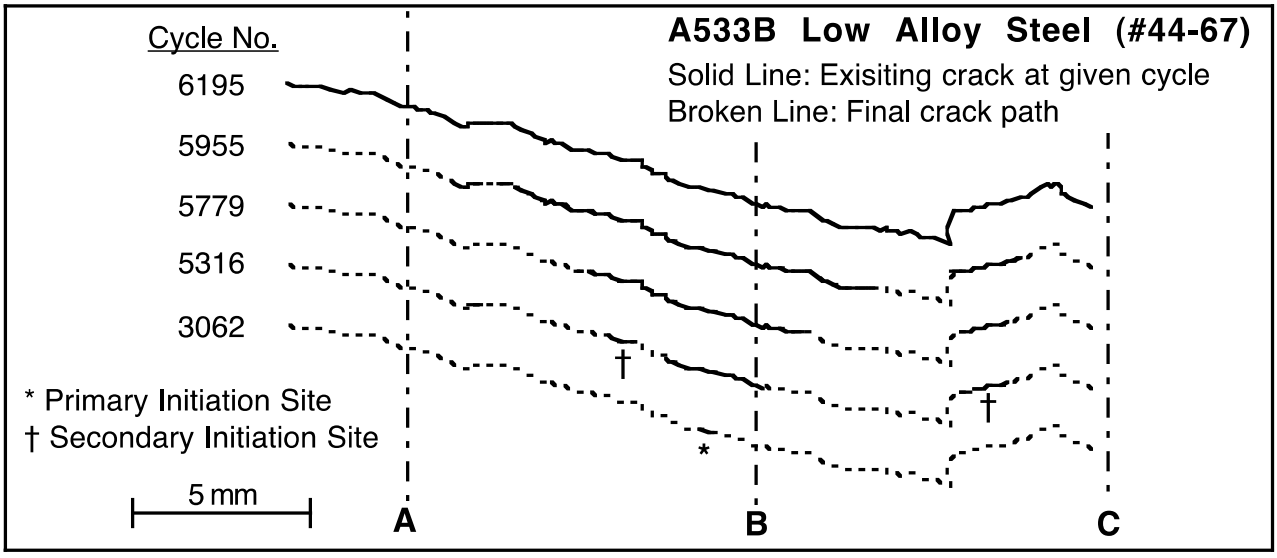


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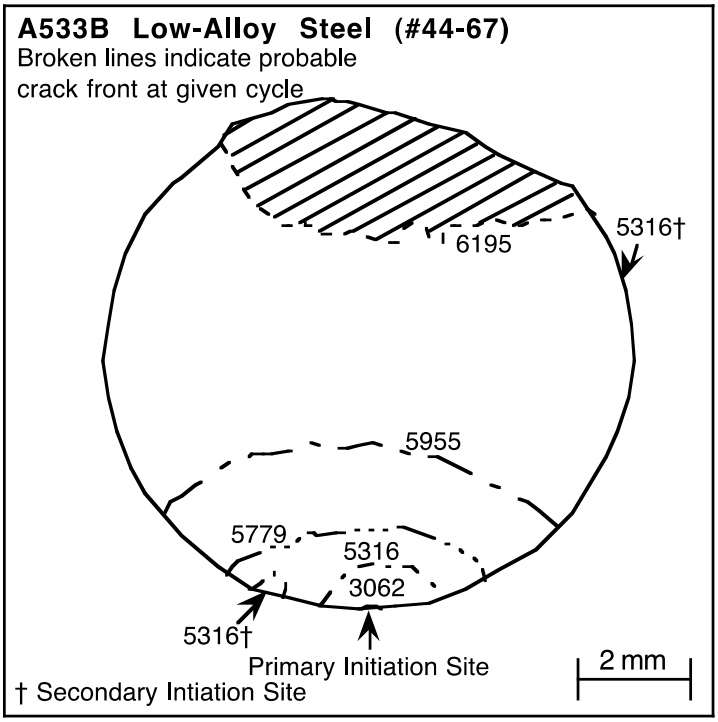


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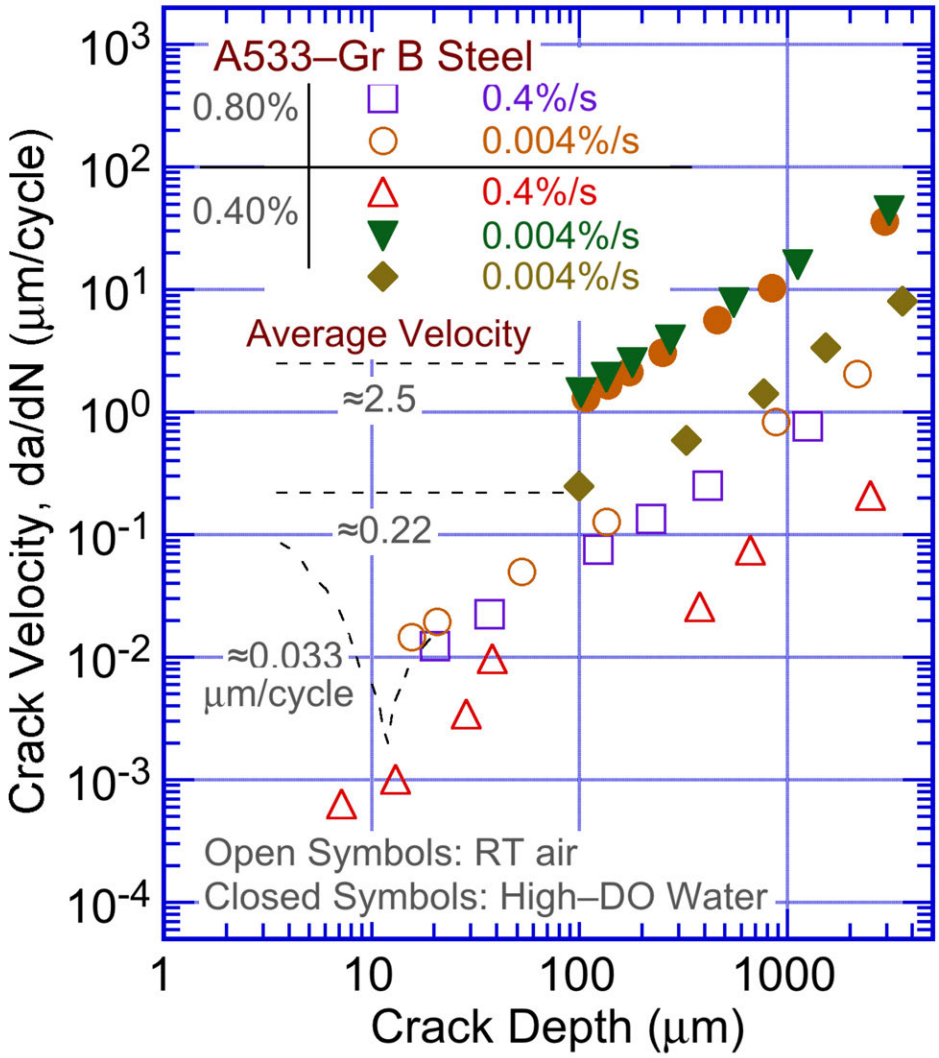

A533–Gr B Steel
0.80%
0.40%
0.4%/s
0.004%/s
0.4%/s
0.004%/s
0.004%/s
Average Velocity
≈2.5
≈0.22
≈0.033
μm/cycle
Open Symbols: RT air
Closed Symbols: High–DO Water
Crack Velocity, da/dN (μm/cycle)
Crack Depth (μm)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
1
10
100
1000

Figure 2-13

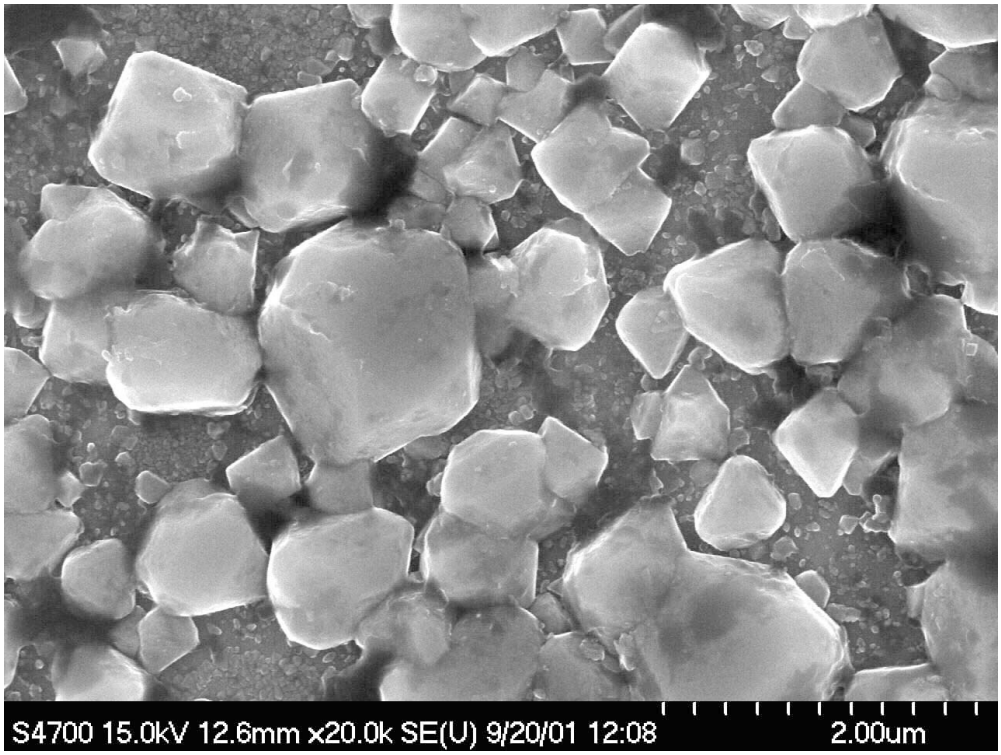


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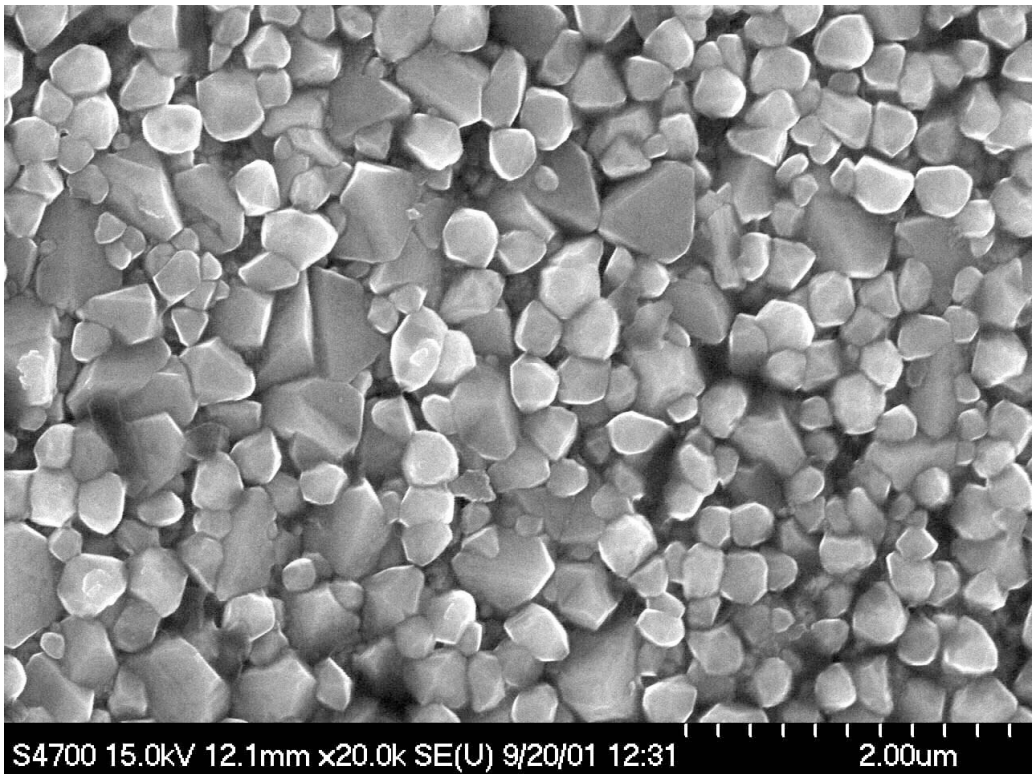


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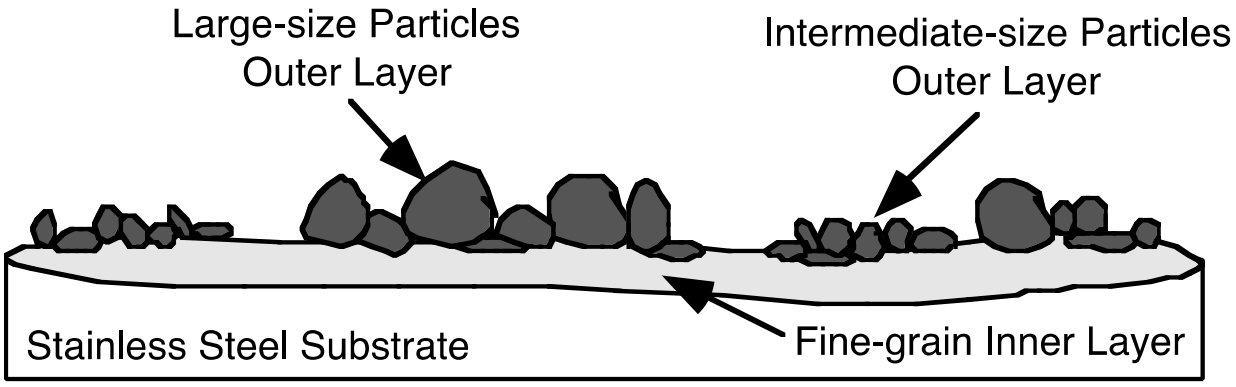


Figure 2-15

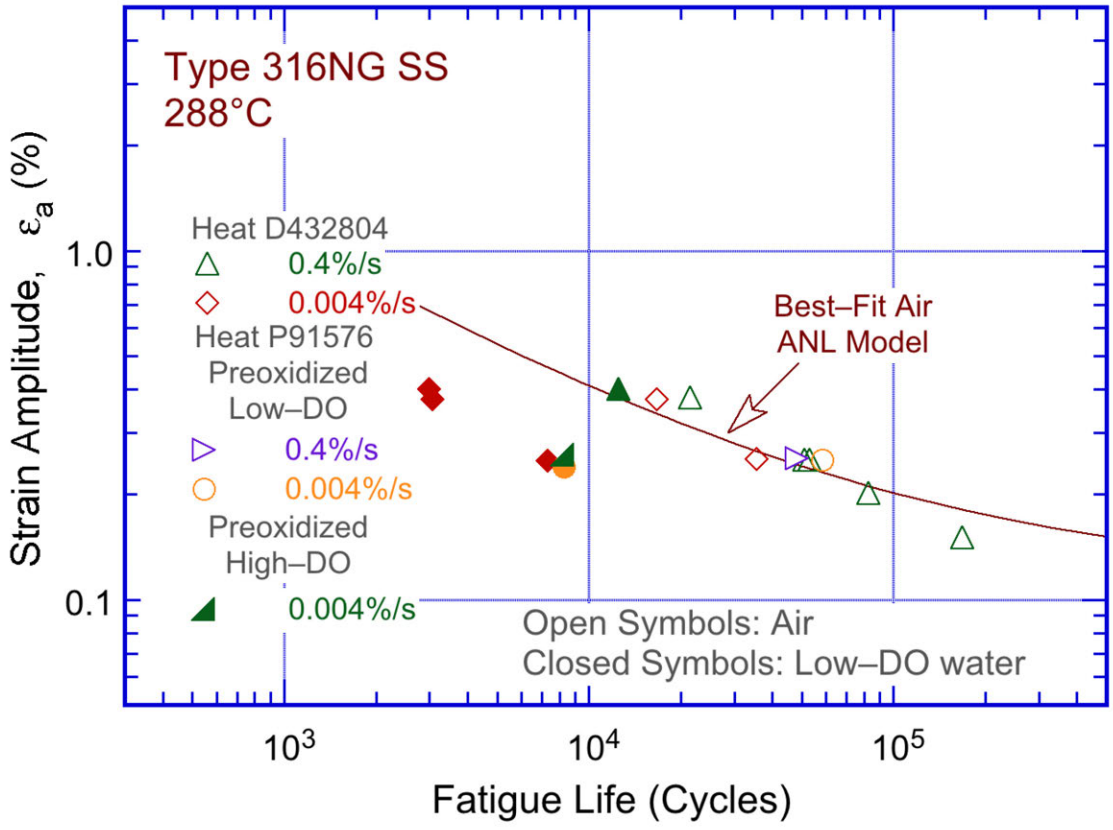


Figure 2-16

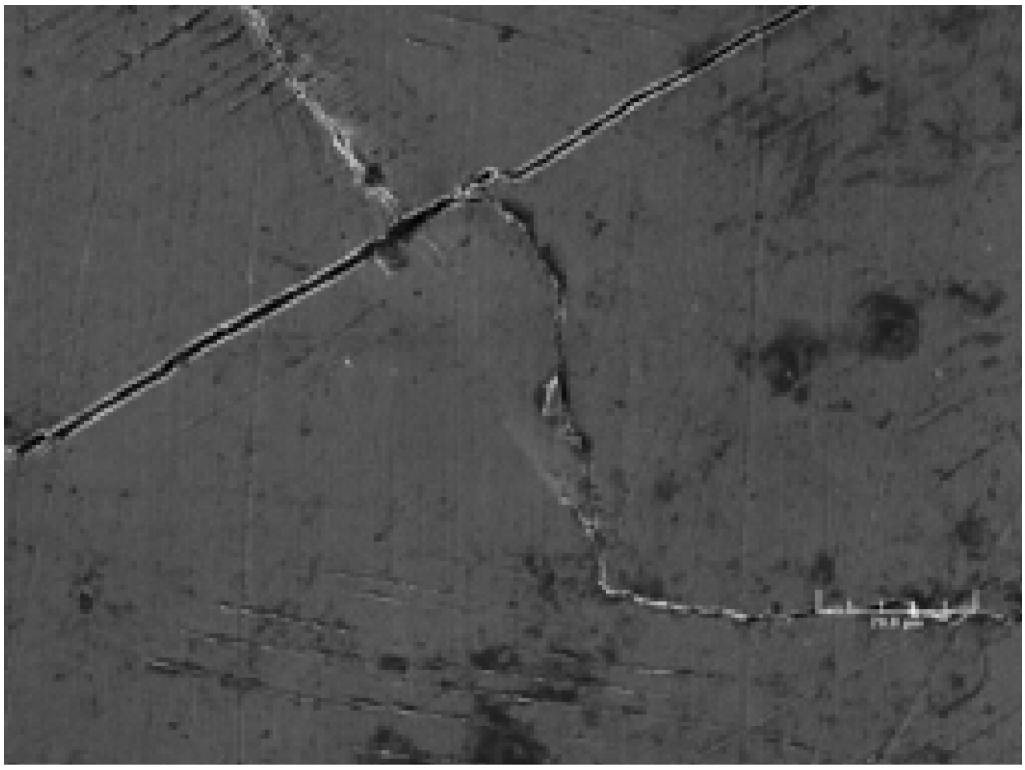


Figure 2-17(a)

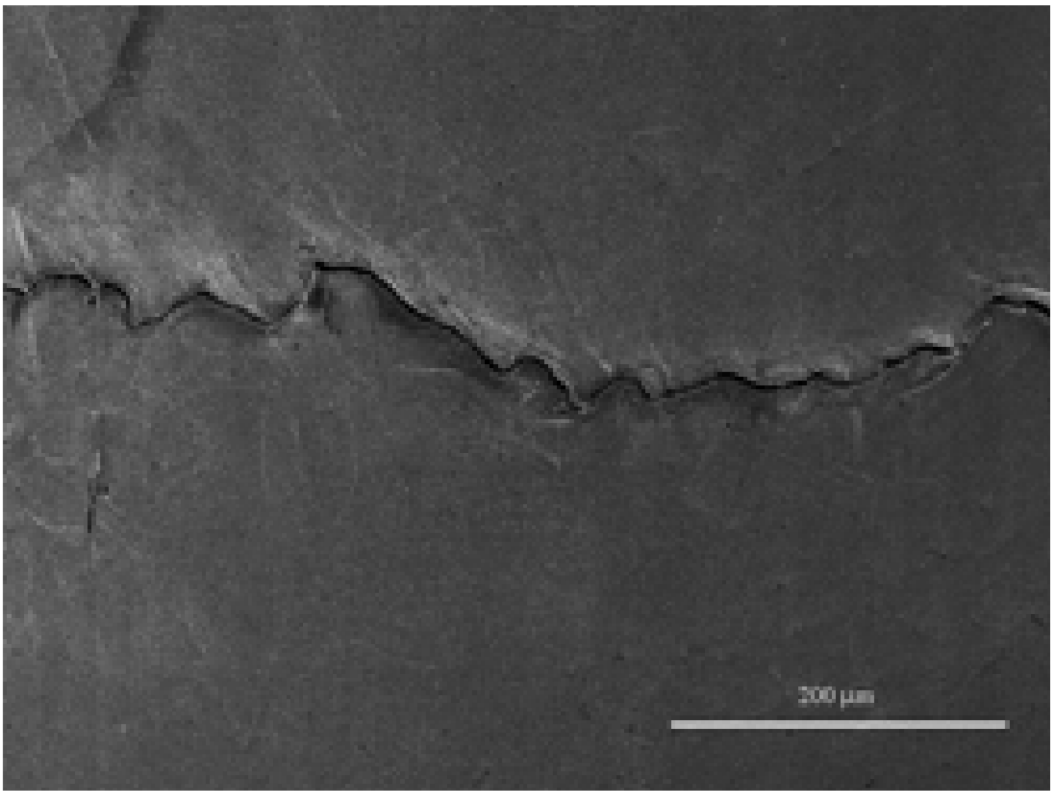


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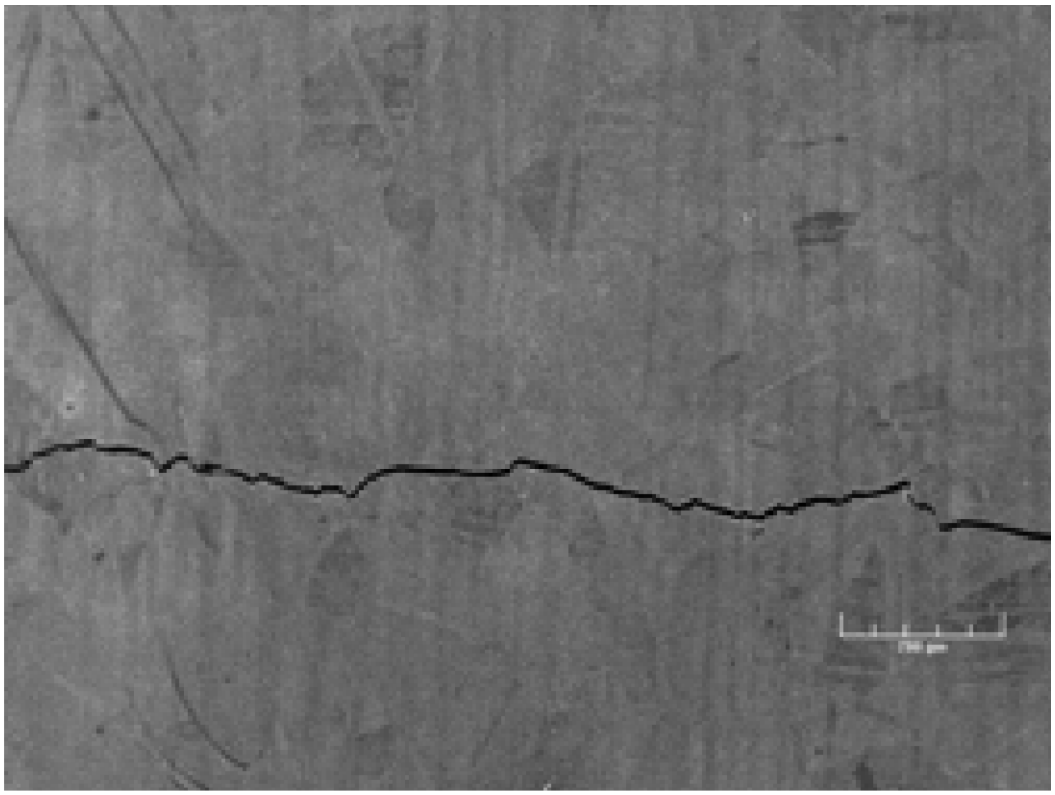


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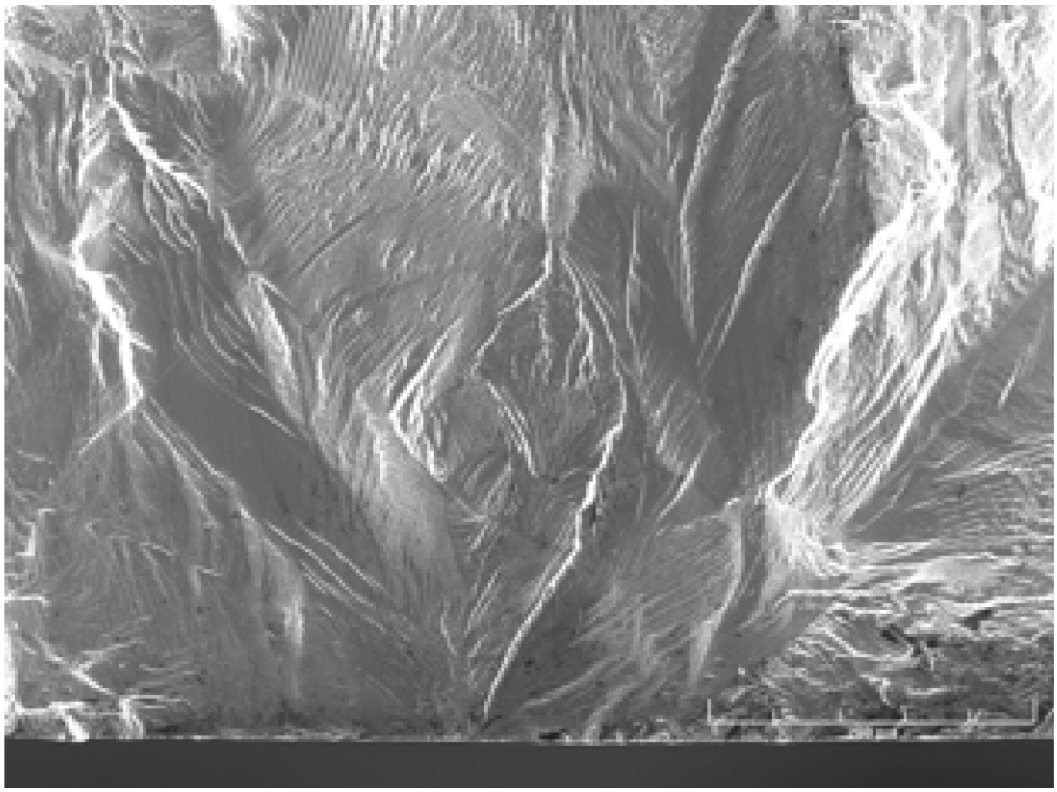


Figure 2-18(a)

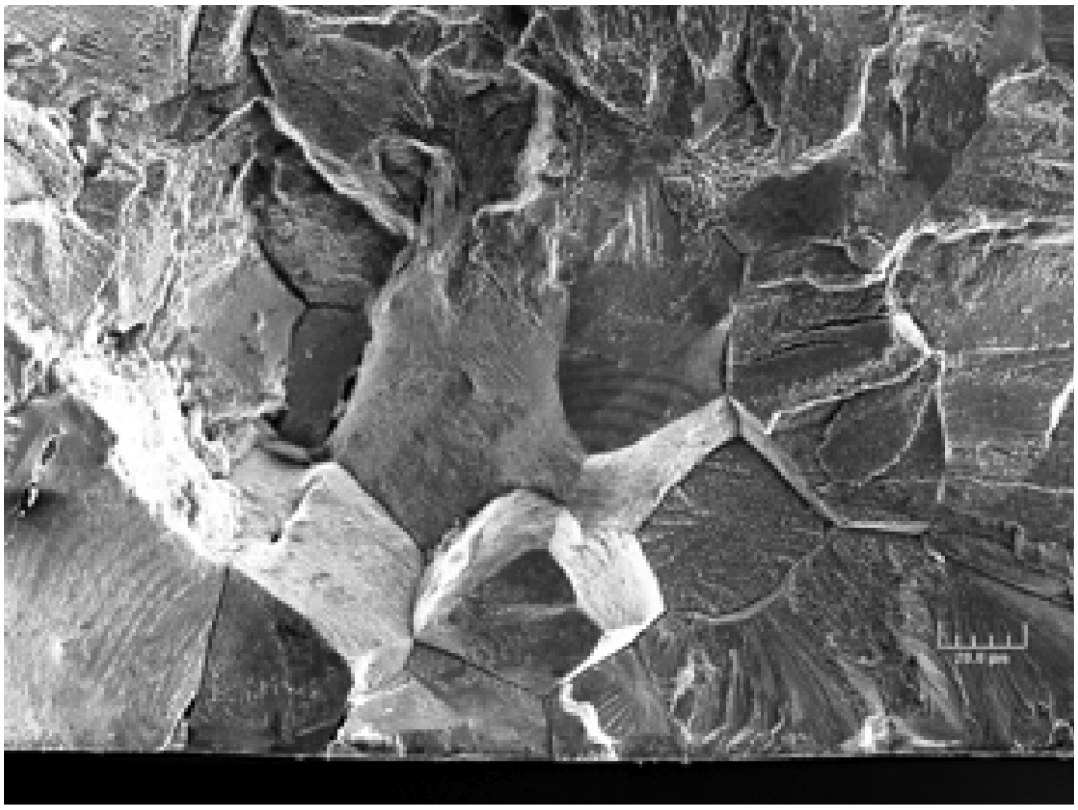


Figure 2-18(b)

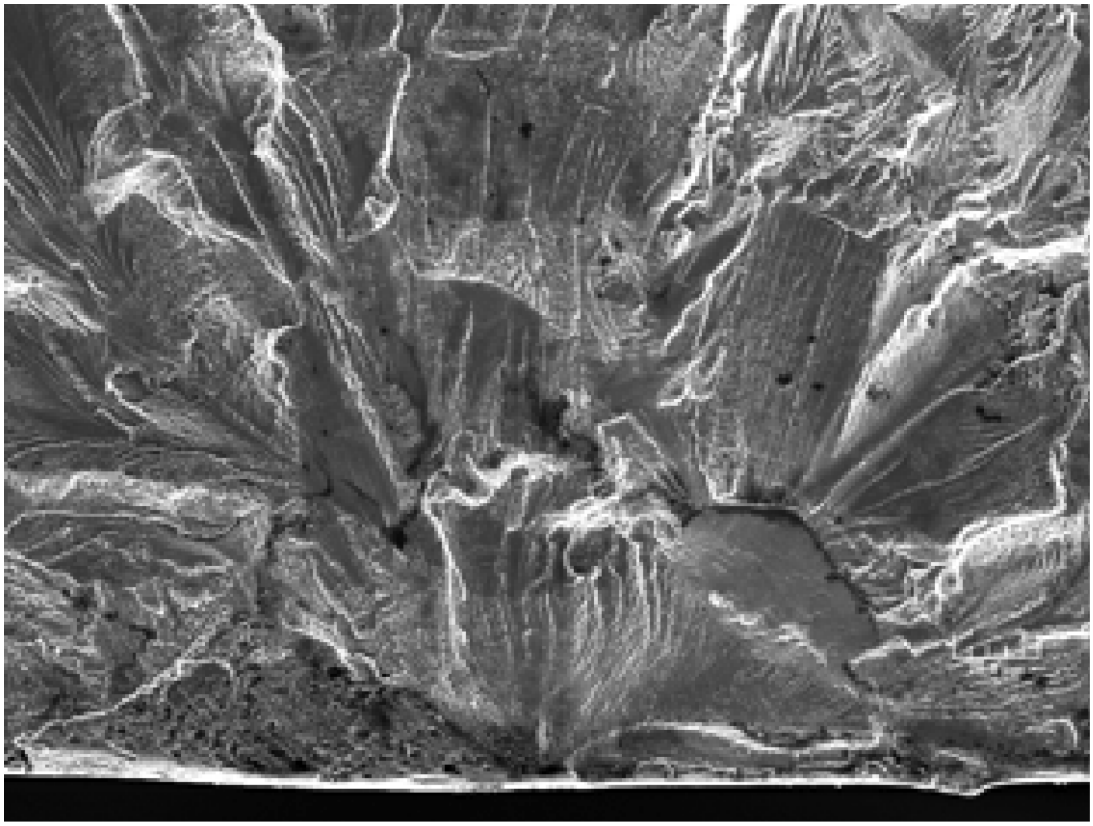


Figure 2-18(c)

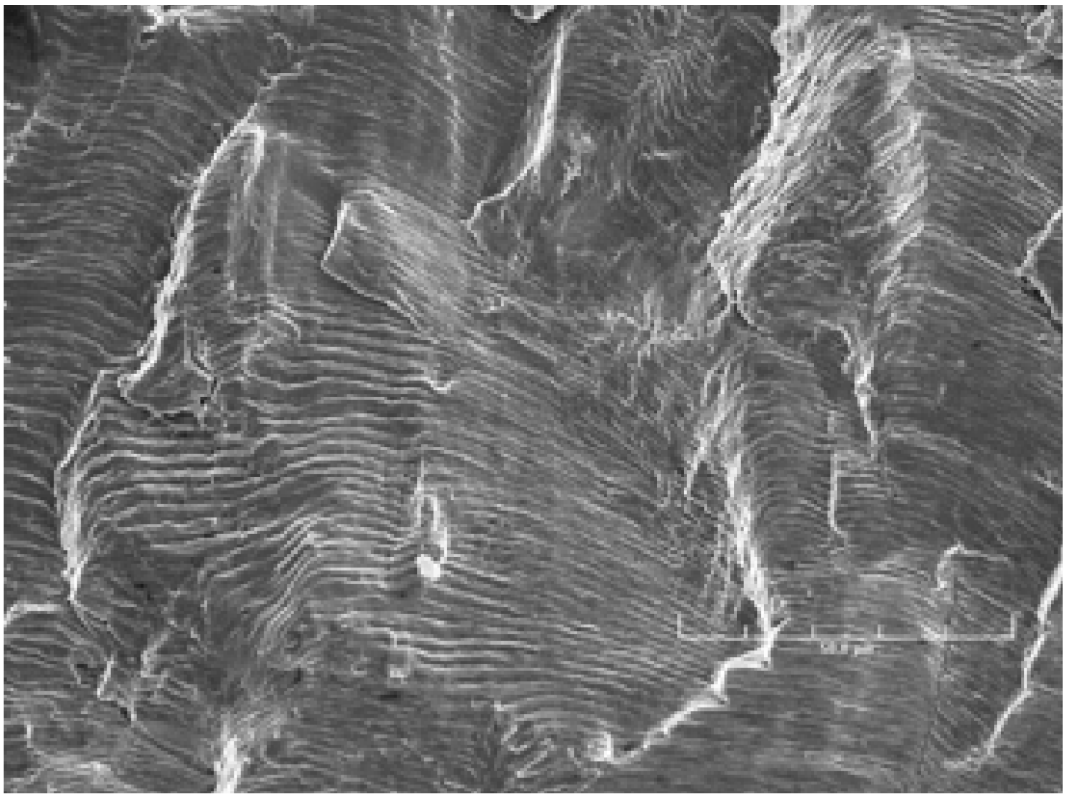


Figure 2-19(a)



Figure 2-19(b)

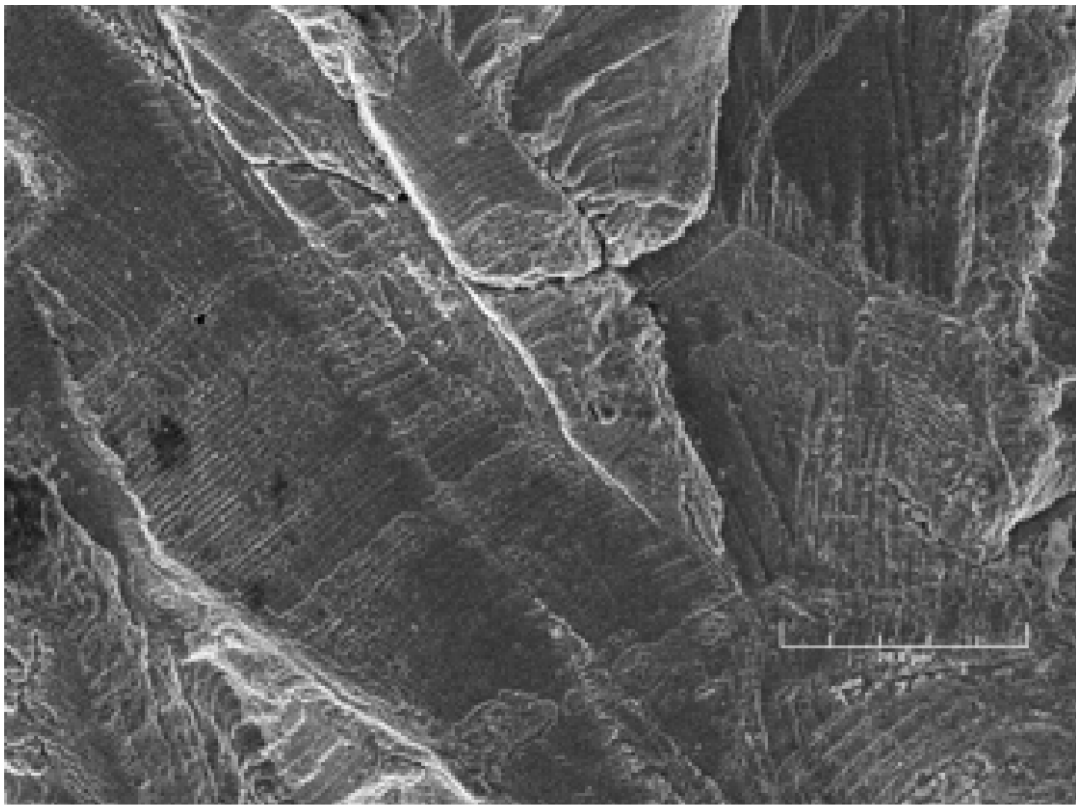


Figure 2-19(c)

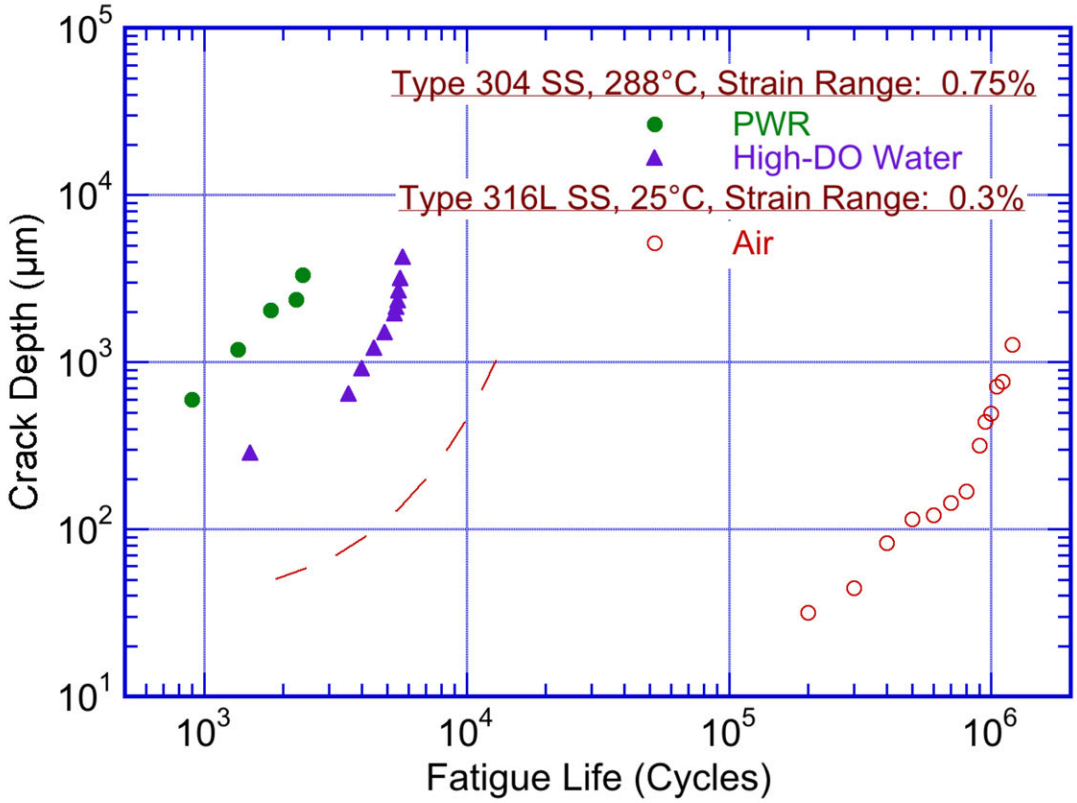


Figure 2-20

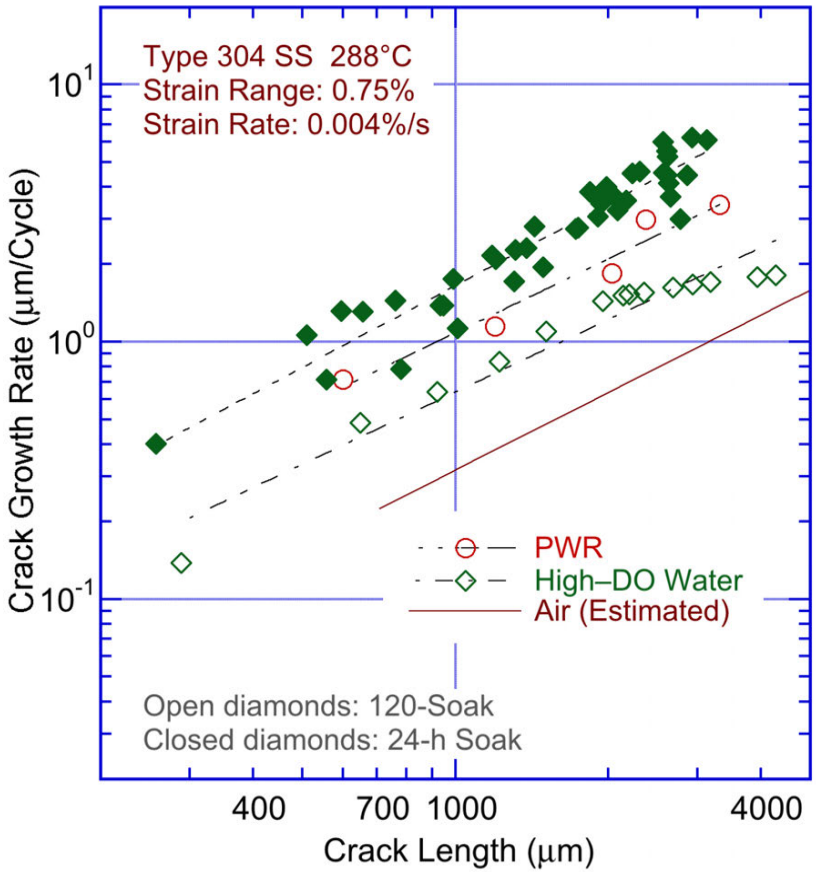


Figure 2-21(a)

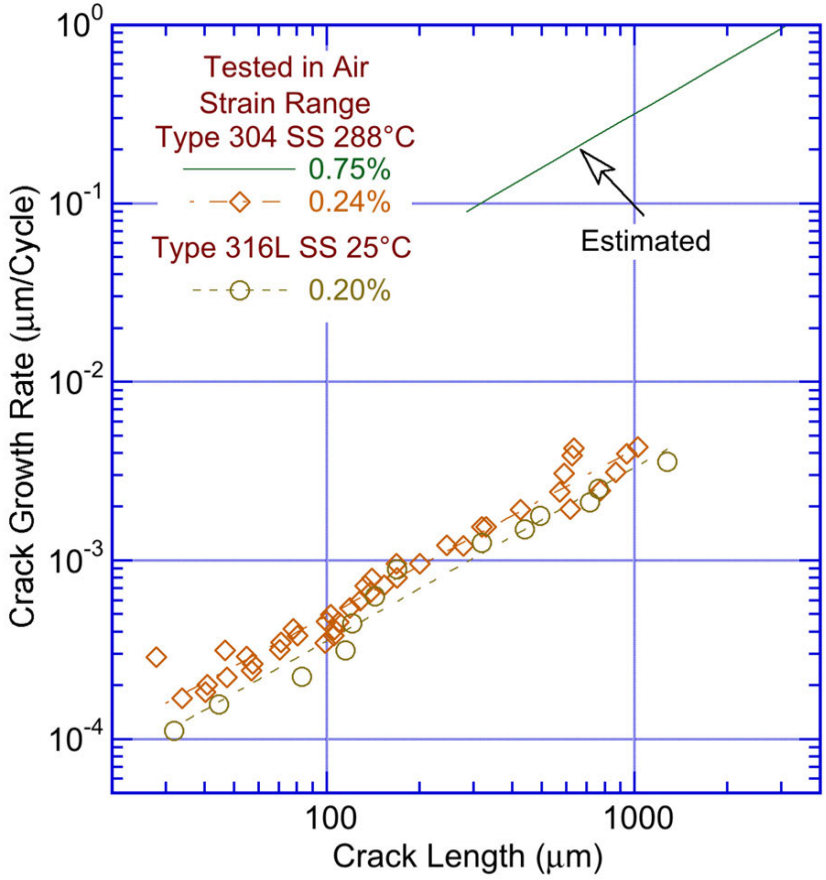


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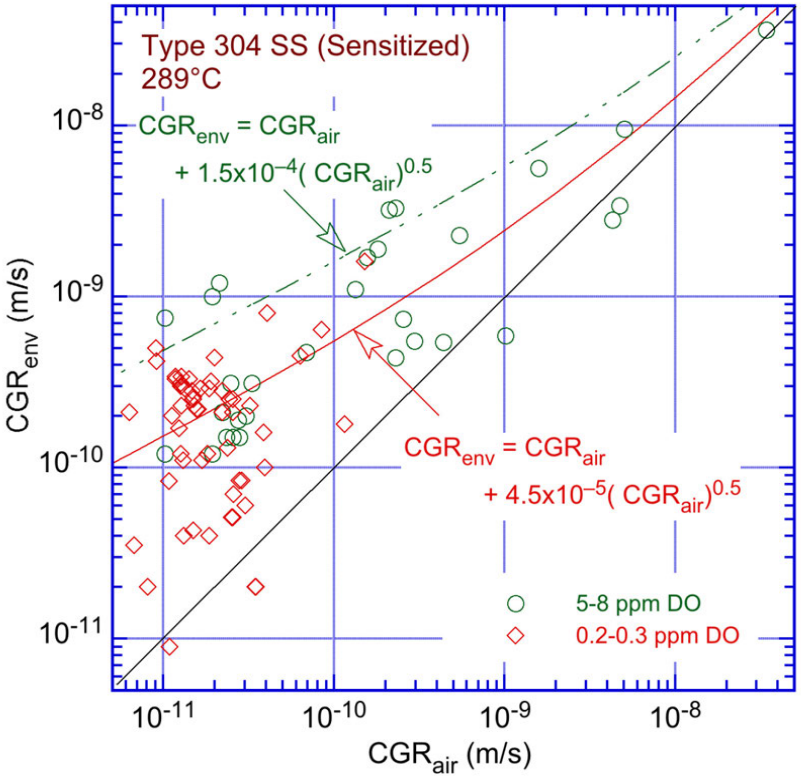


Figure 2-22(a)

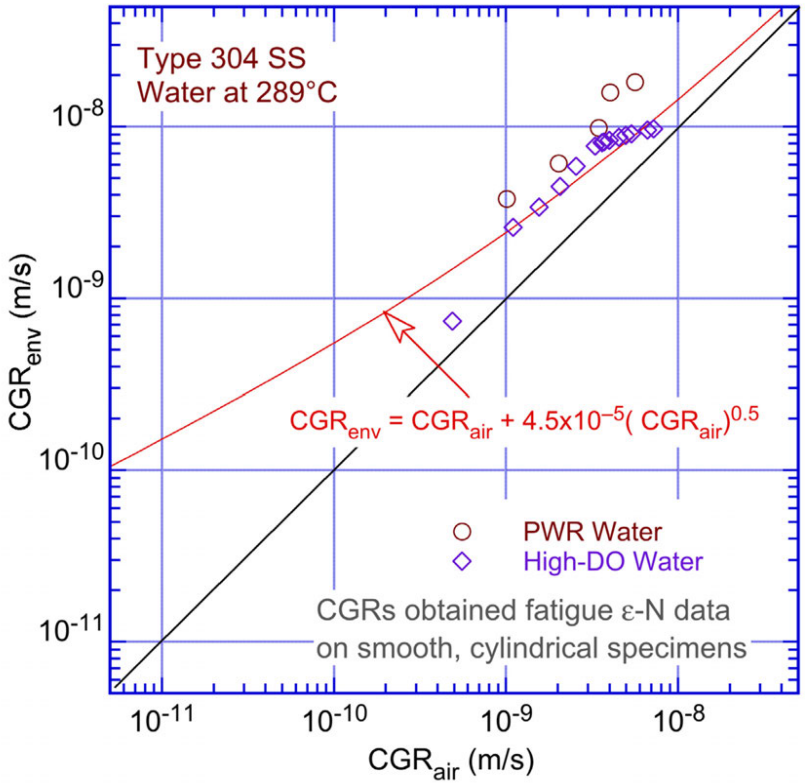


Figure 2-22(b)

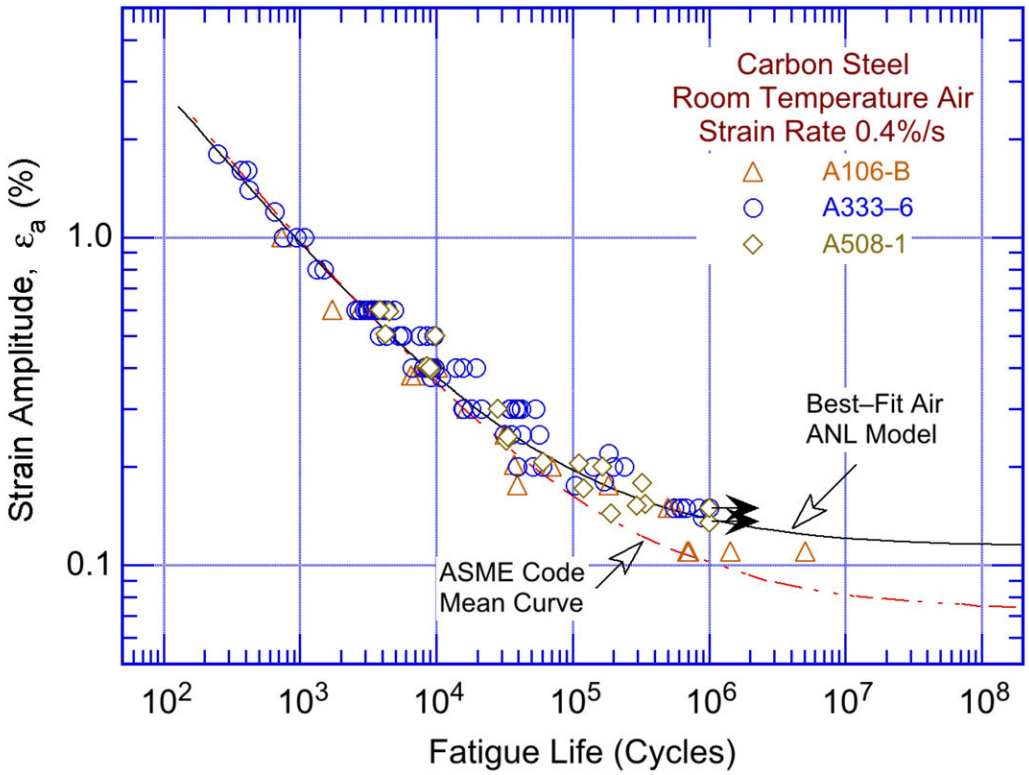


Figure 3-1(a)

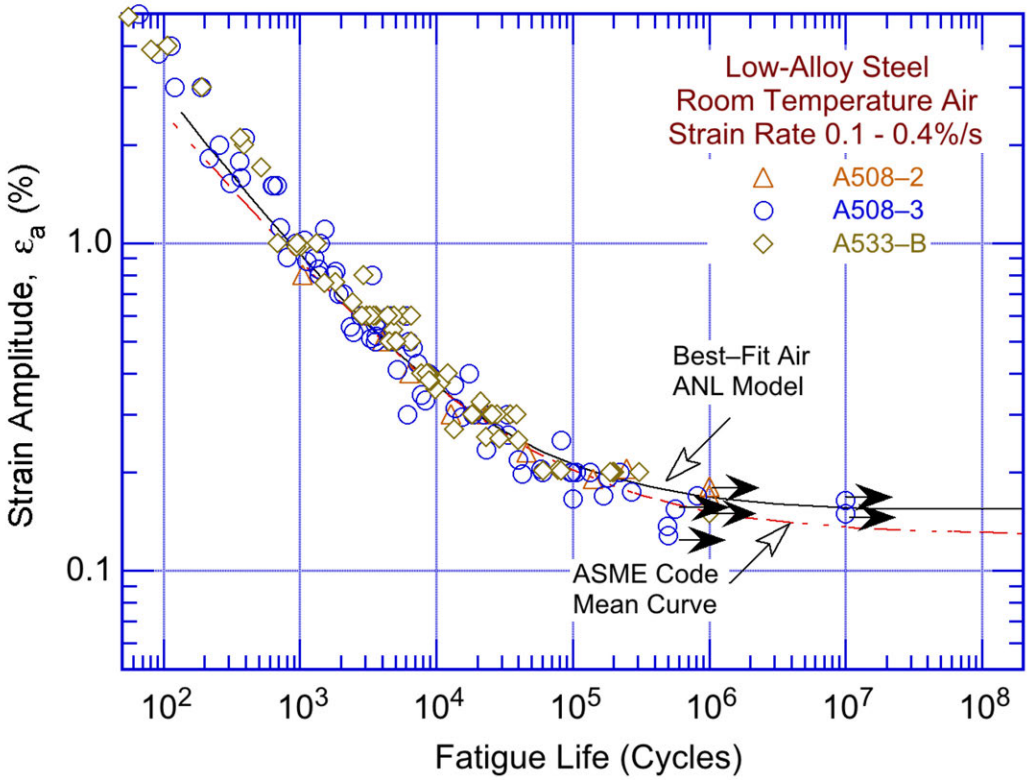


Figure 3-1(b)

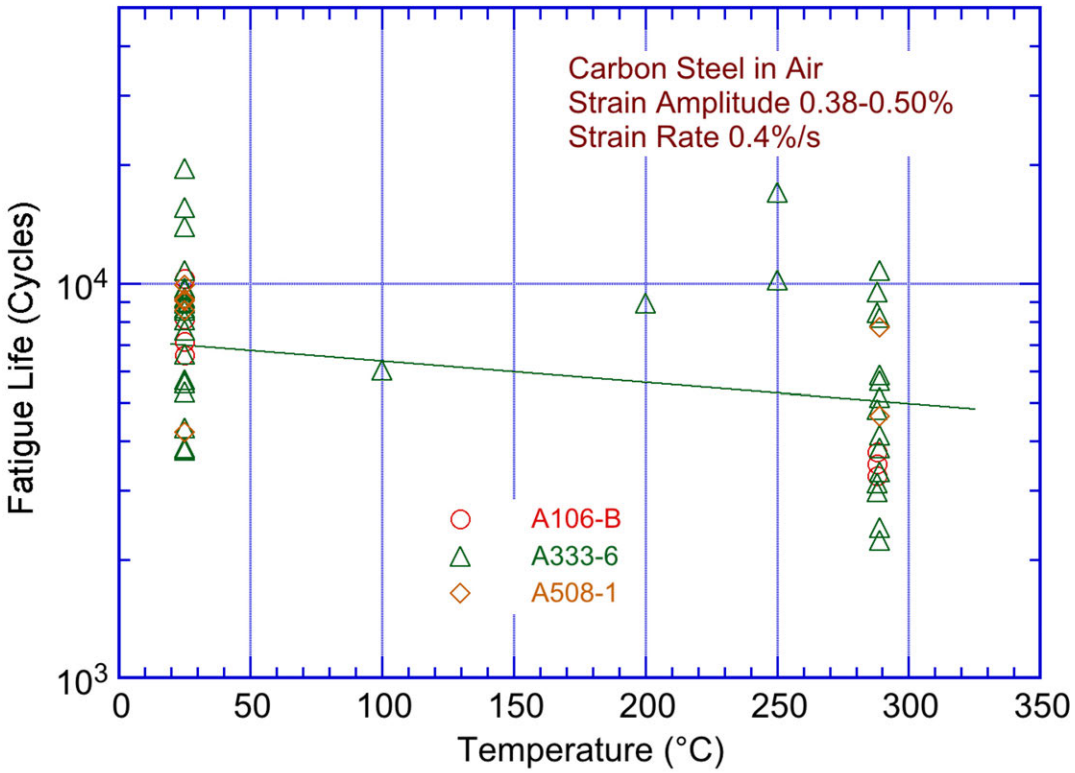


Figure 3-2(a)

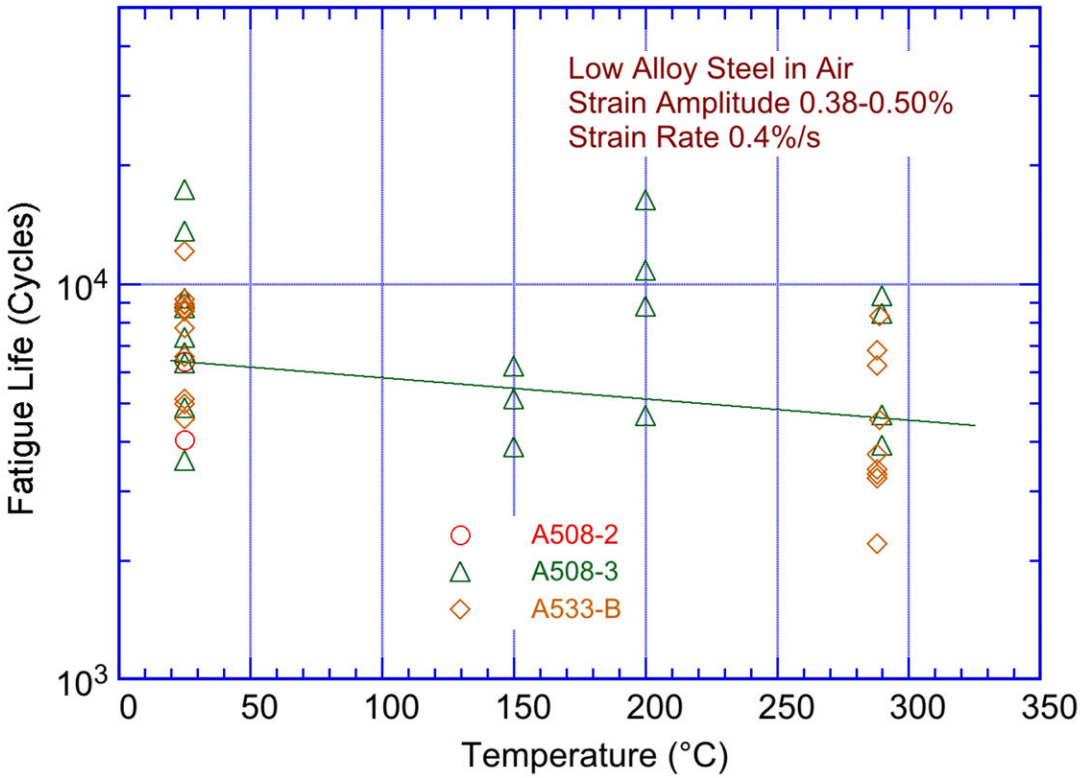


Figure 3-2(b)

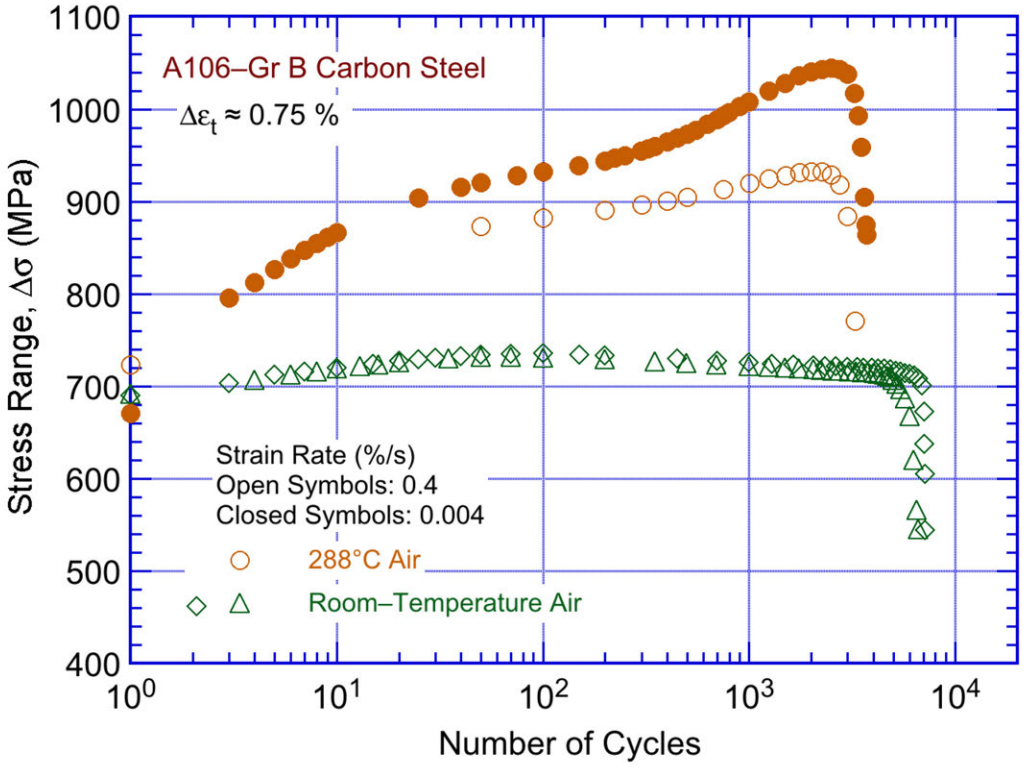


Figure 3-3(a)

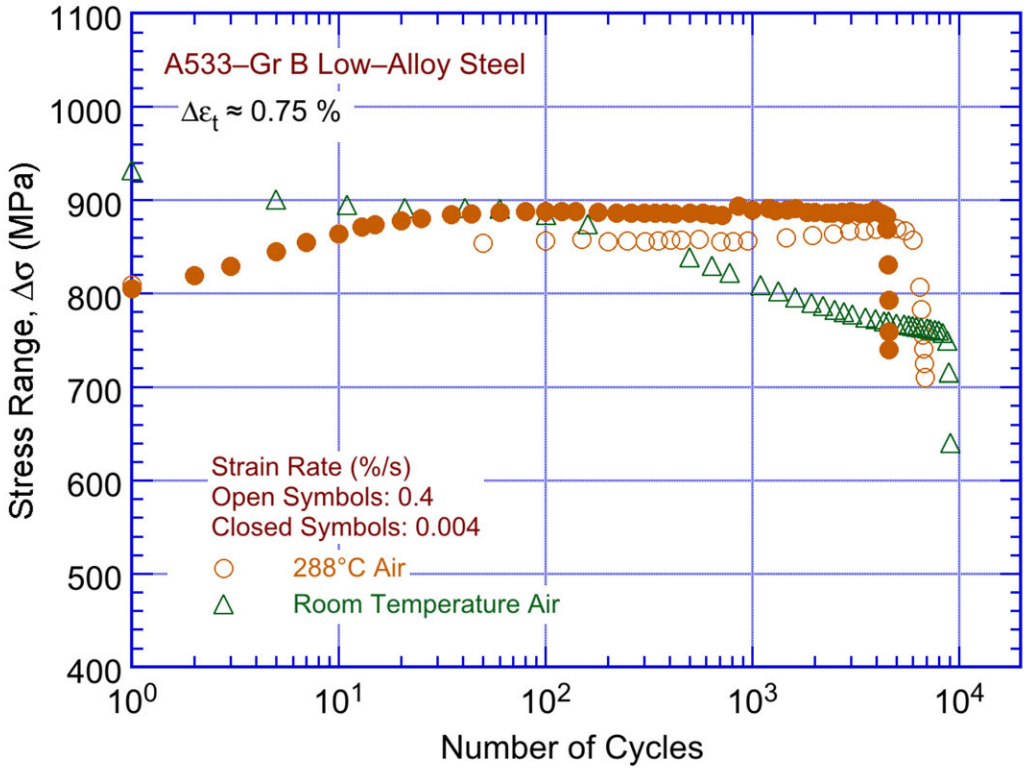


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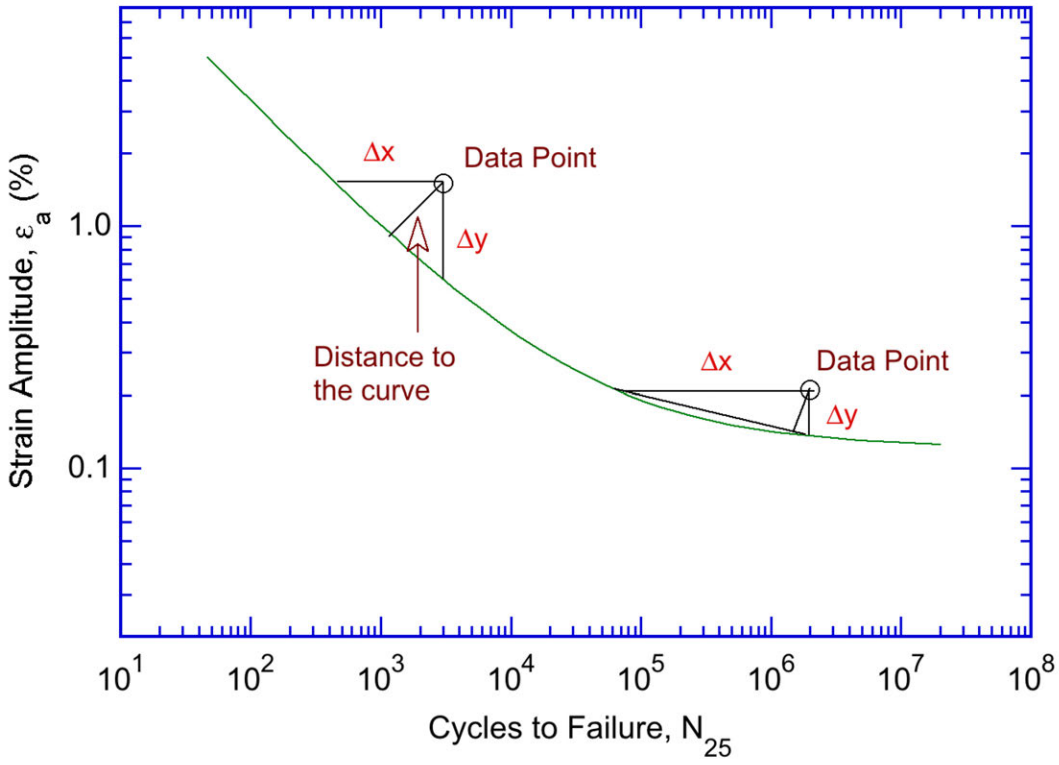

Strain Amplitude, ε_a (%)
1.0
0.1
Δx
Data Point
Δy
Distance to
the curve
Δx
Data Point
Δy
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Cycles to Failure, N_{25}

Figure 3-4

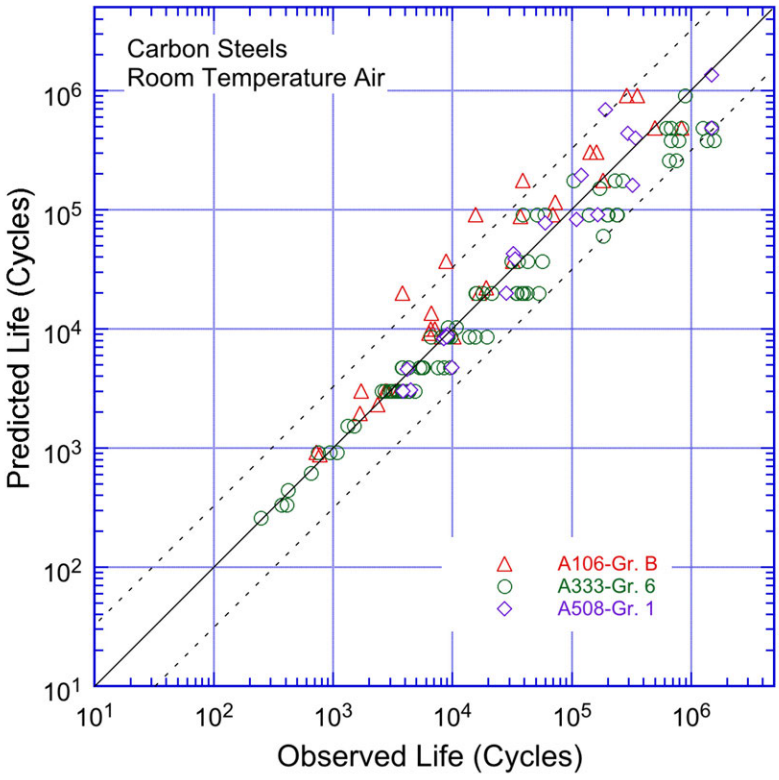


Figure 3-5(a)

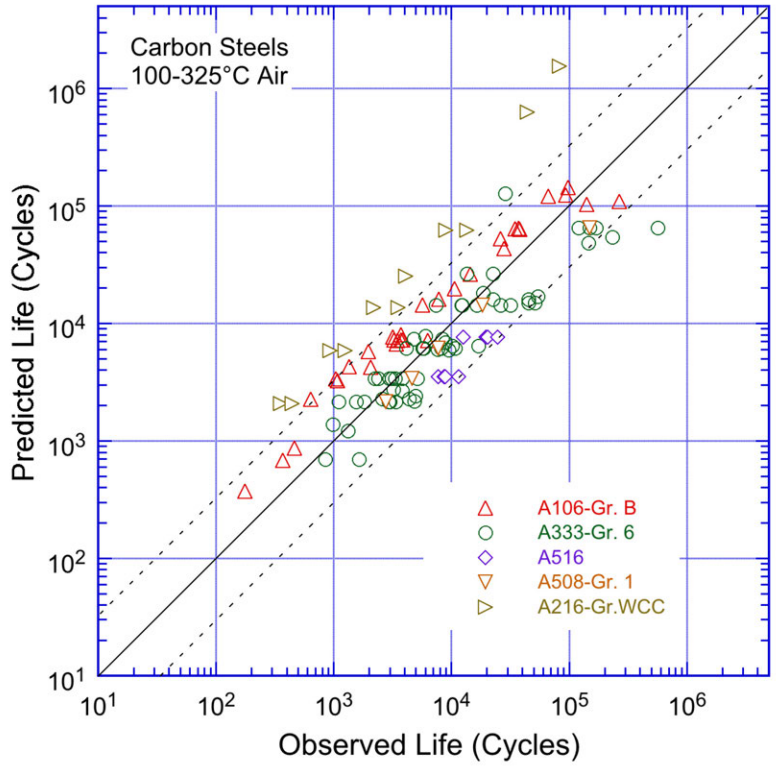


Figure 3-5(b)

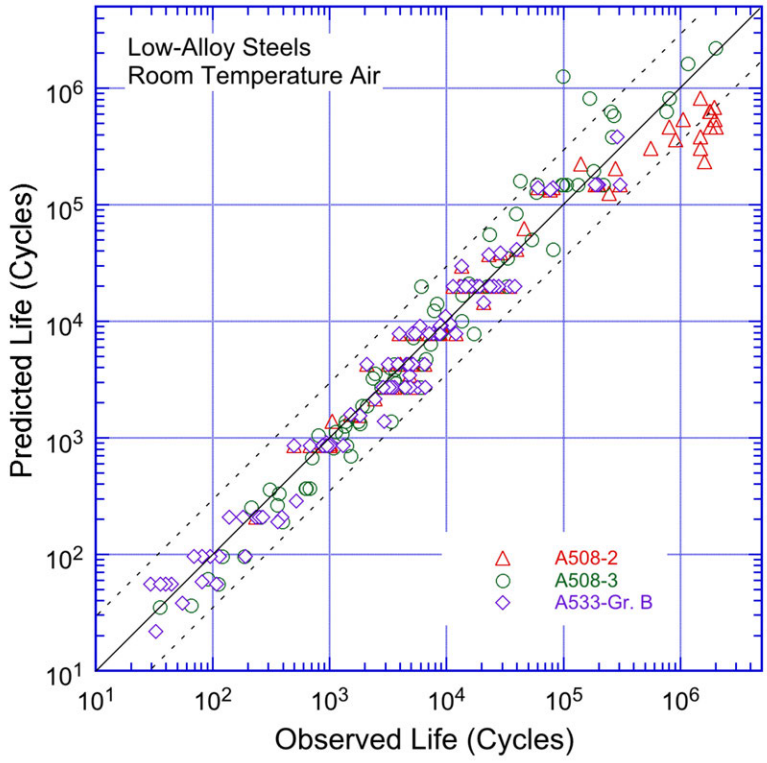


Figure 3-5(c)

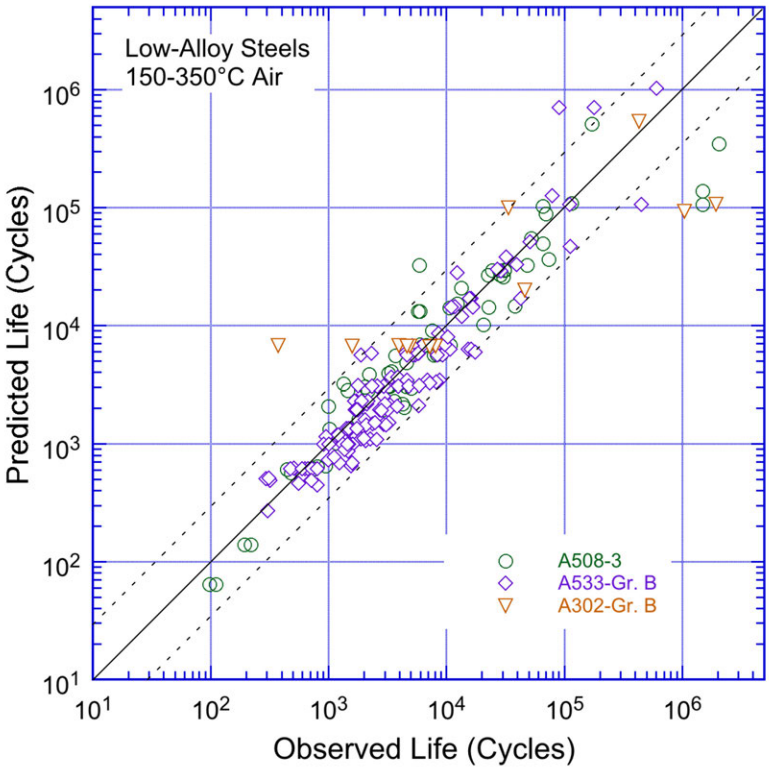


Figure 3-5(d)

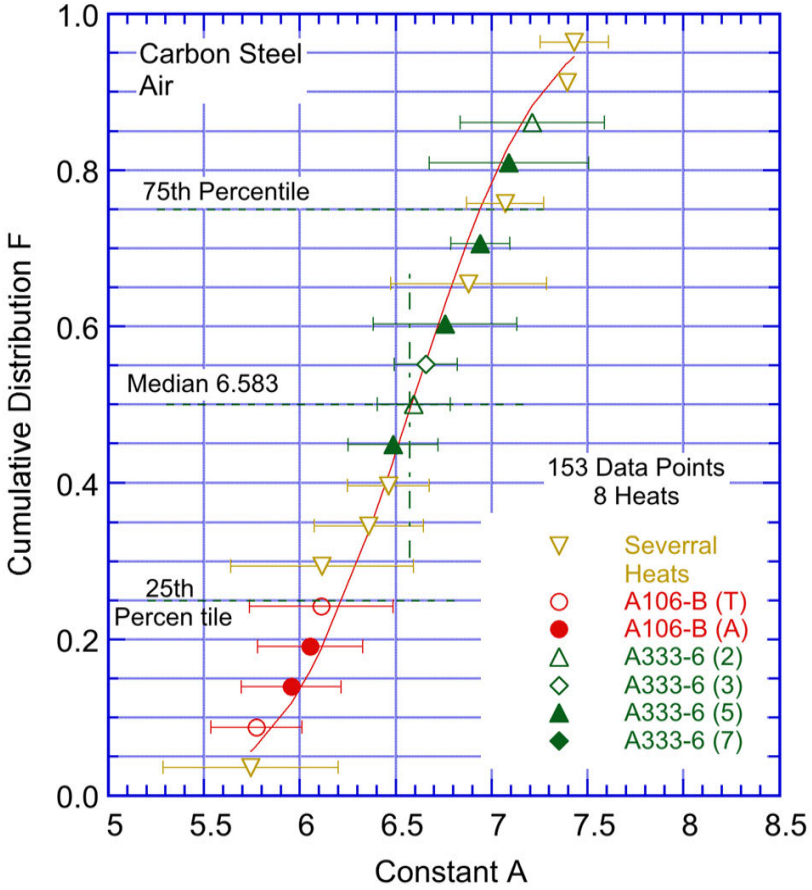


Figure 3-6(a)

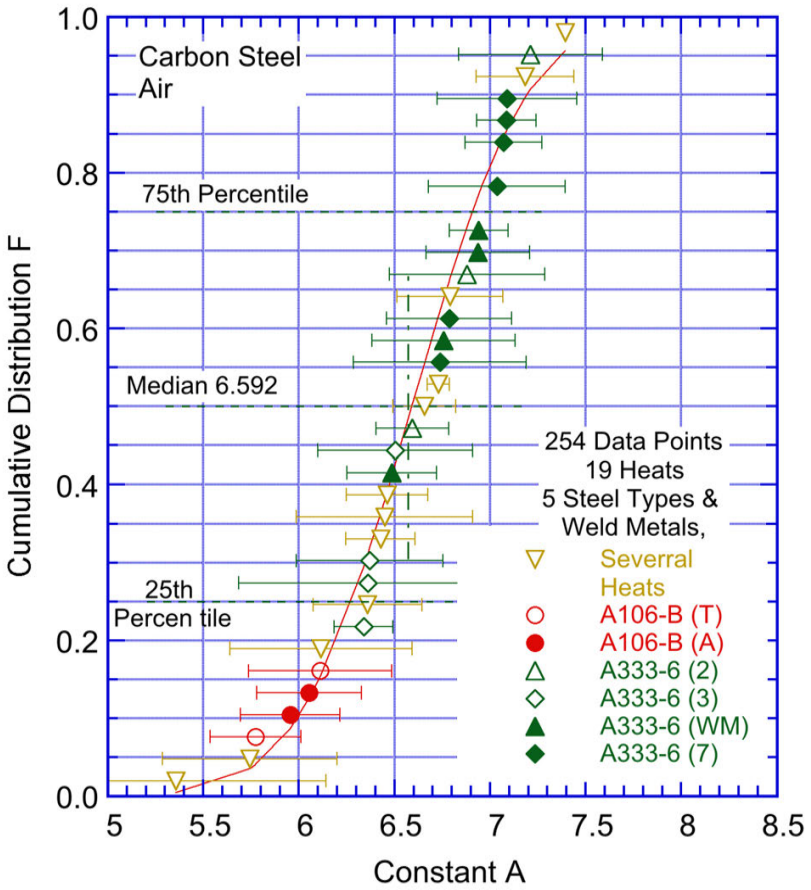


Figure 3-6(b)

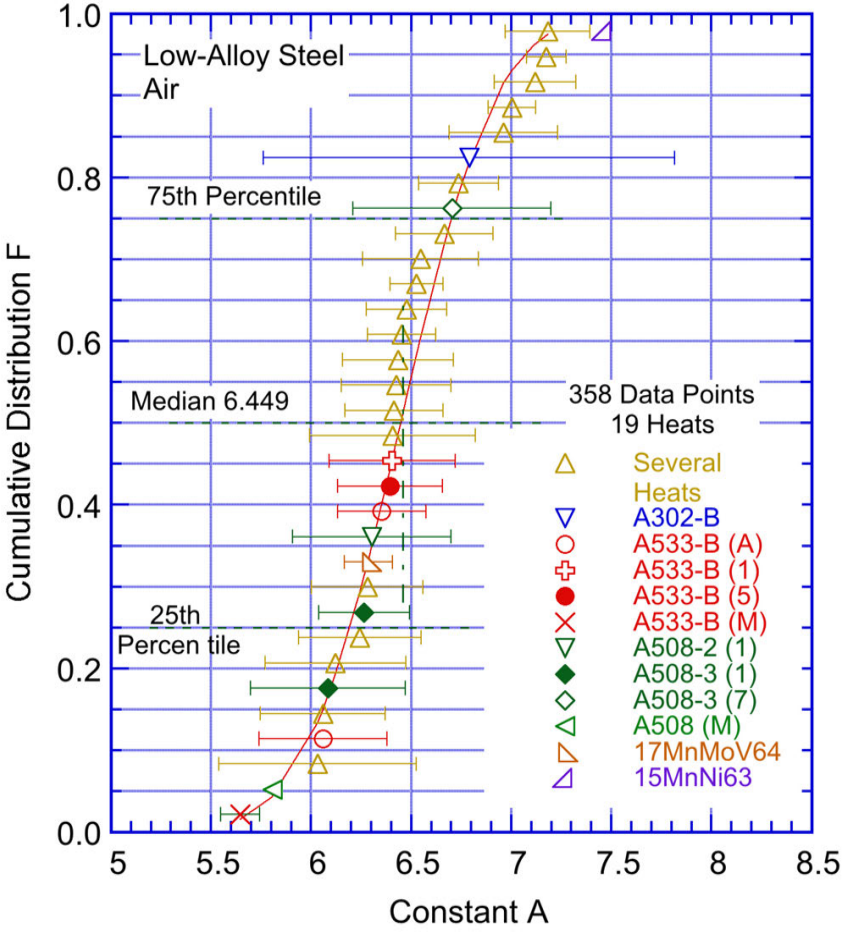


Figure 3-6(c)

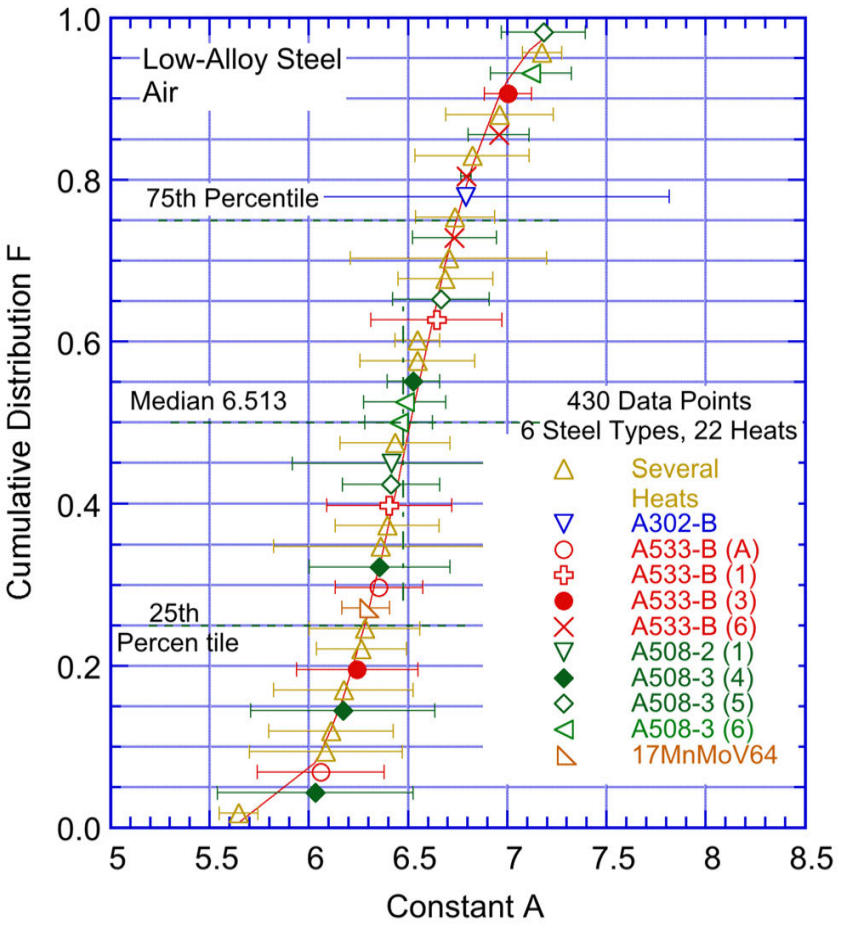


Figure 3-6(d)

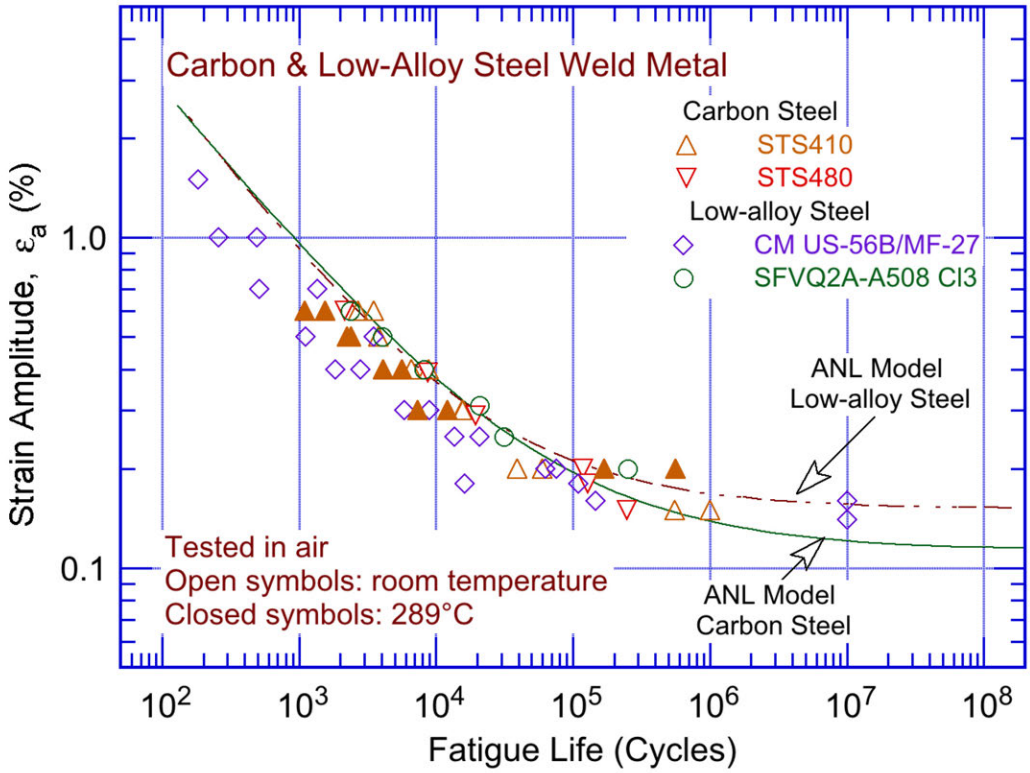


Figure 3-7

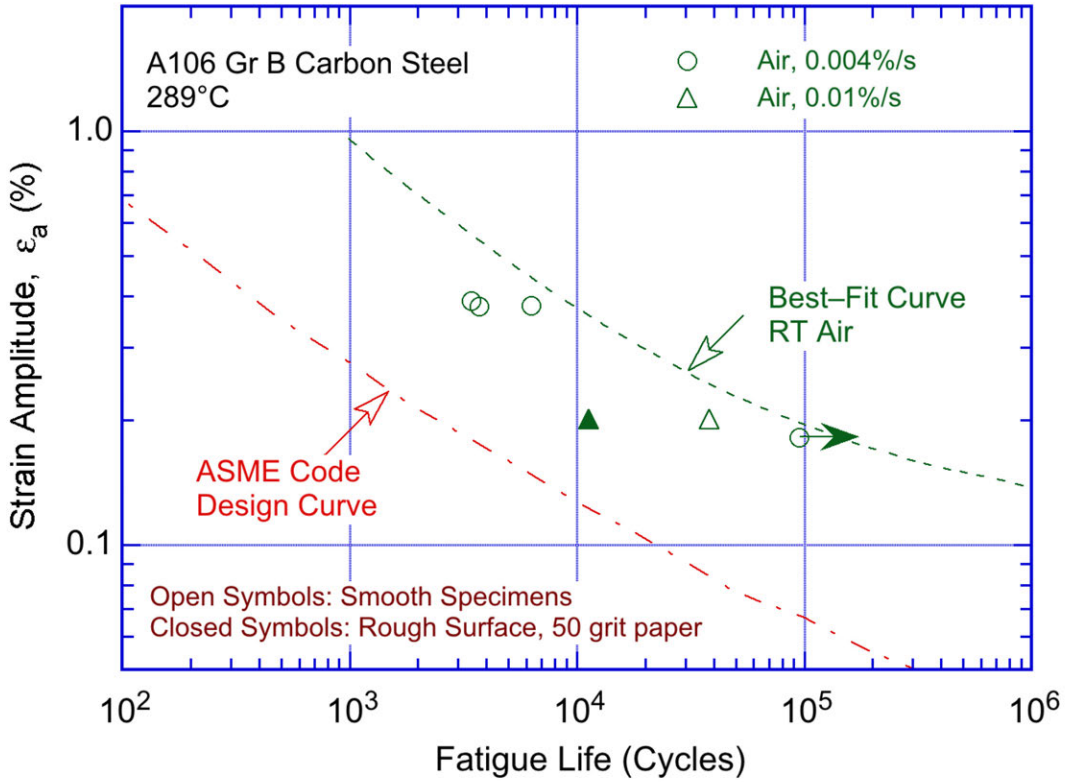


Figure 3-8

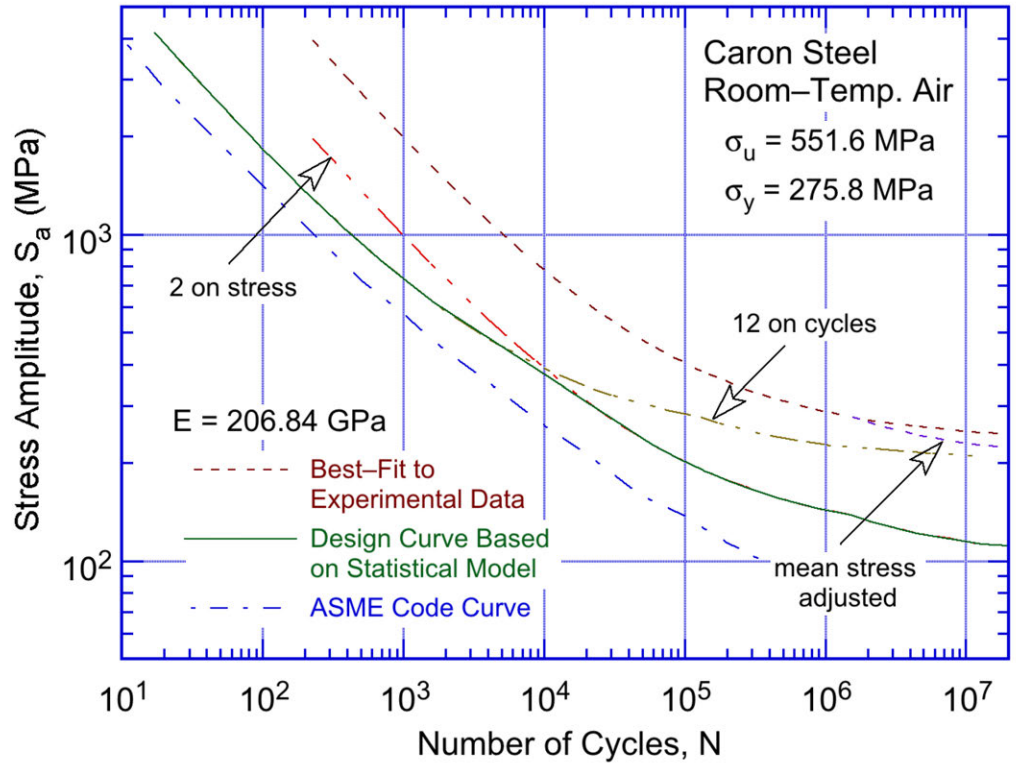


Figure 3-9(a)

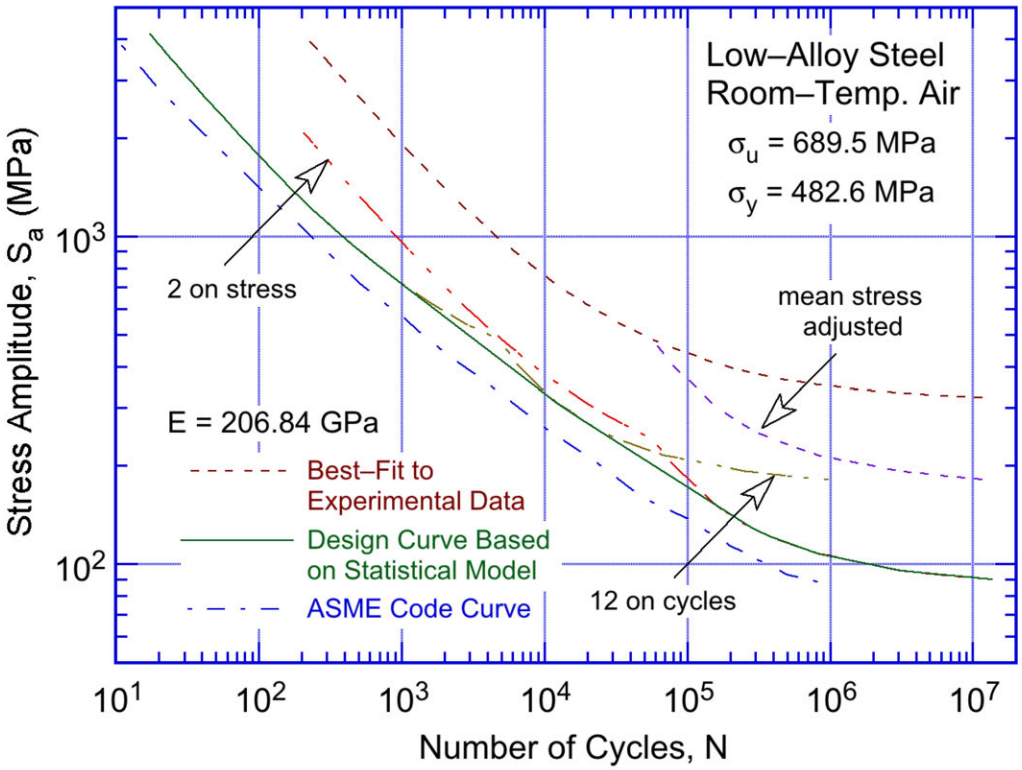


Figure 3-9(b)

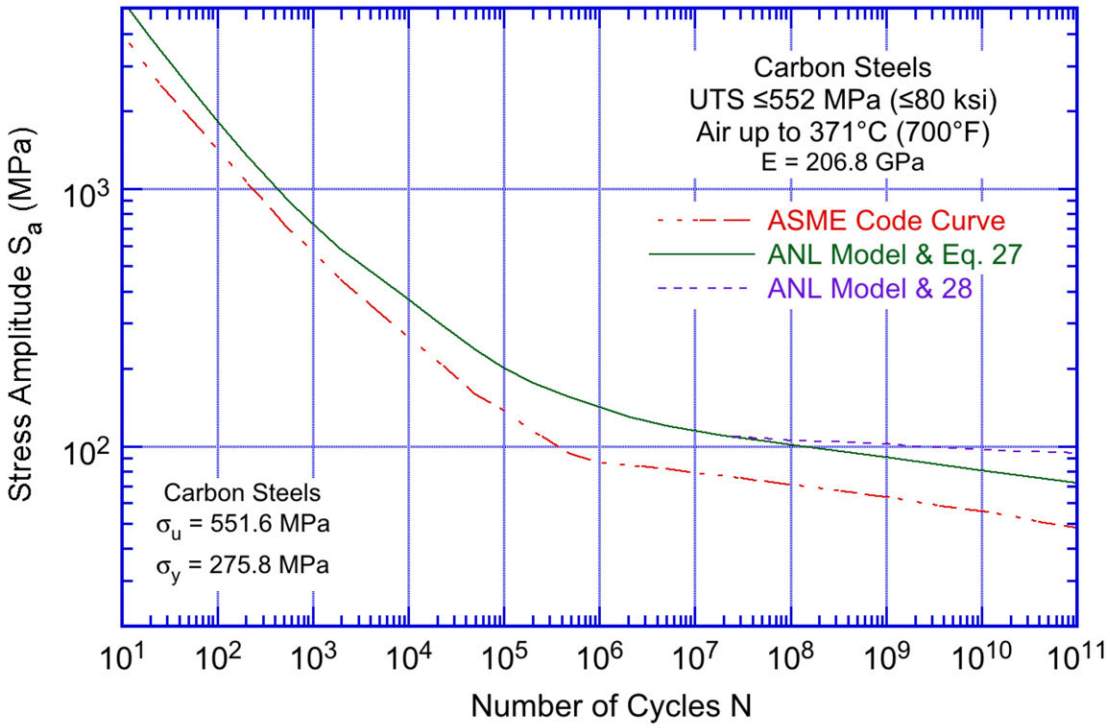


Figure 3-10

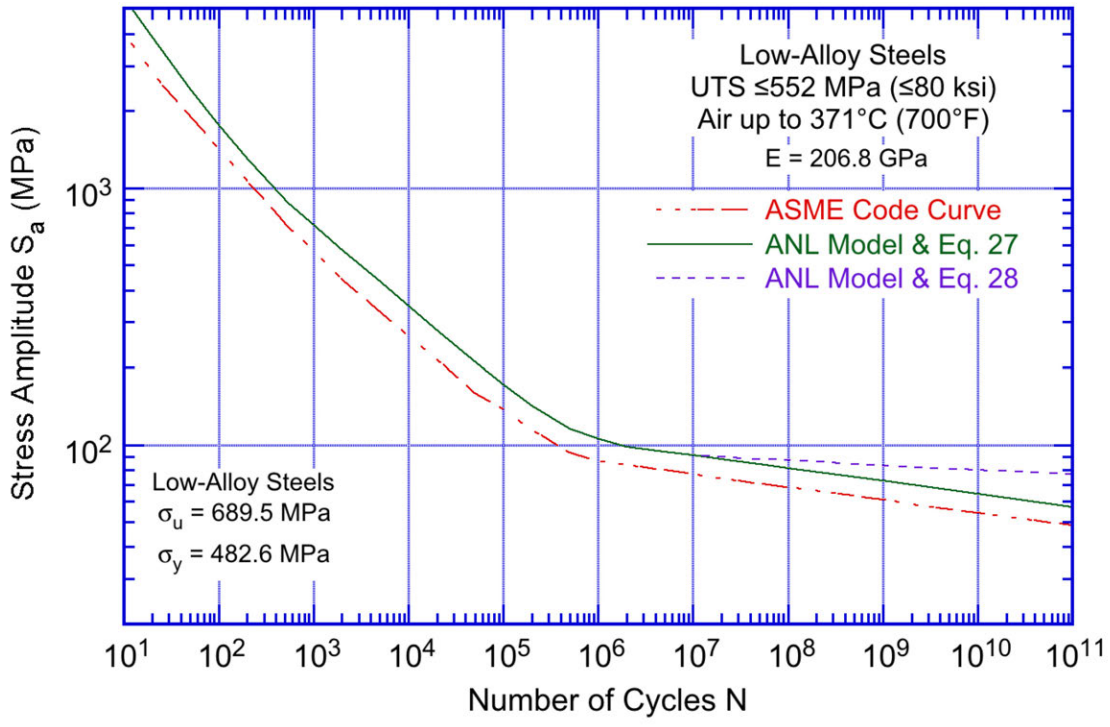


Figure 3-11

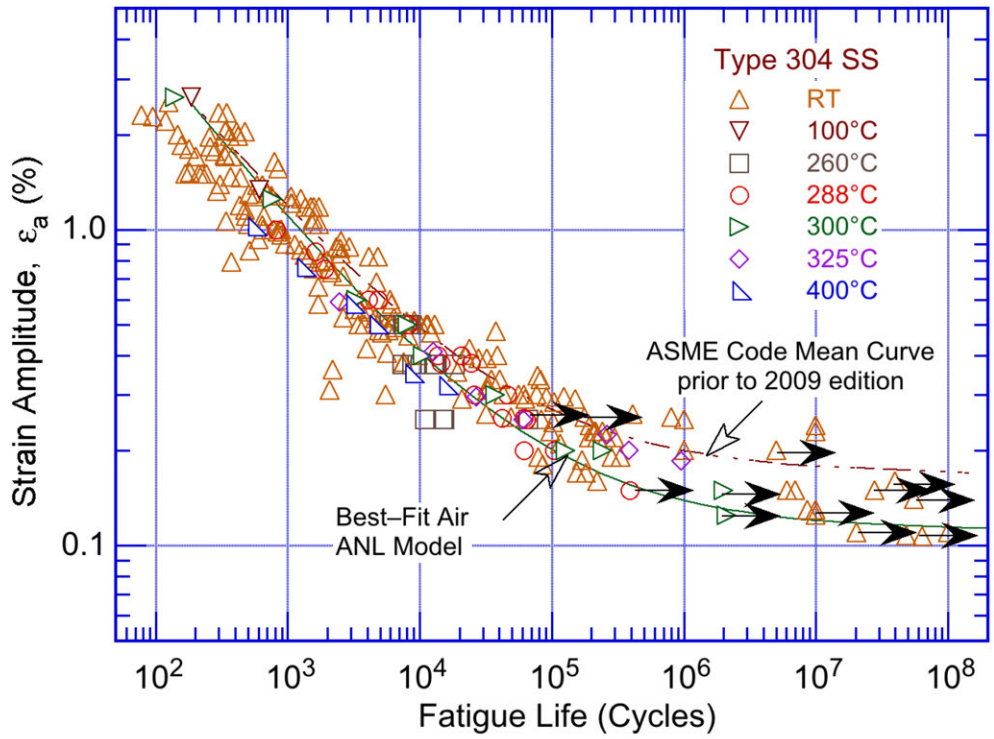


Figure 3-12(a)

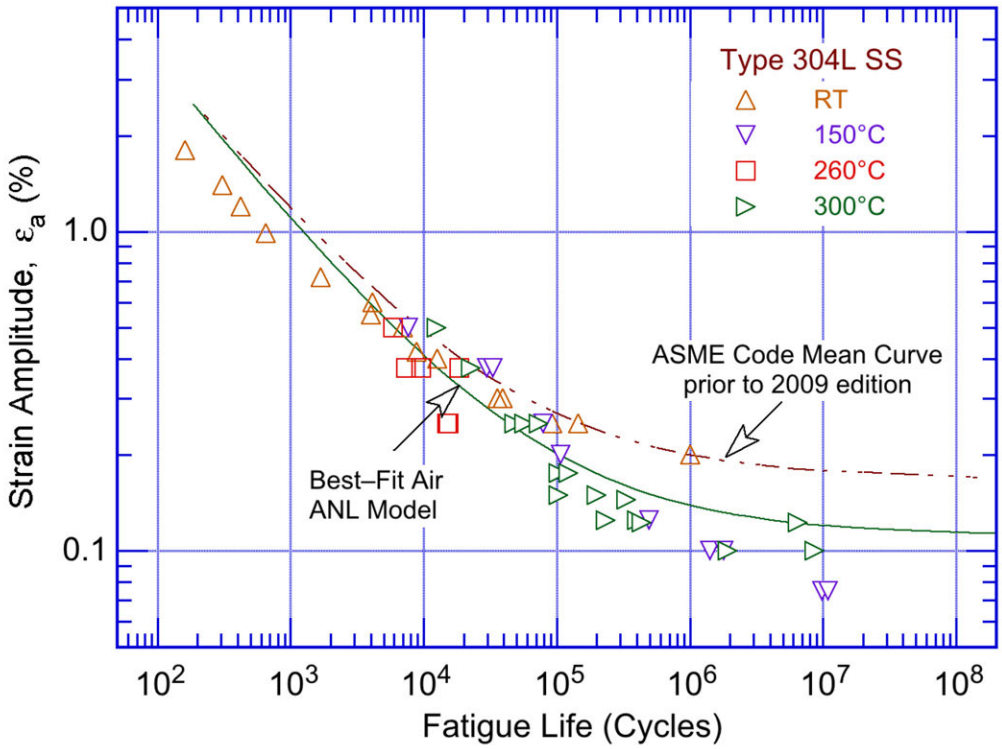


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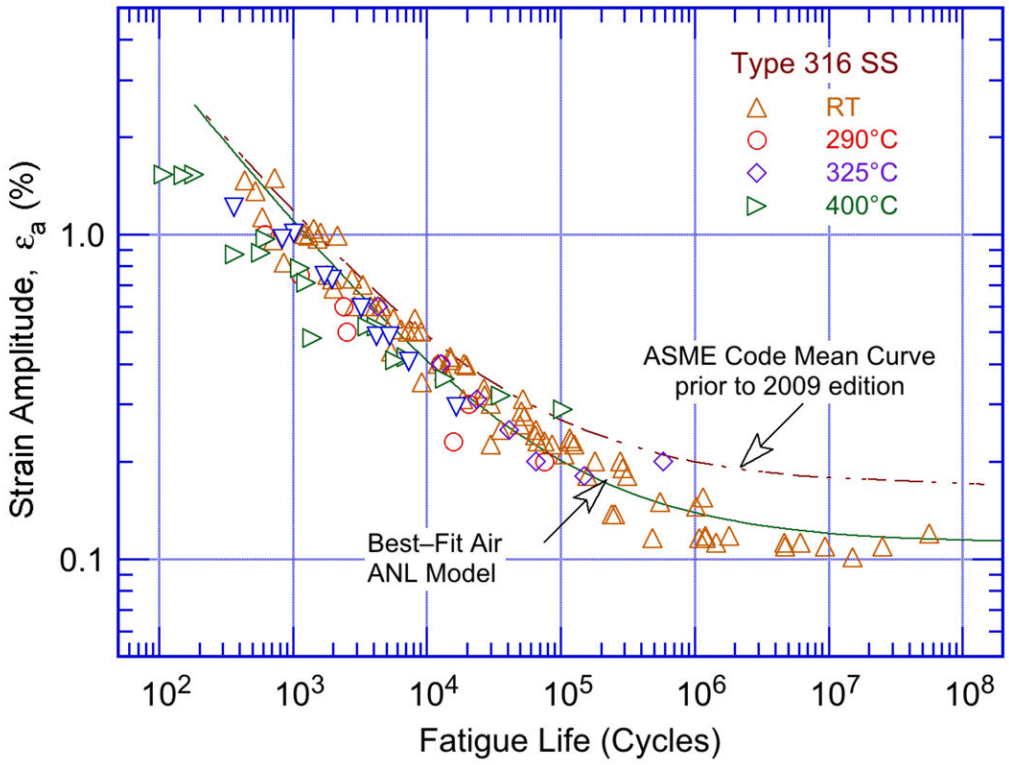


Figure 3-12(c)

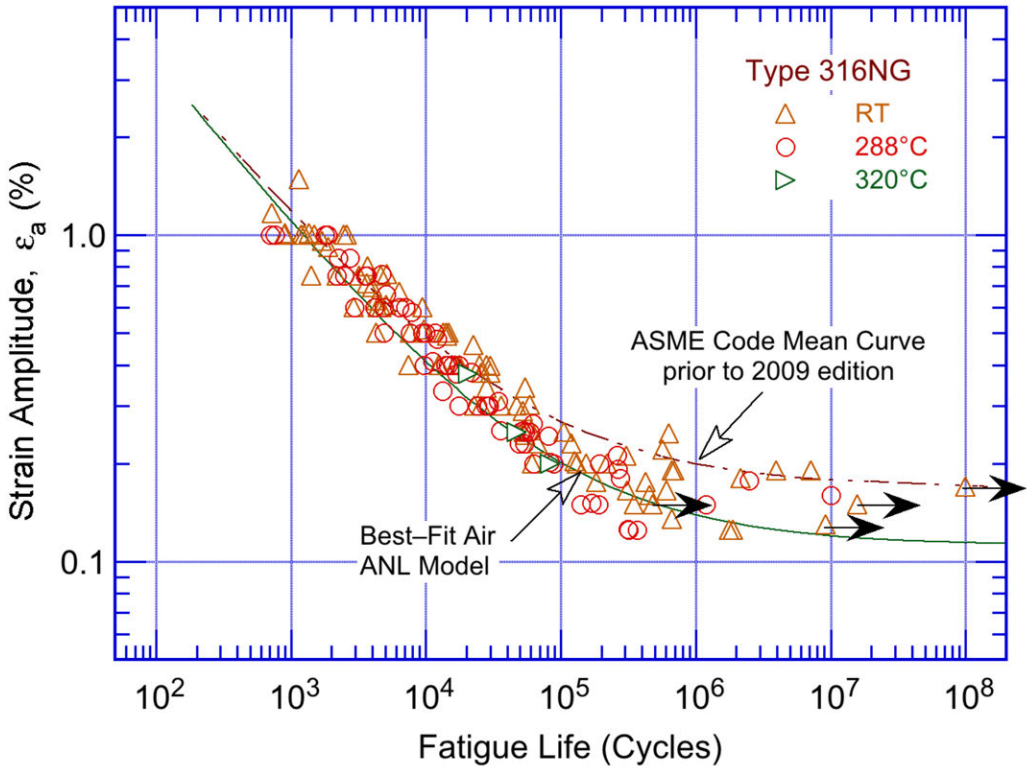


Figure 3-12(d)

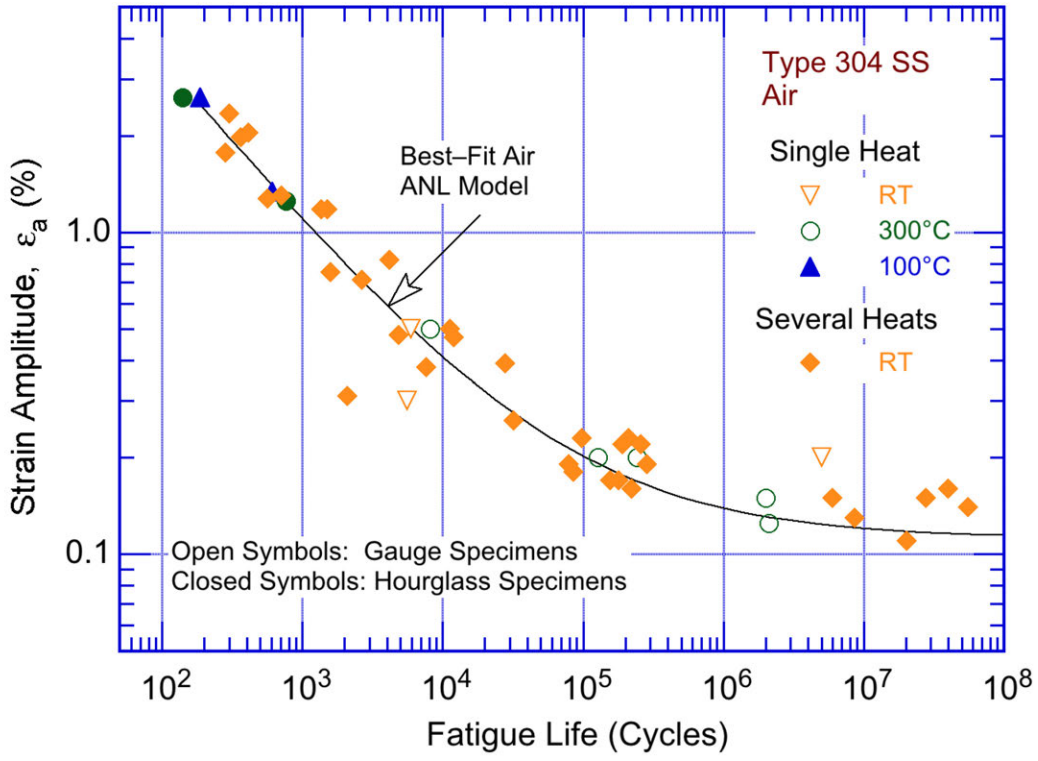


Figure 3-13(a)

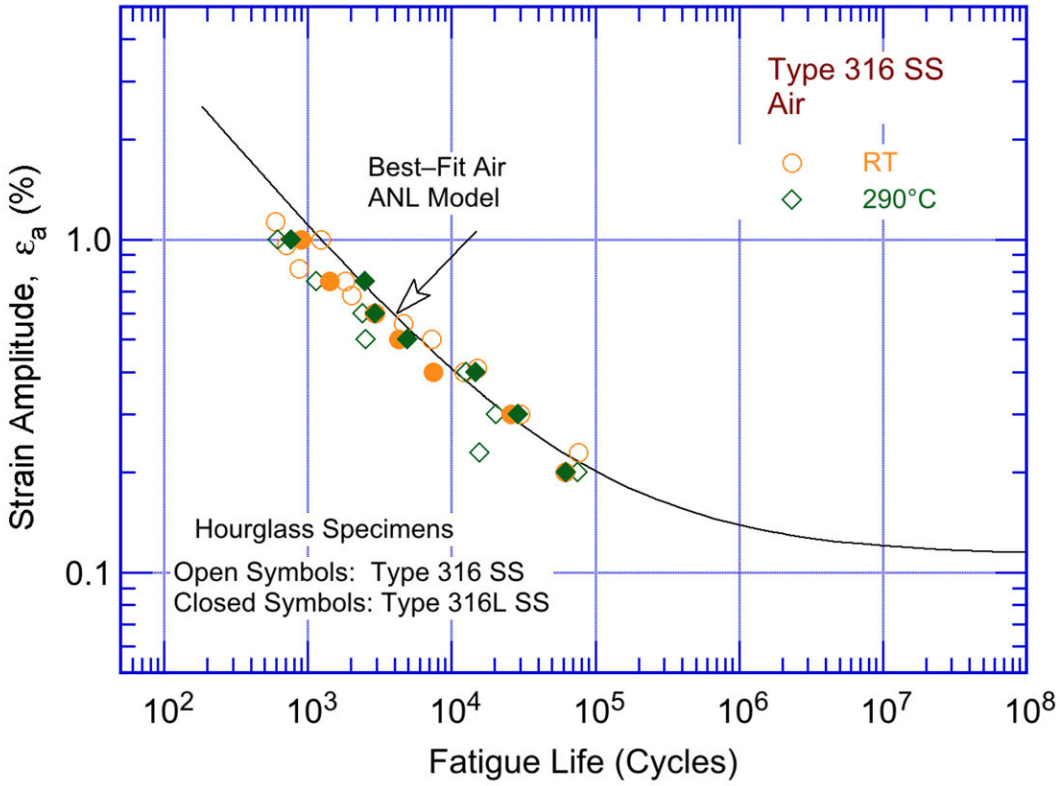


Figure 3-13(b)

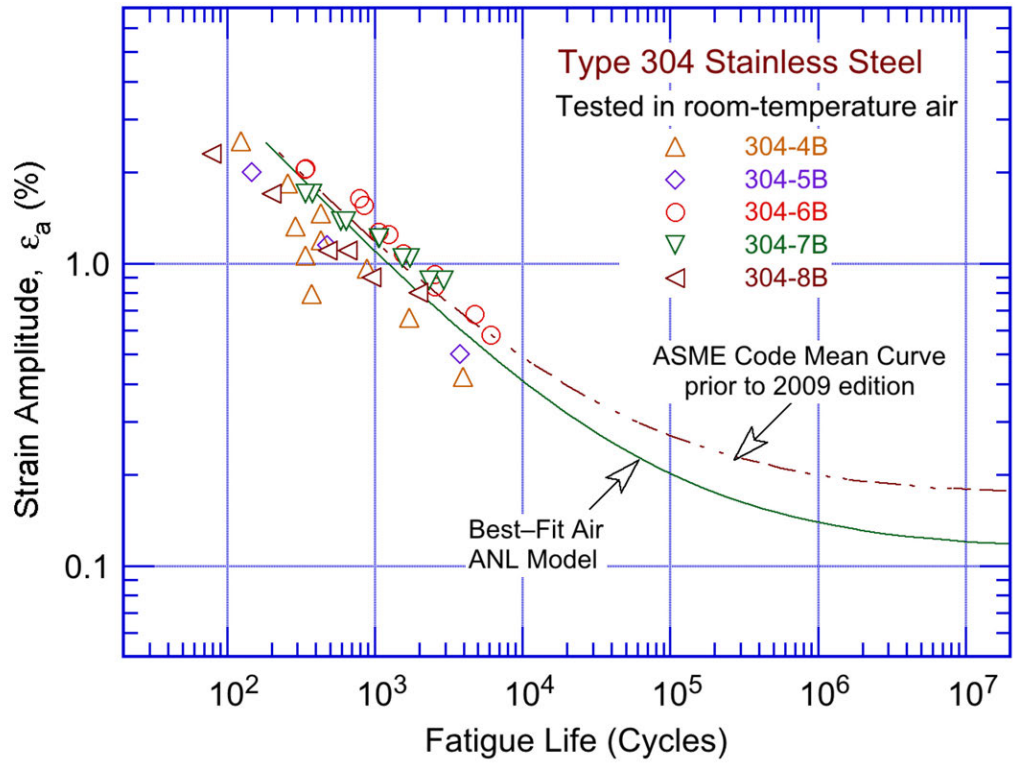


Figure 3-14

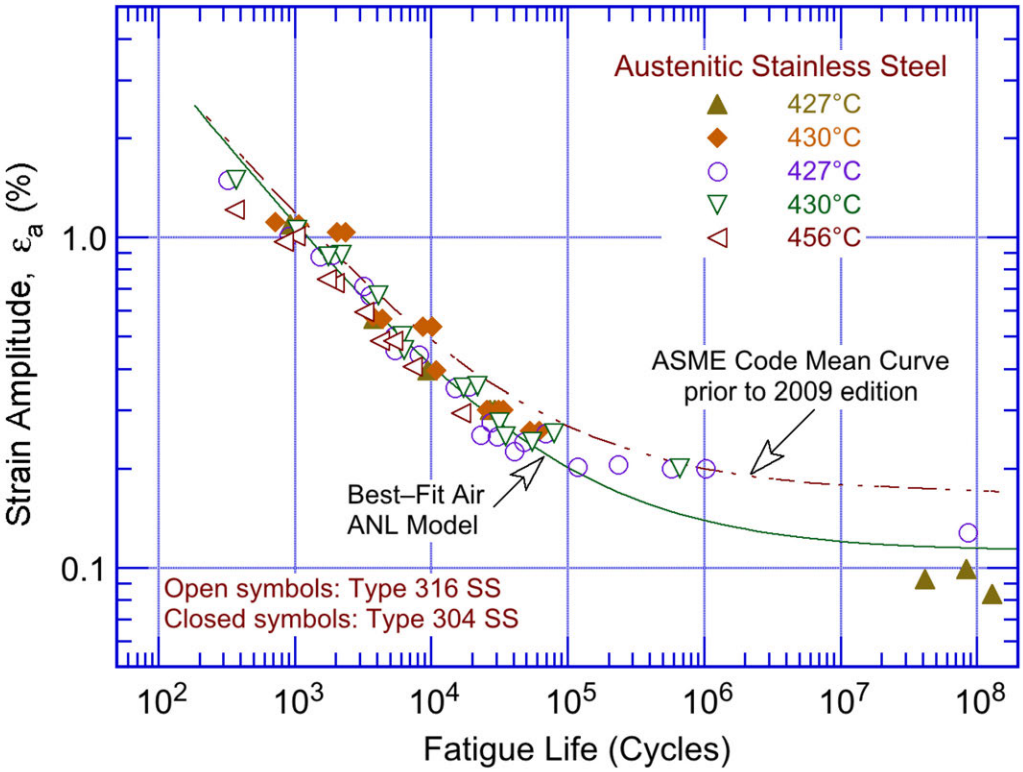


Figure 3-15

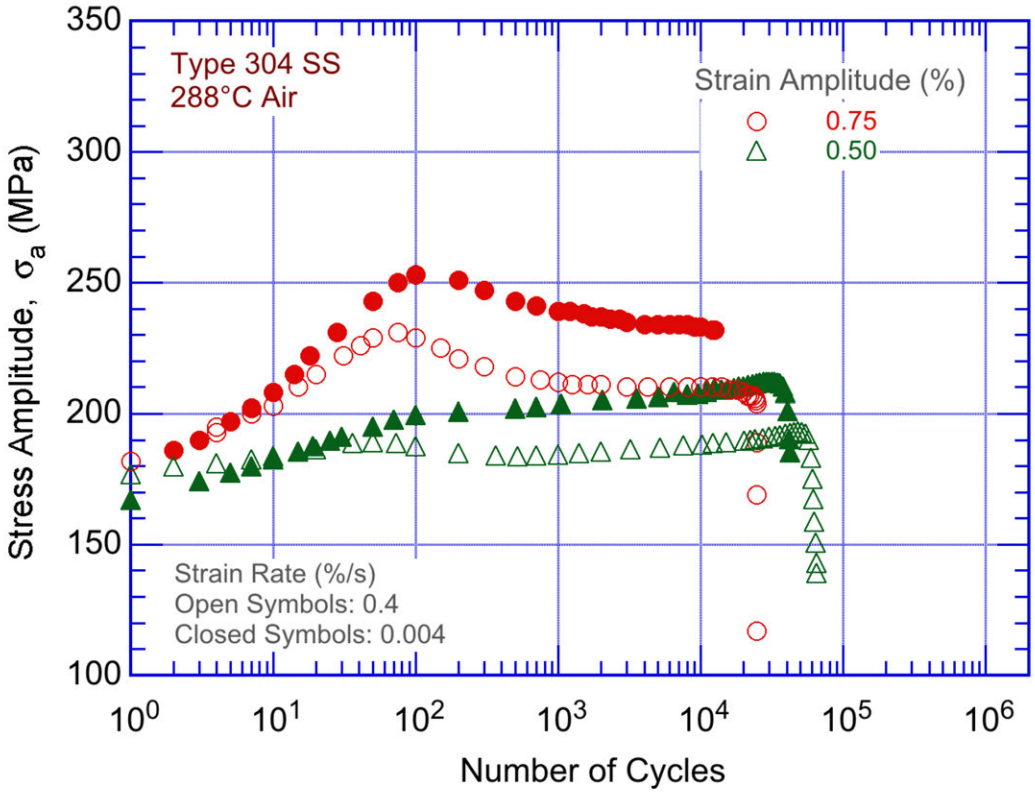


Figure 3-16(a)

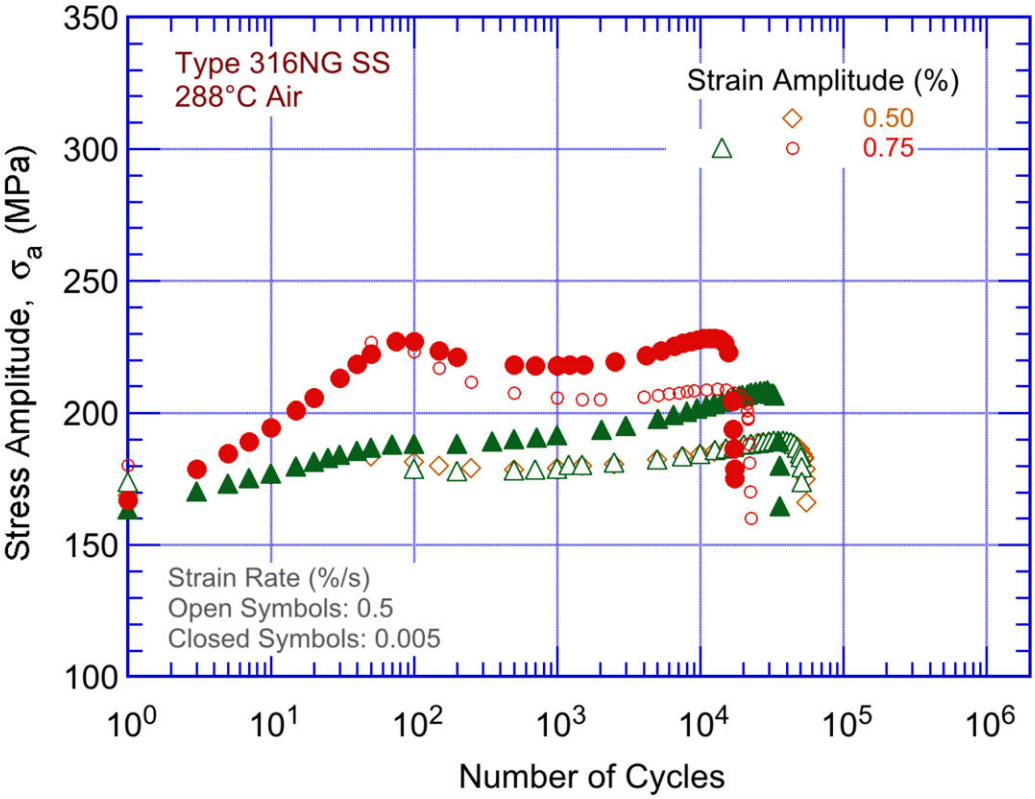


Figure 3-16(b)

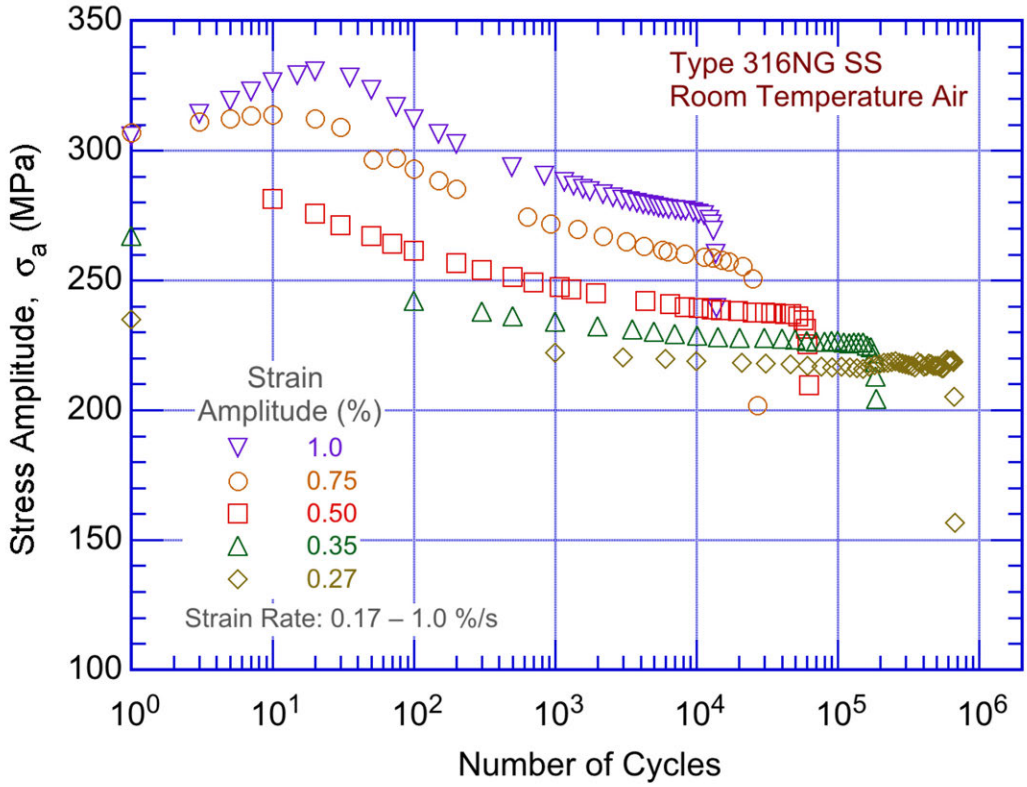


Figure 3-16(c)

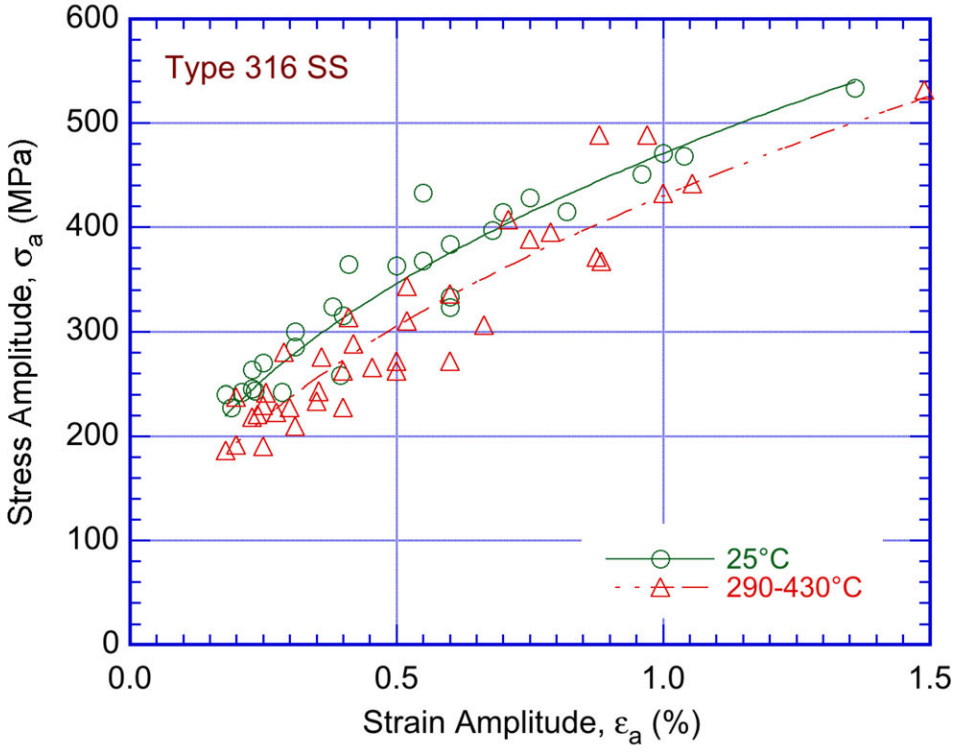


Figure 3-17(a)

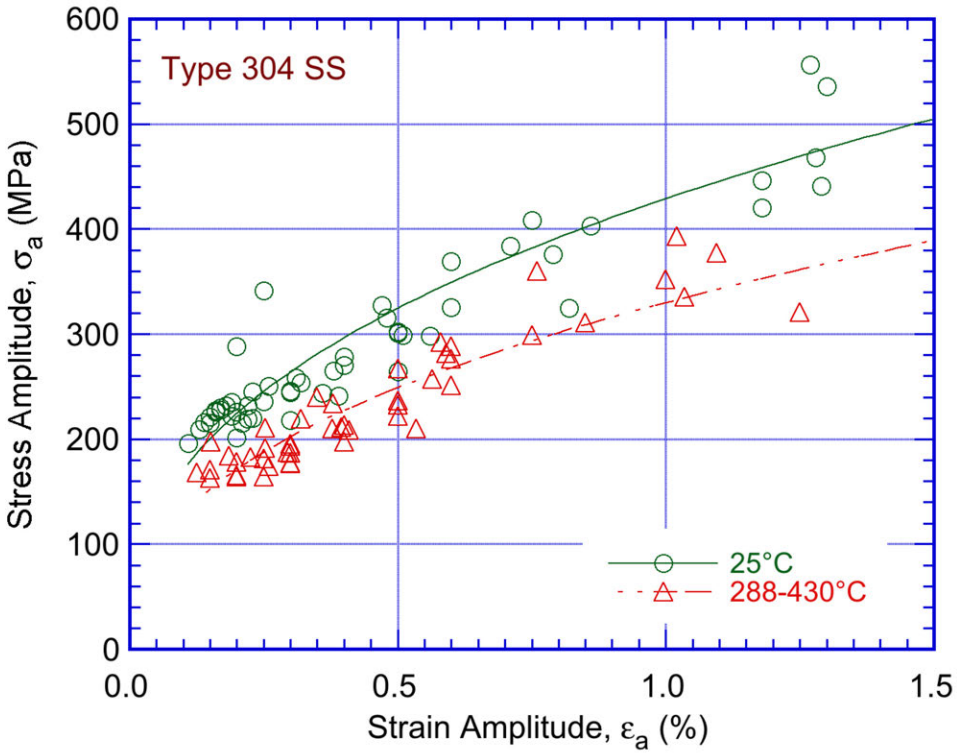


Figure 3-17(b)

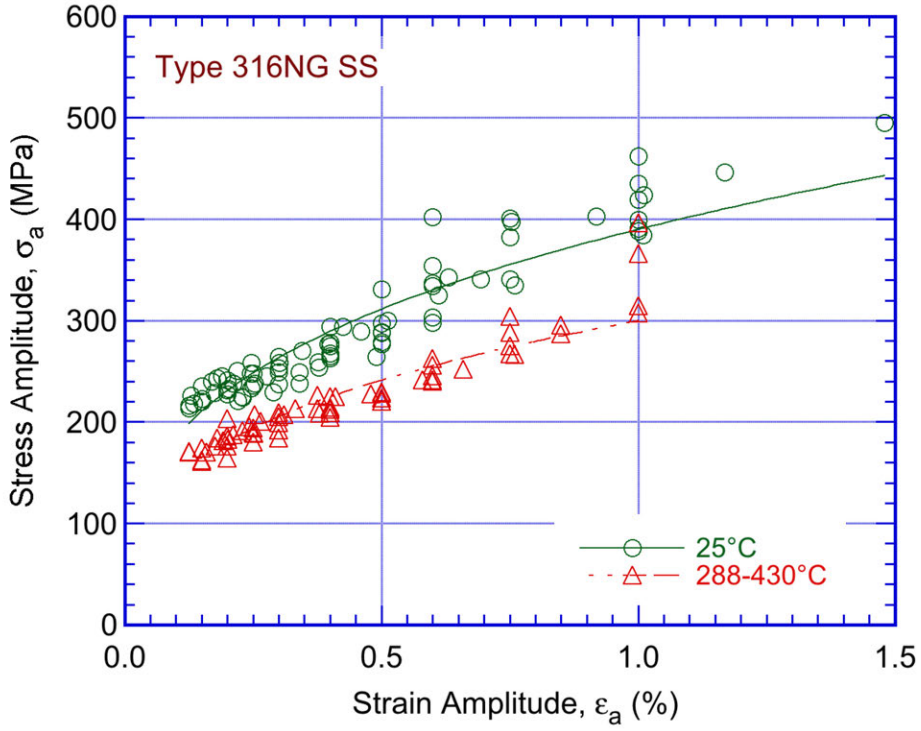


Figure 3-17(c)

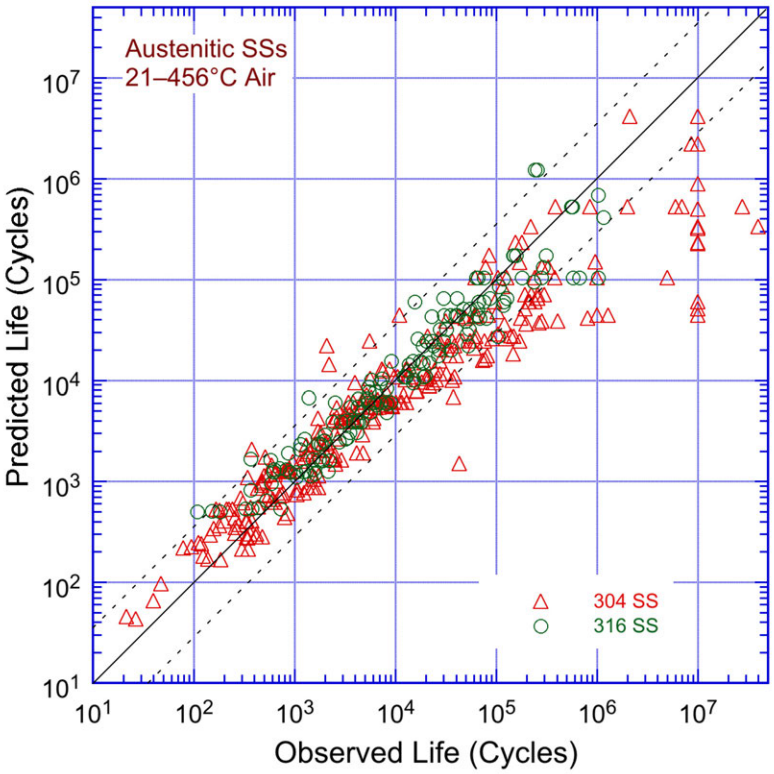


Figure 3-18(a)

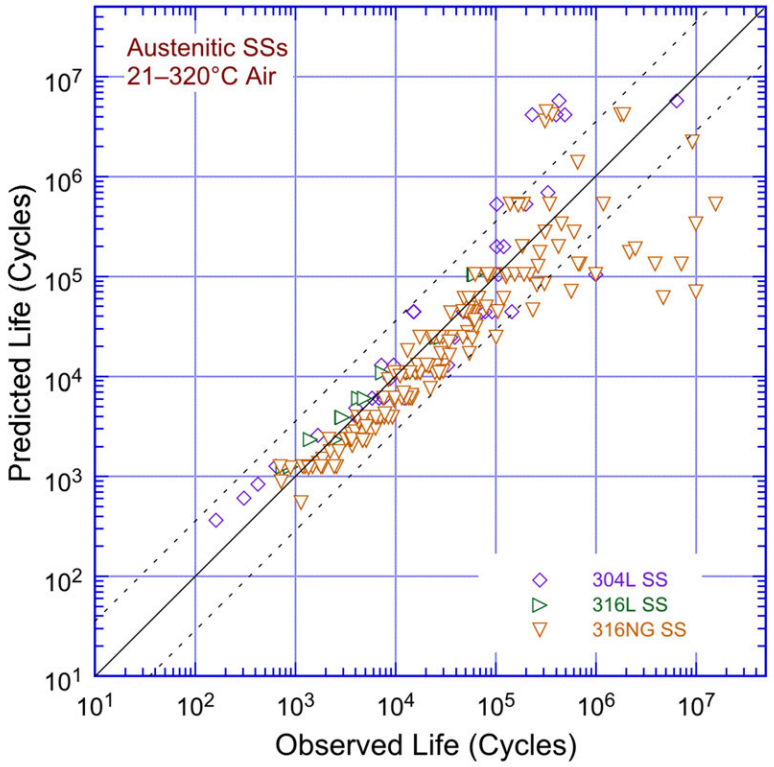


Figure 3-18(b)

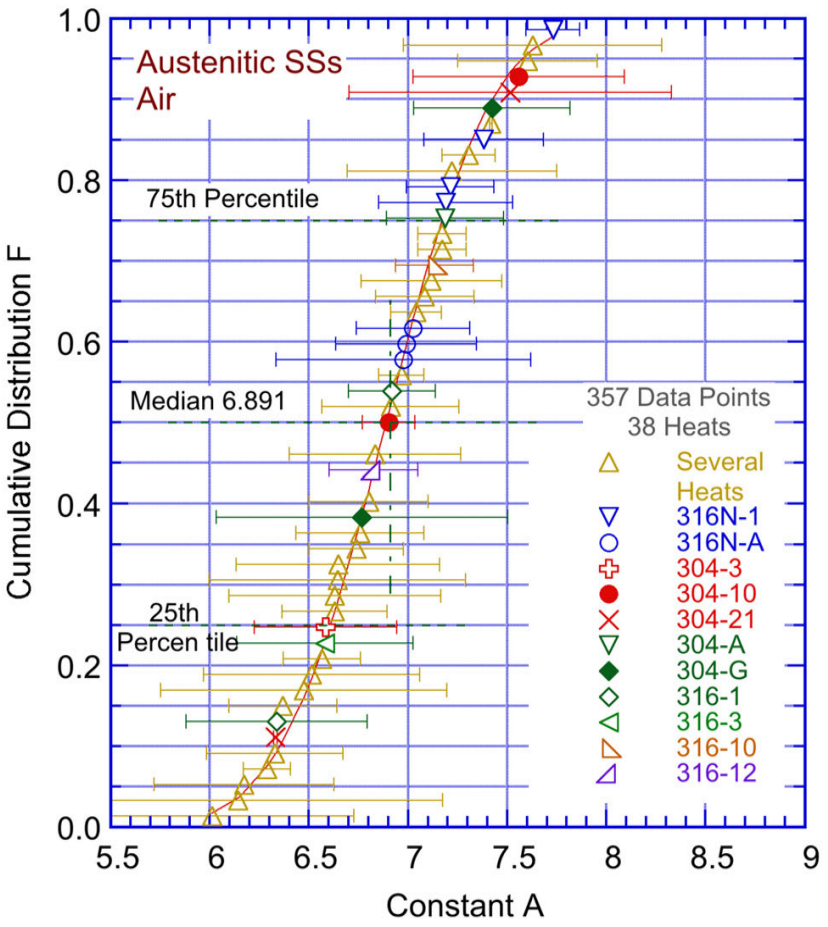


Figure 3-19(a)

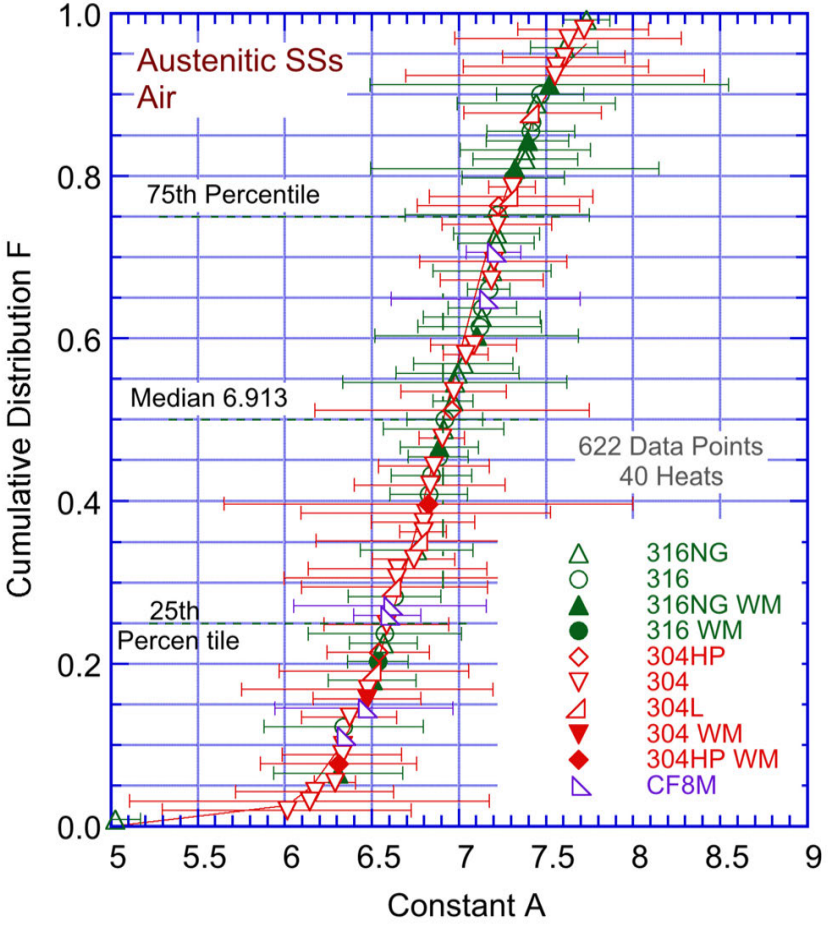


Figure 3-19(b)

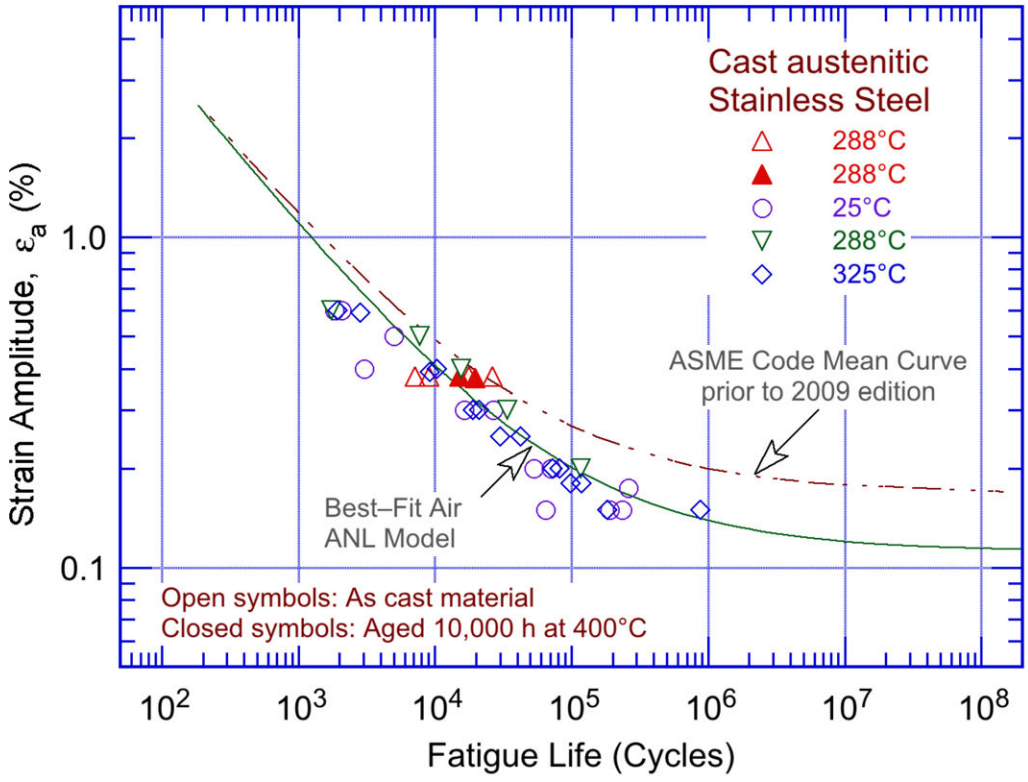


Figure 3-20

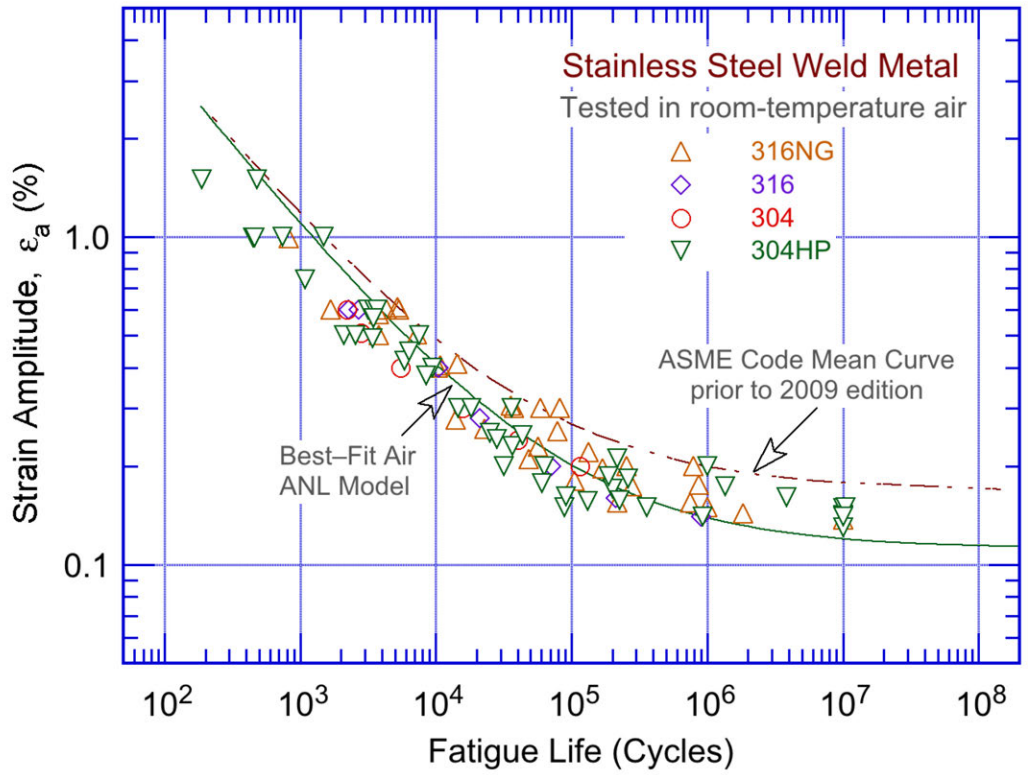


Figure 3-21

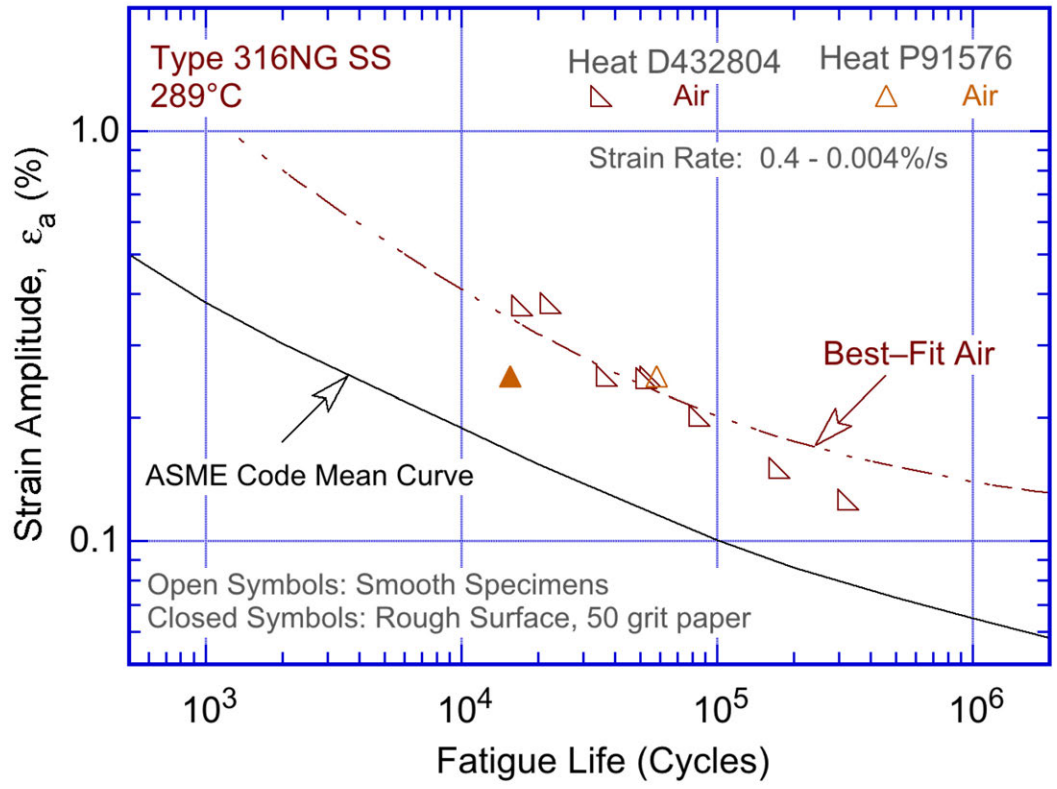


Figure 3-22(a)

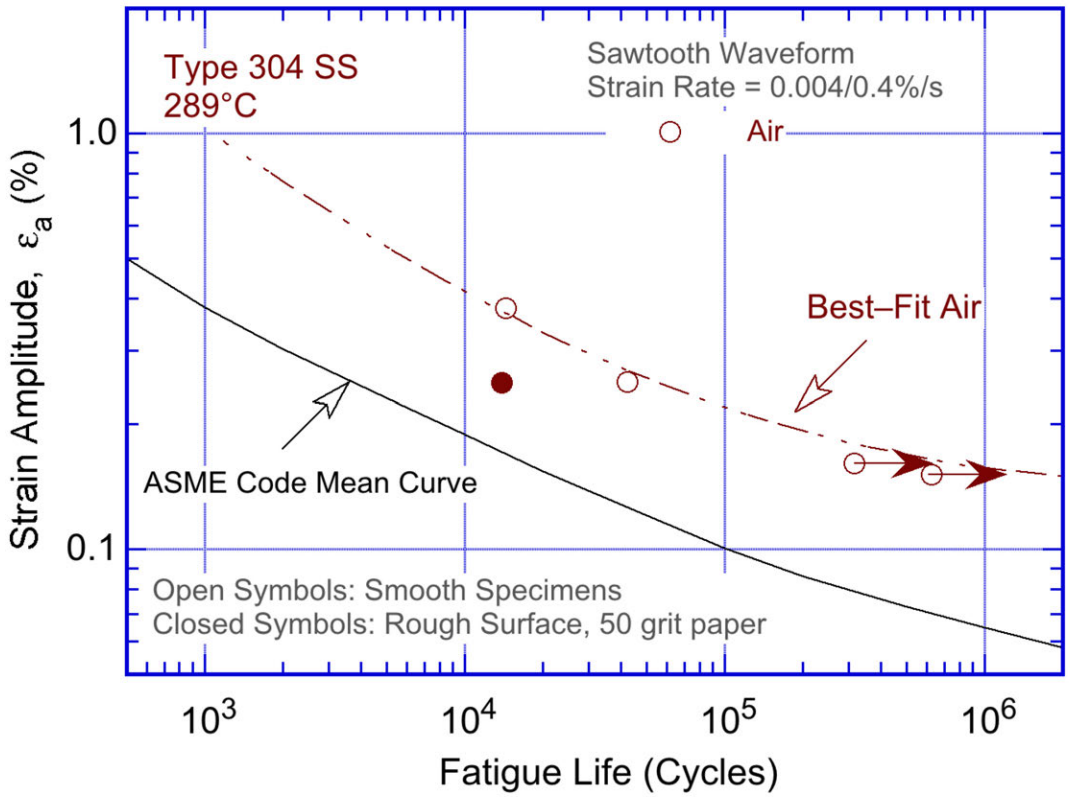


Figure 3-22(b)

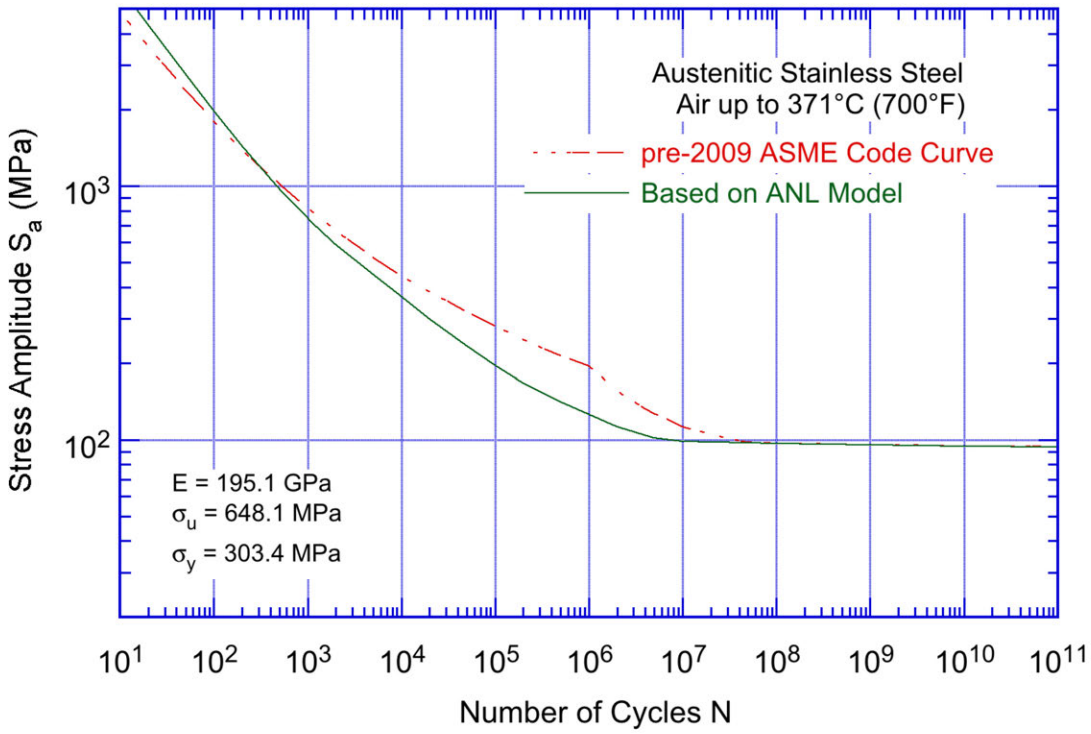


Figure 3-23

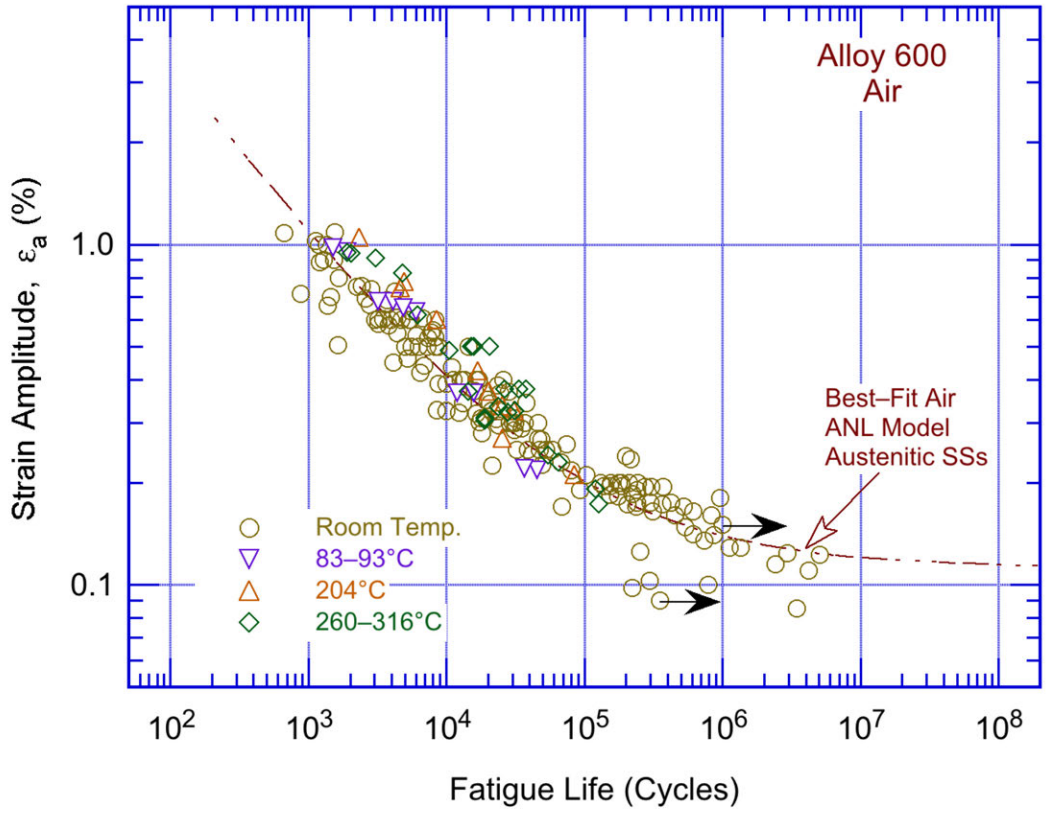


Figure 3-24(a)

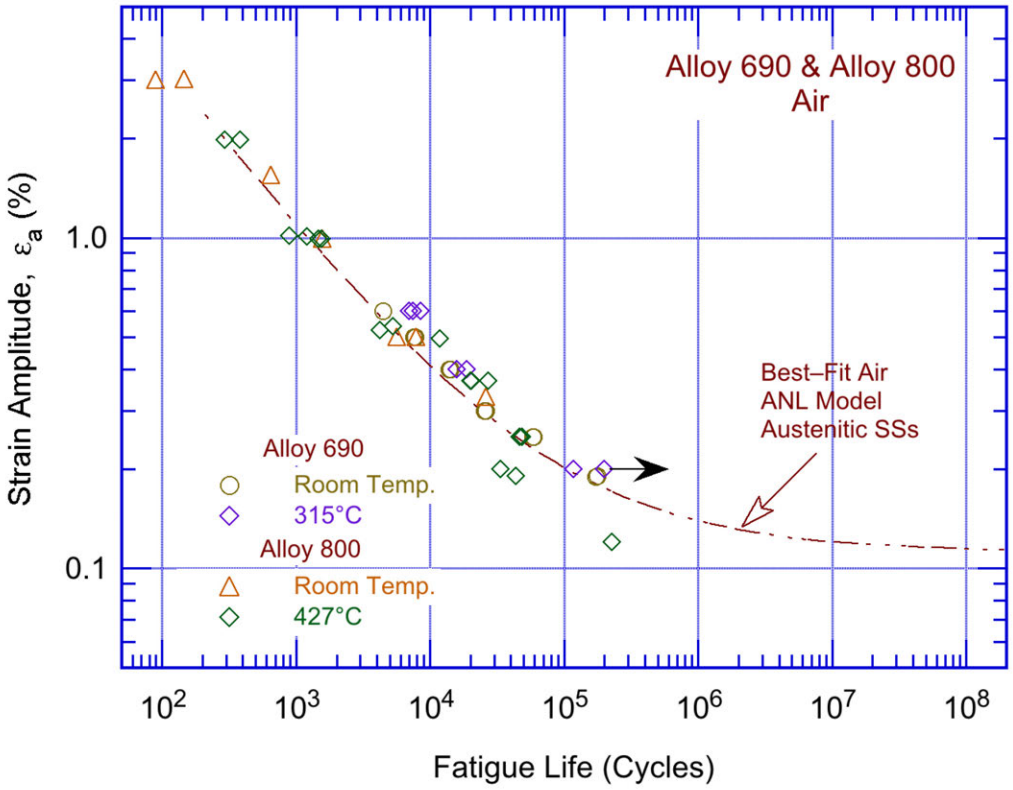


Figure 3-24(b)

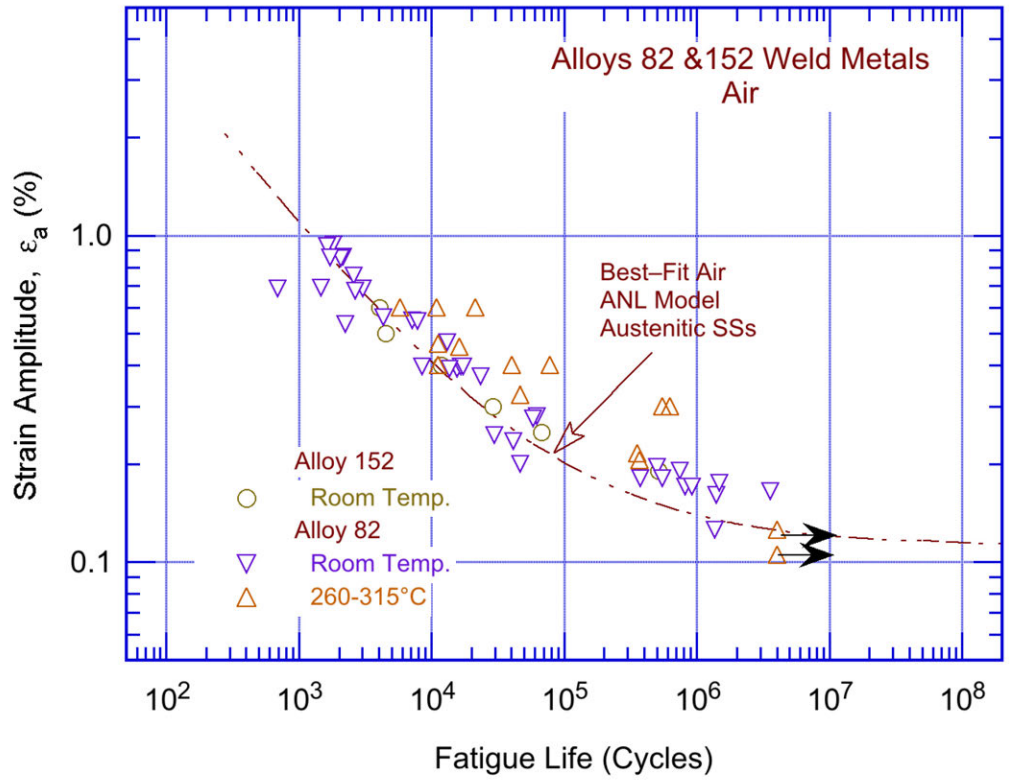


Figure 3-25(a)

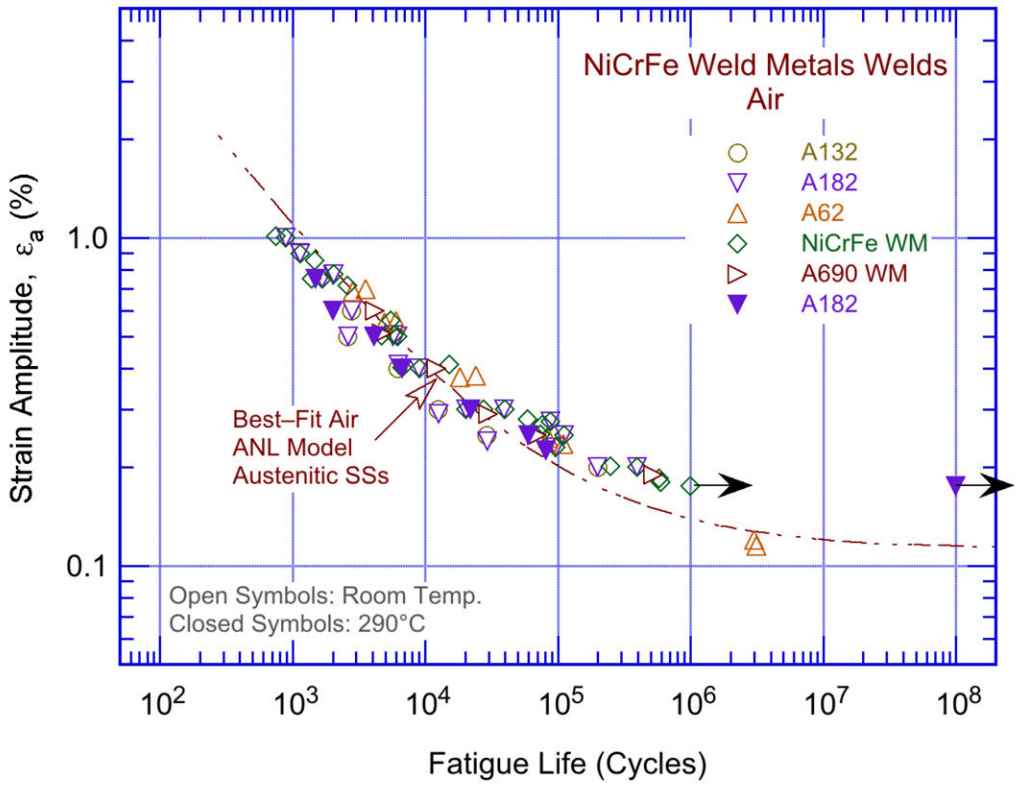


Figure 3-25(b)

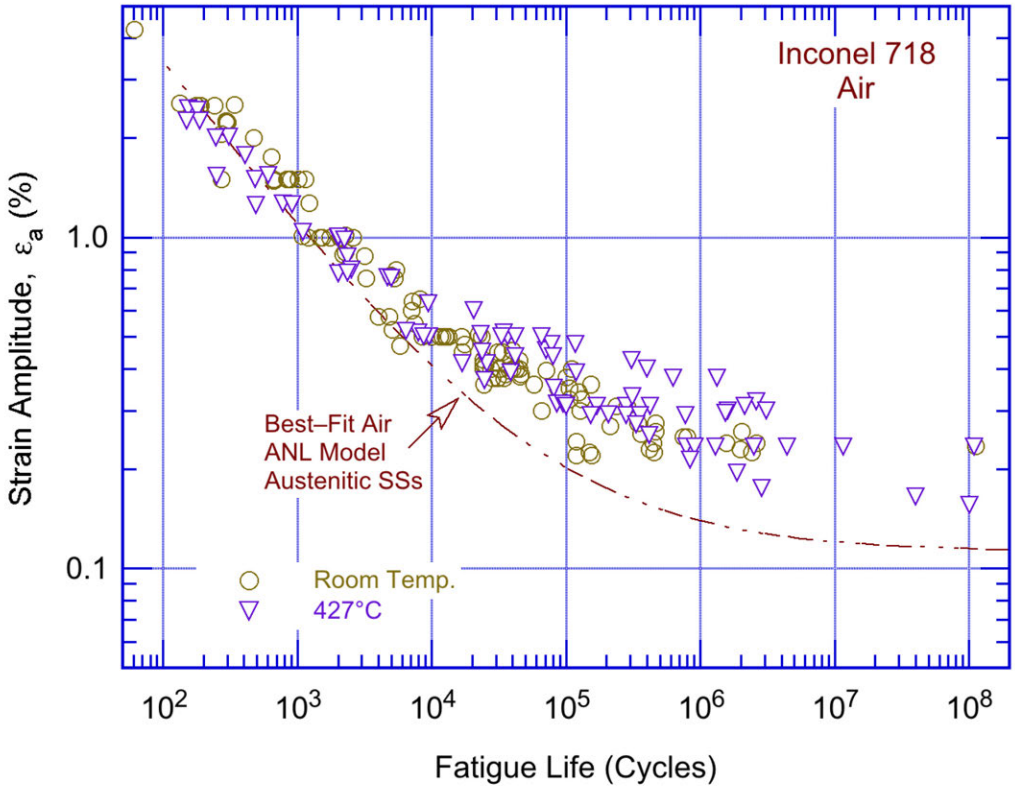


Figure 3-26

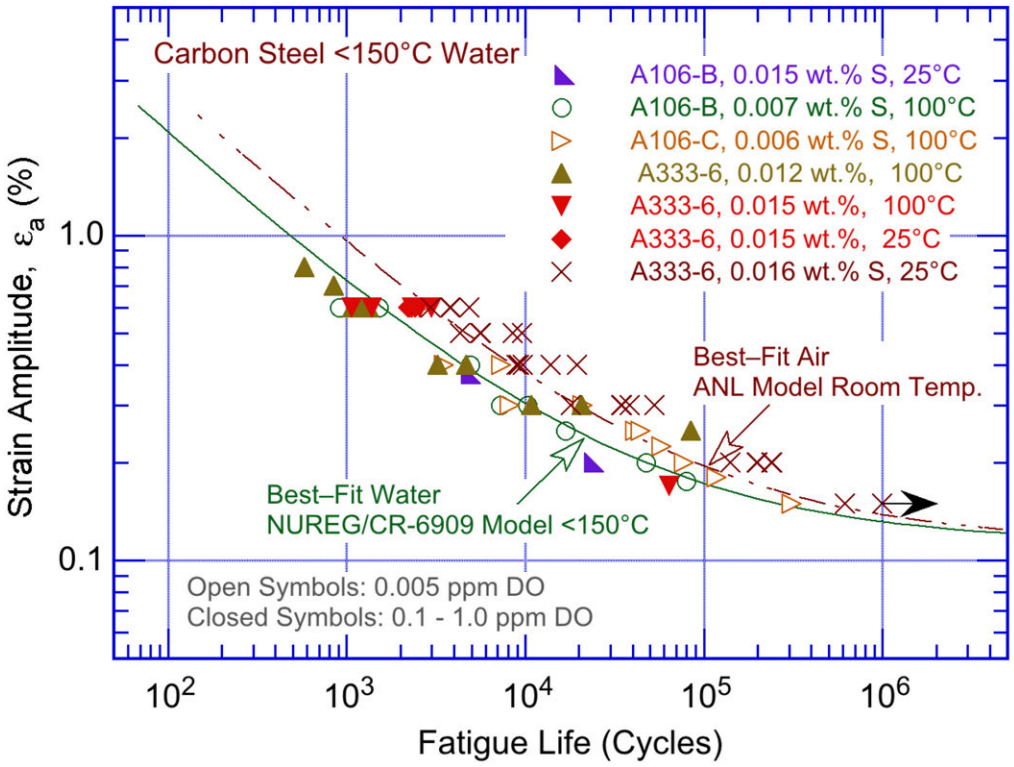


Figure 4-1(a)

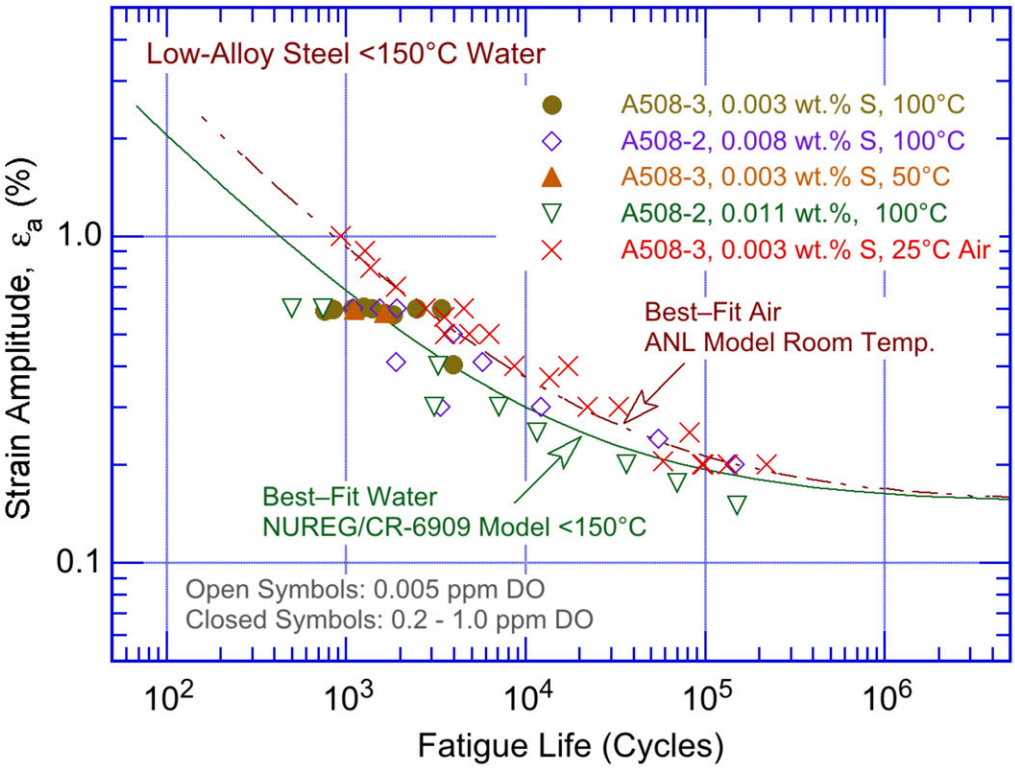


Figure 4-1(b)

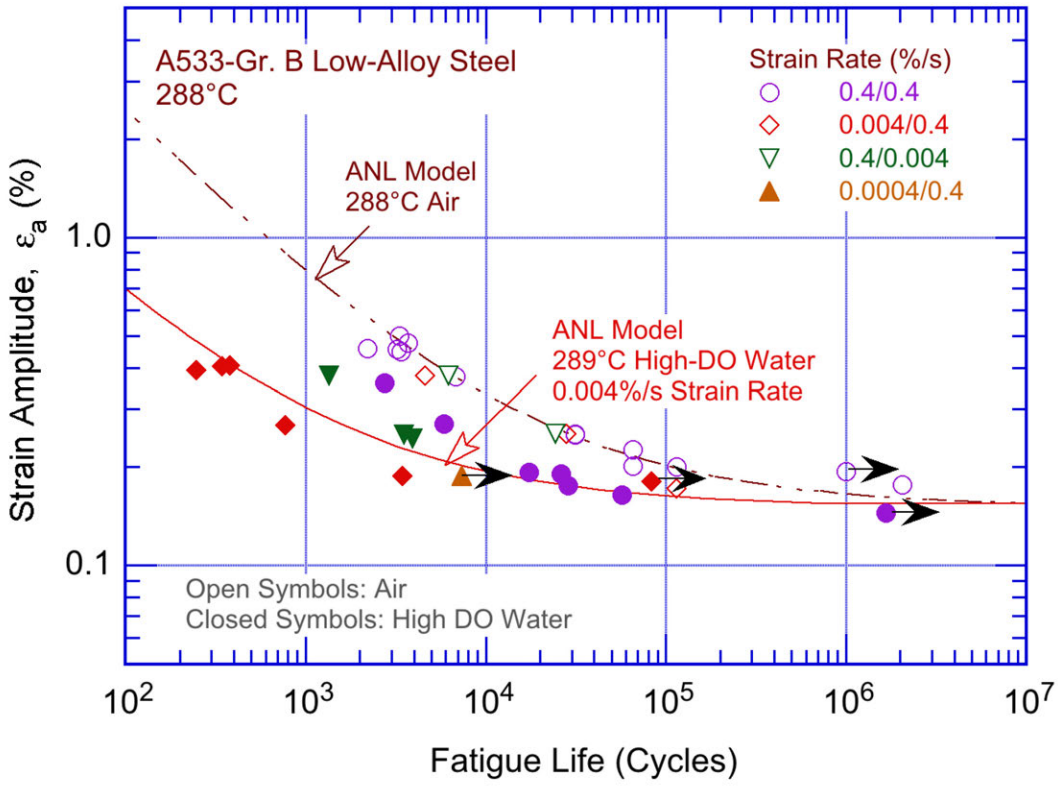


Figure 4-2(a)

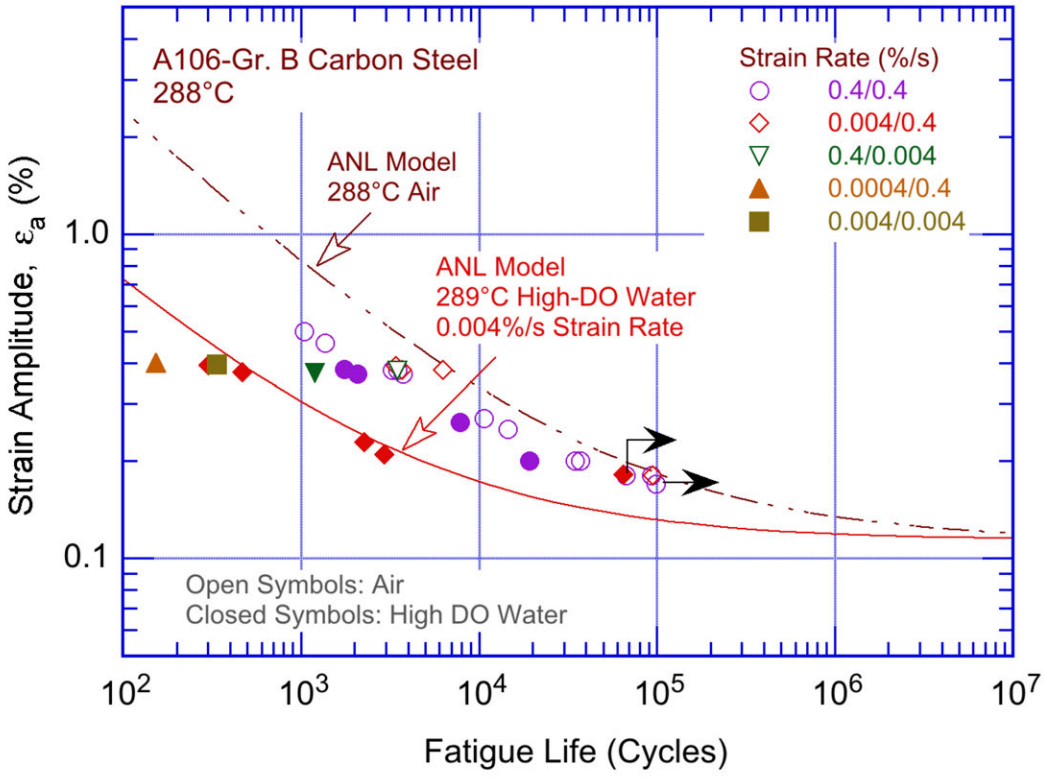


Figure 4-2(b)

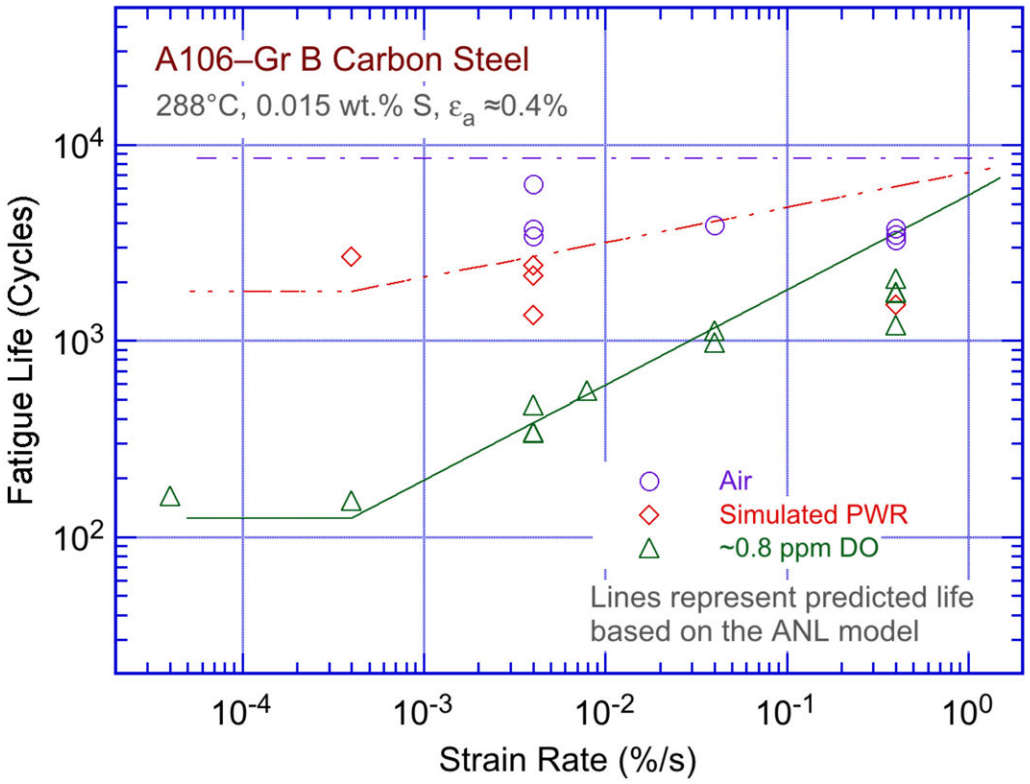


Figure 4-3(a)

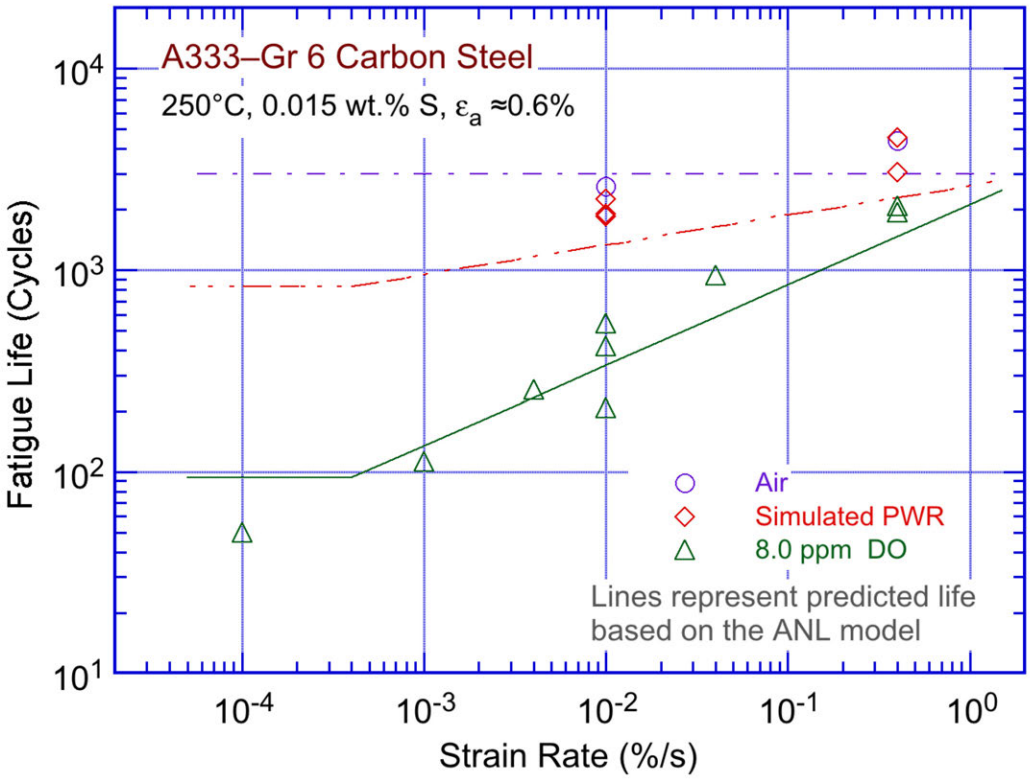


Figure 4-3(b)

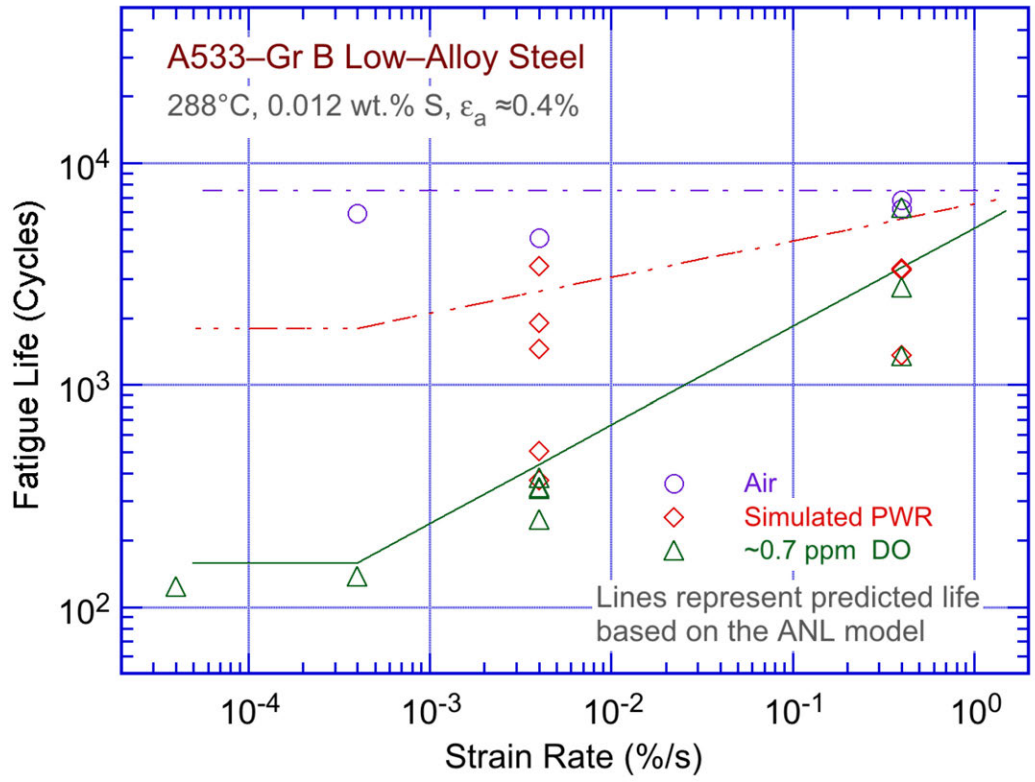


Figure 4-3(c)

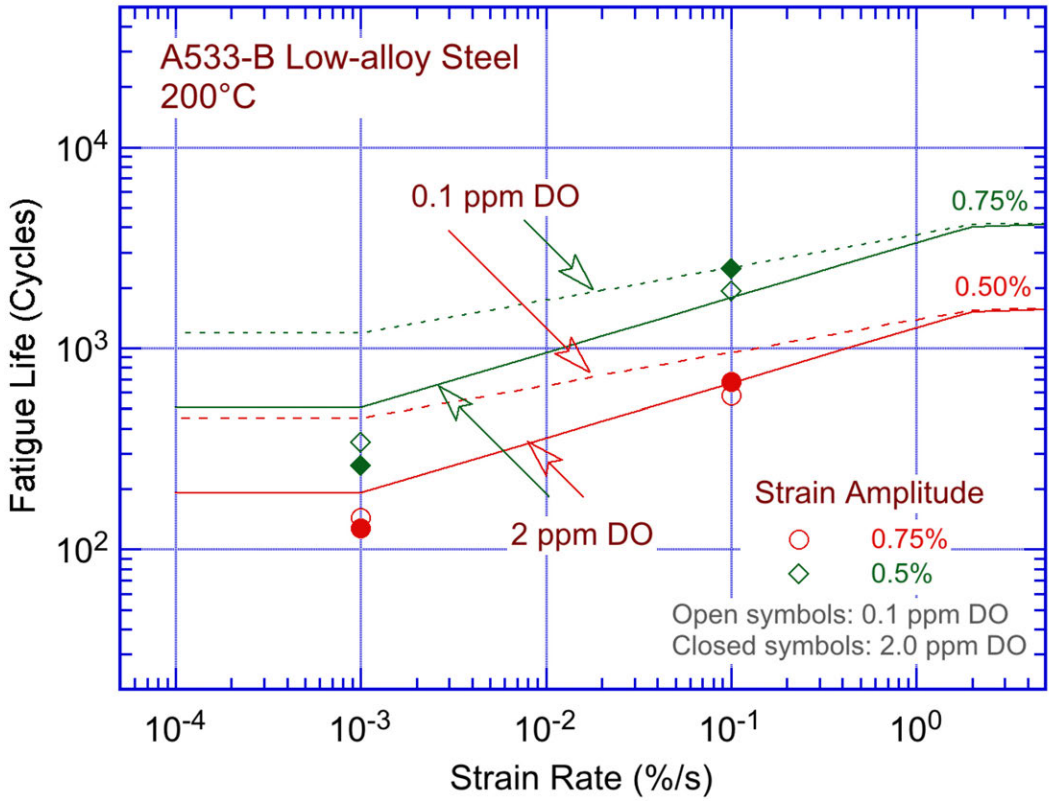


Figure 4-4(a)

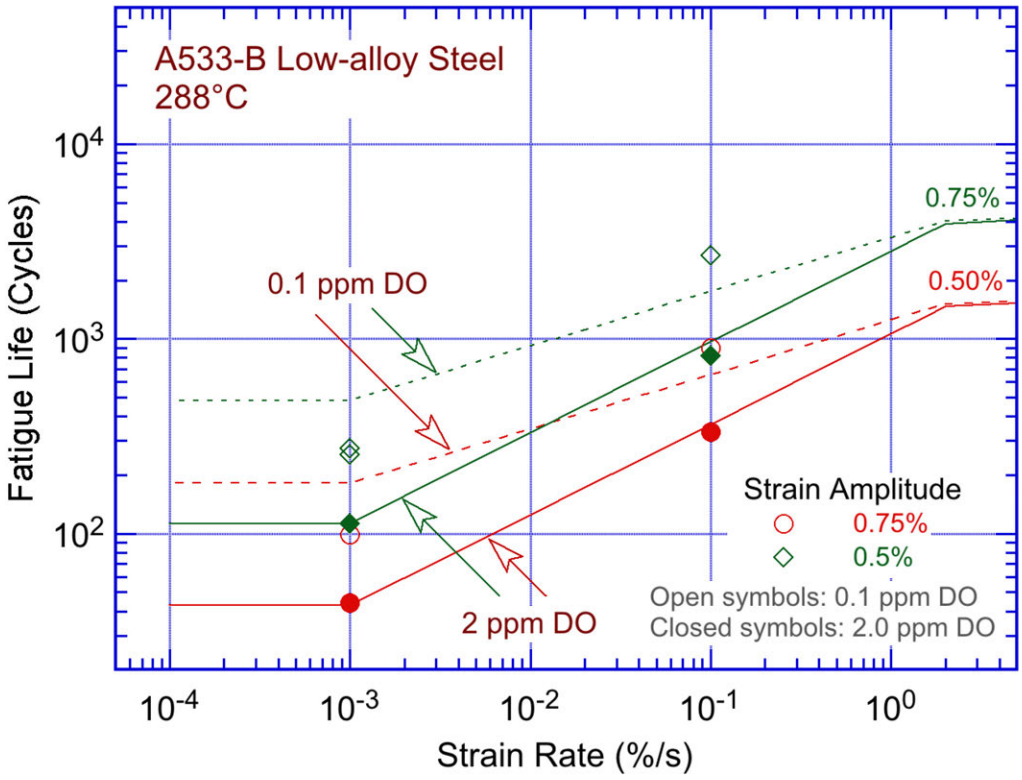


Figure 4-4(b)

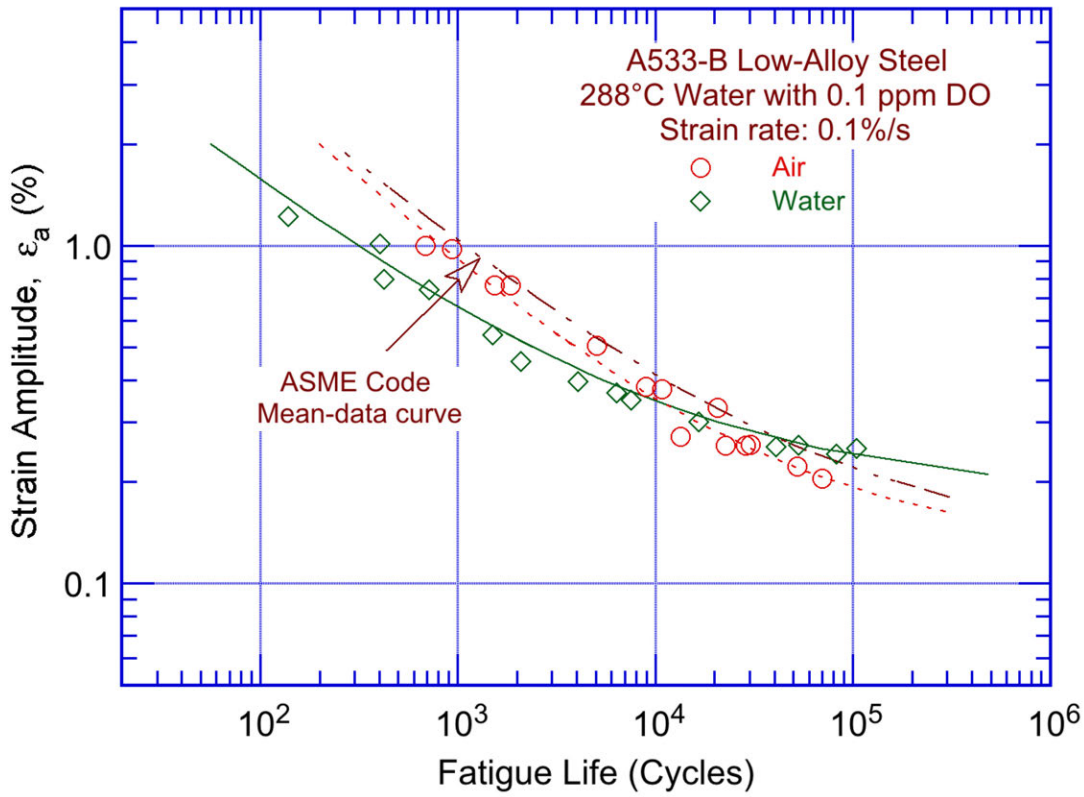


Figure 4-5(a)

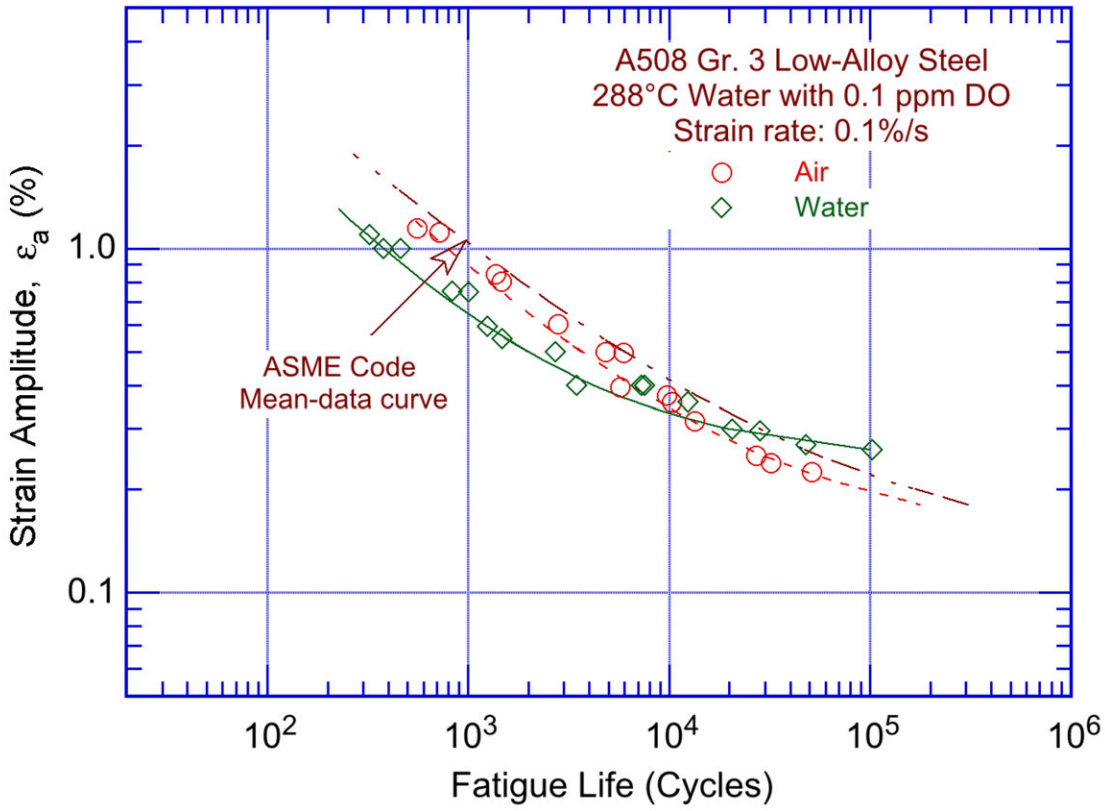

A508 Gr. 3 Low-Alloy Steel
288°C Water with 0.1 ppm DO
Strain rate: 0.1%/s
Air
Water
ASME Code
Mean-data curve
Strain Amplitude, ε_a (%)
1.0
0.1
10^2
10^3
10^4
10^5
10^6
Fatigue Life (Cycles)

Figure 4-5(b)

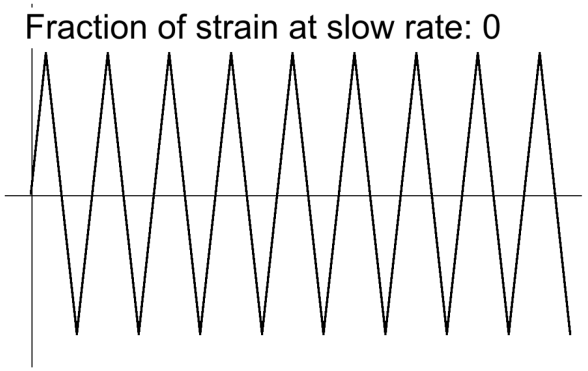


Figure 4-6(a)

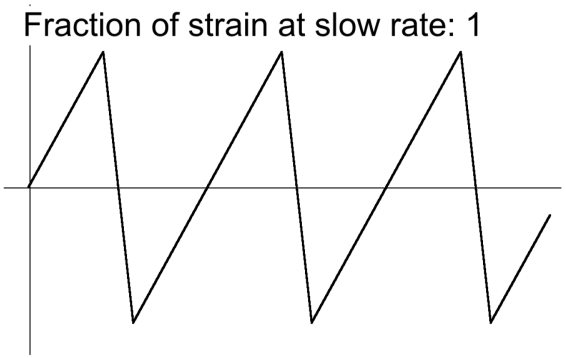


Figure 4-6(b)

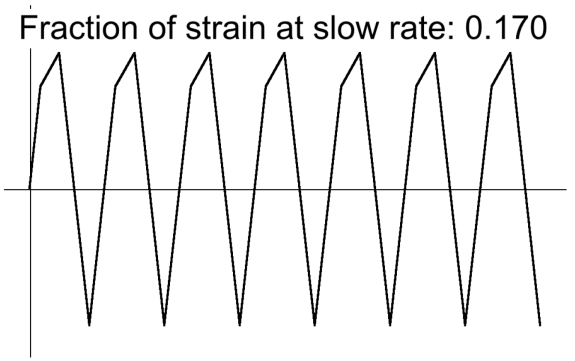


Figure 4-6(c)

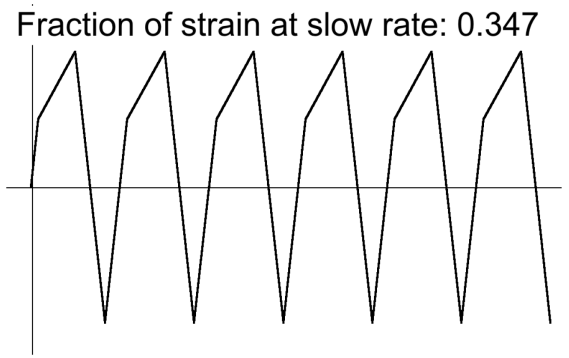


Figure 4-6(d)

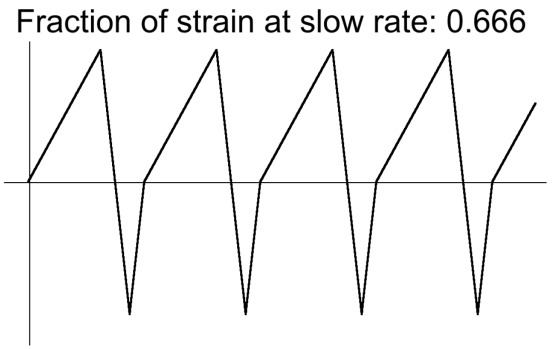


Figure 4-6(e)

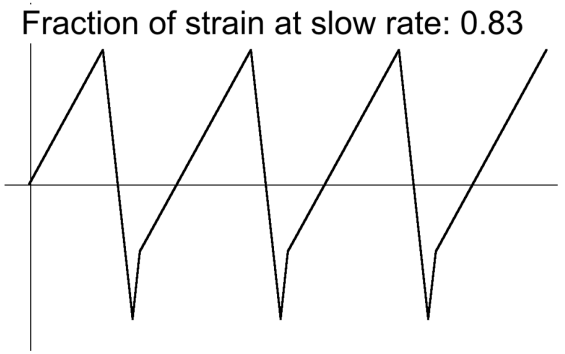


Figure 4-6(f)

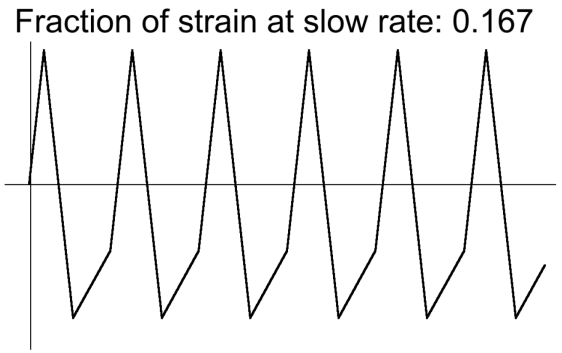


Figure 4-6(g)

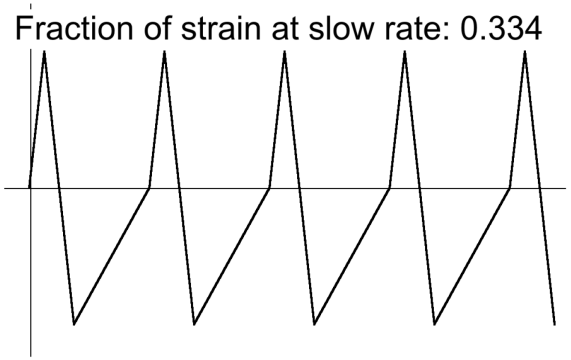


Figure 4-6(h)

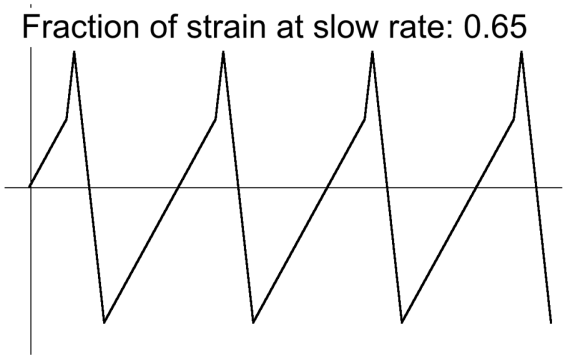


Figure 4-6(i)

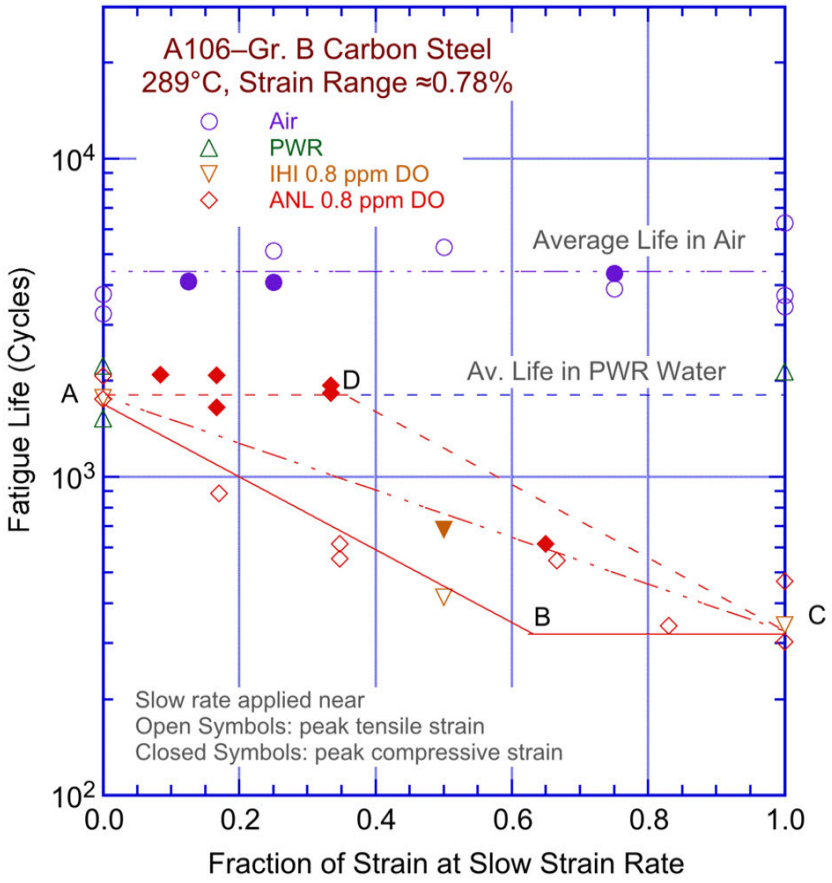


Figure 4-7(a)

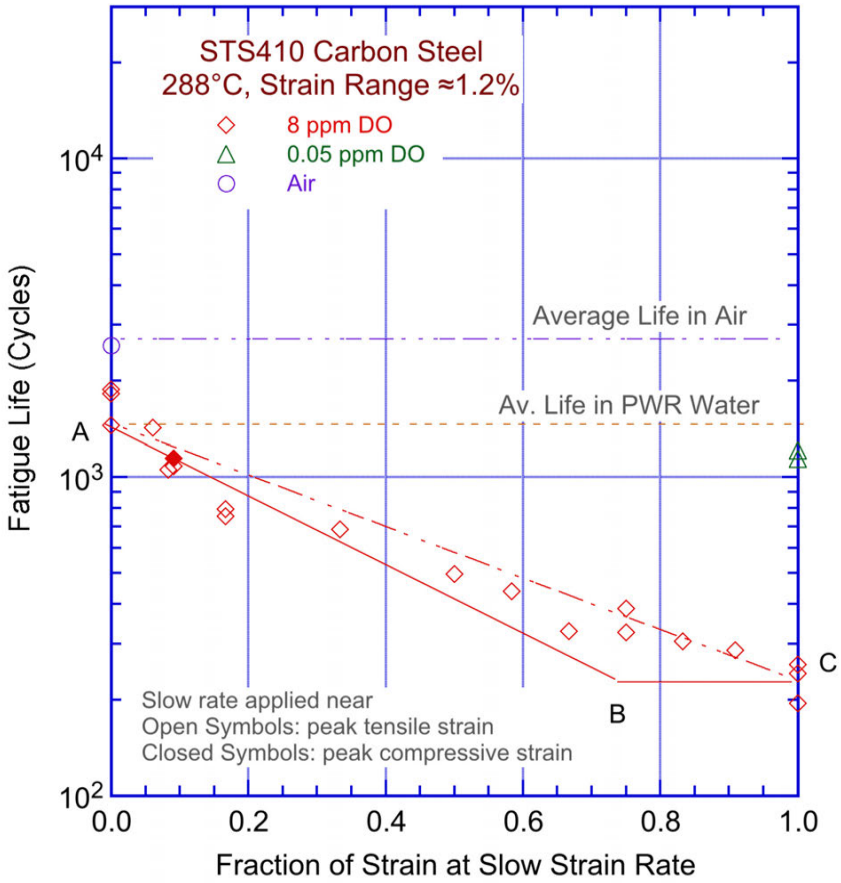


Figure 4-7(b)

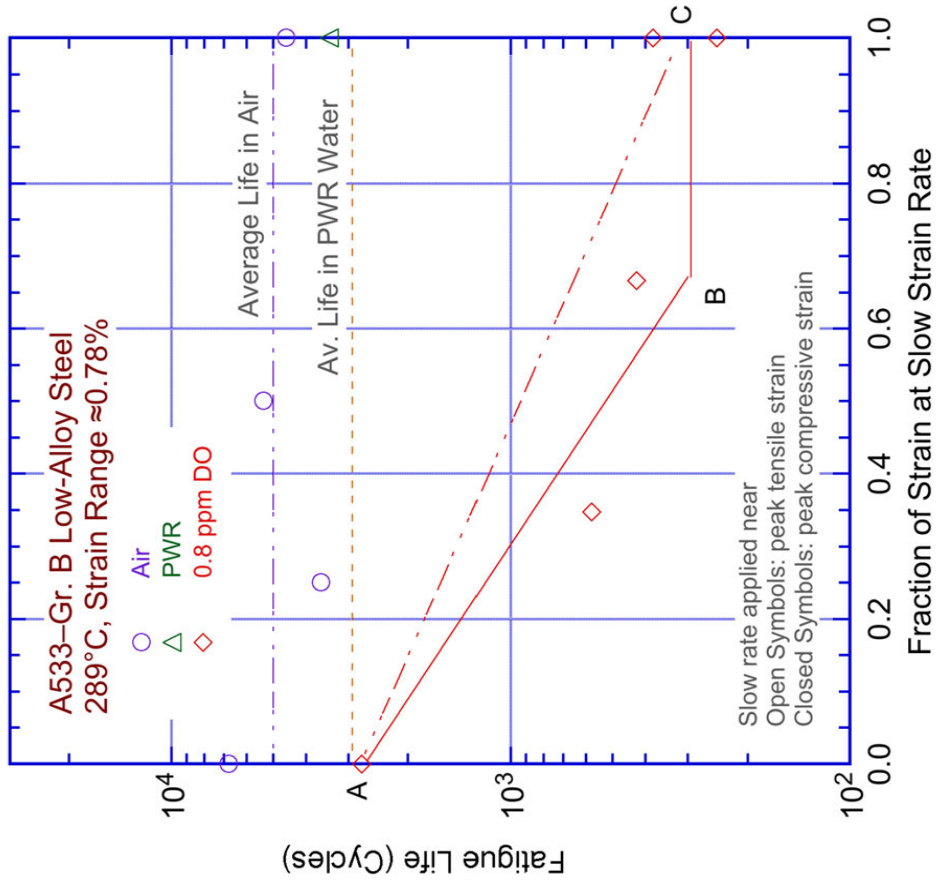

A533–Gr. B Low-Alloy Steel
289°C, Strain Range ≈0.78%
Air
PWR
0.8 ppm DO
Average Life in Air
Av. Life in PWR Water
A
B
C
Slow rate applied near
Open Symbols: peak tensile strain
Closed Symbols: peak compressive strain
Fatigue Life (Cycles)
Fraction of Strain at Slow Strain Rate
10^4
10^3
10^2
0.0
0.2
0.4
0.6
0.8
1.0

Figure 4-7(c)

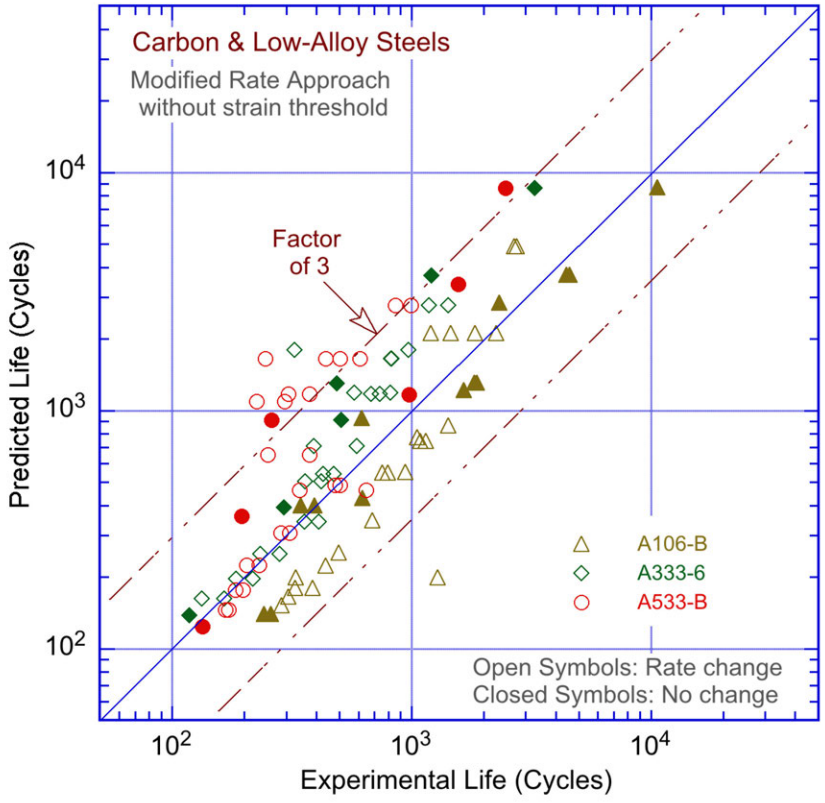


Figure 4-8(a)

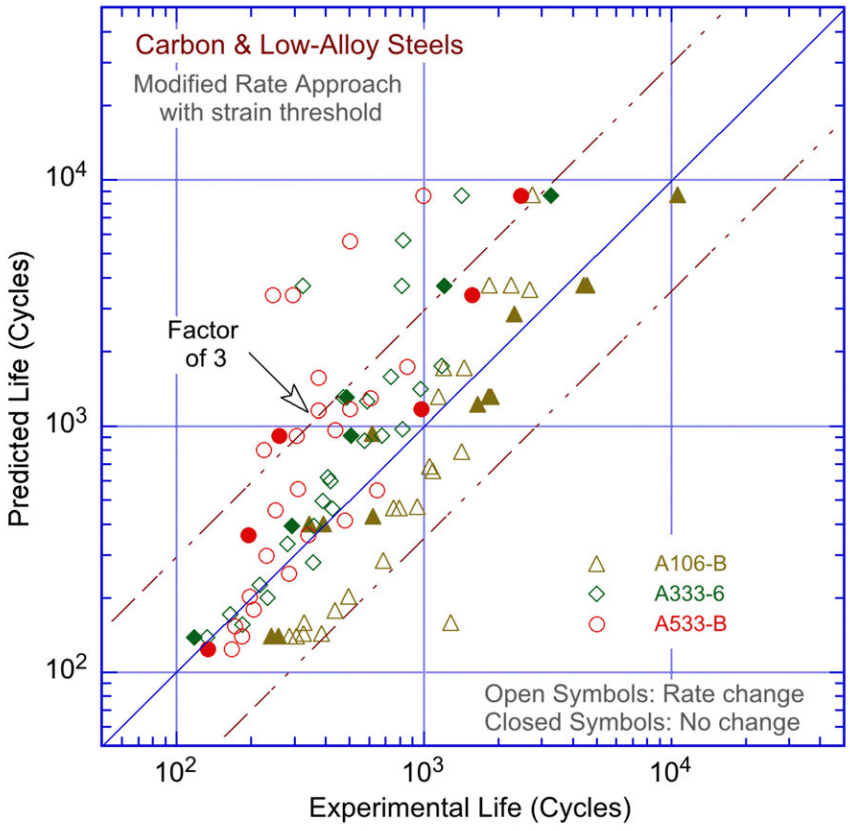


Figure 4-8(b)

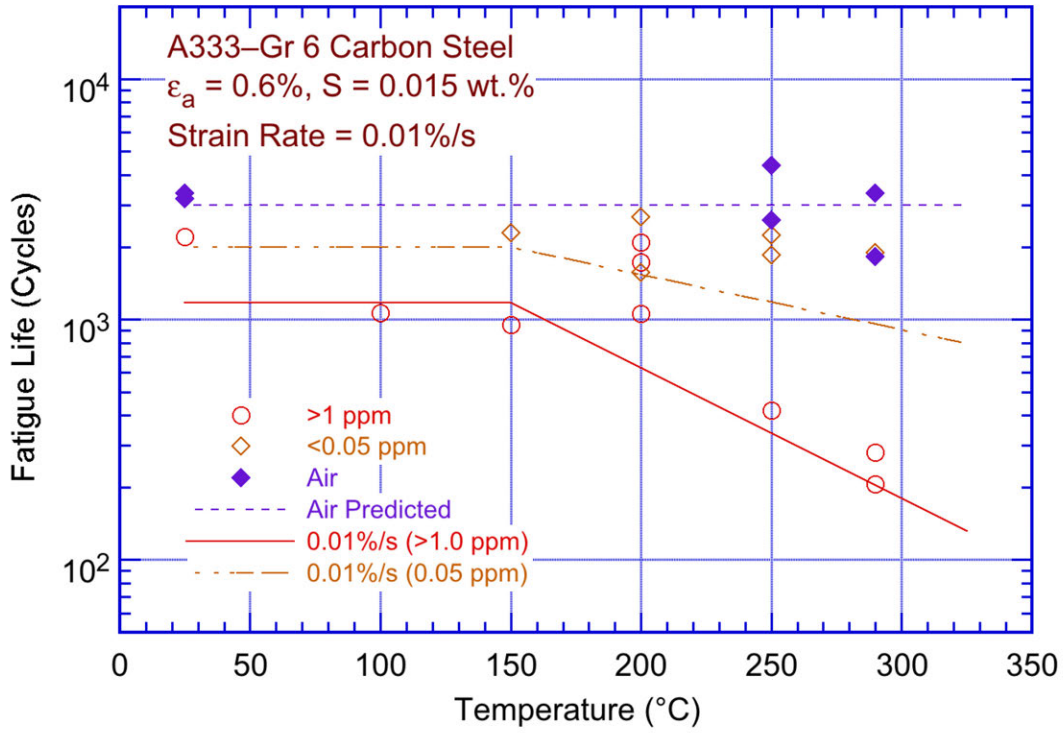


Figure 4-9(a)

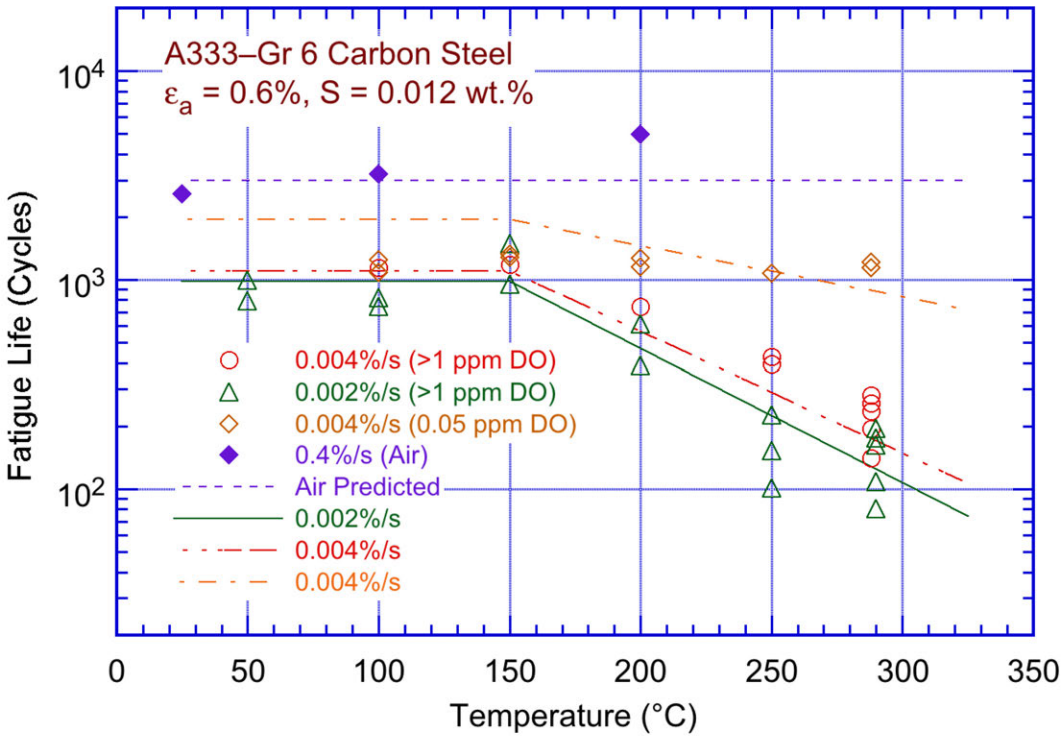


Figure 4-9(b)

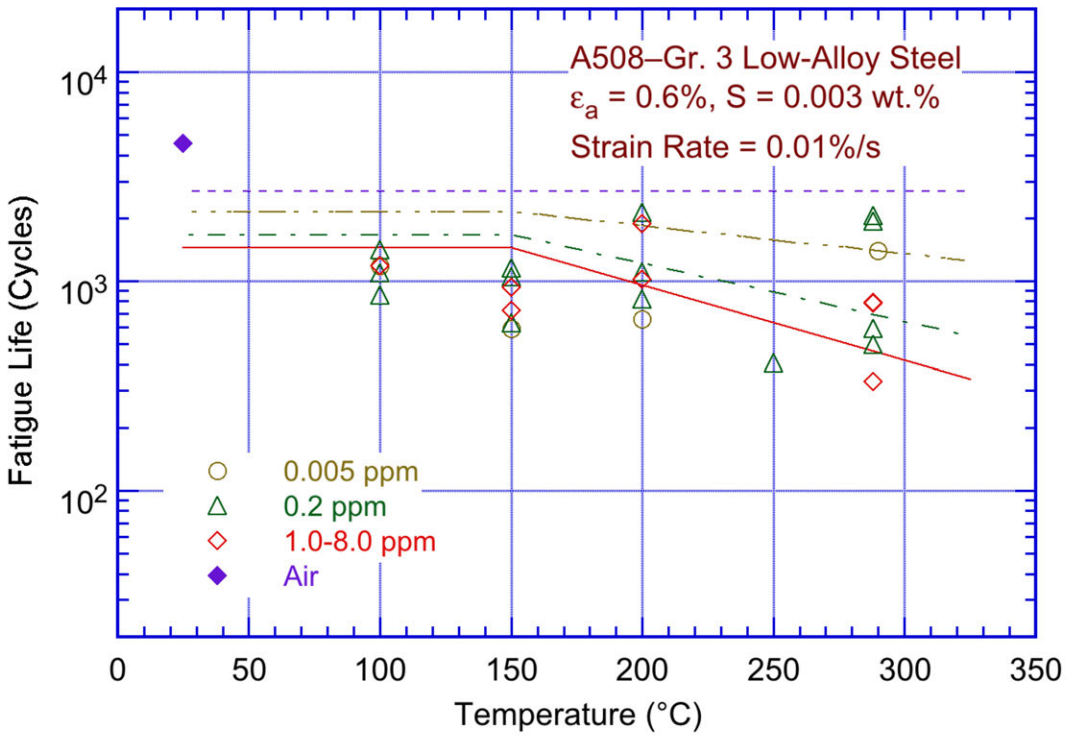


Figure 4-9(c)

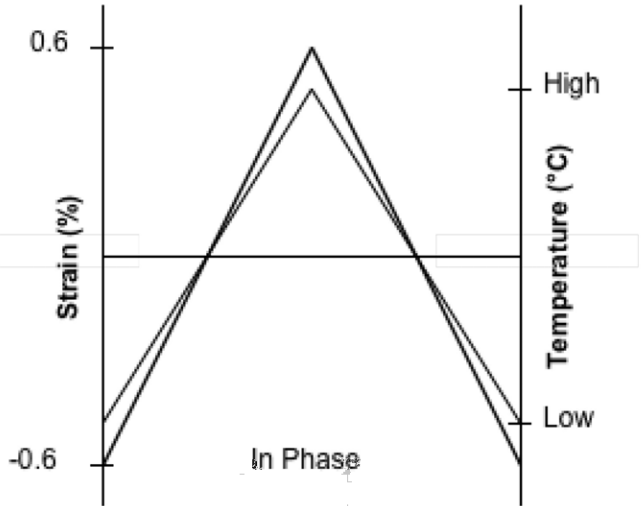


Figure 4-10(a)

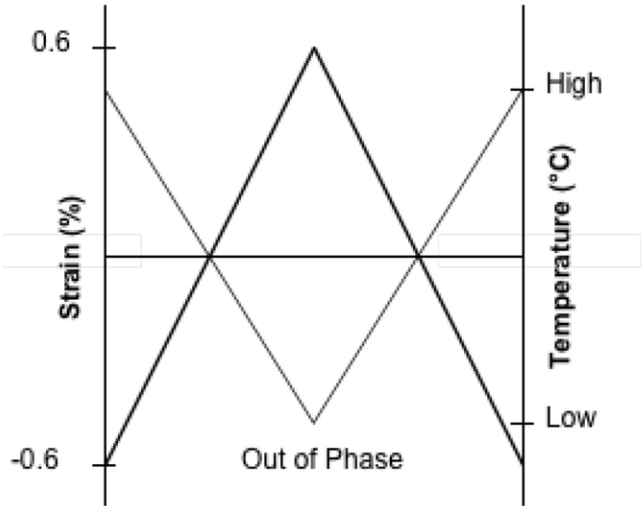


Figure 4-10(b)

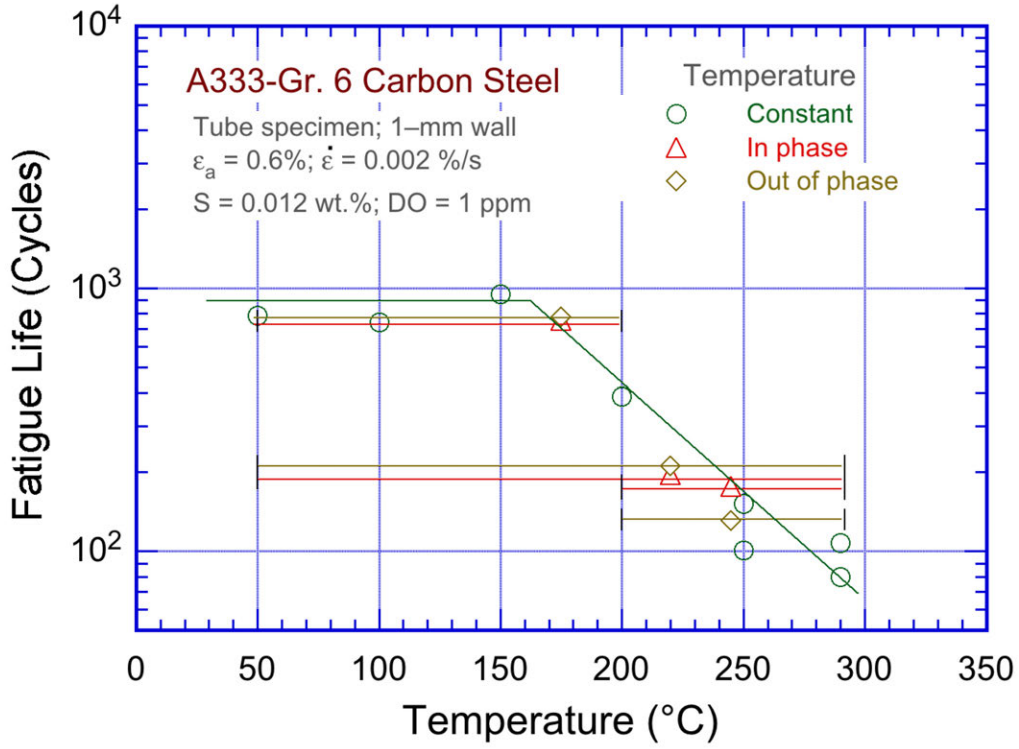


Figure 4-11(a)

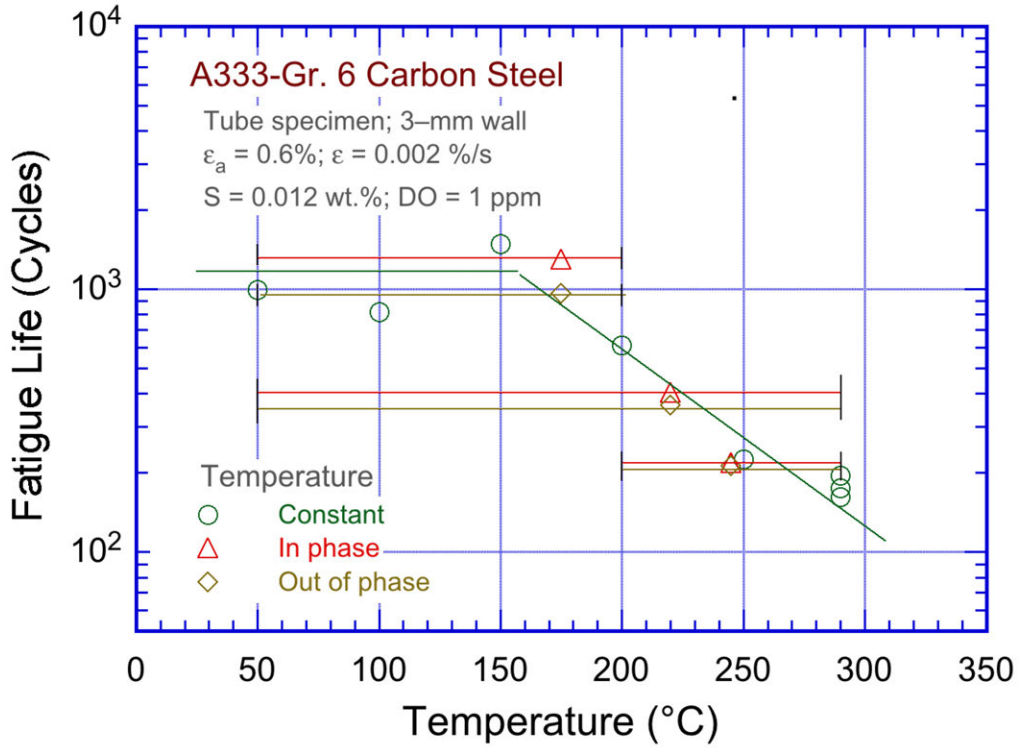


Figure 4-11(b)

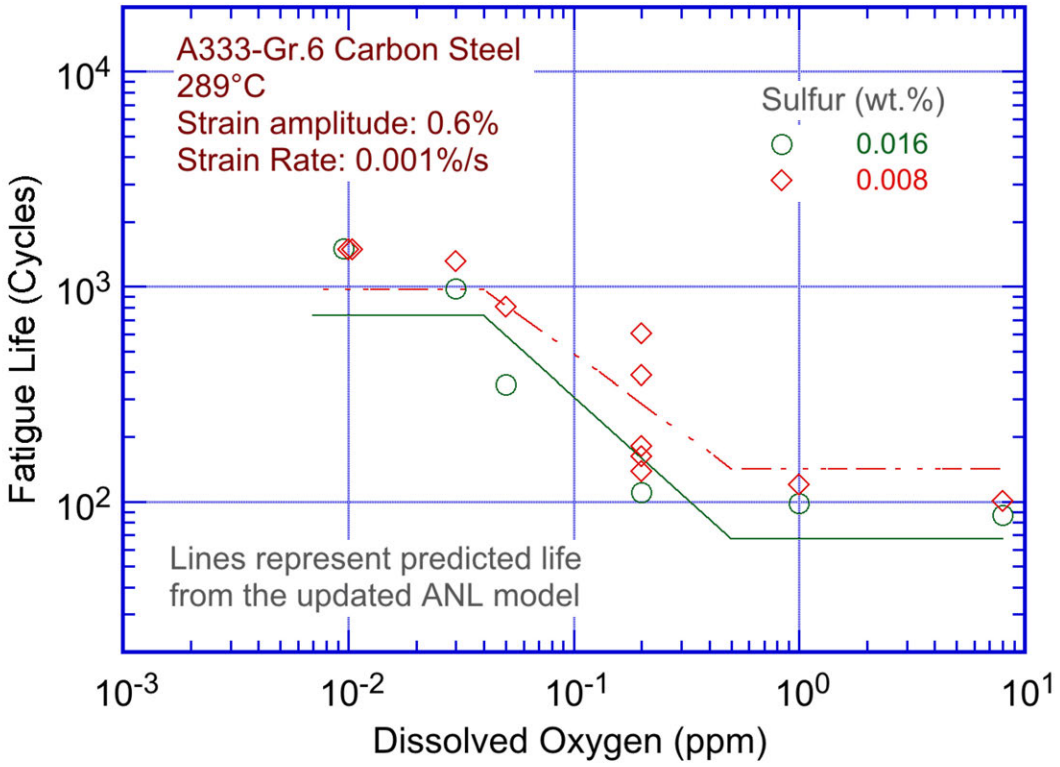


Figure 4-12(a)

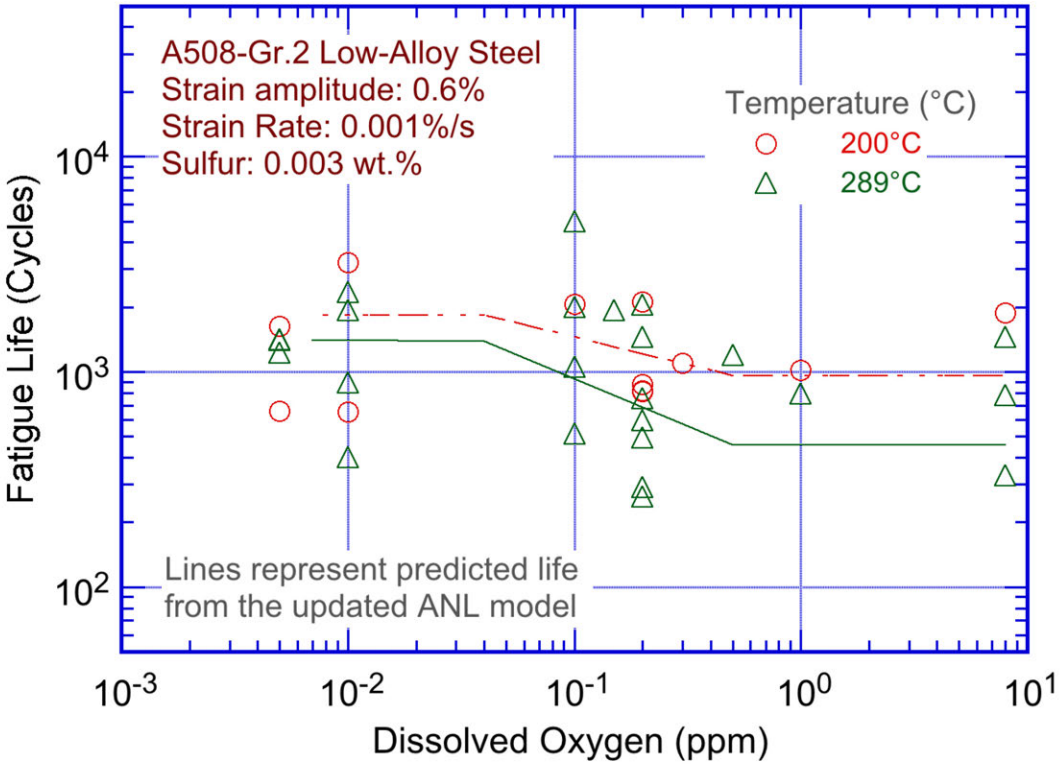


Figure 4-12(b)

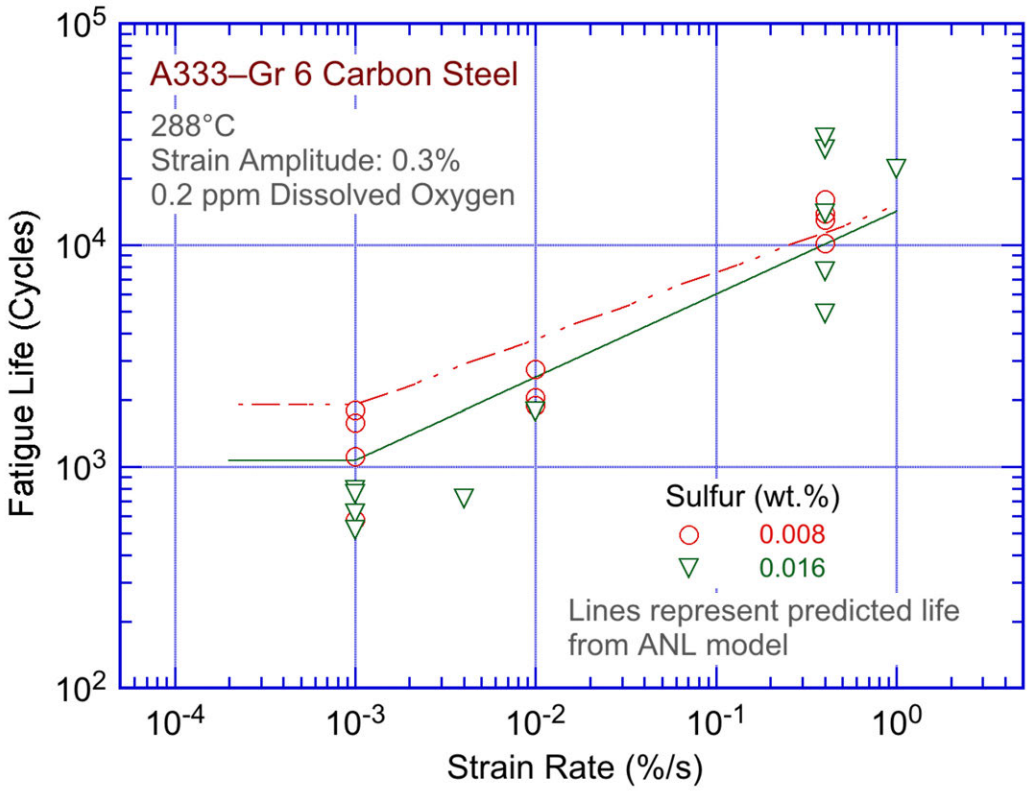


Figure 4-13(a)

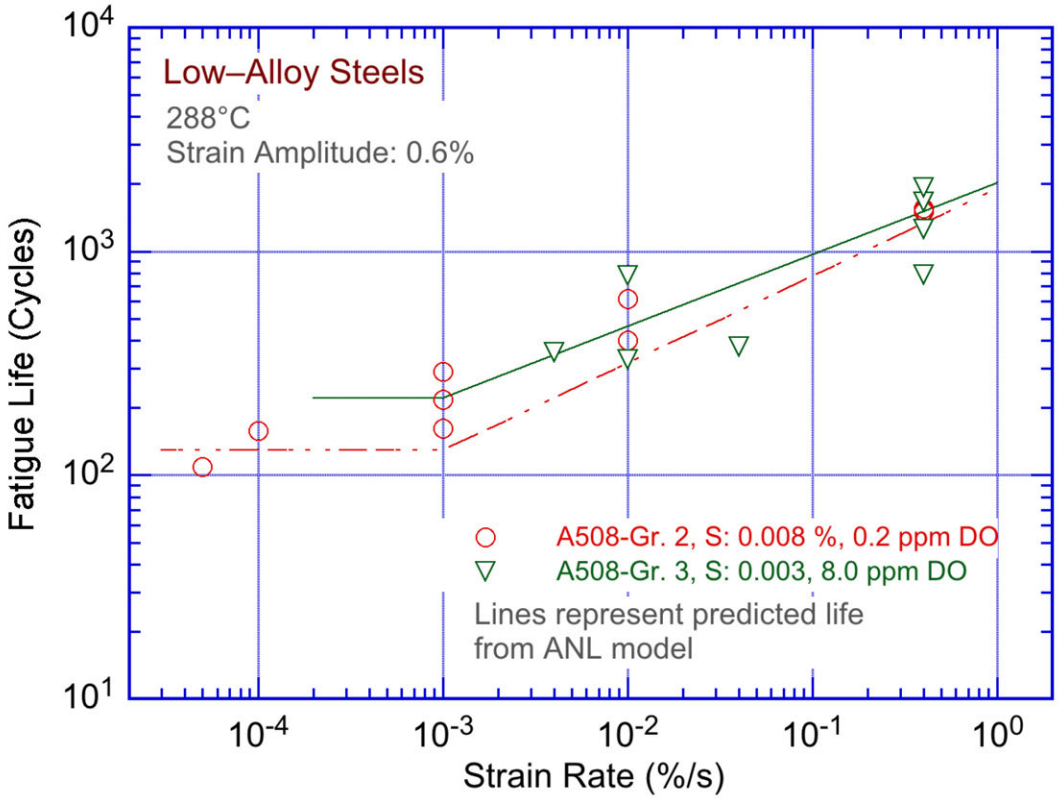


Figure 4-13(b)

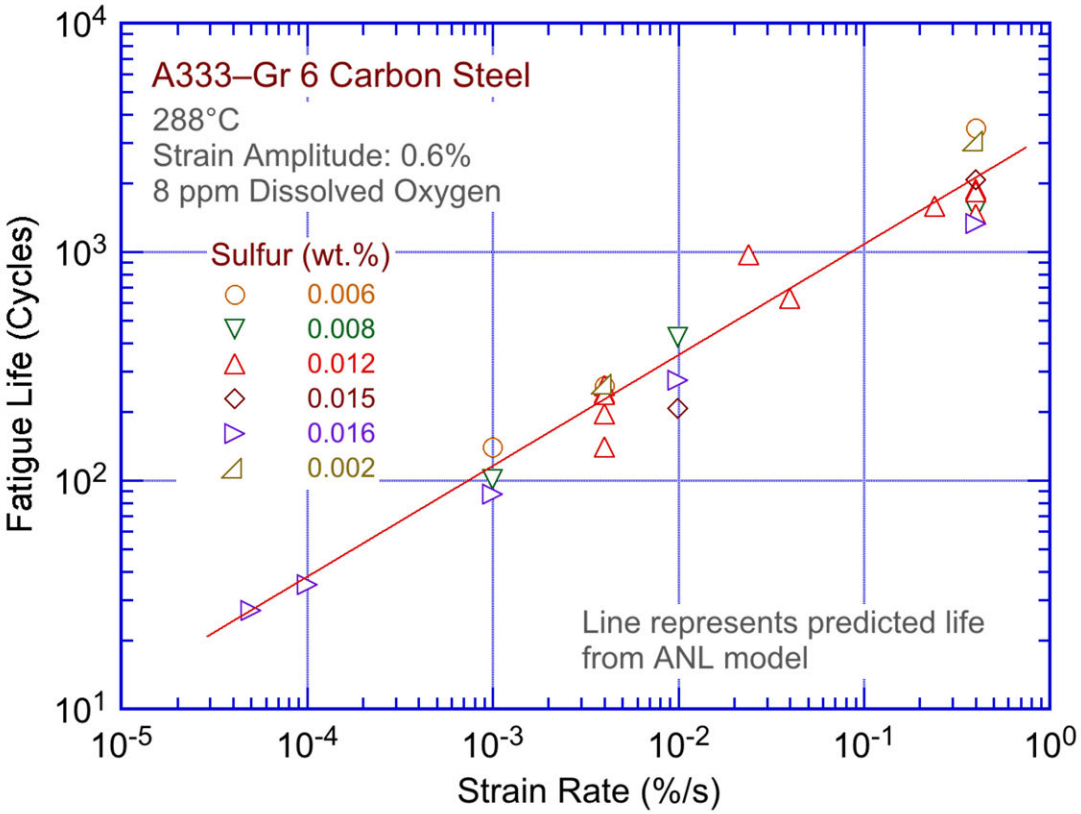

A333–Gr 6 Carbon Steel
288°C
Strain Amplitude: 0.6%
8 ppm Dissolved Oxygen
Sulfur (wt.%)
0.006
0.008
0.012
0.015
0.016
0.002
Line represents predicted life
from ANL model
Fatigue Life (Cycles)
Strain Rate (%/s)
10^4
10^3
10^2
10^1
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

Figure 4-14

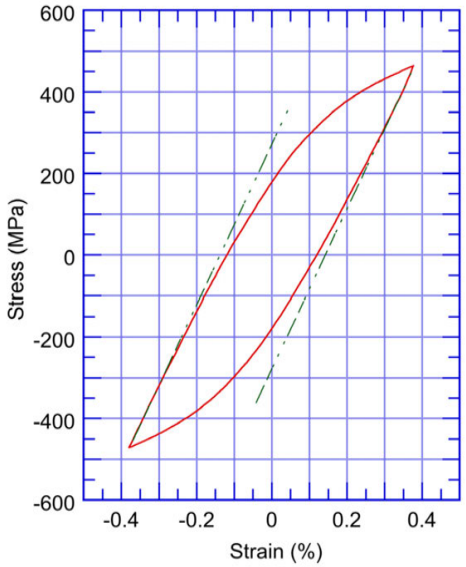


Figure 4-15 Fast-Fast

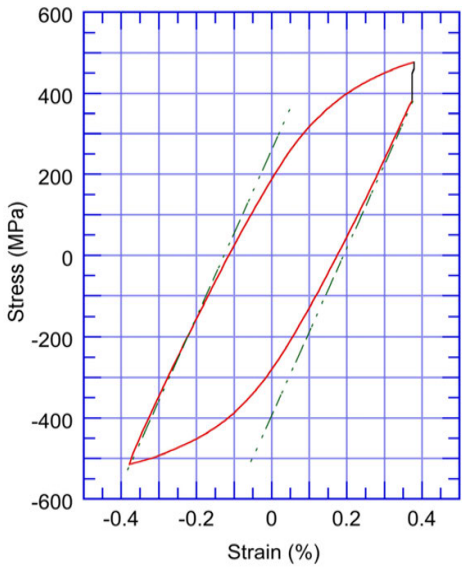


Figure 4-15 Strain Hold

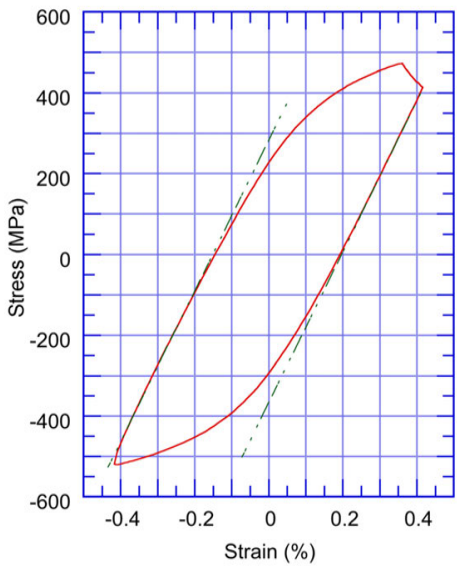


Figure 4-15 Stoke Hold

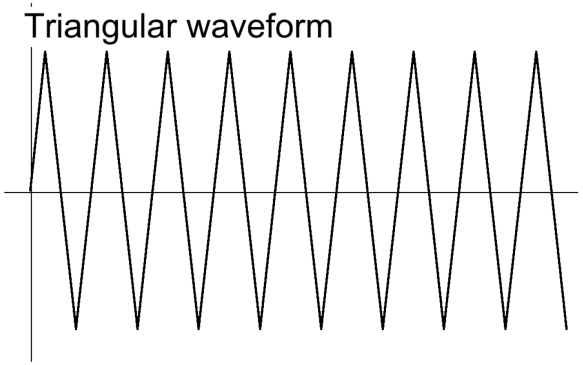


Figure 4-15 Fast-Fast

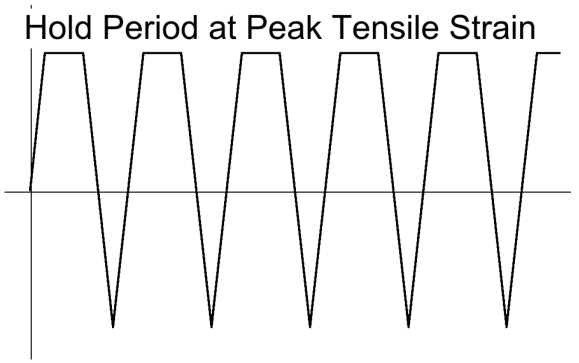


Figure 4-15 Hold

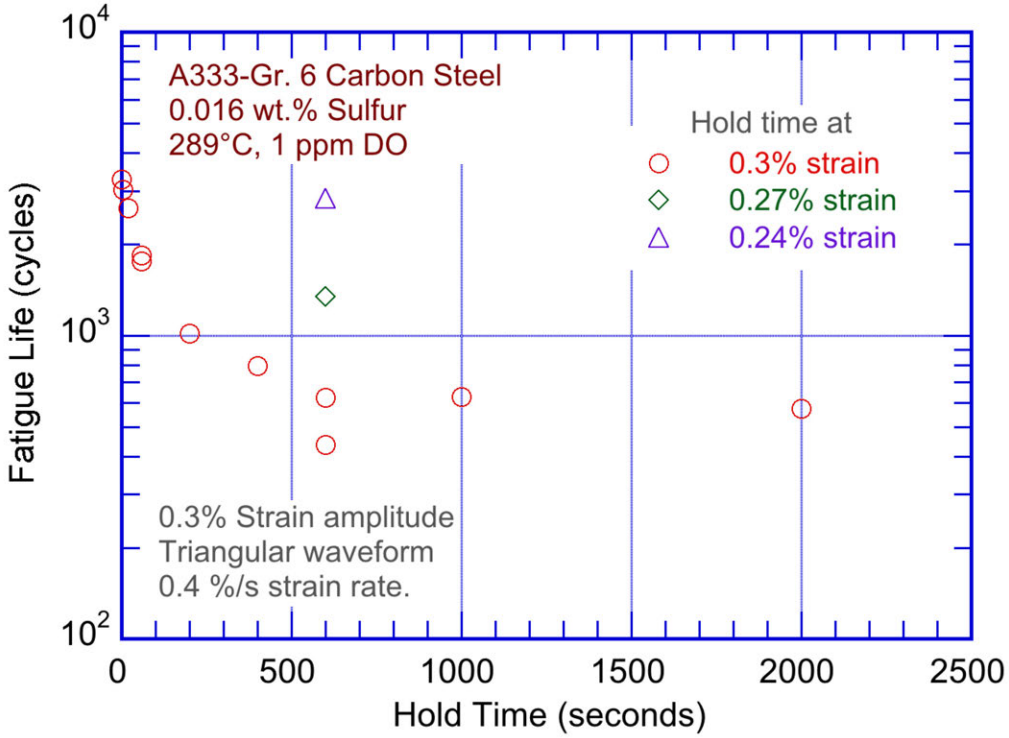


Figure 4-16(a)

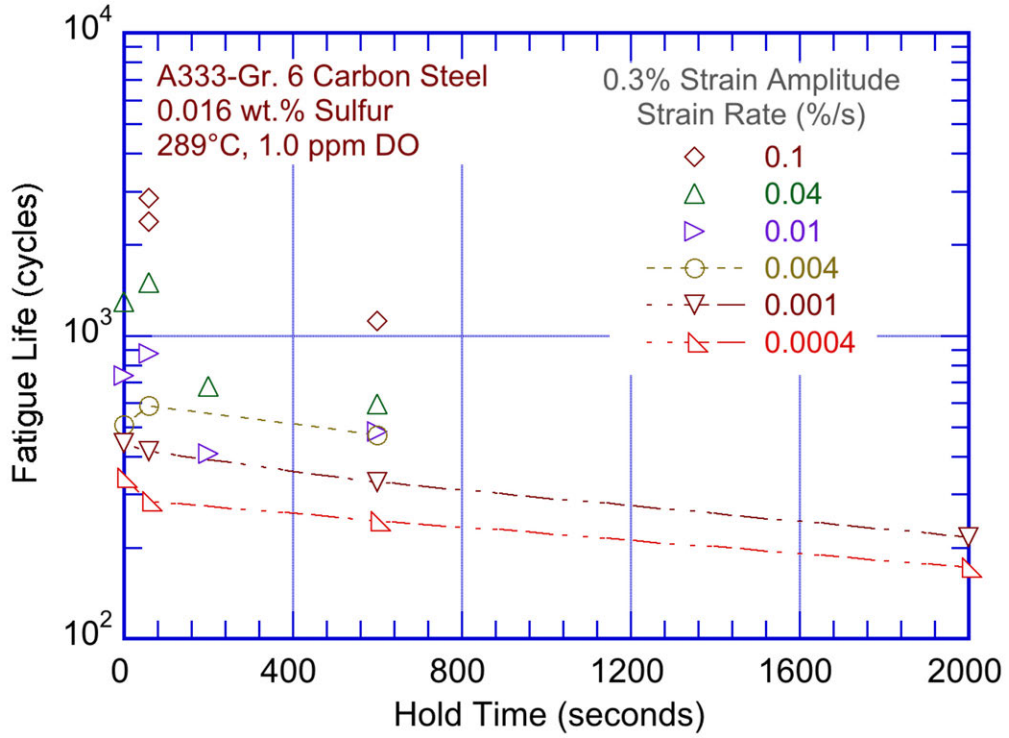


Figure 4-16(b)

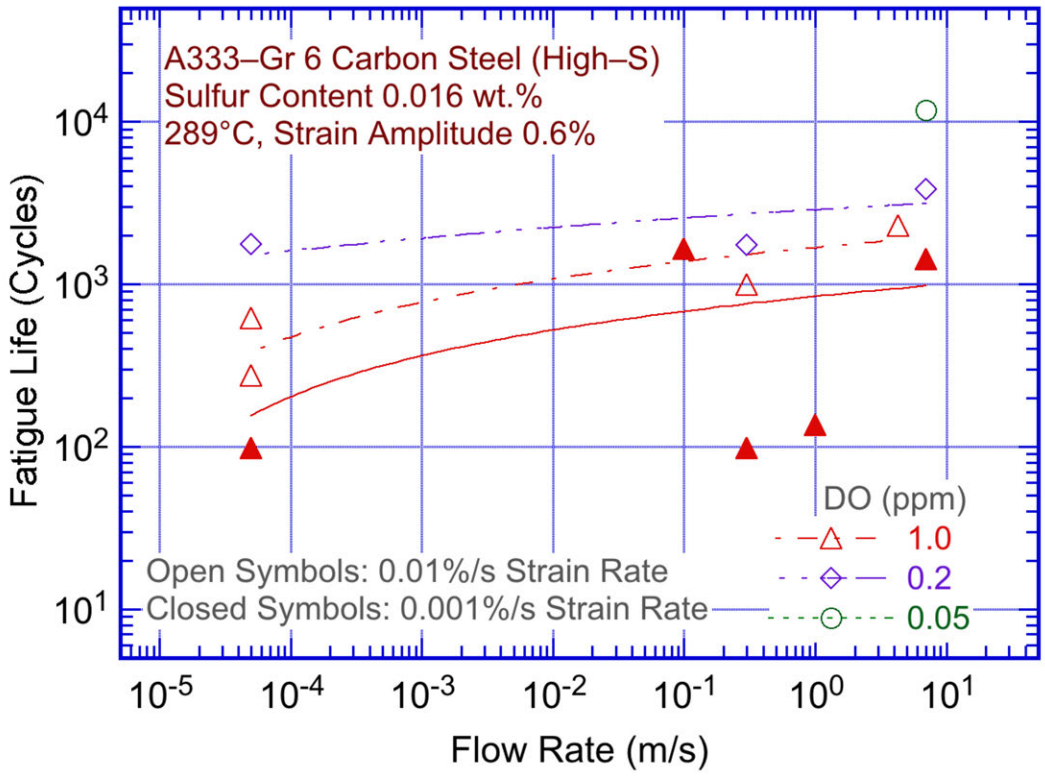


Figure 4-17(a)

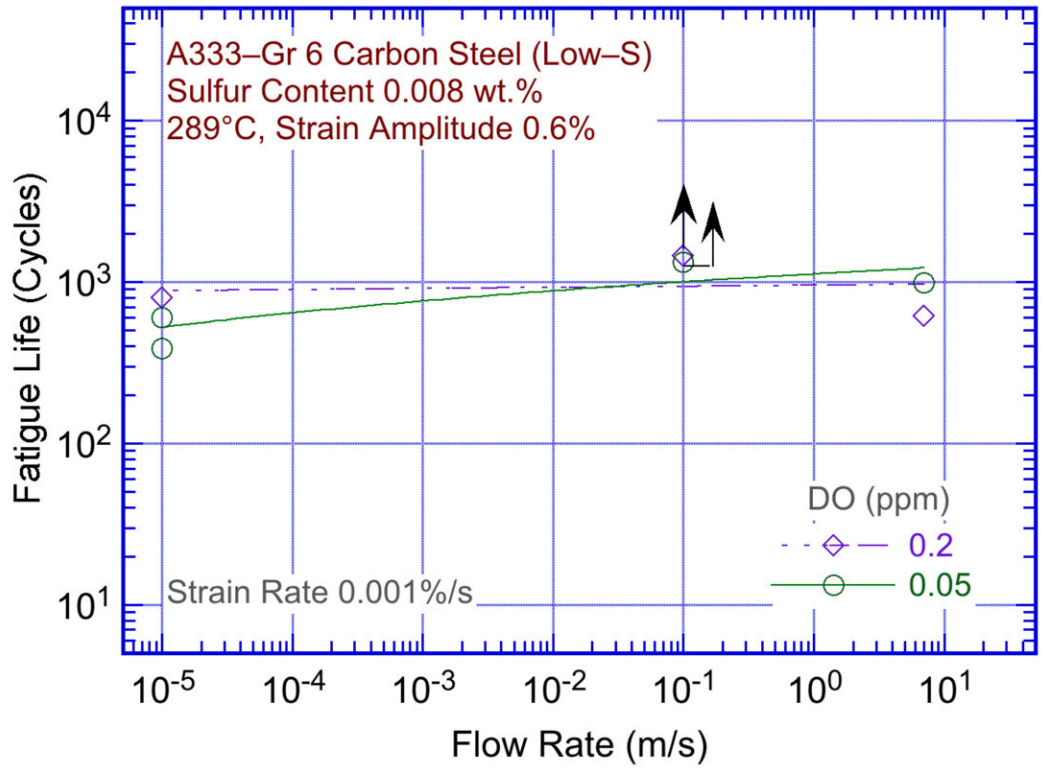


Figure 4-17(b)

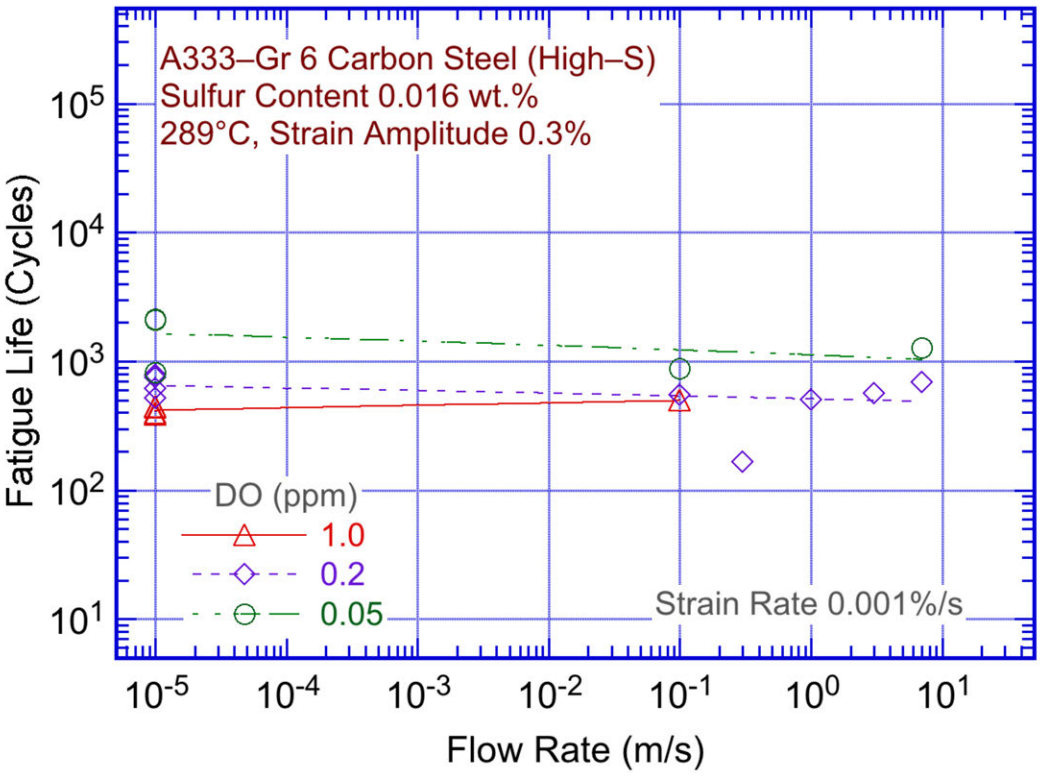


Figure 4-17(c)

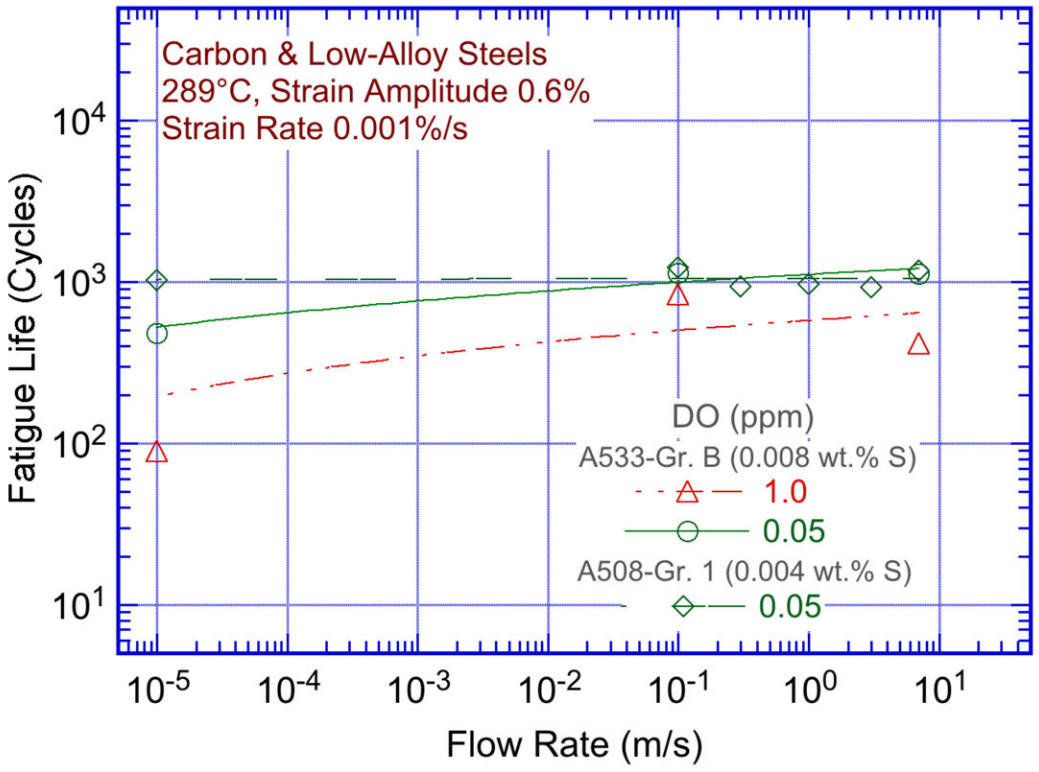


Figure 4-17(d)

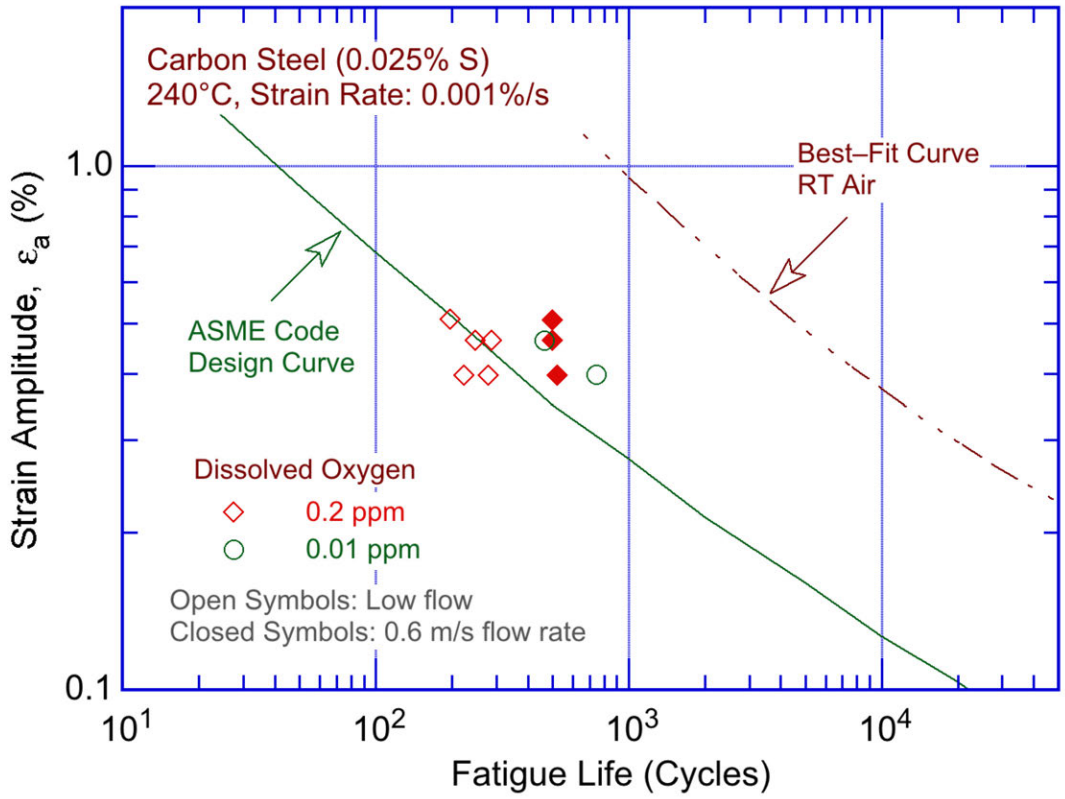

Carbon Steel (0.025% S)
240°C, Strain Rate: 0.001%/s
Best–Fit Curve
RT Air
ASME Code
Design Curve
Dissolved Oxygen
0.2 ppm
0.01 ppm
Open Symbols: Low flow
Closed Symbols: 0.6 m/s flow rate
Strain Amplitude, ε_a (%)
1.0
0.1
10^1
10^2
10^3
10^4
Fatigue Life (Cycles)

Figure 4-18

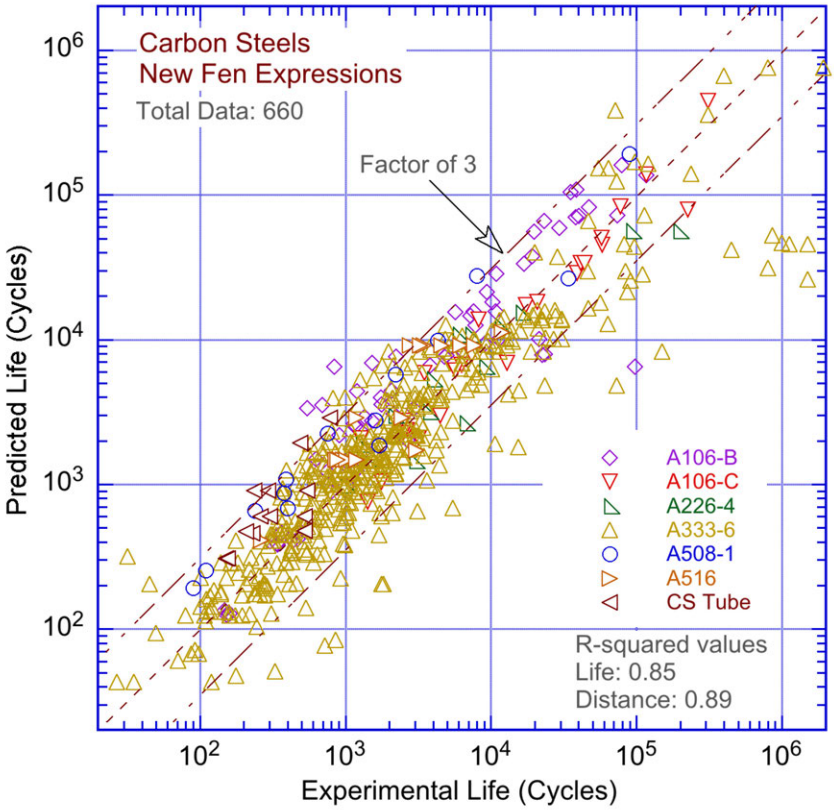


Figure 4-19(a)

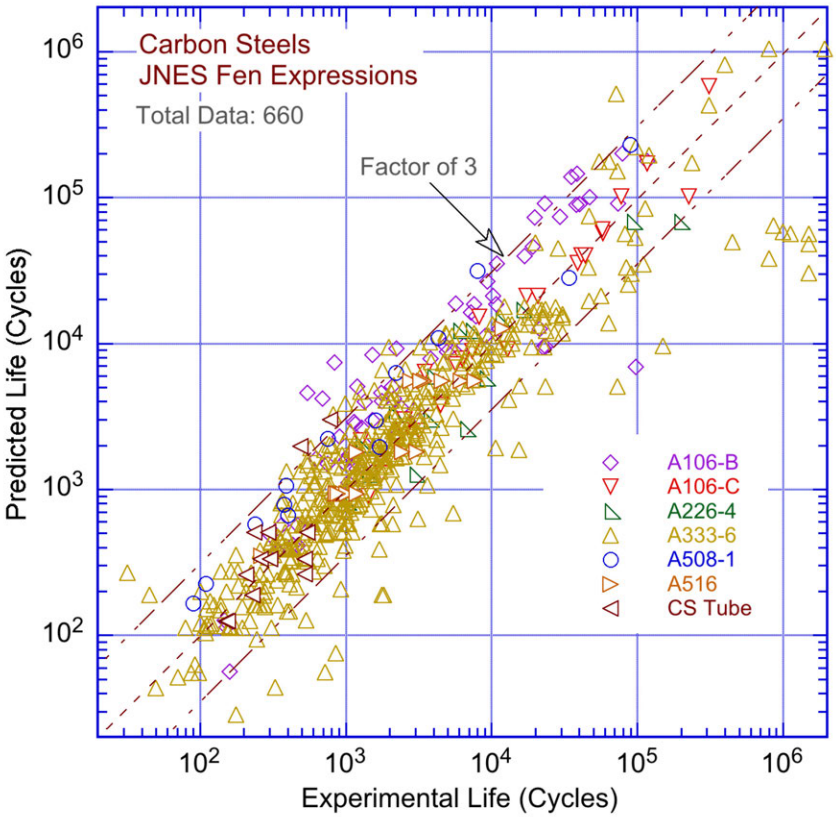


Figure 4-19(b)

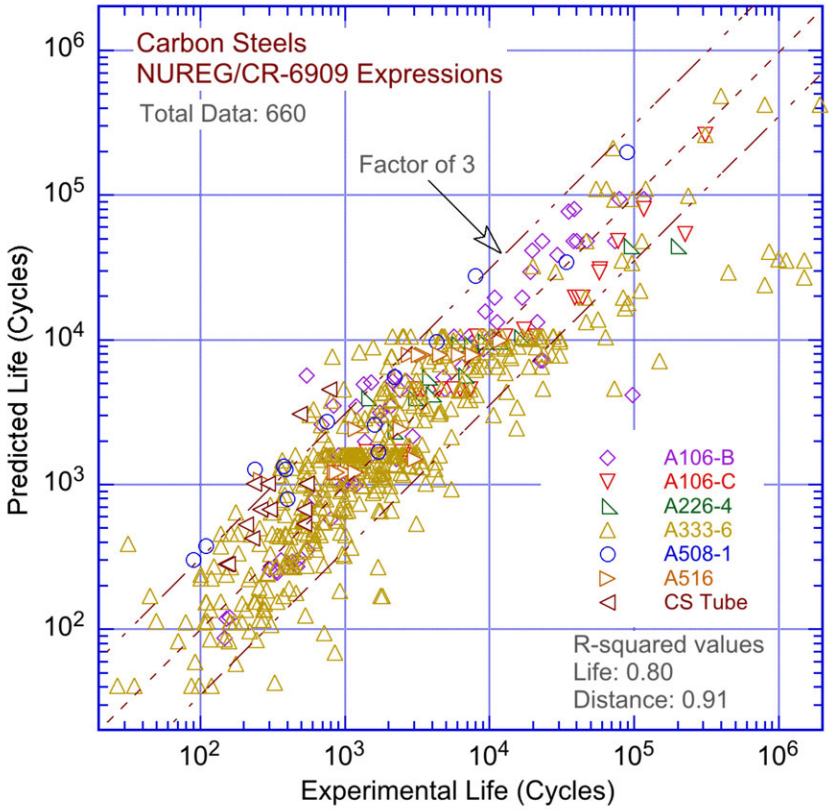


Figure 4-19(c)

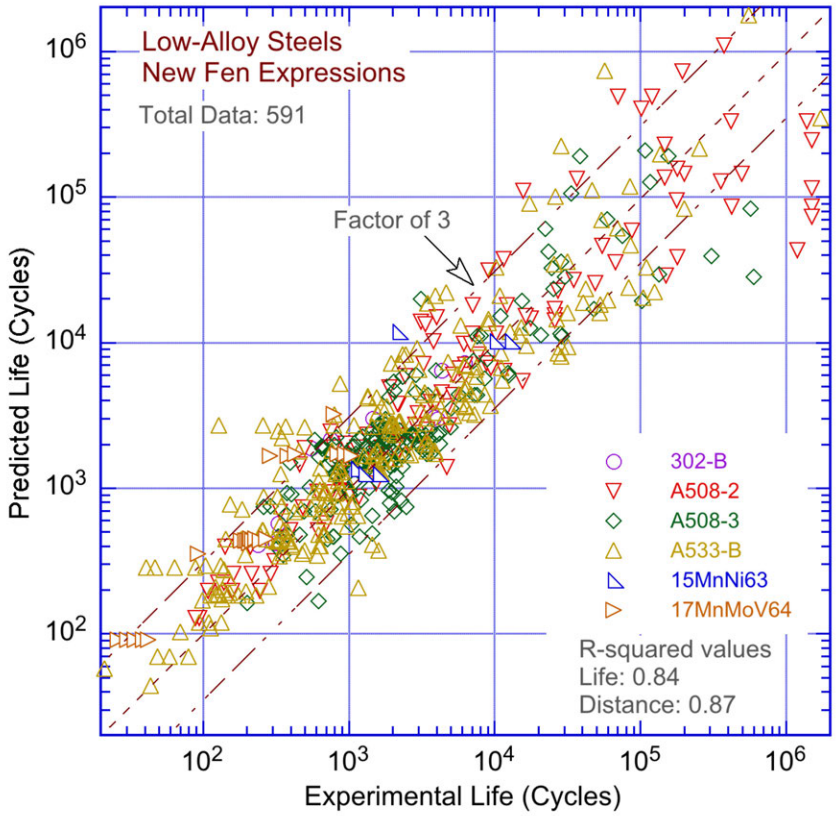


Figure 4-20(a)

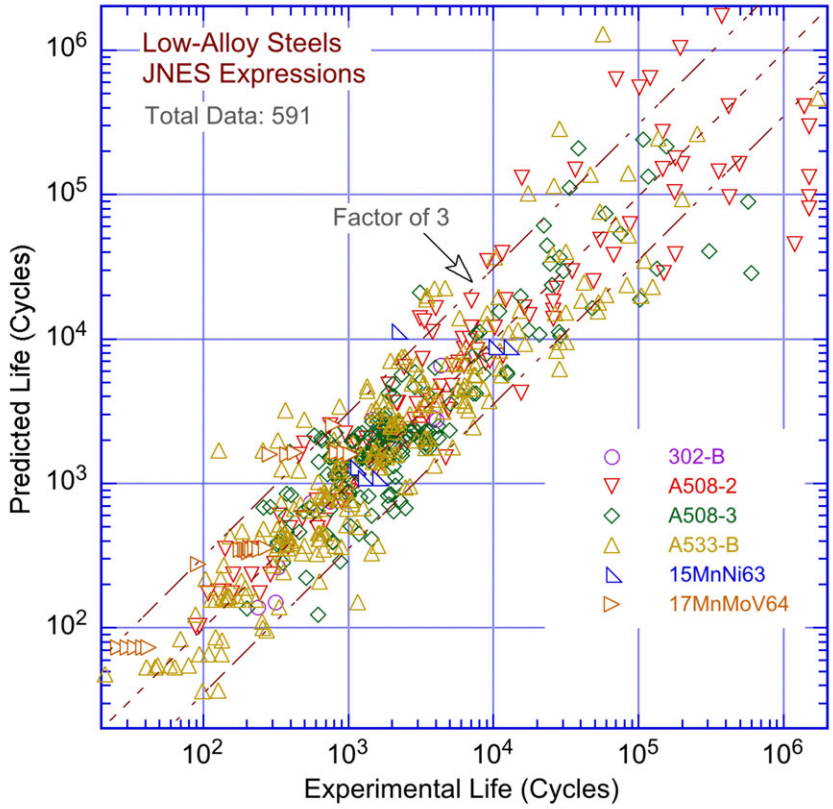


Figure 4-20(b)

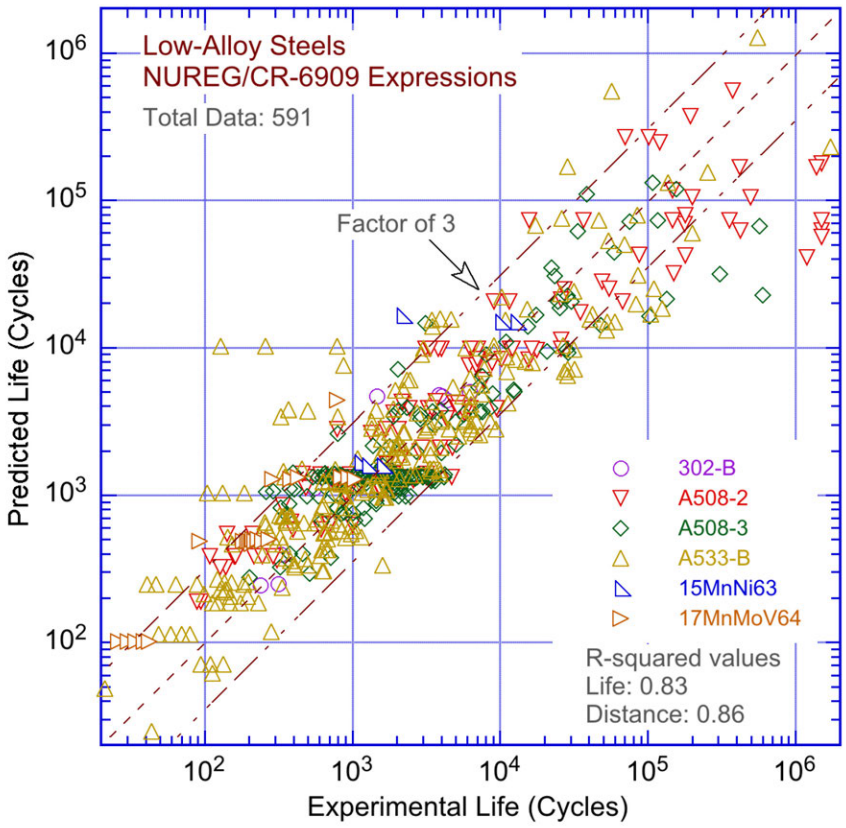


Figure 4-20(c)

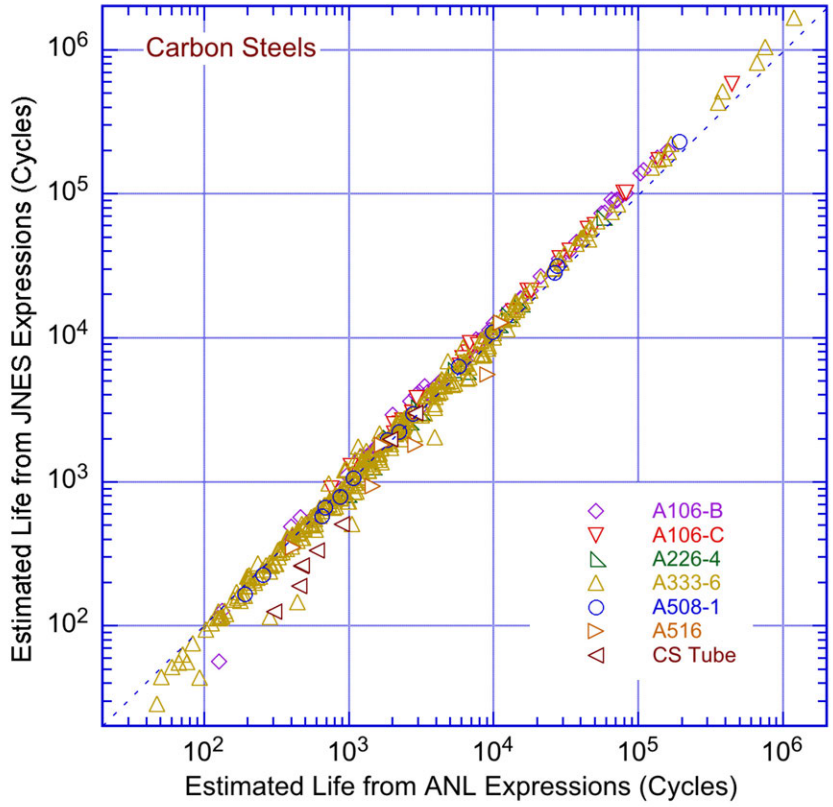


Figure 4-21(a)

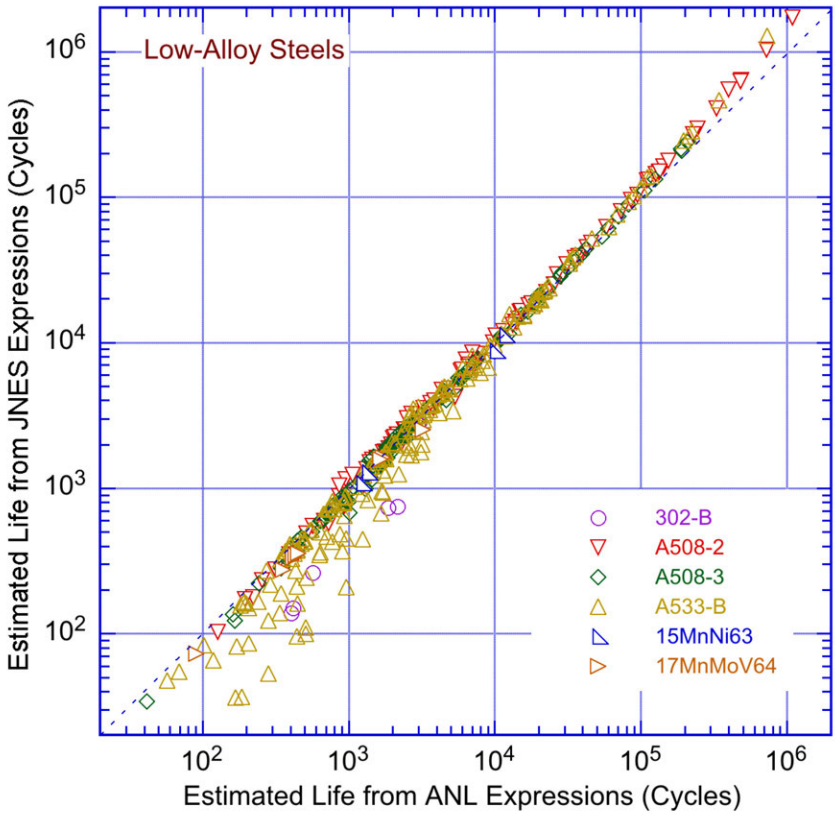


Figure 4-21(b)

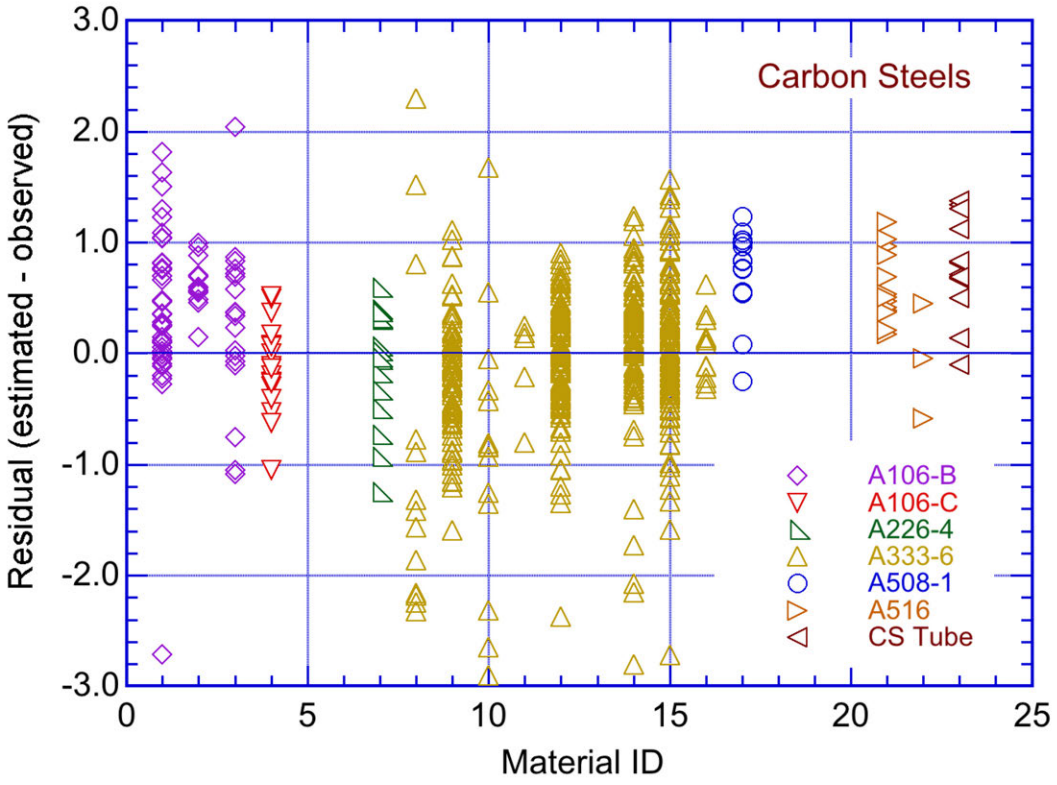


Figure 4-22(a)

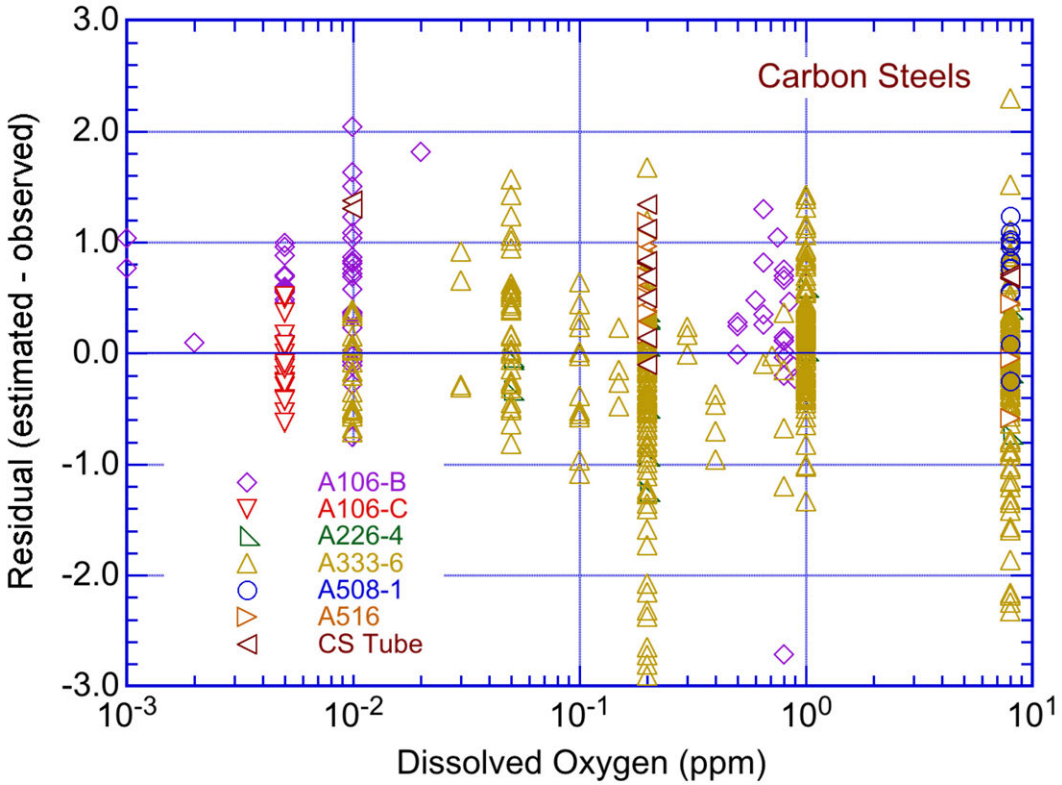


Figure 4-22(b)

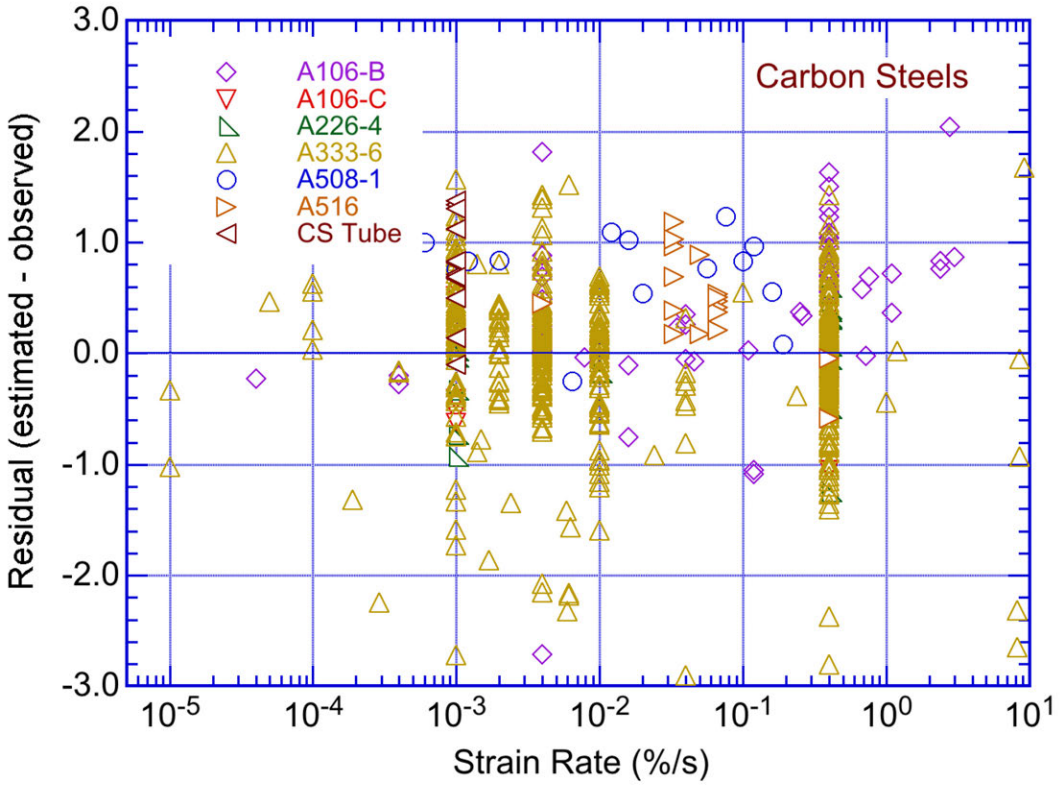


Figure 4-22(c)

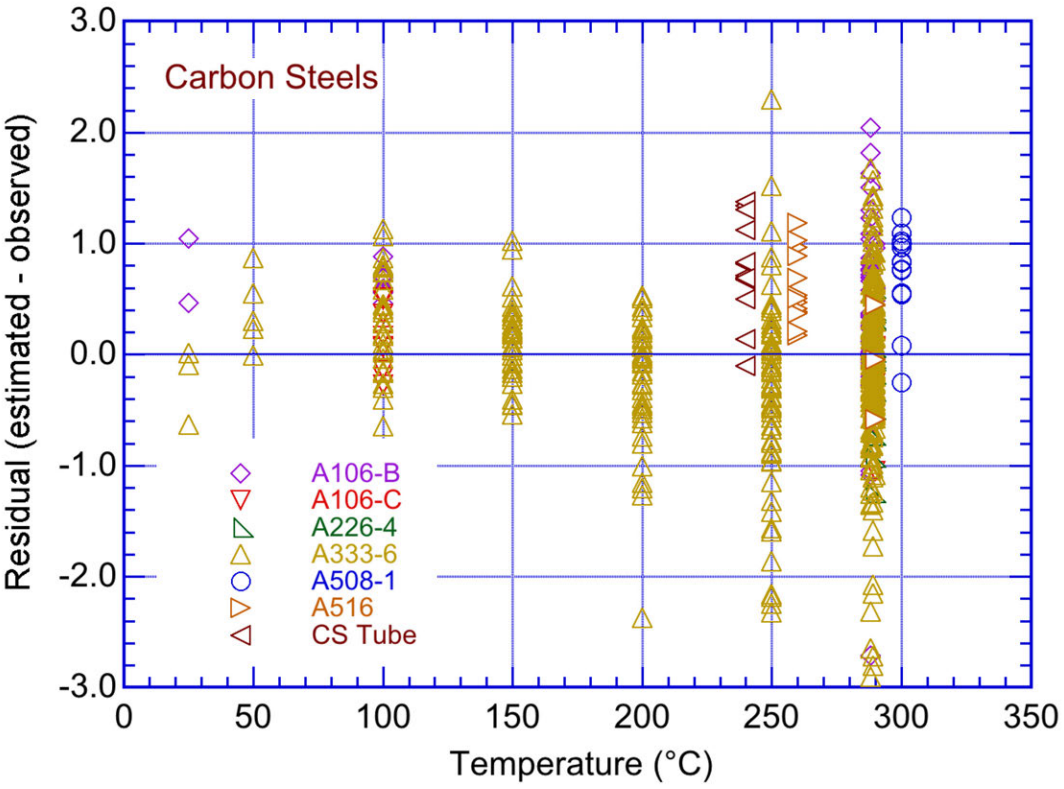


Figure 4-22(d)

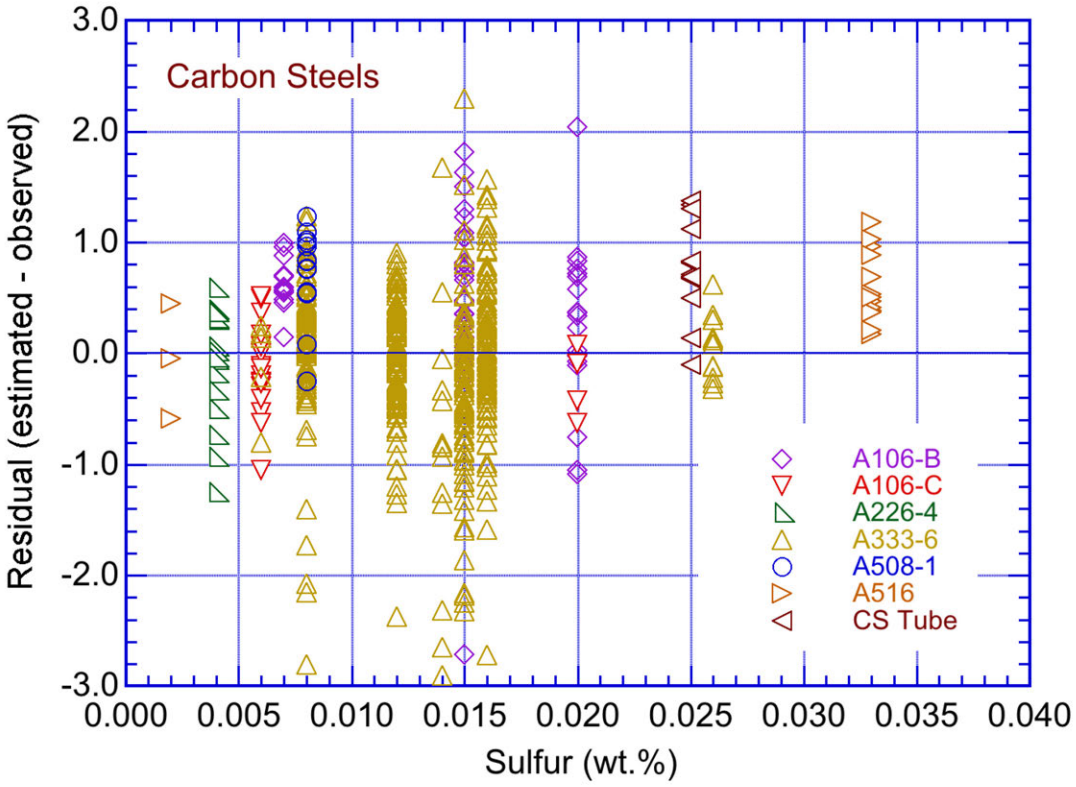


Figure 4-22(e)

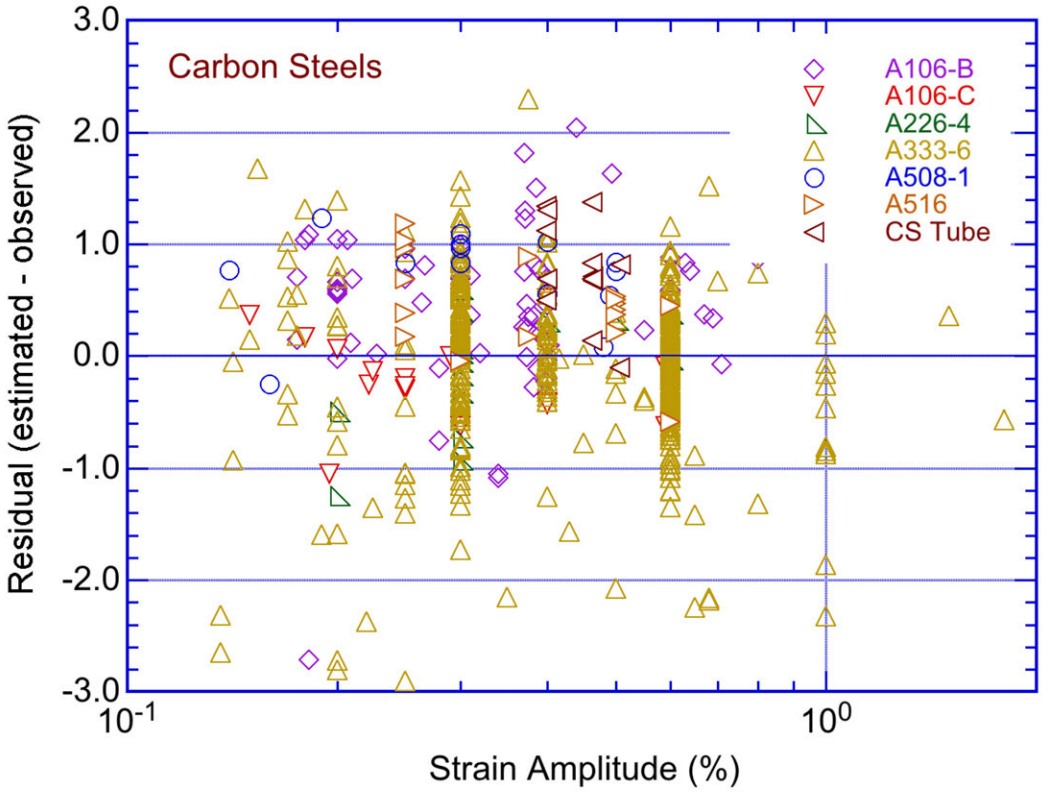


Figure 4-22(f)

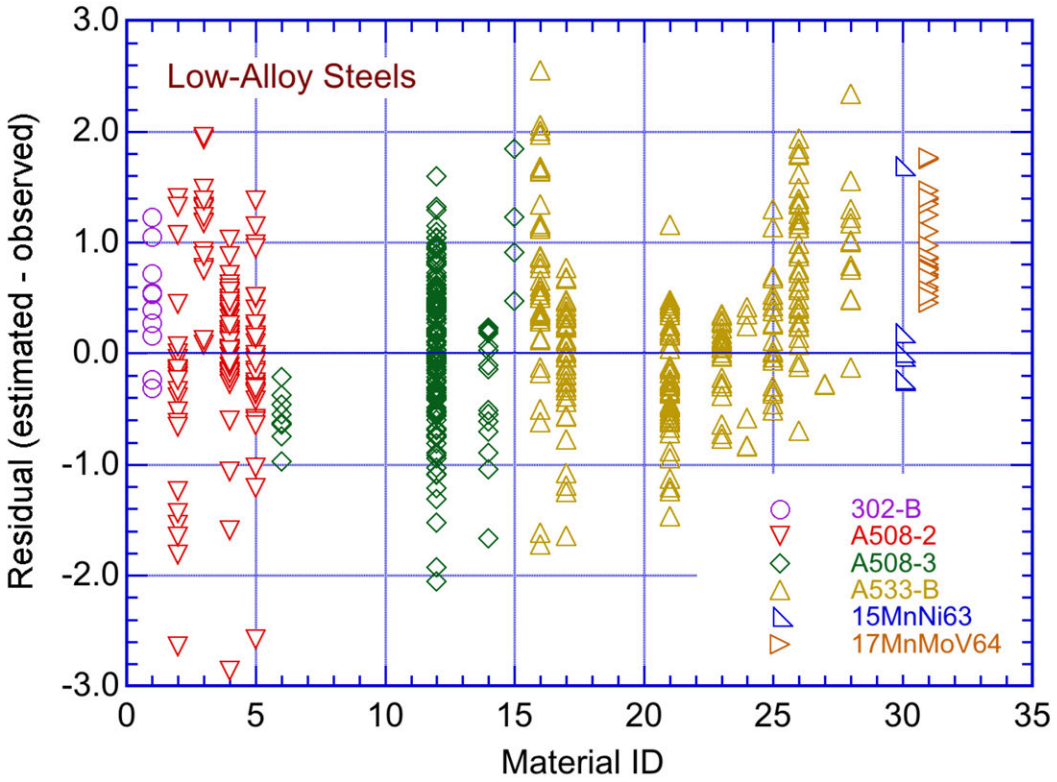


Figure 4-23(a)

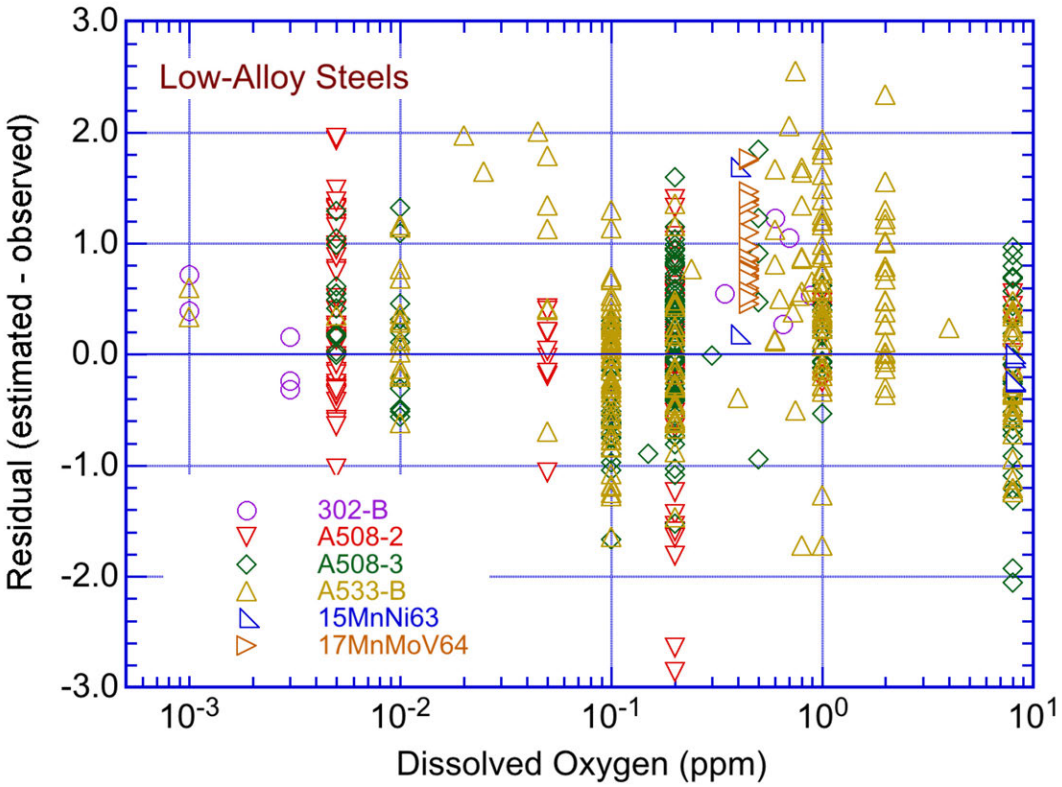


Figure 4-23(b)

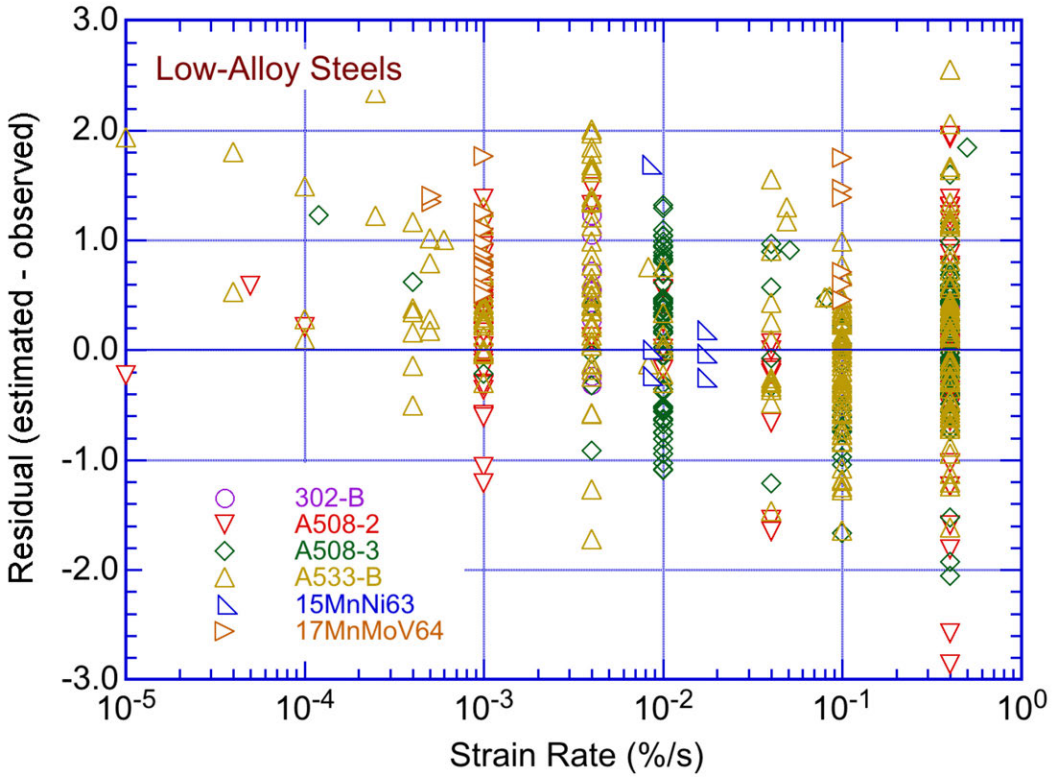


Figure 4-23(c)

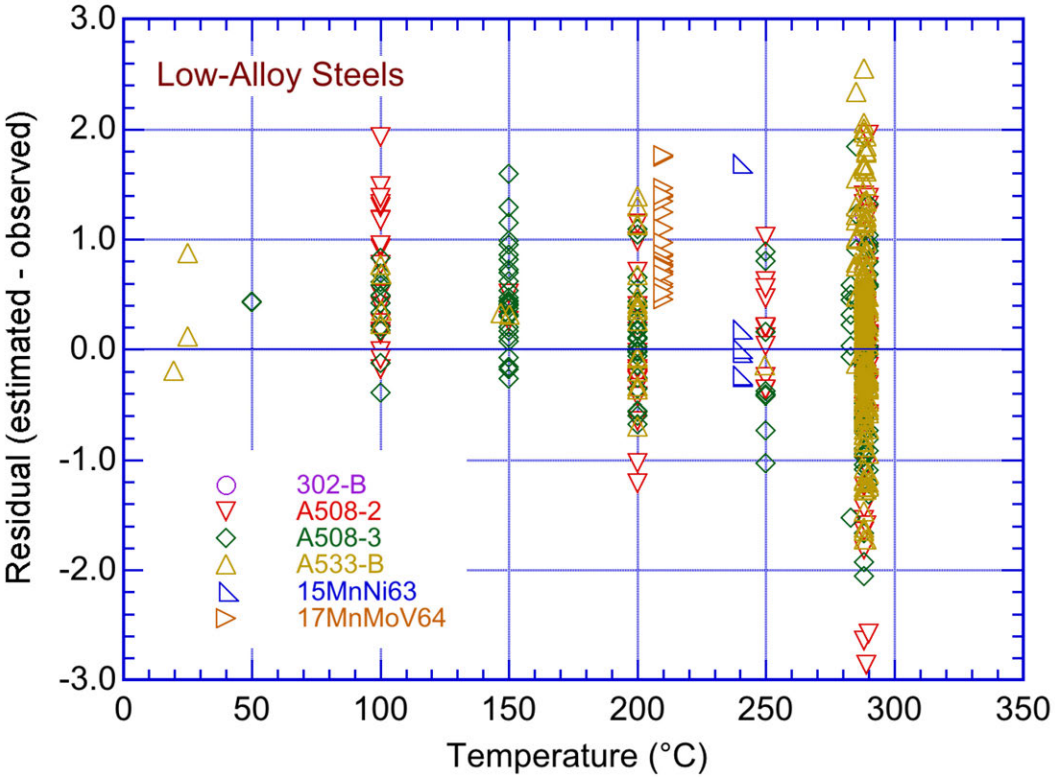


Figure 4-23(d)

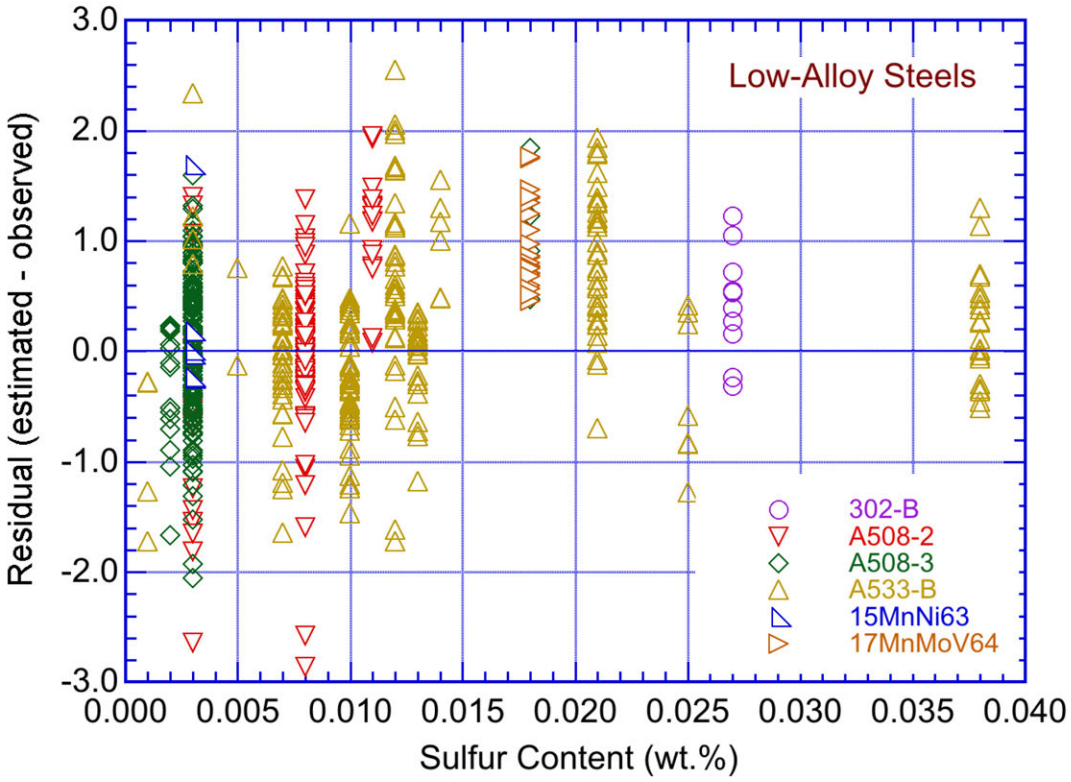


Figure 4-23(e)

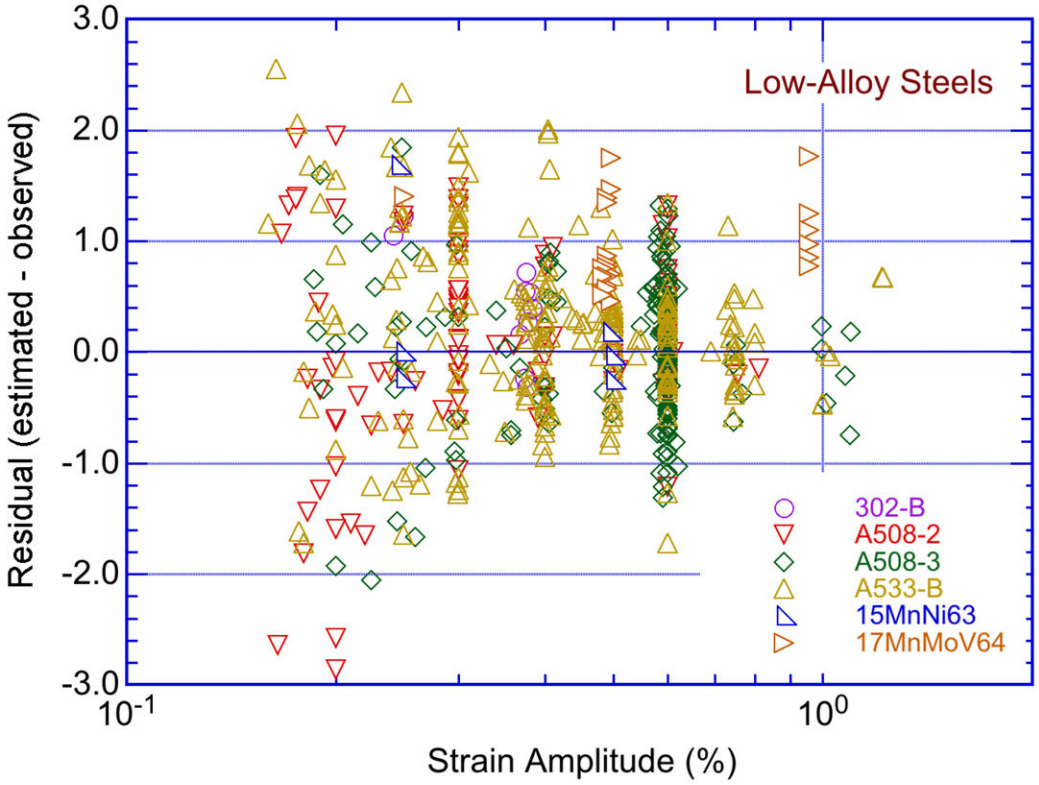


Figure 4-23(f)

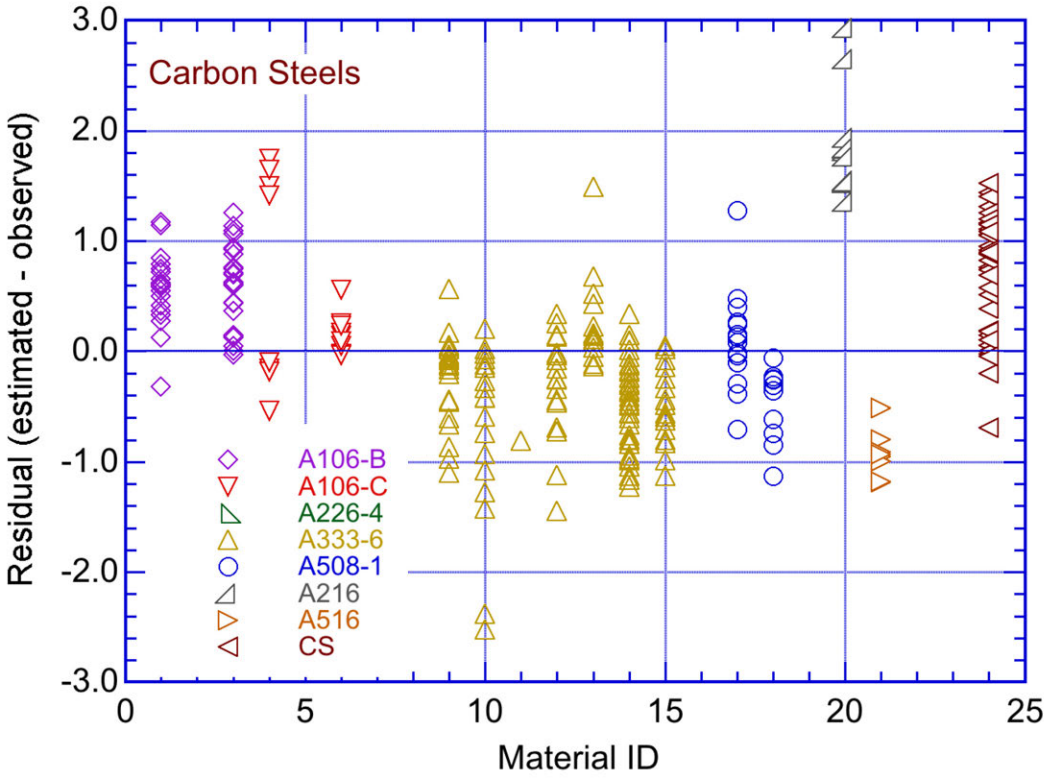


Figure 4-24(a)

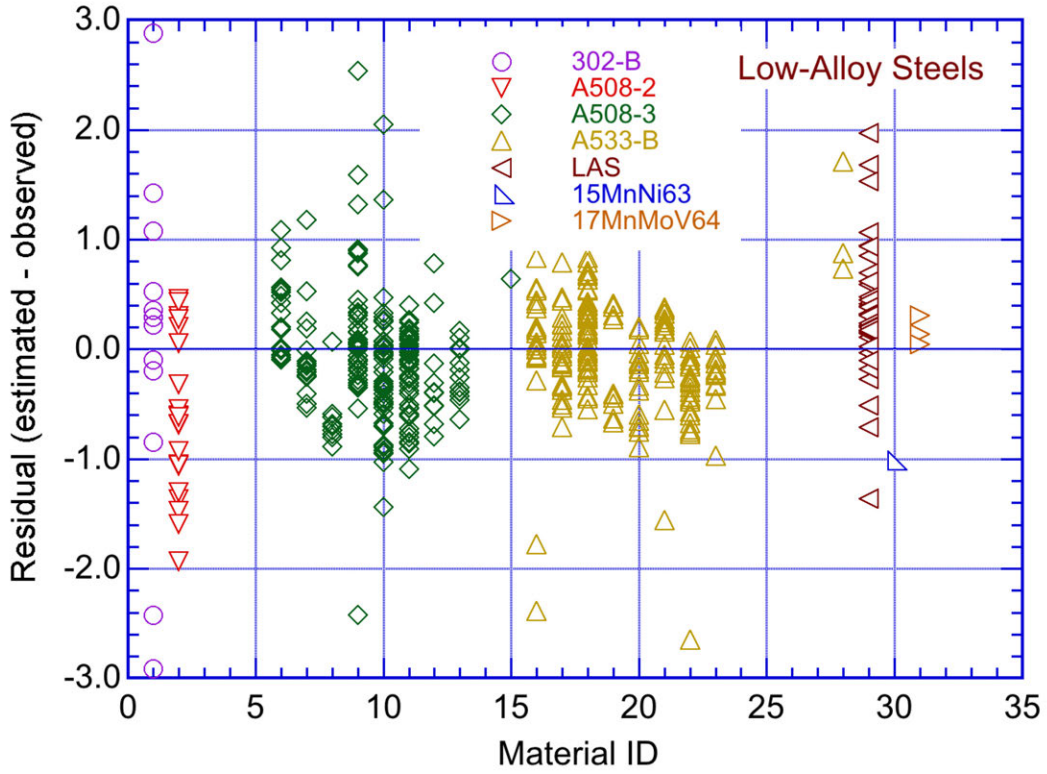


Figure 4-24(b)

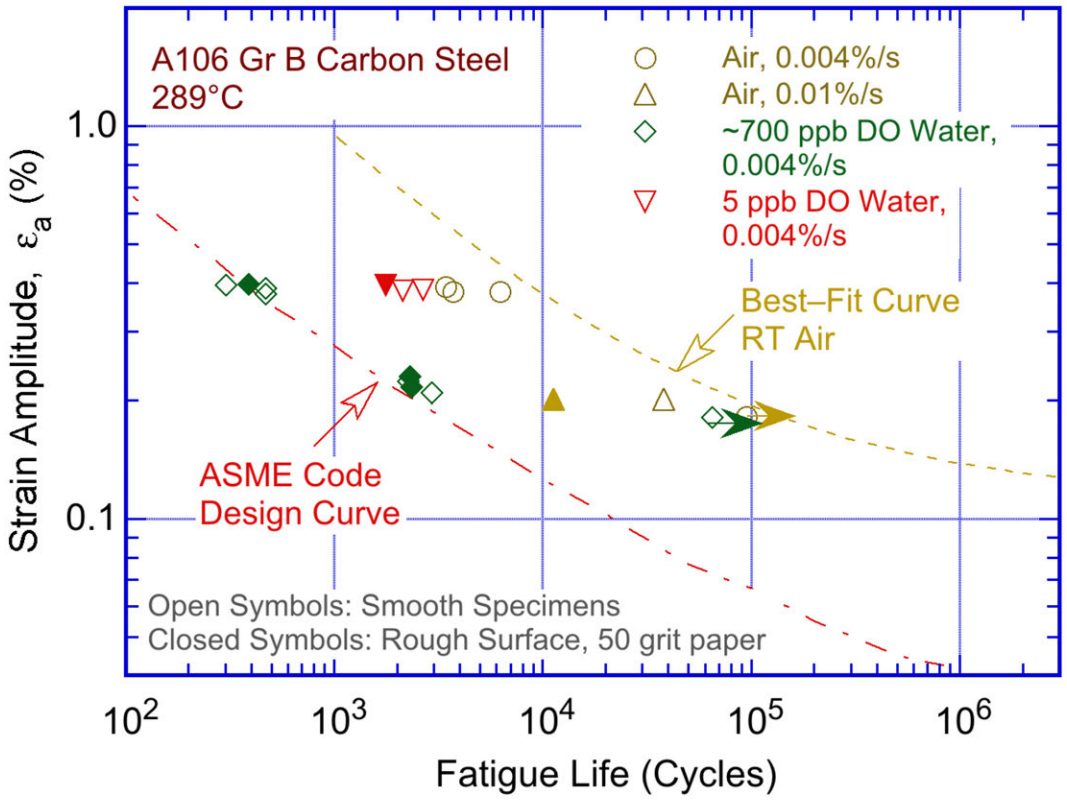


Figure 4-25(a)

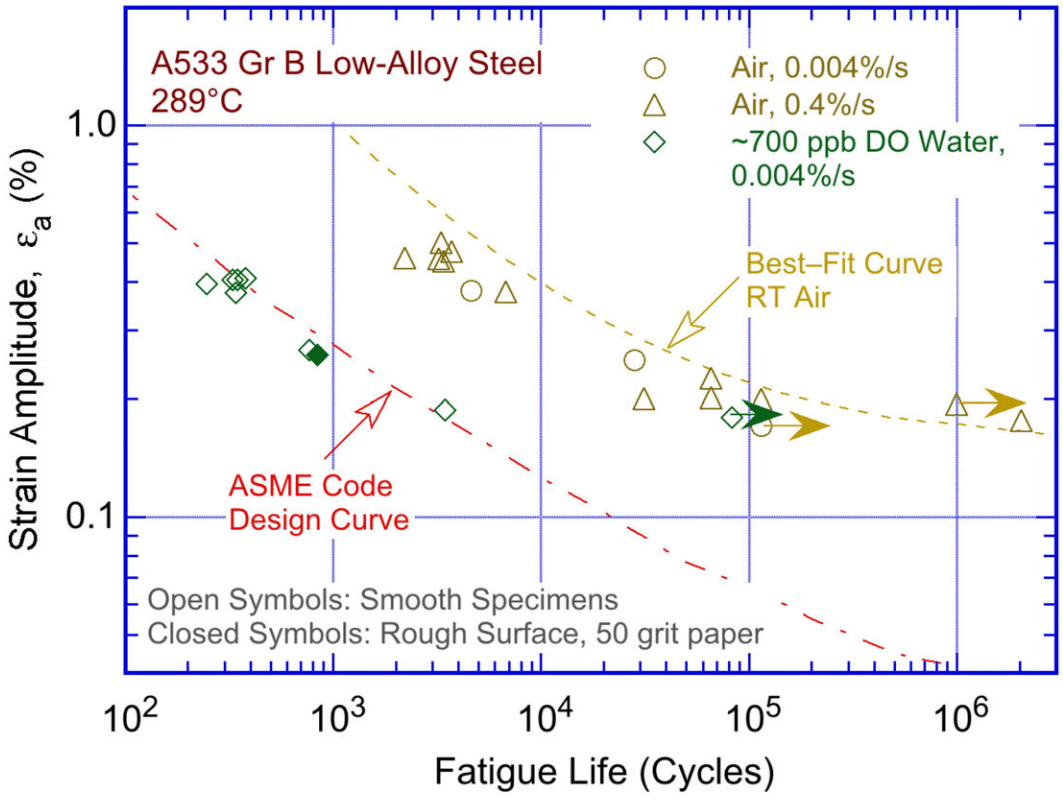


Figure 4-25(b)

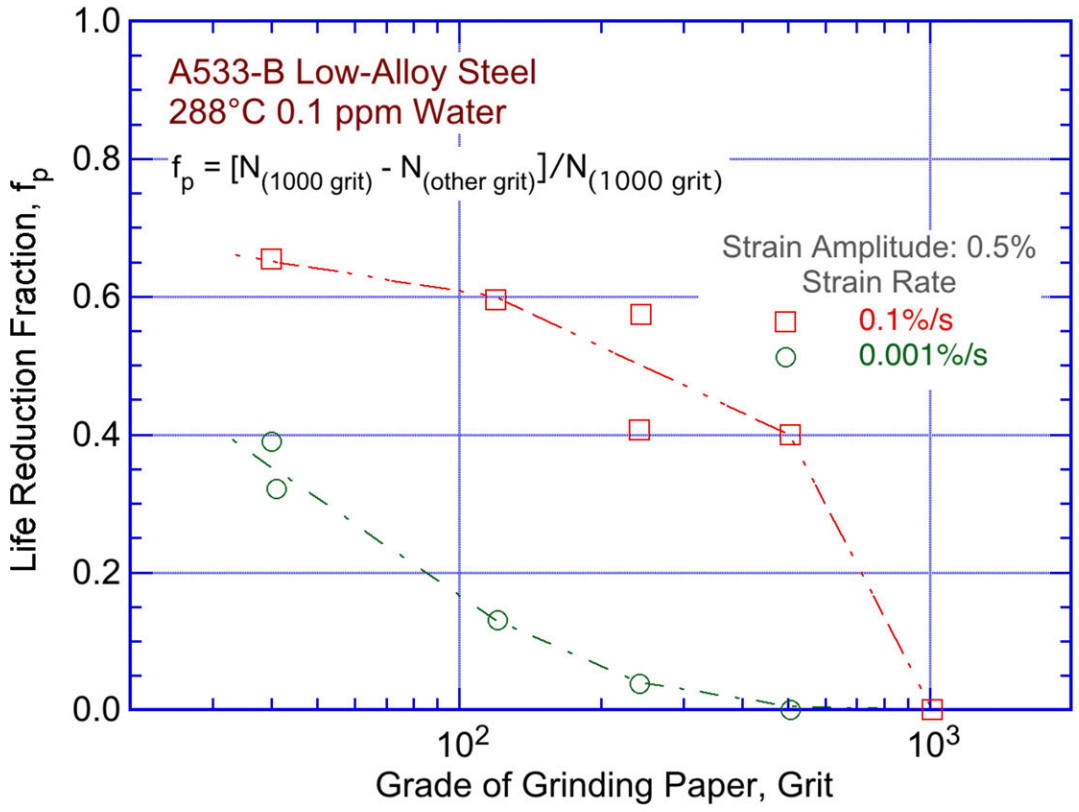

A533-B Low-Alloy Steel
288°C 0.1 ppm Water
$f_p = [N_{(1000\ grit)} - N_{(other\ grit)}]/N_{(1000\ grit)}$
Strain Amplitude: 0.5%
Strain Rate
0.1%/s
0.001%/s
Life Reduction Fraction, f_p
1.0
0.8
0.6
0.4
0.2
0.0
10^2
10^3
Grade of Grinding Paper, Grit

Figure 4-26

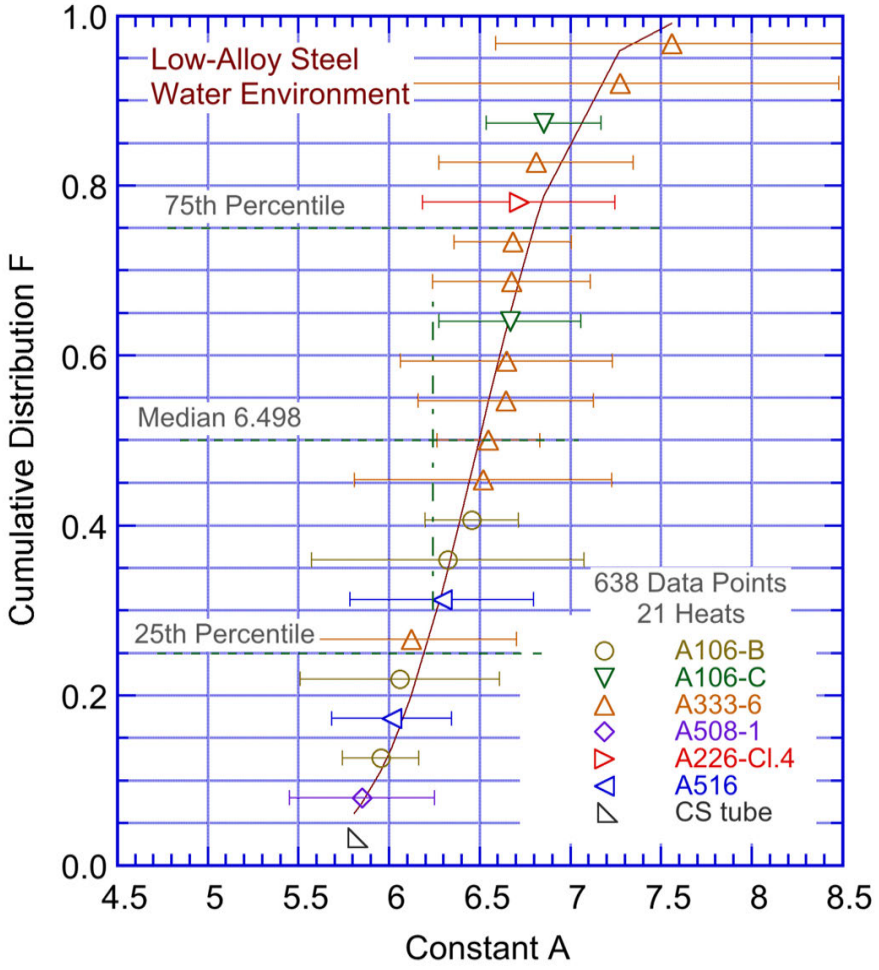


Figure 4-27(a)

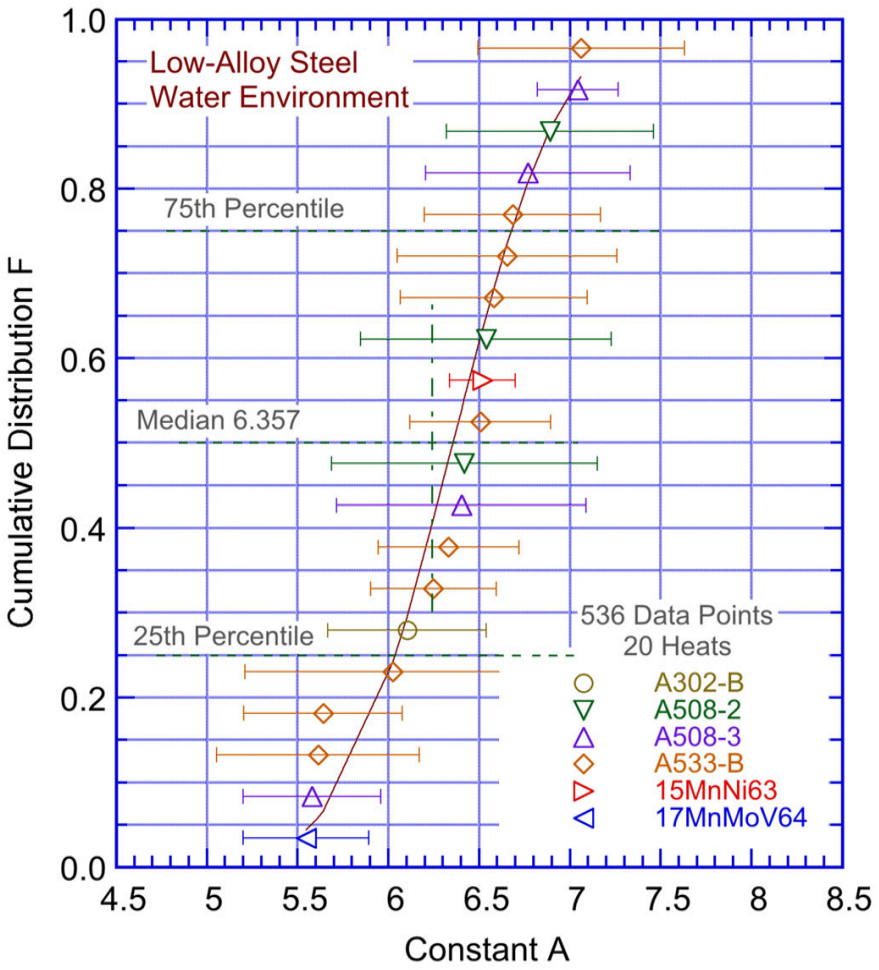


Figure 4-27(b)

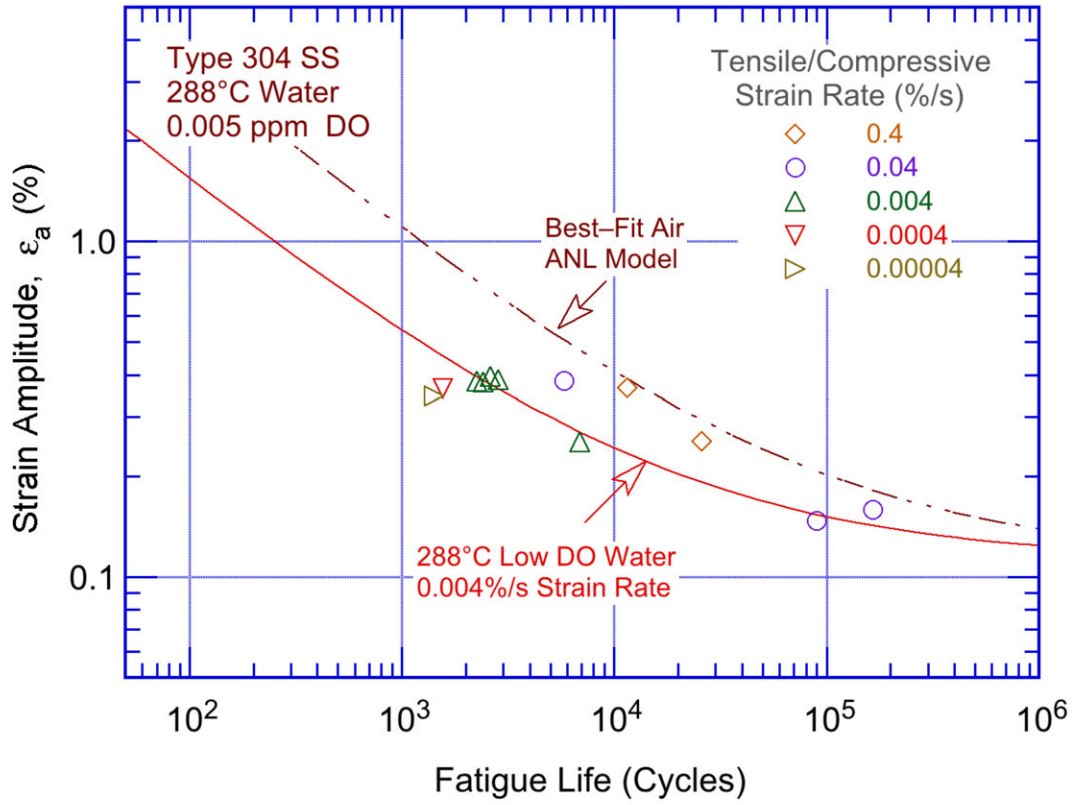


Figure 4-28(a)

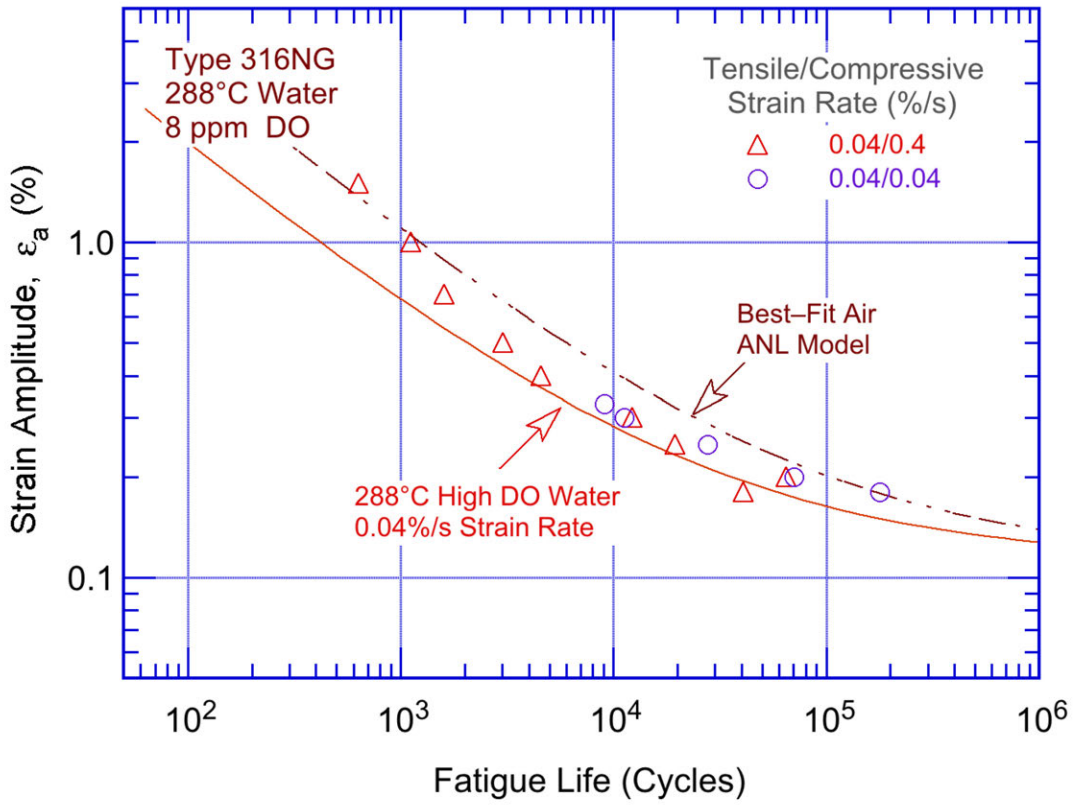


Figure 4-28(b)

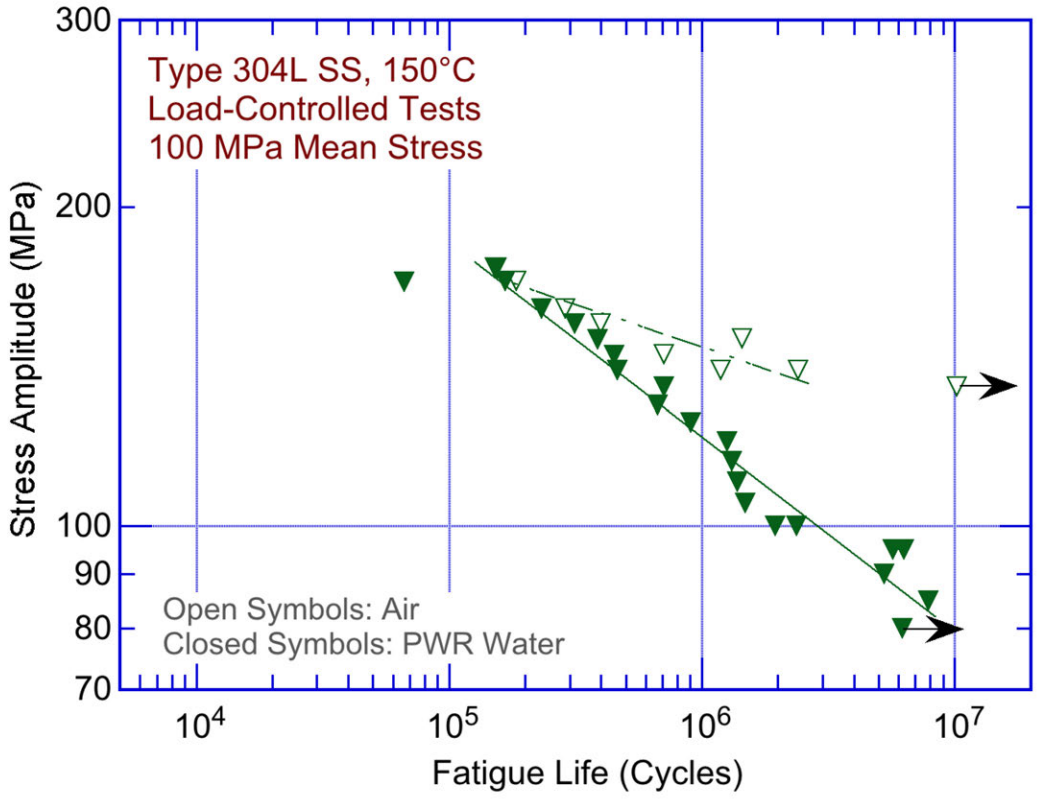


Figure 4-29(a)

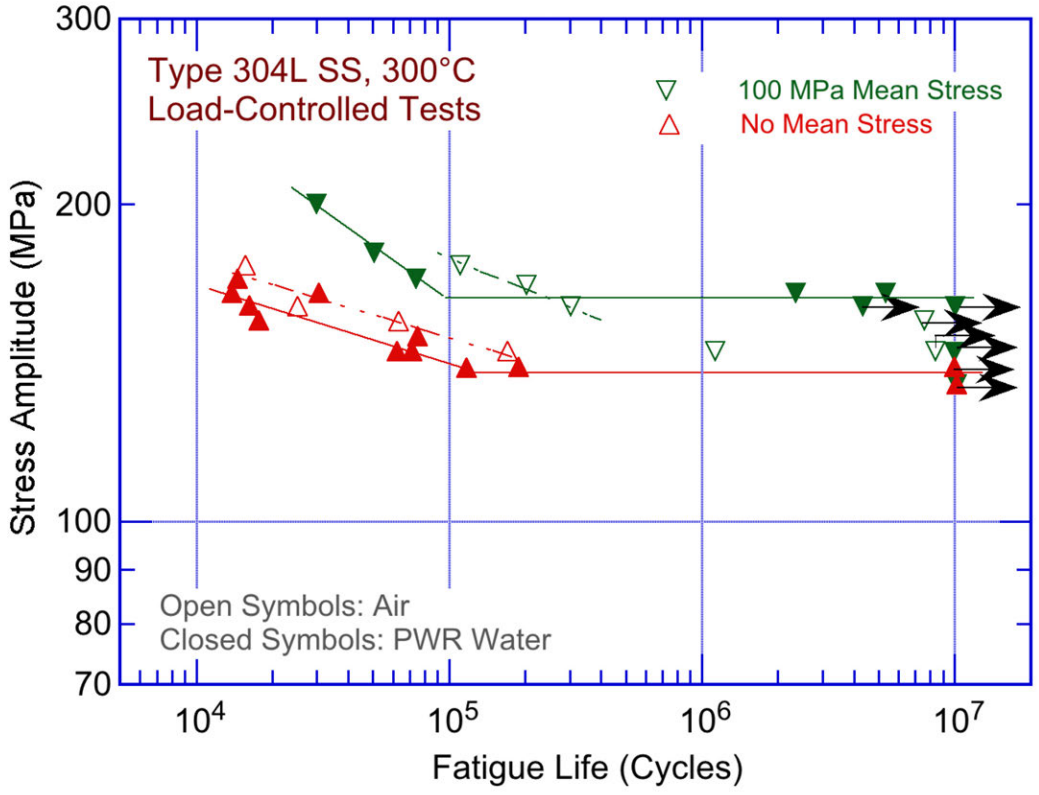


Figure 4-29(b)

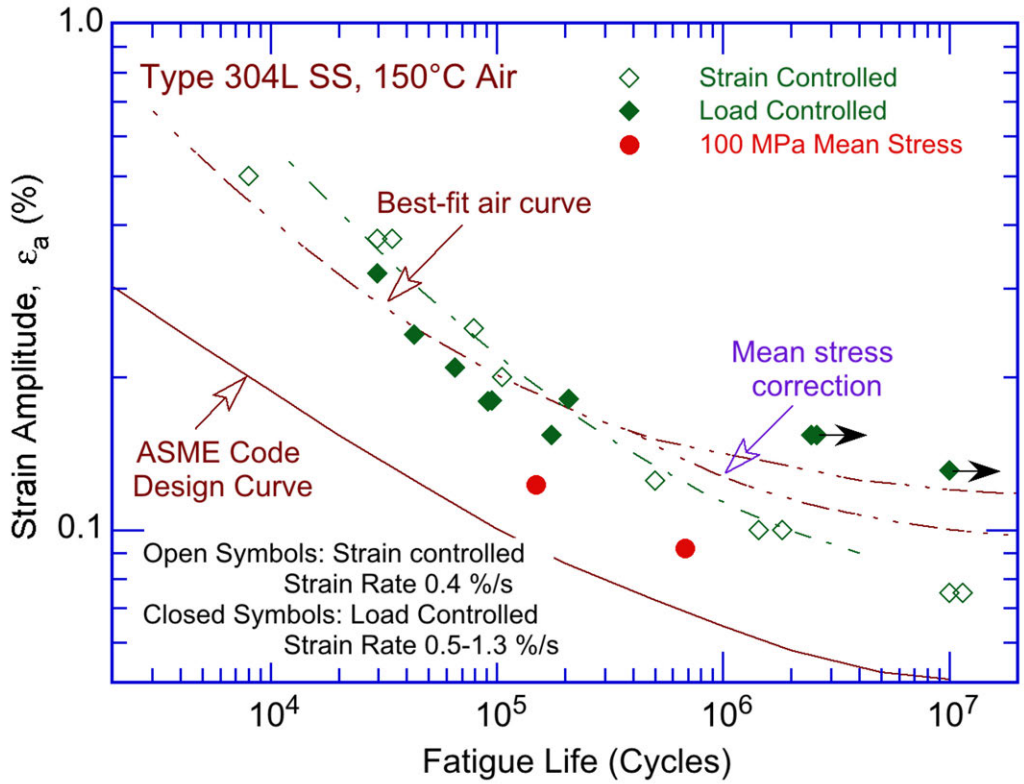


Figure 4-30(a)

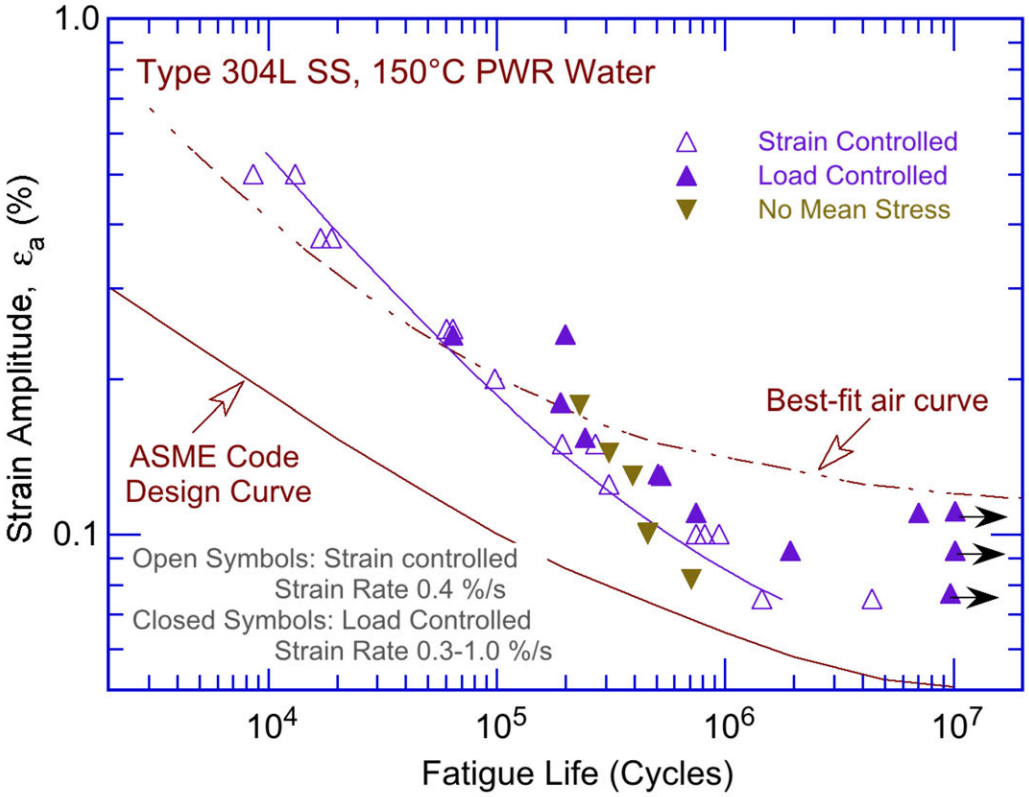


Figure 4-30(b)

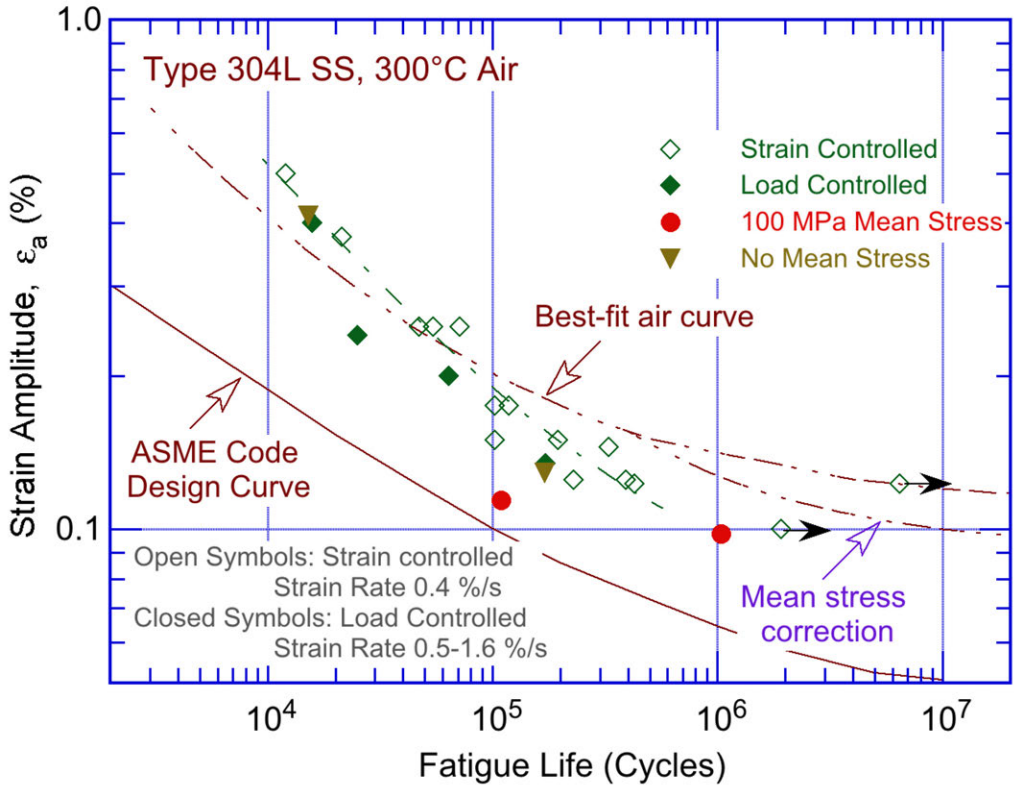


Figure 4-30(c)

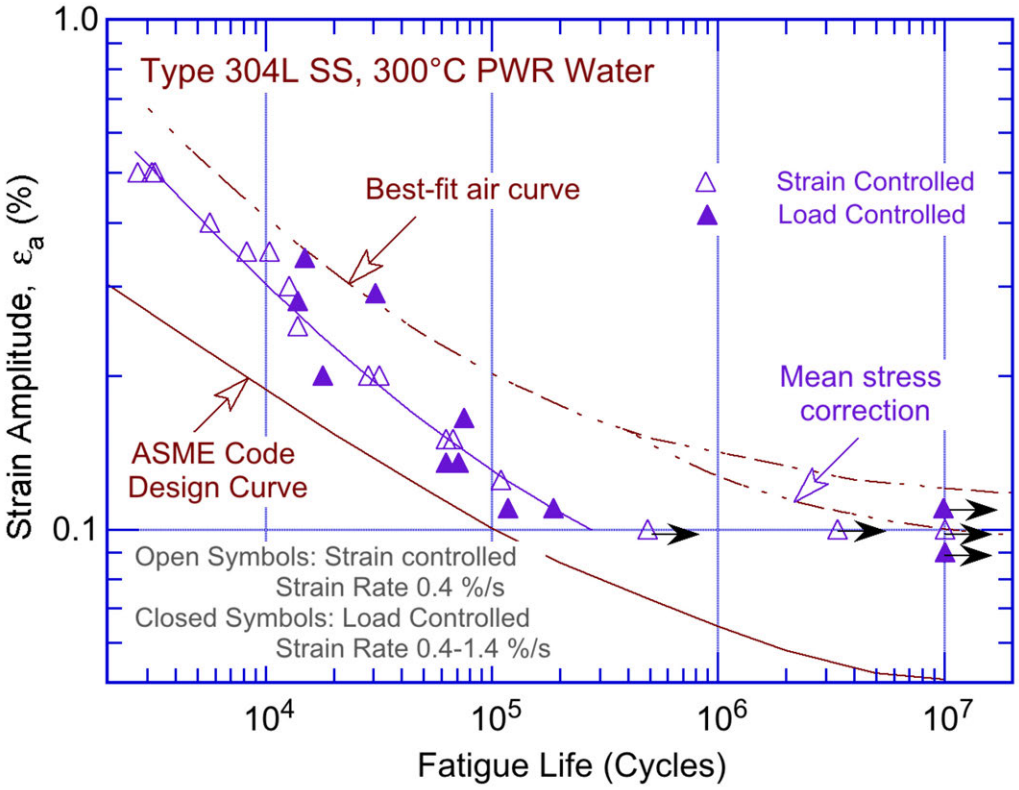


Figure 4-30(d)

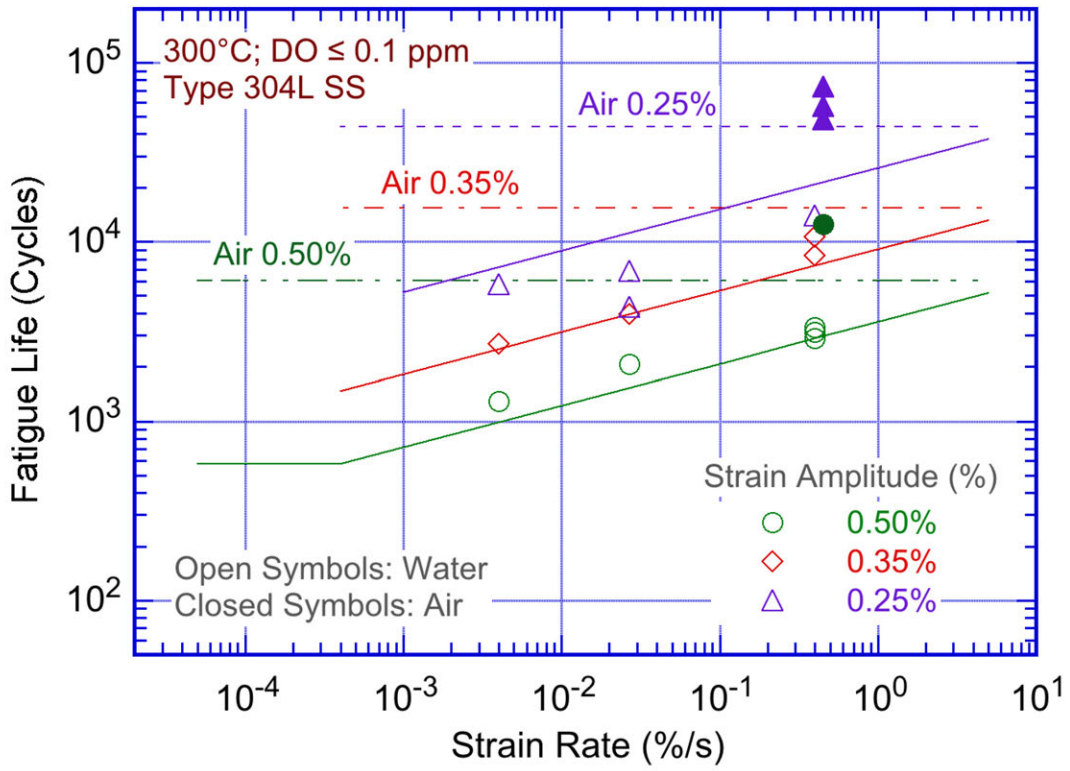


Figure 4-31(a)

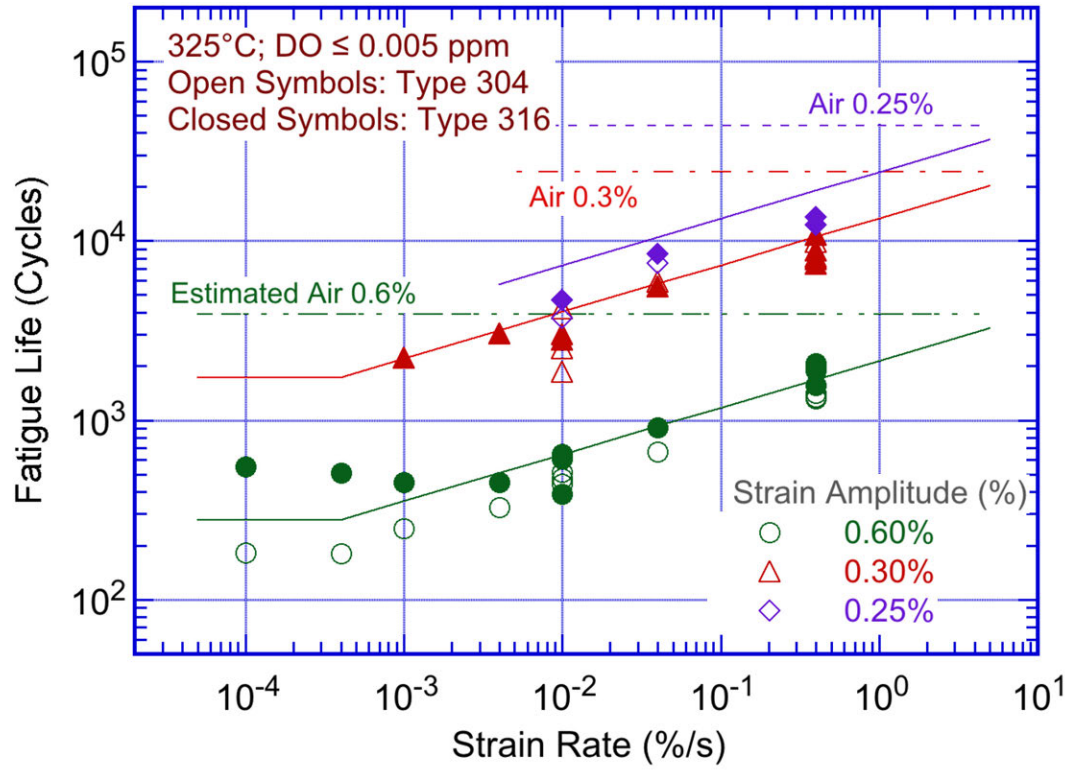


Figure 4-31(b)

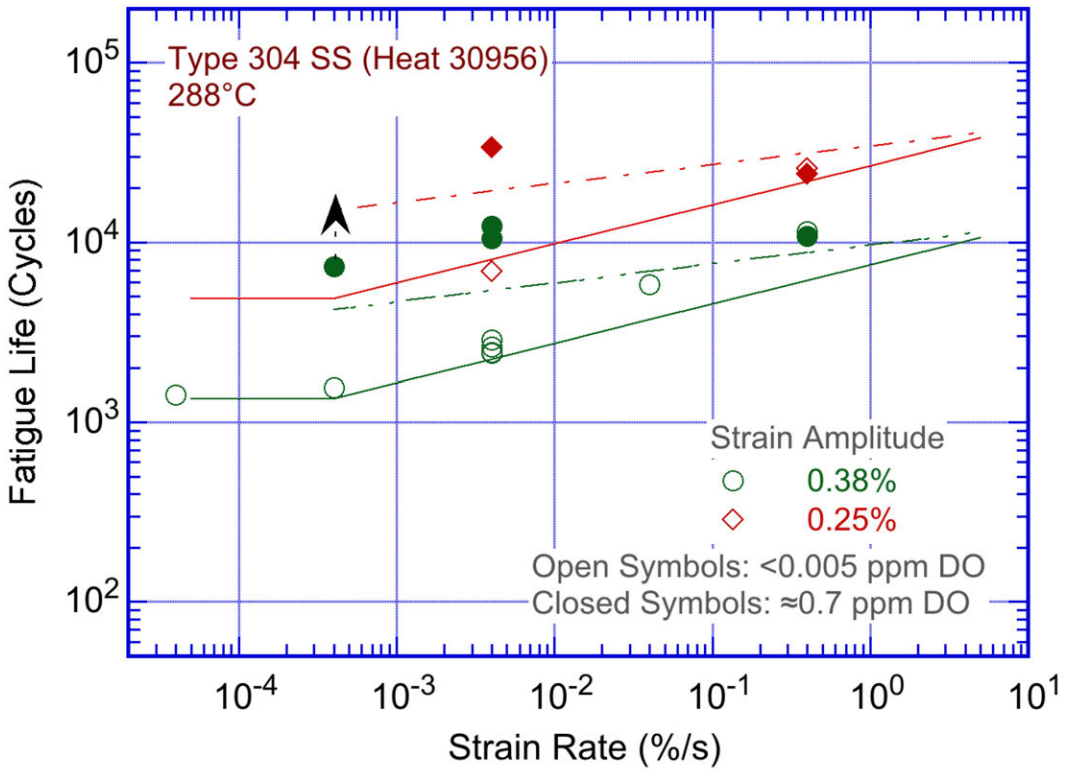


Figure 4-32(a)

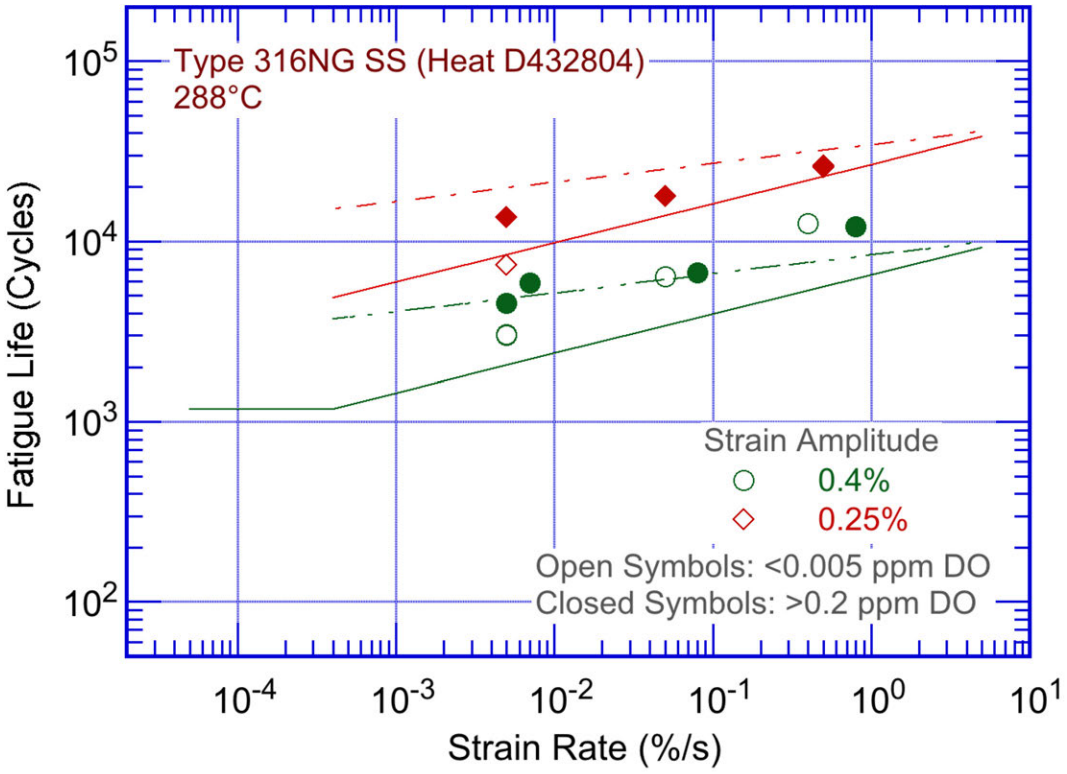


Figure 4-32(b)

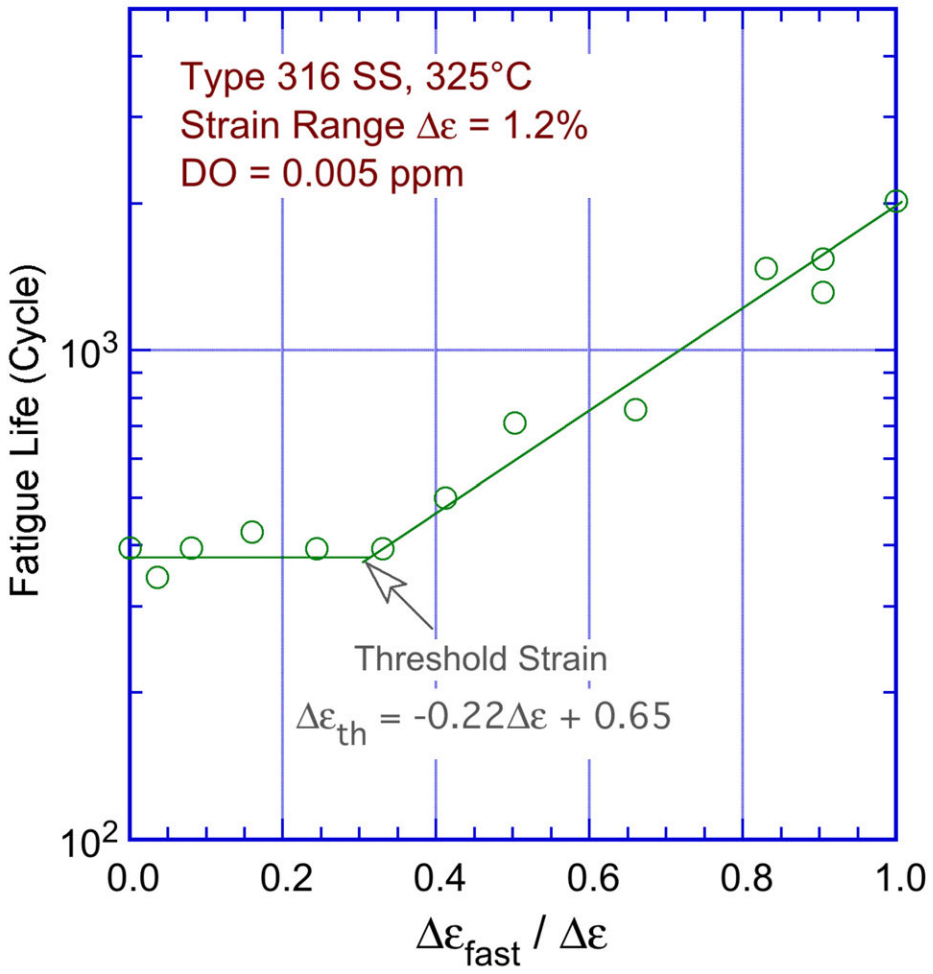

Type 316 SS, 325°C
Strain Range Δε = 1.2%
DO = 0.005 ppm
Fatigue Life (Cycle)
10^3
10^2
0.0
0.2
0.4
0.6
0.8
1.0
Δε_fast / Δε
Threshold Strain
Δε_th = -0.22Δε + 0.65

Figure 4-33

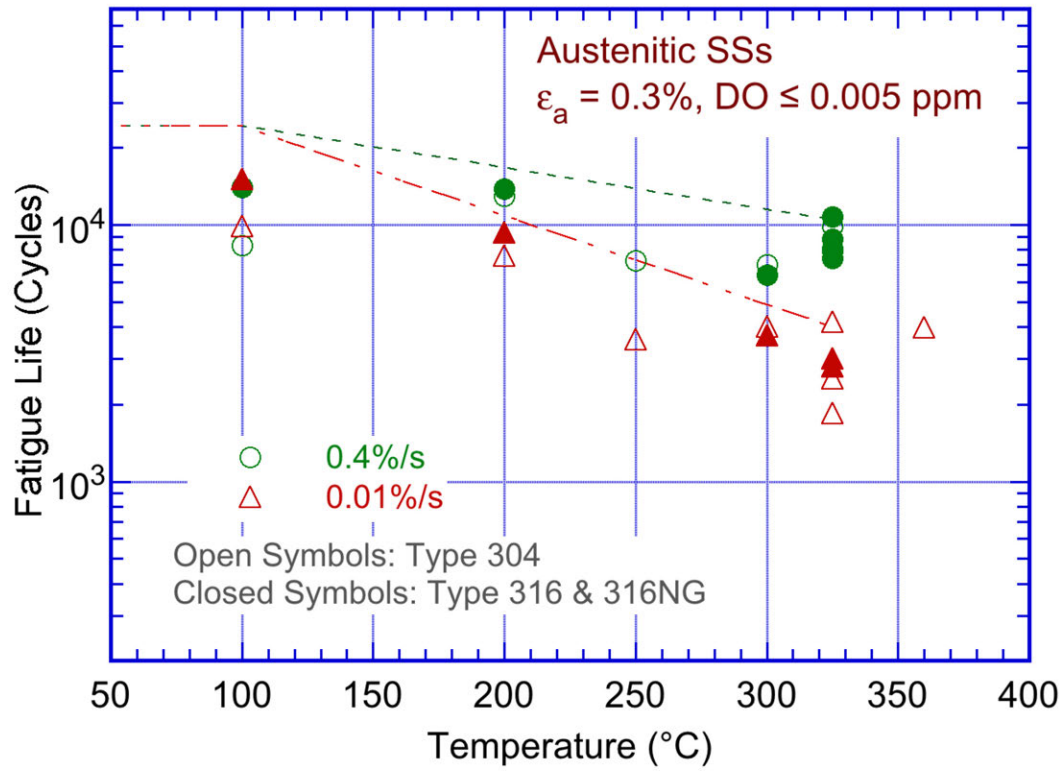


Figure 4-34(a)

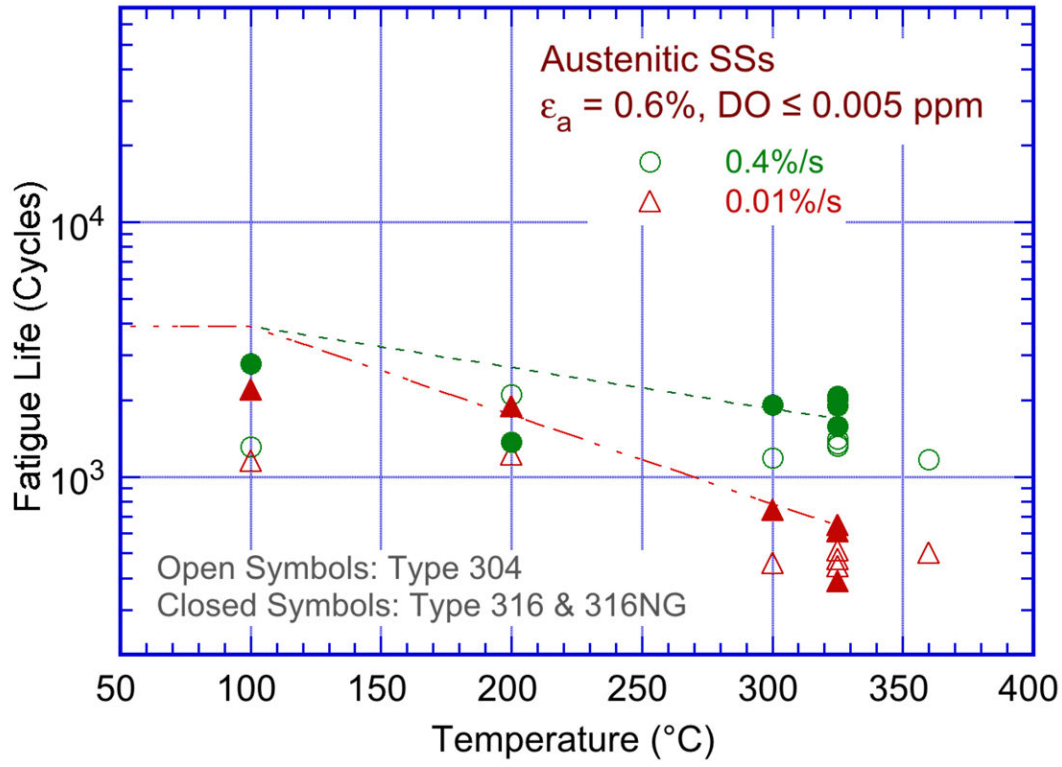


Figure 4-34(b)

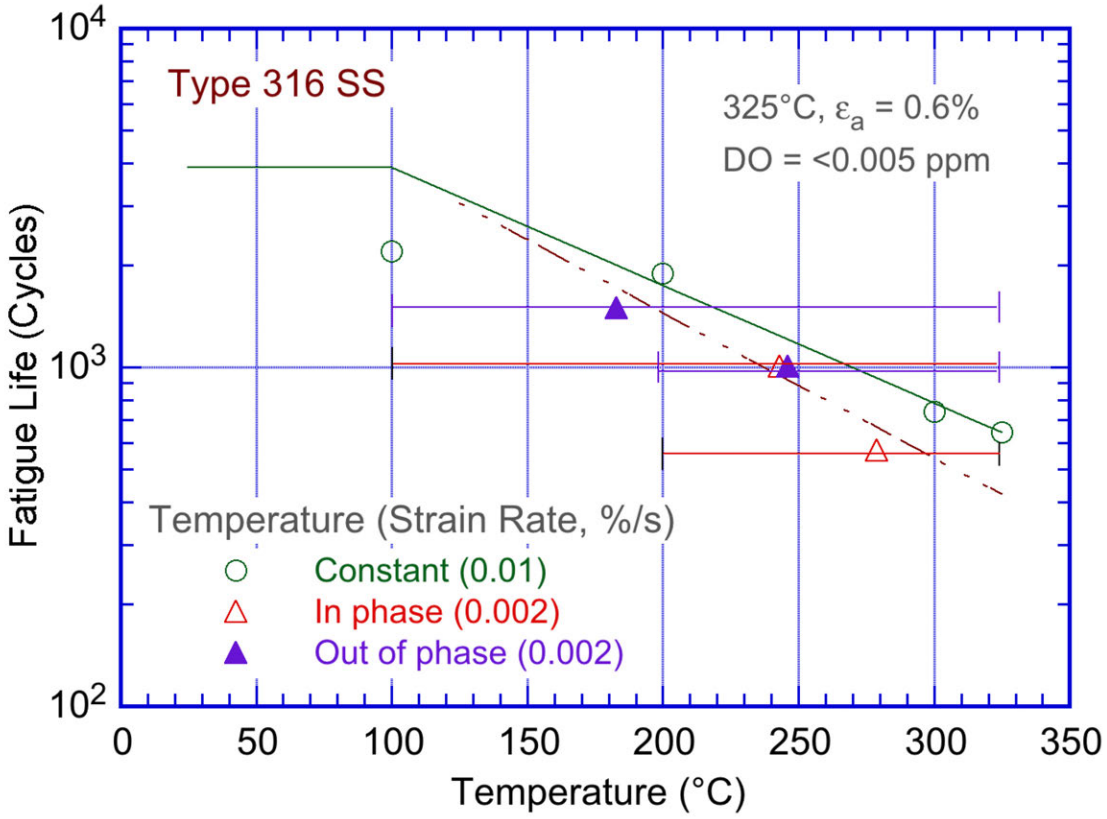


Figure 4-35

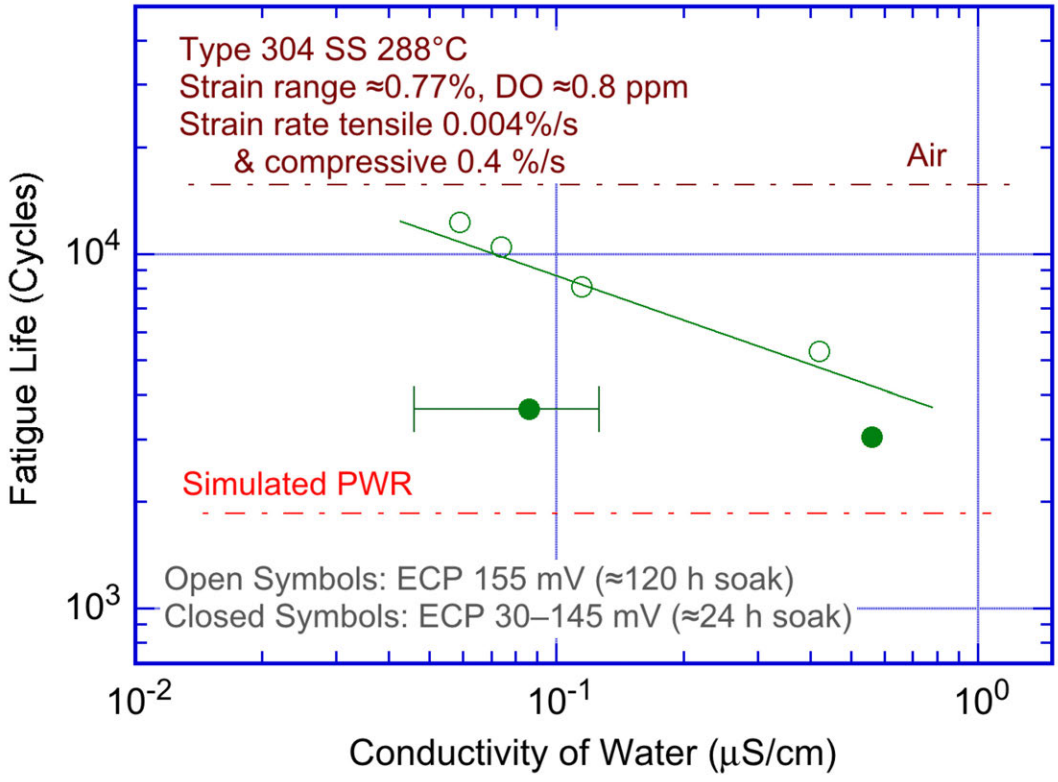


Figure 4-36

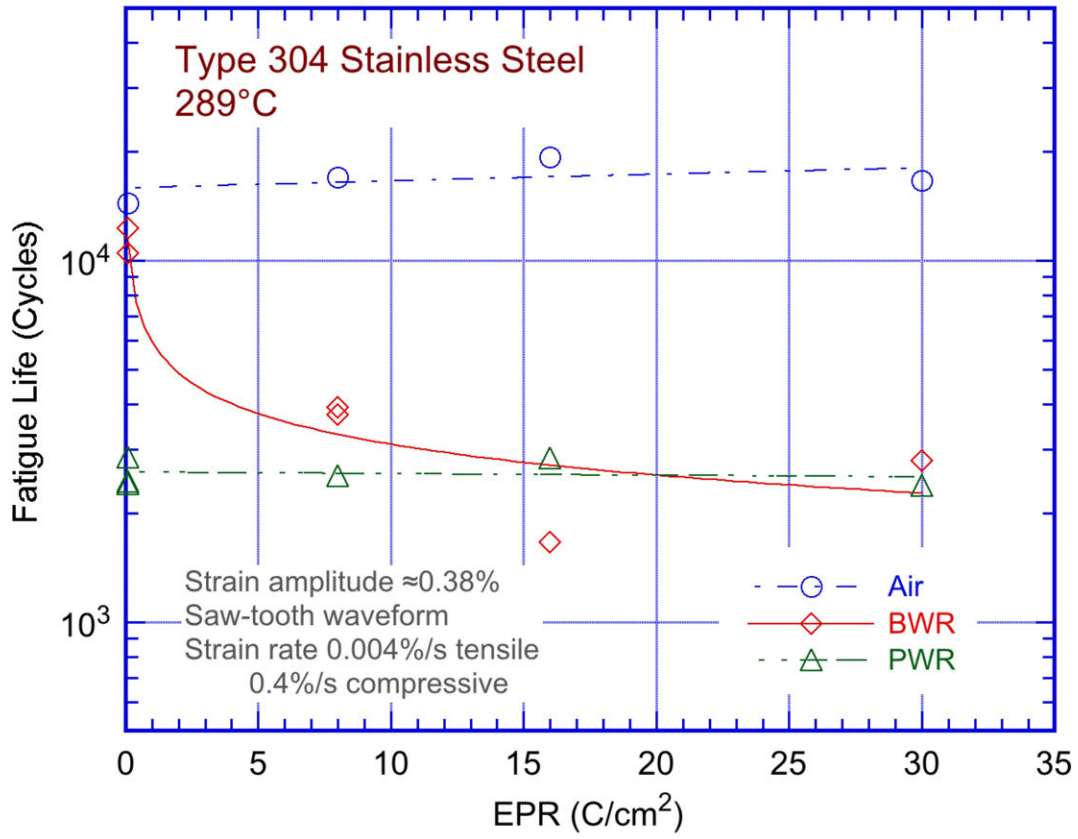


Figure 4-37

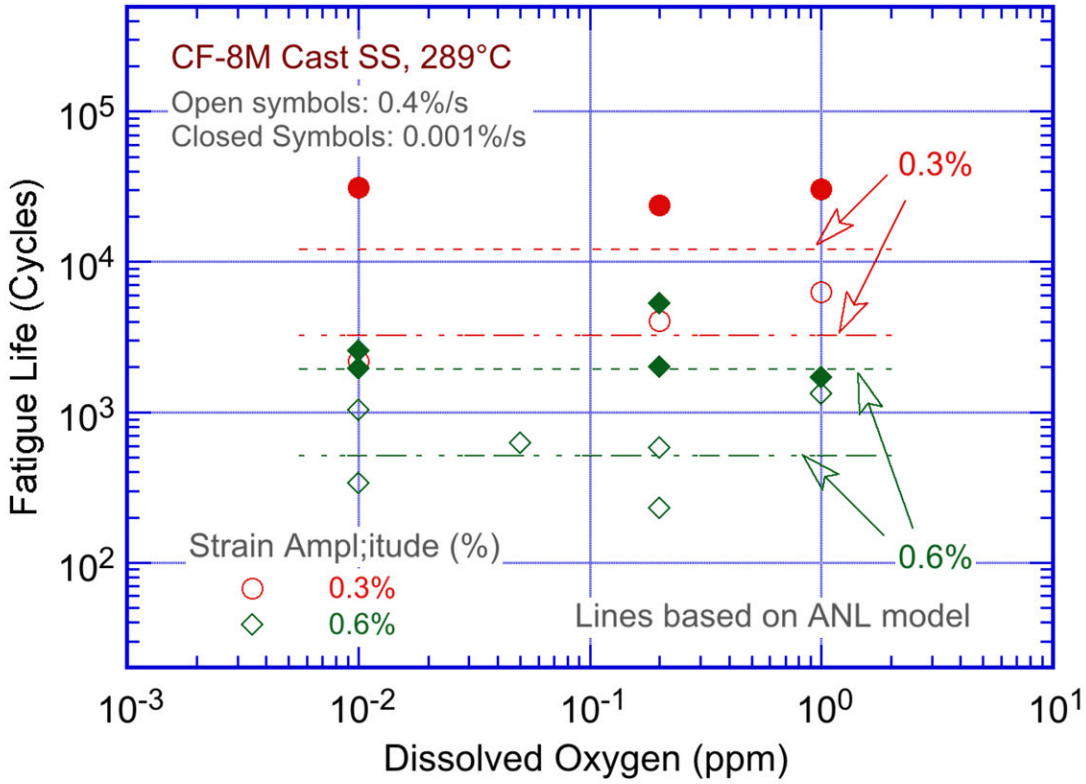


Figure 4-38

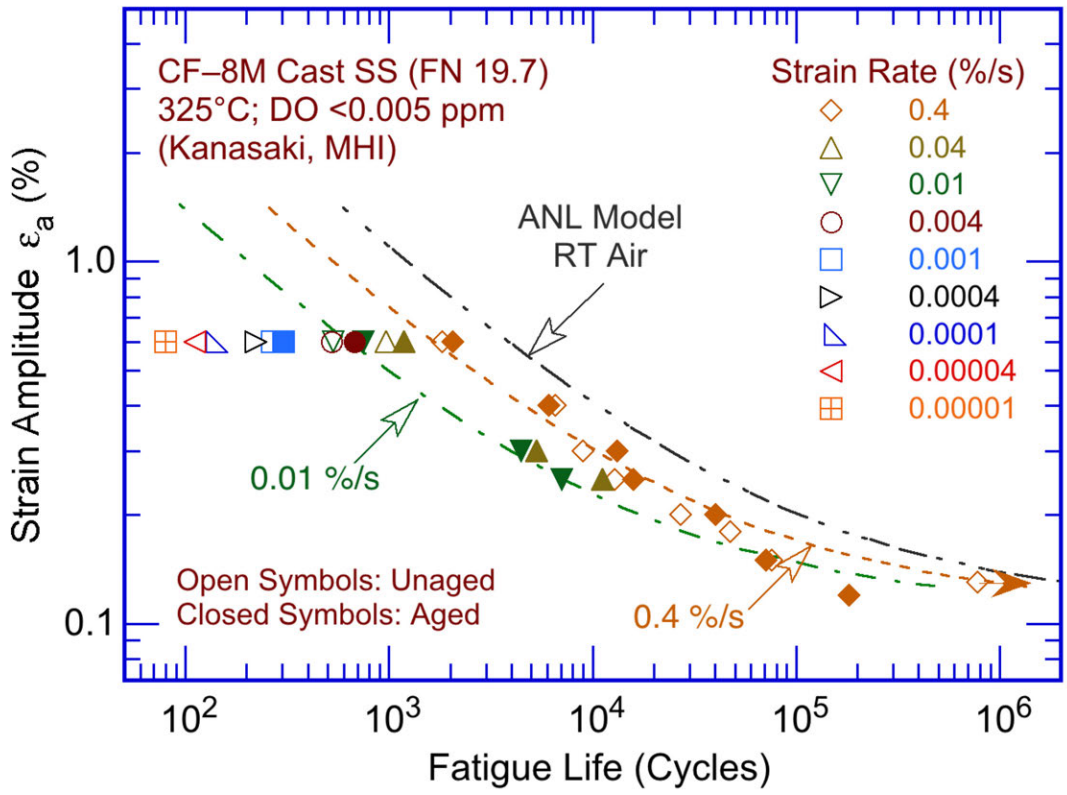


Figure 4-39

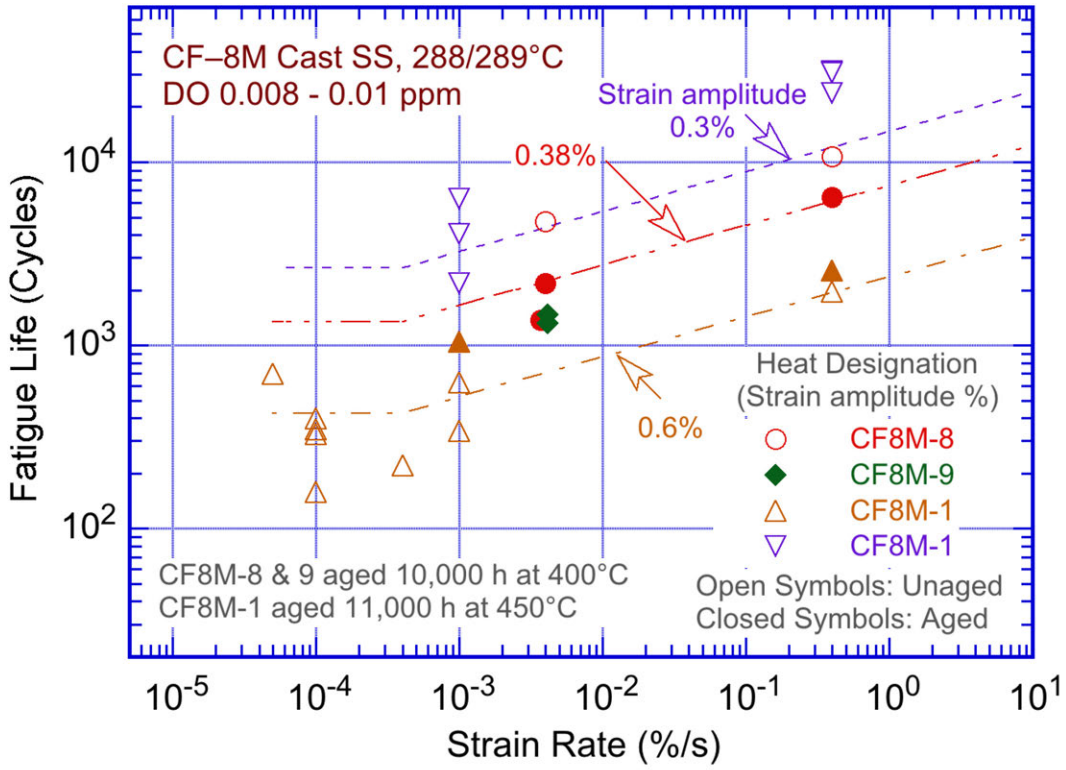


Figure 4-40(a)

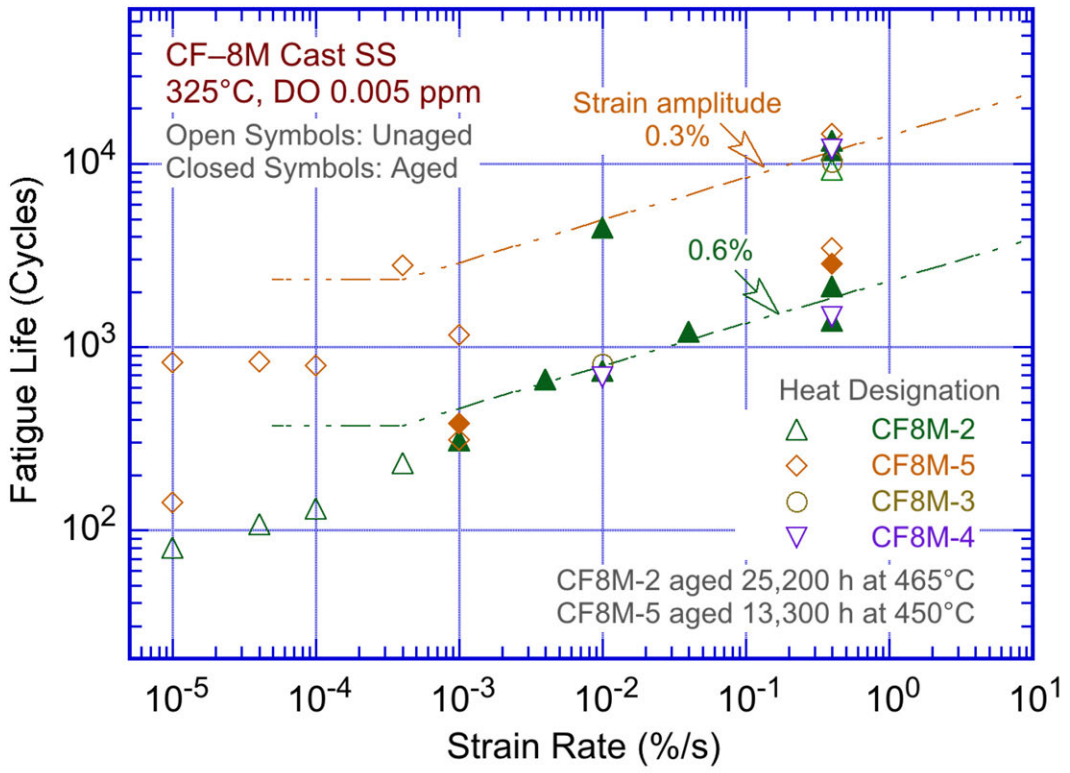


Figure 4-40(b)

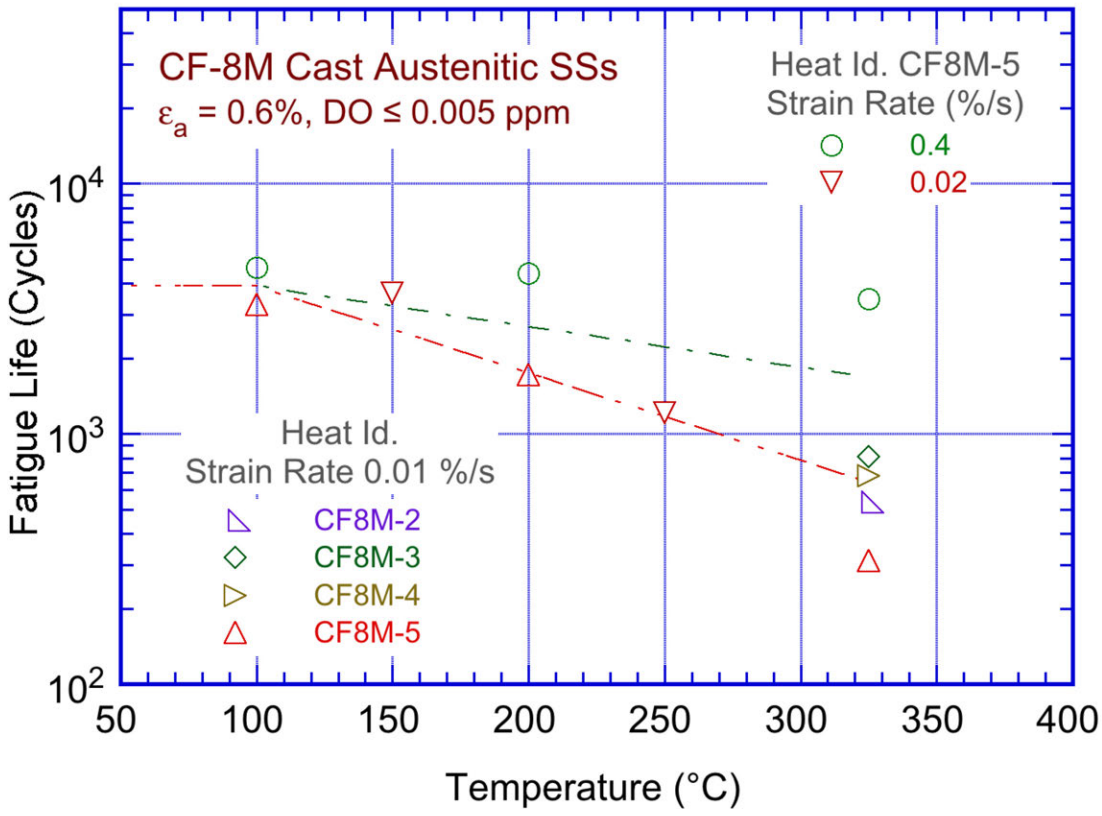


Figure 4-41

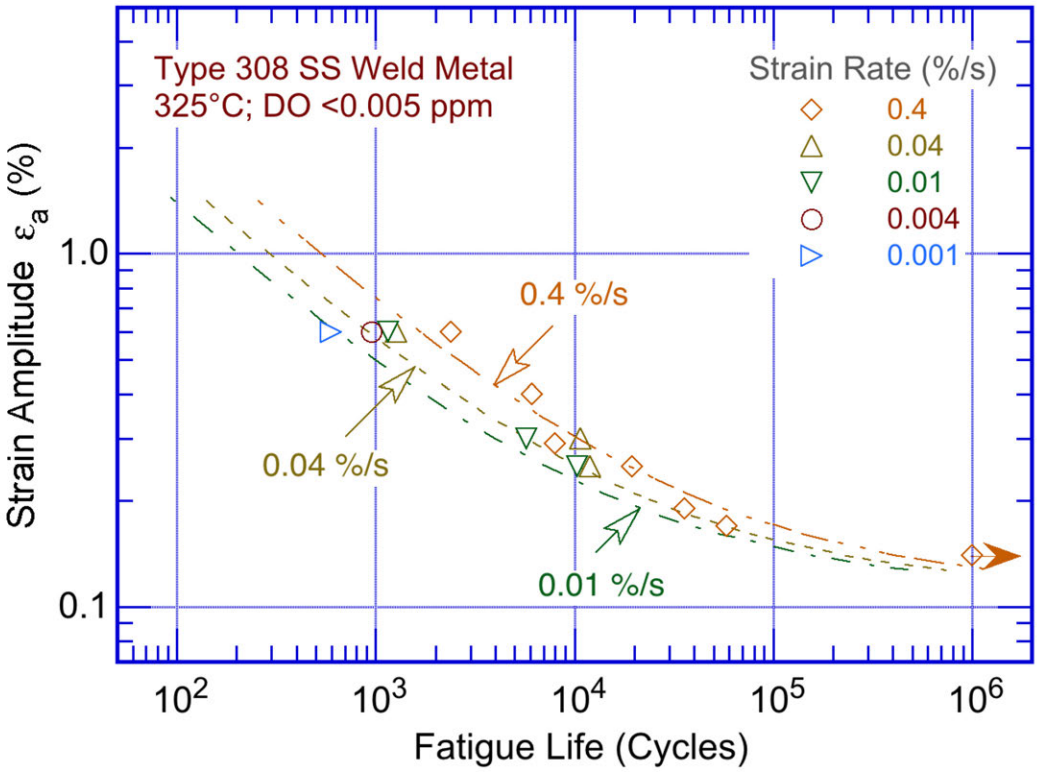


Figure 4-42(a)

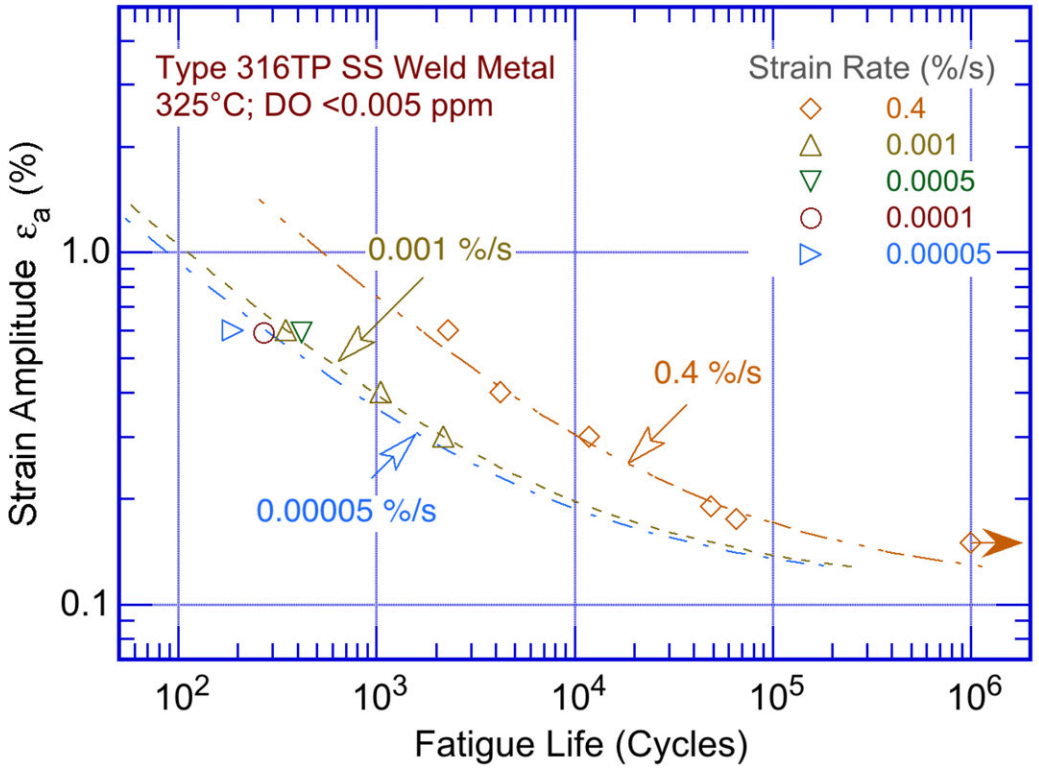


Figure 4-42(b)

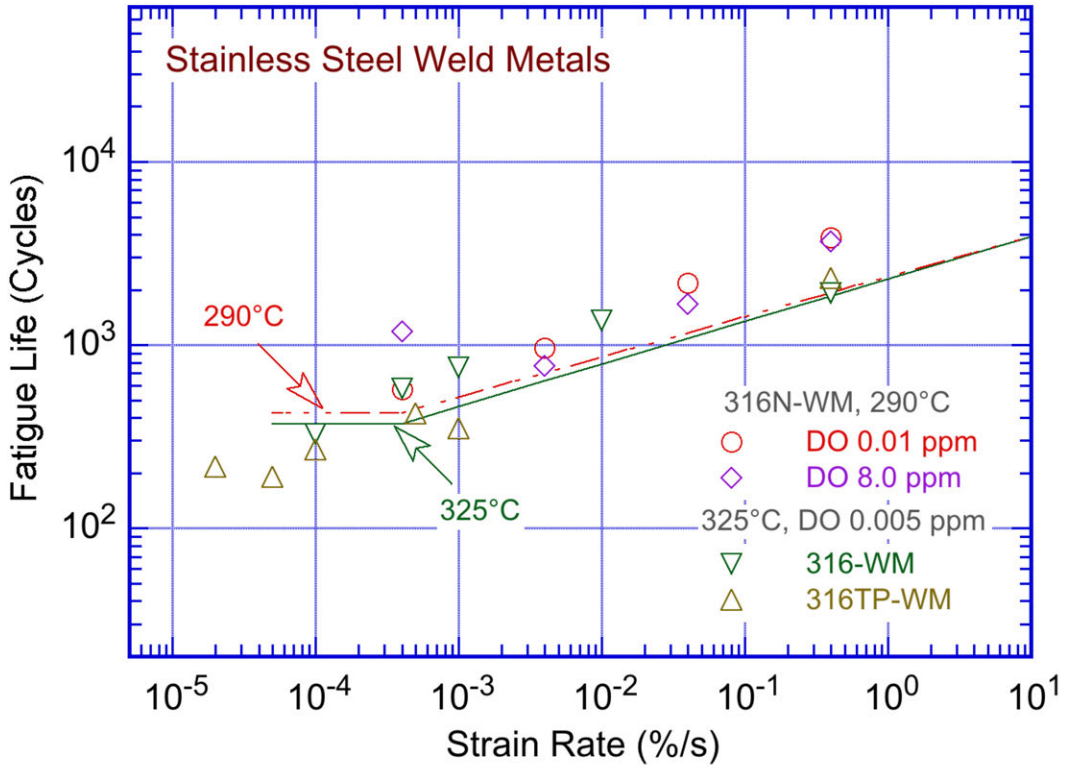


Figure 4-43(a)

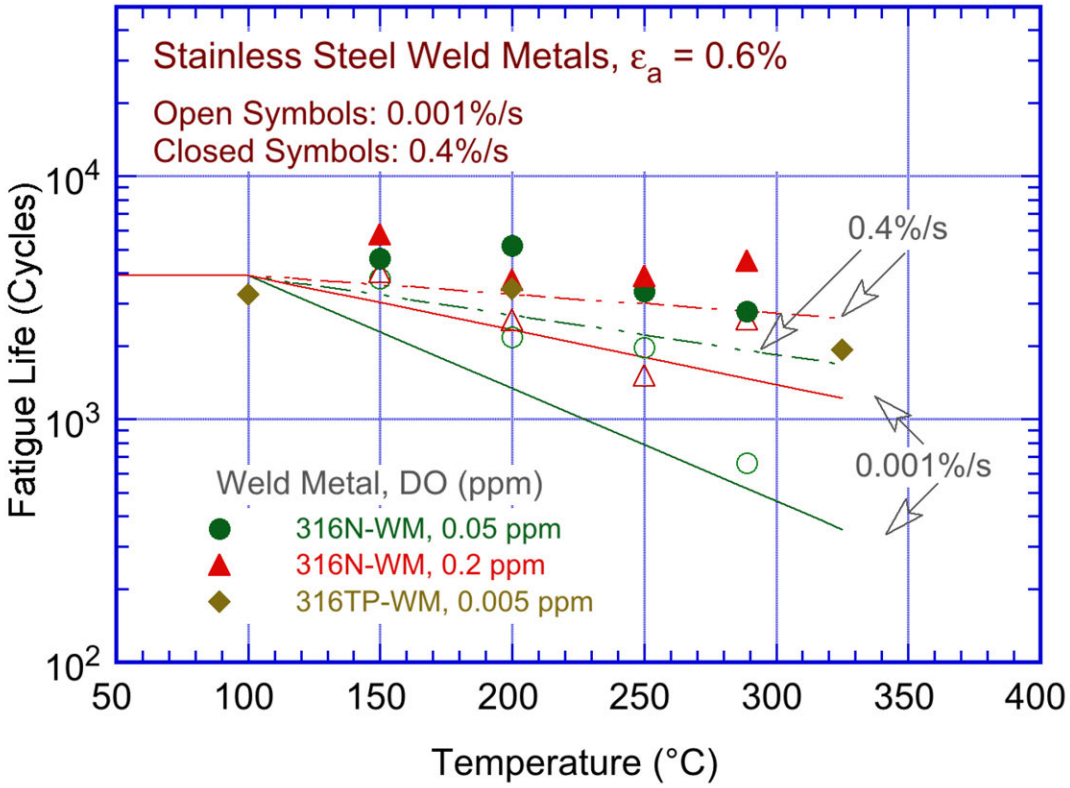


Figure 4-43(b)

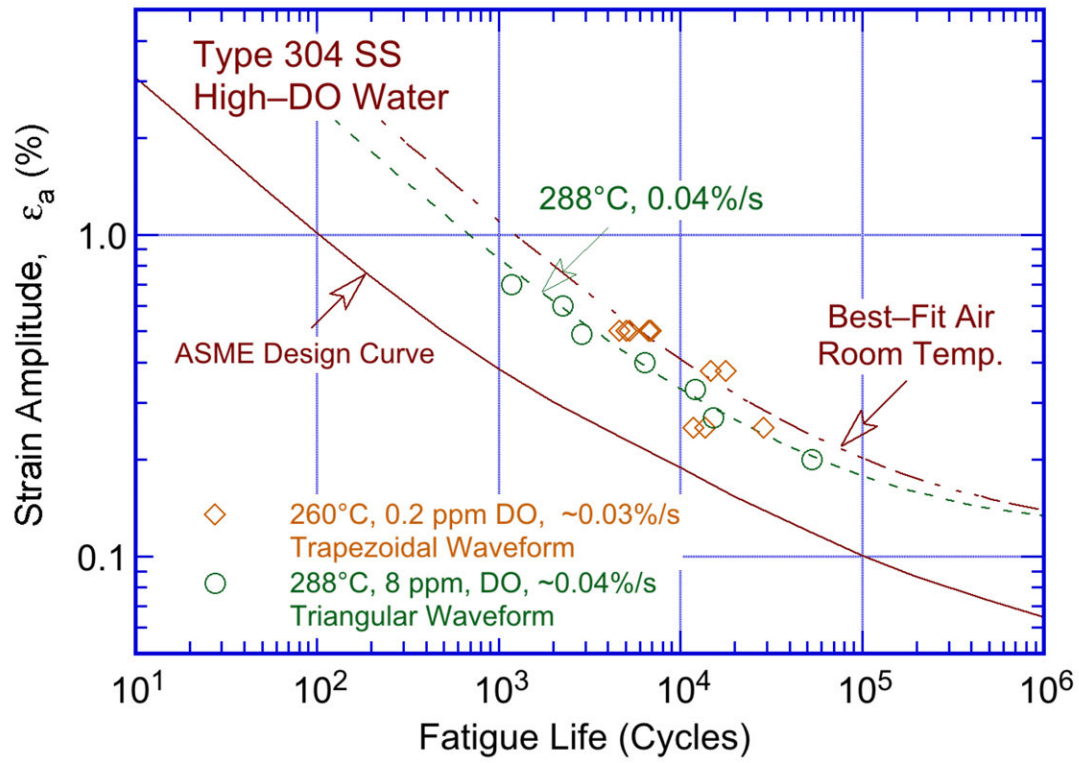


Figure 4-44

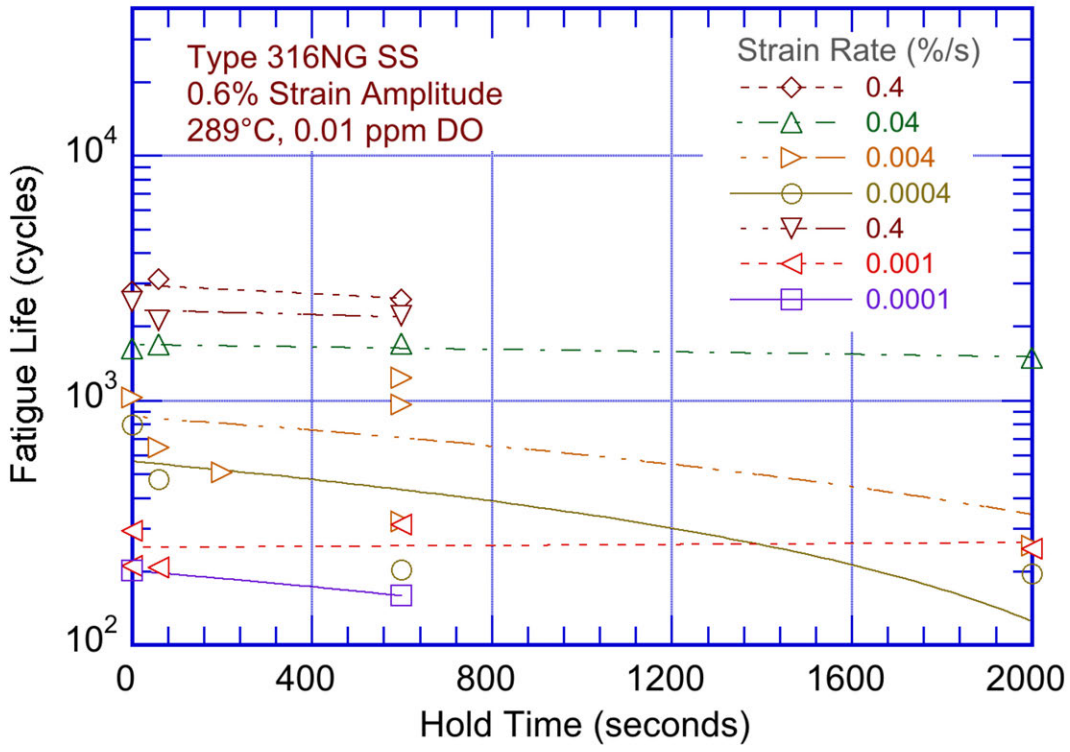


Figure 4-45(a)

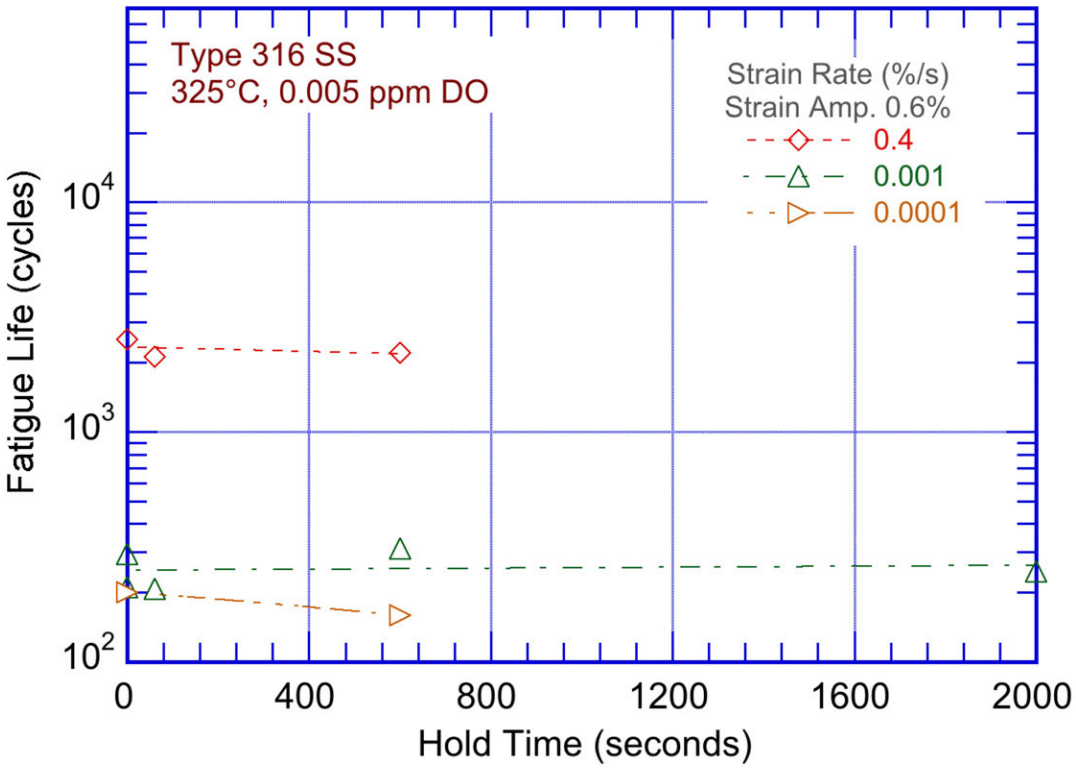


Figure 4-45(b)

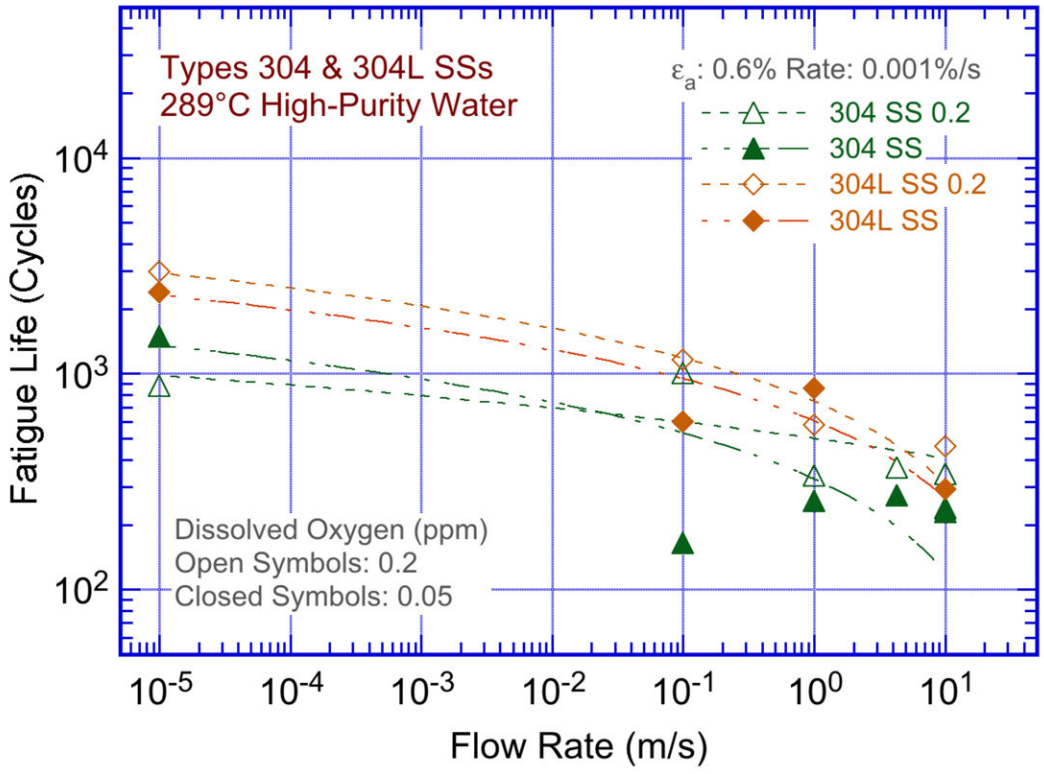


Figure 4-46(a)

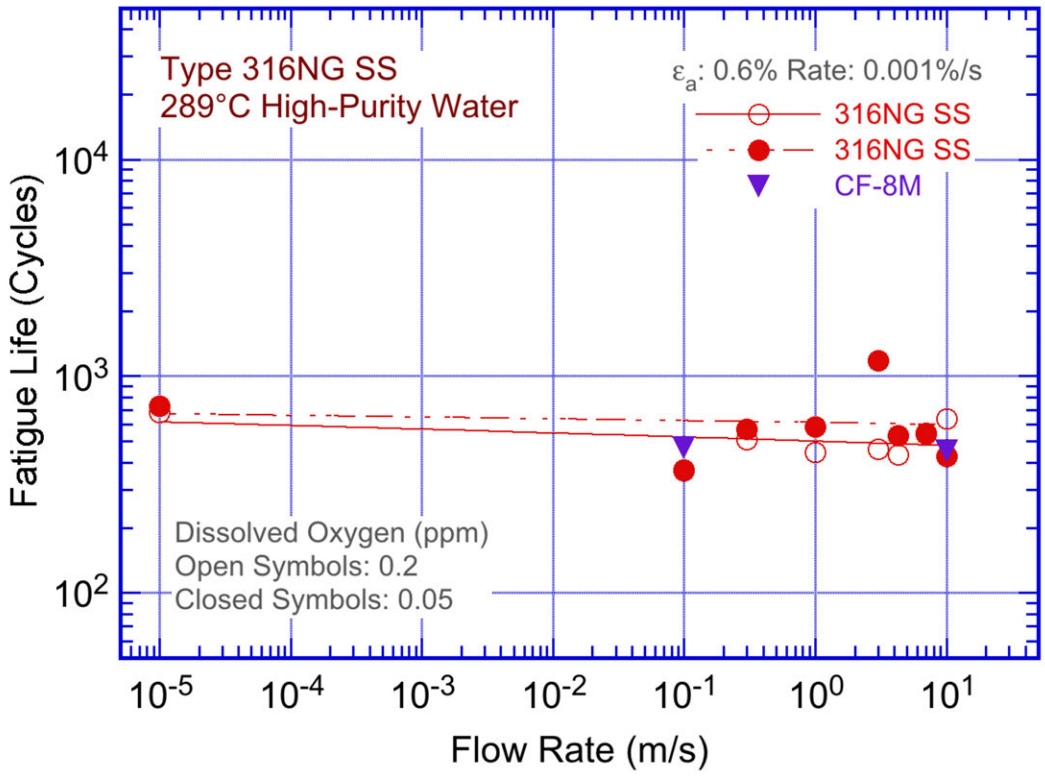


Figure 4-46(b)

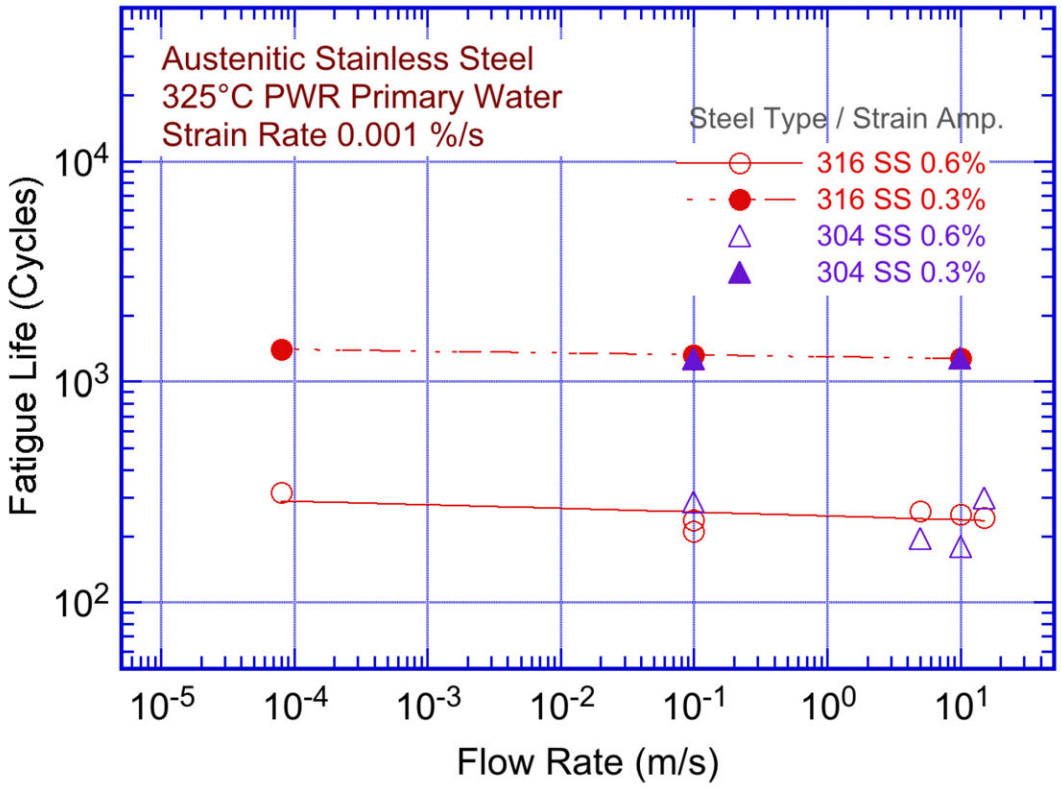


Figure 4-47

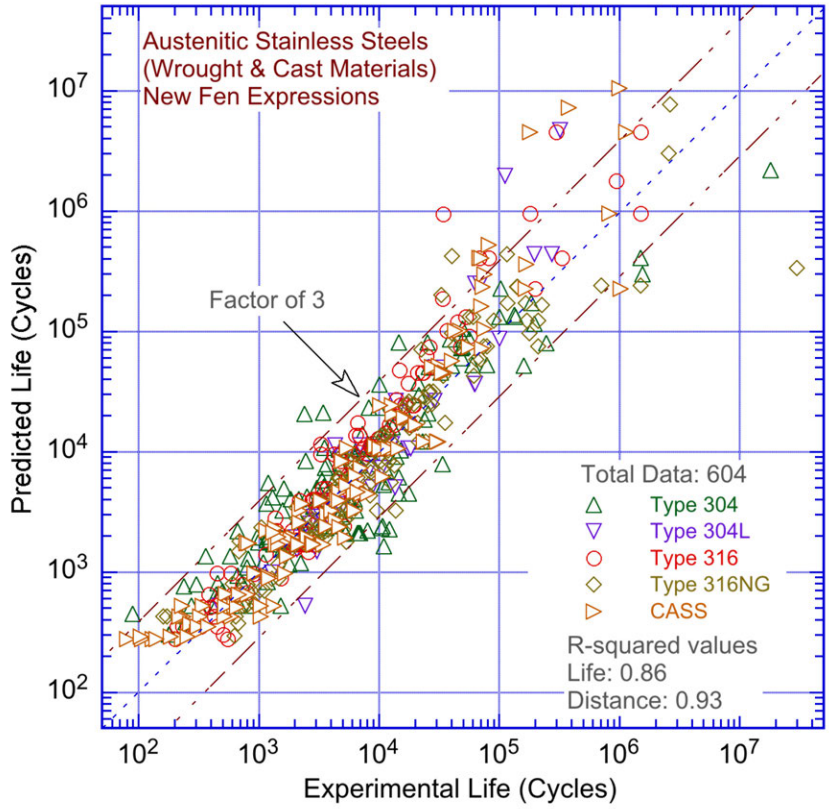


Figure 4-48(a)

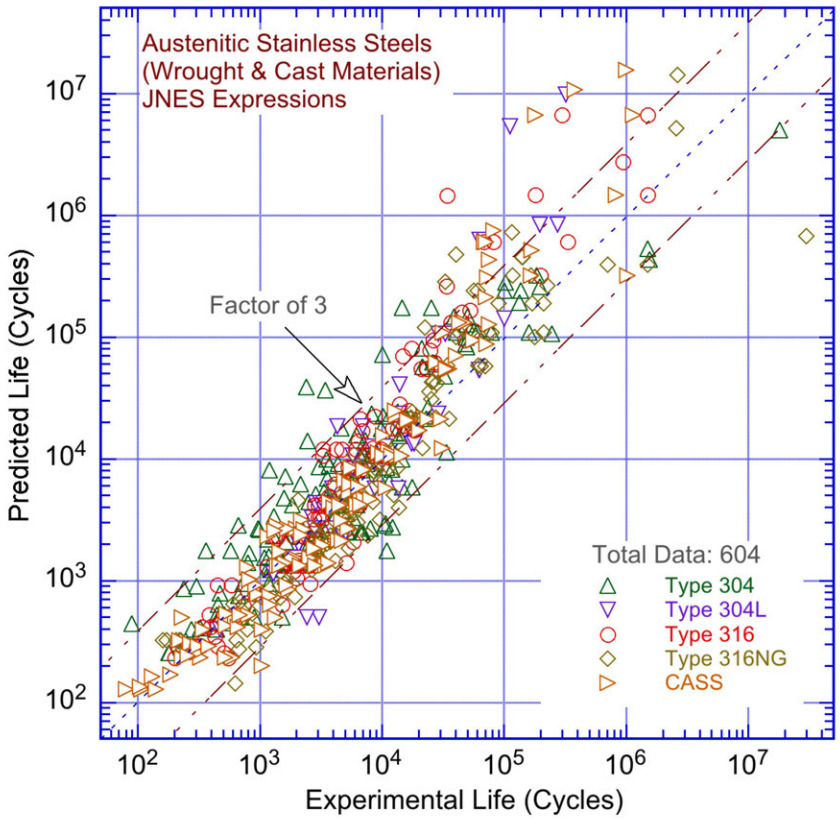


Figure 4-48(b)

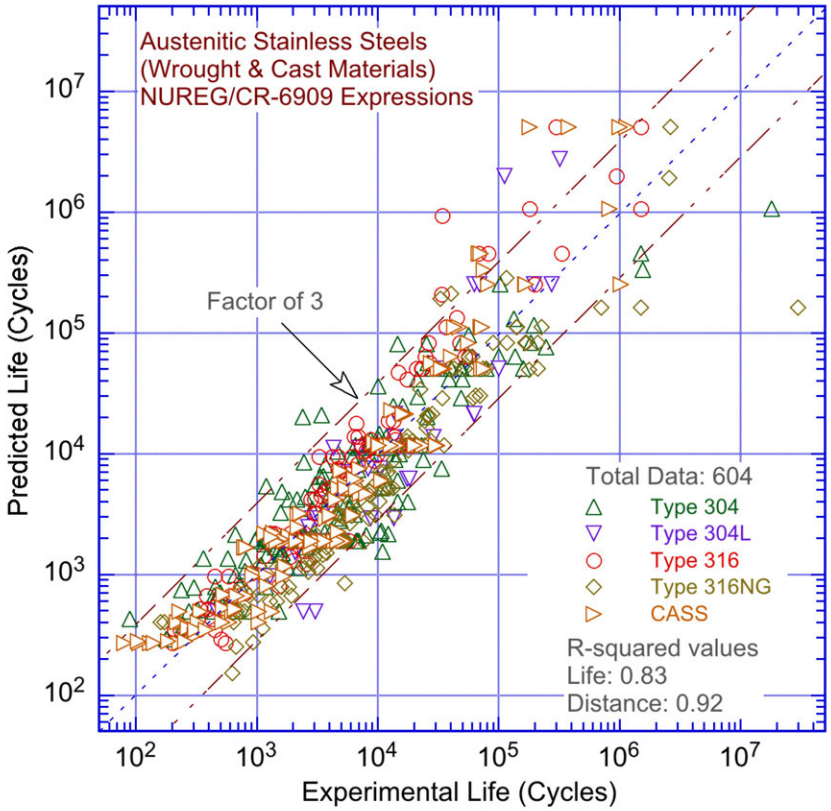


Figure 4-48(c)

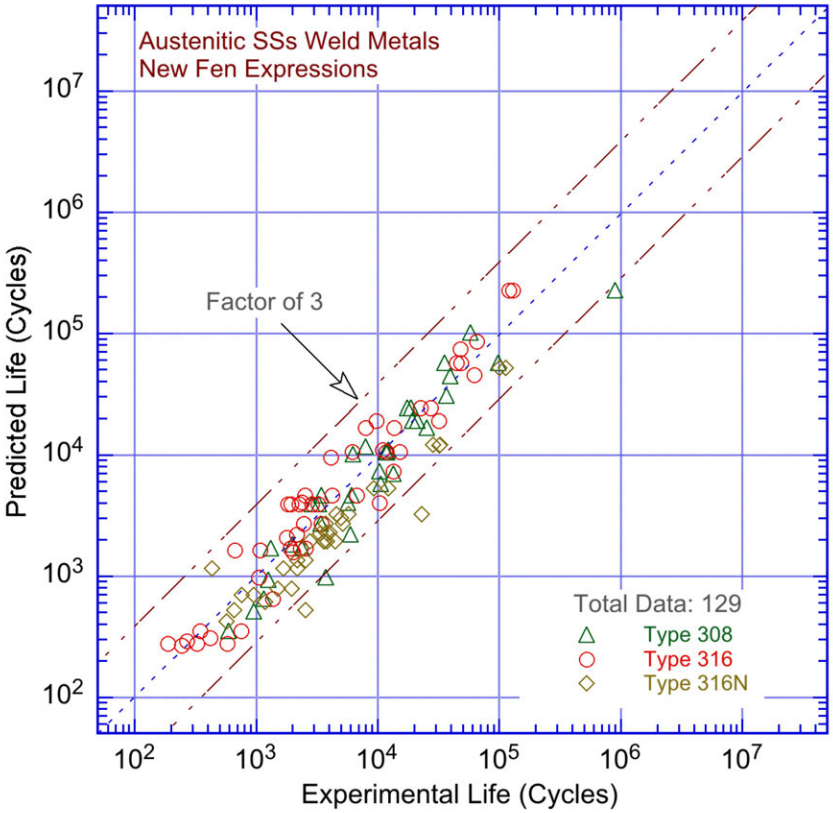


Figure 4-48(d)

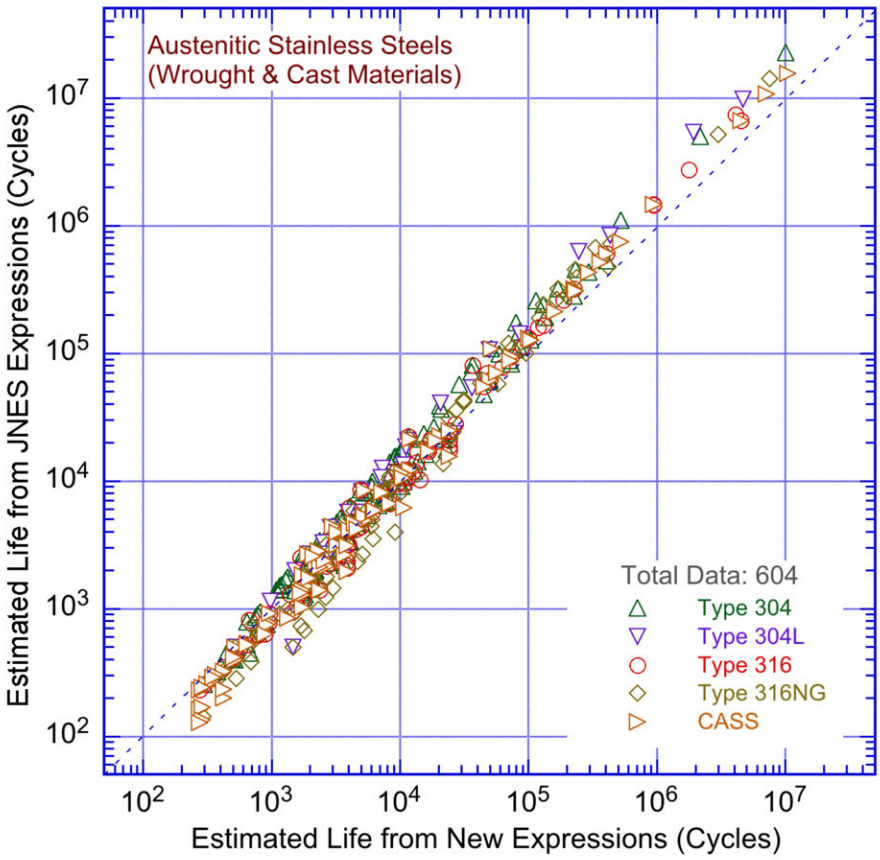

Austenitic Stainless Steels
(Wrought & Cast Materials)
Estimated Life from JNES Expressions (Cycles)
Estimated Life from New Expressions (Cycles)
10^2
10^3
10^4
10^5
10^6
10^7
Total Data: 604
Type 304
Type 304L
Type 316
Type 316NG
CASS

Figure 4-49

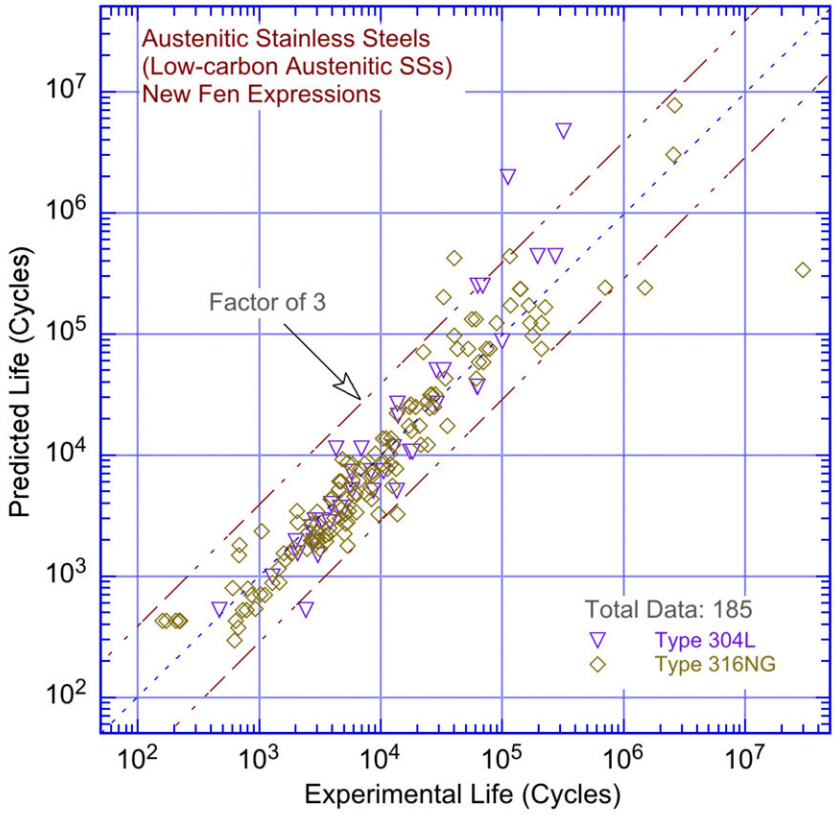


Figure 4-50(a)

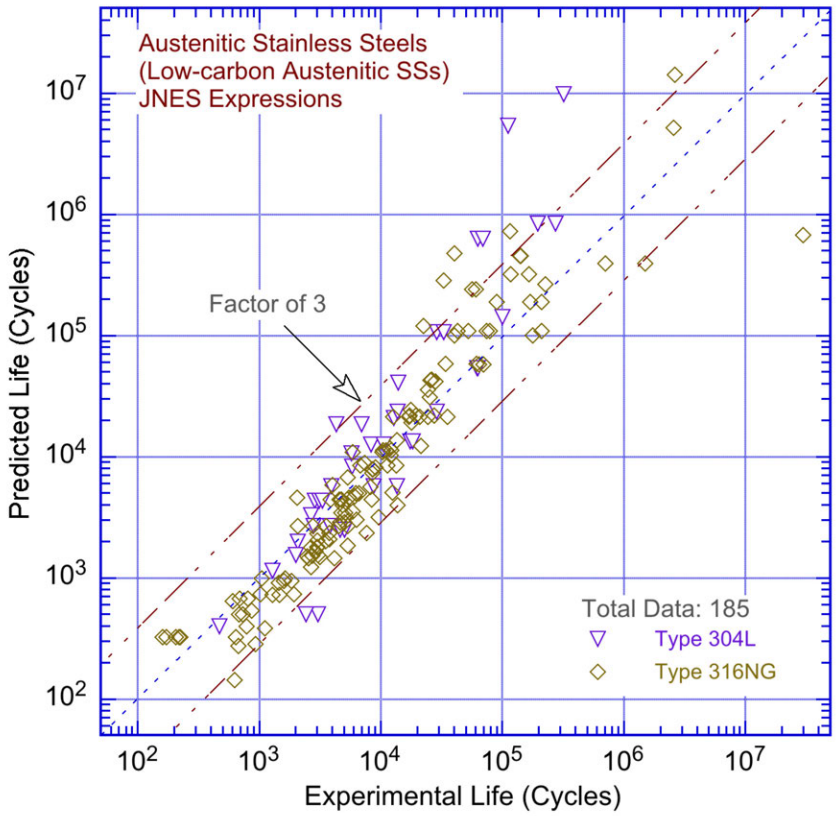


Figure 4-50(b)

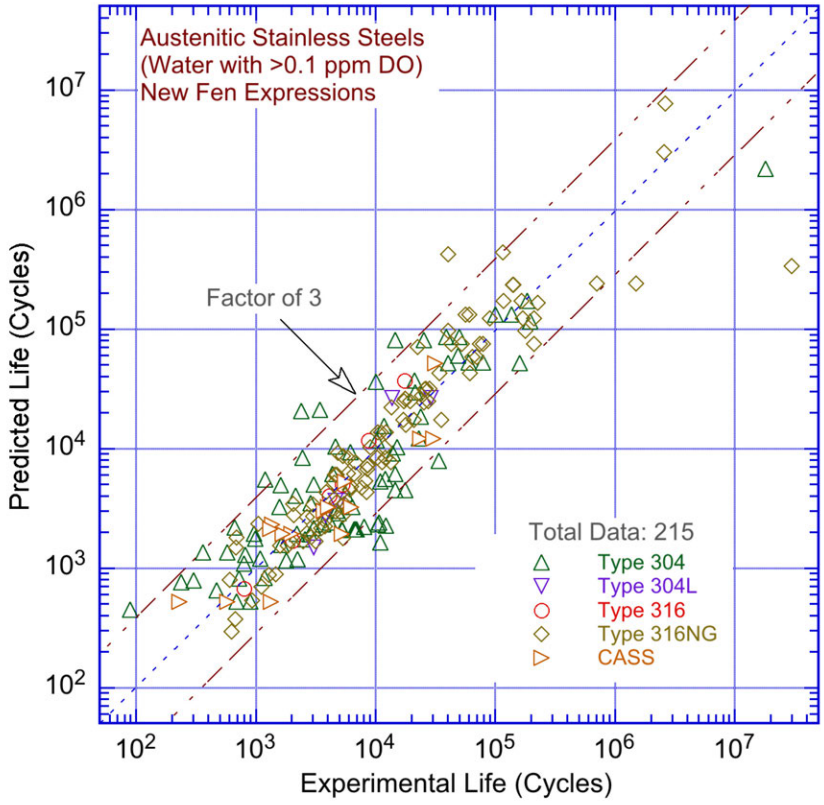


Figure 4-51(a)

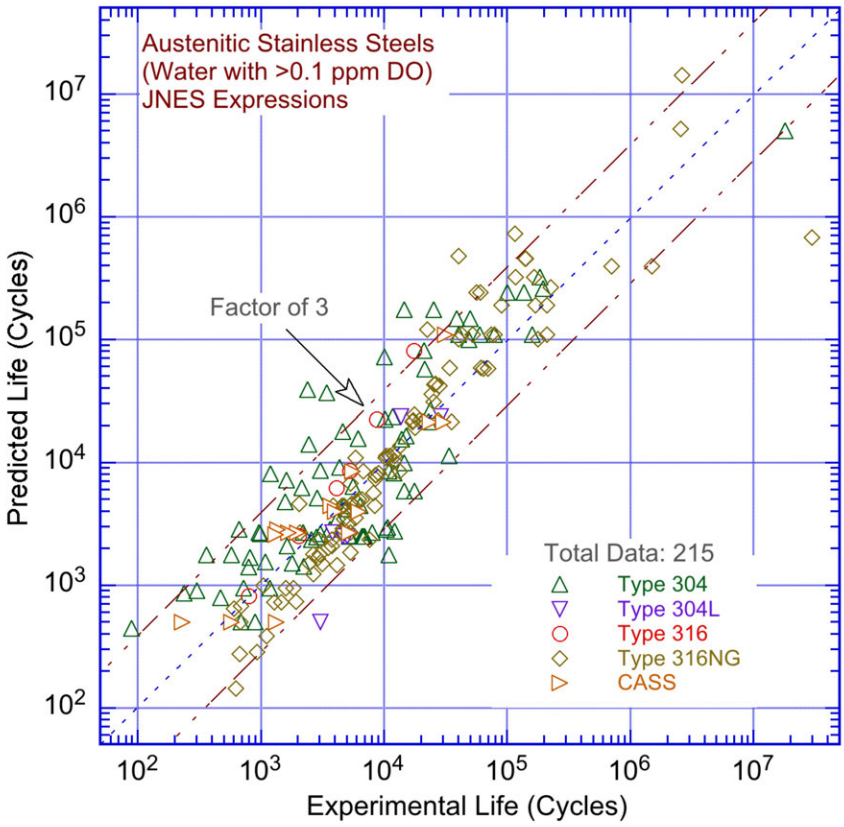


Figure 4-51(b)

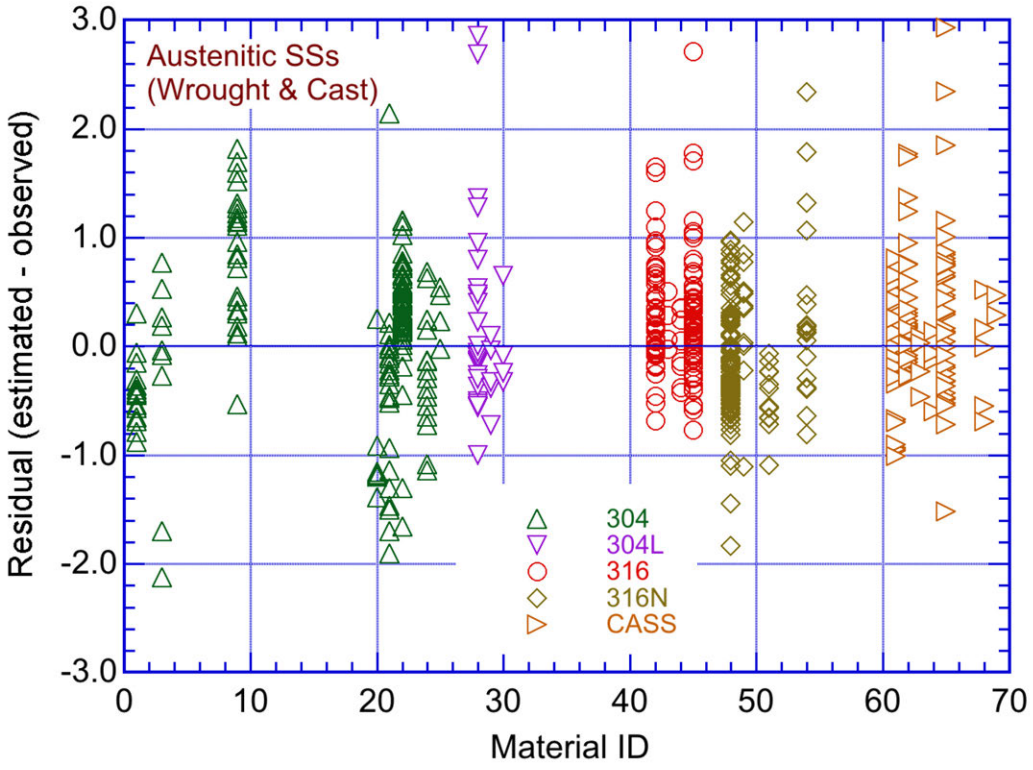


Figure 4-52(a)

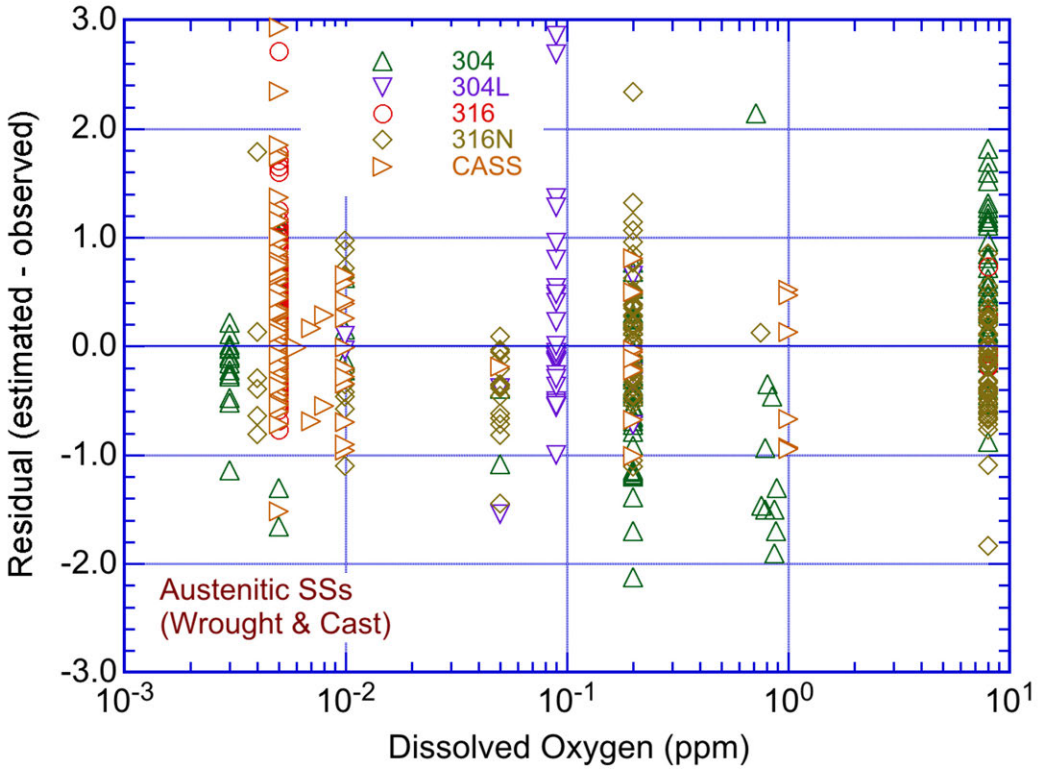


Figure 4-52(b)

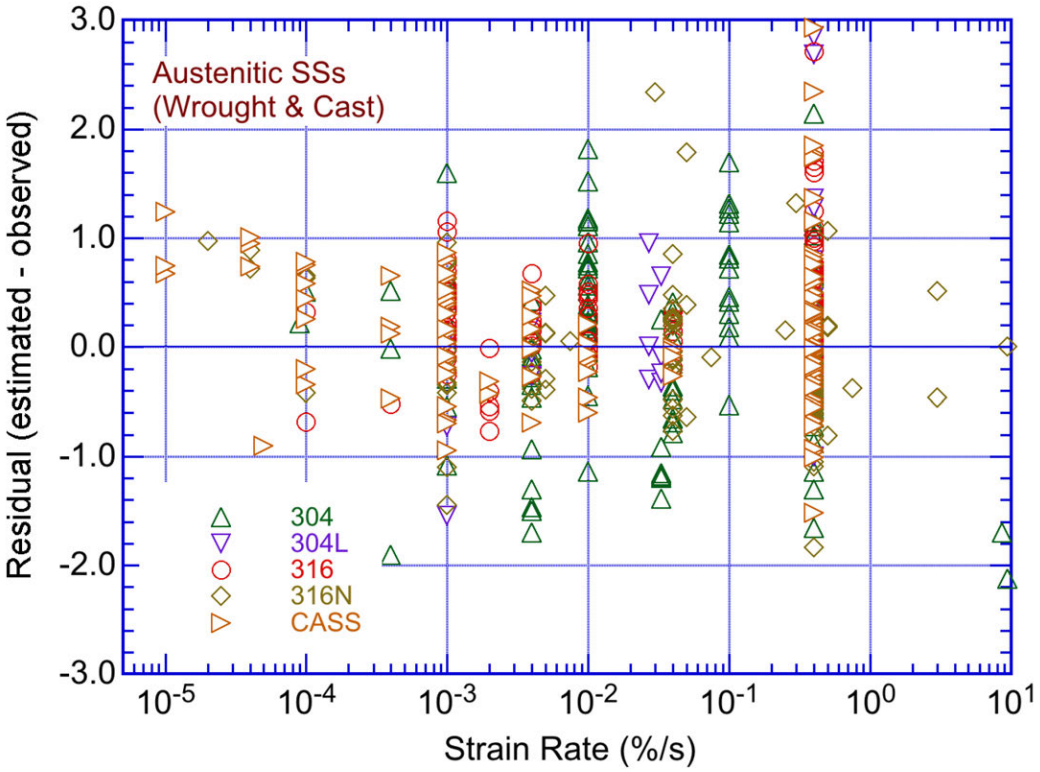


Figure 4-52(c)

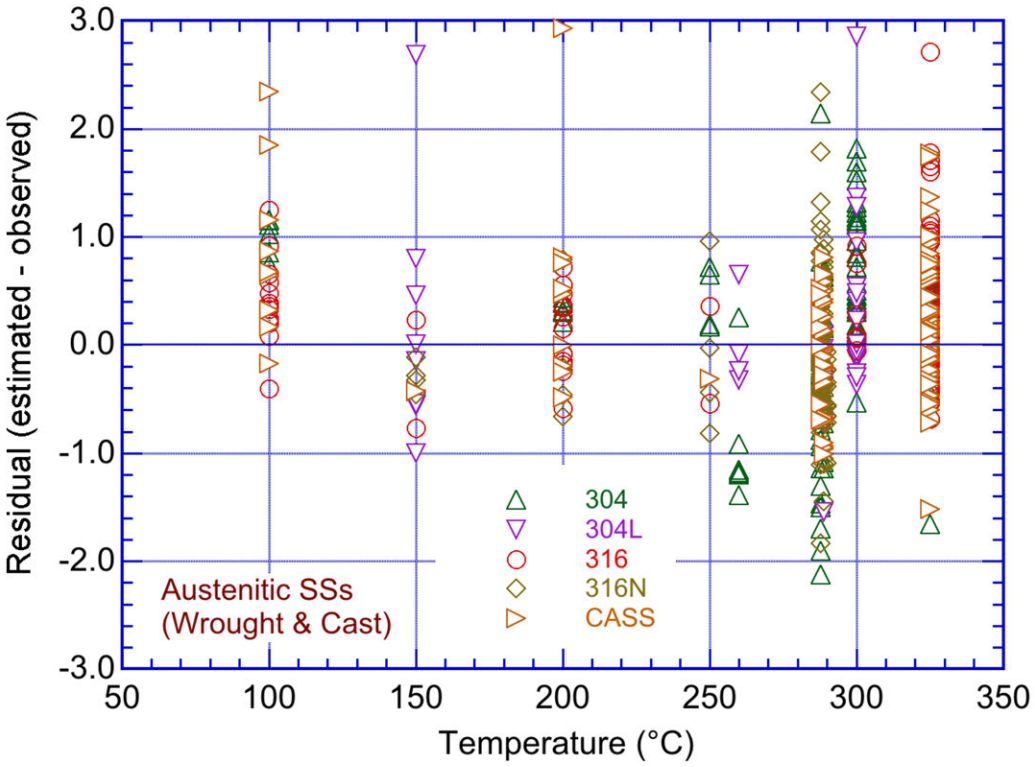


Figure 4-52(d)

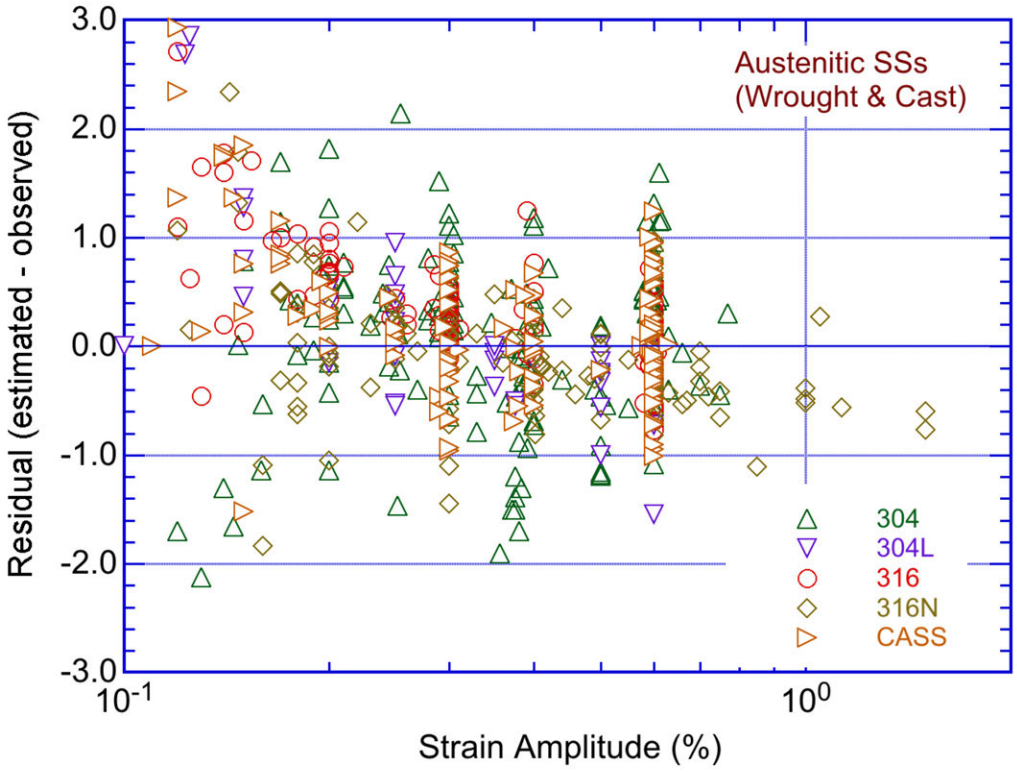


Figure 4-52(e)

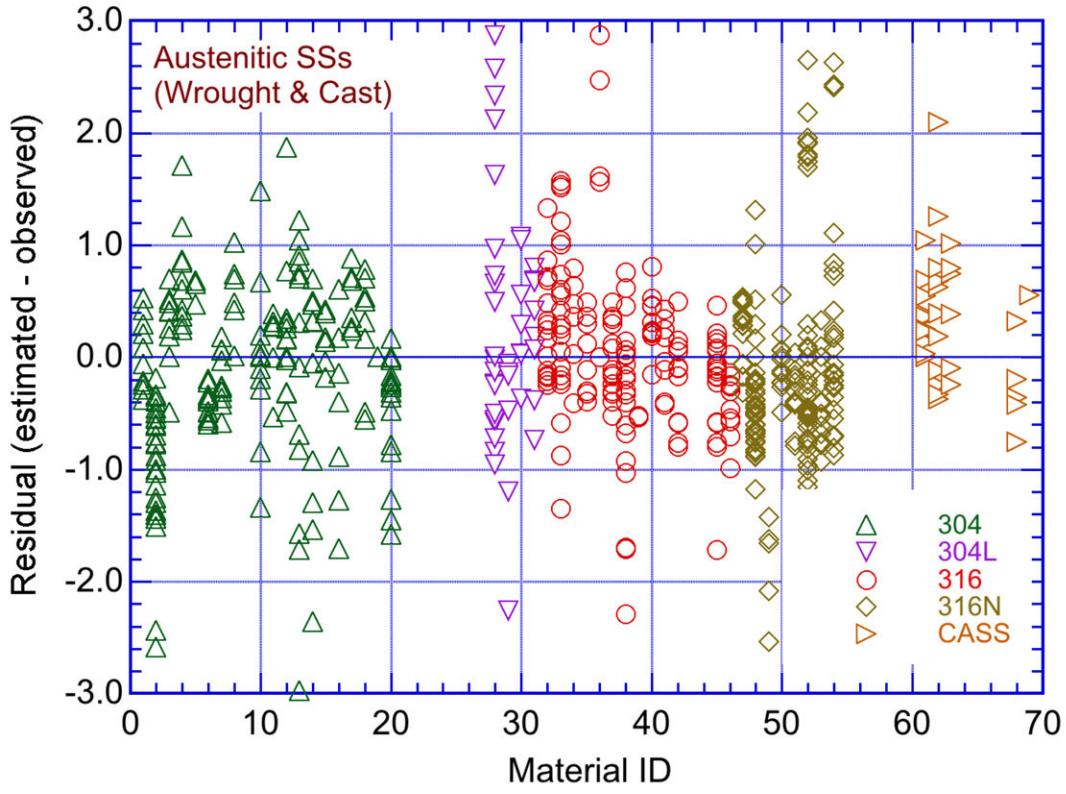


Figure 4-53

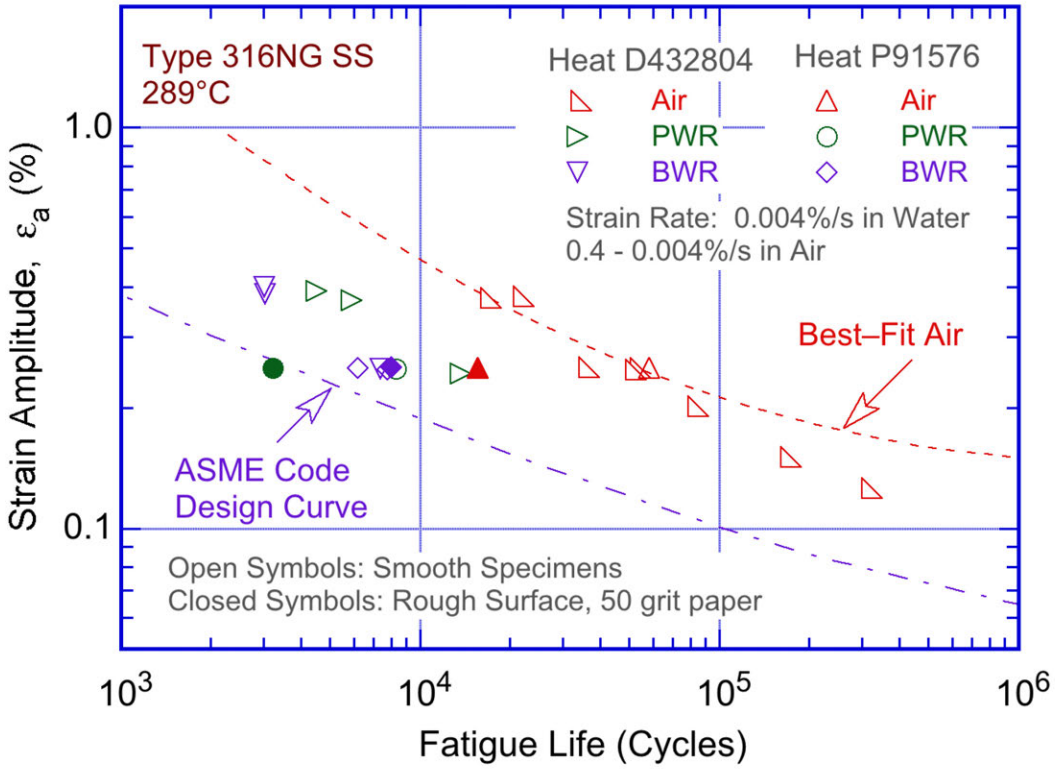


Figure 4-54(a)

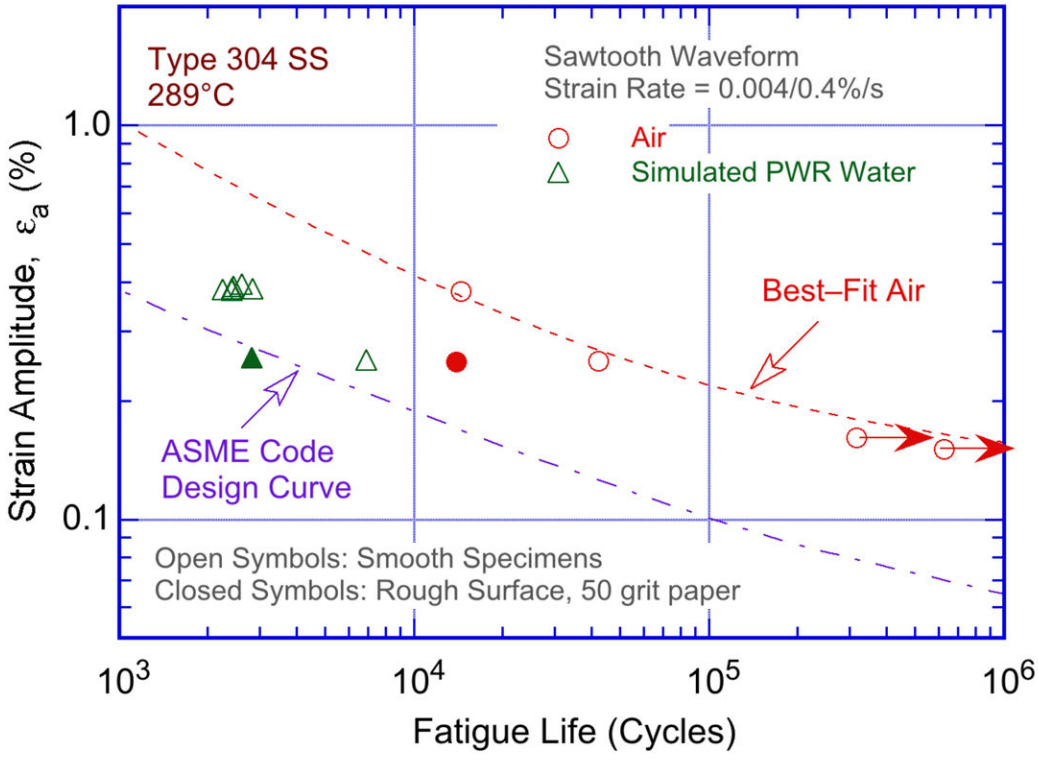


Figure 4-54(b)

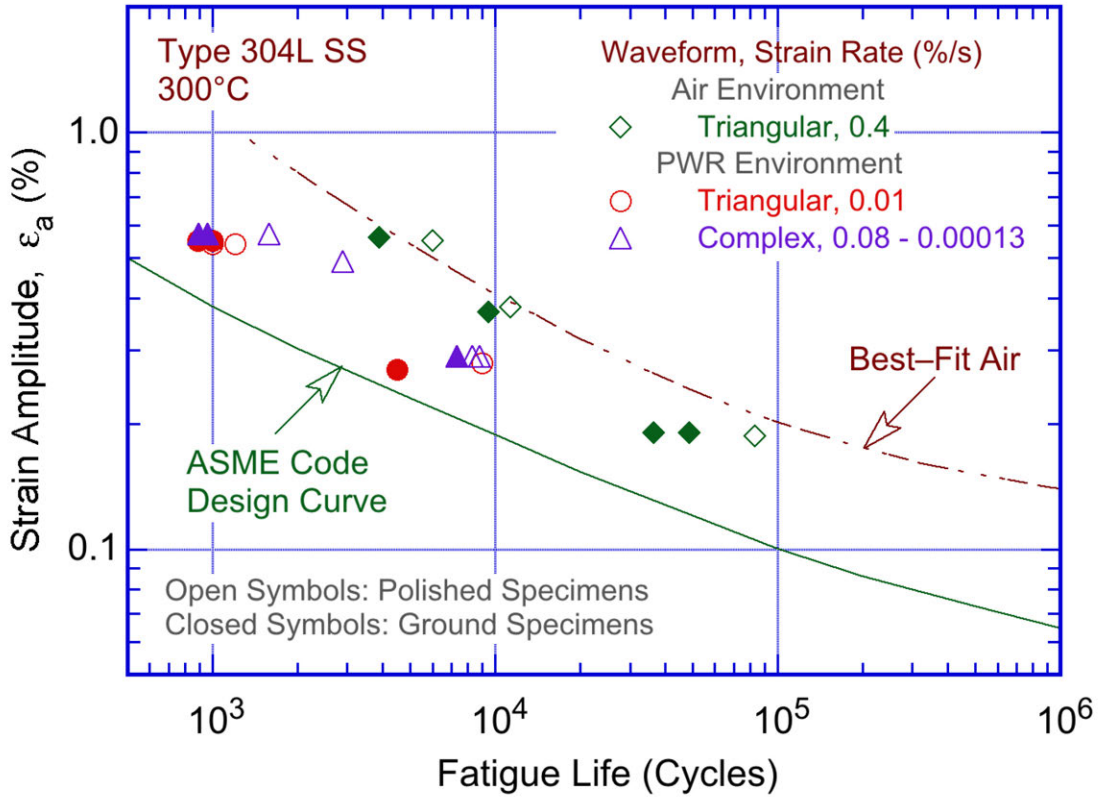

Type 304L SS
300°C
Waveform, Strain Rate (%/s)
Air Environment
Triangular, 0.4
PWR Environment
Triangular, 0.01
Complex, 0.08 - 0.00013
Best–Fit Air
ASME Code
Design Curve
Open Symbols: Polished Specimens
Closed Symbols: Ground Specimens
Strain Amplitude, ε_a (%)
1.0
0.1
10^3
10^4
10^5
10^6
Fatigue Life (Cycles)

Figure 4-55

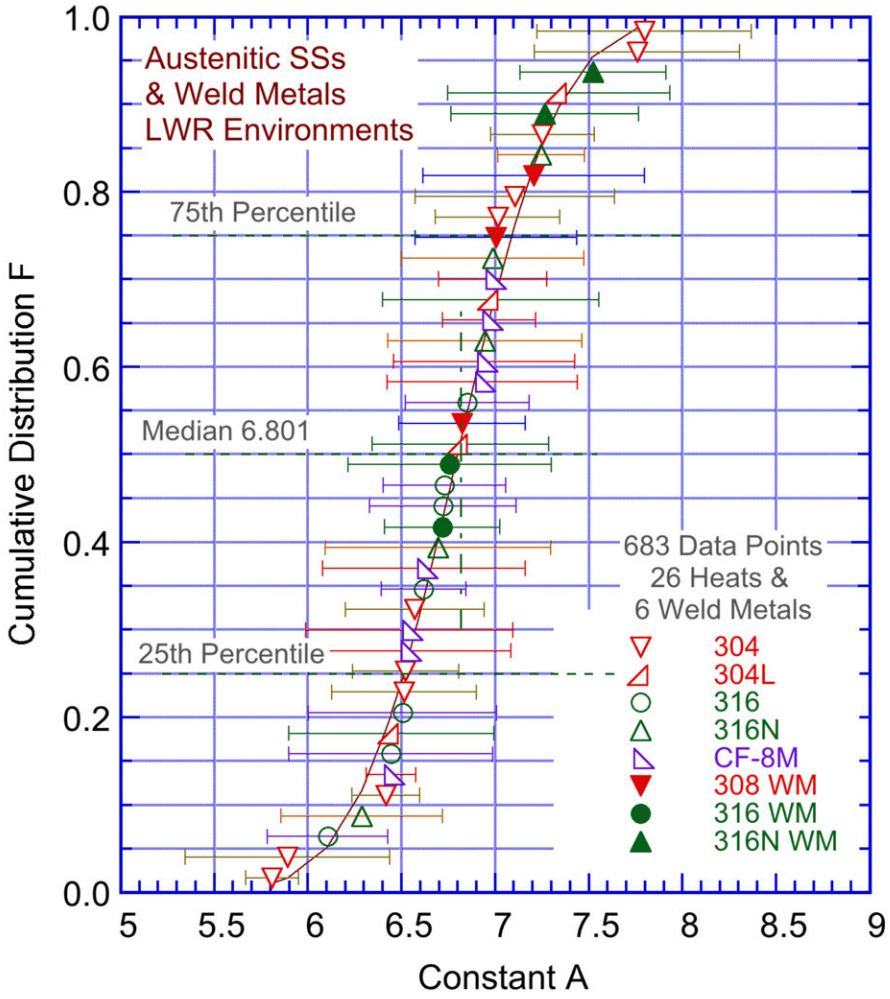

Austenitic SSs
& Weld Metals
LWR Environments
75th Percentile
Median 6.801
25th Percentile
683 Data Points
26 Heats &
6 Weld Metals
304
304L
316
316N
CF-8M
308 WM
316 WM
316N WM
Cumulative Distribution F
Constant A
1.0
0.8
0.6
0.4
0.2
0.0
5
5.5
6
6.5
7
7.5
8
8.5
9

Figure 4-56

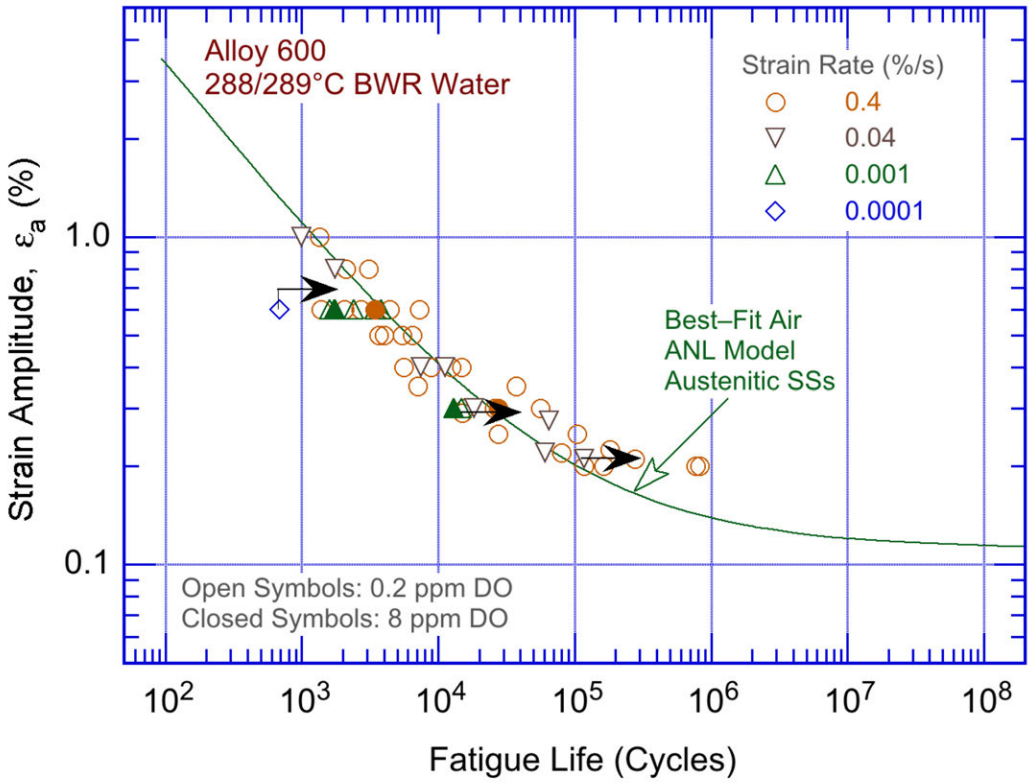


Figure 4-57(a)

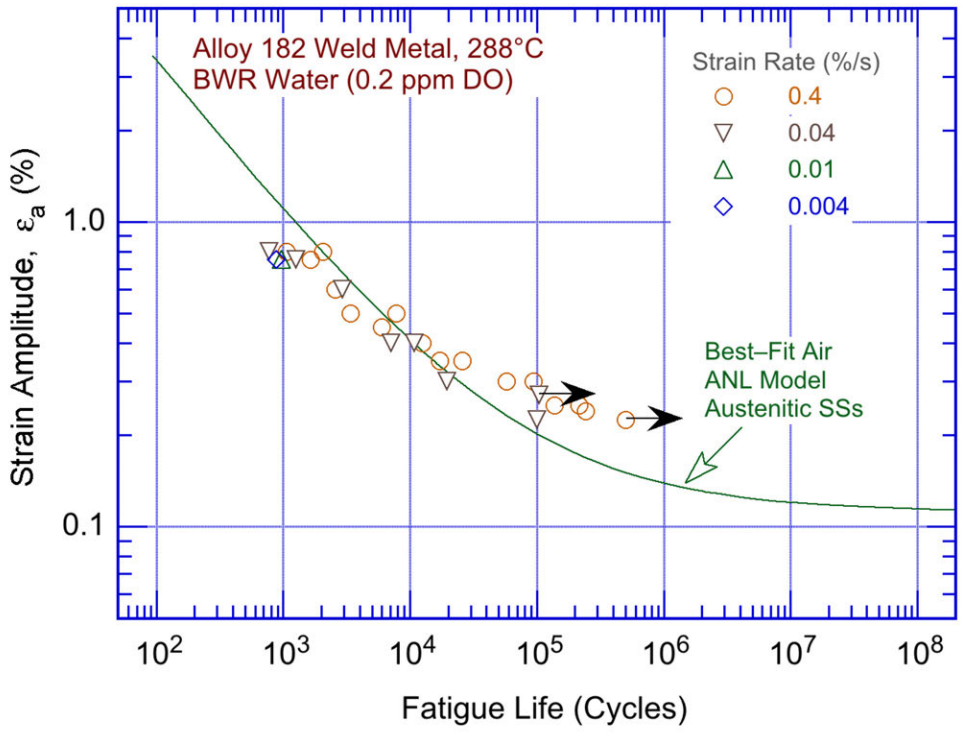


Figure 4-57(b)

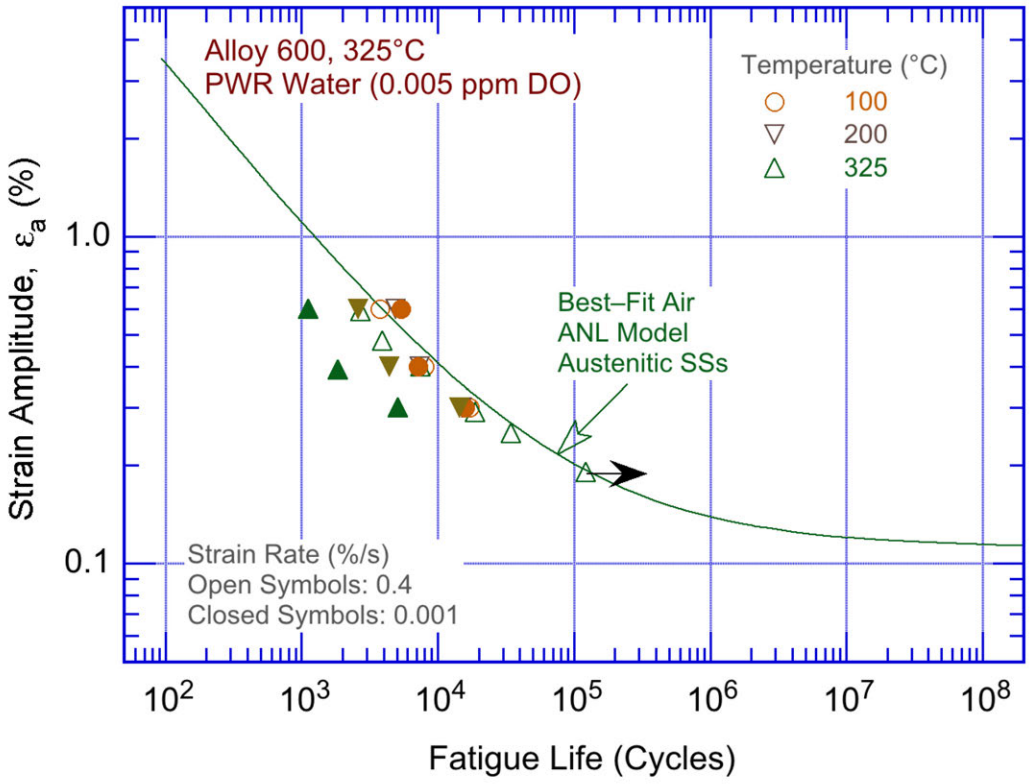


Figure 4-58(a)

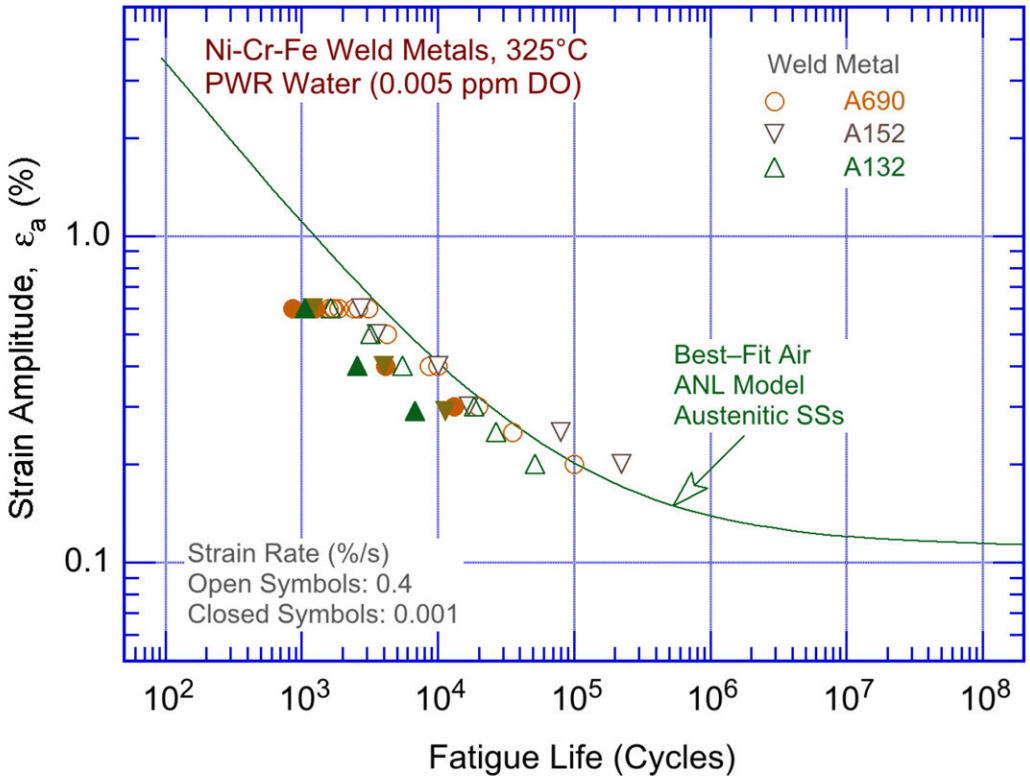


Figure 4-58(b)

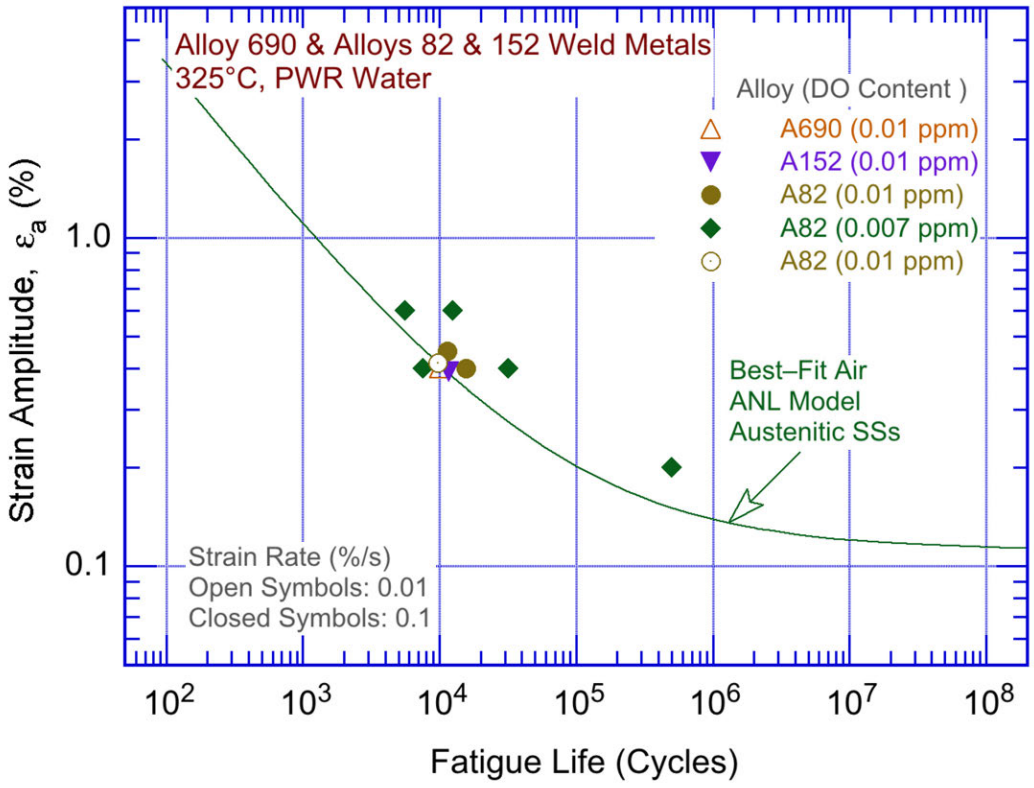


Figure 4-58(c)

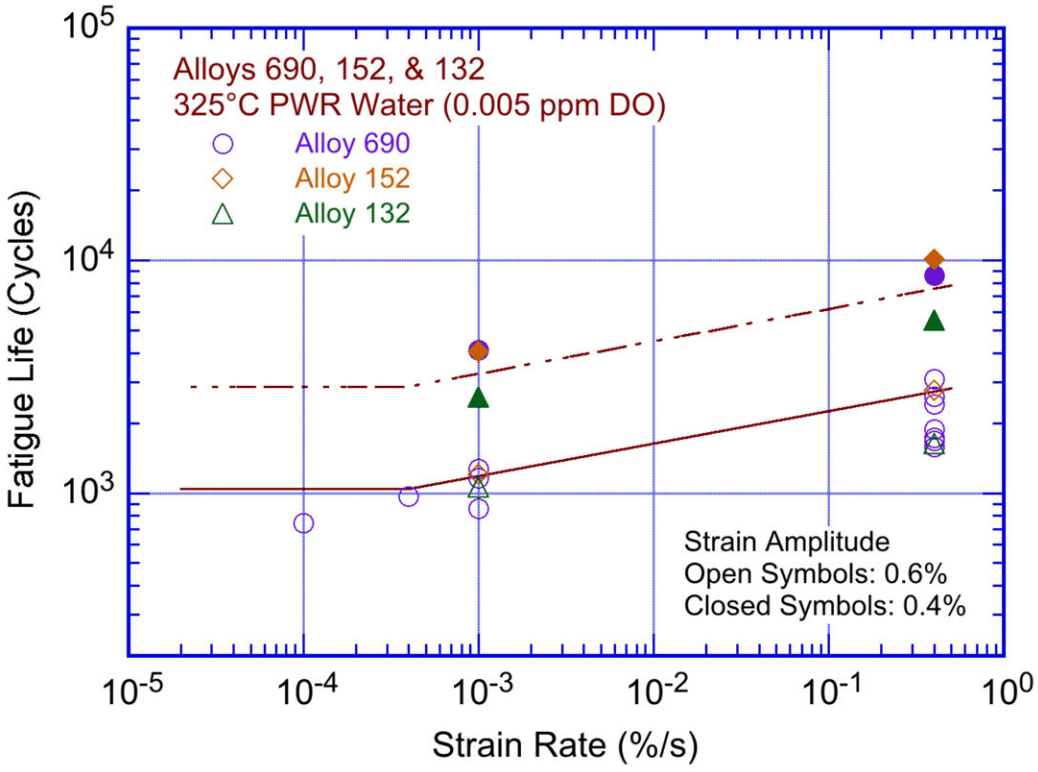


Figure 4-59(a)

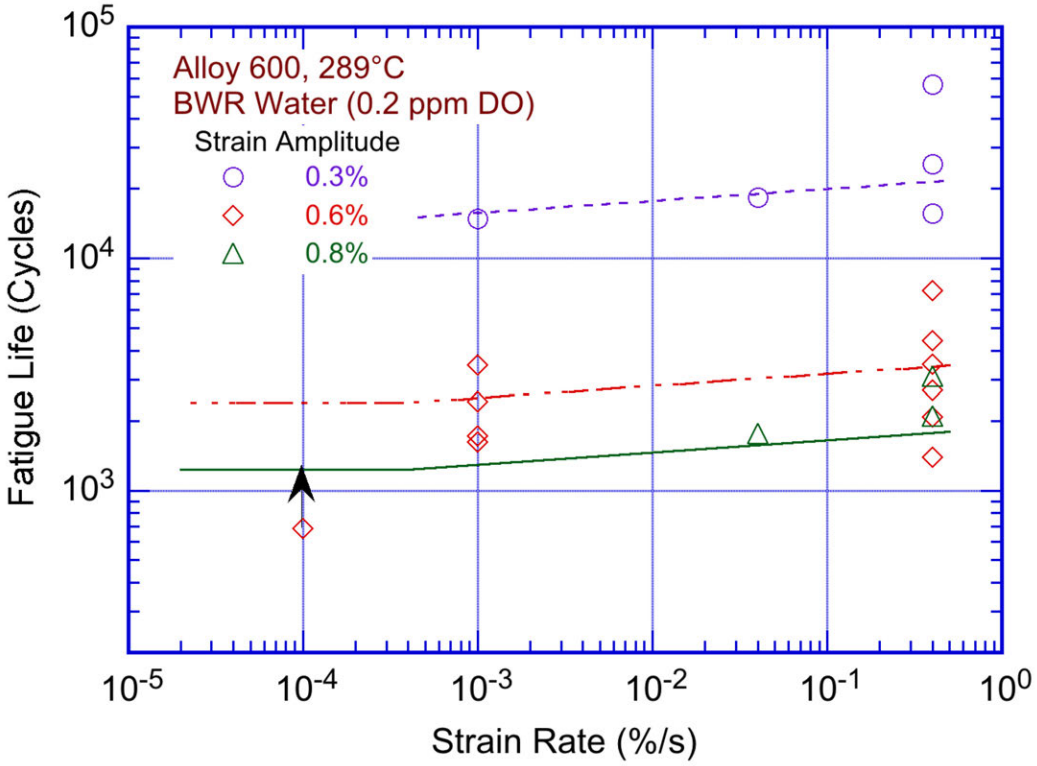


Figure 4-59(b)

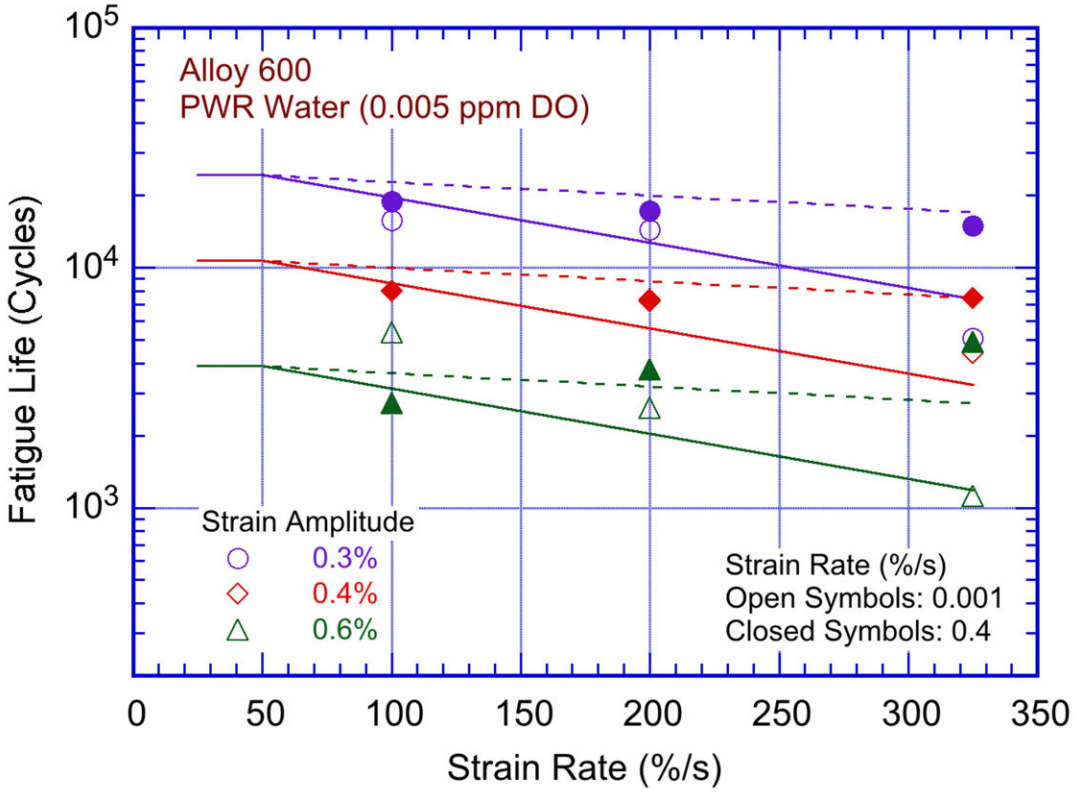


Figure 4-60

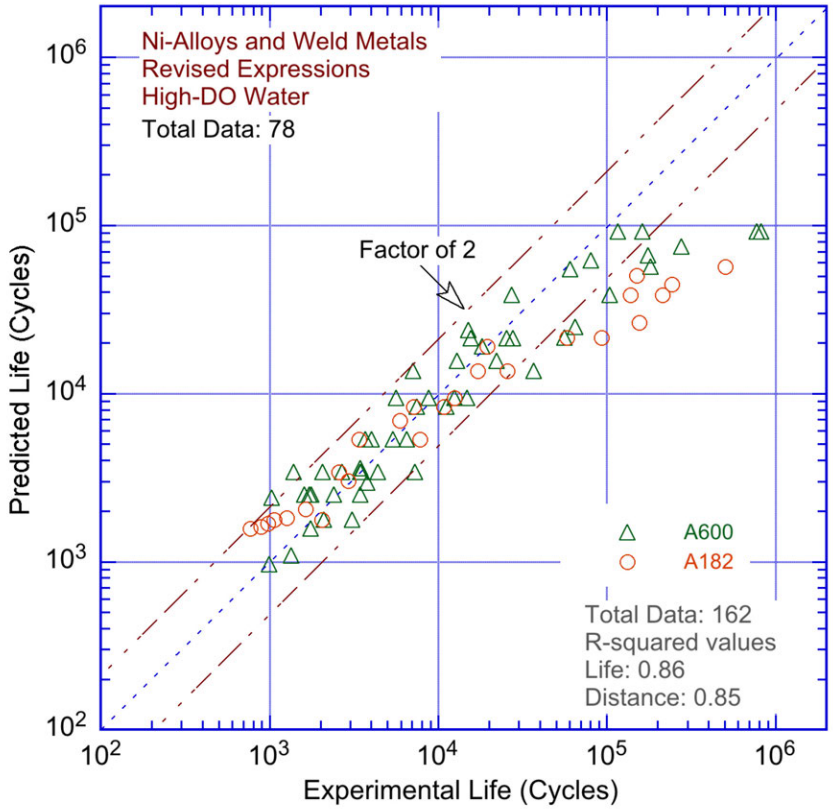


Figure 4-61(a)

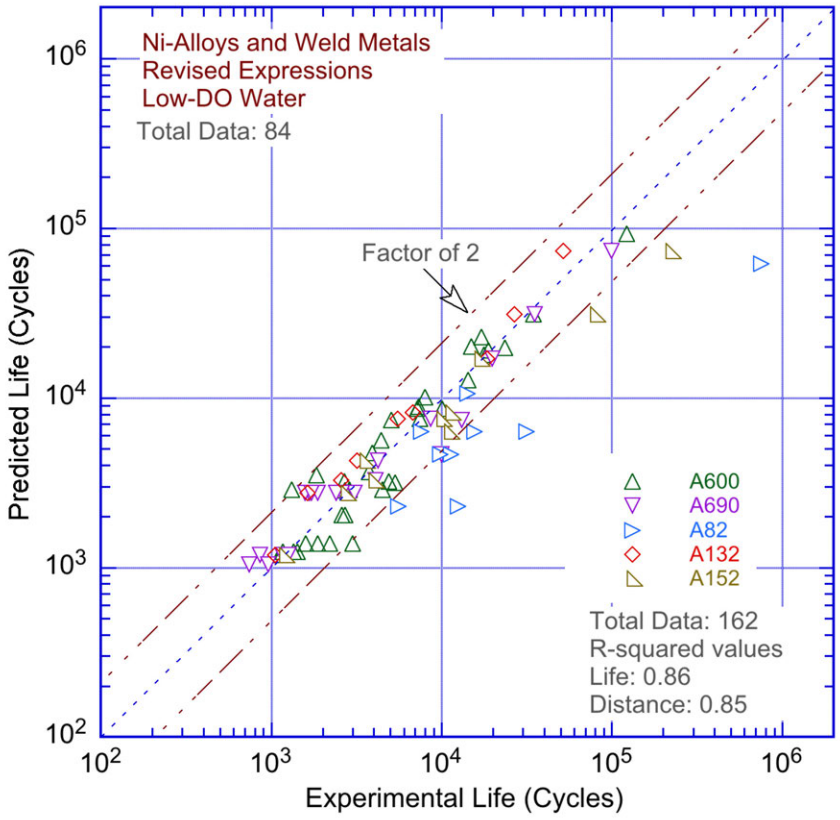


Figure 4-61(b)

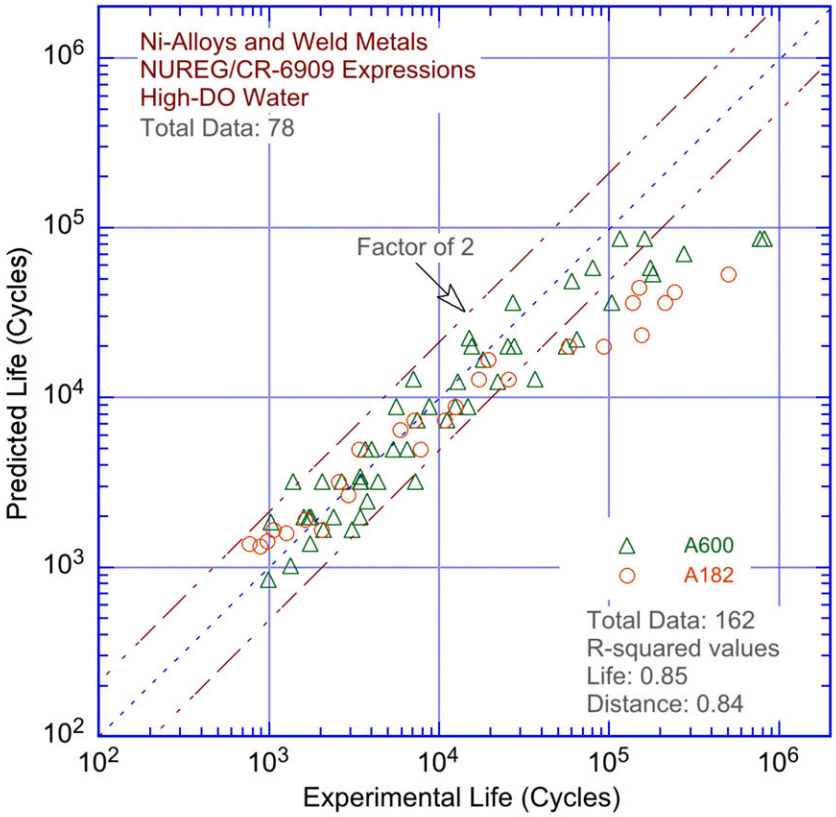


Figure 4-62(a)

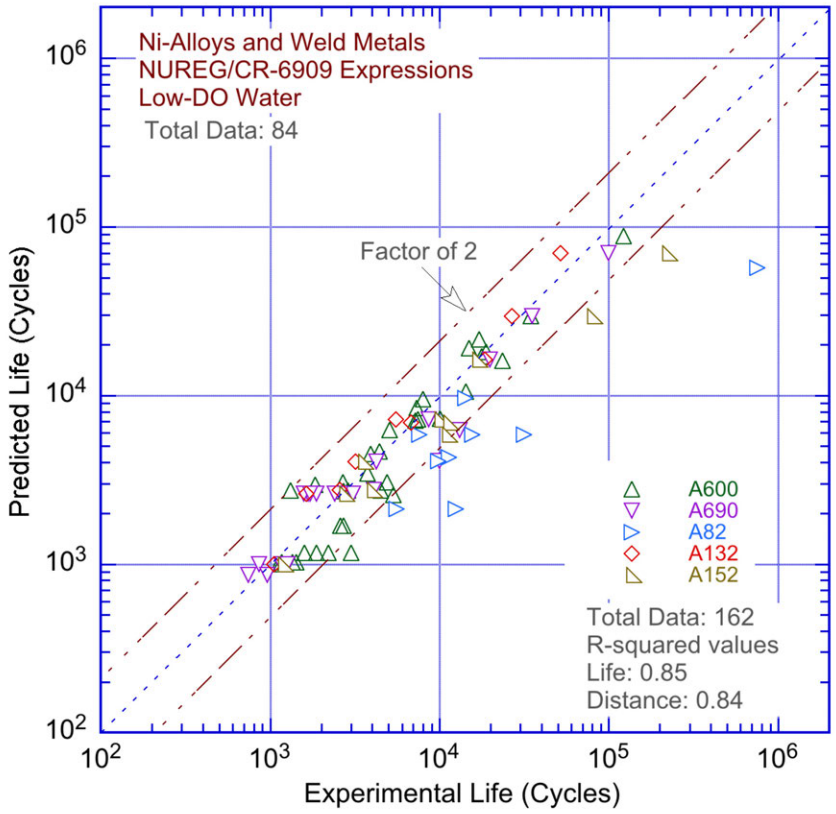


Figure 4-62(b)

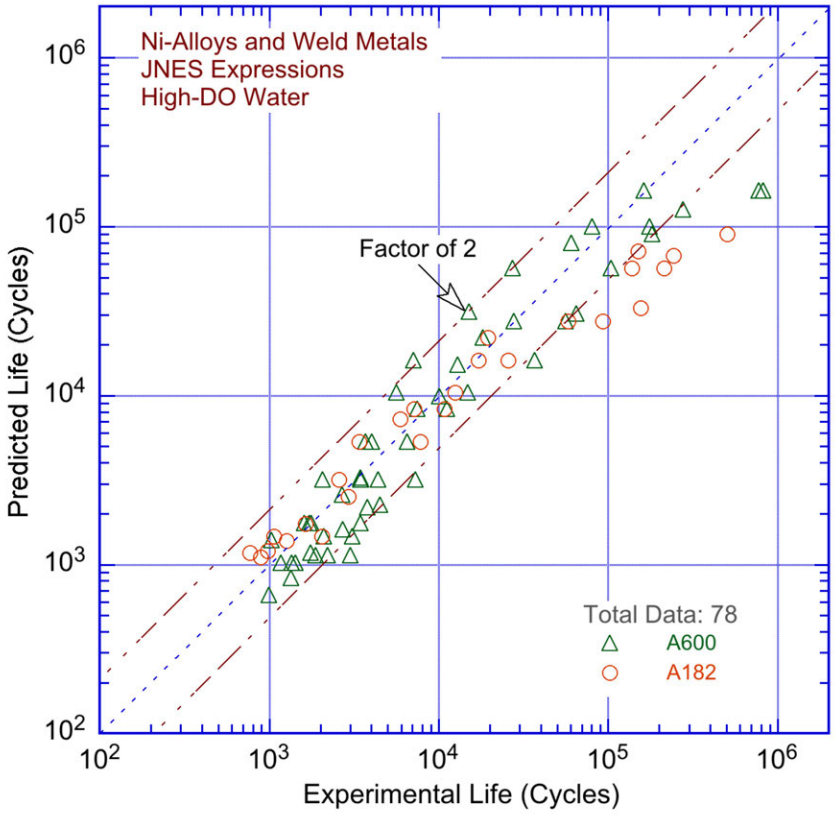


Figure 4-63(a)

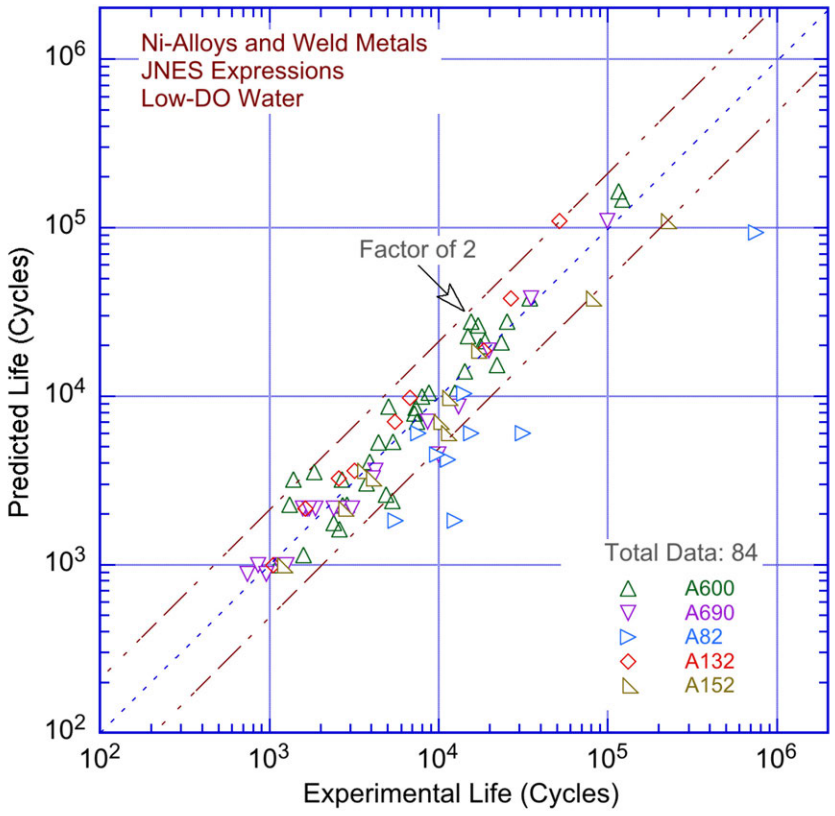


Figure 4-63(b)

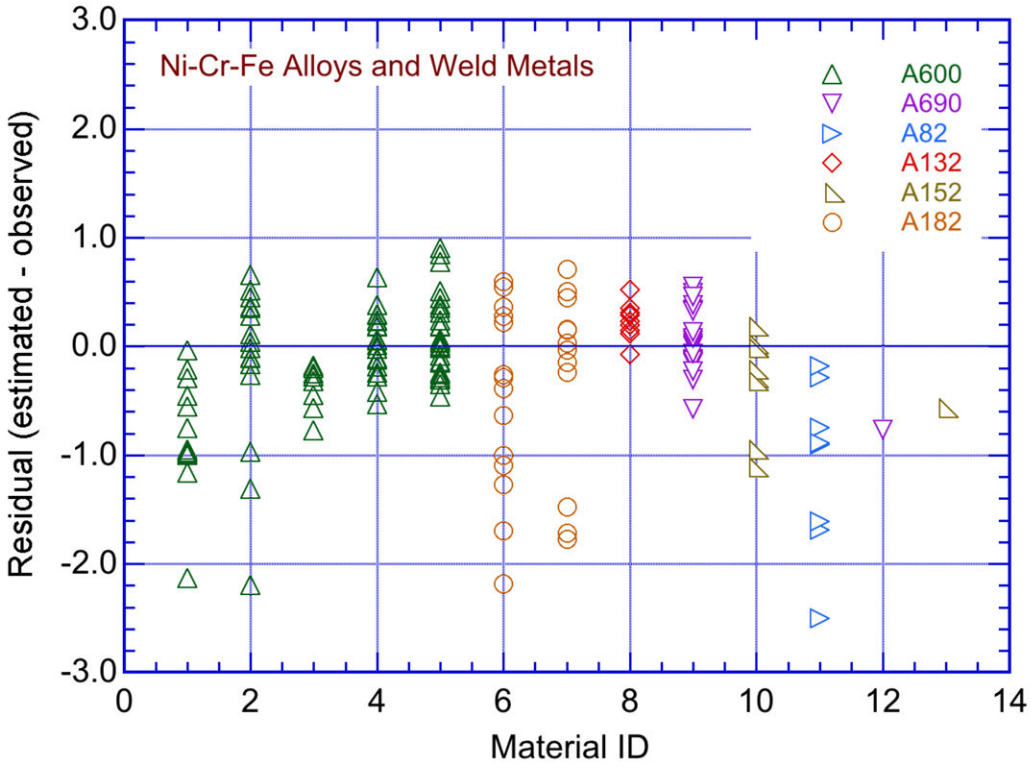


Figure 4-64(a)

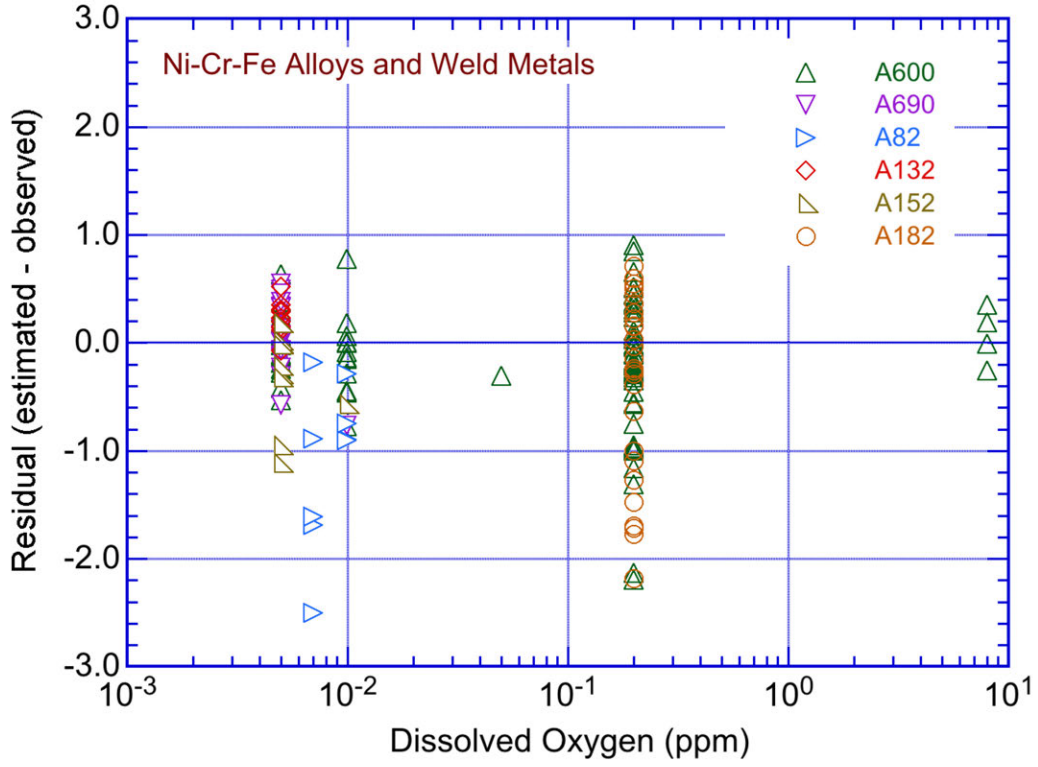


Figure 4-64(b)

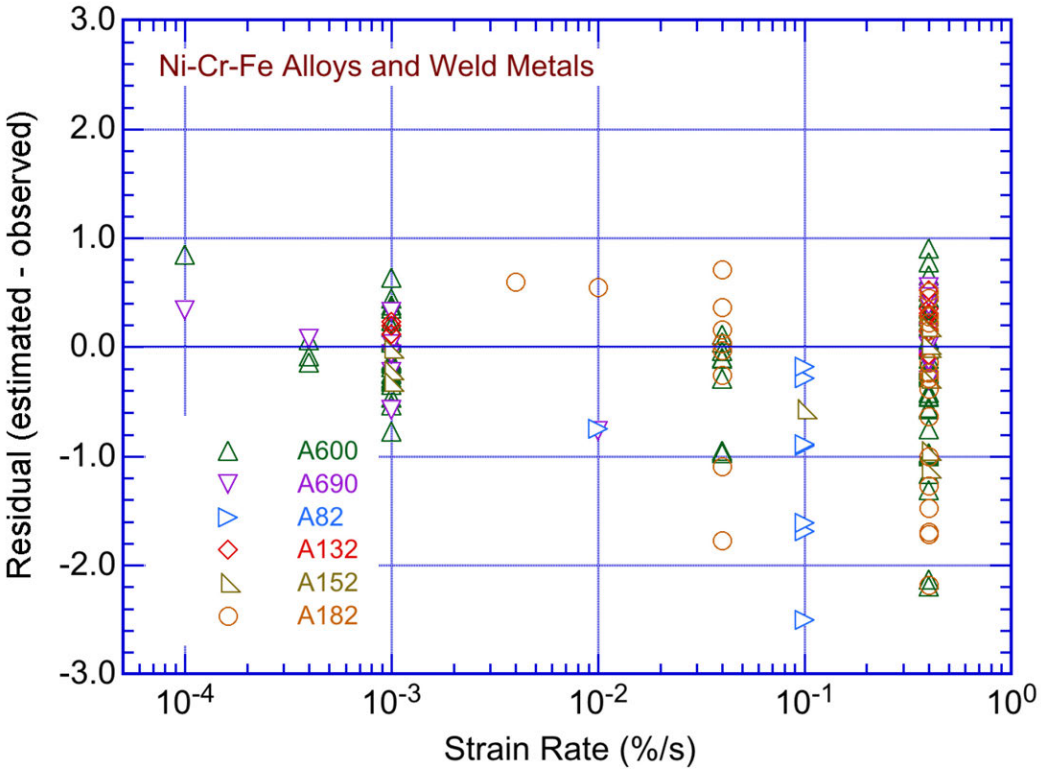


Figure 4-64(c)

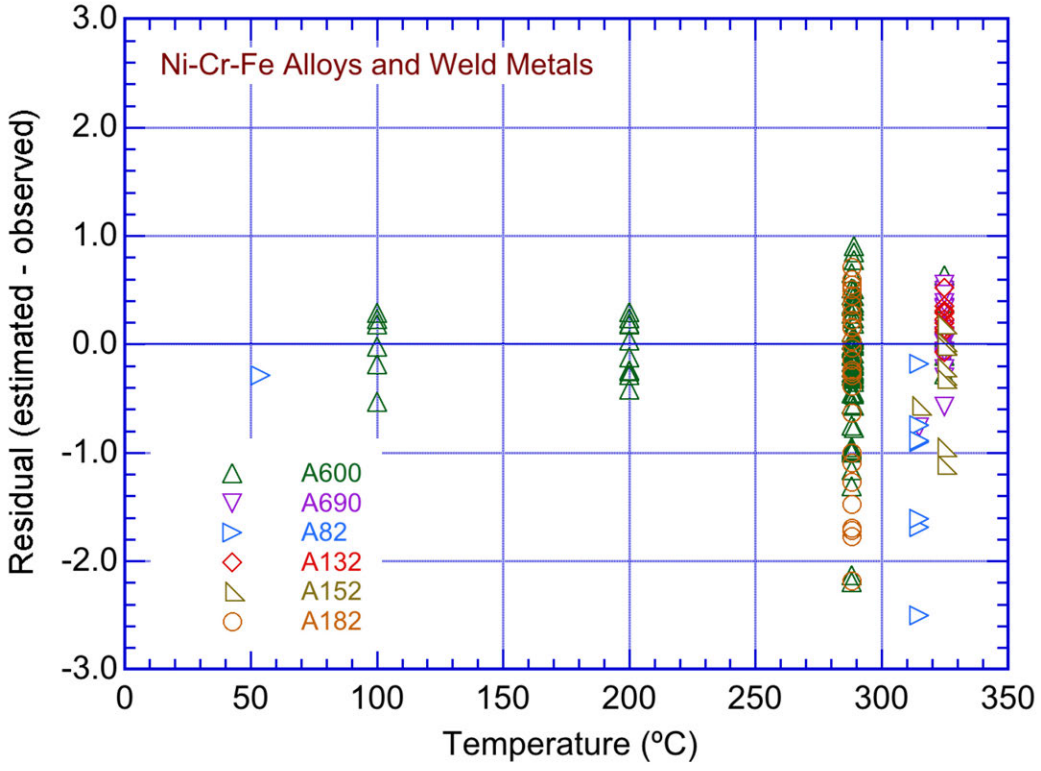


Figure 4-64(d)

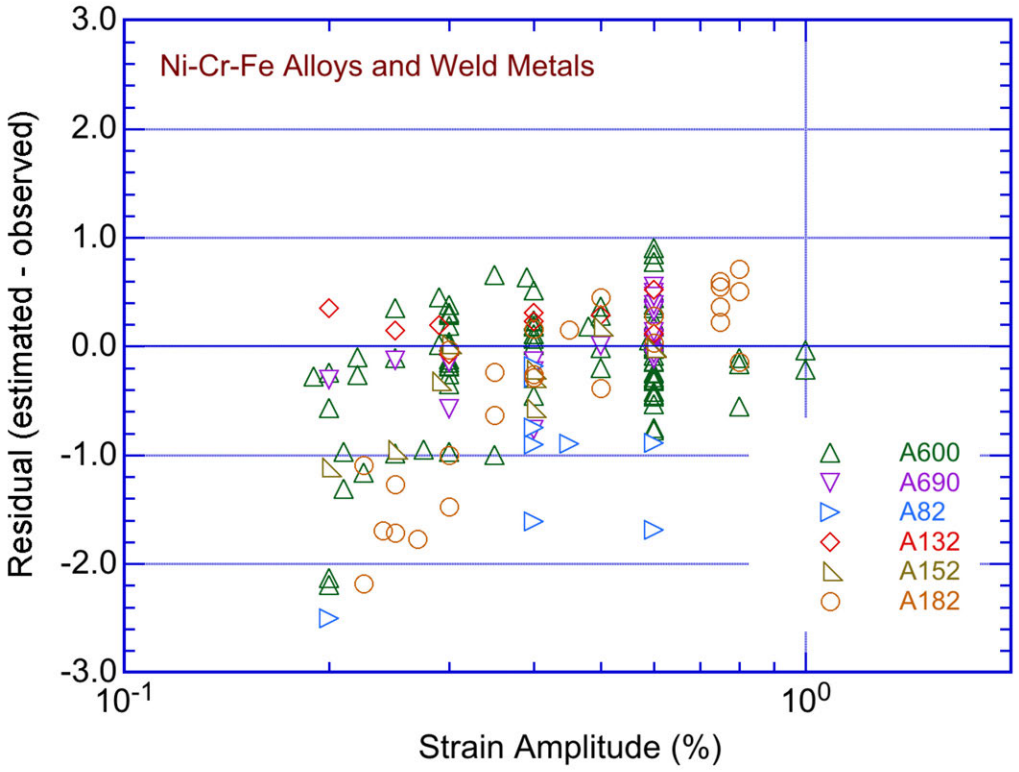


Figure 4-64(e)

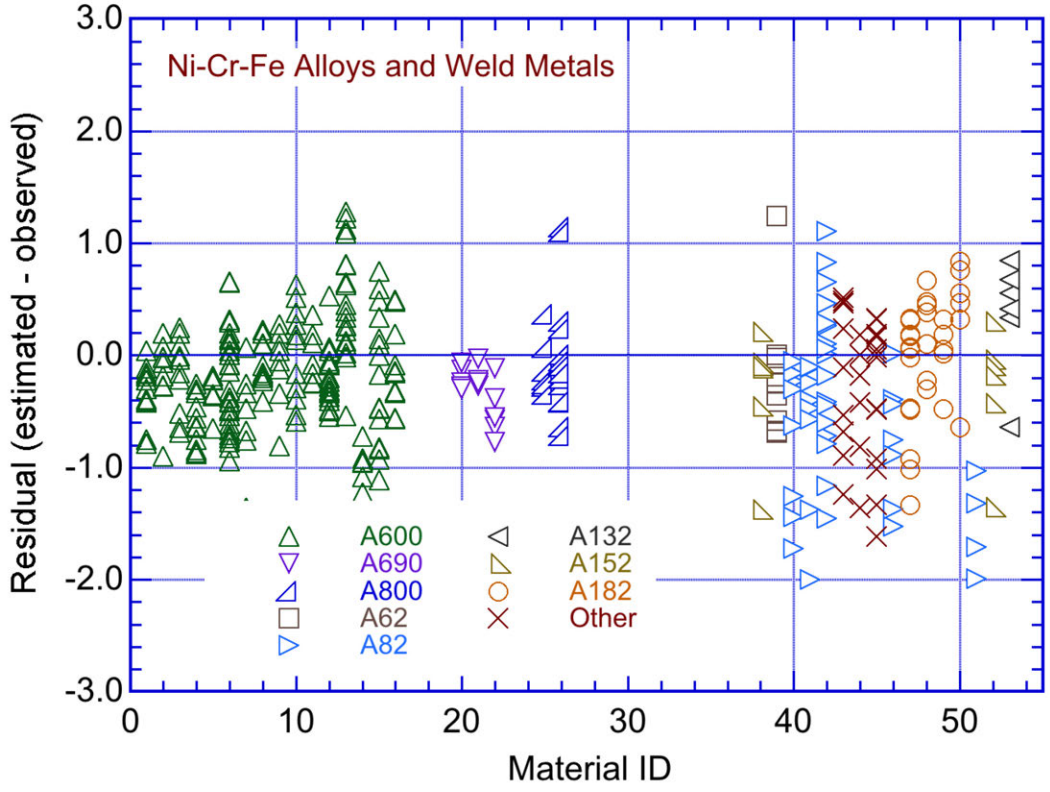


Figure 4-65

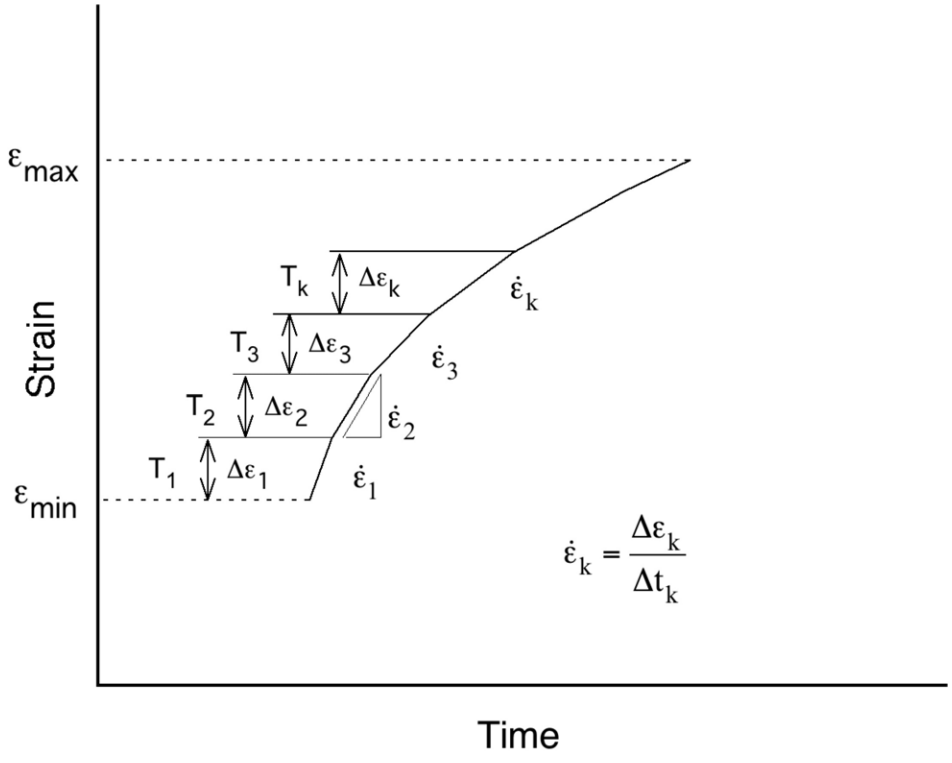


Figure 4-66

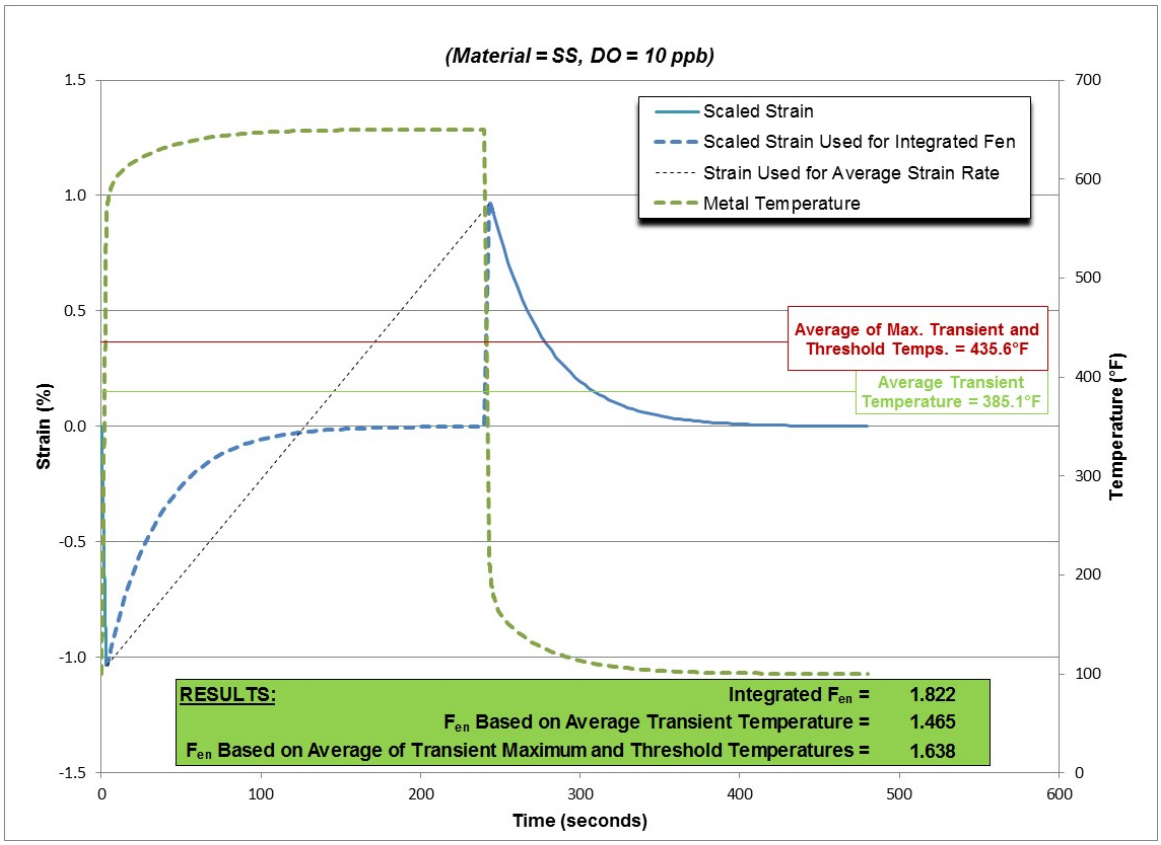


Figure 4-67

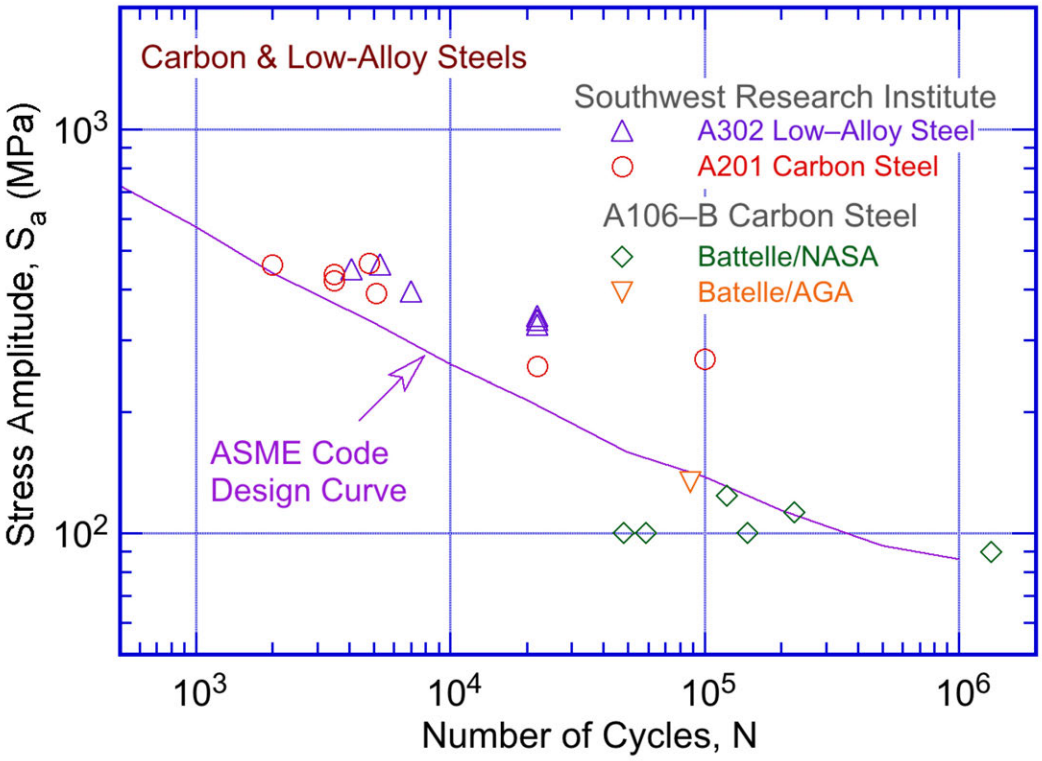


Figure 5-1(a)

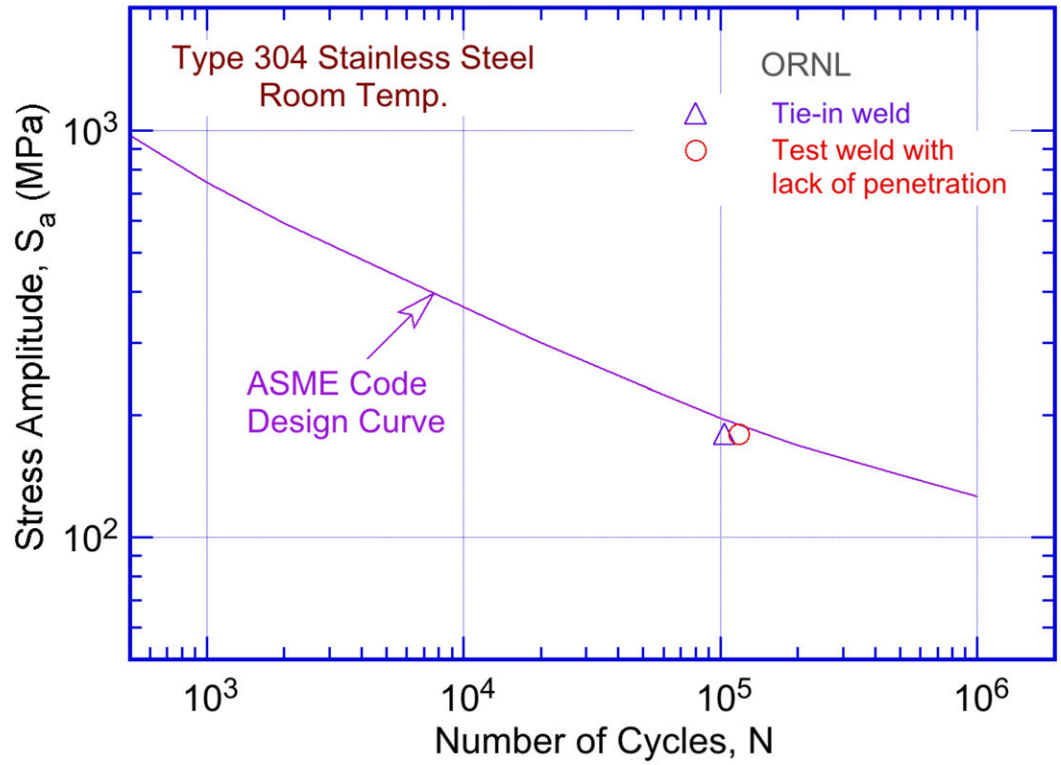


Figure 5-1(b)

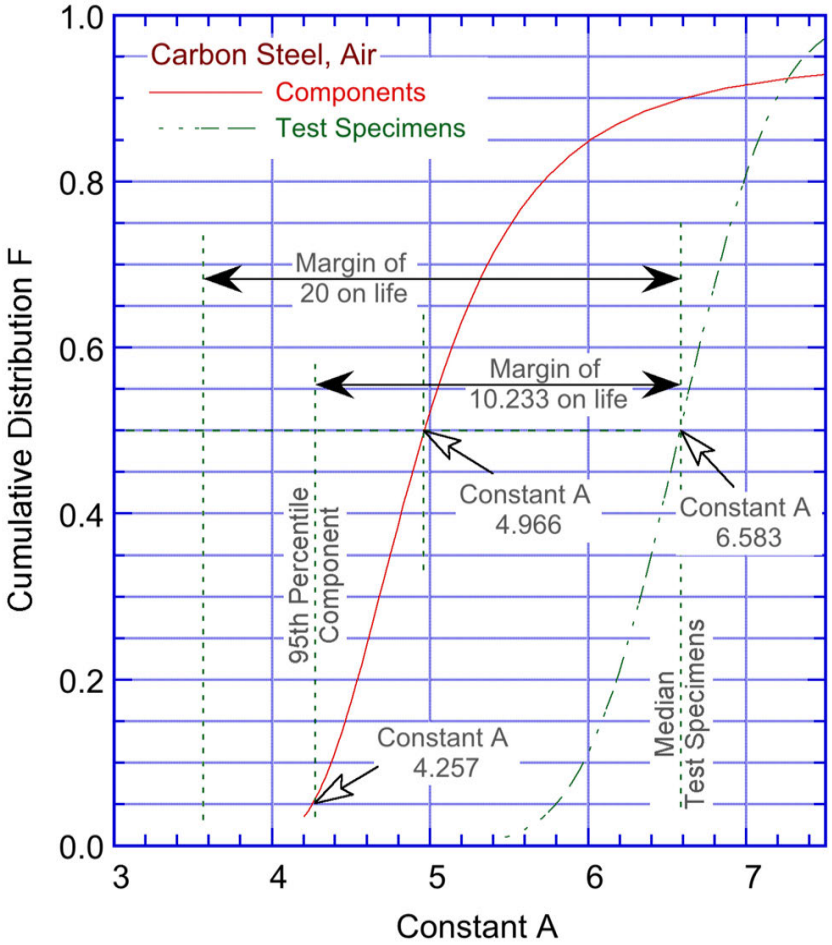


Figure 5-2(a)

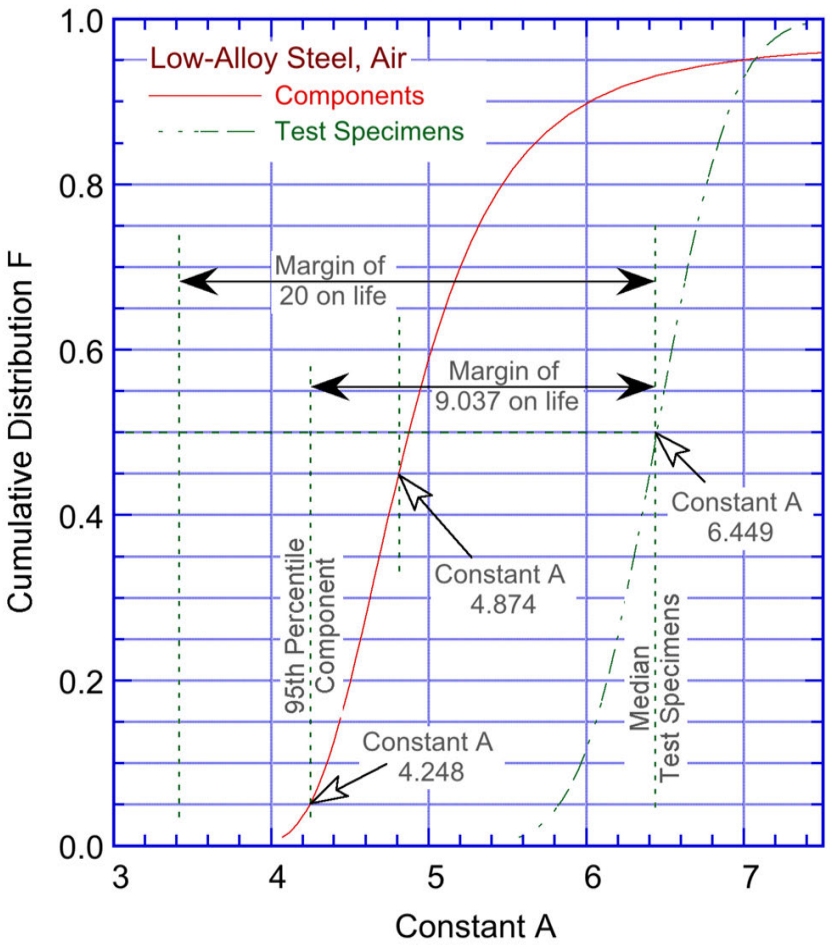


Figure 5-2(b)

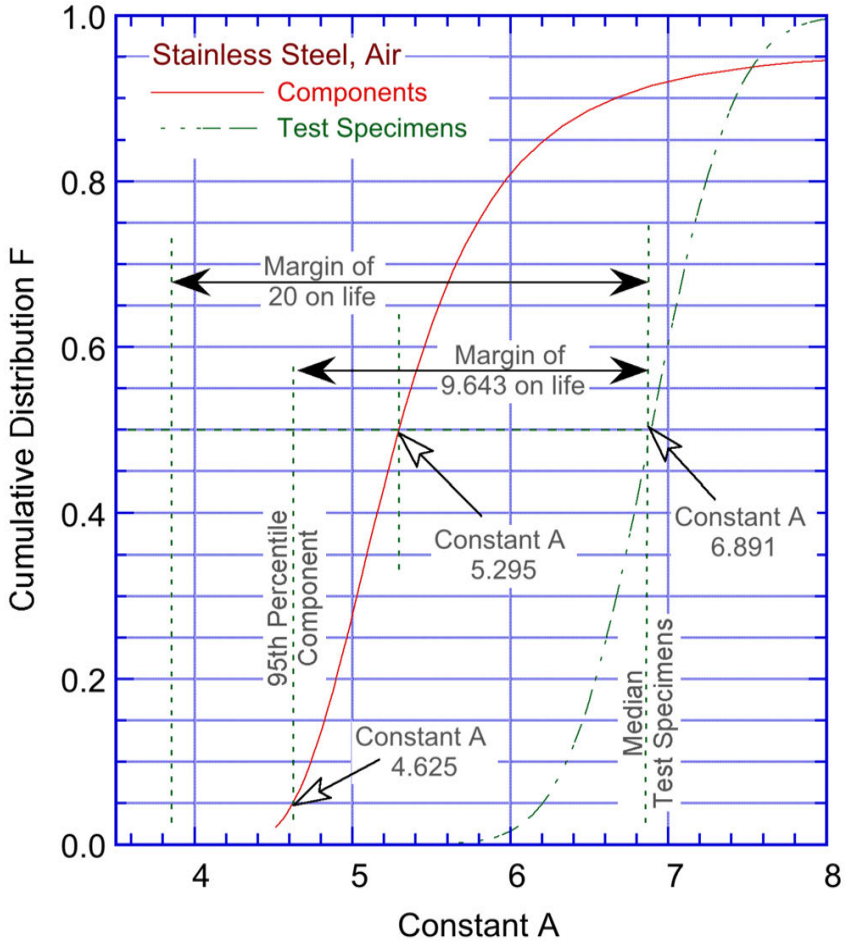


Figure 5-2(c)

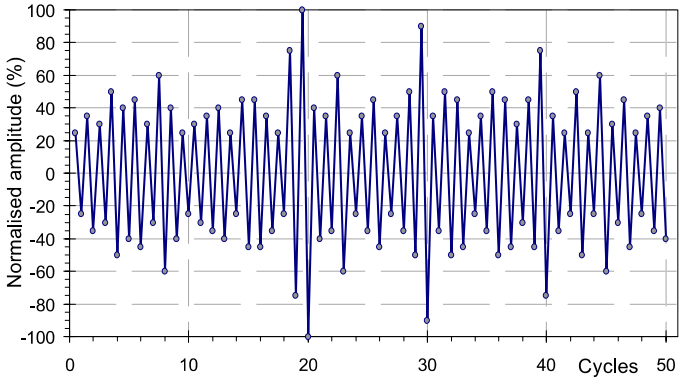


Figure 6-1

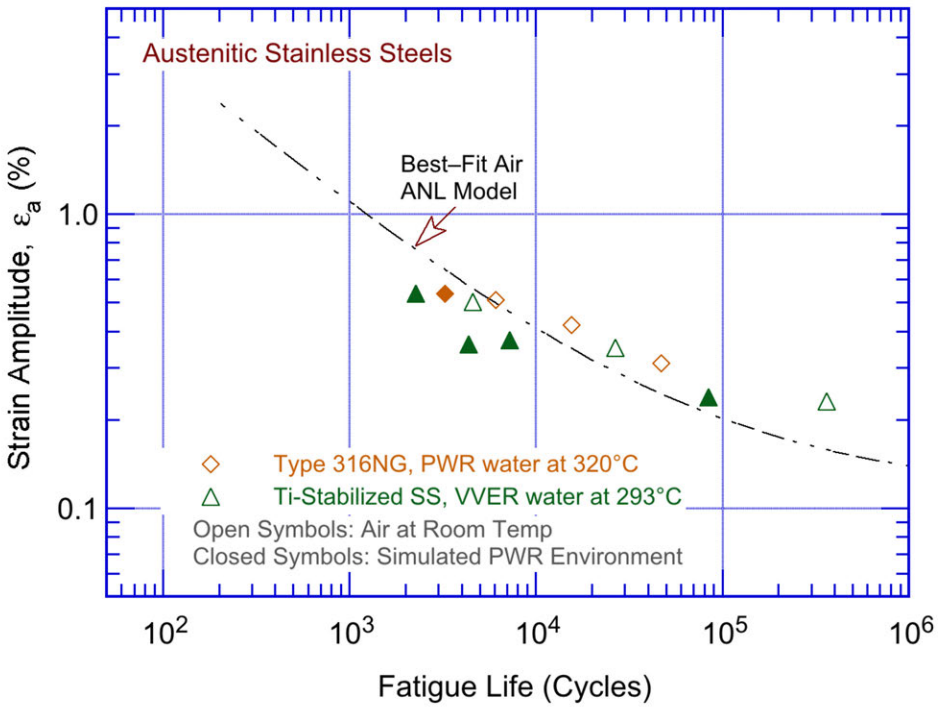


Figure 6-2

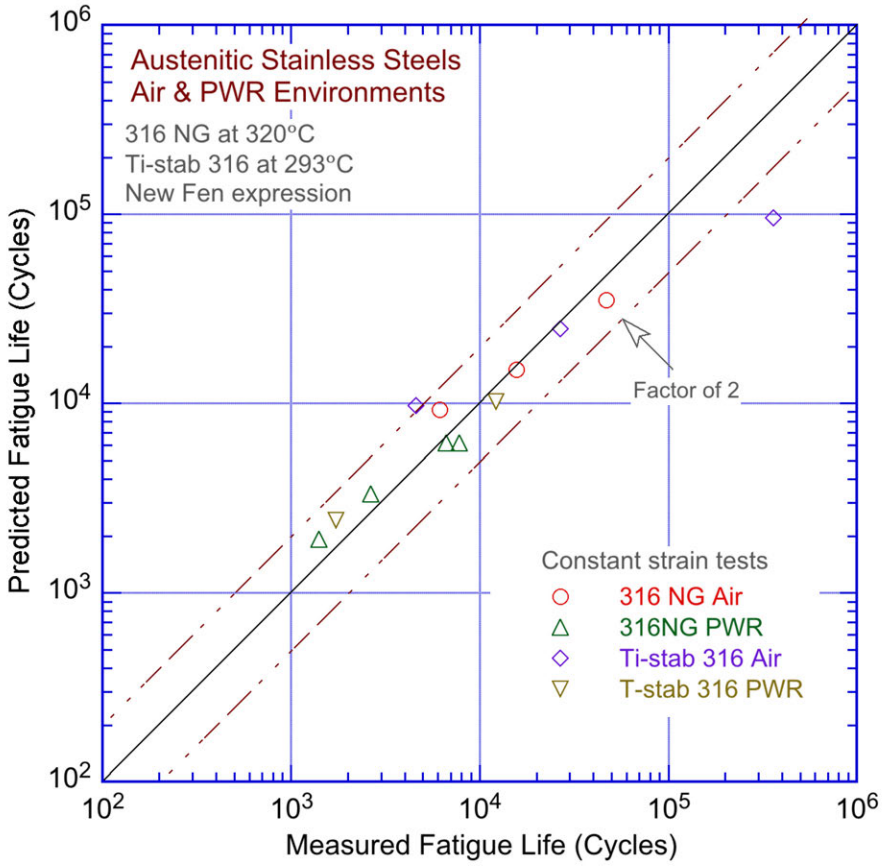


Figure 6-3(a)

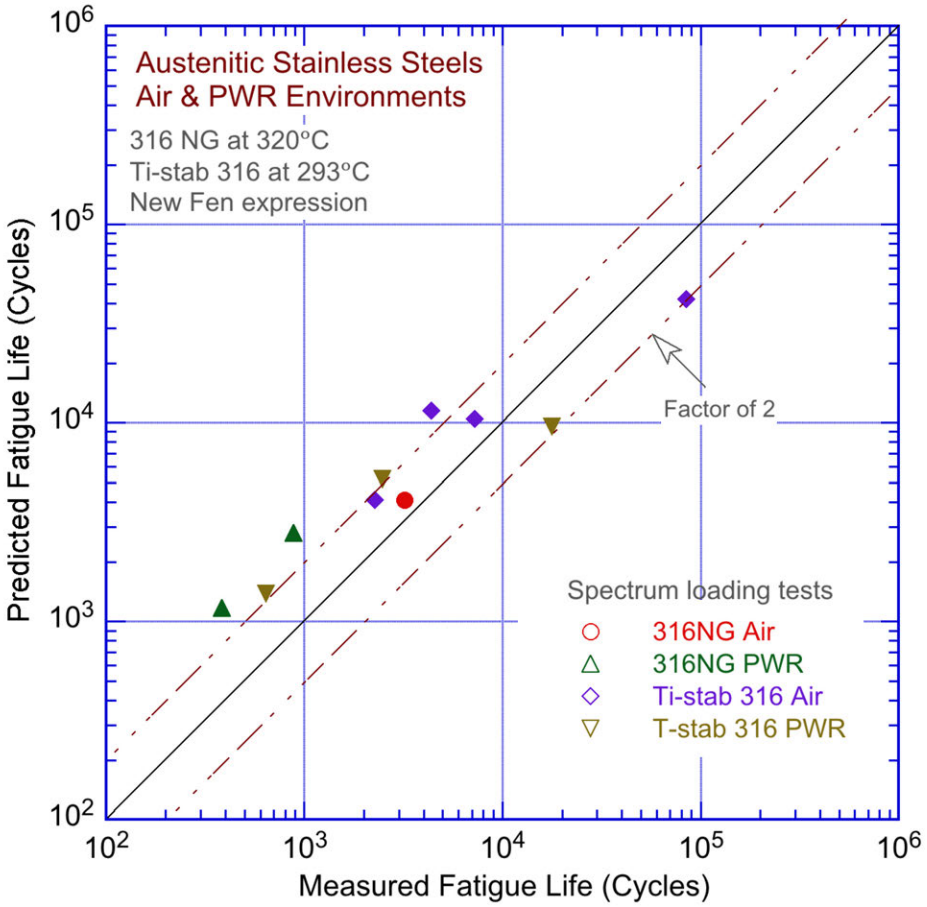


Figure 6-3(b)

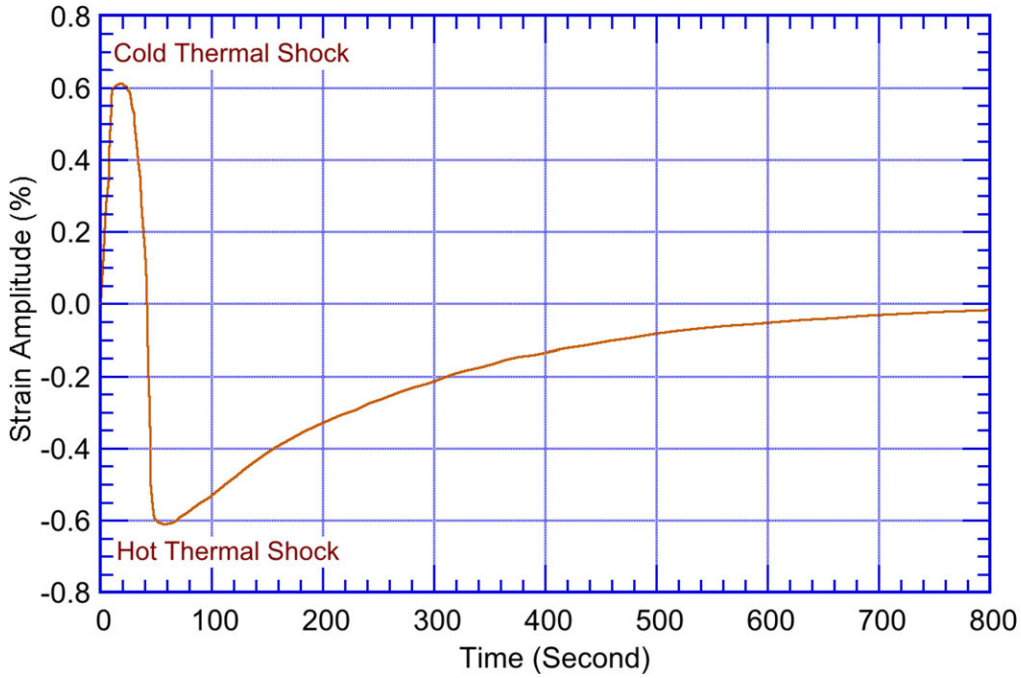


Figure 6-4

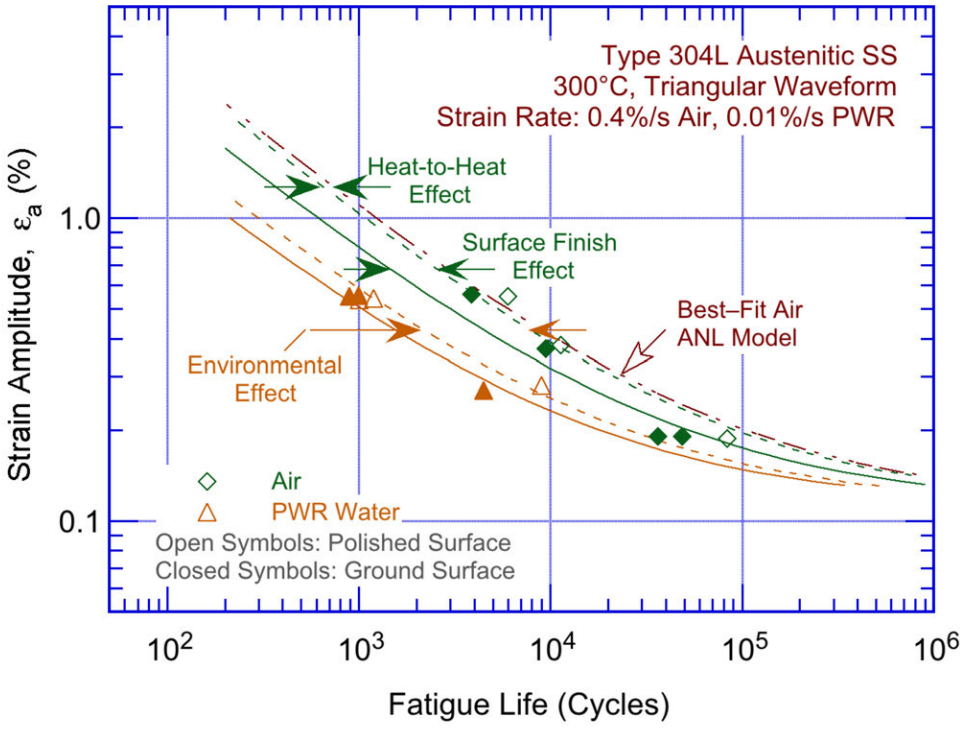


Figure 6-5

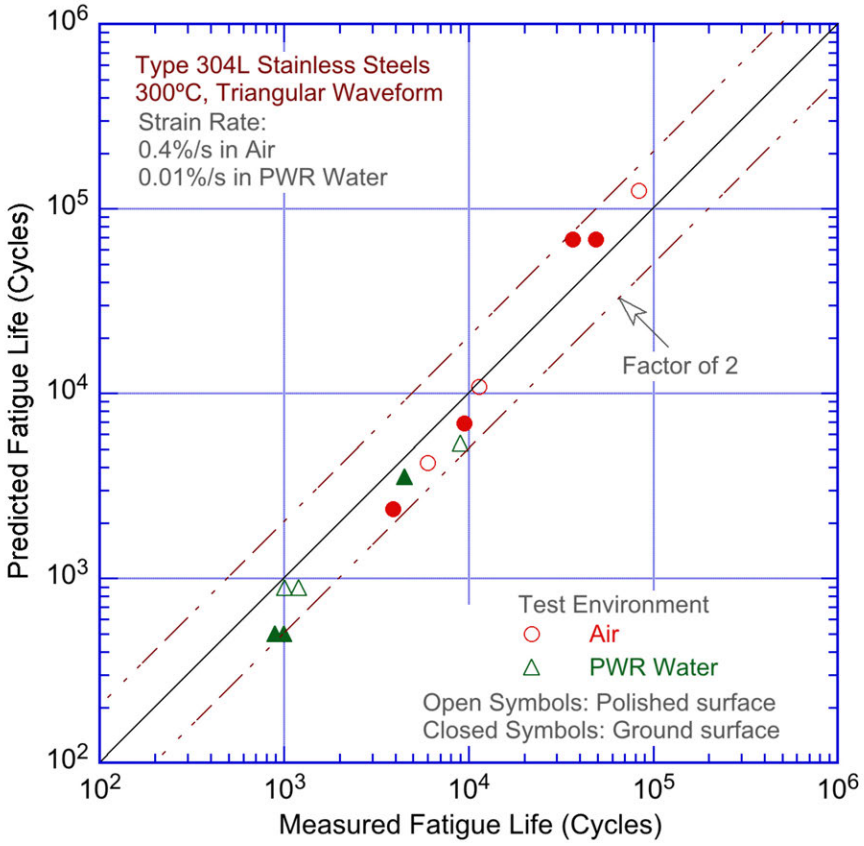


Figure 6-6(a)

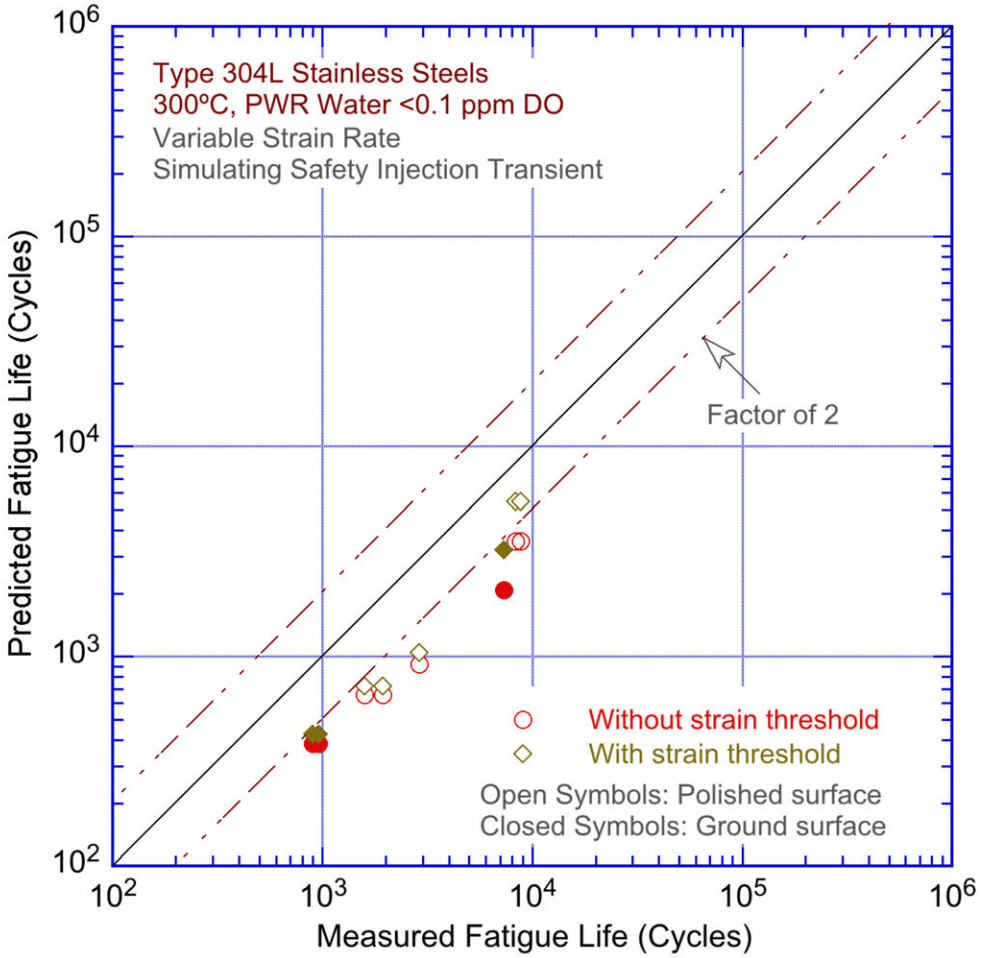


Figure 6-6(b)

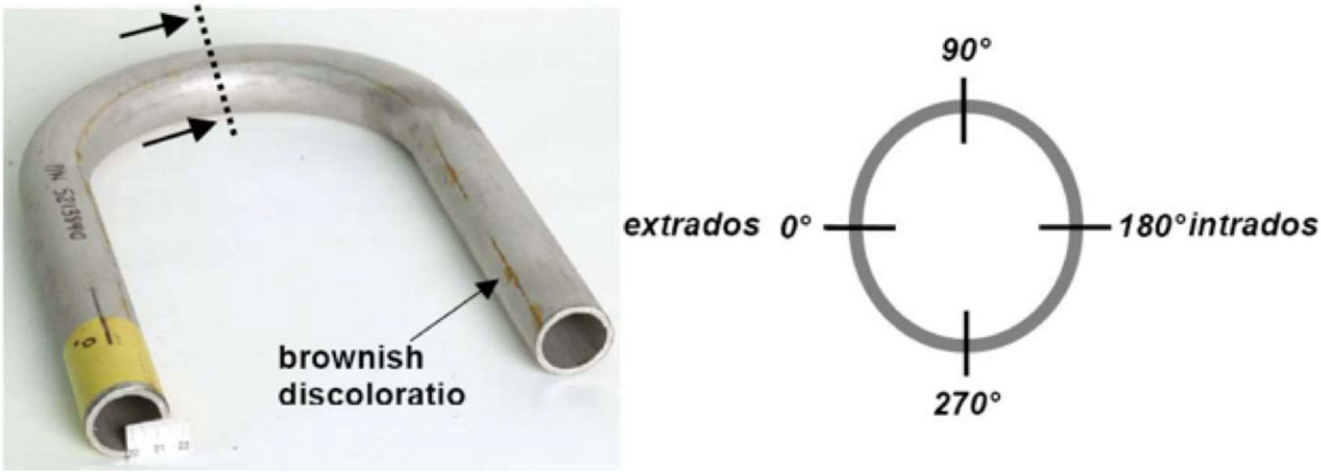


Figure 6-7

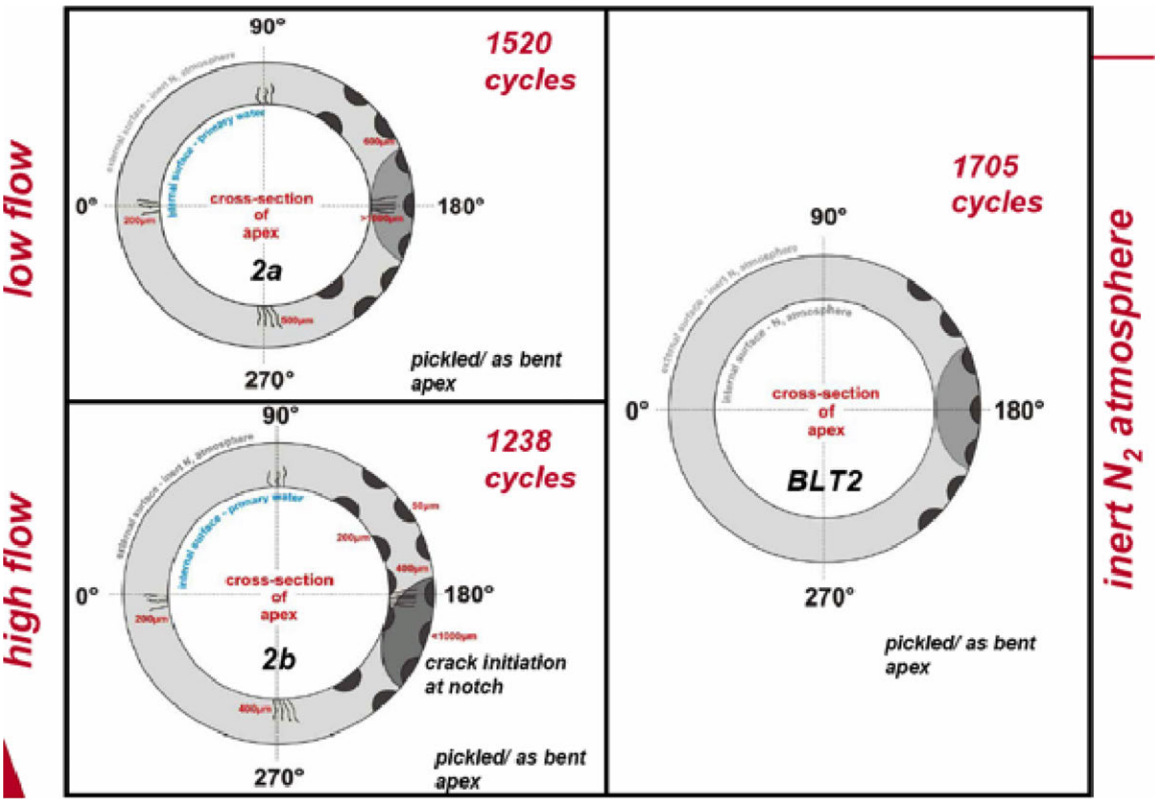


Figure 6-8

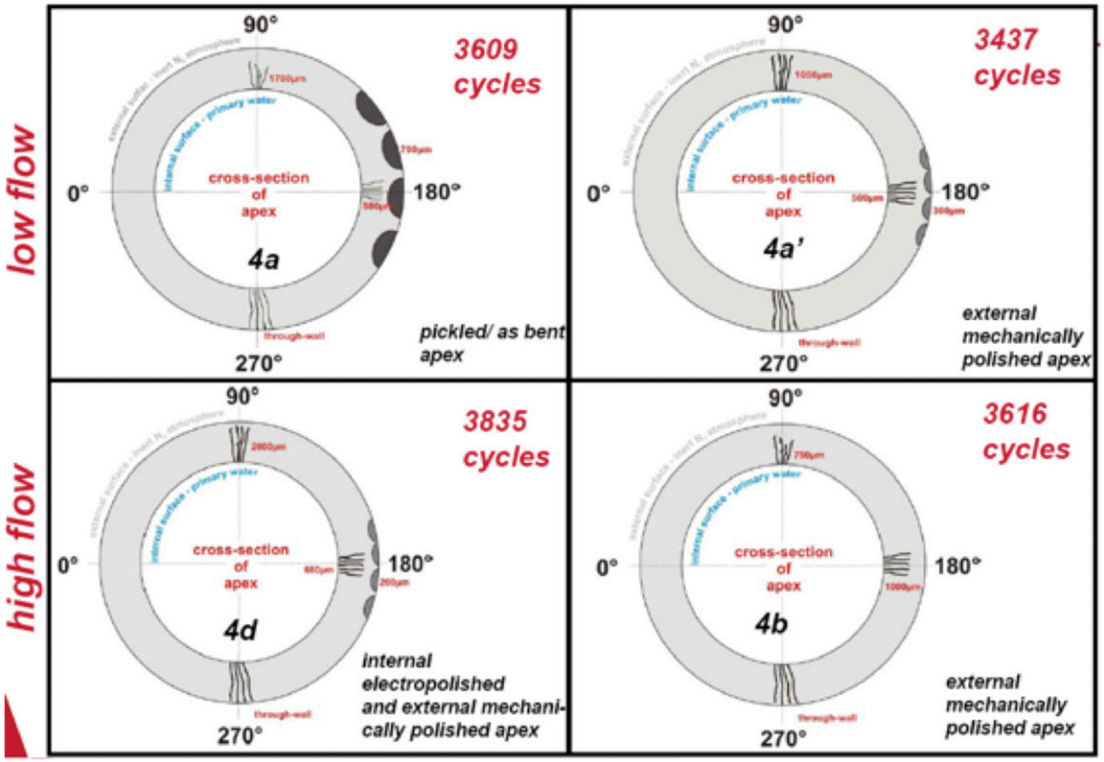


Figure 6-9

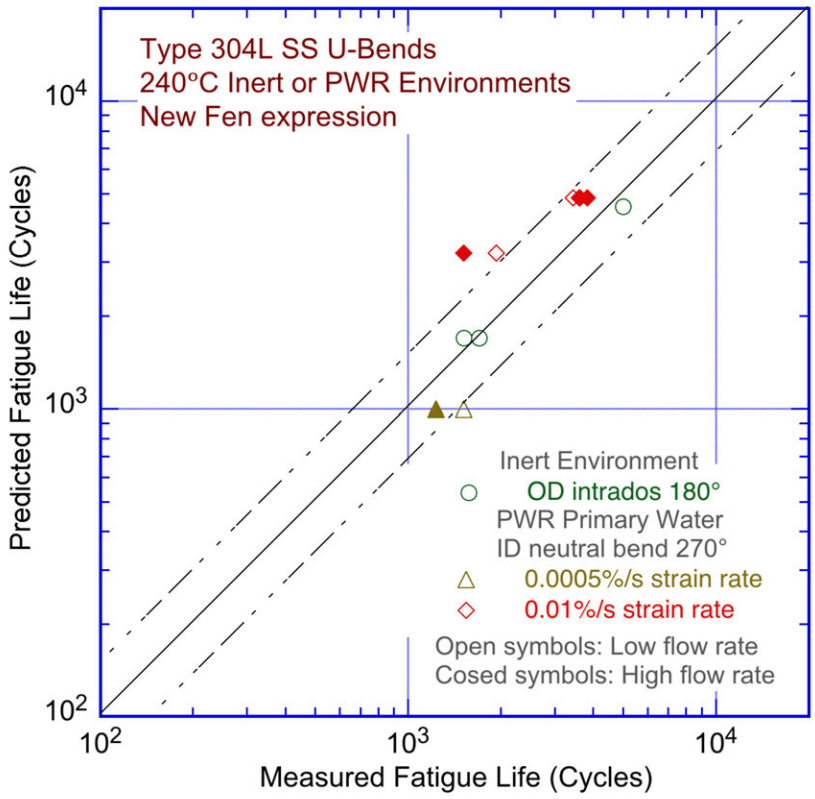


Figure 6-10

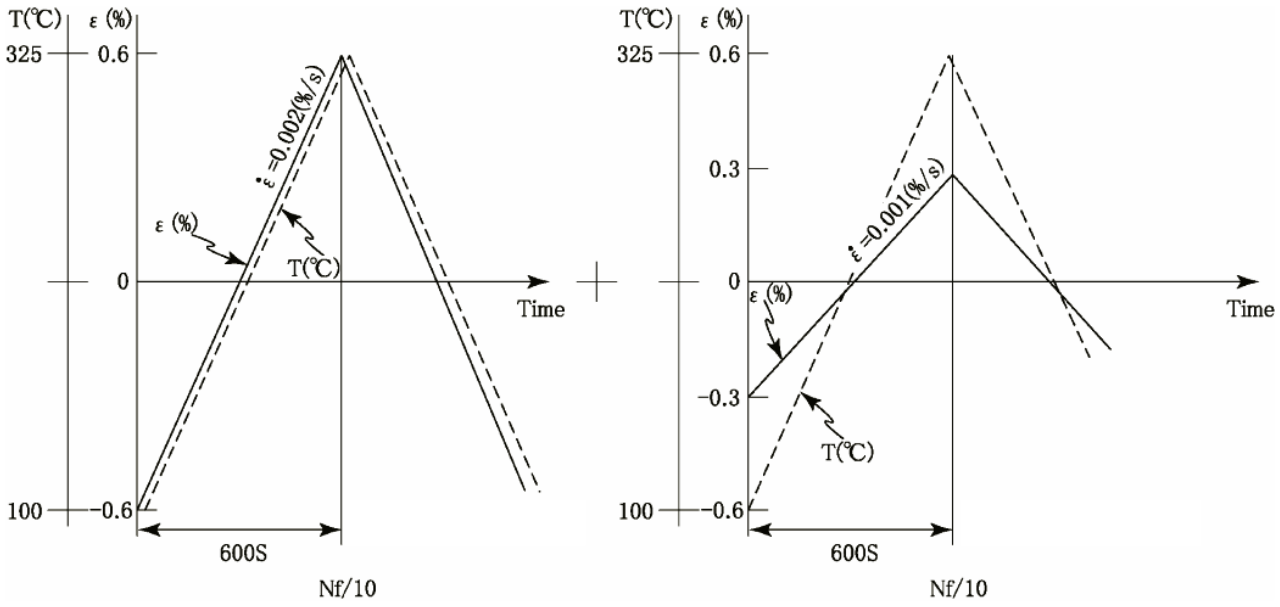


Figure 6-11 Test 1

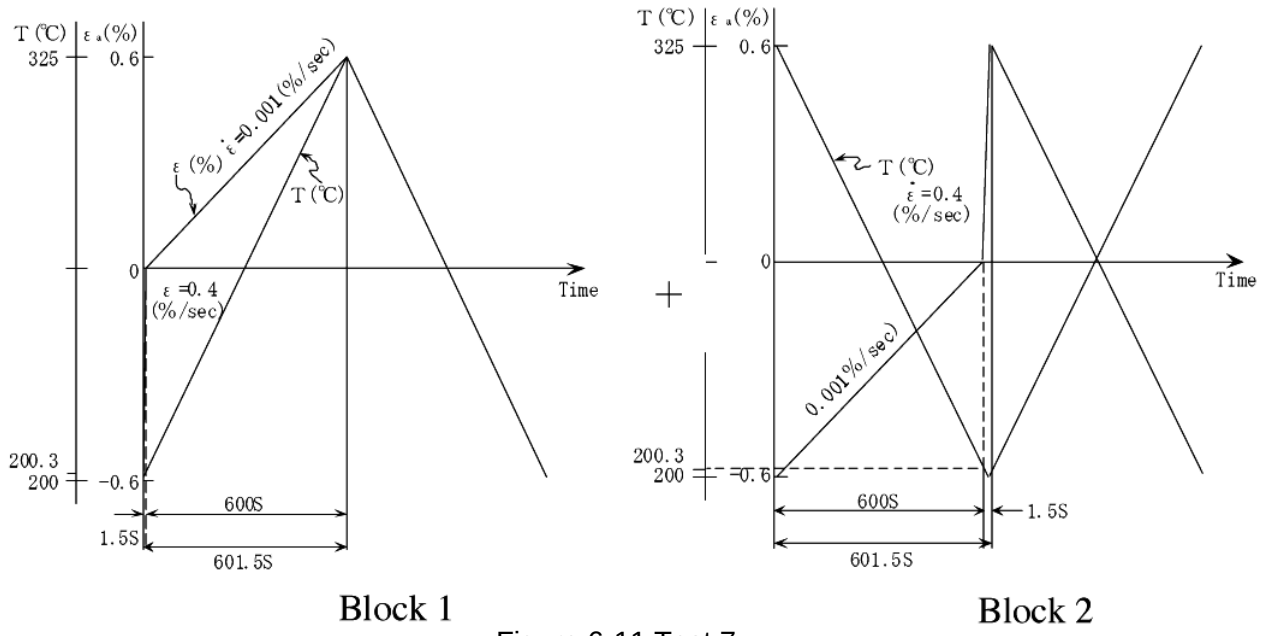


Figure 6-11 Test 7

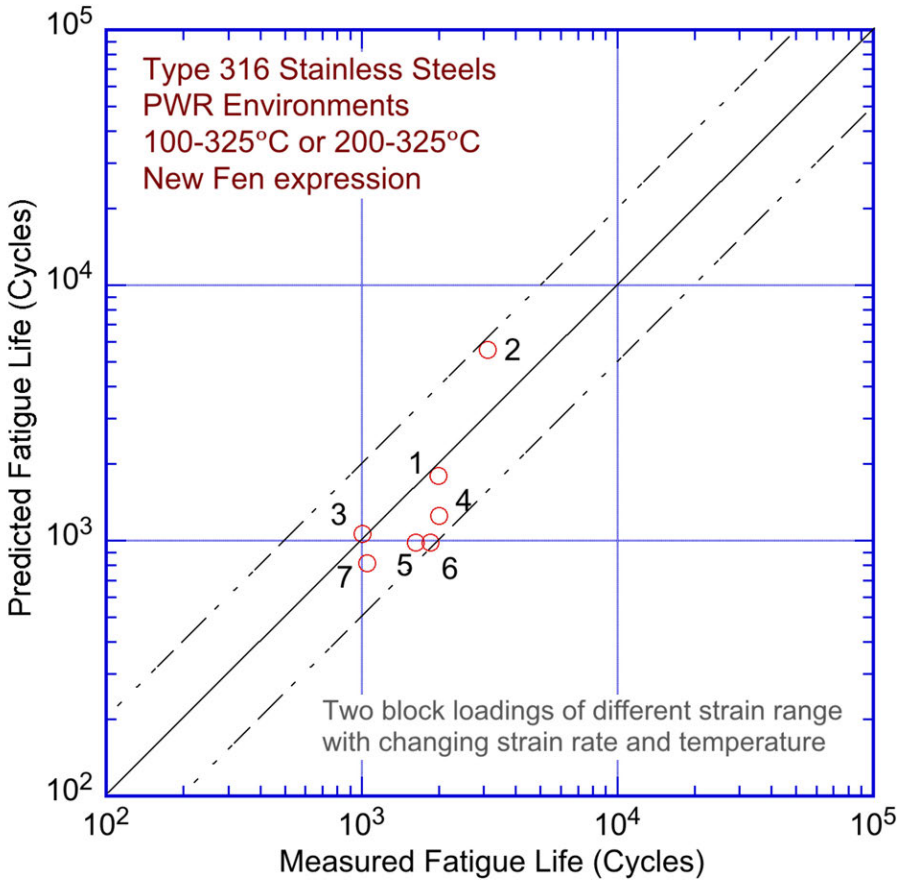


Figure 6-12

APPENDIX E
EQUATIONS IN NUREG/CR-6909 REV. 0 AND REV. 1

E.1 Equations and Equation Numbers from NUREG/CR-6909 Rev. 0

Each equation number is formatted as E0.x to indicate that in Rev. "0", this is equation number "x".

$$\varepsilon_a = A1(N)^{-n1} + A2 \quad \text{(E0.1)}$$

$$S_a = \frac{E}{4\sqrt{N_f}} \ln\left(\frac{100}{100 - A_f}\right) + B_f \quad \text{(E0.2)}$$

$$S_a = 59{,}734\ (N_f)^{-0.5} + 149.2 \quad \text{(E0.3)}$$

$$S_a = 49{,}222\ (N_f)^{-0.5} + 265.4 \quad \text{(E0.4)}$$

$$S_a = 58{,}020\ (N_f)^{-0.5} + 299.9 \quad \text{(E0.5)}$$

$$\ln(N) = A - B \ln(\varepsilon_a - C) \quad \text{(E0.6)}$$

$$\ln(N) = 6.726 - 2.0 \ln(\varepsilon_a - 0.072) \quad \text{(E0.7)}$$

$$\ln(N) = 6.339 - 2.0 \ln(\varepsilon_a - 0.128) \quad \text{(E0.8)}$$

$$\ln(N) = 6.954 - 2.0 \ln(\varepsilon_a - 0.167) \quad \text{(E0.9)}$$

$$S_a' = S_a \left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y \quad \text{(E0.10)}$$

$$S_a' = S_a \qquad \text{for } S_a > \sigma_y \quad \text{(E0.11)}$$

$$N_i(R_q) = 1012\ R_q^{-0.21} \quad \text{(E0.12)}$$

$$\ln(N) = 6.614 - 0.00124\ T - 1.975 \ln(\varepsilon_a - 0.113) \quad \text{(E0.13)}$$

$$\ln(N) = 6.480 - 0.00124\ T - 1.808 \ln(\varepsilon_a - 0.151) \quad \text{(E0.14)}$$

$$\ln(N) = 6.583 - 1.975 \ln(\varepsilon_a - 0.113) \quad \text{(E0.15)}$$

$$\ln(N) = 6.449 - 1.808 \ln(\varepsilon_a - 0.151) \quad \text{(E0.16)}$$

$$S_a = E\varepsilon_a = C_1 N^{-0.05} \quad \text{(E0.17)}$$

$$S_a = E\varepsilon_a = C_2 N^{-0.01} \quad \text{(E0.18)}$$

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\ \Delta\varepsilon + 0.65 \quad \text{(E0.19)}$$

$$\ln(N) = 5.951 - 1.975 \ln(\varepsilon_a - 0.113) + 0.101\ S^*\ T^*\ O^*\dot{\varepsilon}^* \quad \text{(E0.20)}$$

$$\ln(N) = 5.747 - 1.808 \ln(\varepsilon_a - 0.151) + 0.101\, S^* T^* O^* \dot{\varepsilon}^* \quad \text{(E0.21)}$$

$$\begin{array}{ll} S^* = 0.015 & (DO > 1.0 \text{ ppm}) \\ S^* = 0.001 & (DO \le 1.0 \text{ ppm and } S \le 0.001 \text{ wt.\%}) \\ S^* = S & (DO \le 1.0 \text{ ppm and } 0.001 < S \le 0.015 \text{ wt.\%}) \\ S^* = 0.015 & (DO \le 1.0 \text{ ppm and } S > 0.015 \text{ wt.\%}) \end{array} \quad \text{(E0.22)}$$

$$\begin{array}{ll} T^* = 0 & (T \le 150^\circ C) \\ T^* = T - 150 & (150 < T \le 350^\circ C) \end{array} \quad \text{(E0.23)}$$

$$\begin{array}{ll} O^* = 0 & (DO \le 0.04 \text{ ppm}) \\ O^* = \ln(DO/0.04) & (0.04 \text{ ppm} < DO \le 0.5 \text{ ppm}) \\ O^* = \ln(12.5) & (DO > 0.5 \text{ ppm}) \end{array} \quad \text{(E0.24)}$$

$$\begin{array}{ll} \dot{\varepsilon}^* = 0 & (\dot{\varepsilon} > 1\%/s) \\ \dot{\varepsilon}^* = \ln(\dot{\varepsilon}) & (0.001 \le \dot{\varepsilon} \le 1\%/s) \\ \dot{\varepsilon}^* = \ln(0.001) & (\dot{\varepsilon} < 0.001\%/s) \end{array} \quad \text{(E0.25)}$$

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}) \quad \text{(E0.26)}$$

$$F_{en} = \exp(0.632 - 0.101\, S^* T^* O^* \dot{\varepsilon}^*) \quad \text{(E0.27)}$$

$$F_{en} = \exp(0.702 - 0.101\, S^* T^* O^* \dot{\varepsilon}^*) \quad \text{(E0.28)}$$

$$dF_{en} = (F_{en} - 1)\, d\varepsilon / (\varepsilon_{max} - \varepsilon_{min}) \quad \text{(E0.29)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min})} \quad \text{(E0.30)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min}) - \varepsilon_{th}} \quad \text{(E0.31)}$$

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112) \quad \text{(E0.32)}$$

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\, \Delta\varepsilon + 0.65 \quad \text{(E0.33)}$$

$$\ln(N) = 6.157 - 1.920 \ln(\varepsilon_a - 0.112) + T' \dot{\varepsilon}' O' \quad \text{(E0.34)}$$

$$\begin{array}{ll} T' = 0 & (T < 150^\circ C) \\ T' = (T - 150)/175 & (150 \le T < 325^\circ C) \\ T' = 1 & (T \ge 325^\circ C) \end{array} \quad \text{(E0.35)}$$

$$\begin{array}{ll} \dot{\varepsilon}' = 0 & (\dot{\varepsilon} > 0.4\%/s) \\ \dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4) & (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\ \dot{\varepsilon}' = \ln(0.0004/0.4) & (\dot{\varepsilon} < 0.0004\%/s) \end{array} \quad \text{(E0.36)}$$

$$O' = 0.281 \quad \text{(all DO levels)} \quad \text{(E0.37)}$$

$$F_{en} = \exp(0.734 - T' \dot{\varepsilon}' O') \quad \text{(E0.38)}$$

$$F_{en} = \exp(- T^{'} \dot{\varepsilon}^{'} O^{'}) \quad \text{(E0.39)}$$

$$\begin{array}{ll} T^{'} = T/325 & (T < 325°C) \\ T^{'} = 1 & (T \geq 325°C) \end{array} \quad \text{(E0.40)}$$

$$\begin{array}{ll} \dot{\varepsilon}^{'} = 0 & (\dot{\varepsilon} > 5.0\%/s) \\ \dot{\varepsilon}^{'} = \ln(\dot{\varepsilon}/5.0) & (0.0004 \leq \dot{\varepsilon} \leq 5.0\%/s) \\ \dot{\varepsilon}^{'} = \ln(0.0004/5.0) & (\dot{\varepsilon} < 0.0004\%/s) \end{array} \quad \text{(E0.41)}$$

$$\begin{array}{ll} O^{'} = 0.09 & (\text{NWC BWR water}) \\ O^{'} = 0.16 & (\text{PWR or HWC BWR water}) \end{array} \quad \text{(E0.42)}$$

E.2 Equations and Equation Numbers in NUREG/CR-6909 Rev. 1

Each equation number is formatted as E1.x to indicate that in Rev. "1", this is equation number "x".

$$\varepsilon_a = A1(N)^{-n1} + A2 \quad \text{(E1.1)}$$

$$S_a = \frac{E}{4\sqrt{N_f}} \ln\left(\frac{100}{100 - A_f}\right) + B_f \quad \text{(E1.2)}$$

$$S_a = 59{,}734\ (N_f)^{-0.5} + 149.2 \quad \text{(E1.3)}$$

$$S_a = 49{,}222\ (N_f)^{-0.5} + 265.4 \quad \text{(E1.4)}$$

$$S_a = 58{,}020\ (N_f)^{-0.5} + 299.9 \quad \text{(E1.5)}$$

$$\ln(N) = A - B \ln(\varepsilon_a - C) \quad \text{(E1.6)}$$

$$\ln(N) = 6.726 - 2.0 \ln(\varepsilon_a - 0.072) \quad \text{(E1.7)}$$

$$\ln(N) = 6.339 - 2.0 \ln(\varepsilon_a - 0.128) \quad \text{(E1.8)}$$

$$\ln(N) = 6.954 - 2.0 \ln(\varepsilon_a - 0.167) \quad \text{(E1.9)}$$

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112) \quad \text{(E1.10)}$$

$$S'_a = S_a \left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y \quad \text{(E1.11)}$$

$$S'_a = S_a \qquad \text{for } S_a > \sigma_y \quad \text{(E1.12)}$$

$$\bar{V}_t = A(\dot{\varepsilon}_{ct})^n \quad \text{(E1.13)}$$

$$\bar{V}_{in} = \frac{1.27 \times 10^{-6}}{a} \quad \text{(E1.14)}$$

$$\dot{a}_{air} = 3.43 \times 10^{-12}\ S(R)\ \Delta K^{3.3}/T_R \quad \text{(E1.15)}$$

$$\begin{aligned} S(R) &= 1.0 && R \le 0 \\ S(R) &= 1.0 + 1.8R && 0 < R \le 0.79 \\ S(R) &= -43.35 + 57.97R && 0.79 < R < 1.0 \end{aligned} \quad \text{(E1.16)}$$

$$\dot{a}_{env} = \dot{a}_{air} + 4.5 \times 10^{-5}\ (\dot{a}_{air})^{0.5} \quad \text{(E1.17)}$$

$$N_{25} = N_X/(0.947 + 0.00212X) \quad \text{(E1.18)}$$

$$D = \{(x - \hat{x})^2 + [k(y - \hat{y})]^2\}^{1/2} \quad \text{(E1.19)}$$

$$1 - \left(\frac{\Sigma D^2}{\Sigma Z^2}\right) \quad \text{(E1.20)}$$

where $Z = \{(x-x')^2 + [k(y-y')]^2\}^{1/2}$ (E1.21)

$$\ln(N) = 6.614 - 0.00124\,T - 1.975\,\ln(\varepsilon_a - 0.113) \quad \text{(E1.22)}$$

$$\ln(N) = 6.480 - 0.00124\,T - 1.808\,\ln(\varepsilon_a - 0.151) \quad \text{(E1.23)}$$

$$\ln(N) = 6.583 - 1.975\,\ln(\varepsilon_a - 0.113) \quad \text{(E1.24)}$$

$$\ln(N) = 6.449 - 1.808\,\ln(\varepsilon_a - 0.151) \quad \text{(E1.25)}$$

$$N_i(R) = 1012\,R_q^{-0.21} \quad \text{(E1.26)}$$

$$S_a = E\varepsilon_a = C_1 N^{-0.05} \quad \text{(E1.27)}$$

$$S_a = E\varepsilon_a = C_2 N^{-0.01} \quad \text{(E1.28)}$$

$$\ln(N) = 6.891 - 1.920\,\ln(\varepsilon_a - 0.112) \quad \text{(E1.29)}$$

$$\ln(N) = 6.859 - 2.0\,\ln(\varepsilon_a - 0.210) \quad \text{(E1.30)}$$

$$\ln(N) = A - B\,\ln(\varepsilon_a - C) + D\,S^*\,T^*\,O^*\,\dot{\varepsilon}^* \quad \text{(E1.31)}$$

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}) \quad \text{(E1.32)}$$

$$\ln(F_{en}) = A_{air} - A_{water} - D_{water}\,S^*\,T^*\,O^*\,\dot{\varepsilon}^* \quad \text{(E1.33)}$$

$$F_{en} = \exp((0.003 - 0.031\dot{\varepsilon}^*)\,S^*T^*O^*) \quad \text{(E1.34)}$$

$$\begin{aligned} S^* &= 2.0 + 98\,S && (S \le 0.015 \text{ wt.\%}) \\ S^* &= 3.47 && (S > 0.015 \text{ wt.\%}) \end{aligned} \quad \text{(E1.35)}$$

$$\begin{aligned} T^* &= 0.395 && (T < 150°C) \\ T^* &= (T - 75)/190 && (150°C \le T \le 325°C) \end{aligned} \quad \text{(E1.36)}$$

$$\begin{aligned} O^* &= 1.49 && (DO < 0.04 \text{ ppm}) \\ O^* &= \ln(DO/0.009) && (0.04 \text{ ppm} \le DO \le 0.5 \text{ ppm}) \\ O^* &= 4.02 && (DO > 0.5 \text{ ppm}) \end{aligned} \quad \text{(E1.37)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/2.2) && (0.0004\%/s \le \dot{\varepsilon} \le 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/2.2) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad \text{(E1.38)}$$

$$\ln(N) = A - 1.975\,\ln(\varepsilon_a - 0.113) - \ln(F_{en}) \quad \text{(E1.39)}$$

$$\ln(N) = A - 1.808\,\ln(\varepsilon_a - 0.151) - \ln(F_{en}) \quad \text{(E1.40)}$$

$$\ln(N) = A - B\,\ln(\varepsilon_a - C) + T^*\,O^*\,\dot{\varepsilon}^* \quad \text{(E1.41)}$$

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\,\Delta\varepsilon + 0.65 \quad \text{(E1.42)}$$

$$F_{en} = \exp(- T^* \dot{\varepsilon}^* O^*) \quad \text{(E1.43)}$$

$$\begin{aligned} T^* &= 0 && (T < 100°C) \\ T^* &= (T - 100)/250 && (100°C \le T \le 325°C) \end{aligned} \quad \text{(E1.44)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 7\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/7) && (0.0004\%/s \le \dot{\varepsilon} \le 7\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/7) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad \text{(E1.45)}$$

For DO less than 0.1 ppm, i.e., PWR of BWR HWC water,

$$O^* = 0.29 \quad \text{(all wrought and cast SSs \& heat treatments \& welds)}$$

For DO greater than or equal to 0.1 ppm, i.e., NWC BWR water, (E1.46)

$$\begin{aligned} O^* &= 0.29 && \text{(sensitized high-carbon wrought and cast SSs)} \\ O^* &= 0.14 && \text{(all wrought SSs except sensitized high-carbon SSs)} \end{aligned}$$

$$F_{en} = \exp(-T^* \dot{\varepsilon}^* O^*) \quad \text{(E1.47)}$$

$$\begin{aligned} T^* &= 0 && (T < 50°C) \\ T^* &= (T\text{-}50)/275 && (50°C \le T \le 325°C) \end{aligned} \quad \text{(E1.48)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/5.0) && (0.0004\%/s \le \dot{\varepsilon} \le 5.0\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/5.0) && (\dot{\varepsilon} < 0.0004\%/s) \end{aligned} \quad \text{(E1.49)}$$

$$\begin{aligned} O^* &= 0.06 && \text{(NWC BWR water, i.e., } \ge 0.1 \text{ ppm DO)} \\ O^* &= 0.14 && \text{(PWR or HWC BWR water, i.e., } < 0.1 \text{ ppm DO)} \end{aligned} \quad \text{(E1.50)}$$

$$dF_{en} = (F_{en} - 1)\, d\varepsilon / (\varepsilon_{max} - \varepsilon_{min}) \quad \text{(E1.51)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min})} \quad \text{(E1.52)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min}) - \varepsilon_{th}} \quad \text{(E1.53)}$$

$$F_{en} = \frac{\sum F_{en,i}(\varepsilon_i - \varepsilon_{i-1})}{(\varepsilon_{max} - \varepsilon_{min})} \quad \text{(E1.54)}$$

$$F_{en} = \frac{\sum F_{en,i}(\varepsilon_i - \varepsilon_{i-1})}{\varepsilon_{max} - (\varepsilon_{min} + \varepsilon_{th})} \quad \text{(E1.55)}$$

$$F_{en} = \frac{(F_{en,1}\Delta\varepsilon_1 + F_{en,2}\Delta\varepsilon_2 + ..)}{(\Delta\varepsilon_1 + \Delta\varepsilon_2 + ..)} \quad \text{(E1.56)}$$

$$\varepsilon_{a,eq}=\frac{\sum\{n_i D_i(\varepsilon_{a,i})\}}{\sum\{n_i D_i\}},\quad N_{eq}=\sum\left\{n_i\left(\frac{D_i}{D_i(\varepsilon_{a,eq})}\right)\right\} \tag{E1.57}$$

$$D_i=\frac{1}{N_f}=f(\varepsilon_a) \tag{E1.58}$$

E.3 Changes in the Equations or their Number in NUREG/CR-6909 Rev. 0 and Rev. 1

The first nine equations and their numbers (i.e., Equations 1-9) are the same in both Rev. 0 and Rev. 1.

$$\varepsilon_a = A1(N)^{-n1} + A2 \qquad (E0.1 \rightarrow E1.1)$$

$$S_a = \frac{E}{4\sqrt{N_f}} \ln\left(\frac{100}{100 - A_f}\right) + B_f \qquad (E0.2 \rightarrow E1.2)$$

$$S_a = 59{,}734\ (N_f)^{-0.5} + 149.2 \qquad (E0.3 \rightarrow E1.3)$$

$$S_a = 49{,}222\ (N_f)^{-0.5} + 265.4 \qquad (E0.4 \rightarrow E1.4)$$

$$S_a = 58{,}020\ (N_f)^{-0.5} + 299.9 \qquad (E0.5 \rightarrow E1.5)$$

$$\ln(N) = A - B \ln(\varepsilon_a - C) \qquad (E0.6 \rightarrow E1.6)$$

$$\ln(N) = 6.726 - 2.0 \ln(\varepsilon_a - 0.072) \qquad (E0.7 \rightarrow E1.7)$$

$$\ln(N) = 6.339 - 2.0 \ln(\varepsilon_a - 0.128) \qquad (E0.8 \rightarrow E1.8)$$

$$\ln(N) = 6.954 - 2.0 \ln(\varepsilon_a - 0.167) \qquad (E0.9 \rightarrow E1.9)$$

Equation 32 (Rev. 0) is inserted in Rev. 1 as Equation 10 and also as Equation 29.

$$\ln(N) = 6.891 - 1.920 \ln(\varepsilon_a - 0.112) \qquad (E0.32 \rightarrow E1.10)$$

The numbers for the subsequent equations are adjusted accordingly. That is, Rev. 0 Equations 10 and 11 are now Equations 11 and 12 in Rev. 1.

$$S_a' = S_a \left(\frac{\sigma_u - \sigma_y}{\sigma_u - S_a}\right) \qquad \text{for } S_a < \sigma_y \qquad (E0.10 \rightarrow E1.11)$$

$$S_a' = S_a \qquad \text{for } S_a > \sigma_y \qquad (E0.11 \rightarrow E1.12)$$

Equation 12 (Rev. 0) has been moved and is now Equation 26 (Rev. 1).

Rev. 1 Equations 13 to 21 are new. The numbers of the remaining equations have been adjusted accordingly.

$$\bar{V}_t = A(\dot{\varepsilon}_{ct})^n \qquad (E1.13)$$

$$\bar{V}_{in} = \frac{1.27 \times 10^{-6}}{a} \qquad (E1.14)$$

$$\dot{a}_{air} = 3.43 \times 10^{-12}\ S(R)\ \Delta K^{3.3}/T_R \qquad (E1.15)$$

$$S(R) = 1.0 \qquad R \le 0$$
$$S(R) = 1.0 + 1.8R \qquad 0 < R \le 0.79 \qquad \text{(E1.16)}$$
$$S(R) = -43.35 + 57.97R \qquad 0.79 < R < 1.0$$

$$\dot{a}_{env} = \dot{a}_{air} + 4.5x10^{-5} (\dot{a}_{air})^{0.5} \qquad \text{(E1.17)}$$

$$N_{25} = N_X/(0.947 + 0.00212X) \qquad \text{(E1.18)}$$

$$D = \{(x-\hat{x})^2 + [k(y-\hat{y})]^2\}^{1/2} \qquad \text{(E1.19)}$$

$$1 - \left(\frac{\Sigma D^2}{\Sigma Z^2}\right) \qquad \text{(E1.20)}$$

where $Z = \{(x-x')^2 + [k(y-y')]^2\}^{1/2}$ (E1.21)

Equations 13 to 16 (Rev. 0) are Equations 22 to 25 in Rev. 1.

$$\ln(N) = 6.614 - 0.00124\,T - 1.975\,\ln(\varepsilon_a - 0.113) \qquad \text{(E0.13} \rightarrow \text{E1.22)}$$

$$\ln(N) = 6.480 - 0.00124\,T - 1.808\,\ln(\varepsilon_a - 0.151) \qquad \text{(E0.14} \rightarrow \text{E1.23)}$$

$$\ln(N) = 6.583 - 1.975\,\ln(\varepsilon_a - 0.113) \qquad \text{(E0.15} \rightarrow \text{E1.24)}$$

$$\ln(N) = 6.449 - 1.808\,\ln(\varepsilon_a - 0.151) \qquad \text{(E0.16} \rightarrow \text{E1.25)}$$

Equation 12 (Rev. 0) has been inserted in Rev. 1 as Equation 26.

$$N_i(R_q) = 1012\,R_q^{-0.21} \qquad \text{(E0.12} \rightarrow \text{E1.26)}$$

Equations 17 and 18 (Rev. 0) are Equations 27 and 28 in Rev. 1.

$$S_a = E\varepsilon_a = C_1 N^{-0.05} \qquad \text{(E0.17} \rightarrow \text{E1.27)}$$

$$S_a = E\varepsilon_a = C_2 N^{-0.01} \qquad \text{(E0.18} \rightarrow \text{E1.28)}$$

Equation 19 (Rev. 0) is Equation 42 in Rev. 1.

Equation 32 (Rev.0) has also been inserted in Rev. 1 as Equation 29.

$$\ln(N) = 6.891 - 1.920\,\ln(\varepsilon_a - 0.112) \qquad \text{(E0.32} \rightarrow \text{E1.29)}$$

In addition, two new equations have been added as Equations 30 and 31 in Rev. 1.

$$\ln(N) = 6.859 - 2.0\,\ln(\varepsilon_a - 0.210) \qquad \text{(E1.30)}$$

$$\ln(N) = A - B\,\ln(\varepsilon_a - C) + D\,S^*\,T^*\,O^*\,\dot{\varepsilon}^* \qquad \text{(E1.31)}$$

Equation 26 (Rev. 0) has been inserted in Rev. 1 as Equation 32.

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}) \qquad \text{(E0.26} \rightarrow \text{1.32)}$$

New Equation 33 has been added to Rev. 1.

$$\ln(F_{en}) = A_{air} - A_{water} - D_{water}\, S^*\, T^*\, O^*\, \dot{\varepsilon}^* \qquad \text{(E1.33)}$$

Equations 20 and 21 (Rev. 0) have been deleted, Equations 22 to 25 (Rev. 0) are now Equations 35 to 38 in Rev. 1, and Equation 26 (Rev. 0) is now Equation 32 in Rev. 1 as shown above.

Equations 27 and 28 (Rev. 0) have been replaced by a single equation, Equation 34 in Rev. 1.

$$F_{en} = \exp((0.003 - 0.031\dot{\varepsilon}^*)\, S^* T^* O^*) \qquad \text{(E0.27/E0.28} \rightarrow \text{E1.34)}$$

The updated versions of Equations 22 to 25 (Rev. 0) are now Equations 35–38 in Rev. 1.

$$\begin{aligned} S^* &= 2.0 + 98\, S && (S \le 0.015 \text{ wt.\%}) \\ S^* &= 3.47 && (S > 0.015 \text{ wt.\%}) \end{aligned} \qquad \text{(E0.22} \rightarrow \text{E1.35)}$$

$$\begin{aligned} T^* &= 0.395 && (T < 150°C) \\ T^* &= (T - 75)/190 && (150°C \le T \le 325°C) \end{aligned} \qquad \text{(E0.23} \rightarrow \text{E1.36)}$$

$$\begin{aligned} O^* &= 1.49 && (DO < 0.04 \text{ ppm}) \\ O^* &= \ln(DO/0.009) && (0.04 \text{ ppm} \le DO \le 0.5 \text{ ppm}) \\ O^* &= 4.02 && (DO > 0.5 \text{ ppm}) \end{aligned} \qquad \text{(E0.24} \rightarrow \text{E1.37)}$$

$$\begin{aligned} \dot{\varepsilon}^* &= 0 && (\dot{\varepsilon} > 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(\dot{\varepsilon}/2.2) && (0.0004\%/s \le \dot{\varepsilon} \le 2.2\%/s) \\ \dot{\varepsilon}^* &= \ln(0.0004/2.2) && (\dot{\varepsilon} < 0.0004\%/s). \end{aligned} \qquad \text{(E0.25} \rightarrow \text{E1.38)}$$

The following Equations 39 to 41 are new in Rev. 1.

$$\ln(N) = A - 1.975 \ln(\varepsilon_a - 0.113) - \ln(F_{en}) \qquad \text{(E1.39)}$$

$$\ln(N) = A - 1.808 \ln(\varepsilon_a - 0.151) - \ln(F_{en}) \qquad \text{(E1.40)}$$

$$\ln(N) = A - B \ln(\varepsilon_a - C) + T^* O^* \dot{\varepsilon}^* \qquad \text{(E1.41)}$$

Equation 19 (Rev. 0) has been inserted as Equation 42 in Rev. 1.

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\, \Delta\varepsilon + 0.65 \qquad \text{(E0.19/E0.33} \rightarrow \text{E1.42)}$$

An updated version of Equation 38 (Rev. 0) is inserted as Equation 43 in Rev. 1.

$$F_{en} = \exp(-T^*\, \dot{\varepsilon}^*\, O^*) \qquad \text{(E0.38} \rightarrow \text{E1.43)}$$

The updated versions of Equations 35 to 37 (Rev. 0) are inserted as Equations 44 to 46 (Rev. 1).

$$\begin{aligned} T^* &= 0 && (T < 100°C) \\ T^* &= (T - 100)/250 && (100°C \le T \le 325°C) \end{aligned} \qquad \text{(E0.35} \rightarrow \text{E1.44)}$$

$\dot{\varepsilon}^* = 0$ ($\dot{\varepsilon} > 7\%/s$)
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/7)$ ($0.0004\%/s \le \dot{\varepsilon} \le 7\%/s$) (E0.36 → E1.45)
$\dot{\varepsilon}^* = \ln(0.0004/7)$ ($\dot{\varepsilon} < 0.0004\%/s$)

For DO less than 0.1 ppm, i.e., PWR of BWR HWC water,
$O^* = 0.29$ (all wrought and cast SSs & heat treatments & welds)
For DO greater than or equal to 0.1 ppm, i.e., NWC BWR water, (E0.37 → E1.46)
$O^* = 0.29$ (sensitized high-carbon wrought and cast SSs)
$O^* = 0.14$ (all wrought SSs except sensitized high-carbon SSs).

Equation 39 (Rev. 0) and updated versions of Equations 40 to 42 (Rev. 0) are inserted as Equations 47 to 50 in Rev. 1. Additionally, the transformed variables T', $\dot{\varepsilon}'$, and O' (Rev. 0) are T^*, $\dot{\varepsilon}^*$, and O^* for consistency.

$$F_{en} = \exp(-T^* \dot{\varepsilon}^* O^*) \quad \text{(E0.39 → E1.47)}$$

$T^* = T/325$ ($T < 325°C$)
$T^* = 1$ ($T \ge 325°C$) (E0.40 → E1.48)

$\dot{\varepsilon}^* = 0$ ($\dot{\varepsilon} > 5.0\%/s$)
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/5.0)$ ($0.0004 \le \dot{\varepsilon} \le 5.0\%/s$) (E0.41 → E1.49)
$\dot{\varepsilon}^* = \ln(0.0004/5.0)$ ($\dot{\varepsilon} < 0.0004\%/s$)

$O^* = 0.09$ (NWC BWR water)
$O^* = 0.16$ (PWR or HWC BWR water). (E0.42 → E1.50)

Equations 29 to 31 (Rev. 0) are inserted as Equations 51 to 53 in Rev. 1.

$$dF_{en} = (F_{en} - 1)\, d\varepsilon / (\varepsilon_{max} - \varepsilon_{min}) \quad \text{(E0.29 → E1.51)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min})} \quad \text{(E0.30 → E1.52)}$$

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{(\varepsilon_{max} - \varepsilon_{min}) - \varepsilon_{th}} \quad \text{(E0.31 → E1.53)}$$

Equations 54 to 58 in Rev. 1 are new.

$$F_{en} = \frac{\sum F_{en,i}(\varepsilon_i - \varepsilon_{i-1})}{(\varepsilon_{max} - \varepsilon_{min})} \quad \text{(E1.54)}$$

$$F_{en} = \frac{\sum F_{en,i}(\varepsilon_i - \varepsilon_{i-1})}{\varepsilon_{max} - (\varepsilon_{min} + \varepsilon_{th})} \quad \text{(E1.55)}$$

$$F_{en} = \frac{(F_{en,1}\Delta\varepsilon_1 + F_{en,2}\Delta\varepsilon_2 + ..)}{(\Delta\varepsilon_1 + \Delta\varepsilon_2 + ..)} \quad \text{(E1.56)}$$

$$\varepsilon_{a,eq}=\frac{\sum\{n_i D_i(\varepsilon_{a,i})\}}{\sum\{n_i D_i\}},\quad N_{eq}=\sum\left\{n_i\left(\frac{D_i}{D_i(\varepsilon_{a,eq})}\right)\right\} \tag{E1.57}$$

$$D_i=\frac{1}{N_f}=f(\varepsilon_a) \tag{E1.58}$$

APPENDIX F
RESPONSES TO PUBLIC COMMENTS ON DRAFT REPORT

Public comments on draft report NUREG/CR-6909, Revision 1, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials" (ADAMS Accession Number ML14087A068) are available electronically at the NRC's electronic Reading Room at http://www.nrc.gov/reading-rm/adams.html. From this page, the public can gain entry into Agencywide Documents Access and Management System (ADAMS), which provides text and image files of NRC's public documents. Comments were received from the following individuals or groups:

Letter No.	ADAMS Accession No.	Commenter Affiliation	Commenter Name	Abbreviation
1	ML14157A322	Consultant, Japan	Makoto Higuchi	HIGUCHI
2	ML14157A323	Consultant – CF Int. Engineering, France	Claude Faidy	FAIDY
3	ML14157A324	AMEC, United Kingdom	David Tice	AMEC
4	ML14157A325	Westinghouse Electric Company, USA	James Gresham	WEST
5	ML14157A326	Mitsubishi Heavy Industries, Japan	Seiji Asada	MHI
6	ML14157A327	Rolls Royce PLC, United Kingdom	Keith Wright	RR
7	ML14157A328	Electricite de France, France	Thomas Metais	EDF
8	ML14157A330	Hitachi, Japan	Akihiko Hirano	HITACHI
9	ML14157A331	AREVA, Inc., USA	Devin Kelley	AREVA
10	ML14157A332	Korea Electric Power Company, Republic of Korea	June-soo Park	KEPCO

This table lists each public comment by Letter No. For each comment, the NRC has repeated the comment as written by the commenter. Each comment is referred to in the form [XXX]-[YYY]-[ZZZ][a], where: [XXX] represents the Abbreviation from the above table, [YYY] represents the Letter No. from the above table, and [ZZZ] represents the sequential comment number from that commenter. Many of these comments have multiple parts. These parts are denoted as sub-comments throughout this document. The [a] is denotes the sub-comment, as applicable. The sub-comments have all been enumerated alphabetically for consistency which has resulted in some changes from the numbering scheme used in some of the original comments.

HIGUCHI-1-1 Comment

The UTS and YS used in the fatigue design code are given in Figures Al to A3 in NUREG/CR-6909 and shown below:

	CS	LAS	SS
YS (MPa)	275.8	482.6	303.4
TS (MPa)	551.6	689.5	648.1
E (GPa)	206.8	206.8	195.1

The basis of these values is not clear except only ASME data and we have some questions about these values. These values should be used for the adjusting mean stress effects on fatigue curves. In such case, two different YS, static or cyclic YS, should be selected. We are discussing about the relationship of the TS and YS of steels in the DFC (Design Fatigue Curve) sub-committee in JWES (Japan Welding Engineering Society).

The static and cyclic YS data were obtained from a lot of fatigue and material data for carbon and low-alloy steels and plotted vs. TS as shown in Figures F-1 and F-2, respectively. In these figures, a good linear relation can be seen and the linear expressions are also shown in the figures. The static YS is higher than cyclic YS in the higher TS region and lower in the lower TS region and thus the trend line is more steep in Figure F-1.

In these figures, the ASME values listed in the above table are also shown. In Figure F-1, the ASME YS for both of carbon and low-alloy steels are much lower than the trend line, but in Figure F-2, the ASME YS for carbon steel is still lower than the trend line but YS for low-alloy steels is much higher than the trend line.

In any rate, the ASME YS are different from actual material data and seams not reasonable and should be re-examined.

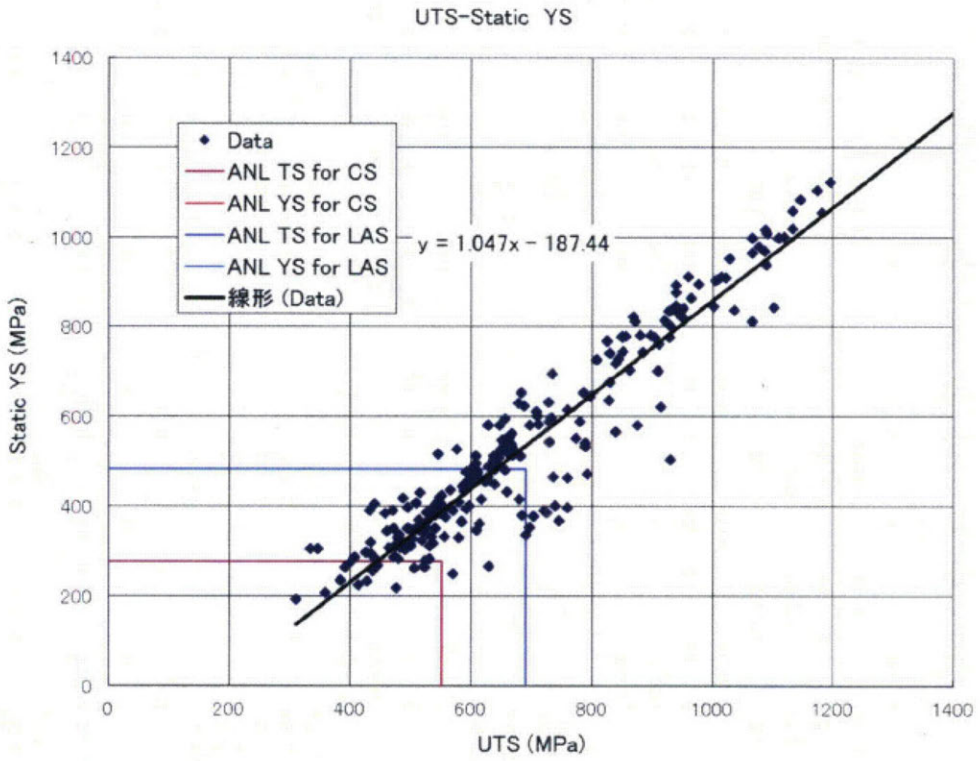


Figure F-1 The relation of Static YS to TS for carbon and low-alloy steels.

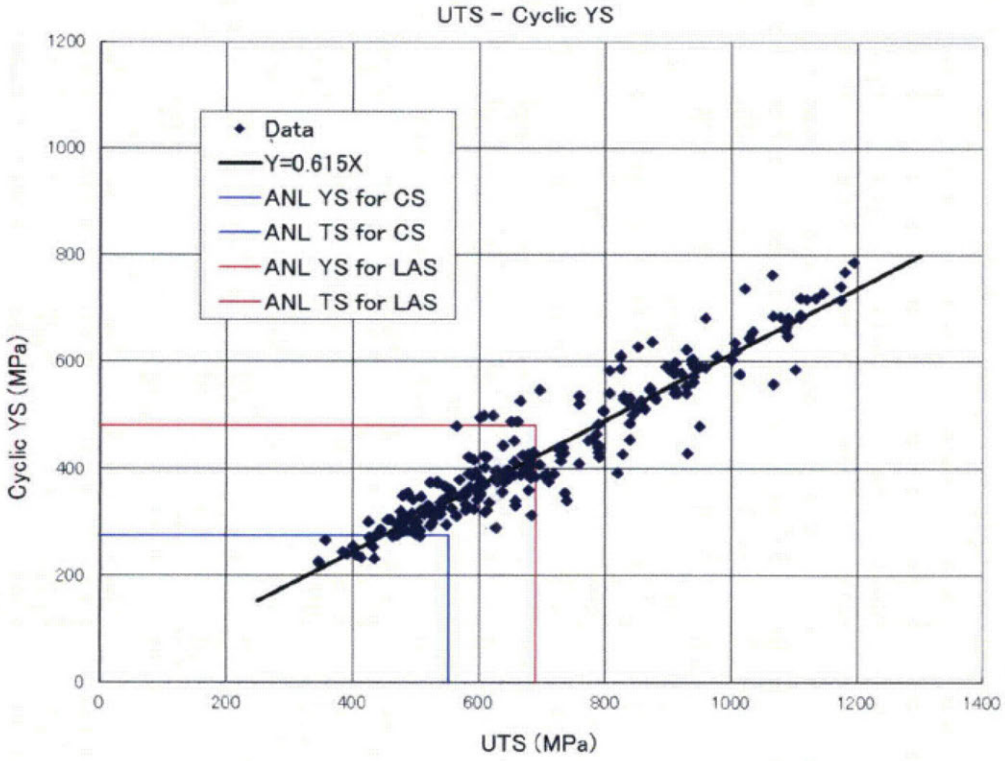


Figure F-2 The relation of Cyclic YS to TS for carbon and low-alloy steels.

NRC Response

A new Section 1.5 has been added that discusses the report's bases and assumptions. The issue raised by this comment is specifically addressed in item (iv) *Material Tensile Properties* contained within this new section.

FAIDY-2-1 Comment

1. Introduction - General remarks

3 parts in the report:
- *Mean and design air curves*
- *LWR environmental effects on Design air curve through Fen factors*
- *Consequences on ASME Code*

a. *Clear justification of environmental effects on fatigue in certain conditions: small specimen under membrane tension loads, R ratio -1, N25 criteria...*

b. *No test on industrial components close to real operation history and conditions: temperature and chemistry changes versus transient time...*

c. *The validity limits of the proposed rules seem to be larger than the tests conditions: like limited number of tests on Alloy 690 or on welds, or non satisfactory results over 10^4-10^5 cycles...*

d. *Some reduction factors use "conservative" unique value, mainly based on engineering judgement, like surface finished or temperature effects...*

e. *All the points are considered as independent each other: in fact it's not the case*

f. *Some definitions have to be added, like:*
   - *LWR environment: in PWR for example the water chemistry has large variation in particular during shutdown (periode affected by thermal transients in some systems)*

g. *Figures are too small in many cases, with frequent large differences due to log-log plots.*

NRC Response

A new Section 1.5 has been added that discusses the report's bases and assumptions. This section has been developed to address many of the general issues raised by this comment, and specifically sub-comment a., including those related to the testing conditions used in the data that forms the basis for the consideration of environmental effects in this report. This comment contains several additional sub-comments that are addressed individually as follows. Sub-comment b. is specifically addressed in item (xv) *Size and Geometry* and item (v) *Environmental Loading* within the new Section 1.5. Sub-comment c. is specifically addressed in item (xix) *Limits of Validity* in Section 1.5.

In response to sub-comment d., the parameters used for the adjustment factors described in the report are based on laboratory tests that have demonstrated the effects of these factors on fatigue life in both air and LWR environments. The tests used have been fully cited in the report and are not based on engineering judgement as indicated in the comment. In all cases, the

ranges of the adjustment factors identified in the report (e.g., Section 5) are based on the experimental data for conditions that are expected to be representative of commercial service applications.

In response to sub-comment e., the report does consider the effects of the adjustment factors to be independent. While it is agreed, as the commenter has stipulated, that some of these effects may be related but the current data does not support the development of rigorous correlations between parameters. The manner in which these factors have been considered in the analysis has been clarified in Section 5.5. Additionally, item (xvi) *Development of Adjustment Factors* has been created within new Section 1.5 to clarify the approach used in the report to develop these factors.

In response to sub-comment f., the term "LWR environment" has been defined at the end of the 3rd paragraph of Section 1.0 as follows: "References made to an 'LWR environment' throughout this report refer to any water environment at a temperature greater than 50°C in an LWR power plant and encompasses both steady-state and transient conditions, such as during a reactor shutdown." Item (i) *Light-Water Reactor Water Environment* has also been added to new Section 1.5 to provide a more expansive definition. Finally, the terms "reactor coolant" and "coolant" have been replaced by "water", as appropriate, throughout the report to clarify that the guidance applies to all LWR water environments.

Finally, in response to sub-comment g., Appendix D has been added to the report which provides enlarged version of the figures in the report.

FAIDY-2-2 Comment

2. Air fatigue mean and design fatigue curves- Stainless Steels

2.1 Carbon and low-alloy steels

a. *How to handle cladded components? And Heat Affected Zone areas?*

2.2 Wrought and cast austenitic steels and weld metal

b. *International agreement on mean curve up to 107 cycles, too limited values over*
c. *Other proposals are available in different other countries for design curves: curve by limited group of materials, limited effect on scatter and no scale effect with the new criteria (3mm)*
d. *Number of low carbon stainless steels (304L and 316L) and SS welds are limited in the data bank*
e. *Are the tests on small weld specimen representative of industrial class 1 components? How grinding areas are considered?*
f. *Justification of effects of specimen geometry (§ 3.2.2) is not largely discussed in connection with the new criteria (3mm): important point to reduce the scale reduction factor and transferability of results to components*
g. *Justification of effects of strain hardening behavior (§ 3.2.5) is not sufficient: secondary hardening in some conditions can affected the crack initiation; include in factor 2 is not quantified.*
h. *Confirmation of large scatter of A value for different heats, that will leads to large conservative results for many cases (§ 3.2.7 and fig. 45)*
i. *§ 3.2.9 on welds: too limited number of data to conclude*
j. *Surface finish effects: too small values of roughness considered, too limited number of data to conclude*

2.3 Ni-Cr-Fe and welds

k. § 3.3:17 data points on 690 Alloys and 6 on Alloy 690 WM:

- *too small number,*
- *to be improved in the future*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. The new Section 1.5, which discusses the report's bases and assumptions, specifically addresses the issues raised in sub-comment a. in item (xxvi) *Clad Components* and item (viii) *Weld Data* while the question related to the validity of the curves beyond 10^7 cycles in sub-comment b. is addressed in item (xix) *Limits of Validity* in new Section 1.5.

In response to sub-comment c., a statement has been added in several places: 1) at the end of the executive summary, 2) as item (xx) *Applicability of Method and Future Work* in new Section 1.5, and 3) as a subsection entitled “Applicability of Method and Future Work” in the summary section. The statement is as follows:

> "The ASME Code Section III fatigue design curves for carbon and low-alloy steels and austenitic SSs are applicable to various grades and compositions of materials having a wide range of tensile strength. Furthermore, the criterion used in establishing the fatigue design curve ensures that the proposed curve bounds 95% of the available fatigue data with 95% confidence. In addition, the mean stress correction for the design curves is based on a conservative value of mean stress at room temperature. Finally, the fatigue loading in laboratory specimens is uniformly tensile which is more severe than in many applications where the loading decreases through the thickness. Therefore, the design curves should be conservative for most materials and applications, particularly at reactor operating temperatures where mean stresses are likely to be lower.
>
> The criteria used for establishing the adjustment factors to account for the parameters that influence fatigue life but were not considered in the experimental data used to develop the fatigue design curves (Section 5) also yield conservative values of fatigue life in applications. These adjustment factors may be further optimized. It should be stressed that other factors (e.g., component size) may lead to decreases in fatigue life in applications compared to laboratory testing. Therefore, any modifications of the design curves or adjustment factors should be performed holistically to develop a technical basis that addresses all the sources of conservatism and uncertainty mentioned above.
>
> It is recommended that guidance should be provided for using the high-cycle portion of the curves for mechanical loading. This guidance is necessary because strain-controlled fatigue test data are used to develop the ASME Code ε–N fatigue design curves, and these must be converted to pseudo-stress vs. life curves in most applications."

Please see also the response to related comment, AREVA-9-17j, for additional information pertaining to this sub-comment.

In response to issues raised in sub-comment d., item (vii) *Material Grouping* and item (viii) *Weld Data* have been added to new Section 1.5 while item (xv) *Size and Geometry* contains information to address both sub-comments e. and f.

As sub-comment g. has stipulated, it is agreed that the potential effects of secondary hardening have not been quantified in this report. The F_{en} expressions have been developed using

experimental strain vs. fatigue life data, and in the case of a few load controlled tests, either the experimental strain at half-life or the total strain determined using the cyclic stress strain curves, was used in the analyses. It is stated in Section 3.2.5 that in the current ASME Code fatigue evaluations, the potential effects of secondary hardening are accounted for in the factor of 2 of stress.

In response to sub-comment h., the following information has been added at the end of Section 3.2.7 (i.e., above Table 3-7) to explain the relatively large adjustment factor that accounts for material variability:

> "Note that a relatively large value of 2.3 for the adjustment factor for material variability and data scatter is due to the fact that the ASME Code fatigue design curve for SSs is applicable to a wide range of material grades; heat-treatments; and compositions, particularly the low-C and high-C grades of SSs."

Sub-comment i. implies that there is insufficient data on stainless steel welds to demonstrate that they are appropriately modeled by the analysis. The analysis is based on the available weld data. While there is less weld data than base material data, the weld data analyzed generally falls within the statistical distribution of the base metal data. While some possible bias between the weld data and the design curves is noted in Section 3.2.9, it is not significant enough to warrant a separate weld metal curve without the development of additional data. In response to this sub-comment, Section 3.2.9 has been modified to reflect the need for more data to justify a separate weld curve. Also, item (viii) *Weld Data* in new Section 1.5 also addresses this issue.

The issues raised in sub-comment j. have been addressed in item (xiii) *Surface Finish* in new Section 1.5.

Finally, it is agreed, as stipulated in sub-comment k. that there is much less data for Ni-Cr-Fe alloys such as Alloys 600 and 690 and associated weld metals in light water reactor (LWR) environments compared with the data available for carbon steel (CS) and stainless steel (SS) materials. As indicated in the report (Section 4.3), the data that is available appears to be reasonably, but conservatively, modeled by the available austenitic SS curves. The Ni-Cr-Fe alloy experimental data, at lower strain levels, appear to be well represented by the SS curves while the SS curves conservatively estimate the high cycle fatigue behavior. Because of these noted differences (see Section 4.3), there does appear to be a basis for developing separate curves for Ni-Cr-Fe alloys. In response to this sub-comment, a sentence has been added to 4.3.3 to indicate that additional Ni data is needed, however, to develop unique Ni-Cr-Fe curves. Also, item (vii) *Material Grouping* in the new Section 1.5 specifically addresses this subject. See also the response to comment RR 6-20 for additional changes to the NUREG related to Inconel 718.

FAIDY-2-3 Comment

3. Environmental effects on fatigue design rules- Stainless Steels

a. *All the reduction factors are considered independent, it's not accepted in all international approaches in particular a constant Ren independently of number of cycles is not justified [stet] clearly*
b. *Application of Fen on air design curve have to be largely discussed*
c. *The final model seems to be too much conservative over 10^4 cycles*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. The first part of sub-comment a. addresses the independence of the adjustment factors. This comment is similar to FAIDY-2-1e. The response to this earlier comment stipulates that while the report does consider these factors to be independent, there is insufficient data to develop correlation factors for a more rigorous analysis. The response to FAIDY-2-1e also identifies clarifications to the report to stress this point.

The second part of sub-comment a. addresses the relationship between F_{en} and strain (or number of cycles). It is correct that the method presented in this report, for simplicity, assumes that F_{en} is not a function of applied strain. The point has been clarified in item (xviii) *F_{en} assumptions* in new Section 1.5. Further clarification on this point is made at the beginning of Section 4 and in the second paragraph of Section 4.2.13. Please also see the response to related comment AREVA-9-13 for additional information.

In response to sub-comment b., it is noted that the application of the F_{en} approach is clearly specified in multiple places in this report. For example, the 3rd and 4th sentences of the 8th paragraph of Executive Summary states, "*An approach was presented that incorporates the effects of LWR coolant environments into the ASME Code Section III fatigue evaluations based on the F_{en}. The fatigue usage for a specific stress cycle or load set pair derived using the ASME Code Section III fatigue design air curves was multiplied by the F_{en} to account for environmental effects.*" Later, the 2nd sentence of the 8th paragraph of Section 1.4 states, "*To incorporate environmental effects into fatigue evaluations, this approach requires multiplying the fatigue usage factor for a specific stress cycle or load set pair, based on the ASME Code Section III design fatigue curves, be multiplied by the F_{en}."*

However, to clarify this point further, the paragraph after Equation A.19 has been revised as follows: *"In the methods in Subarticle NB-3200, 'Design by Analysis,' of Section III, 'Rules for Construction of Nuclear Facility Components', of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), the partial fatigue usage factors are calculated for each type of stress cycle in Subparagraph NB-3222.4(e)(5). For piping products designed using the methods in Subarticle NB-3600, 'Piping Design,' of ASME Code Section III, Paragraph NB-3653 provides the procedures for the calculation of partial fatigue usage factors for each of the load set pairs. The partial usage factors are obtained from the fatigue design curves in the ASME Code Section III editions as of the 2009 Addenda. Note that the ASME Code fatigue design curves for austenitic SS developed in the 1960s (i.e., before publication of the 2009 Addenda) were not consistent with the fatigue database used to develop the environmental fatigue correction factors in this report and, therefore, may give nonconservative estimates of environmental fatigue usage factors for most heats of austenitic SSs used in the construction of nuclear reactor components. Examples of methods used to calculate partial usage factors are as follows:*"

The conservatism of the method raised in sub-comment c. has been previously addressed in the response to related comment, FAIDY-2-2c. As stated in the response to this earlier comment, the method is applicable to a wide range of materials which results in some conservatism and is based on the ASME mean stress method which is also conservative. Please see the response to FAIDY-2-2 c for more information and a summary of changes made to the report to address this topic.

FAIDY-2-4 Comment

4. Code developments

4.1 Global consistency of the Codes

a. *3mm maximum crack is not usable on thin components (less than 30mm thickness); 10% crack size in generally accepted by ASME Code; in the other hand a reduction of 10% is acceptable for level A where the margins are 1.5 versus collapse and 2.7 for instability; what's the consequence of 10% thinning on level D criteria?*
b. *It seems that no roughness requirements are specified in ASME Section III or attached specifications*

4.2 Other points to be considered

c. *Class 1 exemption rules have to be revised*
d. *Crack like defect fatigue analysis has to be reviewed*
e. *Other components are concerned: pumps and valves*
f. *Cladded materials have to be considered*
g. *Class 2 and in some limited cases class 3 components have to be considered*
h. *Thin components, less than 30mm, have to be analyzed*

4.3 Mechanism understanding and new data needs

i. *Effect of pre-hardening on fatigue life*
j. *Effects of bi-axial loads*
k. *New data for many materials: Alloy 690, 304L, 316L....*
l. *Radiation effects and environmental fatigue tests: pre-hardening stainless steels*
m. *Can we consider a correlation between fatigue resistance and stress-strain curves, effects of radiations or thermal ageing on some materials, or DSA? The argument is frequently used in the report*

4.4 More realistic operation cases needed

n. *Temperature variation along the transient*
o. *Effects of strong water chemistry changes*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. There is general agreement with the points raised in sub-comment a. In response, item (ii) *Definition of Fatigue Life* has been added to new Section 1.5, which discusses the report's bases and assumptions. In this section, it is stated that a 3 mm definition of crack initiation is not an appropriate definition of fatigue life for thin-walled components. Rather, fatigue life should be defined as the formation of an engineering-sized crack. It is also recognized that plasticity effects will be different in thin-walled components and that gradient effects can also affect fatigue life differently in such components. An additional item (xxi) *Gradient Effects* has also been added to Section 1.5 to discuss this topic. These complexities can lead to shorter fatigue lives for applications with thin-walled specimens and, as seen in Section 6.4, the F_{en} predictions for such tests are not as conservative as in other applications.

The implication associated with sub-comment b is that surface roughness is not considered within ASME Section III. The commenter is referred to Section 1.3 of the report entitled "Subfactors Included in ASME Code Section III Air Fatigue Design Curves". In this section, the incorporation of surface finish effects within the ASME Code is specifically discussed. Sub-comment c. stipulates that Class 1 exemption rules have to be revised. This issue is addressed in item (xxiv) *ASME Code Class 1 Fatigue Exemption* in new Section 1.5.

Sub-comment d. states that the crack like defect fatigue analysis should be reviewed. There is agreement with this comment in the sense that the method described in NUREG/CR-6909, Rev. 1 only addresses the portion of fatigue life needed to form a 3 mm, or engineering sized, crack. The commenter is referred to item (ii) *Definition of Fatigue Life* in new Section 1.5 which discusses this fact. It is also agreed that an additional flaw tolerance approach is needed to address the further growth of an engineering crack within a component. Treatise of a flaw tolerance analysis is outside the scope of this report and is indicated as such in Section 1.5, item (ii).

Sub-comment e. indicates that fatigue evaluation of pumps and valves should also be considered. The evaluation method described in the report is also applicable to pump and valve components. The following statement has been added to item (xxii) *Use of Method* in new Section 1.5 to clarify this point: *"Generally, the provisions of this document can be used to predict fatigue lives of any component, or portion of a component, that is exposed to water and has been evaluated for CUF using the rules in either Subarticles NB-3200 or NB-3600 of ASME Code, Section III, or in another applicable subarticle. Use extends to both Class 1 and non-Class 1 components. Such components may include piping, pumps, valves, and reactor internals components."*

Sub-comments f. and g. indicate that cladded materials and non-class 1 components should also be considered. Item (xxvi) Clad Components and item (xx) Applicability of Method and Future Work have been added and specifically address both of these sub-comments. Sub-comment h. is similar to FAIDY-2-4a which addresses the applicability of the method to thin-wall components. Please see the response to this comment for disposition of this comment and corresponding changes made to the report to address this topic.

Sub-comment i. has been specifically addressed in item (ix) *Hardening* in new Section 1.5. Sub-comment j. is addressed by clarifying, in item (xiv) *Loading Sequence* and item (xxi) *Gradient Effects* within new Section 1.5, that the method has been based on uniaxial test specimens. Bi-axial loading has not been explicitly considered. Sub-comment k. has been addressed in item (vii) *Material Grouping* in new Section 1.5. Specifically, Section 1.5, item (vii) states that the materials have been grouped in broad categories: carbon and low-alloy steels, wrought and cast austenitic alloys, and Ni-Cr-Fe alloys and welds. The materials identified in the sub-comment k. have been incorporated within these broad categories and, as discussed in the report, the method is applicable to the “newer” materials that are listed in this sub-comment. Section 1.5, item (vii) also discusses that, with more data, it would be possible to develop fatigue curves for specific materials within the broader groupings considered in the report. Sub-comment l. lists radiation and pre-hardening effects as additional considerations. Item (x) *Radiation* and item (ix) *Hardening* in new Section 1.5 specifically address these issues.

Sub-comment m. asks about the possibility of correlations between fatigue resistance and other material properties or effects that lead to material hardening, including dynamic strain aging (DSA). The fatigue analyses, including the effects of the LWR environments on fatigue life have been developed based on strain vs. life data. Potential variations in strain hardening, dynamic strain aging, or irradiation hardening would influence the cyclic stress strain behavior of the material. These effects need to be considered in the ASME Code fatigue evaluation procedures, and therefore addressed by the ASME Code. Item (xi) *Dynamic Strain Aging* has been included in new Section 1.5 to specifically address DSA.

Sub-comment n. implies that more realistic temperature variation along the transient during operating conditions should be considered. As discussed extensively throughout the report, the Modified F_{en} approach has been developed to explicitly address the variation of temperature

throughout the fatigue transient. This method has been demonstrated to be conservative based on limited testing as discussed in the report. However, more testing and evaluation is needed to refine the method further in order to remove some of the current conservatism.
Item (v) *Environmental Loading* in new Section 1.5 also discusses this issue.

Similarly, sub-comment o. implies that the effects of more-realistic, strong water chemistry changes should be considered. The Modified F_{en} approach has been developed to explicitly address the variation of chemical effects throughout the fatigue transient. The method uses first-order approximations to account for chemical effects. This method has been demonstrated to be conservative based on limited testing as discussed in the report. However, more testing and evaluation is needed to refine the method further in order to more accurately consider chemical effects. Item (v) *Environmental Loading* in new Section 1.5 also discusses this issue.

FAIDY-2-5 Comment

5. Conclusion

a. *Clear environmental effects is justified under certain conditions that are material and environment dependent*
b. *In front of a so large number of parameters the existing proposal is probably extremely conservative and more data are required to progress*
c. *In air a design curve can be derived with lower reduction factors than 12 and 2, 10 or 8 and 1.4 for 316L and 304L; all the Fen approach will be also affected*
d. *Surface finish, mean stress and scale reduction factors need more justifications*
e. *F_{en} applied to air design rules, instead of air mean curve, is not an optimum solution; some reduction factors can be different in air and under LWR environment*
f. *Too much materials have to be considered in accordance with Section II and III of ASME Code that leads consequently to conservative predictions*
g. *Application of F_{en} to vessel ASME existing rules is possible, not for piping and valves*
h. *Many other details remarks need larger review time...*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. It is agreed that, as stipulated in sub-comment a. that environmental effects are dependent on the specific environmental conditions and material being assessed. The data and models in the report have been developed to conservatively evaluate these dependencies. Further, to address sub-comment b., the models have been intentionally designed to be somewhat conservative. This approach is necessary to account for the wide variability in fatigue testing results and to recognize that there is little data to evaluate more complex dependencies than are explicitly modeled. As the commenter has indicated, more data is needed if there is an interest in refining the models to explicitly evaluate the effect of more complex dependencies on fatigue life.

In response to sub-comment c., it is noted that the environmental fatigue correction factor F_{en} is the ratio of the fatigue life in room temperature air and fatigue life in water at service temperature. Therefore, changing the fatigue air design curve has no direct effect on the proposed expressions for F_{en}. However, using a different fatigue design curve would change the fatigue life in room temperature air, and consequently, the fatigue life in water would also change. Therefore, using a fatigue design curve other than that in the ASME Code with the current F_{en} approach would have to be justified.

Sub-comment d. is similar to other comments made by this commenter, specifically FAIDY-2-1d, FAIDY-2-1e, and FAIDY-2-3a. There are also similar comments about the basis of the adjustment factors contained in AREVA-9-6a, AREVA-9-6d, and AREVA-9-13. The disposition of this topic and the associated changes made to the report are summarized in the responses to these other comments. Further, item (xiii) *Surface Finish* has been added to new Section 1.5 to summarize the basis for the analysis presented in the report.

Sub-comment e. has two parts. The first part of the comment questions the appropriateness of using the design curve instead of the mean curve to account for environmental effects. The authors believe that the design curve is appropriate because of the variability among the heats of material which fall below the mean curve. These heats would not be conservatively predicted if the mean curve were used as the basis for the environmental effects. An alternative approach could be to develop material-specific curves, but additional data is needed to assure that such curves are statistically significant.

The second part of comment is related to adjustment factors. The only factor that the current data suggests may be different in air and environment is surface roughness. There are some tests which suggest little or no effect of surface finish in LWR environment compared with the effect in air. However, there is not enough data to conclusively demonstrate this. Lacking such conclusive data, it is conservative to assume that the effects of surface roughness are the same in air and LWR environments.

Sub-comment f. is related to earlier comment, FAIDY-2-4k. As indicated in the response to FAIDY 2-4k, item (vii) *Material Grouping* has been added in new Section 1.5 to address this topic. As described in Section 1.5, the materials have been grouped in three broad categories that incorporate all the ASME materials indicated in this comment. Also, as documented in Section 5.1, such grouping contributes to data scatter. Because the design curve has been chosen to bound 95% of the data, such grouping will result in increased margin for some materials. As indicated in Section 1.5, material specific design curves could be developed with additional data.

There is not agreement with the issues raised by sub-comment g. but the NUREG report has been clarified to address the comment. EPRI TR-107943 cited as an example of NB-3600 analyses in item (xxiii) *Use of F_{en} in NB-3600 Analyses* that has been incorporated in new Section 1.5. Also, in all places throughout the NUREG where Appendix C was cited, it has been added that that example problem is an example for NB-3200 methodology. Finally, also see the response to FAIDY-2-4e related to the application of the F_{en} method to pumps and valves.

Sub-comment h. requires no response.

AMEC-3-1 Comment

General comment
This is clearly a very useful update to the original document. However, because it's an update there are a number of confusing statements which arise from retention of text and figures from the earlier version of the report. For example references to the ASME-11 air design line in some cases refer to the pre-2009 line and in others to post 2009. This is made clear in some of the figure captions but not all.

NRC Response

In response to this comment, the report has been reviewed to ensure that the correct edition of the ASME Code fatigue design curve for austenitic SSs is mentioned in the report and figures. Specifically, the reference to "2009b Addenda" has been changed to "2009 Addenda" throughout the report in the text, figures, tables, and associated captions. See also the response to RR-6-1 for related information.

AMEC-3-2 Comment

In Section 6, several "component-like" tests or tests using transients closer to those in plants are evaluated against the recommended ANL model. The overall conclusion drawn is that the data (with one exception) are consistent (within a factor of 2) with the model predictions and the inference is that the model is applicable to predicting fatigue damage in plant. The exception relates to the so-called stepped pipe test which is the only one of these tests to use thermal loading which produces decreasing through-wall stresses rather than the membrane stresses in the remainder of the tests. The stepped pipe loading is more representative of many (but not all) plant transients. In the report, these tests are dismissed on the basis of

NRC Response

In response to this comment, a paragraph has been added to the end of Section 6 (just before Section 6.1) stating that the F_{en} approach yields conservative results for component-type tests, possibly due to stress gradient effects. See also the responses to similar comments, AMEC-3-5, RR-6-4, RR-6-32, EDF-7-8b, AREVA-9-14e, and AREVA-9-7h, on gradient effects for additional information on how this issue has been dispositioned.

AMEC-3-3 Comment

Page 2, penultimate and final paragraphs. It is agreed that a 3mm crack is representative for the typical membrane loaded tensile specimens use to develop the database. It is then stated that this is "assumed to equate to crack initiation in an actual component". It is important that this should not be taken to infer that a cumulative usage factor of 1 corresponds to a 3mm crack in a component, since for many plant transients, the stress field will decrease away from the wetted surface.

NRC Response

Item (ii) *Definition of Fatigue Life* and item (xxi) *Gradient Effects* have been added in new Section 1.5 to specifically address this comment.

AMEC-3-4 Comment

Page 5. Should Ely be cyclic yield stress?

NRC Response

Equations 11 and 12 in the report are based on the modified Goodman relation described in the Section III criteria document (Ref. 8 in NUREG/CR-6909, Rev. 1). In these expressions, the terms σ_y and σ_u represent monotonic yield strength and ultimate strength, respectively. In this report, cyclic stress-strain curves are used only when applied stress from a load control test is converted to applied strain so that the fatigue data can be compared with the fatigue strain vs,

life curves. To further clarify this point, the word “monotonic” has been added before yield strength whenever it occurs in the report.

AMEC-3-5 Comment

Pages 6-8 provides a useful overview of occurrences of thermally-induced fatigue damage. Most of the observations have previously been explained without the need to include an environmental enhancement factor, despite the fact that many of the consequential transients referred to occur at strains rates below the threshold for environmental enhancement. Thermal transients of this type will result in substantial through wall stress gradients. This is likely to reduce fatigue damage compared to uniform stress conditions. The application of a Fen factor to an S-N curve based on membrane stressed test data may be excessively conservative for such transients.

NRC Response

In order to address this comment, the third paragraph in Section 1.3.1 has been revised to discuss the effects of gradient stresses on the calculated fatigue lives of components.

AMEC-3-6 Comment

Page 37. The final paragraph states that enhancement of fatigue crack growth of Alloy 600 and austenitic stainless steels in LWR environments are similar. This isn't consistent with much recent stainless steel data which shows much higher enhancement than Alloy 600 at longer rise times.

NRC Response

It is agreed that the statement cited in the comment requires additional context and clarification. Therefore, the last paragraph of Section 2.2.2.4 (formerly on page 37 in draft report) of the report has been deleted and the following statement has been added at the end of the preceding paragraph to clarify the point that environmental effects on growth of microstructurally small flaws (MSCs) is more significant than environmental effects on the growth of mechanically small cracks:

> "Thus, the reduction in fatigue life in LWR environments relative to that in air cannot be explained on the basis of enhanced CGRs in LWR environments. In LWR environments, the growth of MSCs is increased much more than the growth of mechanically small cracks. The data in Figure 2-21(a) demonstrate that the environmental effects on the growth of cracks less than or equal to 200 μm (i.e., Stage I of crack initiation) are significantly higher than on the growth of cracks greater than 200 μm (i.e., Stage II of crack initiation)."

AMEC-3-7 Comment

Page 59. A monotonic yield stress of 303MPa seems too high. Surely the fatigue limits relates more closely to the cyclic yield stress?

NRC Response

The cited yield strength is a monotonic yield strength value that is within the range of acceptable yield strengths for this material. To clarify that this is the monotonic yield strength, the following

modification has been made to the following sentence in middle of the 5th paragraph of Section 3.2.1 (formerly on page 59 in draft report):

> "Furthermore, for the mean air curve in ASME Code Section III before publication of the 2009 Addenda, the 10^6-cycle fatigue limit (i.e., the stress amplitude at a fatigue life of 10^6 cycles) was 389 MPa, which is greater than the upper range of the room-temperature monotonic yield strength of austenitic SSs used for the mean stress correction in this report (approximately 303 MPa in Table B-2 in Appendix B)."

See also the response to related comment, AMEC 3-4 for additional information.

AMEC-3-8 Comment

Pages 68 and 124. The discussion of surface finish effects for stainless steel in air excludes more recent data. Recent data in water are discussed but no attempt is made to determine whether or not effects of surface finish and environment interact - the recommended approach assumes the surface finish "adjustment factor" and Fen are multiplied.

NRC Response

Sections 4.1.12 and 4.2.14 discuss the effect of surface finish on fatigue life in air, boiling-water reactor (BWR), and pressurized-water reactor (PWR) environments. The results indicate that for carbon and low-alloy ferritic steels and austenitic stainless steels, the surface finish effect is similar in air and a PWR environment, but are insignificant in a BWR environment. However, the available data on surface finish effects are very limited and additional data are needed to accurately establish these effects on fatigue life. Furthermore, as discussed in Section 5.5, the individual adjustment factors for data scatter, size, surface finish, and loading history are not multiplied to determine the cumulative factor. That approach would result in a much larger adjustment factor than the factor of 12 on life used in this analysis.

AMEC-3-9 Comment

Pages 77/78 and 110. The superseded Rev 0 equations presented here are open to misinterpretation by the reader. Modified equations are presented later but the earlier equations could easily be used in error.

NRC Response

It is agreed that the retention of the original NUREG/CR-6909 equations could lead to confusion. The following steps have been taken to address this comment. Appendix E has been created with all the old equations. It is also identified in Appendix E which equations remain the same and which ones have been modified in this revision to the NUREG. Only the updated equations are contained in the main body of the NUREG, although the NUREG does reference the original equations in the new Appendix E.

AMEC-3-10 Comment

Page 115. The justification for the strain rate threshold of 10%/s is unclear from the plotted data.

NRC Response

The strain rate threshold value of 10%/s was an estimate based on the available data on strain rate dependence of austenitic SSs in LWR environments. However, based on the limited data presented in Figure 4-31 and Figure 4-32, a value of 7%/s better represents the existing data. This is the value where the predicted fatigue life from the strain-rate dependence lines in Figure 4-31 and Figure 4-32 is approximately equal to the fatigue life of austenitic SSs in air. Therefore, in response to this comment, the value of the strain rate threshold for SSs has been changed from 10%/s to 7%/s in the entire report.

AMEC-3-11 Comment

Page 141-144. For nickel-based alloys, it is unclear whether the quoted expressions on page 141 or the stainless steel equations in the previous section are preferred.

NRC Response

In response to this comment, the expressions that should be used for Ni-based alloys have been clarified in the report. Specifically, the statement at the end of Section 4.3.3 has been revised to state,

> "The updated Ni-Cr-Fe F_{en} expression should be used along with the SS design fatigue curve to incorporate environmental effects into ASME Code Section III fatigue evaluations for all Ni-Cr-Fe materials except Inconel 718. Because of insufficient experimental data on environmental effects for Inconel 718, the F_{en} expression for Ni-Cr-Fe alloys contained in this section is not applicable to Inconel 718. The modified rate approach discussed in Section 4.4 also applies to Ni-Cr-Fe materials. Appendix C of this report presents a sample application of the F_{en} approach using the methodology in Subarticle NB-3200 of ASME Code Section III."

AMEC-3-12 Comment

Page 176. The discussion about fatigue adjustment factors refers to a factor of 10 on life being supported by Monte-Carlo analysis, but a factor of 12 is recommended for use pending further validation with "applicable fatigue E--N data". It is unclear what validation data are required because the existing database is already large. No clear justification of the factor of 2 on stress is provided.

NRC Response

The report has been clarified to address the issues raised by this comment. While the current analysis supports a factor of 10 without the need for additional data, the report has maintained a factor of 12 to remain consistent with the factor used in the ASME design curve. The factor of 2 was similarly chosen simply for consistency with the factor in the ASME Code. These points have been made in the executive summary. Also, for clarification, the following sentence has been added to the summary (end of 2nd paragraph of the subsection entitled, *Fatigue Design Curve Adjustment Factors*):

> "Although this report justifies an adjustment factor of 10 on life, a value of 12 was used to develop the air design curves from mean-data curves for each material to be consistent with the adjustment factor used in the ASME Code fatigue design curves."

In addition, a similar statement has been included at the end of the second to last paragraph in Section 5.5, *Fatigue Adjustment Factors*. Comments related to this subject were also contained in RR-6-31 and AREVA-9-11a. Please also see the responses to these to comments for additional information.

WEST-4-1 Comment

Introductory Comment
There remains much industry discussion about the applications of factors on fatigue data to determine fatigue curves, the applicability of compounding factors, appropriate curves for the availability of data, etc. We support further investigation and development of these issues with respect to the material presented in this draft report, and encourage acceptance of alternatives as they are developed in industry programs, In light of this, we do not offer further comments on the metallurgical science presented in the report. The comments below are focused on the areas in the draft report that pertain to application of the Fen factors to the fatigue analysis.

NRC Response

No response is required for this particular comment.

WEST-4-2 Comment

Section 4.1.14 Modified Rate Approach

a. *This section seems to be out of place as a subsection of the Carbon and Low-alloy steel fatigue life behavior, as if it only applied to these materials. It would be better placed as Section 4.4 or in Appendix A.*
b. *The section does not address the situation where the strain rate history is not continuously positive between the valley and the peak, as depicted in the ideal examples in the figures, and the impact of such situations on the denominator of Equation 49 for consistent calculation of Fen.*
c. *The context of the introduction of equation 50 could lead the casual reader to conclude that a threshold can be used (i.e., the equation is appropriate), whereas the discussion that follows concludes the opposite (i.e., that only equation 49 should be used). Introductory wording that makes it clear that equation 50 is only hypothetical may be beneficial.*
d. *Application of a strain amplitude threshold in the context of equation 50 should be distinguished from application of the threshold in general for a fatigue pair - i.e., the analyst should be able to apply Fen of 1.0 to pairs whose Salt corresponds to a strain amplitude within the threshold, precluding consideration of a strain rate method needed for the pair. (This comment may be more applicable to the notes in Appendix A that disclaim the use of threshold with modified rate.)*
e. *Points (b) and (c) in this subsection seem to only be talking about application of the average strain rate approach, and not the modified rate approach application, and could be confusing to the reader with respect to their points. Perhaps the subsection should be re-titled and both approaches explicitly described, then addressed with the applicable points about the temperature recommendations for each approach.*
f. *Point (b) concludes that "appropriate temperatures" should be selected for average strain rate calculations, after stating that maximum temperature is most conservative. Is this just a lead-in to point (c), or is the conclusion to use maximum temperature with average strain rate method? Please clarify what is discussion vs. recommendation.*
g. *It is not clear if the conclusion of point (c) is intended for the average strain rate method*

or the modified rate method. It seems to be the former, since modified rate applications use an integration step that results in insignificant difference from using the average or maximum temperature in each step, as stated in its last sentence. Suggest separating what is recommended for temperature input to the average approach, and then for the modified rate approach.

h. *Figure 81: Please check that the legend entries appropriately describe the quantities being represented by the lines on the graph, especially "Average Strain Rate", which would be expected to be one value over the interval.*

i. *The single bullet occurring after Figure 81 seems to get lost. It appears, based on the comments above, that a number of recommendations about strain rate calculation using either average or modified rate should be made in conclusion of this subsection.*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. In response to sub-comment a., Section 4.1.14 has been relocated to new Section 4.4 and all references to the original Section 4.1.14 have been changed accordingly.

The issue raised in sub-comment b. is outside of the scope of the NUREG and is not relevant to the F_{en} approach. In going from a valley to a peak strain, the analyst should only evaluate the increasing strains and ignore any intermittent valley or lower peaks. However, the appropriate source for this clarification is within the ASME Code. The ASME Code is currently working on a strain rate Code Case and this issue is addressed within this Code Case. Therefore, no changes were made to this document.

Three changes were made in response to sub-comment c. in new Section 4.4. First, the sentence before Equation 53 (original Equation 50) was changed to,

> "In application of the modified rate approach when a threshold strain, ε_{th}, is considered, the following equation can be used to calculate F_{en} for the total strain transient:".

In addition, the first sentence of the paragraph following Equation 53 (original Equation 50) was changed to, *"The modified rate approach defined by both Equations 52 and 53 was used to evaluate fatigue lives under cyclic loading conditions where both temperature and strain rate were varied during the test[24,37,38]."*

Finally, Item (1) under Equation 53 (old Equation 50) was changed to, *"The use of a strain threshold, ε_{th}, for calculating F_{en} by the modified rate approach (i.e., Equation 53) was not necessary because it did not improve the accuracy of estimation.[38] As discussed in Section 4.1.3, application of the modified rate approach, without the consideration of a strain threshold (i.e., Equation 52), gave the best estimates of fatigue lives."*

The changes made in response to the sub-comment c., coupled with the existing language in Appendix A, are also used to address sub-comment d. Appendix A already states that "one-half of the strain range" can use $F_{en} = 1.0$ when the strain is below ε_{th} and that the use of ε_{th} is not applicable to the modified rate approach.

In response to sub-comment e., the information on the modified rate approach that was previously contained in Section 4.1.14 has been moved to a new Section 4.4 which solely discusses the modified rate approach. Further, the following statement about the conservative nature of the average strain rate approach and the use of temperature in each method has been added as item (3) to new Section 4.4:

"For the modified rate approach, the difference in F_{en} results is insignificant when either average or maximum temperatures are used if the integration time step is sufficiently small. However, as shown in Figure 4-67, use of an average temperature with the average strain rate approach does not always yield a conservative F_{en} estimate when compared to the results obtained from an integrated F_{en} using the modified rate approach. Therefore, an average temperature should only be used if it is demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach. If an average temperature is justified for the average strain rate approach, the temperature can be calculated to estimate F_{en} during a load cycle using one of the following procedures:

a) as the average of the maximum temperature for the transient and the higher of the threshold temperature for the material under consideration (i.e., 150°C) or the minimum temperature for the transient

b) as the average of the transient maximum temperature and the F_{en} threshold temperature"

Additional changes in response to similar comment, WEST-4-2i, were also made to the report.

To address sub-comment f., the last sentence of Item (2) in new Section 4.4 was changed to,

"Thus, calculations of F_{en} based on an average strain rate for the transient are expected to yield conservative estimates of fatigue lives as long as the calculations use appropriate temperatures (either maximum temperatures or appropriate average temperatures in accordance with Item 3 below)."

Sub-comment g. has been addressed by the changes to item (3) to new Section 4.4 discussed previously to address sub-comment e.

In response to sub-comment h., the legend entry, "Average Strain Rate" was changed to "Strain Used for Average Strain Rate" in Figure 4-67 (Figure 81 in draft NUREG). In response to this sub-comment i., the information on the modified rate approach has been moved to a new Section 4.4. Further, the following statement about the conservative nature of the average strain rate approach and the appropriate use of temperature in each method has been added to the Executive Summary and the Summary:

"The procedure allows evaluation using either a modified rate or an average rate approach. F_{en} calculations based on an average strain rate for the transient are expected to yield conservative estimates of fatigue lives as long as the calculations use appropriate temperatures selected in accordance with the recommended procedures in Section 4.4. Using an average transient temperature within the average strain rate approach does not always yield a conservative estimate of F_{en}. Therefore, an average temperature should only be used if it has been demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach."

See also the response to related comments WEST-4-2e and WEST-4-2g.

WEST-4-3 Comment

Appendix A, Section A2
The final paragraph states that the maximum temperature limit of 325°C (617°F) is "adequate for all expected operating LWR conditions considering the use of average temperature." In the

case of applying the modified rate approach, the integration over the strain history may include time steps for which the temperature over the interval is above 325°C (617°F). Is the statement intended to justify the use of the equation using the upper limit in the situation where the integration interval temperature is higher? Please clarify the intended application of this statement.

NRC Response

The last paragraph of Section A.2 states that to cover all anticipated LWR operating conditions, a maximum temperature limit of 325°C was selected. This is adequate for all expected operating LWR conditions considering the use of average temperature. However, to address this comment in the event that higher average temperatures are required, the following additional language has been added to the end of the last paragraph in A2:

> "If the applicable average temperature for the transient exceeds 325°C, the user should thoroughly document this exceedance and justify the rationale for it as part of the analysis."

This comment is similar to AREVA-9-18e and KEPCO-10-2. See also the responses to those comments for additional information on this issue.

WEST-4-4 Comment

Section A3

a. *The text of the continued sentence after Table A.2 needs to follow equation A. 19; it should not be separated by the figures and tables.*
b. *Wording at the bottom of page A-5: "tensile stress producing portion of the stress cycle" is not consistent with the intent previously described as "increasing strain or stress". A compressive stress producing portion of the stress cycle may still exhibit increasing strain or stress, and vice versa.*
c. *Page A-6, item (2): What is the purpose of requiring a "linear temperature response" for this case? Is this the only case where an average strain rate and average temperature can be used?*
d. *Page A-6, item (2): "the "average" temperature used ... should produce results that are consistent with ... modified rate approach" (emphasis added) - is this a statement of support for using average temperature as described, or is this a requirement that must be demonstrated for each evaluation? It seems to be the former, but this should be clarified considering the statements in Section 4.1.14 regarding the use of average temperature.*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. Equation A19 and the preceding sentence have been moved to after the figures and tables to address sub-comment a. Sub-comment b. has been addressed by revising the sentence cited in the sub-comment (originally on the bottom of page A-5 in draft report) to now clarify that the "…*increasing strain or stress portion of the loading cycle constituting a load pair*…" should be considered. This change now makes this statement consistent with the intent as identified in the sub-comment.

Regarding sub-comment c., it is correct that a linear temperature response is the only case where an average temperature and strain rate can be used. The strain accumulated at different

temperatures would vary for a non-linear temperature response. To address sub-comment d., the original item 2 is intended as a statement of support as indicated in the comment. Therefore, the last two sentences of the second bullet (originally item 2 in draft report) on page A-6 have been clarified as follows:

> "Using the average temperature in fatigue evaluations should produce results that are consistent with the results that would be obtained using the modified rate approach described in Section 4.4 of this report. The maximum temperature can be used to perform the most conservative evaluation."

WEST-4-5 Comment

Appendix C, Section C2
Page C-2: "The transients were linked in sequential order" - There is no sequence to transients in an ASME design analysis, or to those evaluated in this sample problem, as implied by this wording. The order may have been chosen based on anticipated transient pairings and methods of linking to obtain strain rate, but the subject of transient linking with respect to application of the modified rate approach is not addressed in this report. It is suggested that this be clarified and/or expanded.

NRC Response

To address this comment, the paragraph containing this phrase on page C-2 was expanded and modified as follows:

> "For the purposes of this example, the transients were arbitrarily linked in sequential order to obtain the overall stress histories used in the F_{en} evaluation, as shown in Figure C-5. In the general case, the transient order would be defined by the stress history, as required by Subparagraph NB-3216.2, 'Varying Principal Stress Direction,' of Section III, 'Rules for Construction of Nuclear Facility Components,' of the ASME Code (see Section C.3(A) below). Peak cycle counting as specified in the ASME Code was used to calculate CUF in the analysis."

WEST-4-6 Comment

Section C3

a. *Page C-8, point A and sub-point a. - "Table C.2" is not stress history; is the intended reference Table C.5 instead of C.2?*
b. *Page C-8, point A and sub-point b: "maximum total stress" - expanded in step h to also include membrane plus bending stress.*
c. *Page C-8, point A and sub-point h: suggest a reference back to step b to define "which case" to use for the extreme time to provide clarity.*
d. *Page C-9: "Strain rates were calculated based on the total S'31 history which was the limiting CUF case." - Please consider clarifying with respect to the following:*
    - *If the principal stresses were ordered classically, S1>S2>$3, then S'3 I is expected to control the CUF. It would also be expected to provide the maximum strain range over an interval.*
    - *If the principal stresses were not ordered classically, then this result and method may be unique for this example.*
    - *If there are any NRC expectations with respect to the principal stress difference history to be used for strain rate calculation, these should be clarified for general applications.*
    - *Until this sentence in Appendix C, a "case" has been associated with one of the*

stress quantity extremes described in step h. This sentence suggests that there were also principal stress difference "sub-cases" for each of the step h cases evaluated to determine the limiting CUF. If this is correct, please clarify how the principal stress difference subcases were used to determine the limiting CUF value and associated strain rate conditions. If this is not correct, please revise this sentence appropriately.

e. *Page C-9, A. Average Strain Rate Approach, sub-point ii:*
   - *The stress intensity range between the peak and the valley in the general case should be based on the stress component ranges as in NB-3216.2.*
   - *The basis for using E at the maximum temperature should be clarified, as well as any NRC expectation in this regard.*

f. *Page C-9, A. Average Strain Rate Approach, sub-point iii: For the average strain rate approach, linking from valley to peak in each fatigue pair, it is not expected that strain rate should be less than zero. Please clarify this point.*

g. *Page C-10, Average Strain Rate Approach, sub-point v: Assignment of Fen to "both the peak and the valley" is not clear, since Fen is determined for the whole stress range in the pair. Please clarify this point.*

h. *Page C-10, A. Average Strain Rate Approach, point vi: Please see comment above on page C-2 "transient linking issue" with respect to the implied "stress intensity history". The history to be considered for each Fen should be between the valleys and peaks determined from the fatigue pairs formed in step f on page C-8, which is not necessarily the history implied by Figure C-5 in the general case. Therefore, this statement as presented in the context of this example could be misleading.*

i. *Page C- 10, B. Modified Strain Rate Approach, point ii: The stress intensity range between the time points in the general case should be based on the stress component ranges as in NB-3216.2.*

j. *Page C-10, B. Modified Strain Rate Approach, point iii: It is not clear how setting Fen to 1.0 for intervals of negative strain rate provides a consistent integration over the complete strain range, with the denominator of the Fen integration equation being* e_{max} - e_{min}*. It would be helpful to provide the explanation for this.*

k. *Page C-10, B. Modified Strain Rate Approach, point v: The numerator of the Fen-n equation does not agree with Equation 49, which uses delta-strain.*

l. *Page C-10, B. Modified Strain Rate Approach, point vi: Assignment of Fen to "both the peak and the valley" is not clear, since Fen is determined for the whole stress range in the pair. Please clarify.*

m. *Page C- 1l, B. Modified Strain Rate Approach, point vii: Please see comment above on Average Strain Rate Approach, point vi.*

NRC Response

This comment contains many sub-comments that are addressed individually as follows. It is agreed that, as stipulated in sub-comment a., that the cited reference to Table C-2 is incorrect. The reference to "Table C-2" in bullet "C.3.A" has been changed to cite Figure C-3 – Figure C-5. The reference to "Table C-2" in sub-bullet "C.3.A.a" has been changed to cite Figure C-3 and Figure C-4. To address sub-comment b., Step C.3.A.b has been expanded to reference Step C.3.A.h and clarify that six cases were investigated (each of three stresses for both membrane plus bending and total stress histories) and "total" has been deleted from "maximum total stress." It is also agreed that clarification is needed to address the issues raised by sub-comment c. The subscript "i" has been added to refer to the separate cases run at the times when each of the six stress components peak. C.3.A and the footnote on page C-10 have also been revised accordingly.

Sub-comment d. contains several issues. In response to the first part of the comment regarding the arrangement of principal stresses, step C3.A.d has been expanded to note that the principal stress differences were ordered classically. Also, it has been clarified that since the principal stresses were sorted classically, the use of S'31 is expected to produce the highest CUF. In response to the second part of sub-comment d. regarding the sub-cases, Steps C3.A.h through C3.A.m were clarified to discuss how the sub-cases were evaluated in the sample problem.

Sub-comment e. also contains two separate issues. The clarification made to Steps C3.A.b and C3.A.h to address sub-comments b. and d. also address the portion of sub-comment e. pertaining to the selection of the stress intensity range. The portion of this comment pertaining to the use of maximum temperature to compute E has been addressed by expanding the definition of E to state that the maximum temperature was used for this sample problem. Additionally, in Section 4.4 of the NUREG, clarification regarding the use of temperature for determining the value of E was added under new bullet (4).

It is agreed, as stipulated in sub-comment f., that the strain rate should not be less than zero. However, this statement was originally made because of perturbations in the calculated FEA stress response. In response to this comment, step iii of the "Average Strain Rate Approach" section has been clarified to state that setting F_{en} = 1.0 for negative strain rates was necessary only to factor-out anomalies in the FEA calculated stresses. Sub-comment g. asks for clarification of the assignment of F_{en} to both the peak and valley in step v of the Average Strain Rate Approach. For a valley-to-peak portion of a stress history, the strain rate increases over that range, so a F_{en} value is computed over the range. The F_{en} value is assigned to both the valley and the peak associated with the range. Therefore, each peak and valley in the entire stress history has a calculated F_{en}. When peaks and valleys are paired to compute CUF, the maximum of both F_{en} values is selected. In response to this comment, the preceding clarification has been made to step v of Average Strain Rate Approach.

Sub-comment h. is similar to earlier comment, WEST-4-5. As indicated in the response to this earlier comment, the report has been clarified to indicate that while the stress histories were arbitrarily linked in sequential order for the example problem, the more general problem should arrange the transients using the stress history as required by NB-3216.2. Sub-comment i. is similar to comment, WEST-4-6e. The clarification made to Steps C3.A.b and C3.A.h to address WEST-4-6e also addresses this comment.

Sub-comment j. is also analogous to Comment WEST-4-6f related to the average strain rate approach. Similar changes were made to the NUREG report as those identified in the response to WEST-4-6f. Specifically, clarification was added to step iii of the "Modified Strain Rate Approach" section to state that setting F_{en} = 1.0 for negative strain rates was necessary only to factor-out anomalies in the FEA calculated stresses.

The issue related to the numerator of the $F_{en\text{-}n}$ equation in step v of the modified strain rate approach in sub-comment k. is valid. The strain variable in numerator of the $F_{en\text{-}n}$ equation has been changed to reflect that it is the change in strain between points i and i+1 that is to be used. Sub-comment l. is similar to earlier comment WEST-4-6g on the average strain rate approach. Identical changes to the "Modified Strain Rate Approach" section (Step vi) were made to be consistent with the modifications to the "Average Strain Rate Approach" section (Step v) in response to WEST-4-6g. Finally, sub-comment m. raises similar issues as the earlier general comment WEST-4-5 and WEST-4-6h, which is related to the "Average Strain Rate Approach" section. Please see the responses to these earlier comments to identify how this issue has been addressed.

WEST-4-7 Comment

Section C4

a. *First paragraph: It could be inferred from the wording here that only the membrane plus bending stress was used in the fatigue evaluation. Suggest clarification that both membrane plus bending and total stresses were used.*
b. *It would be helpful to address how the strain rate integration period was determined using Total Stress when the valley and/or peak time of the Total Stress did not correspond to the times selected based on the Membrane plus Bending stress difference.*
c. *Table C.4: It would be beneficial to provide the time intervals corresponding to Fen-nA and Fen-nB calculations.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. As stated in sub-comment a., it is agreed that additional clarification on the stresses used in the example is needed. Therefore, the second sentence of first paragraph in Section C.4 has been expanded to state that both the membrane plus bending and the total stresses from the identified case were used in the determination of the cumulative usage factor (CUF). Similarly, it is agreed, as stipulated in sub-comment b., that clarification on determining the strain rate integration period would be helpful. A new paragraph has been added to the end of Section C.3 to explain how the peak and valley times were selected for both F_{en} approaches. Finally, to address sub-comment c., the time values for Loads A and B have been added as new columns in both Table C-3 and Table C-4.

MHI-5-1 Comment

Section 3.1.10: Extension of the Best-Fit Mean Curve from 10A6 to 10^A 1 Cycles Extension of the best-fit mean curve from 10A6 to 10^A 1 cycles is too conservative.

EN 13445 uses the cut-off limit at 10A8 cycles and the following equation based on the Haibach Model is applied to variable amplitude loading.

⊿SR=(C3/N)AO.1 for N>= 2x 10^6 cycles

*Also, Giga-Cycle-Fatigue Subcommittee of the Atomic Energy Research Committee of the Japan Welding Engineering Society studied on fatigue in giga-cycle regime. Fatigue tests of 316NG and SFVQ1A (equivalent to SA 508 Gr.3 Cl. 1) up to 10A9 cycles were performed and confirmed that internal fracture did not cause a sudden drop in fatigue strength [*1, 2].*

Fatigue tests above 10^8 cycles are very difficult and the extension over 10^8 cycles is not realistic. Therefore, the provision of EN 13445 is a reasonable methodology.

** 1: Ogawa, T., et al., "Investigation of Effect of Pre-Strain on Very High-Cycle Fatigue Strength of Austenitic Stainless Steels," Journal of Power and Energy Systems, Vol.3, No. 1, 2009.*
**2: Sato, M., et al., "Giga-Cycle Fatigue Strength Properties of Low-Alloy Steel SFVQ1A Evaluated by Ultrasonic Fatigue Test," Transactions of the Japan Society of Mechanical Engineers, Series A, Vol.78, No.789, 2012. (in Japanese)*

NRC Response

It is agreed, as stated in this comment, that the extension of the fatigue curve is conservative. As indicated in NUREG/CR-6909 Rev. 1, the curve to extend the fatigue life prediction from 10^6 to 10^{11} cycles is the extension proposed by the ASME Code committees. This extension is based on data that has a prominent mean stress component. Basing the curve on such data is meant to be both conservative and also allow application to engineering components, which often experience high mean stress loading. As stated in the NUREG, for data without a significant mean stress effect, this proposed curve could be significantly conservative.

However, it is not agreed, as stipulated in the comment, that this curve should be limited to 10^8 cycles or less. While there is agreement with the commenter that there is limited fatigue data beyond 10^8 cycles, the data that does exist supports the notion that this extensive curve is conservative out to 10^{11} cycles. This extension curve will be reevaluated if additional data become available in the high cycle regime between 10^8 and 10^{11} that challenges its intended conservativism.

MHI-5-2 Comment

Section 3.1.6: Fatigue Life Model
*The dependency of tensile strength on fatigue curve is well-known. The fatigue design curves of EN 13445 are specified for tensile strength class. Design-Fatigue-Curve Subcommittee of the Atomic Energy Research Committee of the Japan Welding Engineering Society is developing design fatigue curves and has confirmed the dependency of tensile strength on fatigue curves [*3].*

And so, the dependency of tensile strength on fatigue curve should be incorporated into the design fatigue curves so as to perform reasonable design.

**3: Kanasaki, H., et al., "Proposal of Fatigue Life Equations for Carbon & Low-Alloy Steels and Austenitic Stainless Steels as a Function of Tensile Strength," PVP2013-97770, ASME, 2013.*

NRC Response

It is agreed that fatigue design curves could be developed as a function of ultimate tensile strength for ferritic materials as long as an appropriate technical basis is established. In response to this comment, the above observation has been inserted in item (vii) *Material Grouping* in new Section 1.5. However, the actual development of fatigue design curves is outside the scope of this report. Such development should occur under the purview of the ASME Code.

MHI-5-3 Comment

4.2.2: Strain Rate (Austenitic Stainless Steels)
*The upper strain rate is determined 10%/s by extrapolating from the data less than 1.0%/s in Figure 85 and 86. However, Fukuta, et al. [*4] showed the data above 0.4%/s in PWR environment and concluded that the threshold strain rate at Fen = 1 was estimated to be lower than 3%/sec for all austenitic stainless steels. Therefore the upper strain rate of 10%/s should be reexamined.*

**4: Fukuta, Y., et al. "High Strain Rate Effects on Environment Assisted Fatigue for Austenitic Stainless Steels in PWR Environment," PVP2013-97158, ASME, 2013.*

NRC Response

Please see the response to AMEC-3-10 which, based on reevaluation of existing data, provided the impetus to change the strain rate threshold from 10%/s to 7%/s throughout the report. However, the existing data on strain rate dependence of austenitic SSs in LWR environments is insufficient to more accurately establish the lower threshold strain rate for these materials. Additional data will be needed to justify decreasing the threshold strain rate further.

MHI-5-4 Comment

3.1.7: Heat-to-Heat Variability
95% criterion is applied. The validity of 95% criterion on fatigue data should be described.

NRC Response

Because the existing fatigue database shows significant variability, the 95/95 criterion has been used to ensure that the estimated values of life bounds 95% of the experimental data, with 95% confidence, to account for the specific parameter. The report cites References 214-216 in support of the approach used.

MHI-5-5 Comment

Errata

a. *The upper side of pp. 100: "(c)" should be deleted.*
b. *Figure 88: "0.3%, DO" should be corrected..*

NRC Response

These errata have been corrected in the final report. Specifically, item a. has been addressed by ensuring that the figure numbers and captions are kept together with the figures. Item b. has been addressed by revising Figure 4-34 (Figure 88 in draft NUREG) to ensure that the dissolved oxygen (DO) contents for the data are correctly displayed in the figures.

RR-6-1 Comment

General
Descriptions of "current" and "new" information need to be reviewed throughout the document to ensure they are clear in the context of the publication date of this Revision i to NUREG/CR-6909. For example, Section 3.2.11 discusses "the current ASME Code Section III fatigue design air curve" for austenitic stainless steels which, it is found later, means the pre-2009-addenda curve (and therefore not the curve that will be "current" when Rev 1 is to be issued). This paragraph is carried over almost unchanged from Rev 0. There are many other examples of this throughout the document, including paragraphs in which it is difficult to distinguish between "new" data added to the database prior to analysis reported in Rev 0, and "new" data added between the update from Rev 0 to Rev 1. Due to these confusions, it would be easy to misinterpret some of the information in the document.

NRC Response

In response to this comment, the report has been reviewed to correctly reference the ASME Code fatigue design curve for austenitic SSs presented in Code editions prior to 2009 from the curve presented in 2009 and later editions of the Code. Appropriate figures and portions of the text have been revised. The reference to "2009b Addenda" has also been changed to "2009 Addenda" throughout the report. Finally, the following corrections were made in the text of the report:

1. Executive Summary, 5th paragraph, 2nd sentence: The term "best-fit mean air data" has been changed to read "best-fit mean air curve",
2. Table 3-8: the 2nd and 5th column headings have been changed to "Current ASME Code Design Curve", and
3. Table A-2: the 2nd and 4th column headings have been changed to "ASME Code Design Curve".

Please also see also response to AMEC-3-1 for related information.

RR-6-2 Comment

General
There are several figures showing predicted life versus experimental life within the document. It would be useful if run-out (runoff) data were identified in these figures to aid visual assessment of the goodness of fit of the model to the data.

NRC Response

All run-out data are identified in the figures in the traditional manner of using arrows after the data-point to indicate that the test was stopped prior to failure so that actual fatigue life for that specimen is greater than indicated on the figure (e.g., see Figure 2-5). For clarification, the following sentence has been inserted after both the reference to Figure 2-5, the first figure with run-out data, and the Figure 2-5 caption: "*Runouts, in this and subsequent figures, are identified in the traditional manner of using arrows after the data-point.*" Also see the response to RR 6-12 which discuss how this data was included in the analysis.

RR-6-3 Comment

General
Some data available in open literature suggest an interdependence of effects considered in the sub-factors and the effect of environment. This leads to possible excessive conservatism when using the approach of applying F_{en} to design curves (which are already adjusted to account for the sub-factors). These interdependencies are not discussed in the document.

NRC Response

Item (xvi) *Development of Adjustment Factors* has been incorporated in new Section 1.5 to discuss the assumptions and approach for the analysis that is more fully discussed in Section 5. Section 5.5 documents how the adjustment factors have been developed based on the accumulated data and a Monte Carlo analysis. It is clarified in this section that independence of these effects is assumed and that there is insufficient data to develop correlation factors among these effects using a more rigorous analysis. In addition, after the first sentence of the paragraph below Table 5-2, the following statement has been added: "*In this analysis, these*

effects are conservatively considered to be independent even though some effects, as discussed previously, may be correlated. However, current data are insufficient to develop quantitative correlation factors needed for a more rigorous analysis."

RR-6-4 Comment

General
Rev 1 of NUREG/CR-6909 provides no comment on strain gradients within a component, which can account for a significant amount of conservatism with the ASME fatigue method. A basic assumption of the ASME III method is that a small crack (ie 3 mm depth) in a cylindrical test specimen initiates and grows at the same rate as in a pressure vessel component when both are subject to the same cyclic surface strain range. This similitude holds true for some definitions of crack initiation (say, the formation of a 0.25 mm crack), but in many cases, with continued cycling, this equality is not maintained. It depends upon the immediate sub-surface conditions into which the crack grows. If the crack enters a decreasing stress field (typical of that due to thermal shock) it will take more cycles for the crack to grow to a pre-defined length (3 mm) than for a stress field that is uniform across the section, as is the case in a standard strain-controlled E-N test. This potential conservatism should be discussed in Rev 1.

NRC Response

There is general agreement with this comment. Please refer to the responses to similar comments AMEC-3-2, and AMEC-3-5, RR-6-4, RR-6-32, EDF-7-8, and AREVA-9-17h for a discussion on modifications to the NUREG to address this issue.

RR-6-5 Comment

General
The Federal Register Notice for NRC-2014-0023 dated April 17, 2014 (Vol.79, No.74) stated that the NRC was particularly interested in stakeholder feedback on three areas, the third of which was: "Accuracy check of the technical content of the NUREG, particularly with respect to all of the numerical content of the report."

As a stakeholder, we do not consider that the time allowed for public comment, ie up to June 2, 2014 allows us to give detailed feedback on the numerical content and accuracy of the report.

NRC Response

It is recognized that it can be challenging to perform a thorough review in the time allotted in the Federal Register Notice (FRN). For future consideration, a reviewer can always request that the NRC extend the public comment period. Additionally, future comments on this document are always welcome and can be provided to the NRC at any time. These comments can be considered and addressed in any future revisions of the document.

RR-6-6 Comment

Section 1.2, Page 4
The NUREG needs to be clear with respect to what the factors applied to derive the design fatigue curve are for. This was clear in the past, ie "not safety margins but rather adjustment factors that are applied to small-specimen data to account for the effects of variables that are known to affect fatigue life but are not accounted for in small-specimen data". Page 4 indicates

that the fatigue design curves are now defined to estimate an acceptable fatigue life for 95% of the population. Please provide a definition of the purpose of the design factors that clearly identifies whether they are transference factors or are derived to provide an acceptable fatigue life for 95% of the population (or both?). Also provide a reference to the section in NUREG/CR-6909 that provides substantiation to the 95% value.

NRC Response

The report clearly states that the factors applied to derive the fatigue design curve are not safety margins but adjustment factors that are applied to the mean-data curve to account for the uncertainties caused by data scatter, component size, surface roughness, and fatigue loading sequence. In order to clarify this, the second sentence of the paragraph after Equation 10 has been revised to state as follows:

> "However, this report includes a rigorous evaluation for defining an adjustment factor to derive the fatigue design curve from the mean-data curve, to account for the variability resulting from data scatter, size, surface roughness, and loading sequence."

Furthermore, the 95/95 criterion has been used in the report to define the maximum values of the adjustment factor needed to account for the effect of a specific parameter. However, as discussed in the response to RR-6-3, the maximum values of these parameters are not used to define the combined adjustment factor. The value of 12 for the combined adjustment factor used to derive the fatigue design curve is less than half the product of the maximum values of the adjustment factor for the four parameters that influence fatigue life. This is discussed more fully in Section 5.5.

RR-6-7 Comment

Section 1.2, Page 5
σ_y should be specified as cyclic yield strength for the modified Goodman relationship – e.g., Jaske and O'Donnell, Journal of Pressure Vessel Technology, November 1977.

NRC Response

The report follows the guidance in the technical basis document for performing the ASME Code Section III fatigue evaluations. The expressions specified for the modified Goodman relation in the technical basis document use the monotonic yield strength to establish the value for maximum mean stress, and not the cyclic stress.

RR-6-8 Comment

Figure 16, Page 28
Figure 16 does not seem to match the text in Section 2.2.1.4 indicating that the figure has not been scanned into the document correctly.

NRC Response

The report content has been verified to ensure that Figure 2-11. (Figure 16 in the draft report) is displayed accurately in the document.

RR-6-9 Comment

Section 2.2.2.4, Page 34
With respect to the cited paper (Reference 44), a more recent paper by Kamaya is available: "Environmental effect on fatigue strength of stainless steel in PWR primary water - Role of crack growth acceleration in fatigue life reduction, Int. Jnl. Fat. 55 (2013) 102- 111".
Kamaya's paper concludes that "reduction in fatigue life due to PWR water environment was brought about not by enhancement of crack initialisation but by the acceleration of crack growth".

The tests reported in the paper were carried out at relatively high strain amplitude. Therefore there is some evidence to suggest that the predominant effects of environment, with respect to the phases of crack development, may be dependent upon strain amplitude. Rev 1 should recognise more recent research in this topic area.

NRC Response

This comment discusses the role of crack growth rates on environmental effects on fatigue crack initiation. The report acknowledges that the environmental effects on fatigue crack initiation show dependence on strain amplitude, in fact, environmental effects are greater at low strain amplitudes. But the decrease in fatigue life is due to the effect of environment on growth of microstructurally small cracks (i.e., cracks <200 micron) as well as mechanically small cracks. Environmental effects on the former are much greater, but do not adhere to a fracture mechanics methodology. Therefore, the overall environmental effects cannot be accurately estimated using solely a crack growth rate approach as in the Kamaya study. These details are already discussed in the report.

In addition, it should be noted that the Kamaya study is on Ti-modified stainless steel, which shows temperature effect on fatigue life at temperatures >300°C. The stainless steel data evaluated in this report does not include Ti-modified stainless steels and therefore, the proposed methods are not applicable to such steels. To reinforce this point, the authors have added the following statement in the Executive Summary (at the end of the 4th paragraph):

> "Note that, as with the original evaluation, the reevaluation in this report was still based on various compositions of wrought Type 304 and 316 SSs, associated weld metals, and a few heats of CF-8M cast austenitic SSs. The reevaluation did not consider other grades of austenitic SSs, particularly the titanium- or niobium-modified SSs, which have better fatigue resistance. Therefore, fatigue lives based on the proposed fatigue design curve are expected to be conservative for SSs with improved fatigue resistance, such as the titanium- or niobium-modified steels. "

It is also clarified that in new Section 1.5 (item (vii) *Material Grouping*) that the method is only applicable to the materials listed in Table B-1, Table B-2, and Table B-3, except for Inconel 718.

RR-6-10 Comment

Section 2.2.2.4, Page 35
With respect to referring to Reference 208 "as existing fatigue crack growth data", this data is very old, circa mid-nineties. For PWR it has been superseded by that which forms the basis of the draft ASME Code Case N809. This data is extensive and has been reported via several PVP papers and unlike Reference 208 fully recognises the possible deleterious effects of PWR environment. Reference to the more up to date data should be made.

NRC Response

Section 2.2.2.4 presents results of the analysis described in the original version of NUREG/CR-6909 report. The slope of the log(da/dN) vs. log(ΔK) curve is 3.3 in the NUREG/CR-6909 expressions and 2.25 in Code Case N-809. There are also other minor differences in the adjustment factor used in the two expressions. No attempt was made to update the analysis in this revision. However, the differences are not expected to have any significant effect on the analysis presented in the report.

This comment has been addressed by inserting the following footnote in Section 2.2.2.4 after reference 208 is introduced:

> "Since the study by Shack and Kassner was completed, American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Case 809, 'Reference Fatigue Crack Growth Rate Curves for Austenitic Stainless Steels in Pressurized Water Reactor Environments,' dated June 23, 2015, has been approved. ASME Code Case 809 is based on a more extensive data base than the Shack and Kassner expressions. While there are differences in the CGR parameters used in the Code Case and the Shack and Kassner expressions, these differences are not expected to affect the conclusions drawn in this section on the importance of the effects of environment on the growth of MSCs."

RR-6-11 Comment

Section 2.2.2.4, Page 37
It is judged that based upon more recent SS fatigue crack growth (FCG) rate data a comparison of Alloy 600 with austenitic SS in PWR environments would show the SS to be significantly higher. The statement "Fatigue CGR data indicate that enhancement of CGRs of Alloy 600 and austenitic SSs in LWR environments is also comparable" is therefore open to question. To substantiate the statement made, a comparison of the SS laws of Code Case N809 with those in NUREG/CR-6176 should be provided.

NRC Response

This comment is similar to comment AMEC-3-6 and has been addressed by the modification to the last paragraph of Section 2.2.2.4 as described in the response to comment AMEC-3-6.

RR-6-12 Comment

Section 3.1.6
The description of the method used by ANL to develop a best-fit line is greatly improved. However, there is no mention of how run-out (runoff) data are considered in the analysis. It would be useful for this to be clarified in the text.

NRC Response

The report describes in details that unlike most best-fit analyses of fatigue strain vs. life data, which ignore runoffs, the runoffs are included in the analyses because the error in the distance of the data points from the best-fit-curve is minimized. The details are presented in Section 3.1.6. For clarification, the sixth sentence of the first paragraph of Section 3.1.6 has been modified to state, *"A predictive model based on a least-squares fit on N or ln(N) is biased for low*

strain amplitude (ε_a). In addition, the data obtained at strain amplitudes less than the constant C in Equation 6 (e.g., most runouts) cannot be included in the analysis."

RR-6-13 Comment

Section 3.1.7, Page 49
Why is the dataset for A216-Gr WCC excluded? Is it excluded because it is a casting? It does not appear that inclusion of the value of A of 4.899 for this dataset would significantly change the median value for carbon steels. Does exclusion of this material mean that the best-fit for carbon steels is not considered relevant to this alloy? If so, which best-fit should be used for this alloy?

NRC Response

As described in Section 3.1.7, the average value of Constant A for this material at 325°C was significantly lower than the average value for the rest of the data. Therefore, it was considered an outlier and was not included in the analysis. Since there is no other data for this material, it is difficult to assess whether this value is representative of this material or unique to this particular heat. If it is the latter, including this value would unnecessarily bias the result. Additional data are needed to confirm whether the proposed methodology is applicable to A216-Gr materials.

RR-6-14 Comment

Section 3.2.1, Figure 38, Page 58
For lives > 10^5 cycles, data for Type 304L SS at both 150'C and 300°C show significantly lower lives than suggested by the ANL best-fit. There is no reference to this in the text except a generic statement that "`results...show excellent agreement with the ANL model with respect to the mean data curve". Figure 38 suggests that the high cycle fatigue behaviour of Type 304L is quite different to the ANL model; this requires further clarification and discussion. A difference in behaviour of Type 304L compared to other austenitic stainless steels is discussed in Section 4.2.1 (Page 114).

NRC Response

It is agreed that a few heats of Type 304L or 316NG show poor agreement with the ANL best-fit curve. To address this issue and the comment, the following paragraph has been inserted on Page 3-22 during the discussion of the data in Figure 3-12 (Figure 38 in the draft report):

> "A few heats of Type 304L and 316NG show poor agreement with the ANL best-fit curve. Typically, for such heats, the slope of the fatigue ε–N curve is steeper; therefore, fatigue lives are slightly longer at high strain amplitudes and lower at low strain amplitudes. This behavior is also observed in PWR environments, as shown in Figure 4-28 and Figure 4-30 in Section 4.2.1. Because the methodology is applicable to several grades, heat-treatments, and compositions of materials, a single slope of the fatigue ε–N curve is assumed for all materials."

RR-6-15 Comment

Section 3.2.1, Page 59
The quoted "commonly used" monotonic yield strength for austenitic stainless steels of 303 MPa is well above the average yield strength for materials in the database, from review of the information provided in Appendix B2. It is suggested that this value is updated or a range of

"typical" values quoted. Also, in the context of mean stress correction described here, should a cyclic yield strength be quoted instead of a monotonic value? (see also Comment No. 7)

NRC Response

Several clarifications have been made to the NUREG to address this and similar comments. First, the term "monotonic" has been added before yield and tensile strength throughout the document to emphasize that it is the monotonic and not cyclic strengths that are considered in mean stress correction. Also, it has been clarified in the 5th sentence of the 5th paragraph in Section 3.2.1 that 303 MPa is at the upper range of yield strength values for SSs. Finally, item (iv) *Material Tensile Properties* has been incorporated in new Section 1.5, which documents the bases for the values used in the report. See also the response to similar comment EDF-7-4 for more information on how this comment has been addressed.

RR-6-16 Comment

Section 3.2.2, Page 60
The effects of specimen geometry are considered, but only for parallel- sided gauge and hourglass specimens, whereas the database includes tube specimens. Are results from tube specimens also comparable?

NRC Response

The experimental fatigue lives obtained using tube specimens were within the data scatter observed for the solid cylindrical gauge specimens. The constant A for a dataset obtained from tube specimens under specific temperature, loading, and environmental conditions, were within the range of cumulative distribution plots shown in Figure 3-19 (Figure 45 in draft report), but had a marginally lower median value.

RR-6-17 Comment

Section 3.2.3, Page 61
The effect of strain rate on fatigue life of stainless steels in air is concluded to be insignificant. For temperatures less than 400°C, this is based on a single paper. More recently published data suggests that there could be a significant effect in this temperature range, for example:
De Baglion and Mendez, "Low cycle fatigue behaviour of a type 304L austenitic stainless steel in air or vacuum, at 20°C or at 300°C: relative effect of strain rate and environment", Procedia Engineering 2 (2010), pp 2171-2179.

Similarly, Figure 42 of NUREG/CR-6909 Rev 1, shows a potentially significant effect of strain rate on life at 288°C for Types 316NG and 304 SS.

NRC Response

The paper by Baglion and Mendez on Type 304L SS has been reviewed and it is noted that the strain rate dependence at 300°C is comparable to what was reported in NUREG/CR-5704. Further, the results indicate that effect of strain rate are rather small and within the scatter due to material variability and experimental data scatter. Therefore, in NUREG/CR-6909, Rev. 1, the strain rate effects in air have been ignored. Regarding the effect of temperature, the results obtained by Baglion and Mendez exhibit little or no difference in fatigue lives at 20 and 300°C. For example, at a strain rate of 0.4%/s, N_f values obtained from the figures at 20 and 300°C are

approximately 4800 and 5300 cycles, respectively, at strain amplitudes of 0.6%. At a 0.3% strain amplitude, the N_f values at 20 and 300°C are 31000 and 30500 cycles.

RR-6-18 Comment

Equation 29, Page 64 and Figure 38, Page 58
Equation 29 is stated to be valid for Types 304, 304L, 316, 316L and 316NG stainless steels. Following the addition of a chart for Type 304L, data for all of these grades are now shown in Figure 38 (Page 58) with the exception of Type 316L. Could a chart for Type 316L also be added to Figure 38?

NRC Response

The only 316L data in the database is ANL material ID 47 which is a dataset from JNES as indicated in Table 3-6 in the report. There are few data points (i.e., less than 10) and the behavior is consistent with the 316NG data. Therefore, the 316L data have been grouped with the 316NG data in Figure 3-12 (bottom right) (Figure 38 in the draft report). Because the data is so similar, it is not meaningful to differentiate between the 316L and 316NG data in this figure. However, it is agreed that more data is needed to develop statistically significant curves solely for 316L

RR-6-19 Comment

Section 3.2.10, Page 68
The implication here is that the "surface finish and environment" sub-factor is sufficient to account for the effects of variations in surface finish in the air environment, but this is based on just two data points for specimens with non-standard surface finish that show an approximate factor of 3 reduction in life. Additional relevant data for the air environment from Le Duff is shown in Figure 109 (Page 136) and should also be discussed here. Further data of relevance is available in open literature and could also be discussed.

NRC Response

Although the maximum value of the adjustment factor for surface finish is 3, the combined adjustment factor to account for all for parameters is not the product of the maximum values of individual parameters. The combined adjustment factor of 12 is based on a Monte Carlo statistical evaluation. Please see also the responses to AMEC-3-8, which discuss the surface finish effects specifically, and the responses to RR-6-3 and RR-6-6 which discuss the development of the design curve adjustment factors.

RR-6-20 Comment

Section 3.3
The fatigue behaviour of Inconel 718 is discussed. It is stated that "the fatigue behaviour of Inconel 718 should be represented by a separate fatigue E-N curve", but it is not clear whether the Jaske and O'Donnell model reviewed in the text is being recommended or if development of a new fit is proposed. Further, this statement of a requirement for a separate curve is not consistent with the summary at the end of Section 3.3.2, which suggests that the current model for austenitic stainless steels is acceptable (if conservative) for Inconel 718. Is a separate curve required or not?

NRC Response

In order to clarify the document and address this comment, Section 3.3 has been modified to reflect the fact that Inconel 718 is more resistant to fatigue than typical Ni-Cr-Fe alloys. While the use of either the NUREG/CR-6909, Revision 1 stainless steel or the ASME Section III curves is recommended, it is now recognized that these curves are conservative for Inconel 718. The following change was also made at the end of the first paragraph of Section 4.3 to indicate that the environmental fatigue correction factors are not applicable for Inconel 718 due to lack of experimental data: "*Note that experimental data on environmental effects for Inconel 718 are not available. Therefore, the F_{en} expression for Ni-Cr-Fe alloys contained in this section is not applicable to Inconel 718.*" See also the response to related comment FAIDY-2-2k on changes to the report to address other Ni-Cr-Fe alloys.

RR-6-21 Comment

Section 4.1
The potential non-conservatism of environmental factors for low-sulphur steels is dismissed as "associated with laboratory test data and not likely to be applicable to LWR operating conditions". Presumably this is because the DO content (2ppm) is greater than found in operating LWRs. The reason for the dismissal of this identified nonconservatism should be stated.

NRC Response

In response to this comment, the last sentence of the 2nd paragraph after Equation 33 has been revised as follows: *"However, because this behavior was observed in laboratory data at DO concentrations (i.e., 2 ppm) that are much greater than those in LWR environments, the behavior is not likely to be applicable to LWR operating conditions.*"

RR-6-22 Comment

Section 4.1, Pages 77 and 78
Equations presented on Pages 77 and 78 should be clearly marked as being superseded by the updated equations presented in Sections 4.1.10 and 4.1.11. There is only a brief mention in this section that these equations have been updated, within the text and without a reference to the section containing updated equations. There is a risk that users of this large updated document (Rev 1) could unwittingly use the old equations, believing that they are the current versions.

NRC Response

In response to this comment and similar comment AMEC-3-9, the original, Rev. 0 expressions that have been revised have been deleted from the main body of the report. The original Rev. 0 expressions are now only contained in new Appendix E. Please see also the response to comment AMEC-3-9 for more information.

RR-6-23 Comment

Page 82, Paragraph, Line 10
First Clarify what is meant by "'...slow compressive loading near peak tensile loads." Is it a reducing strain, but just after reaching the peak tensile condition?

NRC Response

It is agreed that the clarification stipulated in this comment is needed. In response, the 5th sentence of the 3rd paragraph in Section 4.1.1 has been revised as follows: *"However, the decrease in life was relatively small. For fast/slow strain rate tests, the major contribution of environment occurred during the slow reducing strain, but just after the peak tensile condition.*"

RR-6-24 Comment

Equation 41, Page 98
The new form of Fen expression is not consistent with statements elsewhere in the document. For example, Section 4.1.2 (Page 82) states that "only a moderate decrease in fatigue life was observed in ...PWR water"; Section 4.1.3 (Page 88) states that "the equations may consider a threshold strain rate below which environment has no effect on fatigue lives (i.e., F_{en} = 1)"; Section 7 (p174) states that, for carbon and low-alloy steels, "expressions were revised so that the value of F_{en} was 1... when any one of the threshold conditions was not satisfied". In fact, F_{en} values considerably greater than 1 can result when one or more of the threshold values is not satisfied.

NRC Response

This particular comment contains 3 separate issues. The document has been revised as follows to address each issue.

1. In Section 4.1.2, the 4th sentence of the 2nd paragraph has been changed to read: *"The decrease in fatigue lives in simulated (low-DO) PWR environments (e.g., DO levels ≤ 0.04 ppm) was less than in high-DO environments (i.e., a maximum of a factor of 3.5 to 4.5 lower)."*
2. The 1st sentence of the bullet in Section 4.1.3 has been revised and the second half of the sentence has been deleted. The modified sentence is as follows: *"Section 4.1.11 describes the procedure for calculating F_{en} in LWR water environments and Section 4.4 discusses the modified rate approach."*
3. In Section 7, the 4th sentence of the 3rd paragraph of the section on carbon and low-alloy steels has been revised to read: *"In the present report, the F_{en} expressions for carbon and low-alloy steels were revised so that the F_{en} value is 1.0 (i.e., no environmental effects) when the strain rates are very high (i.e., greater than 2.2%/s), the DO level is less than 0.04 ppm, and the temperature is less than 150°C.*"

RR-6-25 Comment

Sections 4.1.11 and 4.2.13
Threshold strain amplitudes are not mentioned in these sections (which deal with environmental fatigue correction factors). Reference to these thresholds should be included for clarity; although it is noted that the factors are included in preceding sections - ie Sections 4.1.10 and 4.2.12 - and in Appendix A. It is suggested elsewhere in the document that these thresholds are documented in these sections – e.g., the final paragraph of Section 4.2.3 (Page 118).

NRC Response

To address this comment, the following sentence has been added to Section 4.1.11 at the end of the 4th paragraph:

"A threshold strain amplitude (one-half of $\Delta\varepsilon$) is also defined, below which LWR water environments have an insignificant effect on fatigue life. The threshold strain amplitude is specified as 0.07% or a 145 MPa (212 ksi) for both carbon and low-alloy steels."

The following similar statement has been added at the end of the 5th paragraph in Section 4.2.13:

"In addition, a threshold strain amplitude (one-half of $\Delta\varepsilon$) has been defined, below which LWR water environments have insignificant effects on fatigue lives (i.e., $F_{en} = 1$). The threshold strain amplitude is specified as a strain of 0.10% or as a stress amplitude of 195 MPa (28.3 ksi) for wrought and cast austenitic SSs."

Finally, a similar statement has been added to the first paragraph after Equation 50 of Section 4.3.3 for Ni-Cr-Fe alloys

RR-6-26 Comment

Section 4.1.11
There is no mention of whether the revised F_{en} expression is recommended only for fatigue lives up to 10^6 cycles. The previous (Rev 0) expression was recommended only for up to 10^6 (Section 4.1, Page 78), as are the Rev 0 and revised (Rev 1) expressions for stainless steels (Section 4.2, Page 110; Section 4.2.13, Page 129). The figures in Section 4.1.11 suggest that this limitation should apply. Please clarify.

NRC Response

The sentence stating, "These models were recommended for predicting fatigue lives of less than or equal to 10^6 cycles," was included in Rev. 0 of the report, and also in the draft version of Rev. 1 of the report in Section 4.1 after Equation 38 for carbon and low-alloy steels and Section 4.2 after Equation 55 for austenitic SSs. This sentence is no longer needed because applying the strain threshold for these materials would limit the applicability of the F_{en} expressions for cases with fatigue lives $\leq 10^6$ cycles. Therefore, the above sentences have been deleted in the final report. Additionally, similar statements in Section 4.1 (the first sentence of the 2nd paragraph after Equation 33), Section 4.2 (the 1st sentence of the 2nd paragraph), and Section 4.2.13 (the 3rd sentence of the paragraph after Equation 46) have been deleted in the final report.

RR-6-27 Comment

Section 4.2, Page 110
As for Section 4.1, equations in this Section should be clearly marked as being superseded by equations in Section 4.2.13 (Page 129).

NRC Response

As discussed in the response to RR-6-22, the original Rev. 0 expressions that have been revised have been deleted from the report. The original Rev. 0 expressions are now only contained in new Appendix E.

RR-6-28 Comment

Section 4.2.2
The upper threshold for an effect of strain rate has been increased from 0.4%/s (Rev 0) to 10%/s (Rev 1). It is stated that this change is based on re-analysis of the increased database, yet Figures 85 and 86 show only the same data that were presented in Rev 0 (Figures 44 and 45) which extend to a maximum strain rate of 0.4%/s. What is the basis of the increase to 10%/s?

NRC Response

Please see the responses to similar comments AMEC-3-10 and MHI-5-3 which provide the basis for the strain rate threshold and identify subsequent changes to the NUREG related to this issue.

RR-6-29 Comment

Section 4.3.3, Pages 141 and 144
It is confusing that on Page 141 a set of equations are provided for F_{en} factors for Ni-Cr-Fe Alloys, yet on Page 144 the following statement is made "Due to significantly less available data for Ni-Cr-Fe materials compared to carbon and low-alloy steels and austenitic SS, the updated austenitic SS Fen expression may be used to incorporate environmental effects into ASME Code Section III fatigue evaluations for Ni-Cr-Fe materials". The inference is that there is little confidence attached to the equations given on Page 141 and their use is questionable. A clear statement should be provided on whether:
(i) the austenitic SS Fen expression should be used for Ni-Cr-Fe alloys, or,
(ii) the Ni-Cr-Fe Fen expression described earlier in the section should be used (which is consistent with Appendix A), or,
(iii) the Ni-Cri-Fe Fen expression should be used but it is acceptable to use the austenitic SS expression instead.

NRC Response

It is agreed that the recommendations related to Ni-Cr-Fe materials were unclear in the draft report. See response to AMEC-3-11, which also raised this issue. As stated in this response (and in the changes made to the NUREG resulting from this comment), for Ni-Cr-Fe alloys, the updated Ni-Cr-Fe F_{en} expression should be used along with the SS air design fatigue curve to incorporate environmental effects into ASME Code Section III fatigue evaluations for Ni-Cr-Fe materials.

RR-6-30 Comment

Section 5
This section should clearly state a recommendation for factors that should be used to derive design curves from best fit data. It is implied elsewhere that the continued use of factors of 12 and 2 is proposed. If this is the case, why is it not appropriate to recommend use of the revised factor of 10 on life? A brief explanation is included in the Executive Summary, but not in the Section 5 discussion.

NRC Response

The report clearly states that to be consistent with the adjustment factor used in the ASME Code fatigue design curve for austenitic stainless steels, a value of 12 was used to develop the air design curves from mean-data curves for each material. Although a preliminary analysis indicates that it may be adequate to further reduce the adjustment factor on life from 12 to 10, such reduction is not proposed in the report because of other potential uncertainties due to the effects of temperature and strain rate on the secondary hardening behavior and DSA and their subsequent effect on fatigue life. The authors believe that further optimization of the factor on life should be performed together with a detailed evaluation of the adjustment factor of 2 on strain (or stress). Please also see the response to similar comment RR-6-31 for related information.

RR-6-31 Comment

Section 5, Pages 148 and 154
It is a concern that significant effort has been made in shifting the factor on cycles from 20 to 12 and now 10, but very little time and effort has been spent in understanding and explaining the factor of 2 on stress.

NRC Response

In this report, no attempts were made to evaluate an acceptable value of the adjustment factor on strain or stress because the existing data are inadequate. At present the adjustment factor of 2 on strain/stress is used to account not only for data scatter, size, surface finish, and loading sequence, but also for potential effects of a combination of temperature and strain rate on secondary hardening and DSA. Significantly more data are needed to accurately evaluate the individual effects of these parameters and their potential interaction (either detrimental or beneficial). Changes have been made to Section 5.5 to address this comment. Further, item (xvii) *Factor of Two on Strain (or Psuedo-Stress)* has been added to new Section 1.5 to discuss this issue. Similar comments are provided in AMEC-3-12 and AREVA-9-11. Please see those responses as well for additional information on this issue.

RR-6-32 Comment

Section 6, Page 158
This section assesses validation of the revised Fen expressions against a number of existing component feature tests and claims that they all tie-in with the model in terms of experimental versus predicted cycles to within a factor of x2 that would be expected for material variability/data scatter. However, all of the feature tests are considered to be mainly membrane loading tests. The one key test that is repeatedly discussed by those involved with this environmental fatigue issue, and appears in various PVP papers, is the Bettis Stepped Pipe test. This test did include a strain gradient from severe thermal shocks yet the NUREG/CR-6909 Rev 1 discounts this test due to the claim (Page 158) that the reported estimates of elastic and plastic total strains are not reliable. This is something that is vitally important to resolve. There are reliable elastic and elastic-plastic strain estimates available from several independent sources that could be used to compare numerical predictions with the stepped pipe results. The basis for excluding the stepped pipe tests from the validation study should be further explained, or the results included.

NRC Response

It is agreed that the Bettis stepped pipe test provides a good example for validating estimations of environmental effects on fatigue life. The criteria for selecting the examples for validating the proposed methodology was the availability of required information to accurately estimate the fatigue life. Because the stepped pipe test did include a strain gradient, and its effect on the fatigue life was not well known, an accurate estimation of fatigue life was not considered possible as part of this report. However, the potential effects of strain gradients are currently being evaluated in the ASME Code Subgroup on Fatigue Strength.

The results of the stepped pipe test could be used for validating the methodology proposed in this report once the effects of strain gradients are finalized. In order to address this issue more clearly in the report, the following text was added to the second paragraph from the end of Section 6.0 (i.e., just prior to Section 6.1):

> "In addition, the assessments to estimate the overall F_{en} for the thermal fatigue tests of a stepped pipe indicated that the reported estimates of the total applied strain (elastic and plastic) were not reliable. Therefore, additional finite element analyses are needed to provide meaningful thermal strain values for use in the evaluation. As a result, the dataset for the stepped pipe thermal fatigue tests was not considered further, and this report does not include those results."

See also the response to similar comment AMEC-3-2.

RR-6-33 Comment

Section 6.1, Page 159
Figure 122 is missing.

NRC Response

The report has been revised to ensure that Figure 6-1 (Figure 122 in draft report) is displayed accurately in the document.

RR-6-34 Comment

Section 6.2, Page 164
With regard to the data from Le Duff et al, it is stated that the "behaviour is considered unique to this specific strain loading cycle". In fact, the loading rates and waveform are representative of an actual load cycle within plant, unlike the idealised triangular waveforms used in the standard cylindrical test specimen testing. Further explanation is therefore required to explain why the behaviour is considered unique. The same comment applies to discussion of these tests in the summary (Section 7) on Page 176.

NRC Response

The term "unique" refers to the fact that the estimation method assumes that once the protective surface oxide film is ruptured it remains ruptured until the end of the transient. In reality, the oxide film is likely to re-form during the very low strain rates at the end of the lower half of the transient, and an additional minimum strain would be needed to again rupture the film for environmental effects to occur.

The following statement has been added for clarification in both Sections 6.2 and 7 after invoking the term “unique”:

> "For example, the calculations assumed that the surface oxide film forms during the decreasing strain portion of the cycle and does not re-form until the peak strain. The protective oxide film is likely to re-form at the end of the transient when strain rates are very low and strain accumulation is negligible. Therefore, an additional threshold strain would be needed to rupture the surface oxide film for environmental effects to occur."

RR-6-35 Comment

Section 6.2, Page 164
The summary statement "....however the predicted values were within the range of data scatter", is true, but all the values are consistently at the lower extreme, and this conclusion is misleading in suggesting that the results obtained were due to data scatter. Apart from loading waveform, all other parameters (surface finish, loading, size) are the same between the tests, and a reasonable expectation would be that the complex waveform tests should provide experimental F_{en} values closer to those calculated, not consistently under-predict them. Reasons for the apparent conservative nature of the calculated F_{en} values should be provided. Are the calculated F_{ens} "best estimate", in which case the experimental values would reasonably be expected to be scattered either side, or are they purposefully conservative? In light of the results provided by Le Duff this should be discussed in NUREG/CR-6909 Rev 1.

NRC Response

The F_{en} approach is expected to be conservatively biased, in part because it adjusts the ASME air design curves which are generally conservative and also because fatigue loading in many applications is not uniformly tensile as in the laboratory tests (i.e., there are gradient effects). Item (xxi) *Gradient Effects* has been added to new Section 1.5 to address this latter point. However, other factors may lead to decreases in fatigue life in applications compared to laboratory testing (e.g., component size). All of these factors need to be considered in assessing the conservatism of the method in any service application.

To address this comment within the report, the following statement has been added to item (xx) *Applicability of Method and Future Work* in new Section 1.5 of the report:

> "The fatigue design curves developed in this report for carbon and low-alloy steels and austenitic SSs are applicable to various grades and compositions of materials having a wide range of tensile strength. Furthermore, the criterion used in establishing the fatigue design curve ensures that the proposed curve bounds 95% of the available fatigue data with 95% confidence. In addition, the mean stress correction for the design curves is based on a conservative value of mean stress at room temperature. Finally, the fatigue loading in laboratory specimens is uniformly tensile which is more severe than in many applications where the loading decreases through the thickness. Therefore, the fatigue design curves should be conservative for most materials and applications, particularly at reactor operating temperatures where mean stresses are likely to be lower.
>
> The criteria used for establishing the adjustment factors to account for the parameters that influence fatigue life that were not considered in the experimental data used to develop the fatigue design curves (Section 5) are also expected to yield conservative estimates of fatigue life in most applications. These adjustment factors may be further optimized. Note that other factors (e.g., component size) may lead to decreases in fatigue life in field applications compared to laboratory testing. Therefore, any

modifications of the design curves or adjustment factors should be performed holistically to develop a technical basis that addresses all the sources of conservatism and uncertainty mentioned above."

Similar statements have been added to the Executive Summary and Summary sections of the report.

RR-6-36 Comment

Appendix A
The recommendation that Fen expressions should be used only for predicting fatigue lives up to 106 cycles is not mentioned in this section. It should be included to avoid inappropriate application of these expressions.

NRC Response

This comment is similar to earlier comment RR-6-26. Please see the response to this comment.

RR-6-37 Comment

Appendix B, Table B2
Please check that the values of YS and UTS are correct for Mat. ID 13 and 14.

NRC Response

The values presented in Table B-2 are correct. Mat. ID 13 was hot rolled and annealed by the supplier and Mat. ID 14 was cold drawn. As indicated in the last column of Table B-2, the properties for these materials were obtained from the following reference:

Smith, R. W., M. H. Hirschberg, and S. S. Manson, "Fatigue Behavior of Materials Under Strain Cycling in Low and Intermediate Life Range," NASA TN D-1574, Lewis Research Center, April 1963.

RR-6-38 Comment

Appendix B, Table B3
Please check that the values of YS and UTS are correct for Mat. ID 8.

NRC Response

The yield strength (YS) and ultimate tensile strength (UTS) values in Table B-3 for Mat. ID 8 are correct. This material is a high-strength Alloy 600 forged bar, hot-cold worked, Heat #NX0173. As indicated in the last column of Table B-3, the properties for this material were obtained from the following reference:

Mowbray, D. F., G. J. Sokol, and R. E. Savidge, "Fatigue Characteristics of Ni–Cr–Fe Alloys with Emphasis on Pressure–Vessel Cladding," KAPL–3108, Knolls Atomic Power Laboratory, Schenectady, NY, July 1965.

Specifically, the information is located on page A.26 of this report.

RR-6-39 Comment

Appendix C, Figure C-1
Please show the x, y and z axes on Figure C.A in order to correlate with the stresses shown in Figures C.3 to C.5.

NRC Response

As requested by this comment, the x, y, and z axis labels have been added to Figure C-1.

RR-6-40 Comment

Appendix C, Section C3
The value of Young's Modulus used in the sample problem should be provided.

NRC Response

It is agreed that the requested information should be provided. A new Table C-1 was added to the report that provides the material properties as a function of temperature used in the calculation.

RR-6-41 Comment

Appendix C, Page C-10, B iv
There is incorrect wording or missing text.

NRC Response

It is agreed the wording in B(iv) in the draft is incorrect. The wording in B(iv) was corrected by eliminating the term "for" from the draft document.

RR-6-42 Comment

Appendix C Table C5
Consideration should be given to presenting this data graphically.

NRC Response

The S'31 stresses in Table C-5, which were used for the CUF calculation, are already plotted in Figure C-6. These are the most important stresses in the analysis. Therefore, no changes were made to the report in response to this comment.

EDF-7-1 Comment

p.5 - Paragraph under equation (12): it seems from former References(1)(2) that oy is the cyclic yield stress.

NRC Response

This comment is nearly identical to comments AMEC-3-4, RR-6-7 and AREVA-9-10. It is also similar to comments RR-6-15 and EDF-7-4. Please see the responses to AMEC-3-4 and RR-6-7

for the disposition of this comment. Related information is also contained in the responses to RR-6-15 and EDF-7-4

EDF-7-2 Comment

p. 48 - Figure 32:

a) What do the Data points "Several Heat" correspond to in relation to the data exposed in Table 1?

b) How are the categories of data points arranged together? Based on similar temperature loads, similar specimen type? This affects greatly the statistical analysis performed to obtain the coefficient A and should be clarified.

c) The hypothesis for performing the analysis with the t-distributions is the unbiasedness and the normality of the residuals: was these checked when running the analysis?

NRC Response

This comment contains three sub-comments which are addressed as follows using the corresponding label.

a. As indicated in Section 3.1.1, the database used in these analyses consisted of 19 heats of carbon steels and 22 heats of low-alloy steels. In the plots shown in Figure 3-6 (Figure 32 in draft report), data for 6 heats of carbon steel and 10 heats of low-alloy steels are identified separately, nearly all of the other datasets are presented as "other heats" in these plots. No change resulted in the report from this comment.

b. The fatigue design curves for carbon and low-alloy steels and austenitic stainless steels were developed using completely reversed, strain-controlled fatigue tests on smooth cylindrical test specimens in an air environment, only a few tests were conducted on hourglass specimens. The various data sets were categorized in accordance with the material compositions (i.e., heats) and test temperature. The data sets were not categorized on the basis of strain rate, although the strain rate varied over a wide range of 0.05 to 10 %/s.

c. Such information is documented in Ref. 130 (NUREG/CR-6335, 1995, by J. Keisler, et al.), where rigorous statistical analysis was used to obtain best-fit curves for fatigue strain vs. life data. This reference provides the information of how the t-test was performed. This reference is already cited in the NUREG and the commenter can refer to this document for additional information on this analysis. Therefore, no changes to the report have been made to reflect this comment.

EDF-7-3 Comment

p. 49 - First paragraph: from a statistical point of view, it should not be authorized to withdraw a set of data points from the analysis, except if it is based on experimental or physical arguments. What is the reason for withdrawing the set of data pertaining to A216-Gr from the analysis?

NRC Response

This comment is similar to comment RR-6-13. This comment has been addressed in the response to comment RR-6-13.

EDF-7-4 Comment

p. p. 59 - "...than the monotonic yield strength of austenitic SSs most commonly used (approximately 303 MPa).": it seems from former References(1)(2) that the value given is the cyclic yield strength of austenitic steels. It is unclear in those References(1)(2) how the value of 303 MPa was obtained, and a more typical value of cyclic yield strength for austenitic stainless steels range from 180 MPa to 250 MPa: could NURER/CR-6909 clarify this value?

(1) *Manjoine, M., Tome, R.E., 1983, "Proposed Design Criteria for High Cycle Fatigue of Austenitic Stainless Steel," International Conference on Advances in Life Prediction Methods, D.A. Woodford and J.R. Whithehead, eds, ASME, pp.51 - 57*
(2) *Jaske, C.E., Mindlin, H., and Perrin, J.S., "Cyclic Stress-Strain Behavior of Two Alloys at High Temperature," Cyclic Stress-Strain Behavior Analysis, Experimentation, and Failure Prediction, ASTM STP 519, American Society for Testing and materials, 1973, pp. 13 -27*

NRC Response

The term "room-temperature" has been added after, " … which is greater than the upper range of the…" in the 5th sentence of the 5th paragraph of Section 3.2.1. The revised sentence reads:

> "Furthermore, for the mean air curve in ASME Code Section III before publication of the 2009 Addenda, the 10^6-cycle fatigue limit (i.e., the stress amplitude at a fatigue life of 10^6 cycles) was 389 MPa, which is greater than the upper range of the room-temperature monotonic yield strength of austenitic SSs used for the mean stress correction in this report (approximately 303 MPa in Table B-2 in Appendix B)."

EDF-7-5 Comment

p.98 - Equation 41: the paragraph 4.1.5 concludes on no environmental effect of dissolved oxygen for DO<0.04 ppm which is in contradiction with the equation 41 which gives a value of Fen of up to about 6 for DO<0.04 ppm. This seems inconsistent with the Rev. 0 as well as with the paragraph 4.1.5 of Rev. 1. It is also in direct contradiction with the Section 7 - Summary, p. 174, where it is stated "In the present report, the Fen expressions for carbon and low-alloy steels were revised so that the value of Fen was 1 (i.e. no environmental effects) when any one of the threshold conditions was not satisfied".

NRC Response

In response to this comment, the 1st sentence of the 2nd paragraph in Section 4.1.5 has been revised to read:

> "Environmental effects on the fatigue lives of carbon and low-alloy steels were insignificant at DO levels of 0.04 ppm and strain rates greater than or equal to 1%/s; they increased with decreasing strain rate (F_{en} was about 2 at 320°C, 0.010% S, 0.04 ppm DO, and 0.04%/s strain rate)."

EDF-7-6 Comment

p. 152 - Section 5.5: in the first paragraph, it is stated that the effects of various parameters are not cumulative because the various parameters affect life through the propagation of small cracks. It is then concluded that the parameter with the largest effect is therefore the controlling one. This should be clarified as it seems unclear why cumulating various aggravating parameters would not enhance crack initiation, even though the cracks are of a short size.

NRC Response

The comment and the quoted reference from Section 5.5 is referring to the adjustment factor for strain. Starting at the 3rd sentence, Section 5.5 has been clarified and now reads:

> "… the adjustment factor of 2 on strain is used to account not only for data scatter, size, surface finish, and loading sequence but also for the potential effects of a combination of temperature and strain rate on secondary hardening and dynamic strain aging. These effects are not cumulative within the high-cycle fatigue region and only the most dominant of these effects controls the net adjustment factor. However, these parameters principally affect the growth of MSCs and their significance depends on the operating conditions, environment, material, and fabrication process. Therefore, the effect that dominates is a function of material and environmental conditions. The factor of 2 on strain is sufficient to account for the dominant effect within the high-cycle fatigue region. In addition, when comparing the fatigue lives of laboratory test specimens to those of actual reactor components, the factor of 2 on strain used to develop the ASME Code Section III air design curves was adequate to account for the uncertainties associated with material variability, component size, surface finish, and load history."

Also item (xvii) *Factor of Two on Strain (or Pseudo-Stress)* in new Section 1.5 has been added which discusses the basis for the factor of two on strain.

EDF-7-7 Comment

p. 176 - First paragraph: it is stated that the behavior with complex type loadings is unique to the specific strain loading cycles used in the [AREVA] tests. This loading signal is nevertheless very close to what is experienced on real life components and this should be emphasized in the report rather than calling the results unique.

NRC Response

This comment is nearly identical to RR-6-34. Please see the response to this comment for how this issue has been dispositioned.

EDF-7-8 Comment
General comments:
a) The NUREG/CR-6909 document recognizes many detrimental effects in air such as surface finish, size effects, etc... Many of these effects have not been studied in PWR environment and many testing carried out around the world seems to indicate that some effects might be intricately linked to one another (e.g. surface finish and PWR environment as demonstrated by Le Duff et al. (1) and other organizations).
b) NUREG/CR-6909 does not recognize any effect of thermal gradients that may be beneficial on general fatigue life, as indicated in presentations made by Rolls-Royce during the 2013 EPRI Fatigue Workshop held in San Francisco from July 30th - August 1st.

(1) Le Duff J. A., Lefranqois A., Vernot J. P. And Bossu D., 2010, "Effect of Loading Signal Shape and of Surface Finish on the Low Cycle Fatigue Behavior of 304L Stainless Steel in PWR Environment," PVP2010-26027, ASME 2010 Pressure Vessels and Piping Conference, Bellevue, USA.

NRC Response

In response to part a. of this comment, the investigation by Le Duff et al. has been reviewed and referenced in the report (Refs. 155-157). In addition, fatigue tests have been conducted at ANL on rough and smooth specimens of austenitic stainless steels in PWR environments. The proposed methodology is consistent with the results from both studies. Note that the combined adjustment factor is not based on the product of the maximum values of the individual subfactors. The adjustment factor of 12 on life is less than half of the product of individual subfactors. Additional limitations are also listed item (xvi) *Development of Adjustment Factors* in new Section 1.5. This comment is also similar to earlier comments FAIDY-2-1e, FAIDY-2-3a, and RR-6-3. See the responses to these comments for additional information.

In response to part b. of this comment, the effect of thermal gradients is being addressed by the ASME Code committees associated with Code fatigue design procedures. These effects can be incorporated into the fatigue design procedure independently by using another adjustment factor similar to the F_{en} factor used for incorporating environmental effects. There are also other similar comments on the effects of strain gradients, including RR-6-4, RR-6-32, AMEC-3-2, AMEC-3-5, and AREVA-9-17h. Please see the responses to these comments for additional information and the changes made to the report to address this issue.

HITACHI-8-1 Comment

Section 5.3 Surface Finish
This comment is about the sentence 'Limited data in LWR environments on specimens that were intentionally roughened indicated that the effects of surface roughness on fatigue lives were the same in air and water environments for austenitic SSs, but were insignificant in water for carbon and low-alloy steels, particularly in NWC BWR environments.'

It is better that the references on this topic are shown.

NRC Response

Section 5 simply presents a summary of the results that have been previously discussed. A detailed discussion on surface finish effects is presented in Section 3.1.9 and 4.1.12 for carbon and low-alloy steels in air and water environments, respectively, and in Section 3.2.10 and 4.2.14 for austenitic stainless steels in air and water environments. All related references are identified in these specific sections.

HITACHI-8-2 Comment

Section 5.4 Load Sequence
This comment is about the sentence 'Therefore, because the fatigue c-N data used to develop the ASME Code Section III fatigue design curves were obtained from fatigue tests at constant strain amplitudes, the effects of loading sequence on the fatigue lives and the fatigue limits of materials were included in the ASME air design curves.'.

Current fatigue design curves do not seem to include design margin for load sequence effect. Is the description of the sentence correct?

NRC Response

It has been well documented since the late 1960s that a few cycles of high strain amplitude prior to cycling at constant low strain amplitudes, decreases the fatigue life significantly. More recently, the studies by J. Solin on austenitic stainless steels tested with random blocks of random cycle as well as at constant strain amplitude, indicate similar results. Since the concept of cumulative fatigue usage factor is based on Miner's rule, such effects need to be considered in ASME Code fatigue evaluations.

In order to clarify this point further, the end of the 2nd paragraph of Section 5.4 (2nd to last sentence) has been changed from, "*Therefore, because the fatigue ε–N data used to develop the ASME Code Section III fatigue design curves were obtained from fatigue tests at constant strain amplitudes, the effects of loading sequence on the fatigue lives and the fatigue limits of materials were included in the ASME air design curves.*" to "*Therefore, because the fatigue ε–N data used to develop the ASME Code Section III fatigue design curves were obtained from fatigue tests at constant strain amplitudes, the effects of loading sequence on the fatigue lives and the fatigue limits of materials were incorporated into the adjustment factor of 12 on the number of cycles when developing the ASME Code fatigue design curves from the best-fit curves of the data.*"

HITACHI-8-3 Comment

Section 5.5 (d) Air Fatigue Design Curve Adjustment Factors Summarized
This comment is about the sentence 'Factors ranging from 1.0 to 2.0 were used to incorporate the possible effects of load histories on fatigue lives in the low-cycle regime.'.

The technical basis for the range from 1.0 to 2.0 is required to be shown.

NRC Response

As also noted in the response to comment HITACHI-8-1, Section 5.5 merely summarizes the results from previous sections. The technical basis supporting the range of 1.0 to 2.0 to account for loading history effects on fatigue lives is provided in Section 5.4.

HITACHI-8-4 Comment

Appendix C, Section C3
This comment is about the equation which calculates the strain rate in the descriptions about the Average Strain Rate Approach.

The description indicates that the Young's Modulus is determined at the maximum metal temperature. In this case, a higher value of the strain rate is calculated comparing with the case employing the Young's Modulus at the average metal temperature. To estimate the conservative Fen, the Young's Modulus determined at the maximum metal temperature is not considered to be relevant. It is better to employ the Young's Modulus at the average metal temperature for example.

NRC Response

It is agreed that more clarification is needed on how to determine the Young's Modulus, E, especially for the average strain rate approach. Therefore, to address this comment, in new

Section 4.4 of the NUREG, clarification was added under new bullet (4) regarding the use of temperature for determining the value of E. Similarly, the definition of E in Section C.3 was expanded to state that the maximum temperature was used for the sample problem in Appendix C. Finally, Section A.3 was modified to refer to this expanded definition of E. This comment is also similar to part of the WEST-4-6e comment. Please refer to this response for additional information.

AREVA-9-1 Comment

Comments on the definition of the design crack initiation

a. *It is stated in several places and for example on pages 2 and 20 that the "fatigue life is described in this report as the number of cycles of a specified strain amplitude that a specimen can sustain before the formation of a 3-mm-deep crack (i.e., an "engineering crack") and that this "equates to a 25% load drop in test specimens, and is assumed to equate to crack initiation in an actual component". Please provide the depth of the crack corresponding to the crack initiation in an actual component. Is it 3mm too?*
b. *The 25% load drop criterion may be questionable for the specimen sizes used in the studies that used the "5.1 - 9.5mm (0.2 - 0.375 in.) diameter cylindrical specimens" on page 39. Indeed this criterion is closely linked to the macroscopic crack growth in the specimen. It is very likely that using 5.1mrm diameter cylindrical specimens cannot correspond to a 3-mm deep crack with the 25% load drop criterion but to a significantly lower deep one. The same comment may be reported for using 4mm diameter cylindrical specimens (page 158). This generates prejudicial data scatter, and the objective to share a common fatigue damage target is not reached. Please provide an explanation for this assessment.*
c. *In the same way, the failure criterion for 1 or 3 mm wall thickness tubular specimens (pages 39, 128, and 170) and 3.38 mm wall thickness tube U-bend specimens (page 166) may be questionable. Macroscopic crack growth kinetics in these specimens is significantly different from those in 9 mm diameter cylindrical specimens, mainly because of plasticity effects in the remaining un-cracked section. Again this necessarily generates prejudicial data scatter and the objective to share a common fatigue damage target is not reached. Please provide an explanation for this assessment.*
d. *Equation 18, on page 39, provides the relation between cycles N25 and cycles Nx, where X is the failure criterion (e.g., 10, 50 or 100% decrease in peak tensile stress). Since this formula is supposed to model the growth of a macroscopic crack, it is very surprising that such a unique relationship can be found with no dependence on materials, strain amplitudes, and specimen sizes. Please provide a justification for the use of this formula.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. Sub-comment a., and other similar components, asked that the definition of fatigue life used in the report for test specimens be clarified and then discuss how this definition applies to structural components. In response to sub-comment a. and other similar comments, item (ii) *Definition of Fatigue Life* has been incorporated in new Section 1.5 to explain the definition of fatigue live used in the report.

Sub-comment b. questions the uniformity of the 25% load drop criterion for other specimen sizes. In the report, fatigue life in not defined in terms of a 25% load drop, but as the number of cycles to create a 3-mm crack. The 25% load drop was a convenient way to monitor the crack depth during a fatigue test on solid 9.5-mm diameter cylindrical fatigue specimen. Most of the

tests in air have been conducted on 9.5-mm cylindrical specimens. None of the LWR environment data used in the analysis was taken from 5.08 mm cylindrical test specimens. In order to clarify this point, the last two paragraphs of Section 1.1 have been rewritten. See also the response to AREVA-9-1a in the preceding paragraph for additional related information.

In response to sub-comment c., it is generally agreed, as stipulated in the comment, that differences between thin-walled tubular and solid diameter specimens can lead to different fatigue test results. As stated in Section 4.2.12, the experimental fatigue lives for the 1 to 3 mm thick tube specimens were up to a factor of approximately 4 lower than the predicted values. Of course, the predicted values are based largely on the solid diameter test results. Sub-comment c. identifies some of the reasons for these differences. While it's true that exclusion of the thin-wall tests would decrease the scatter in the fatigue database, their exclusion wouldn't not significantly alter any of the findings in the report. Therefore, they have been included in the fatigue database both for completeness and as a recognition of the historical significance of these tests.

Sub-comment d. requests that additional justification be provided for the use of Equation 18. Equation 18 correlates the crack depth and percentage load drop and was developed by monitoring the crack depth vs. load drop during constant-strain fatigue testing. This equation is used in the report to convert the measured fatigue lives from testing that used a percentage load drop other than 25% to the lives associated with a 25% load drop. This conversion is necessary so that the measured fatigue lives all correspond to a 25% load drop which, as discussed in item (ii) of new Section 1.5, is approximately equivalent to a 3 mm crack for the cylindrical specimen geometry and size used in the fatigue database. The technical basis for this equation is provided in cited reference 10. However, the percentage load drop really reflects the percentage of cracked area in the specimen which is why it is largely insensitive to material, strain amplitude, and even specimen size for the relatively narrow range of specimen sizes used to develop this test data.

AREVA-9-2 Comment

Comments on test data base

a. *The use of bending fatigue tests (page 15) increases the scatter and does not allow for a uniform fatigue damage target to be achieved. Macroscopic crack growth kinetics in these specimens may be significantly different from the one in 9 mm diameter cylindrical specimens. Please state in the report the type of the bending fatigue test (3 or 4-point bending, rotating bending), the load ratio, and the definition of the fatigue criterion. Figures such as Figure 38 on page 58 could specify the points obtained through bending tests. Using this kind of tests necessarily generates prejudicial data scatter.*
b. *Few test results in the high cycle regime are under load control. This data should only be used, plotted, and compared to strain-controlled data that has been properly adjusted under consideration for cyclic deformation behavior, which has not been conducted.*
c. *Using load control tests (page 15) raises the same question about the objective to share a common fatigue damage target. The interpretation of these tests is made significantly difficult by hardening issues. Figure 38 on page 58 should specify the points obtained through load control tests. Again this essentially generates prejudicial data scatter. Please provide a justification.*
d. *Chapter 4.2.1: Should cantilever beam specimens tested in deflection control really be included in the database (Ref. 14 and 15, Hale et al.)?*
e. *A lot of papers compile the database, which do not contain listed fatigue data values, (e.g., Ref. 59) and instead only pictures of the results (fatigue e-N data plots). Was the fatigue*

data obtained from the institutes, or were the fatigue lives read out of the diagrams?

f. *On page 110, it is mentioned: "The least-squares fit of the experimental data in LWR environments yielded a steeper slope for the E-N curve than the slope of the curve obtained in air (Ref. 45 and 121)." Is the literature reference 121 correct?*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. Sub-comment a. addresses the inclusion of bending fatigue tests. The fatigue database used by JNES to develop fatigue strain vs. life data includes a relatively small number of strain-controlled bending tests. As shown in Figure 3-14 (Figure 40 in the draft report), the data from the bending tests are evenly distributed along the ANL best-fit mean data curve for austenitic stainless steels. Therefore, these results do not appear to unnecessarily bias the statistical analysis. The test details for the bend tests are given in reference 210 which is cited in the report.

It is agreed, as stipulated in sub-comment b., that there are few load control tests in the high-cycle regime. This exact notion is discussed in detail at the end of Section 4.2.1. See the discussion related to Figure 4-29 and Figure 4-30 (Figures 83 and 84 in the draft report), and the summary statement at the end of the section. The report further argues that improper interpretation of the test data can lead to incorrect conclusions regarding environmental effects in PWR environments. The typical ANL test procedure is to start the test in strain control and only convert to load control once the cyclic deformation behavior has stabilized.

Sub-comment c. further questions the inclusion of constant load data in the analysis. This report presents a methodology for estimating environmental effects on fatigue life of carbon and low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys used as structural materials in nuclear power plants. The experimental data used to develop this methodology is based mostly on strain-controlled tests. A few tests performed at ANL at low strain amplitudes (i.e., high-cycle regime), were conducted partially under load control. As previously indicated, these tests were started and run under strain control until the material (e.g., austenitic stainless steel) reached a steady state strain hardening condition (i.e., the cyclic stress reached a steady-state value). The test is then switched to load control for the remaining duration of the test. Because the applied strain also reaches a steady-state value, results from these load-control tests can be compared with the data obtained on strain-controlled tests without biasing the results.

Sub-comment d. questions the inclusion of cantilever beam test data from references 14 and 15 in the report. The values of the constant A in the cumulative distribution curve in Figure 4-56 are 7.25 (Ref. 14 data) and 7.63 (Ref. 15 data) compared to the average of 6.81. These data points are within the data scatter of the population and as such, do not significantly alter the results. However, the results in references 14 and 15 were the first study that evaluated environmental effects on the fatigue life of reactor structural materials. Given their historical significance, the results were included in the present analysis.

Sub-comment e. asks about the nature (i.e., tabular or digitized) of the fatigue data. Most of the data were obtained from the authors of the cited references, including the large database from Japan. At least 80% of the data is from tabulated values. The data from a few studies were digitized from strain vs. life plots. The authors have also performed quality assurance auditing on many of the digitized data points to verify that the digitization is within 10% of the actual strain and life values. Errors less than 10% are insignificant with respect to fatigue life.

Finally, in response to sub-comment f., reference 121 is the correct reference. This reference contains fatigue strain vs. life data on austenitic stainless steels in air and LWR environments.

AREVA-9-3 Comment

Comment on austenitic SS best fit mean air curve

a. *Figures 38 and 44 (pages 58 and 64 respectively) show that the fit of the austenitic Stainless Steel (SS) data points is not optimal. Data points are not homogeneously distributed in the scatter band according to the number of cycles. It seems that the prediction in Low Cycle Fatigue (LCF) is a little bit un-conservative and that the one in the High Cycle Fatigue (HCF) is too conservative. This choice impacts significantly the fatigue limit of the final design curve.*
b. *Chapter 3.2.1 lists the experimental data (770 tests in total). The data base concentrates on some types of SS (primarily 304 and 316). The applicability to other grades of SS remains open. This also substantiates the derivation of separate design fatigue curves for grade 347 SS in the German KTA 3201.2 Safety Standard according to the reference [1]:*
   [1] Schuler, X.; Herter, K.-H.; Rudolph, J.: Derivation of design fatigue curves for austenitic stainless steel grades 1.4541 and 1.4550 within the German Nuclear Safety Standard KTA 3201.2. Proceedings of PVP2013, Paper No. PVP2013-97138, 2013 ASME Pressure Vessels & Piping Division Conference, July 14-18, 2013, Paris, France
c. *The in-air stainless steel mean fatigue curve is a fatigue curve based on the worst between different types of stainless steel. This penalizes a lot the stainless steels that have a more favorable fatigue resistance. In addition to existing technical papers on that sub-topic, this discrepancy (design stainless steel fatigue curve being much too low) can be seen very clearly in the Tables A.1 and A.2 of Page A-5: stainless steel at 1E+04, 1E+05, 1E+06 and 1E+07 cycles: 368, 196, 126 and 99 MPa versus for Carbon Steel at 1E+04, 2E+05, 1E+06 and 1E+07 cycles: 373, 201, 142 and 115 MPa, respectively. This would mean that - for the same stress or strain range - stainless steel sees fatigue damage before carbon steel, which is the opposite of what should be expected. Therefore, the in-air stainless steel Design Fatigue Curve needs to be moved upward (less severe) in the future.*
d. *The data scatter obtained in this report for 55 may also be questionable because of the choices such as no potential temperature effects and inappropriate interpretation of the load control tests. Again, this choice could result in a too conservative fatigue limit in the final design curve.*
e. *Concerning the influence of temperature on the in-air fatigue data it is stated that "Temperature had no significant effect on the fatigue lives of austenitic SSs in air at temperatures from room temperature up to 450°C." The comprehensive database used to derive new design fatigue curves for the German KTA 3201.2 Safety Standard (see [1]) clearly required a temperature differentiation for grade 347 SS in the high cycle regime. The presented data in Rev. 1 of NUREG/CR-6909 is relatively sparse specifically in the high cycle regime, where the expected temperature differentiation is most significant (see Figure 41).*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. Sub-comment a. is similar to previous comment RR-6-14. Please see the response to this comment to see how this comment has been addressed. Sub-comment b. questions the applicability of other stainless steels (SSs), such as 347, to the method. The fatigue database used in this study consists entirely of high- and low-C Types 304 and 316 SSs. As stated in the report, for these materials, the existing data indicate no effect of temperature at temperatures below

400°C. Experimental data on other grades of SSs such as the Ti or Nb modified SSs are not included in the report. These modified SSs do exhibit effects of temperature on fatigue life at temperatures ≥300°C. These results have recently been confirmed by studies in support of the German Nuclear Safety Standard KTA 3201.2. Therefore, the use of the ASME Code fatigue design curve for estimating fatigue lives in air for these Ti and Nb modified SS would require an adjustment to account the effects of temperature and strain rate on fatigue life. Please see the response to RR-6-9, which is also related to this topic, for additional information.

It is agreed, as stipulated in sub-comment c., that since the ASME Code Section III fatigue design curve for austenitic stainless steels is applicable to a wide range of grades, heat treatments, and compositions of material, it is conservative for high-strength stainless steels. Separate fatigue design curves, based on material strength need to be developed to avoid such conservatism. However, the existing fatigue data for austenitic stainless steels indicate that the difference among the different grades and compositions most significant affects the value of the fatigue limit (at low strain amplitudes) and the slope of the strain vs. life curve (at high strain amplitudes). See also the response to similar comment RR-6-14 for additional information on how the report has been modified to address this issue.

Sub-comment d. raises two concerns, one regarding the effect of temperature on fatigue life and the other about the interpretation of load-control tests. The effect of temperature of the fatigue life of stainless steels is addressed above in the response to AREVA-9-3b. Regarding the interpretation of load-control tests, the comment does not identify what is considered inappropriate treatment of the data. However, the database used in this study essentially consists of data from strain-controlled tests. Less than 20 test results were from load-control tests. For these tests, the applied load is converted to strain either using the cyclic stress strain curve or the strain at the half-life reported by the authors. Furthermore, the fatigue data used to develop the ASME fatigue design curve is based only on completely reversed strain-controlled tests at constant-strain amplitudes. For solution annealed Types 304 and 316 SS, the cyclic stress during these tests reaches a steady state value within few hundred cycles.

However, for load control tests, since the strain is continuously changing, a true steady-state behavior is not achieved. The strain at half-life is used in used to compare such results with the fatigue strain vs. life behavior from the strain-controlled tests. This procedure is described while discussing Figure 4-29 and Figure 4-30 in the report. These issues are also discussed more fully in item (vi) *Testing Procedures for High-Cycle Fatigue* in new Section 1.5.

Finally, the issue raised in sub-comment e. about the applicability of 347 grades to the method in the report and the need for material-specific fatigue curves has been previously addressed above for sub-comment b. and also in the response to RR-6-9. As previously discussed, the development of fatigue curves specifically for the German Ti or Nb modified SSs which do require a temperature correction is encouraged.

AREVA-9-4 Comment

Comment on the heat-to-heat variability

a. *Please provide how the analyses on heat-to-heat variability (pages 48 and 65) have been treated. More precisely, how are the categories of data points arranged together e.g., same temperature conditions, same specimen geometries, same laboratories?*
b. *What do the data points named "Several Heats" in Figures 32 and 45 of pages 48 and 65, respectively correspond to?*

NRC Response

Sub-comment a. asks how data was categorized for the analyses on heat-to-heat variability. For a specific heat of material, the various datasets were based on similar temperature, strain rate, and in a few cases comparable heat treatment. Therefore, the plots of cumulative distribution of the constant A, would also account for the variability of fatigue life due to processes that are influenced by temperature and/or strain rate (e.g., secondary hardening, DSA, etc.). This comment is similar to EDF-7-2b. Please see the response to this comment for additional information.

In response to sub-comment b., as stated in Section 3.1.1, the database used in these analyses consisted of 19 heats of carbon steels and 22 heats of low-alloy steels. In the plots shown in Figure 3-6 (Figure 32 in draft report, data for 6 heats of carbon steel and 10 heats of low-alloy steels are identified separately, and in Figure 3-19 (Figure 45 in draft report) only 11 out of 38 heats are identified. Most of the other datasets are presented as "other heats." This comment is similar to EDF-7-2a. Please see the response to this comment for additional information.

AREVA-9-5 Comment

Comments on the size effect

a. *It is stated on page 150 that "specimen sizes are not likely to influence crack initiation in specimens with rough surfaces" and "Consequently, for rough surfaces, the effects of specimen sizes are not appropriate for consideration in the factor of 12 applied to the fatigue design curves developed in this report". But finally it is added that "a factor ranging from 1.0 to 1.4 on fatigue lives was used to incorporate size effects on fatigue lives in the low-cycle regime." Please provide if 2 parameter ranges (one for size effect and one for surface finish effect) have been well taken into account in Monte-Carlo statistical evaluation. Considering the first statements and the fact that the actual components have an industrial surface finish and not a laboratory smooth one, why only one for surface finish effect is not enough?*
b. *In this report the size effect is only presented as a statistical probability to present "an increased number of sites for crack initiations" (page 150). But it is well known that the fatigue failure of the specimen is not necessarily driven by the first initiated crack. Microstructural fatigue crack growth mechanisms are more complex. The theory of the weakest link cannot be applied for fatigue failure prediction. So the size effect, as presented in this report without any consideration of beneficial or detrimental effects on fatigue crack growth, may be questionable for design purpose. Please comment.*
c. *Factor of 12.0 from Table 14: The size and the surface finish effects are considered in the calculation of the stress ranges, for example through the piping design stress indices. Therefore, considering those size and surface finish effects again for the calculation of the factor of 12.0 on the number of cycles means that the same effects are considered twice (and therefore much too penalizing) for the calculation of the allowable number of cycles when applying that factor of 12.0 of Table 14 to the number of cycles from the specimen mean fatigue curve.*
d. *Has a detailed examination for dependency been conducted for the sub-factors considered in the factor on cycles of 12 or 10? For example, the surface finish and size are correlated and in several cases they coincide. Have the variables been correlated in the Monte Carlo simulations?*
e. *For variables such as size a normal distribution could have been used. Instead, a lognormal distribution was selected. Please specify the degree of introduced conservatism and the reason behind it.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. In response to sub-comment a., the effects of size and surface roughness are both included in the analyses to ensure that the estimates bound 95% of the data. However, the maximum values of the individual factors for size and surface roughness are not used. The final adjustment factor is only 12, which is not the product of the maximum values for all factors. In the same paragraph of Section 5.2 that the commenter quotes, it is stated that the adjustment factor for size was varied between 1.0 and 1.4 in the Monte Carlo statistical evaluation instead of between 1.2 and 1.4 as in the earlier evaluation in Rev. 0 of NUREG/CR-6909. The lower bound of 1.0 reflects data where the size and surface roughness effects are insignificant. To provide further clarification and address this comment, the 3rd sentence of the second paragraph of Section 5.2 has been revised to read: "*However, specimen sizes are not likely to have a significant effect on crack initiation in specimens with rough surfaces because cracks would initiate at existing irregularities on the rough surface.*"

In response to sub-comment b., it is agreed that hundreds of cracks are formed along even a short gauge length of a test specimen and that the first cracks that initiate do not necessarily lead to failure. Out of the hundreds of cracks that form, only one or two cracks ultimately lead to failure and it is the initiation and growth of these cracks that define the fatigue life of a specimen or component. Potential effects of size, or the interaction between other parameters, on the beneficial and detrimental aspects on fatigue crack growth were not evaluated in this study. The existing data on fatigue crack initiation in air and LWR environments is inadequate to accurately establish the individual effects and interaction of certain variables that can influence fatigue life. Until such information is available, the use of adjustment factors is an appropriate engineering incorporate such effects in fatigue evaluations.

Sub-comment c. stipulates that size and surface finish effects are considered in the calculation of the stress range. While the ASME stress indices do consider gross geometric discontinuities, it is not apparent that they also account for smaller surface variations that are representative of surface finish effects. However, the ASME design curves do explicitly account for surface finish effects and, as discussed in this report, part of the adjustment factor of 12 from the mean to the design curve is due to surface finish effects. If the commenter is concerned that surface finish has been accounted for in both the stress indices and the design curves, this issue should be raised to the appropriate ASME code committee.

Sub-comment d. asks if dependencies were considered during the development of the adjustment factors. In the Monte Carlo simulations, for each iteration the value of the four parameters is independently and randomly varied between the minimum and maximum values and their product is used in the calculation. As shown in Table 5-2 (Table 14 in draft report), the factors for size and loading history were varied between 1 and the maximum value, and surface finish was varied between 1.5 and 3.5. As discussed above, there is not expected to be a size effect on crack initiation for rough surfaces but any dependencies on the growth of microstructurally small cracks have not been studied in this report. Therefore, there is no basis for developing a correlation between surface roughness and size effects on the formation of a single, dominant engineering crack (i.e., a 3 mm crack). Such work would require further research.

In response to sub-comment e., a normal distribution for variables such as size was not used in this analysis. Both the normal and lognormal distributions can be considered consequences of a central limit theorem, which can be expressed in several forms. In the case of the normal

distribution, averages of random variables independently drawn from independent distributions become normally distributed when the number of random variables is sufficiently large. A log-normal process is the statistical realization of the multiplicative product of many independent random variables, each of which is positive.

Thus normal distributions have values that range from -∞ to +∞, lognormal distributions range from 0 to +∞. Lognormal variation is widely observed in physical processes that result in values from 0 to +∞ such as would be expected by the variables considered in this analysis. The lognormal distribution is also a maximum entropy distribution which minimizes the amount of prior information built into the distribution. There is not sufficient data to demonstrate that a lognormal is the best distribution to describe the distribution of A, but it is a plausible distribution that fits the available data reasonably well.

AREVA-9-6 Comment

Comments on the surface finish effect

a. *Some conclusions on surface finish effect are based on inadequate literature for design purpose, regarding the in-service conditions. Ref. 217 and 218 (page 51) is inappropriate in terms of temperature conditions (high temperature of 593°C), specimen surface finish (low Ra close to 1) and fatigue damage definition (0.1-mm-deep crack). Finally, Equation 26 (page 51, Ref. 217) is obtained with only a few data points. Please provide an explanation for this method.*
b. *Figure 48 (page 68) for austenitic SS in air, and Figure 108 (page 136) for austenitic SS in PWR or BWR water exhibit very few data points to discuss about surface finish effect. A larger literature review could have been performed. For that purpose, Ref 155-157 could notably be used as well (page 135).*
c. *Please add to the abbreviations list the meaning of surface finish parameters: Ra = Average surface roughness, Rq = Root-mean-square value of surface roughness and Rt = Maximum height of the surface roughness profile.*
d. *Please provide the choices made in paragraph 5.5 (page 152) for air fatigue design curve adjustment factors. Table 14 presents a parameter range for surface finish but in the text, it is stated that a "factor of 2.0 was used for austenitic SSs in both air and water environments for surface finish effects". How have Monte Carlo simulations been performed for austenitic SS? More precisely, is a parameter range or a unique value considered for the surface finish effect?*
e. *Please clarify the link between the surface finish effect covered by the present report and the potential other specifications of the ASME Code. In other words, is the surface finish effect presently covered consistent with the ASME Code specifications in terms of Ra? Please explain this point which is not currently addressed in NUREG/CR-6909 Rev. 1.*
f. *Please clarify the following statement on Ref. 155-157 (page 135): "Note that the strain accumulated under specific strain rates decreased with decreasing strain rates". Does it mean that given total strain amplitude, the cumulated plastic strain decreases because of DSA?*
g. *On page 135, sub-section 4.2.14 is not definitive concerning the effects of the surface finish in LWR environments. The second sentence of that sub-section states that the contribution from the surface finish effect is assumed to be 1.5 or lower, although Table 14 of page 153 states that it is 2.3 (geometric average between 1.5 and 3.5). Also, sub-section 4.2.14 mentions the effect of the surface finish in air and in LWR environments, but does not discuss the fact that both of those effects (surface finish and LWR environment) should not be multiplied.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. The two references identified in sub-comment a. provide information on the effect of surface finish on fatigue life for specimens with RMS value of surface roughness in the range of 0.0075 to 2.9 mm. This range of surface finish falls within the range of the roughness of machined surfaces, which is between 0.8 to 6.0 mm (Section 5.3). These data are obtained at a higher temperature than in commercial nuclear applications but they provide an indication of the possible order of magnitude of surface finish effects. As stated in the report, other lower temperature data corroborate these results, and indicate that a factor of 2 to 3 appears to be appropriate to account for surface finish effects in air for carbon and low-alloy steels.

Sub-comment b. is similar to the previous sub-comment. All of the information related to surface finish effects available when the report was prepared has been presented. As indicated in the response to the previous sub-comment, there is limited data related to surface finish effects, but the data that does exist supports the adjustment factors discussed in the report. More data is needed to further refine these factors. It is agreed, however, that the available information on surface finish effects on fatigue life in LWR environments is limited and additional data is required to more accurately quantify these effects. In response to sub-comment c., the authors have added the abbreviations suggested by the commenter to the list of abbreviations in the report.

It is agreed, as stipulated in sub-comment d., that the following statement, "*A factor of 2.0 was used for austenitic SSs in both air and water environments for surface finish effects,*" is inaccurate and leads to confusion. The following changes have been made to the report based on this comment. The last sentence in the third bullet in Section 5.5 (formally item (c)) has been deleted and the third sentence has been revised to state,

> "Because additional data are not available to verify that the surface finish effects are lower or insignificant in LWR environments, this investigation used a range of 1.5 to 3.5 to account for the effects of surface finish on the fatigue lives of carbon and low-alloy steels and wrought and cast austenitic SSs both in air and LWR environments."

Sub-comment e. asks for clarification on the link between surface finish effects and other ASME Code specifications. The surface finish effects presented in this report are characterized with respect to R_q. These effects have not been evaluated with respect to other ASME Code Specifications for surface roughness, such as R_a, for consistency. That evaluation is beyond the current scope of the report.

It is agreed that this statement identified in sub-comment f. is confusing and has been deleted. The end of the 2nd paragraph of Section 4.2.14 now reads as follows:

> "In these tests, the F_{en} value for the portion of the transient at the slowest strain rates was high, but this was compensated by the small total accumulated strain during the same portion of the transient. Therefore, the slow strain rate portion of the transient did not significantly contribute to the overall F_{en} value for the entire transient."

The intent of this statement has always been to indicate that the effects of the lowest strain rate portions of the transient in these tests is not particularly significant.

In response to sub-comment g., the 1st sentence of the 1st paragraph in Section 4.2.14 has been deleted because it was confusing and appeared to contradict the rest of the section. Section 4.2.14 now starts with "Fatigue tests were conducted on Types 304 and 316NG SSs that were …". Additionally, some minor clarifications have been made to this section so that the factors

are consistent with those in Table 5-2 (Table 14 in draft report), and to more clearly indicate the effect of surface finish in high-DO (i.e., BWR) and low-DO (i.e., PWR) environments for the limited data presented.

AREVA-9-7 Comment

Factor on sequence effect

a. *In Table 14 of page 153, the sequence effect of 1.41 (geometric average of 1.0 and 2.0) should not be considered due to the choice of the most severe combination of the Peaks and Valleys within the ASME-Code Fatigue Methodology and due to the fact that - in a nuclear power plant - the cycles are well distributed within the 40-year or 60-year plant life. Therefore, the factor of 12.0 should be approximately 8.5 (12.0 / 1.41, where 1.41 is the sequence effect factor; see above). Also, the simple multiplication of the factor of 12.0 on the number of cycles by the Fen factor is not at all reasonable and much too severe. This combination should be a square-root of the sum of the squares combination, and not a simple multiplication. This is one of the most important points. As an additional reference, PVP Paper PVP2010-26027 (by Jean Alain Le Duff and others) has clearly shown that - for example - the surface finish effects and the Fen factor should not simply be multiplied by each other. A less severe combination of those effects needs to be established for the future Fatigue Design Rules of the Class 1 Components.*
b. *On page 154, from the explanation in the paragraph above Table 15 and from Table 15 itself, the current factor of 12.0 on the number of cycles needs to be reduced to 9.6 for stainless steel, and then to 9.6 / 1.41 = 6.8 to consider the fact that the load sequence effect is not required when applying the ASME-Code Fatigue methodology for nuclear power plant Class 1 components.*

NRC Response

There are two separate points contained within sub-comments a. and b. that will be addressed together. The first part argues that a factor for load sequence effects should not be applied to the life "due to the choice of the most severe combination of the Peaks and Valleys within the ASME-Code Fatigue Methodology and due to the fact that - in a nuclear power plant - the cycles are well distributed within the 40-year or 60-year plant life." There is not agreement with this contention because the load sequence factor does not result from ASME Code requirements to consider the most severe load combinations. The effect of load sequence has been well documented since the mid-1960s; a few fatigue cycles at high strain amplitude decreases the life of subsequent fatigue at low strain amplitudes more than that predicted by Miner's Rule. Since the concept of the cumulative fatigue usage factor is based on Miner's Rule, such effects need to be considered in ASME Code fatigue evaluations. However, this adjustment is not needed in purely random load tests.

The second part of this comment refers to the inappropriateness of simply multiplying the most detrimental effects for each of various factors on fatigue life to develop the overall adjustment factor. It is agreed that such an approach is inappropriate and, as discussed in Section 5.5, a simple multiplication of these factors is not performed to get the adjustment factor. Rather, a Monte Carlo analysis is done to consider the full range of possible combinations of these factors. This point has been clarified in revisions to Section 5.5 as discussed in the responses to RR-6-3 and AMEC-3-8. Also, as discussed in responses to similar comment FAIDY-2-1e and FAIDY-2-3a, item (xvi) *Development of Adjustment Factors* has been incorporated in new Section 1.5 to address this issue.

AREVA-9-8 Comment

Comments on the temperature effect

a. *Figure 38 (page 58) shows a potential temperature effect. Could inappropriate data points such as results from bending tests, load control tests, or very high temperature conditions be the cause of this situation? Moreover, it is finally stated (page 61) that "Temperature had no significant effect on the fatigue lives of austenitic SSs in air at temperatures from room temperature up to 450°C". Please explain this assumption, which in fact contributes to potentially a large number of data scatter.*
b. *Please clarify the conclusions on secondary hardening. It is stated (page 61) that "For a heat of Type 304L SS, the fatigue limit was higher at 300°C than at 150C because of significant secondary hardening at 300*C" and that "Variations in fatigue lives due to the effects of secondary hardening behavior were accounted for in the factor applied on stress that was applied to obtain the design air curve from the mean data air curve." How practical has this beneficial effect been taken into account in the decision to consider a factor of 2 on stress for austenitic SS fatigue design curve?*

NRC Response

In response to sub-comment a., there are two aspects of the data in Figure 3-12 (Figure 38 in draft report) that could be interpreted to be potential effects of temperature. As mentioned in the report, nearly all of the data are evenly distributed along the ANL best-fit curve, except for the 316 SS data at 400°C and the low-C Type 304L SS. However, the difference in the data for Type 304L SS is because the slope of the strain vs. life curve is steeper than that for the other SSs; fatigue lives at high strain amplitudes are slightly longer and at low strain amplitudes are shorter. This trend is consistent for all the data up to 400°C. However, it is agreed, as stipulated in this sub-comment, that temperature effects may be significant above 400°C and have changed the bullet at the end of Section 3.2.4 to reflect this. This change is due to limited data between 400 and 460°C and the possible role of secondary hardening on fatigue life above 400°C. This bullet now reads as follows:

> "Temperature had no significant effect on the fatigue lives of austenitic SSs in air at temperatures below 400°C. Limited additional data also showed no temperature effects up to 450°C. However, the existing fatigue data are inadequate to establish the effects of secondary hardening on fatigue life, especially at temperatures above 400°C. In the proposed methodology, these secondary hardening effects are accounted for in the factor applied on stress that was applied to obtain the design curve from the mean-data curve."

It is also agreed, as stipulated in sub-comment b., that the discussion on secondary hardening effects in Section 3.2.4 of the draft report needs clarification. The sentence at the end of the 2nd paragraph of Section 3.2.4 stating that the results that fatigue limit was higher at 300°C than at 150°C has been deleted from the report for clarity. These results are discussed in detail later in the report while discussing the effects of PWR environments. However, the difference in fatigue limit in these tests is likely due to a misinterpretation of the load control data, and is not a real effect. Additionally, as indicated in the above response, the sentence quoted in sub-comment b. has been revised to state,

> "However, the existing fatigue data are inadequate to establish the effects of secondary hardening on fatigue life, especially at temperatures above 400°C. In the proposed methodology, these secondary hardening effects are accounted for in the factor applied on stress that was applied to obtain the design curve from the mean-data curve."

AREVA-9-9 Comment

Comments on the Dynamic Strain Aging (DSA) effect

a. *The Dynamic Strain Aging (DSA) phenomenon is first treated on page 16 and most specifically on page 34 for the austenitic SS and in several other pages of the report. Please note that the DSA phenomenon is temperature and time dependent but appears to be independent of the environment as shown in the following references [2] and [3].*
   [2] L. De Baglion, J. Mendez, Low cycle fatigue behavior of a type 304L austenitic stainless steel in air or in vacuum, at 20 degrees C or at 300 degrees C: relative effect of strain rate and environment, in: P. Lukas (Ed.) Fatigue 2010, 2010, pp.2171-2179.
   [3] L. De Baglion et aL.; PVP 2012-78767, "Influence of PWR Primary Water on LCF Behavior of Type 304L Austenitic Stainless Steel at 300'C - Comparison with Results Obtained in Vacuum or in Air"; July 15-19, 2012, Toronto, Ontario, Canada.
b. *The pieces of information reported on page 61 for the DSA effect are questionable because this phenomenon is also strain rate dependent and is mainly observed for austenitic SS's between 300 and 400°C at low strain rates (see references [2] and [3]). Please provide a justification or explanation for this information.*
c. *It is not clear, if the potential detrimental effect of DSA on the fatigue lives of austenitic SS's, mentioned on page 113 for instance, is also considered for fatigue life predictions in this report. Please clarify.*

NRC Response

This comment identifies various issues related to the dynamic strain aging (DSA) effect discussed within the report. In response, item (xi) *Dynamic Strain Aging* has been incorporated in new Section 1.5 to clarify how DSA was treated in the report. As stated in new Section 1.5, the potential effects of dynamic strain aging (DSA) are provided in the report for information only and are not included in any of the evaluations contained in this report. This is a topic that requires further research and data in order to adequately assess its effects, several of which are identified in this comment.

AREVA-9-10 Comment

Comment on the mean stress correction

a. *Please clarify the mean stress correction discussed on pages 5 and 59. Parameters σu and σy remain ambiguous in literature. Is cy a cyclic yield stress or a monotonic yield stress? Is it a total or half amplitude? In particular the value of 303 MPa for austenitic SS is unclear in the following references [4] and [5]. Please clarify.*
   [4] Manjoine, M., Tome, R.E., 1983, "Proposed Design Criteria for High Cycle Fatigue of Austenitic Stainless Steel," International Conference on Advances in Life Prediction Methods, D.A. Woodford and J.R. Whithehead, eds, ASME, pp.51 -57.
   [5] Jaske, C.E., Mindlin, H., and Perrin, J.S., "Cyclic Stress-Strain Behavior of Two Alloys at High Temperature," Cyclic Stress-Strain Behavior Analysis, Experimentation, and Failure Prediction, ASTM STP 519, American Society for Testing and Materials, 1973, pp.13-27.

NRC Response

There are several similar comments related to use of monotonic or cyclic yield strength throughout the report. Please see the responses to comments AMEC-3-4, AMEC-3-7, RR-6-7,

RR-6-15, EDF-7-1, and EDF-7-4 for information on how these comments have been dispositioned and how the report has been modified to address these issues.

AREVA-9-11 Comment

Comments on air fatigue design curve adjustment factor on strain

a. *Please clarify the references or figures of the present report that support the decision to consider a factor 2 on strain for air fatigue design curve adjustment factor (page 152).*
b. *Assuming that "the adjustment on strain is controlled by the variable that has the largest effect on fatigue life" (page 152), please clarify which is the most detrimental effect among material variability and data scatter, component size, surface finish and load history.*
c. *Please clarify the following statement (page 152): "Because these variables affect life through their influence on the growth of short cracks (less than 100pm), the adjustment on strain to account for such variations is typically not cumulative." It is unclear why cumulating detrimental effects would not enhance fatigue growth of short cracks.*
d. *In High-Cycle Fatigue (> 10^6 cycles), the Curves A, B and C from before the 2009 Edition of the ASME-Code make sense, are logical and should remain. The current factor of 2.0 on the High-Cycle Fatigue portion of the specimen mean fatigue curve is much too high and needs to be reduced to a value between 1.33 and 1.4, as suggested by others.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. In response to sub-comments a., b., and c., item (xvii) *Factor of Two on Strain (of Pseudo-Stress)* has been incorporated within new Section 1.5. This item discusses the rationale for choosing this factor primarily to be consistent with current ASME Code practices but then verifying its acceptability through Monte Carlo analysis in the report. As indicated in this item within new Section 1.5., the adjustment factor on stress or strain of 2 was assumed to be consistent with current ASME factors. No attempt was made to evaluate an acceptable value of the adjustment factor on strain or stress or the individual effects of different parameters such as material variability and data scatter, component size, surface finish, and load history.

However, the controlling parameter will vary in actual applications such that any of these effects could dominate. In order to clarify this point, the following phrase has been added to item (xvii) in new Section 1.5:

> "At present, the adjustment factor of 2 on strain is used to account not only for data scatter, size, surface finish, and loading sequence, but also for the potential effects of a combination of temperature and strain rate on secondary hardening and dynamic strain aging. These effects are not cumulative within the high-cycle fatigue region, and only the most dominant of these effects controls the net adjustment factor. However, these parameters principally affect the growth of microstructurally small cracks, and their significance depends on the operating conditions, environment, material, and the fabrication process. Therefore, the effect that dominates is a function of material and environmental conditions. The factor of 2 on strain is sufficient to account for the dominant effect within the high-cycle fatigue region."

A similar statement has been used in Section 5.5 to replace the statement quoted by the commenter. Please also see the responses to similar comments AMEC-3-12, RR-6-30 and RR-6-31 for additional information on how this issue has been addressed.

Sub-comment d. raises two issues. The first issue is that the A, B, and C curves before the 2009 edition of the ASME code should remain. This issue is outside the scope of this report and the

commenter should raise this concern to the appropriate ASME Code Committee. However, it is the authors' opinion that these pre-2009 fatigue curves for stainless steels should not be used because the best-fit curve of fatigue data used in developing these curves was based on very limited data. This was pointed out in the paper by Jaske and O'Donnell in 1978. The details regarding the procedure for developing the current ASME fatigue design curve for austenitic SSs and the difference between the pre-2009 design curves and the current design curve are discussed in the original version of NUREG/CR-6909.

The second issue expressed in sub-comment d. is that the factor of two on high cycle data is too high. The additional data evaluated in this revision of the report continues to support the current ASME fatigue design curve. The existing data is also inadequate to more accurately determine this factor such that it can be reduced. Therefore, additional study is required to develop an appropriate technical basis.to support reducing this factor as stipulated in the sub-comment.

AREVA-9-12 Comment

Comment on temperature effect in water

a. *In Figure 88 (page 118) it is unclear why the threshold temperature has been reduced from 150°C to 100°C. Indeed, data points were the same in the Rev.0 of the NUREG/CR-6909 and the choice of a 150'C threshold was appropriate. Please comment.*
b. *Moreover, it is reported that "the results from the EdF sponsored study at GE on Type 304L SSs tested in PWR water at 150'C showed significant environmental effects in the high-cycle regime" (page 128). This statement is questionable considering Figure 18 of Ref.60 where few differences are shown between fatigue lives experimentally obtained at 150*C in Air and in PWR water. Please comment.*

NRC Response

In response to sub-comment a., as shown in Figure 4-34 (Figure 88 in draft report), the revised figure shows that fatigue life varies with temperature even at 0.4%/s strain rate. Compared to the expressions in the original version of NUREG/CR-6909, this change does not affect the fatigue life at 150°C, but the life at 100°C is longer than that in the original version of NUREG/CR-6909. In order to clarify this point further, the following sentence has been added at the end of the first paragraph of Section 4.2.4:

> "Note that the F_{en} expression in the original version of NUREG/CR-6909 included a temperature threshold of 150°C below which environmental effects were considered insignificant. In addition, the F_{en} expressions developed by JNES do not consider a temperature threshold. Therefore, to better represent the existing fatigue ε–N data, the temperature dependence relationships in the F_{en} expression were modified and the temperature threshold was decreased from 150°C to 100°C."

The work by GE referenced by the commenter in sub-comment b. is presented in Figure 4-29 and Figure 4-30. Figure 4-30 is a recreation of Figure 18 of Ref. 60. This figure has been created by recalculating the strains from the load data in Ref. 60 and plotting the results together with other data obtained from strain control tests. The data sets show excellent agreement. However, in the recalculated data of Ref. 60, the effect of environment at 150°C is minimal, consistently lower. Therefore, to address the issue raised by sub-comment b., the first four sentences of the 3rd paragraph of Section 4.2.13 have been revised as follows:

> "A review of the updated fatigue database indicated that the results from the EdF-sponsored study at GE on Type 304L SSs tested in PWR water at 150°C showed some

environmental effects in the high-cycle regime (i.e., greater than 10^4 cycles). Therefore, as discussed earlier, to better represent the existing fatigue ε–N data, the temperature-dependent relationships in the F_{en} expression have been modified and the temperature threshold has been decreased from 150°C to 100°C."

AREVA-9-13 Comment

Comment on water reduction factor

a. *It is noted that at a given strain rate and temperature, the water reduction factor increases with decreasing strain amplitude. Why was this effect not considered in the report's model?*

NRC Response

The approach followed in the report uses a simple environmental adjustment factor, F_{en}, which presumes that the slope of the fatigue strain (or stress) vs. life curve is the same in air and water environments. Based on the totality of the data in the report, this assumption appears reasonable. If environmental effects increase with decreasing strain, the use of an adjustment factor would be a function of strain and the concept becomes more complex. It is not clear whether the apparent increase in environmental effects with decreasing strain is a true strain dependence or just an artifact of the dataset being used to evaluate environmental effects. Most of the fatigue data on austenitic SSs in PWR environments is for low-C Type 304L or 316NG SSs. As mentioned in the report, the slope of the fatigue strain vs. life curve in air for these low-C SSs is steeper than that for the high-C SSs. Additional data are needed to investigate this topic more completely. This point is clarified in item (xviii) *F_{en} Assumptions* that has been added to new Section 1.5. Further clarification on this point is made at the beginning of Section 4 and in the second paragraph of Section 4.2.13.

AREVA-9-14 Comment

Comments on validation of Fen expressions

a. *A validation of Fen expressions is presented in paragraph 6 (page 157). The choice made by the authors is to study only the environmental effects by considering a best fit assessment of the other effects (material variability, surface finish, etc.); in the various test campaigns the air fatigue design curve is never used. Please explain why no global assessment of the fatigue design process (air design curve + Fen expressions) has been performed. The latter is the most important for design purpose and the level of conservatism should be clarified.*
b. *For the VTT tests please specify surface roughness values of the specimens (page 158) and please correct Figure 122 (page 159), which is not visible.*
c. *For the tests on U-bend specimens (page 166), please specify the level of theoretical Fen values.*
d. *No Fen value higher than 6 has been tested in the various test campaigns; please provide a comment.*
e. *On page 158, the five lines just above the title for sub-section 6.1 states the NRC was not able to complete the stepped pipe fatigue finite element analyses to calculate the thermal strains and, therefore, was not able to include the stepped pipe fatigue test results in this Report. The official PVP technical paper of the Bechtel-Bettis stepped pipe fatigue tests (PVP technical Paper PVP2004-2748, by Dr. David Jones and others) gives the strain range of 1.63 %, based on the actual stress-strain curve of the stepped pipe material. Thus, based on that strain range, the ASME-Code in-air number of cycles is 161, when*

compared with the minimum number of cycles of 365, leading to a severity for the ASME-Code in-air Design Fatigue methodology of 365 / 161 = 2.27. This means that the in-air ASME-Code Fatigue Design Methodology is already leading to a number of allowable cycles that is 2.27 times too small, and this is before reducing the number of cycles of 161 by the Fen factor. These results, including the strain range of 1.63 % above, have been confirmed by others in their finite element analyses of these tests. The crack depth considered in these fatigue tests for the recordings of those numbers of cycles (minimum 365) is 0.25 mm crack depth, which is 12 times less than the 3.0 mm crack depth postulated in NUREG/CR-6909 and much smaller than the through-wall crack depth of the ASME Code Fatigue Design methodology (see 11-1520(b) of the Appendix II of Section III, Division 1 of the ASME-Code). The code clearly states: "Failure is herein defined as a propagation of a crack through the entire thickness, such as would produce a measurable leak in a pressure retaining member." In addition, 11-2340(b) of the same Appendix states:" ... subjected to fully reversed cyclic displacements until a visible through-wall leak develops in the component or its weld to the pipe." Furthermore, pipe fatigue tests at the origin of the stress indices were performed up to through-wall leakage to calculate the number of allowable cycles. The conclusion from the stepped pipe fatigue tests is that the Section III Division 1 Design Fatigue methodology, before applying any penalizing Fen factor, is already very severe for these usual nuclear power plant events; such as the sudden in-surges and out-surges of alternating high temperature and low temperature flows. This needs to be made very clear inside NUREG/CR-6909, Rev. 1, and this is the main point for not applying any penalizing Fen factor for those typical nuclear power plant transients.

f. *In sub-section 6.3 (EPRI U-bend fatigue tests), Figure 131 of page 170 is not clear as it shows environmental data points on both sides of the main diagonal line. It is not clear whether this confusion is due to the approximate estimate of the ratio between the inside surface strain and the axial control strain (75% is unclear; see middle of page 167) or due to the factor of 2.3 from the top of page 168 (2.3 is unclear). The very simple conclusion of these EPRI U-bend fatigue tests is that the Fen factors based on these component tests are lower than 1.0 for the strain rate of 0.01 % / sec. and only 1.92 for the very low strain rate of 0.5E-03 % / sec. As a result, these EPRI U-bend fatigue tests have clearly shown that the Fen factors from NUREG/CR-6909, Rev. 1, are between four times and eight times too severe.*
g. *The sub-sections 6.1, 6.2 and 6.4 only pertain to specimen fatigue tests. It should be noted that component fatigue tests have shown the Design Fatigue Methodology - especially when applying the Fen factors to the revised Design Fatigue Curves from 2009 and beyond - is overly conservative.*
h. *As the stresses leading to the maximum cumulative usage factors of the nuclear power plant components are in most cases peakish (or very peakish), using the fatigue results from specimen fatigue tests does not represent what actually happens, as far as fatigue of the component is concerned. As in the example of the stepped pipe fatigue tests, the peakish stress ranges do not grow the crack through the thickness and the specimen fatigue tests cannot simulate those conditions appropriately.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. In response to sub-comment a., the purpose of Section 6 is to validate the accuracy of the F_{en} expressions for estimating environmental effects, not to validate the ASME Code Section III fatigue evaluation procedure. Given the conservativism of the ASME Section III procedure, this combined use of the ASME design curve with F_{en} is also conservative. The level of

conservatism for individual materials increases as their margin above the design curve increases. A more rigorous assessment of the conservativism in this approach could be performed to remove conservatism but it is outside the scope of this current report.

In response to sub-comment b., the report provides all the information that is available for the tests in Refs. 158 and 159. Also, Figure 6-1 (Figure 122 in draft report) is visible in the final report. Sub-comment c. requests information about the evaluation of the U-bend tests. The F_{en} value for the U-bend tests was predicted using the equations provided in the NUREG and it is compared with the experimental results in Figure 6-10. The adjustment factor for these tests is 1.4 (recalculated from 2.3 as indicated in the draft report) and it is provided in the 6th paragraph of Section 6.3, just below Figure 6-9, of the report.

Sub-comment d. requests a comment on the F_{en} limit in the tests presented in Section 6. The F_{en} values are below six for the tests documented in the report, which use complex loading to simulate actual plant transients. In these tests, the F_{en} value for the portion of the transient at the slowest strain rates was high, but this was compensated by the small total accumulated strain during the same portion of the transient. Therefore, the contribution of the slowest strain rate portion of the test to the overall F_{en} is not significant and the overall F_{en} is less than six. Similarly, the sample problem in Appendix C uses the modified rate approach and to compute an average F_{en} of less than 5. However the F_{en} for slowest strain rate portions of the transient (see Table C-5) are significantly higher than the average. This feature is characteristic of most plant transients as most of the strain during a transient is accumulated at relatively high strain rates. However, it is not possible to categorically presume that F_{en} will be lower than 6 for all actual plant transients. Please also see the response to AREVA-9-6f for additional information on how this point has been clarified in the final report.

It is agreed, as stipulated in sub-comment e., that tests like the cited Bettis stepped pipe test, which simulate more closely actual components and loading transients, are extremely valuable. However, as stated in the responses to similar comments AMEC 3-2 and RR 6-32, it was not possible to calculate the overall F_{en} for the stepped pipe tests because accurate thermal strain values could not be determined for these tests. As stated in the responses to these other comments, the NUREG has been clarified to reflect this point. It is also agreed, as implied in sub-comments e. and f., that the ASME Code fatigue design curves will conservatively predict fatigue life for tests such as the Bettis stepped pipe test because, in part, the loading has a strain gradient while the design curves are based on uniform-strain tests. Please also see the responses to comments AMEC-3-2, AMEC-3-5, RR-6-4, EDF 7-8, and AREVA 9-17h for additional discussion of gradient effects and their conservatism, and changes made to this report to discuss these effects. In particular, several areas in new Section 1.5 have been added to discuss gradient effects and several other potential conservatisms with both the ASME Code procedure and the F_{en} approach.

However, there is not agreement with the notion in sub-comment e. that environmental effects should not be considered because of inherent conservativisms in the ASME evaluation procedures. There are conservativisms in the ASME procedures and these conservativisms often lead to conservative predictions of environmental effects when the adjustment factor is applied. However, laboratory testing has demonstrated that environmental effects affect fatigue life and there is no basis to neglect these effects simply due to the presumption that they are always compensated for by existing ASME Code conservativisms. The existing conservatisms in the ASME Code procedures should be addressed specifically by additional research and evaluation.

In response to sub-comment f., the results plotted in Figure 6-10 (Figure 131 in draft report) were from an earlier analysis which was updated as part of this report. Unfortunately, the information in figure presented in the draft report had not been updated. The figure has now been updated and represents the correct analysis. The main difference in the figure is in the value of adjustment factor used to estimate the fatigue life of a component from small, smooth test specimen data; the adjustment factor is 1.4 instead of 2.3 as in the original figure. As can be seen in the updated Figure 6-10, the predicted values fall on both sides of the diagonal, within a factor of ±1.7.

This variability seems quite reasonable considering the several sources of uncertainties in estimating the actual strain and surface conditions of the test specimens. The adjustment factor and the ratio of inside surface strain and axial control strain are just two sources of uncertainties. For example, Ref. 99 states, that the strains resulting from cyclic loading at the apex were expected to be entirely symmetrical but they are not because of factors such as out-of-roundness and wall thickness variations arising from tube manufacturing/bend fabrication, as well as from bend residual stress. While the residual stress in the U-bend specimens may relax somewhat during pre-conditioning under simulated primary water conditions, it is not clear that the stress will fully relax which causes uncertainty in the fatigue life predictions.

Differences between the assumed and actual loading conditions is indicated in the test results from Ref. 99. In all tests, failure occurred by axial cracking at the 270° location while the extent of cracking at the 90° location is significantly less. The information presented in Table 6-7 of the NUREG/CR-6909 Rev. 1 report indicate that the average depth of the axial cracks at the 90° location for 3 of the 4 tests are only 1.7, 1.05, 0.75 mm instead of 3 mm, the value used for fatigue crack initiation. Section 6.3 of the NUREG has been extensively rewritten to address this comment by reflecting the considerations identified above.

The issues raised in sub-comments g. and h. are outside the scope of this report. As stated in response to sub-comment a. above, the objective of the report is not to evaluate the ASME Code fatigue method, it is to address the principal environmental effects on fatigue life. As stated previously, it is agreed the ASME Code fatigue method, when used to predict the results of component fatigue tests, has generally been shown to be conservative. However, any issues or concerns with the current ASME Code fatigue method should be addressed as part of the process that ASME uses to maintain and, as needed, update their Code procedures. In response to this, and other similar comments concerned with the conservatism of the ASME Code procedures, a new section of the report, Section 1.5, has been created in this report. This section addresses the scope and assumptions used in the report and addresses several topics related to conservatisms in the ASME Code procedures and the F_{en} approach.

AREVA-9-15 Comment

Hold time effects

a. *Consideration of hold times is generally discussed in chapter 4.1.8. In this chapter, published work was used for assessment. In these papers, hold times up to 1800 s were applied. With regards to plant operating conditions, such hold times are much shorter than realistic hold times which might appear under real plant conditions. Such realistic hold times are rather in the range of several days, weeks or even months, when the plant operates under base load conditions. Public (but still not published) work by AREVA GmbH indicates that significant recovery effects occur due to hold times in the range of days at steady-state operating temperature. This is complemented by published work from VTT, reference [6].Fatigue tests in air show that specimen-lives in SN-tests may increase*

up to a factor of 2 by intermediate hold times. More experimental work is recommended related to hold time effects.

[6] J. So/in, VT, Espoo, Finland; S. H. Reese, Ertugrul Karabaki, E. ON Kernkraft GmbH, Hannover, Germany; W. Moyinger, Fennovoima Oy, Helsinki, Finland: FATIGUE PERFORMANCE OF STABILIZED AUSTENITIC STAINLESS STEELS – EXPERIMENTAL INVESTIGATIONS RESPECTING OPERATIONAL RELEVANT CONDITIONS LIKE TEMPERATURE AND HOLD TIME EFFECTS, PVP2013-97502

NRC Response

There is general agreement with the points raised in this comment. As discussed in the report, the beneficial effects (with respect to fatigue life) of hold time appear to occur during the stress relaxation period. Based on the data evaluated, the most significant effects appear to occur during the first hour of hold time when the bulk of the stress relaxation occurs. The effects of longer hold times on F_{en} appear to be less significant. However, the assessment of this finding using longer hold-time testing, including hold times that are more representative of plant component loading, is certainly justified. More research of the kind cited by the commenter should be helpful in characterizing these effects.

AREVA-9-16 Comment

Comments on the analyses of the AREVA test for validation of Fen expressions

a. *On page 162, please provide that the specified surface roughness (of 4011m) corresponds to an Rt value: the maximum height of the surface roughness profile.*
b. *The experimental Fen factors for a polished specimen and ground specimen, 3.62 and 2.90 respectively (page 163), are inconsistent with data reported in Table 21 (page 165). Please explain the reason for the deviation and the explicit quantitative data used.*
c. *The recommended practice for calculating Fen expressions is presented in Appendix A2: "For wrought and cast austenitic stainless steels, a threshold value of 0.10% for strain amplitude (one-half the strain range for the cycle) is defined, below which environmental effects on the fatigue lives of these steels do not occur." In addition, "the strain amplitude should not be applied when using a modified rate approach, as it may yield non-conservative results."*
   However, it was noted on Page 164 that the AREVA experiments were analyzed in the draft report by:
   i. *Using the modified rate approach coupled with a strain amplitude threshold. This violates the method detailed in Appendix A2.*
   ii. *Considering a 0.16% strain amplitude threshold, instead of the recommended 0.10% value; this is inconsistent with page 117 of the report. The draft states "For simplicity, in the initial revision of NUREG/CR-6909, a single value of 0.10% was proposed for the strain amplitude threshold."*

   This illustrates that the Fen evaluation process is currently not robust enough for representing the behavior of real components.
d. *On page 164 the draft states: "The predicted fatigue lives were generally lower than the experimental values; however, the values were within the range of data scatter." AREVA asserts data scatter cannot be a reasonable cause for the results with complex signals because the data points are not homogeneously distributed in the scatter band. Indeed Figure 127 (page 165) shows the predictions are systematically conservative by a factor close to 2 and most cases greater than 2. However, AREVA does not find this a reasonable justification to attribute data ranges to scatter. Please provide further statistical judgment on this statement.*

e. *The draft report states that the "behavior is considered unique to this specific strain loading cycle" (page 164). AREVA would like to note that the loading is similar to what is experienced on actual components; please provide further explanation of the unique behavior.*

f. *Please consider the following Table 21 data corrections:*
   i. *Few Ea (%) have been corrected;*
   ii. *Few "Measured Nf" in Air have been corrected;*
   iii. *Few "Measured Nf" in PWR have been corrected;*
   iv. *According to the corrected Ea (%), the "Estimated Nair" has been corrected; The "Estimated Fen without strain threshold" and "Estimated Fen with strain threshold" for "Complex Strain Cycles" have been corrected. Actually, strain rates in complex signals were adapted for the various strain amplitudes in order to yield approximately the same theoretical Fen*

*The corrections to Table 21 are provided in **red** below.*

Table 21 Corrections:

Environment/ Surface Finish	Strain Rate (%/s)	εa (%)	Measured Nf	Estimated Nair	Without Strain Threshold		With Strain Threshold	
					Estimated Fen	Predicted Nf	Estimated Fen	Predicted Nf
Triangular Waveform								
Air, Polished	0.40	0.550	6,798	4,798	1.00	*	-	-
Air, Polished	0.40	0.380	11,325	12,323	1.00	*	-	-
Air, Polished	0.40	0.187	83,500	142,104	1.00	*	-	-
Air, Ground	0.40	0.560	4,667	4,595	1.00	*	-	-
Air, Ground	0.40	0.370	10,314	13,256	1.00	*	-	-
Air, Ground	0.40	0.190	37,469	131,796	1.00	*	-	-
Air, Ground	0.40	0.190	55,000	131,796	1.00	*	-	-
PWR, Polished	0.01	0.540	1,002	5,016	4.97	*	-	-
PWR, Polished	0.01	0.560	1,200	4,594	4.97	*	-	-
PWR, Polished	0.01	0.280	9,000	30,209	4.97	*	-	-
PWR, Ground	0.01	0.550	890	4,798	4.97	*	-	-
PWR, Ground	0.01	0.550	1,000	4,798	4.97	*	-	-
PWR, Ground	0.01	0.272	4,506	33,175	4.97	*	-	-
Complex Strain Cycle								
PWR, Polished	variable	0.590	1,588	4057	≈ 5.70	*	≈ 5.37**	*
PWR, Polished	variable	0.575	1,936	4,313	≈ 5.80	*	≈ 5.37**	*
PWR, Polished	variable	0.490	2,900	6,367	≈ 5.80	*	≈ 5.37**	*
PWR, Polished	variable	0.288	8,318	27,627	≈ 5.70	*	≈ 5.37**	*
PWR, Polished	variable	0.288	8,810	27,627	≈ 5.70	*	≈ 5.37**	*
PWR, Ground	variable	0.570	895	4,404	≈ 5.80	*	≈ 5.37**	*
PWR, Ground	variable	0.570	960	4,404	≈ 5.80	*	≈ 5.37**	*
PWR, Ground	variable	0.290	8,000	27,034	≈ 5.70	*	≈ 5.37**	*
PWR, Ground	variable	0.290	6,665	27,034	≈ 5.70	*	≈ 5.37**	*

*** Please update these values, with consideration taken to our provided corrections on strain amplitude and estimated Fen values.**

**** The estimated Fen value with a 16% strain amplitude threshold is approximately equal to 5.37. The values should not range from 3.14 to 5.37.**

NRC Response

This comment contains several sub-comments that are addressed individually as follows. In response to sub-comment a., the 2nd to last sentence of the first paragraph of Section 6.2 has been modified as follows for clarity:

> "The specimen surface finish was specified as R_t = 40 µm. This value corresponds to the material surface height between the maximum peak and minimum valley measured over a length of 4 mm"

Sub-comment b. requests clarification for the difference in F_{en} factors reported in the text of Section 6.2 and Table 6-6 (Table 21 in draft report). The values of the adjustment factor in Table 6-6 are the F_{en} values determined by analysis. The factors reported in the text of the 3rd paragraph of Section 6.2 are measured factors comparing the results of the tests in air with those in the environment. The report has been clarified to indicate this. Further, as explained in the responses to comments RR 6-34 and EDF 7-7, the protective oxide film is likely to reform during the very low strain-rate portion of the transient, and it has to be ruptured again for environmental effects. As shown in Figure 6-6, the estimated fatigue lives are a factor of 2.5 lower than the measured values. If the effect of reformation of the oxide film during the transient is considered, the agreement between the experimental and estimated values is expected to be better.

There is not agreement with either the specific points raised or the general sentiment expressed in sub-comment c. that "… the F_{en} evaluation process is currently not robust enough for representing the behavior of real components." The evaluation of the AREVA tests (Section 6.2) is based on the actual experimental data and uses a strain threshold of 0.16%, whereas the strain threshold mentioned in Appendix A.2 is for general use with the fatigue design curve. The two evaluations are quite different and the thresholds used in each should not be compared. As indicated, the 0.16% strain amplitude is the experimental value for the AREVA tests which evaluated Type 304L SS in both air and PWR environments using a constant strain rate triangular waveform. Given these conditions, the use of 0.16% strain threshold in the analysis summarized in Section 6.2 provides a more accurate F_{en} estimate for these particular tests.

Conversely, the examples in the report demonstrate that the proposed general method (as summarized in Appendix A.2) is robust enough to conservatively represent the behavior of real components in light of the large variability in these types of tests. While generally proposing the use of a strain threshold of 0.1% for the method, the report also states that this value should not be used when calculating F_{en} using the modified rate approach because it may yield nonconservative estimates. The use of a strain threshold in these instances may be unconservative if a protective oxide film is not formed before the transient. However, the report states that a threshold value can be used with the modified rate approach if it is demonstrated that, for the specific loading and environmental conditions, the estimate is accurate or conservative.

In response to sub-comment d., the report clearly states in several places that the fatigue life estimates using this method are either accurate or conservative. Therefore, the results are not expected to be evenly distributed about the estimated values. As stated previously in the response to AREVA-9-14, the ASME air fatigue design curves are intentionally conservative and new Section 1.5 has been added to the report to discuss some of these conservatives along with others associated with the F_{en} method. However, even after consideration of these expected conservatisms, the predictions of fatigue life that are within a factor of 2 of the measured values which are, as the report states, within the scatter typically associated with these types of tests.

Sub-comment e. is similar to earlier comments RR-6-34 and EDF-7-7. Please see the response to RR-6-34 for the further information pertaining to this issue. Sub-comment f. provides several suggested corrections to Table 6-6 in the report. The information contained in Table 6-6 is consistent with the results presented in Refs. 155 and 157 of the report, which are the source references for the information. A few typographical errors in the Table 6-6 have been corrected so that the information is now completely aligned with the source references. Such corrections include the F_{en} value estimated with a strain threshold in the second last row, which has been changed from 3.14 to 4.60, and the estimated fatigue lives with the strain threshold for the last 3 rows, which have been changed from 425, 425, and 3217 to 496, 496, and 3625.

However, none of the additional changes to the table suggested in sub-comment e. that are different than the information published in Refs. 155 and 157 have been made. A publicly available, published source reference that acknowledges any erroneous results in Refs. 155 and 157, and provides the corrected values is needed before further changes can be made. Once such a document is available, errata for the NUREG report can be developed.

AREVA-9-17 Comment

Miscellaneous points

a. *Paragraph 1.3.1 exhibits a series of failures attributed to fatigue. It is stated that "In most cases, these failures were associated with thermal loading due to thermal stratification and striping, or mechanical loading due to vibratory loading" (pages 6-7). In addition, "Thermal loading due to flow stratification or striping was not typically included in the original design basis analyses for most U.S. nuclear power plants" (page 7). So in fact these failures illustrate a lack of knowledge of real loadings and not a non-conservatism of fatigue analysis methods (strain evaluation + design curve). A direct link has not been highlighted between these failures and environmental effects. Moreover this kind of thermal loadings deals with HCF and the proposal of strain thresholds in this report lead to the idea that environmental effects are less significant in HCF. Considering these various reasons, the following statement "The increased fatigue duty caused by such thermal loading increases the importance of evaluating environmental effects" (page 7) should potentially be toned down. Please address this concern.*
b. *The report exhibits a series of detrimental effects which have to be taken into account to determine fatigue design curves: material variability, size, surface finish, loading sequence, environmental effects. However no beneficial effect has been evoked in global codified fatigue analysis methods. For instance, a detrimental adjustment factor is taken for loading sequence but no position is given about the conservative way to combine transients in fatigue analyses. Another example is that a detrimental size effect is proposed but a beneficial stress gradient in the thickness of the real component is not discussed. Please address this concern.*
c. *It is stated in page 148 that "However, the Section III of the ASME Code is not fully prescriptive, so there is a wide variation in the specific procedures that are applied to fatigue evaluations by different analysts. For example, modern computer capabilities, particularly modern finite element methods, fatigue monitoring, and improved Ke factors, allow for evaluation refinements that significantly decrease the conservatisms traditionally applied in fatigue evaluation procedures performed in the past". These sentences contain a lot of very important messages and should be more detailed. In this way, the responsibility of the analyst should be emphasized. No conservatism hierarchy can be reported between past analytical methods and modern finite element ones if input data have changed. In other words, it is the analyst's responsibility to take into account adequate input data and "methods and tools" to perform the fatigue justification of the*

component. Fatigue design curves could be more and more severe, but if reasonable conservatisms are not considered by the analyst for fatigue loading definition and mechanical strain evaluation, prior to using fatigue design curves, the final result will not be conservative. As a conclusion responsibility of the analyst should be emphasized and fatigue design curves should not be made excessively severe to counterbalance bad choices of bad analysts. Please provide more detail or explanation in this section.

d. *It is stated on page 148 that "However, the Section III of the ASME Code is not fully prescriptive, so there is a wide variation in the specific procedures that are applied to fatigue evaluations by different analysts. For example, modern computer capabilities, particularly modern finite element methods, fatigue monitoring, and improved Ke factors, allow for evaluation refinements that significantly decrease the conservatisms traditionally applied in fatigue evaluation procedures performed in the past". As previously reported these sentences contain a lot of very important messages and should be more detailed. To extend the previous comment, it should be emphasized that this report only deals with ASME Code. As it is stated "the Section III of the ASME Code is not fully prescriptive," so this proposal is consistent with the ASME Code framework and prescriptions. But more prescriptive codes could face justification difficulties to apply the present method and the latter is not supposed to become the unique one to deal with fatigue and environmental effects. This comment could be extended to the whole report and a message could be added in the abstract, the executive summary or the introduction.*
e. *Operational experience has not been considered for the development of the Fen Methodology and the Fen equations of this report. To develop the Fen equations (listed in Appendix A of this Document), only specimen fatigue data have been considered. This is a very important part of the explanation why the fatigue failures that could be expected when calculating those high usage factors based on the Fen factors have not occurred in reality inside the nuclear power plants.*
f. *There has not been a good reconciliation between the specimen fatigue test data on one side and the complete ASME-Code Fatigue Methodology on the other side, with a big emphasis here on the word "Complete." For example, this complete ASME-Code Fatigue Methodology already contains a lot of multiplication of effects that have not been considered by the developers of both the in-air design fatigue curves and the Fen factors.*
g. *The calculations of the Fen factors are very complex, and thus "error likely" due to their complexities (function of temperature (time) and strain rate (time)). In-air fatigue is not a trivial calculation and environmental fatigue is very complex unless the analyst chooses a very conservative path and calculates a conservative Fen and thus an extremely high usage factor.*
h. *Primary vs. Secondary stress: the small specimen fatigue tests involve imposed displacements that act much more on the specimen as a primary membrane-type of stress rather than a secondary peak-type of stress. On the other side, the highest usage factors are in general the results of thermal transients that generate secondary peak-types of stresses/strains.*
i. *Redistribution of the stress and the strains during the cycles may not be simulated in the specimen fatigue tests, although they could very well occur during the actual nuclear power plant transients.*
j. *Numerous factors, which affect the fatigue strength, are discussed thoroughly in the current report. So, the results could also be used for a detailed engineering fatigue assessment method: the factors could be categorized into three groups (component, material, loading) - for each group the relevant factors of influence can be superimposed and corrected, if necessary, by a correction factor. Please refer to reference [7]:*

[7] PVP2014-28728: "ENVIRONMENTAL INFLUENCES ON THE FATIGUE ASSESSMENT OF AUSTENITIC AND FERRITIC STEEL COMPONENTS INCLUDING WELDS"

k. In general, the only concerns we should have are for those transients with low strain rates (slow transients). The other transients (for example, in-surges and out-surges) need to be evaluated for fatigue, but the current ASME-Code Class 1 Component classic Fatigue Methodology (without any Fen penalty factors) is very appropriate for those transients (the transients with relatively high to very high strain rates).

l. The suggested rules for the application of the threshold are unclear, inconsistent, and lack solid justification throughout the report.

NRC Response

This comment contains several sub-comments that are addressed individually as follows. It is not agreed, as requested in sub-comment a., that the statement, "The increased fatigue duty caused by such thermal loading increases the importance of evaluating environmental effects," should be toned down. This statement reflects the notion that Section III ASME fatigue analyses currently do not assess environmental effects. As demonstrated in this report, these effects are real and have been shown to reduce fatigue life in both laboratory specimens and structural components. In fact, as indicated in the report, environmental effects were shown to contribute to the fatigue life reduction of the nozzle components subject to thermal loading.

Further, many fatigue evaluations are close to the design life acceptance criteria without consideration of environmental effects and additional duty cycles due to extended operations or changes in operating conditions could exceed these criteria. While the ASME fatigue analysis method is known to be conservative, consideration of environmental effects, possibly in concert with more accurate analysis is necessary to better understand the fatigue margins to determine what, if any, additional actions should be taken to ensure structural and/or component integrity.

Sub-comment b. identifies the lack of credit for stress gradient effects and the method to combine fatigue transients as two areas of conservatism within the ASME Code. As stated in the responses to AREVA-9-14 and AREVA-9-16, it is agreed that ASME Code fatigue evaluations are intentionally conservative. A new section has been added to the report, Section 1.5, which documents some of these conservatives and additional ones associated with the F_{en} method. However, additional work is needed to develop a basis for relaxing these ASME Code conservativisms. Comments related to conservativism in the Code evaluation method including the approach used for combining transients should be directed to appropriate ASME Code committees

Sub-comment c. requests that the report provide more details about the responsibilities of the analyst when conducting an ASME Code fatigue evaluation. While there is no disagreement with the sentiments of this comment, guidance on conducting a Section III ASME fatigue analysis is clearly outside the scope of this report. While it is recognized that conservatisms exist in the ASME methods, these should be addressed specifically by ASME. However, item (xxv) *ASME Code Procedures* has been incorporated within new Section 1.5 to partially address this topic and clarify the scope of the report. The following statement has been also added to the Executive Summary (end of 8th paragraph) and Summary (end of the 1st paragraph) for clarification: “Further, this report does not address any conservatisms associated with the ASME Code fatigue evaluation procedures.”

It is agreed, as stipulated in sub-comment d., that the method presented in NUREG/CR-6909 is only valid when using the ASME approach for evaluating fatigue life. This is already stated

prominently in the Abstract, Executive Summary, and Summary of the draft report. However, it has been further stressed that the F_{en} method presented in this report is only applicable to ASME fatigue evaluations to make it even more apparent. The following sentence was added before the last sentence of 8th paragraph in the Executive Summary to make this point: "Note that the F_{en} approach described in this report is only applicable for use as part of an ASME Code fatigue evaluation". A similar sentence has also been added at the end of the next to last paragraph of Section 1.4.

It is agreed, as stipulated in sub-comment e., that the F_{en} method is based on laboratory testing. Additionally, as stated previously, it is also agreed that the original ASME Code procedures are conservative and is a principal reason why high usage factor calculations have not been correlated with indications of significant fatigue cracking in reactor components. This report addresses the environmental fatigue correction factor, which is just one of the many parameters that affect fatigue life. Refinement of current ASME Code evaluation methods and more accurate fatigue evaluations requires a more realistic assessment of the actual loading applied to reactor components and experimental testing of such components under realistic environmental and loading conditions. Such work is beyond the scope of this report.

Sub-comment f. addresses the lack of reconciliation between specimen fatigue testing data and ASME Code fatigue procedures. As stated previously, a new Section 1.5 has been developed to identify some of the ASME Code conservatisms. Also, as stated in the report, the F_{en} approach, when used in concert with the ASME design curve, will lead to predictions of environmental effects that are either accurate or conservative. This point has been demonstrated by the successful evaluation of several more realistic experiments using this approach, as documented in Section 6. A more rigorous study to elimination conservatisms in the ASME Code fatigue evaluation procedures are outside the intended scope of this report. Such study could be used to develop a technical basis for revising ASME Code procedures by working through the appropriate Code committees.

It is agreed, as stipulated in sub-comment g., that fatigue evaluations in air are not simple and fatigue evaluations in a reactor environment are even more complex. As stated previously, the information presented in this report provides a best estimate, although somewhat conservative, method for calculating an adjustment factor for incorporating environmental effects into the ASME Code fatigue evaluations. The report is structured to aid the user in understanding and applying the F_{en} method. The technical basis for the F_{en} approach is provided in the first 5 sections of the report. There are then several applications of the F_{en} method to more complicated experiments in Section 6. These applications can be used to benchmark user results. The method is also summarized in Appendix A so that the user has one location with all the needed information to apply the method. Finally, there is a sample problem in Appendix C that can be used to ensure that calculations are being performed correctly. It is believed that this information, in its totality, provides a user with sufficient information for successfully performing a F_{en} adjustment assuming that they are also sufficiently knowledgeable in the application of the ASME Code fatigue evaluation procedure.

Sub-comment h. identifies the difference in the loading applied in laboratory specimens with the loading typically applied to reactor components. There is general agreement on this point. However, the treatise of this particular issue is outside the scope of this report. More realistic testing and stress analysis is required to more accurately account for these effects. See also the responses to comments AMEC-3-2, AMEC-3-5, RR-6-4, RR-6-32, and EDF-7-8 which also address gradient and thermal effects.

It is agreed, as stipulated in sub-comment i., that localized plasticity during transients can cause stress and strain redistribution within an actual component. However, the treatise of such effects is outside the scope of this report. More realistic testing and stress analysis is required to more accurately account for these effects. Similarly, it is generally agreed, as stipulated in sub-comment j., that other approaches for evaluating environmental effects could be developed. One of the principal objectives of this report is to clearly document the technical basis that exists for addressing the various environmental factors that are described within the report. The current report applies these factors to the ASME Code fatigue methodology and demonstrates an overall level of conservativism with this approach. However, this is just one approach for addressing environmental effects. The data and the evaluation of individual environmental factors as presented in this report can be used to develop and justify other methods that could be equally acceptable for evaluating fatigue life. Please also see the responses to similar comment FAIDY-2-2c for related information.

Sub-comment k. postulates that environmental effects should only be considered for slow transients. In reality, most transients consist of a wide range of strain rates and the importance of environmental effects is not always obvious without evaluating their effects in totality. The entire transient has to be evaluated to determine both the environmental adjustment and the accumulated strain associated with each strain rate range. Then, the average F_{en} for the transient can be determined. The strain rates where environmental effects are insignificant (i.e., F_{en}=1), are ≥2.2%/s for carbon and low-alloy steels, ≥7%/s for austenitic SSs, and ≥5%/s for Ni-alloys. Transients that contain portions at strain rates less than these threshold levels should be evaluated for the impact of environmental effects.

Finally, sub-comment l. states that the rules for applying the threshold are "…unclear, inconsistent, and lack solid justification throughout the report". As discussed in previous related comments AMEC-3-10 and MHI-5-3, the threshold strain rates are based on existing data. While the authors agree that there is limited data, these thresholds have been conservatively chosen for each material. Additional data are needed to establish these thresholds more accurately. The justification and use of the threshold values in the equations is clearly and consistently presented within the sections pertaining to strain rate effects for each material. However, it is noted that it is conservative to not adopt a strain rate threshold in a fatigue analysis, and that such an approach is acceptable as well.

AREVA-9-18 Comment

Editorial

a. *In Figure 45(b), page 65, the median for A is equal to 6.913 not 6.917 but the text states that "The constant A increased from 6.891 to 6.917."*
b. *In Eq. A.6 and Eq. A.10 (but not in Eq. A.15) the Strain Rate has the same notation as the Transformed Strain Rate (epsilon*'). Please delete apostrophe for the Strain Rate notation.*
c. *The automatically created PDF bookmarks could be better. (Please exclude figures, equations ...).*
d. *It will be useful to add a list of figures, tables, and equations at the beginning of the document.*
e. *Appendix A does not report the transformed temperature for values higher than 325°C.*
f. *Different symbols (asterisk or prime) are used in the main body of the report and Appendix A for the transformed properties of temperature, oxygen, etc.*
g. *Section 5.3 states that the factor used in the present report for surface finish is in the range of 2.0 to 3.5, but according to Table 14 the range should be instead 1.5 to 3.5.*

NRC Response

This comment contains several sub-comments that are addressed individually as follows. The text identified in sub-comment a. is incorrect and the identification of this error is appreciated. The value 6.917 in the 3rd sentence of the 2nd paragraph of Section 3.2.7 has been changed to 6.913. The identification of the error in sub-comment b. is also appreciated. All the transformed parameters should be identified as ε*, S*, T*, and O*. These parameters are shown only on the left of the equal sign in the equation. All parameters on the right side of the equations or shown in the ranges of the individual parameters should not have any added symbol. All equations have been revised to make these corrections. Also, to be consistent with the expressions listed in the main body of the report and Appendix A.2, for wrought and cast austenitic SSs and Ni-Cr-Fe alloys, the apostrophe (') sign has been changed to an asterisk (*) in all expressions.

It is agreed, as stipulated in sub-comment c., that automatically created PDF bookmarks could be helpful, but the present NRC technical publication instructions do not allow for such bookmarks to be created. Sub-comment d. asks that lists of figures, tables, and equations be provided at the beginning of the document. The list of figures and tables is included, along with a Table of Contents, and is part of standard NUREG report format. It is not standard practice, however, to have a list of equations.

Sub-comment e. is similar to WEST-4-3 and KEPCO-10-1. A maximum temperature limit of 325°C was selected to cover all anticipated LWR operating conditions. It is believed that this limit is adequate for all expected operating LWR conditions that would use the average temperature. However, the last paragraph of Section A.2 has been clarified as follows to address this issue:

> "For all materials, a maximum temperature limit was selected at 325°C as a reasonable bound to cover most anticipated LWR operating conditions. This is adequate for expected operating LWR conditions, especially when considering the use of average temperature. If the applicable average temperature for the transient exceeds 325°C, the user should thoroughly document this exceedance and justify the rationale for it as part of the analysis."

It is agreed, as stipulated in sub-comment f., to use the same expressions for the transformed properties, As indicated previously in the response to sub-comment b., to be consistent with the expressions listed in the main body of the report for wrought and cast austenitic SSs the apostrophe (') sign has been changed to an asterisk (*) for the expressions in Appendix A.2. All the transformed parameters for Ni-Cr-Fe alloys also use the asterisk sign.

Finally, the error identified in sub-comment g., is also appreciated. The range of the surface finish has been changed from 2.0 to 3.5 to 1.5 to 3.5 throughout the report. Additionally, the 4th sentence in the 3rd paragraph of Section 5.3 has been revised as follows:

> "Because additional data are not available to verify that surface finish effects for carbon and low-alloy steels are insignificant in LWR environments, the ANL investigations used a range of 1.5 to 3.5 to account for the effects of surface finish on the fatigue lives of carbon and low-alloy steels and wrought and cast austenitic SSs."

KEPCO-10-1 Comment

Technical Comments:
Variable transformation for temperatures higher than 325 'C should be provided in Equations (A.4), (A.9), and (A. 14) of Appendix A to the draft report revision 1, as was done for revision 0 of the report.

NRC Response

This comment is similar to WEST-4-3 and AREVA-9-18e. As stated in the response to these comments, a maximum temperature limit of 325°C was selected to cover all anticipated LWR operating conditions. It is believed that this limit is adequate for all expected operating LWR conditions that would use the average temperature. However, as discussed in the disposition of comment AREVA-9-18e, the last paragraph of Section A.2 has been clarified to indicate that if the applicable average temperature for the transient exceeds 325°C, the user should thoroughly document this exceedance and justify the rationale for the exceedance as part of the analysis.

KEPCO-10-2 Comment

Editorial Comments on Typo:
Variable of strain rate before its transformation should be differently defined from that after its transformation in Equations (A.6), (A. 10), and (A. 15) of Appendix A to the draft report revision 1.

NRC Response

This comment is virtually identical to earlier comments AREVA-9-18b and AREVA-9-18f. Please see the responses to these comments for the disposition of this issue.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Appendix I to Section III, "Rules for Construction of Nuclear Facility Components," of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) specifies fatigue design curves for applicable structural materials. However, the ASME Code design curves do not explicitly address the effects of light water reactor (LWR) water environments on fatigue life. The original version of NUREG/CR 6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials—Final Report," evaluates existing fatigue ε-N data to establish the effect of key material, environmental, and loading parameters on fatigue life. The report presents models for estimating fatigue lives and uses an environmental fatigue correction factor (Fen) for incorporating the effects of LWR environments into ASME Code Section III fatigue evaluations. The report also reviews the ASME Code Section III fatigue adjustment factors of 2 on stress (or strain) and 20 on life. This revised report updates and improves the Fen approach based on additional fatigue ε-N data from results available since the original report was published. The Fen methodology was also validated by comparing the results of five different fatigue tests that simulate actual plant conditions with estimates of fatigue life using the updated Fen expressions.

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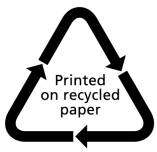
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