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Fatigue (materials)
Piping system
Plant operating criteria
Environmental effects

EPRI TR-105759
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Final Report, December 1995

An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations

Prepared by
GE Nuclear Energy

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Electric Power Research Institute

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REPORT SUMMARY

An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations

This report provides a method that selectively applies an environmental correction factor (K_{en}) to the current Code fatigue evaluation procedures. It gives information on implementing screening criteria that allows stress analysts to correct for reactor water effects only on applicable load set pairs. The report reviews current laboratory data and offers simplified procedures that account for environmental effects in ASME Code-type fatigue evaluations in operating nuclear power plants. Also included are proposed changes to Section III fatigue evaluation procedures for possible consideration by ASME Code Committees.

INTEREST CATEGORIES

Plant life cycle management
Piping, reactor vessel and internals

KEYWORDS

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Fatigue (materials)
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Environmental effects

BACKGROUND Fatigue usage in nuclear pressure vessel and piping components due to stress cycles under reactor water conditions has been a major regulatory issue in the plant life extension process. Recently, the NRC expanded its concern to current operating plants and the generic license approach for advanced light water reactors (LWRs). The NRC's interest stems from recent test data showing that, when smooth test specimens were subjected to strain-controlled cyclic loads under reactor water conditions, fatigue failures occurred earlier than the current ASME Section III S/N design curves would have predicted. In NUREG 5999, the NRC proposed a set of interim S/N fatigue curves that address reactor water effects in operating plants. If implemented, the proposed S/N curves would impose significant penalties on Code fatigue calculations.

OBJECTIVES To review current laboratory data and develop simplified procedures for use in ASME Code-type fatigue evaluations in operating nuclear power plants.

APPROACH Based on a review of past and current studies evaluating environmental fatigue effects in light water reactor applications, the Argonne statistical model was used to develop an approach to calculate an environmental fatigue correction factor, F_{en}, for ASME Code Section III, NB-3600- and NB-3200-type fatigue analyses. When existing fatigue usage was multiplied by F_{en}, a new fatigue usage reflecting environmental effects was obtained. A threshold criteria was used to eliminate load state pairs for which environmental correction was not necessary. The parameters in the mathematical expression for F_{en} were determined using information generally available to stress analysts.

Mathematical expressions for F_{en} and the approach for applications to NB-3600 and NB-3200 fatigue evaluations were developed. Materials considered were carbon and low-alloy steels, stainless steels, and Alloy 600 materials. The proposed approach was applied to several example cases: boiling water reactor (BWR) feedwater piping, BWR recirculation piping, feedwater nozzle safe end, and pressurized water reactor surge. A modest increase in calculated fatigue usage over that obtained using current Code procedures was noted.

RESULTS This report summarizes past and current studies of the environmental fatigue effects in LWR applications. Current Argonne and Japanese research efforts are reviewed and an approach to calculate an environmental correction factor is described. A description of how the proposed approach can be implemented in Section III, NB-3600- and NB-3200-type fatigue evaluations is presented along with examples of applying the approach to piping (NB-3600) and safe end fatigue evaluations. These procedures were applied to several BWR and PWR example cases. The results of these case studies indicated that there is generally a modest increase in calculated fatigue usage, which is considerably less than the results obtained when the NUREG/CR-5999 curves are applied directly. A proposed ASME Code Section III non-mandatory appendix are proposed is included in the back of this report. Finally, Section 7 provides a summary.

EPRI PERSPECTIVE The NRC has noted in SECY-95-245 that, although no immediate licensee actions are pending for operating nuclear plants, the concerns associated with Generic Safety Issue (GSI) 166 "Adequacy of Fatigue Life of Metal Components" will be evaluated as part of the license renewal process. EPRI's work in developing the environmental fatigue procedures in this report, as well as applying flaw tolerance fatigue evaluation procedures (EPRI TR-104691) are expected to provide practical solutions to many of the issues in GSI-166.

PROJECT

Work Order 3321-03

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Nuclear Power Group

System and Component Integrity Technology Program

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An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations

TR-105759

Work Order 3321-03
Final Report, December 1995

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INTRODUCTION

Pressure-retaining components in the light water reactor (LWR) primary systems are designed to meet the requirements of Section III of the ASME Boiler and Pressure Vessel Code or an equivalent Code. The Class I rules of Section III require a fatigue evaluation for the transient stresses that occur during normal/upset condition operation. The fatigue design curves in Section III are based on the cyclic life observed in strain-controlled fatigue tests conducted in air environment and include either a factor of two on stress or 20 on cycles over the mean curves. The effects of a high-temperature reactor water environment was not explicitly considered, although a factor of 4 in the factor of 20 on cyclic life was attributed to atmosphere.

Although there have been relatively few corrosion fatigue failures in materials typically used in LWR applications, the laboratory data generated in various test programs (e.g., EPRI-sponsored testing at GE, NRC-sponsored testing at Argonne, and testing conducted in Japan) indicate that fatigue lives shorter than the Code design values are possible, especially under low-frequency loading conditions in oxygenated water environments at elevated temperatures.

The laboratory testing identified strain rate, temperature, strain amplitude, and oxygen content as significant variables affecting the fatigue-initiation life. The laboratory testing has generally been with one or a combination of the significant variables held at a specified fixed value during the test. However, during the course of a typical plant transient, the temperature and the strain rate generally vary continuously; but the stress analyses are not detailed enough to evaluate the values of these variables. Furthermore, it is unreasonable to burden the piping or vessel stress analysts by requiring such detailed evaluation. Therefore, there is a need for simplified, but not overly conservative, procedures for ASME Section III, NB-3600- and NB-3200-type analyses in which reactor water environment effects need to be accounted for. The objective of this report is to review the current laboratory data and develop simplified procedures for use in ASME Code-type fatigue evaluations in operating nuclear power plants.

Section 2 of the report provides the background summary of the past and current studies conducted to evaluate the environmental fatigue effects in LWR applications. The current Argonne and Japanese research efforts are reviewed in Section 3, and the outline of an approach is described to calculate an environmental correction factor. How the proposed approach can be implemented in a Section III, NB-3600- and NB-3200-type fatigue evaluations is described in Section 4. Section 5 presents examples of applying the approach to piping (NB-3600) and safe end (NB-3200) fatigue evaluations.

Section 6 proposes changes to Section III fatigue evaluations procedures that might be considered by ASME Code Committees. A proposed ASME Section III non-mandatory appendix is included in the back of this report. Finally, Section 7 provides a summary.

2

BACKGROUND

Pressure-retaining components in the reactor primary systems are designed to meet the requirements of Section III of the ASME Boiler and Pressure Vessel Code [2-1] or an equivalent Code. In addition to prescribing stress limits for various applied loads (e.g., internal pressure, dead weight, thermal, and seismic), the Code also requires a fatigue evaluation for the transient stresses that occur during normal/upset condition operation. Specifically, the Code provides procedures for fatigue usage calculation and requires that cumulative fatigue usage, based on a conservative fatigue design curve, should be less than 1.0. The Code fatigue design curves were obtained from the results of strain-controlled fatigue tests on small specimens of austenitic and ferritic steels by applying a factor of two on stress or 20 on cyclic life to the mean curve. Reference 2-2 states that the factor of 20 on life is the product of the following subfactors:

Scatter of data (minimum to mean)	2.0
Size effect	2.5
Surface finish, atmosphere, etc.	4.0

W.E. Cooper in Reference 2-3 states that the *atmosphere* in the last line was intended to reflect the effects of an industrial atmosphere in comparison with an air-conditioned lab, not the effects of a specific coolant.

Since the introduction of Section III fatigue evaluation procedures, a number of studies on carbon, low-alloy, and stainless steels have shown that the fatigue life of laboratory specimens can be affected in the presence of a high-temperature water environment typically present in the reactor pressure vessels and associated piping. The amount of laboratory data has recently increased considerably with the work done at Argonne under NRC funding and in Japan under the auspices of the Thermal and Nuclear Power Engineering Society's EFD Committee. These studies indicate that the reduction in fatigue life under environmental conditions is a function of such variables as strain rate, strain range, dissolved oxygen level, temperature, and sulfur content of the steel (in the case of carbon and low-alloy steels). Both the Japanese and Argonne research are discussed in detail in the next section. Work, other than that of the Japanese and the Argonne researchers, is of some interest in terms of its historic perspective and is, therefore, briefly reviewed next. Also reviewed are the activities of the USNRC, DOE, and ASME.

2.1 A Brief Review of Earlier Studies on Environmental Effects

One of the earliest studies on the effects of a high-temperature water environment on low-cycle fatigue performance of materials typically used for LWR primary piping and internal structures was reported in Reference 2-4, based on the work conducted by GE for the Atomic Energy Commission under the auspices of the Reactor Primary Coolant Pipe Rupture Study. Testing was conducted in a test loop installed in ComEd's Dresden Unit 1 nuclear power plant. Four materials were included in the testing: Type 304 and 304L stainless steels, Inconel 600, and A 516 KC-70 carbon steel. The cyclic loading frequency was four cycles per hour. This study noted a reduction in fatigue performance of carbon steel material in the boiling water reactor (BWR) environment. However, all data fell above the ASME Section III design curve and, thus, the material was judged fully adequate for field performance.

References 2-5 and 2-6 reported on the results of a combined experimental/analytical program conducted under the auspices of EPRI. Two types of piping carbon steels (SA 106-Gr B and SA 333-Gr 6) were studied in air and high-temperature water environments. The study suggested several improvements in the fatigue analysis procedures: (1) a notch factor for local strains, (2) a mean stress factor, (3) improved fatigue strength reduction factor for butt welds, and (4) an environmental correction factor. A similar approach was presented in Reference 2-7. References 2-8 and 2-9 incorporated the results of References 2-5 and 2-6 into an approach suitable for ASME Code implementation.

Fatigue life of SA 106-B carbon steel in pressurized water reactor (PWR) environments has been reported by Terrel [2-10]. One of the conclusions of the study was that although PWR environment fatigue life of smooth specimens tested in the low-cycle regime do not appear to be affected by strain ratios of 0.05 and 0.50, notched specimens tested under the same conditions suggest a degradation in fatigue life as a result of positive strain ratios.

Investigations by James and coworkers [2-11] addressed the effect of environmental contaminants on the corrosion fatigue of SA 210-Gr A-1 carbon steel (0.014%S) boiler tubing. Although data applied to failure of fossil-fired water-tube boilers using all-volatile-treatment (AVT) or phosphate water chemistries, the temperature studied (274°C) and the nature of the results are of interest to LWR environment. A recent review of environmentally assisted fatigue crack initiation in low-alloy steels is given in Reference 2-12.

Some investigators have generated environmental fatigue S-N curves based on the hypothesis that the cycles to initiation or failure for an initially uncracked specimen might be predicted solely from the kinetics of crack propagation. The works of O'Donnel [2-13, 2-14] and Coffin [2-15] are notable in that area.

2.2 USNRC, DOE, and ASME Actions

The USNRC issued a Branch Technical Position (BTP) [2-16] outlining criteria to account for environmental effects on cyclic fatigue. The intent of this document was to provide license extension guidelines on fatigue of nuclear power plant components. The BTP prescribes a screening test where a penalty factor of 10 is applied to the calculated fatigue usage for carbon steel components in a BWR environment. Essentially, this meant that any carbon steel component with fatigue usage greater than 0.1 is not acceptable. For low-alloy ferritic steels, the penalty factor is 3.0.

Recently, Majumdar and Shack have proposed interim fatigue curves that are based on the Japanese data and other data from Argonne [2-17]. These proposed curves are discussed in more detail in the next section. To assess the significance of interim fatigue curves, Ware, et al. [2-18], performed fatigue evaluations of a sample of the components in the reactor coolant pressure boundary.

The Department of Energy (Sandia National Laboratories), in cooperation with EPRI, published a study [2-19] on evaluating conservatisms and the environmental effects in ASME Code, Section III, Class 1 fatigue analysis. The study concluded that the potential increase in predicted fatigue usage due to environmental effects should be more than offset by decreases in predicted fatigue usage if reanalysis were conducted to reduce the conservatisms present in existing component fatigue evaluations.

As part of its effort to reexamine ASME Code fatigue curves for environmental effects, the ASME Board of Nuclear Codes and Standards (BNCS) requested the Pressure Vessel Research Committee (PVRC) to evaluate the adequacy of the fatigue curves in Sections III and XI of the ASME Code in the light of current worldwide data on environmental effects. The PVRC steering committee on cyclic life and environmental effects in nuclear applications has completed an initial study and submitted a draft progress report [2-20] to the ASME/BNCS. More recent updates on the activities of the committee are given in References 2-21 and 2-22.

2.3 Objective of This Report

The laboratory testing has generally been conducted with any or a combination of these variables held at a specified fixed value during the test. However, during the course of a typical plant transient, the temperature and the strain rate generally are continuously varying, but the stress analyses are not detailed enough to evaluate the values of these variables. Furthermore, it is unreasonable to burden the piping or vessel stress analysts by requiring such detailed evaluation. Therefore, there is a need for simplified but not overly conservative procedures for both NB-3600- and NB-3200-type analyses in which reactor water environment effects need to be accounted for. The main objective of this report is to develop such simplified procedures.

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3

REVIEW OF CURRENT RESEARCH STUDIES ON ENVIRONMENTAL EFFECTS

The two major experimental efforts to characterize the effect of LWR environment on the fatigue-initiation lives of materials commonly used in reactor primary pressure boundary, are by the Japan EFD committee and the NRC-sponsored work at Argonne National Laboratory. The researchers associated with both of these efforts have also proposed analytical approaches to incorporate the environmental effects into the ASME Code-type fatigue analyses. The proposed approach in this report for Code fatigue evaluations considering environmental effects drew upon the best features of these two efforts. Each of these efforts are summarized in this section.

3.1 Review of Japanese Environmental Fatigue Research Results

One of the earliest Japanese studies investigating environmental effects on fatigue-initiation life of carbon and low-alloy steels in oxygen-containing high-temperature water was conducted by Higuchi and Iida [3-1 through 3-5]. An additional study on low-alloy steel was reported by Nagata, et al. [3-6]. The materials covered in Reference 3-5 were: (a) carbon steel pipe of specification STS42 in JIS G 3455, equivalent to ASME SA333 Gr.6, and (b) forged low-alloy steel of specification SFV3 in JIS G 3212-1977, equivalent to ASME SA508 Cl.3. The dissolved oxygen content ranged from 0.01 to 20 ppm. All of the tests were push-pull-type tests similar to those used in generating the original ASME Code fatigue curves. The initiation life in terms of cycles, N_{25}, was defined as the number of cycles to a 25% drop in tensile peak stress (at the maximum tensile strain in the hysteresis loop) from the maximum value in the characteristic cyclic curve of tensile stress in a test. Based on the test results, Higuchi and Iida suggested the following relationship:

$$N_{25W} = N_{25A} (\dot{\varepsilon}_T)^P \qquad \text{(Eq. 3-1)}$$

where

N_{25W} = Fatigue life (cycles) in water at temperature

N_{25A} = Fatigue life (cycles) in air at room temperature

$\dot{\varepsilon}_T$ = Strain rate during the rising phase of testing (%/sec)

P = Strain rate exponent dependent upon temperature and dissolved oxygen content

Equation 3-1 can be rewritten in the following form:

$$F_{en} = N_{25A}/N_{25W} = (\dot{\varepsilon}_T)^{-P} \qquad \text{(Eq. 3-2)}$$

The factor F_{en} can then be understood as an environmental correction in terms of cycles. Thus, a partial fatigue usage for a load state pair based on an air fatigue curve in an ASME Code fatigue analysis could be multiplied by F_{en} to obtain the fatigue usage with the environmental effects factored in.

Higuchi and Iida also defined a fatigue strength correction factor K_{en} as the following:

$$K_{en} = 1 + [(\dot{\varepsilon}_T)^{PB} - 1](1 - C/\varepsilon_{ta}) \qquad \text{(Eq. 3-3)}$$

where

B	=	-0.472 for carbon steels, -0.568 for low-alloy steels		
P	=	0.1 + MN		
M	=	Factor to account for dissolved oxygen (DO) content		
	=	0.0		DO ≤ 0.1 ppm
	=	(DO-0.1)/0.1)	0.1 <	DO < 0.2 ppm
	=	1.0		DO ≥ 0.2 ppm
N	=	Factor to account for temperature (T)		
	=	0.2T/100		T < 100°C (212°F)
	=	0.2	100°C (212°F) ≤	T ≤ 200°C (392°F)
	=	0.2 + 0.4(T-200)/100		T > 200°C (392°F)
C	=	0.00108 for carbon steels, 0.00140 for low-alloy steels		
ε_{ta}	=	Applied strain amplitude		

The factor K_{en} is a multiplier to be applied to the calculated value of alternating stress amplitude. Thus, if one were to use the Higuchi-Iida approach to account for the environmental effects in an ASME Code fatigue evaluation, the alternating stress amplitude S_a would be multiplied by this factor prior to entering the fatigue curve for determining the allowable number of cycles.

The following observations are made regarding the Higuchi-Iida model:

- Environmental effects are assumed to be significant down to 100°C (212°F). Recent data from Argonne and others indicate that the environmental effects are insignificant below 150°C [302°F] and that this threshold temperature might be as high as 200°C (392°F).

- The fatigue damage is assumed to saturate at the dissolved oxygen level of 0.2 ppm. This might have been due to the fact that a large number of tests were conducted at 8 ppm oxygen level and very few tests at 0.2 ppm level.

- There is a threshold strain amplitude level below which there is no environmental fatigue damage. This threshold strain amplitude level is equal to the constant C in Equation 3-3.

Most of the laboratory data has been generated at constant temperature and strain rate values. In contrast, plant components normally undergo varying temperatures and strain rates during plant operation. Accordingly, a number of experimental studies were performed by the Japanese researchers to determine the effective values of strain rate and temperature when these parameters are changing during the test [3-7 through 3-9]. The effective values are defined using the improved rate approach first developed by Asada [3-10]. An application of the effective damage parameters to LWR plant components is described in Reference 3-11.

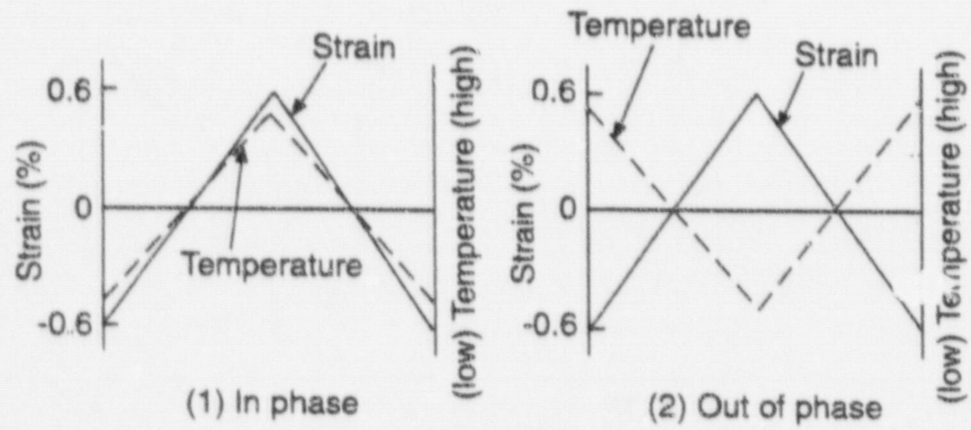

Figure 3-1
Patterns of Temperature and Strain Change Used in Reference 3-8.

The results from one of the important set of tests are described in Reference 3-8. In these tests, the temperature and strain rates were varied in-phase and out-of-phase as shown in Figure 3-1. The test results showed that the cyclic fatigue life under the in-phase temperature change was almost equivalent to that under the out-of-phase condition. The authors also concluded that fatigue life under changing temperature conditions could be predicted by the improved-rate method with fatigue lives at constant temperature. A fatigue life reduction factor *F'en* for changing temperature, oxygen content, and strain rate condition, was defined as:

$$F'_{en} = 1 + \int [(F_{en} - 1)/(\varepsilon_{max} - \varepsilon_{min})] d\varepsilon \qquad \text{(Eq. 3-4)}$$

where F_{en} is as defined in Equation 3-2, ε_{min} is minimum strain and ε_{max} is maximum strain in a strain cycle. Alternately, the cyclic life, N'_{25W}, under varying temperature conditions was defined as:

$$[1/N'_{25W}] = \int [1/N_{25W}][1/(T_{max} - T_{min})]dT \qquad \text{(eq. 3-5)}$$

where T_{max} and T_{min} are maximum and minimum temperatures, respectively. Using these concepts, the authors could establish a good correlation between predictions and actual leak cycles. Figure 3-2 shows a plot of the $1/N_{LEAK}$ as a function of test temperature. The data appears to support a threshold temperature of 180°C for the environmental effects. A concept similar to the preceding ones (such as F'_{en} and N'_{25W}) is developed later in this report and is used to calculate an effective value of factor F_{en}.

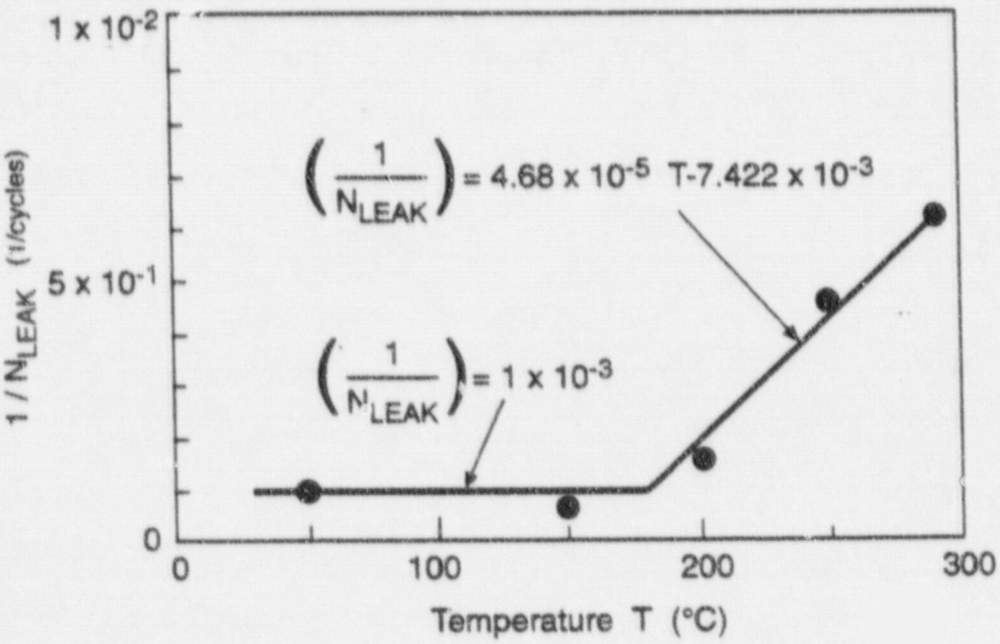

Figure 3-2
Relation between $1/N_{LEAK}$ and Temperature (Reference 3-8).

Other important information generated from the latest Japanese tests is the effect of oxygen concentration on environmental fatigue life. Figure 3-3 from Reference 3-8 shows fatigue life N_{25W} as a function of dissolved oxygen content. The data indicates that the reduction in fatigue life is gradual, from 0.1 ppm to 8 ppm oxygen level. This is in contrast to the Higuchi-Iida model in which the predicted fatigue life reduction reaches a maximum at 0.2 ppm and then does not change. Further discussion appears later in this section.

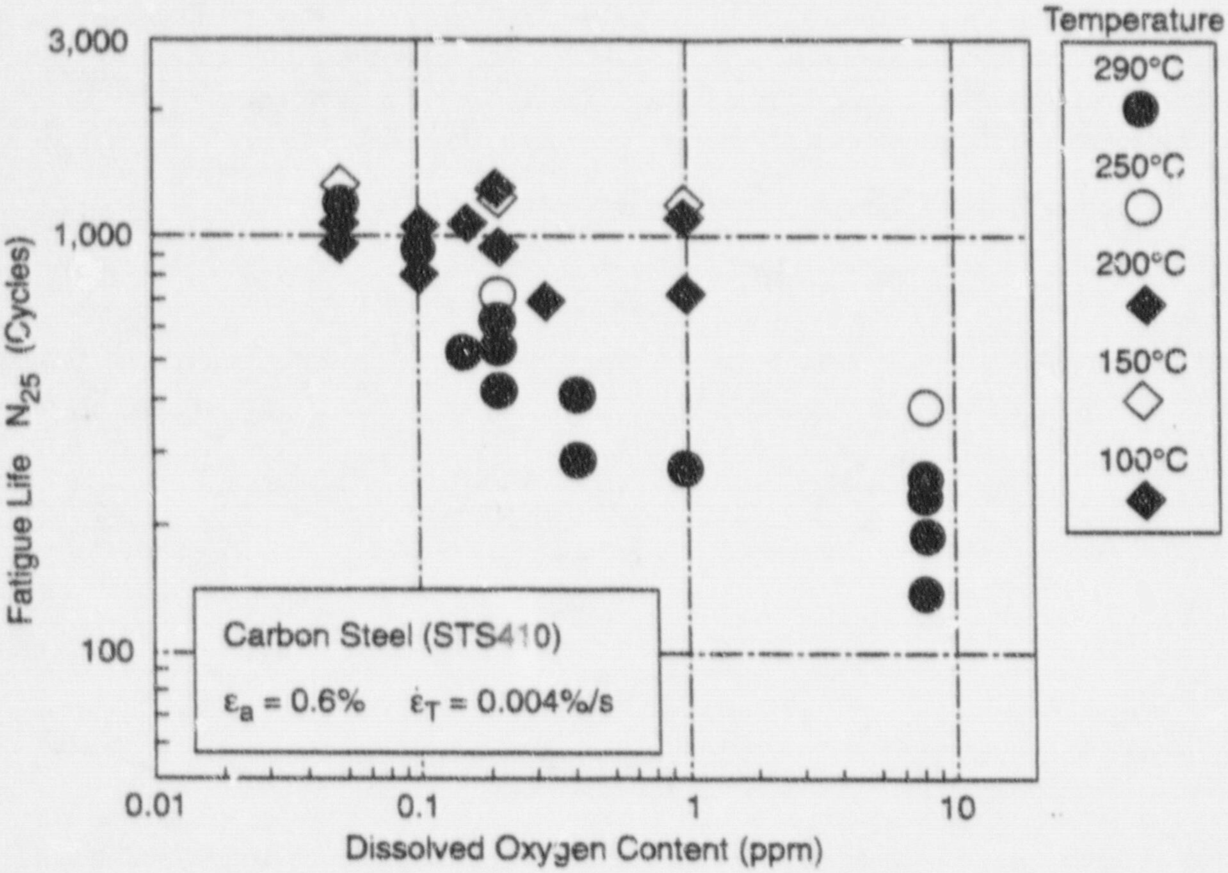

Figure 3-3
Effects of Dissolved Oxygen on Fatigue Life.

3.2 Review of Argonne Environmental Fatigue Research Results

Under NRC funding, extensive testing has been conducted at Argonne on the fatigue-initiation life of carbon, low-alloy, austenitic stainless steels, and Alloy 600 in LWR environments [3-12 through 3-15].

3.2.1 NUREG-5999

In NUREG-5999, the Argonne team developed interim fatigue curves based on a modification of the Higuchi-Iida equation:

$$N_W = N_A \, \phi(T) \, (\dot{\varepsilon})^P \quad \text{(Eq. 3-6)}$$

where $\phi(T) = 0.6e^{148.5/(T+273)}$

T = Temperature in Celsius

The values for strain exponent *P* for the high-sulfur (s > 0.008% by weight) case were slightly different from those given by Higuchi-Iida. For the *oxygenated water* case, the oxygen level was assumed to be 0.2 ppm. Figures 3-4 through 3-6 show the interim curves for various conditions and materials.

Equation 3-6 can be recast in terms of F_{en} as the following:

$$F_{en} = N_A/N_W = 1/[\phi(T)(\dot{\varepsilon})^P] \qquad \text{(Eq. 3-7)}$$

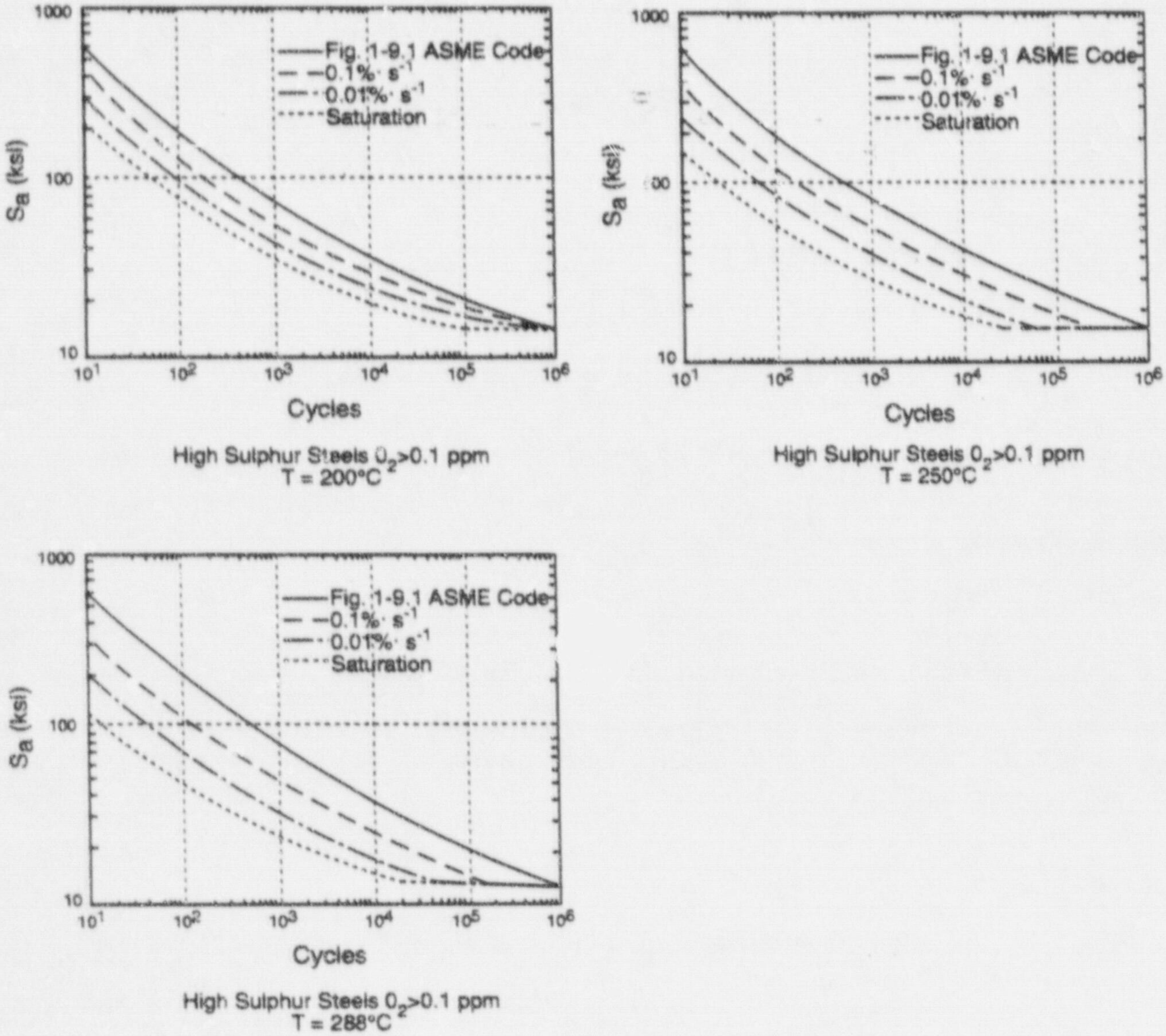

Figure 3-4
Proposed EAC-adjusted Design Fatigue Curves in NUREG/CR-5999 for High-sulfur Carbon Steels in Oxygenated Water at 200, 250, and 288°C.

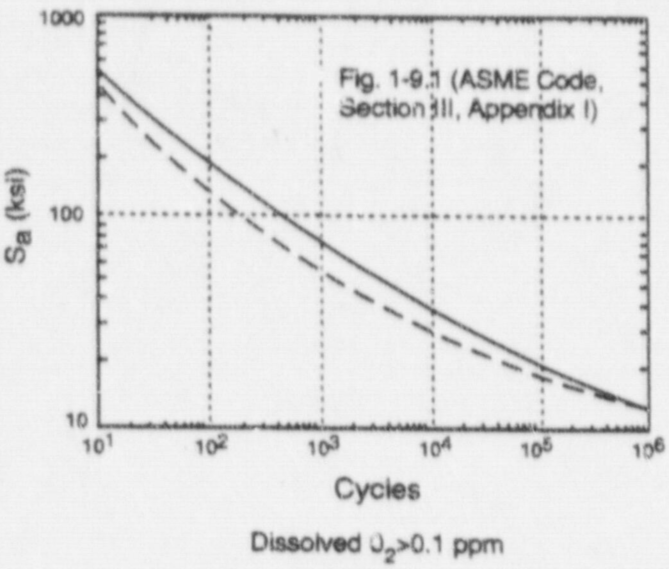

Figure 3-5a
Proposed EAC-adjusted Design Fatigue Curve in NUREG/CR-5999 for Carbon and Low-alloy Steels in Water with ≤ 0.1 ppm Dissolved Oxygen.

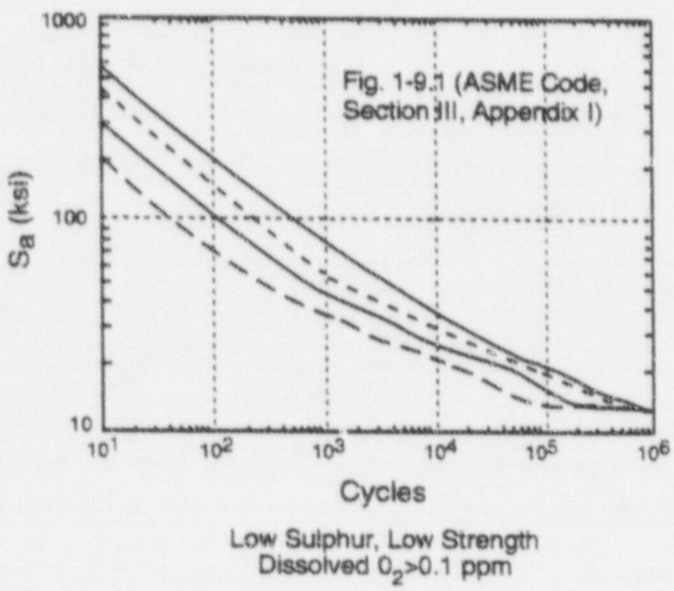

Figure 3-5b
Proposed EAC-adjusted Design Fatigue Curve in NUREG/CR-5999 for Low-sulfur Carbon Steels in Water with > 0.1 ppm Dissolved Oxygen.

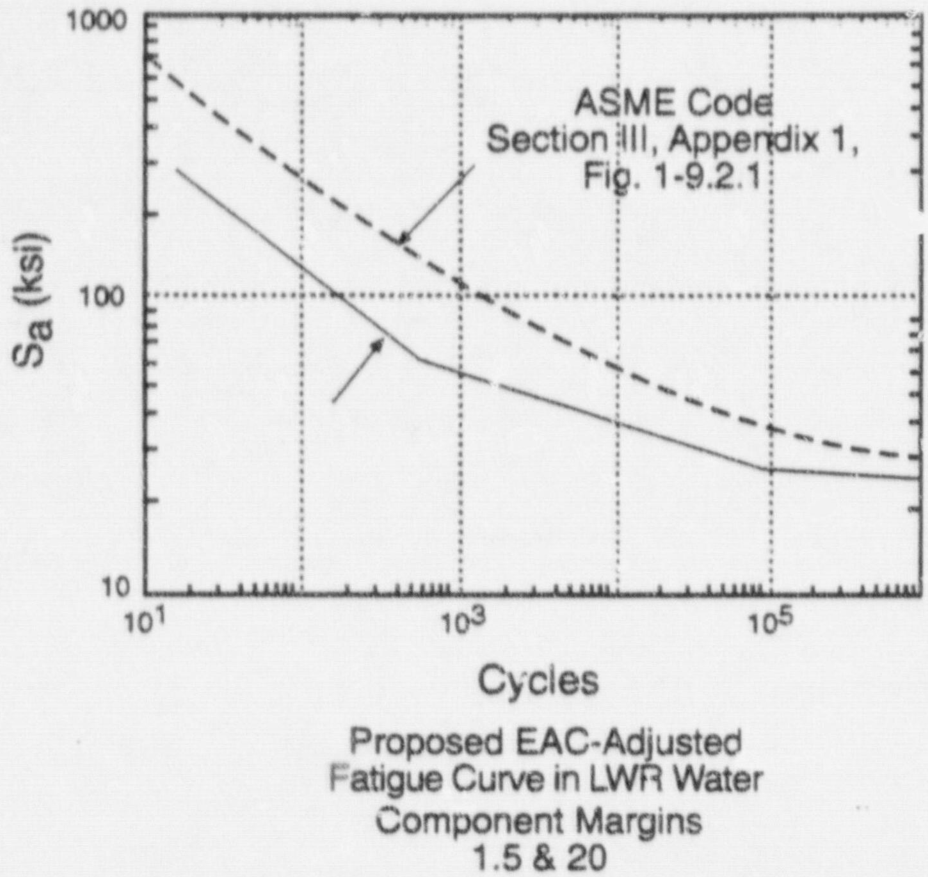

Figure 3-6
Proposed EAC-adjusted Design Failure Curves in NUREG/CR-5999 for Austenitic Stainless Steels in Water at Temperatures between 200 and 320°C.

3.2.2 Statistical Characterization

Following the NUREG-5999 work, the Argonne researchers presented a statistical analysis of existing fatigue S-N data, both foreign and domestic, for carbon steel and low-alloy steel, austenitic stainless steels, and Alloy 600 [3-15]. The statistical model considers the effects of various material, loading, and environmental conditions on fatigue-initiation life of these materials. The expressions are the following:

Carbon and Low-alloy Steels

$$\begin{aligned} ln(N_{25}) = \; & (6.667-0.766I_w) - (0.097-0.382I_w)I_s + 0.52F^{-1}[x] \\ & -(1.687+0.184I_s)ln(\varepsilon_a-0.15+0.04I_s+0.026F^{-1}[1-x]) \\ & -0.00133T'(1-I_w) + 0.554S^*T^*O^*\dot{\varepsilon}^* \end{aligned} \quad \text{(Eq. 3-8)}$$

where

N_{25}	is the fatigue life defined as the number of cycles for the peak tensile stress to drop 25% from its initial value (consistent with Higuchi-Iida definition)
ε_a	is the applied strain amplitude in %
$F^{-1}[x]$	is the inverse of the standard normal cumulative distribution function for the xth percentile of probability
T	is the test temperature in °C
I_w	is = 1 for water and = 0 for air environment
I_s	is = 1 for carbon steel and = 0 for low-alloy steel

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

$S^* = S$ $(0<S<0.015\ wt\%)$
$S^* = 0.015$ $(S>0.015\ wt\%)$

$T^* = 0$ $(T< 150°C)$
$T^* = T-150$ $(T> 150°C)$

$O^* = 0$ $(DO<0.05\ ppm)$
$O^* = DO$ $(0.05\ ppm < DO < 0.5\ ppm)$
$O^* = 0.5$ $(DO > 0.5\ ppm)$

$\dot{\varepsilon}^* = 0$ $(\dot{\varepsilon} > 1\%/sec)$
$\dot{\varepsilon}^* = ln(\dot{\varepsilon})$ $(0.001 \leq \dot{\varepsilon} \leq 1\%/sec)$
$\dot{\varepsilon}^* = ln(0.001)$ $(\dot{\varepsilon} < 0.001\%/sec)$

Austenitic Stainless Steels

$$ln(N_{25}) = 6.69 + 0.52F^{-1}[x] - 1.98ln(\varepsilon_a-0.1225+0.026F^{-1}[1-x]) + 0.382I_{316N} + I_w(0.134\dot{\varepsilon}^* - 0.359) \quad \text{(Eq. 3-9)}$$

where I_{316N} is = *1* for Type 316NG stainless steels and = *0* otherwise. All other terms are as defined in Equation 3-7.

Alloy 600

$$ln(N_{25}) = 6.94 + 0.42F^{-1}[x] - 1.776ln(\varepsilon_a-0.12+0.021F^{-1}[1-x]) + 0.498I_T - 0.401I_w \quad \text{(Eq. 3-10)}$$

where I_T is = *0* for <150°C and is = *1* for 150-320°C. All other terms are as defined in Equation 3-7.

3.3 Evaluation of the Various Approaches

The Higuchi-Iida approach and the NUREG/CR-5999 approach presented earlier are in the form of an environmental correction factor on the cycles, which is convenient for use in the ASME Code fatigue evaluations. Therefore, the Argonne statistical equations were recast in terms of an environmental damage factor on cycles F_n (as defined in Equation 3-2):

Carbon Steel

$$F_{en} = N_{25A}/N_{25W} = exp\ (+0.384 - 0.00133T - 0.554S^{*}T^{*}O^{*}\dot{\varepsilon}^{*}) \quad \text{(Eq. 3-11)}$$

Low-alloy Steel

$$F_{en} = N_{25A}/N_{25W} = exp\ (+0.766 - 0.00133T - 0.554S^{*}T^{*}O^{*}\dot{\varepsilon}^{*}) \quad \text{(Eq. 3-12)}$$

Stainless Steels Except 316NG

$$F_{en} = N_{25A}/N_{25W} = exp\ (+0.359 - 0.134\dot{\varepsilon}^{*}) \quad \text{(Eq. 3-13)}$$

Type 316NG Stainless Steel

$$F_{en} = N_{25A}/N_{25W} = exp\ (-0.023 - 0.134\dot{\varepsilon}^{*}) \quad \text{(Eq. 3-14)}$$

Alloy 600

$$F_{en} = N_{25A}/N_{25W} = exp\ (0.401) = 1.49 \quad \text{(Eq. 3-15)}$$

Note that the ratio in the preceding equations is between the at-temperature air cycles to at-temperature water environment cycles. In the Higuchi-Iida case and in the modified Higuchi-Iida equations used in NUREG/CR-5999, the ratio was defined between the room temperature air cycles and the at-temperature water environment cycles.

Some observations regarding the preceding expressions:

- Both the carbon and low-alloy steel factors have a temperature dependency. This comes from the fact that the air fatigue curves in the Argonne database have temperature dependency.
- The Alloy 600 factor is a constant, implying that no matter what the environmental parameters are, there is always a reduction in fatigue cyclic life in the LWR environment.
- The probability terms cancel out when the same percentile probability levels are used for both the air and water environments.

- The presence of a constant term in the exponent of carbon and low-alloy steels means that even if any of the O^*,S^*,T^* or $\dot{\varepsilon}^*$ terms are zero (i.e., any of these parameters satisfy a threshold criteria value), the calculated value of F_{en} is still greater than 1.0, implying some residual environmental effect. A similar conclusion also applies for stainless steels.

A key output from the environmental fatigue testing is generally a predicted or implied value of F_{en} (or, equivalently, K_{en}) as a function of a set of environmental variables such as the sulfur content, DO, strain rate, and temperature. The preceding review of the Japanese and the Argonne research results indicates that there are basically three distinct approaches to calculating the environmental fatigue correction factor, F_{en}. The first one is that proposed by Higuchi-Iida, as shown in Equation 3-2. The Argonne-modification of the Higuchi-Iida proposal (Equation 3-7) represents the second approach, which formed the basis of the NUREG/CR-5999 interim fatigue curves. Equations 3-11 through 3-14 are derived from the statistical characterizations in NUREG/CR-6335 and represent the third approach. It is instructive to compare the F_{en} values predicted by the three approaches.

Figures 3-7(a) through (c) show a comparison of the predicted F_{en} values for carbon steels using the three approaches. The pred[illegible] values at three constant temperatures (289°C, 250°C, and 200°C) are plotted [illegible]ction of dissolved oxygen content. The assumed strain rate was 0.001% pe[illegible]d and the sulfur content was assumed as 0.015% by weight. As expected, the [illegible] approaches yield significant differences in the predicted values between the DO levels of 0.1 and 0.5 ppm. In the first two approaches, DO effects are accounted for between 0.1 to 0.2 ppm; after which the DO effect is assumed to saturate at 0.2 ppm. In contrast, the Argonne statistical fit (the third approach) incorporates the DO effect gradually from 0.05 ppm to 0.5 ppm. The differences in the predicted F_{en} values are especially significant at 0.2 ppm DO, the nominal DO level for BWRs operating with normal water chemistry (NWC). For example, at 289°C (Figure 3-7a), the Higuchi-Iida approach predicts a value of 92.9 and the Argonne modification of the Higuchi-Iida approach (the second approach) predicts a lower value of 41.9. On the other hand, the Argonne statistical fit predicts a value of 4.93 only. To assess whether the predicted trend of the Argonne statistical model with respect to the DO level is realistic, its predictions of cyclic life were compared with the experimentally obtained cyclic life where the DO level was systematically varied from 0.05 ppm to 8.0 ppm. Blunt notch cyclic fatigue-initiation test data reported in Reference 2-5 was also examined.

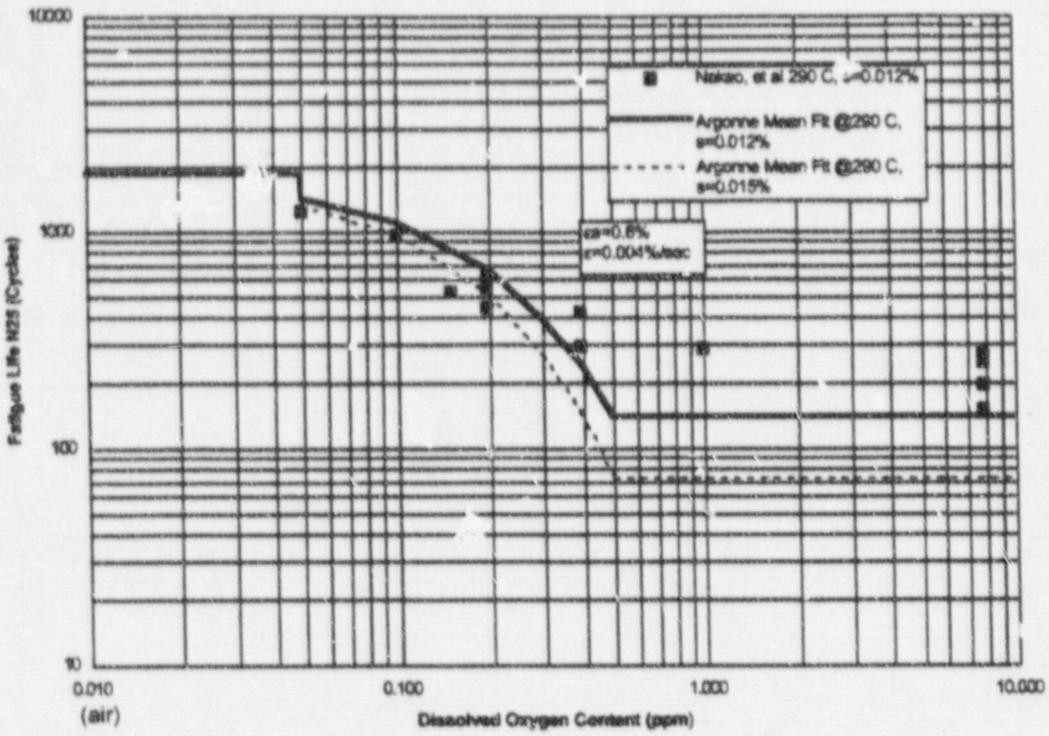

Figure 3-8a
Comparison of Nakao, et al., N_{25} Carbon Steel Cyclic Life Test Data and Argonne Statistical Mean Fit at 290°C.

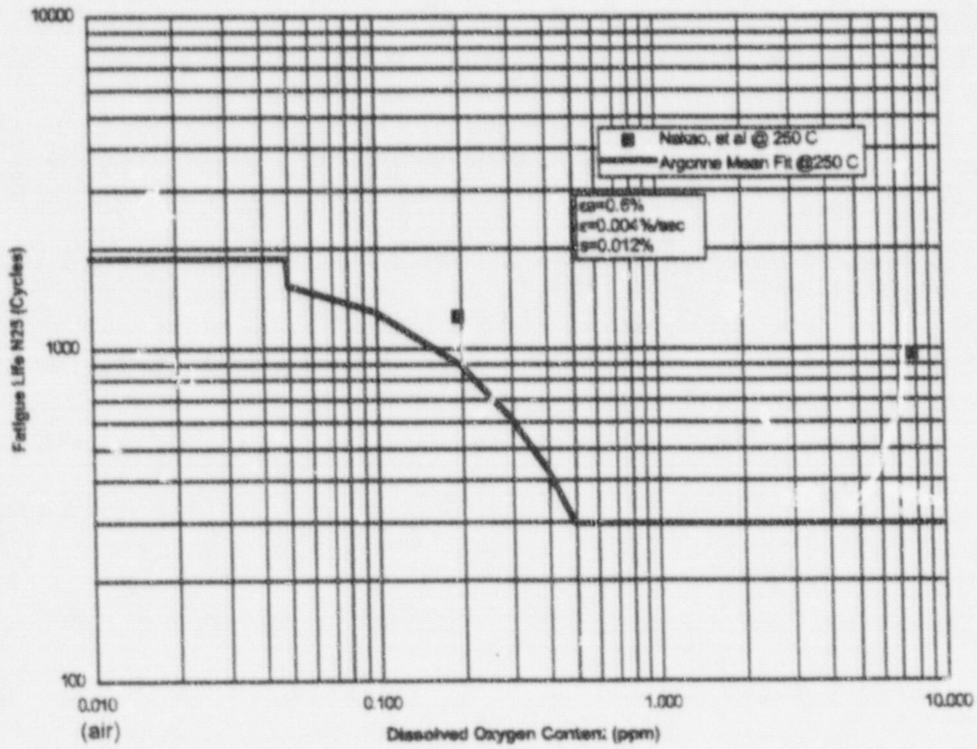

Figure 3-8b
Comparison of Nakao et al., N_{25} Carbon Steel Cycle Life Test Data and Argonne Statistical Mean Fit at 250°C.

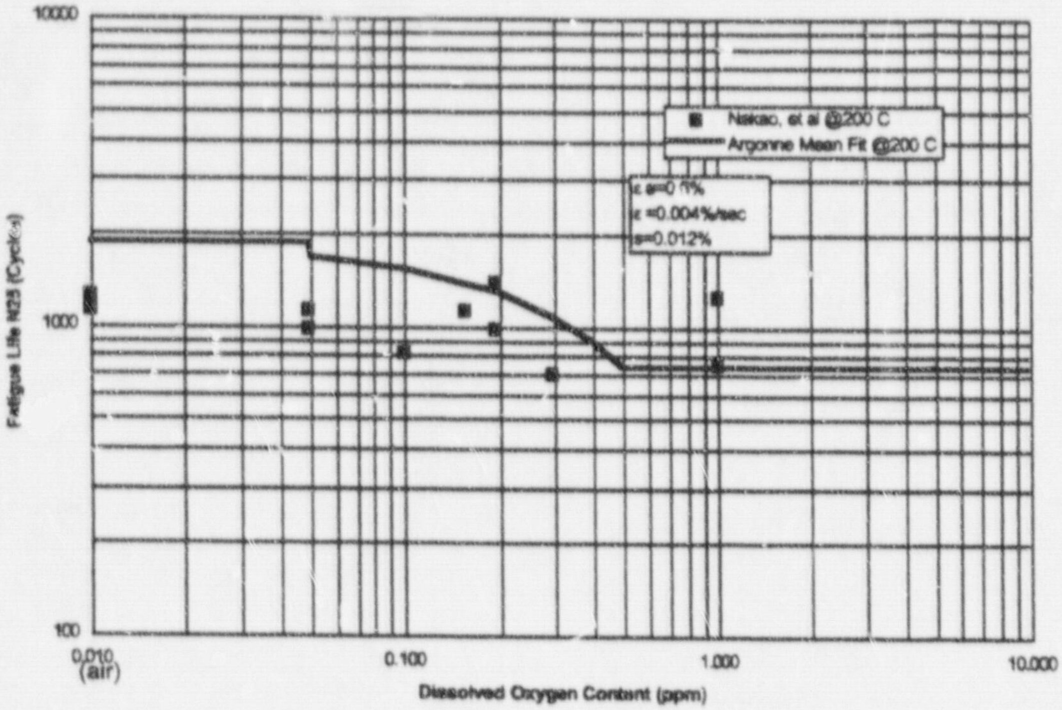

Figure 3-8c
Comparison of Nakao, et al., N_{25} Carbon Steel Cycle Life Test Data and Argonne Statistical Mean Fit at 200°C.

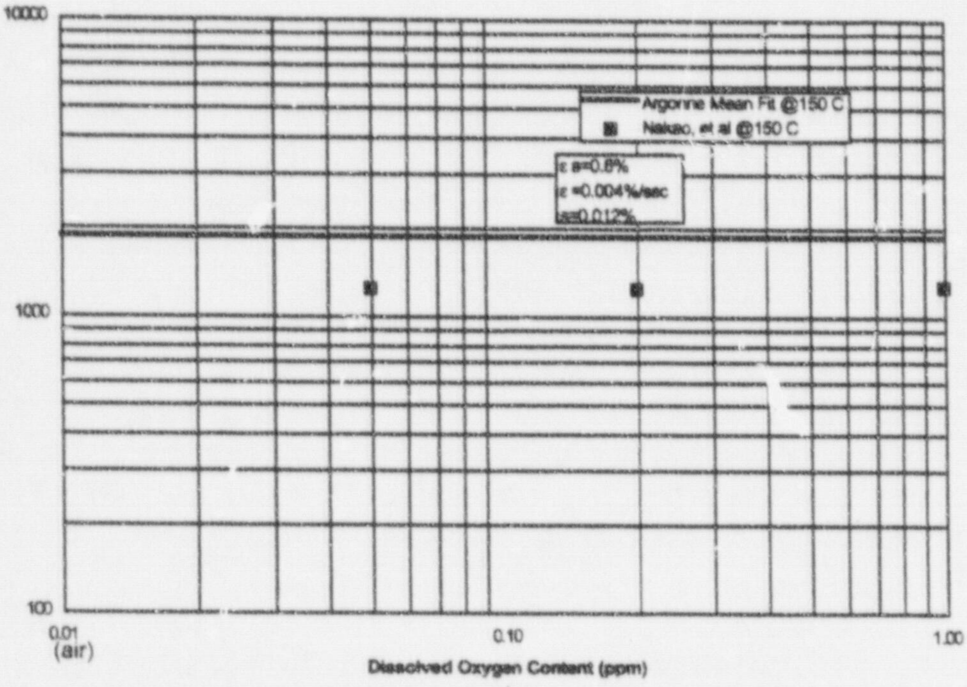

Figure 3-8d
Comparison of Nakao, et al., N_{25} Carbon Steel Cycle Life Test Data and Argonne Statistical Mean Fit at 150°C.

Figure 3-9 shows the cyclic fatigue-initiation life results for blunt notch test specimens at various DO levels. The data on the extreme left, although plotted as with 0.01 ppm DO, is, in fact, in the air environment. The material was SA 333 Gr. 6 carbon steel and the test temperature was 550°F. The initiation was defined as a crack growth of 0.016 inch. A review of Figure 3-9 clearly indicates that there is a significant difference between the cyclic life at 0.2 ppm DO and that at 8 ppm DO.

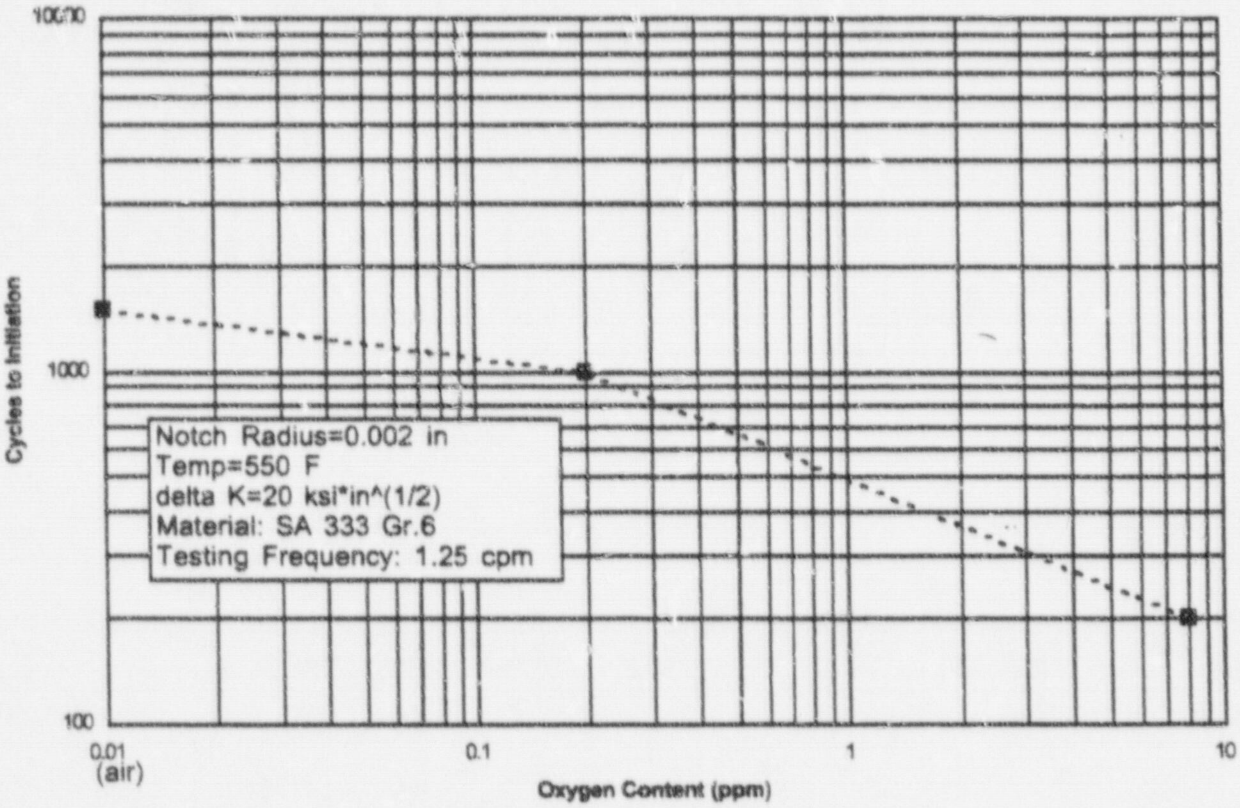

Figure 3-9
Blunt Notch CT Crack Initiation Test Results.

From the preceding review of cyclic fatigue life data, it can be concluded that the predicted trend in cyclic life reduction as a function of DO by the Argonne statistical model is far more realistic compared to the other two models. Therefore, Equations 3-11 through 3-14 were used in this report for application to ASME Code fatigue evaluations, as described in Section 4.

3.4 Environmental Effects Thresholds

The information in this subsection is based on the work reported by Van Der Sluys and Yukawa [2-21 and 2-22] as a part of the PVRC effort.

Although the detrimental effect on S-N life can be large for the worst combinations of environmental parameters, these worst-case combinations generally are not typical of LWR operating conditions. The combination of very low strain rates and relatively large strain ranges that result in large environmental effects do not seem to be typical of events in operating plants. In addition, the high oxygen levels at which much of the data have been obtained are above the levels typical of BWR plants. Therefore, one of the tasks in the PVRC activity consisted of defining a tentative set of criterion values for test and material parameters where the environmental effects would be expected to be moderate or acceptable. This required quantifying *moderate* or *acceptable* environmental effects with respect to the air environment data used in developing the ASME Code fatigue design curves. Recalling that the analysis of the collected air environment test data indicated a factor of about four for temperature and data scatter effects, a factor of four on the ASME mean life was chosen as a working definition of moderate or acceptable water environment effect.

Based on the examination of the database, Van Der Sluys and Yukawa determined that values of independent parameters listed below should result in only a moderate detrimental effect on cyclic life of carbon and low-alloy steels.

Parameter	Range
Strain amplitude	≤ 0.1%
Strain rate	≥ 0.1%/sec
Oxygen content	≤ 0.1 ppm
Temperature	≥ 150°C or 300°F
Sulfur content	< 0.003%
Fluid velocity	> 10 ft/sec or 3 m/sec

Note that independent means that only one criterion needs to be satisfied, regardless of the values of the other parameters. It has been observed that, to have a large effect of the environment on the S-N fatigue life, a critical combination of conditions is necessary. If any one of the conditions is missing, the effect of the environment on fatigue life will be moderate. For example, if the strain rate is greater than 0.1% per second, only a moderate environmental effect is expected, even if the dissolved oxygen is high, the temperature is 288°C, and the material has a high sulfur content.

Reference 2-22 presented a plot, shown here as Figure 3-10, which demonstrated the validity of the values derived for each of the independent criterion for moderate environmental effects for carbon and low-alloy steels. From Figure 3-10, it is seen that a factor of four on the ASME mean curve encompasses a large portion of the data for tests that meet any one of the independent criterion value. Another consistency check of the criterion values can be made by using the Argonne statistical model. From Figure 3-7a, it is seen that the predicted value of F_{en} for parameter values of 0.1 ppm DO, 289°C, 0.015% sulfur, and 0.001% per second strain rate is 2.2. The corresponding value for the low-alloy steel is 3.2. These values are well within the factor of four.

A major task of the PVRC Working Group on S-N data analysis is the validation of each of the criterion listed above, specifically the sulfur content and the flow-velocity criterion. Nevertheless, for this report, it was judged that each threshold criterion value is reasonable and can be used in evaluating the environmental fatigue life of carbon and low-alloy steels.

For the stainless steels, the PVRC Working Group has not yet recommended the threshold values for strain amplitude and strain rate. Nevertheless, a review of the LWR-type water environment test data for annealed austenitic steels and nickel-base Alloy 600 presented in Reference 2-22 indicates that a threshold strain amplitude level of 0.1% might be justified for these materials also. The strain rate threshold for the purpose of this report was assumed as 0.1% per second, as in the case of carbon and low-alloy steels.

A strain amplitude of 0.1% is equivalent to a pseudo stress amplitude of (0.1x30000/100) or 30 ksi. Because the Code fatigue curve for carbon and low-alloy steels uses a value of 30,000 ksi for *E*, the same value was used in this calculation also. In the case of stainless steel and Alloy 600 for which the Code fatigue curve uses a value of 28,300 ksi, the corresponding threshold alternate stress amplitude would be 28.3 ksi.

If the alternating stress amplitude associated with any load set pair in an ASME Code fatigue evaluation is less than the preceding value, then that load state pair can be dropped from the environmental effects considerations. Similarly, if the strain rate exceeds 0.1% per second, then the environmental effects need not be considered. A seismic event meets this criteria as shown next.

If the seismic stress amplitude is less then the threshold alternating stress value discussed earlier, then it is automatically excluded from the environmental effects considerations. Now, consider the case when the seismic strain amplitude is at slightly higher than the 0.1% level. To calculate the strain rate, we need to divide it by the rise time in seconds. The seismic event encompasses a range of frequencies from as low as few Hertz to 20 Hertz and higher. For the sake of this calculation, a frequency of 5 Hertz is assumed. Assuming a sine wave form, the rise time is expected to be 1/4 of the time duration for one cycle. Accordingly, the estimated rise time for this case would be 1/(5x4) or 0.05 seconds, giving a strain rate of 0.1/0.05 or 2.0% per second. This strain rate clearly meets the strain rate threshold criterion of 0.1% per second. Based on this, it is concluded that the load state pair consisting of a seismic event can be excluded from consideration of environmental effects.

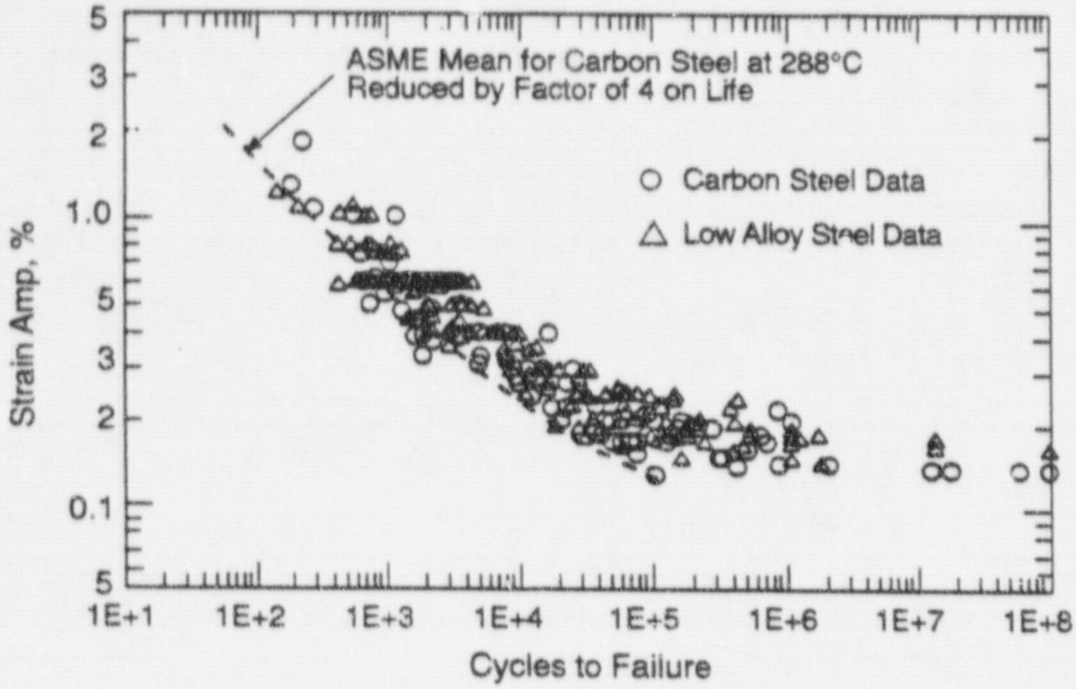

Figure 3-10
Compilation of LWR-type Water Environment Test Data Satisfying Any of the Independent Criteria for Moderate Environmental Effects and Comparison to ASME Mean Curve Reduced by a Factor of 4 on Life.

3.5 Summary of Review

The review indicated that the Argonne statistical model provides a reasonable basis for developing methods to include environmental effects in ASME Code fatigue evaluations. Therefore, F_{en} equations based on the Argonne statistical model were developed for use in ASME fatigue evaluations. The tentative threshold values suggested by the PVRC group appear to be reasonable and were used in developing the fatigue design rules as discussed in the next section. Load state pairs associated with the seismic events should be excluded from the consideration of environmental fatigue effects.

3.6 References

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[3-14] O.K. Chopra and W.J. Shack. "Effects of LWR Environments on Fatigue Life of Carbon and Low-Alloy Steels." ASME PVP-Vol. 306, 1995.

[3-15] J. Keisler, O.K. Chopra, and W.J. Shack. "Fatigue Strain Life Behavior of Carbon and Low-Alloy Steels, Austenitic Stainless Steels, and Alloy 600 in LWR Environments." NUREG/CR-6335. August 1995.

4

PROPOSED FATIGUE EVALUATION PROCEDURE

This section describes the details of the proposed methodology to account for the environmental effects in the ASME Code fatigue evaluations. Before describing the details of this methodology, it is helpful to first summarize the current ASME Section III Code fatigue-evaluation approach.

4.1 ASME Section III, NB-3600 and NB-3200 Fatigue Analysis Methodology

References 2-18 and 2-19 summarize the current ASME Code fatigue procedures for piping and vessels. The current Code fatigue methodology described in this section is extracted from these references. The stresses for the fatigue analysis are elastically computed. ASME Code NB-3600 methodology is used almost exclusively for piping and sometimes for branch nozzles. The ASME Code, Section III, NB-3200 (design by analysis) methodology is applicable to any component. It is generally used exclusively for vessels (sometimes augmented by NB-3300), fairly frequently for nozzles, and occasionally for piping.

4.1.1 ASME Code NB-3600 Fatigue Analysis Method

The equations for service levels A and B are provided to ensure satisfactory cyclic (fatigue) behavior. To satisfy the range of primary-plus-secondary stresses, Equation 10 (Reference 4-1) must be satisfied. The stress range is calculated based on the effect of changes that occur in mechanical or thermal loadings that take place as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to any other load set that could also exist. The following must be satisfied for all pairs of load sets:

$$S_n = C_1 \frac{P_0 D_0}{2t} + C_2 \frac{D_0}{2I} M_i + C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b| \leq 3S_m \qquad \text{(Eq. 4-1)}$$

where

C_1, C_2, C_3 = secondary stress indices for the specific component under investigation (defined in Table NB-3681(a)-1 of Reference 4-1)

D_o, t, I, S_m = as defined in Equation 9 of Reference 4-1

P_o = range of service pressure, psi.

M_i	=	resultant range of moment which occurs when the system goes from one service load set to another, in-lb
E_{ab}	=	average modulus of elasticity of two sides of a material or structural discontinuity at room temperature, psi
α_a, α_b	=	coefficient of thermal expansion on side *a* and side **b** of a structural or material discontinuity, in/in-°F
T_a, T_b	=	range of average temperature on side a and side b of a structural discontinuity, when the system goes from one service load to another, °F

The fatigue resistance of each piping component is assessed by evaluating the range of peak stress. For every pair of load sets, S_p values are calculated using the following equation (Reference 4-1, Equation 11) :

$$S_p = K_1C_1\frac{D_0P_0}{2t} + K_2C_2\frac{D_0}{2I}M_i + K_3C_3E_{ab}\,|\alpha_aT_a - \alpha_bT_b| + \frac{1}{2(1-\nu)}K_3E\alpha|\Delta T_1| + \frac{1}{1-\nu}E\alpha|\Delta T_2| \qquad \text{(Eq. 4-2)}$$

where

K_1, K_2, K_3	=	local stress indices for the specific component under investigation (defined in Table NB-3681(a)-1 of Reference 4-1)
$E\alpha$	=	modulus of elasticity (E) times the mean coefficient of thermal expansion (α), both at room temperature, psi/°F
ΔT_1	=	range of the temperature difference for each load set pair between the temperature of the outside surface T_o and the temperature of the inside surface T_i of the piping product, assuming a moment generating equivalent linear temperature distribution, °F
ΔT_2	=	range for that portion of the nonlinear thermal gradient through the wall thickness not included in ΔT_1, °F
ν	=	Poisson's ratio

A load set pair is defined as two loading sets or cases used to compute a stress range.

If Equation 4-1 cannot be satisfied for all load set pairs, the alternative analysis described below may still permit qualifying the component. Only those load set pairs that do not satisfy Equation 4-1 need to be considered.

where

M_i = moment as defined for Equation 9 of Reference 4-1, in-lb, and all other terms as previously described

C'_3 = stress index (values defined in Table NB-3681 (a)-1 of Reference 4-1)

If these conditions are met, the value of S_{alt} shall be calculated by the following equation:

$$S_{alt} = K_e \frac{S_p}{2} \qquad \text{(Eq. 4-6)}$$

where K_e is as defined later and

S_{alt} = alternating stress intensity, psi

S_p = peak stress intensity value calculated by Equation 4-2, psi

The alternating stress for all load set pairs is computed as one-half of the peak stress ranges calculated from Equation 4-2, or by the alternate approach of Equation 4-6 if Equation 4-1 is not met. The fatigue analysis is then performed using the applicable Code fatigue curve and the number of design cycles for each load case from the design specification.

For ASME Section III Code editions prior to the Summer 1979 Addenda, Equation 4-1 contained an additional term. In these earlier Code editions, the ΔT_1 term of the peak stress in Equation 4-2 was also included in the primary plus secondary stress Equation 4-1:

$$S_n = C_1 \frac{P_0 D_0}{2t} + \frac{C_2 D_0}{2I} M_i + C_3' E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| + \frac{E\alpha \left| \Delta T_1 \right|}{2(1-\nu)} \le 3S_m \qquad \text{(Eq. 4-7)}$$

Adding this term frequently increased the stress S_n above $3S_m$. When this occurred, Equations 4-3 and 4-5 had to be met, and the fatigue analysis was conducted using a relatively high K_e factor, increasing the alternating stresses used in the fatigue analysis. The ASME Section III Committee on Piping Design decided that this was overly conservative and modified the equation accordingly, starting with the Summer 1979 Addenda. However, most current Section III plants were designed according to the earlier version of the Section III Code.

The following equation must be met (Reference 4-1, Equation 12):

$$S_e = C_2 \frac{D_0}{2I} M_i^* \leq 3S_m \quad \text{(Eq. 4-3)}$$

where

S_e	=	nominal value of expansion stress, psi
M_i^*	=	same as M_i in Equation 4-1, except that it includes only moments due to thermal expansion and thermal anchor movements, in-lb

When the limits of Equation 4-1 are exceeded, and before the rules of Equation 4-5 can be used, the value of the range of ΔT_1 cannot exceed that calculated per NB-3653.7, as follows:

$$\Delta T_1 \; range \leq \frac{y' S_y}{0.7 E\alpha} C_4 \quad \text{(Eq. 4-4)}$$

where

y'	=	3.33, 2.00, 1.20, and 0.80 for x = 0.3, 0.5, 0.7, and 0.8, respectively
x	=	$(PD_o/2t)(1/S_y)$
P	=	maximum pressure for the set of conditions under consideration, psi
C_4	=	1.1 for ferritic material
	=	1.3 for austenitic material
$E\alpha$	=	as defined in Reference 4-1, Equation 11, psi/°F
S_y	=	material yield strength value, psi, taken at average fluid temperature

Note that the limitations on the ΔT_1 range are to ensure that thermal ratcheting due to the transient under consideration does not occur.

The primary-plus-secondary membrane plus bending stress intensity, excluding thermal bending and thermal expansion stresses, will be <3 S_m. This requirement is satisfied by meeting the following equation:

$$C_1 \frac{P_0 D_0}{2t} + C_2 \frac{D_0 M_i}{2I} + C_3' E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3S_m \quad \text{(Eq. 4-5)}$$

Step 6. For each pair of load sets, the six components of stress are subtracted and the three principal stress ranges are computed. The peak stress-intensity range for each pair is computed by subtracting the principal stresses, as described in Step 4, and choosing the largest.

Step 7. The S_{alt} for each load set pair is one-half the peak stress intensity range. To adjust for temperature and material, S_{alt} is multiplied by the ratio of the modulus of elasticity on the appropriate fatigue curve to the modulus of elasticity used in the analysis. The allowable number of cycles N_i for each load set pair is read from the appropriate design fatigue curve.

Step 8. The individual fatigue usage factor u_i at each location is determined by the ratio of the number of design cycles (n_i) to the allowable cycles (N_i) for each pair of load sets. Once the individual usage factor for the load set pair with the largest S_{alt} is computed, the cycles associated with that load set pair are eliminated, and the process is repeated until the cycles associated with all the load sets have been exhausted.

Step 9. The cumulative usage factor (CUF) is the sum of the individual usage factors. The ASME Code Section III limit is that the CUF at each location must not exceed 1.0. This assumes a linear damage relationship, known as Miner's rule.

As stated in Step 4, if the primary plus secondary stress intensity range S_n for a load state pair does not meet the $3S_m$ limit, a multiplier, the K_e factor, is applied to the peak stress intensity to adjust for the effects of plasticity:

$$S_{alt} = \frac{1}{2} K_e S_p \qquad \text{(Eq. 4-8)}$$

where

S_p = peak stress-intensity range

$$K_e = 1.0 \text{ for } S_n \le 3S_m$$

$$= 1.0 + \frac{(1-n)}{n(m-1)}\left(\frac{S_n}{3S_m} - 1\right) \text{ for } 3S_m < S_n < 3mS_m \qquad \text{(Eq. 4-9)}$$

$$= \frac{1}{n} \text{ for } S_n \ge 3mS_m$$

where

S_n = primary plus secondary stress intensity range

S_m = design stress intensity

and m and n are defined as follows:

4.1.2 ASME Code NB-3200 Fatigue Analysis Method

The first step in the NB-3200 fatigue evaluation methodology is to calculate the stress differences and the alternating stress intensity S_{alt} in accordance with NB-3216. The stress state changes occur as a result of changes in the mechanical and thermal loadings as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to any other load set that could also exist. The following procedure is generally followed:

Step 1. The analyst must obtain a set of loadings for the component. This is generally in the form of a set of design- and service- level transients in the design specification. These loadings define the temperature and pressure changes that the component is expected to undergo during its lifetime and the number of cycles n_i for each of the i loadings.

Step 2. The analyst needs to determine the stress distribution at the most highly stressed locations in the component. This includes the thermal and pressure stresses, and sometimes the preload stresses and thermal expansion stresses imposed on the component by the connecting piping. The determination of stress distributions generally requires a finite element temperature and stress analysis.

Step 3. The three principal primary-plus-secondary stresses (S_1, S_2, and S_3) for each load set need to be determined. This sometimes involves separating the peak stress from the total stress, such as by linearizing the thermal stress distribution. Also, one needs to take into account the possibility of rotating the principal stresses at the point being considered during the stress cycle.

Step 4. From the results of Step 3, three stress intensities are calculated by subtracting the principal stresses.

$$S_{12} = S_1 - S_2$$
$$S_{23} = S_2 - S_3$$
$$S_{13} = S_1 - S_3$$

The maximum primary-plus-secondary stress-intensity range is the largest difference between the S_{12}, S_{23}, or S_{13} values, determined by comparing the stress intensities of all the load sets. Two values (one with the highest tensile stress intensity and the other with the highest compressive stress intensity of all the load sets) are used to form a load pair that determines the maximum primary-plus-secondary stress-intensity range. This stress-intensity range must meet the $3S_m$ limit; otherwise, the simplified elastic-plastic method or a plastic analysis may be used.

Step 5. Using the stress values determined in Step 2, the peak stresses are calculated. This might involve using stress indices, stress concentration factors, experimental stress analysis, etc. The six components of stress for each time and location of interest are determined for each load set.

Material	m	n
Low-alloy steel	2.0	0.2
Carbon steel	3.0	0.2
Austenitic stainless steel	1.7	0.3
Alloy 600	1.7	0.3

For the K_e factor to be applicable, the primary-plus-secondary stress-intensity range excluding thermal bending, must meet the $3S_m$ limit.

4.1.3 Summary of Code Fatigue Evaluation Approach

From the preceding descriptions of the Code fatigue procedures, some of the common features of both the NB-3600 and the NB-3200 fatigue evaluations relevant, from an environmental effects point of view, can be summarized as:

- A number of distinct load states are defined at a given location where fatigue usage calculation is desired. In the case of NB-3200 analysis, the load states are defined in terms of the three principal stresses. In the NB-3600 analysis, the load states are defined in terms of the internal pressure, the three moment components, the average temperatures on the *a* and *b* sides (T_a and T_b), and the two temperature gradients, ΔT_1 and ΔT_2.
- The load state pairs are formed and a peak stress-intensity range is calculated for each load state pair. An alternating stress-intensity amplitude S_a is then calculated. This value of S_a is used to enter the appropriate Code fatigue curve to calculate the allowable number of cycles and then the fatigue usage associated with this load state pair.
- The partial fatigue usages from the various load state pairs are summed to obtain a cumulative, or total, fatigue usage factor.

4.2 Environmental Factor Approach

4.2.1 Overview

The proposed approach includes as much information as typically available to the piping or vessel stress analyst, thus minimizing the need for additional information. The essential steps of this approach are shown in the flow diagram in Figure 4-1 and are briefly summarized below:

- Determine the load state pairs that satisfy the threshold values listed in Subsection 3.3. A discussion on how to use the available information in a typical Class 1 stress report for comparison with the threshold values is provided later in this section. The fatigue usage of the load state pairs satisfying the threshold criteria remains unchanged by the environmental effects.

- For the selected load state pairs that do not meet the threshold criteria, determine the appropriate values of the parameters such as T, T^*, S^*, O^*, and ε^*. Calculate the F_{en} (Equations 3-11 through 3-14) and multiply it by the partial fatigue usage associated with this pair to obtain a new partial fatigue usage.
- Sum the partial fatigue usage factors calculated in Step 2 and add it to the partial fatigue usage of the load state pairs not selected in Step 1. This overall sum is the total fatigue usage including the environmental effects.

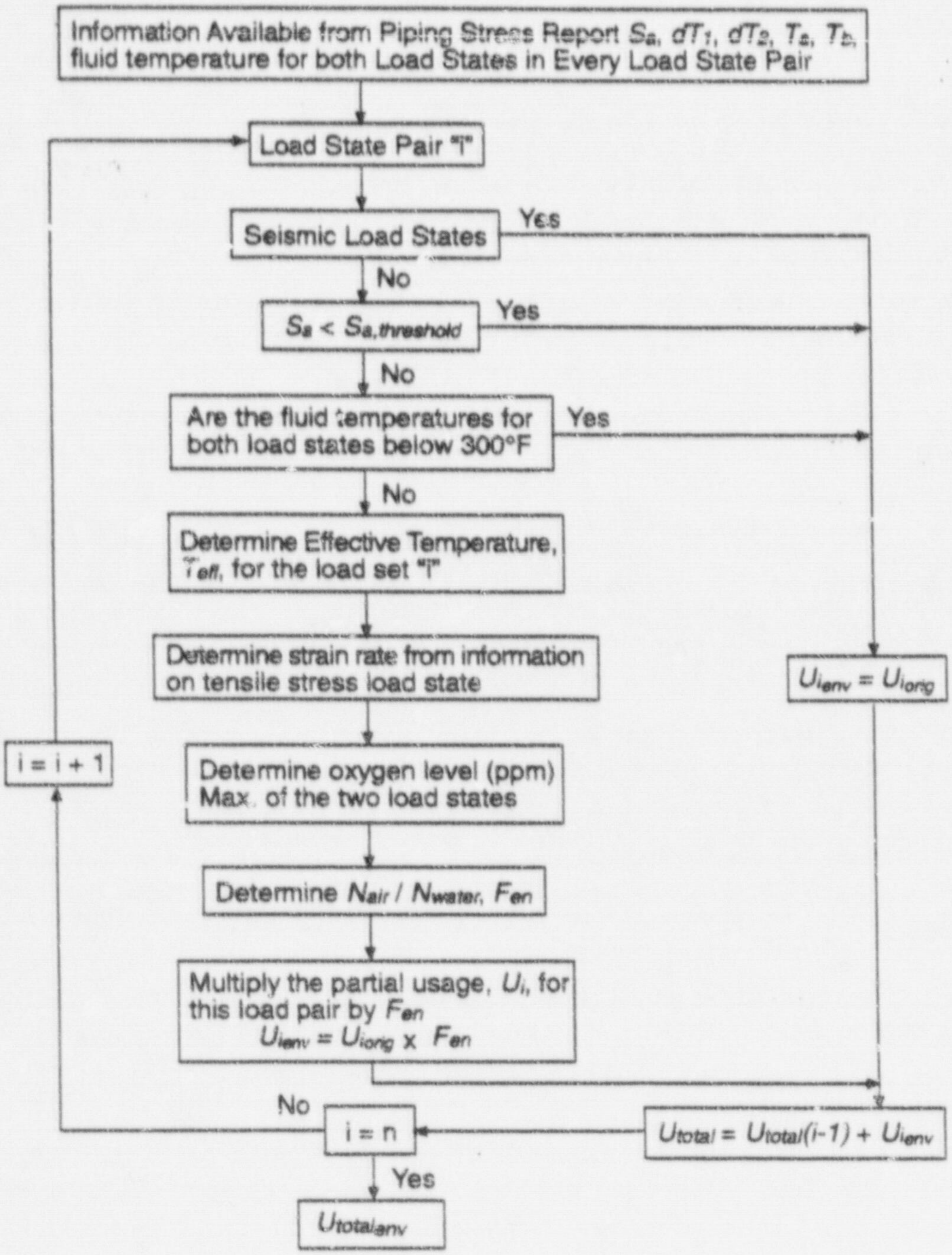


Figure 4-1
Flow Diagram for Environmental Fatigue I.

4.2.2 Load State Pair Screening

To identify which load state pairs are sensitive to reactor water effects, the threshold criteria in Table 4-1 (discussed in Subsection 3.3) can be applied.

Table 4-1
Load State Pair Screening Threshold Criteria

S_a	≤ 30,000 psi (carbon steel)
	≤ 28,300 psi (stainless steel, Alloy 600)
O	≤ 0.1 ppm
T	≤ 300° F
Sulfur	< 0.003%
Flow	> 10 ft/sec

The first criterion that can be easily checked is alternating stress amplitude. The S_a value for each load state pair is listed in both the NB-3600 and NB-3200 fatigue evaluations. As stated in Subsection 3.3, the threshold value, S_a, for carbon and low-alloy steels is 30,000 psi, and for stainless steels and Alloy 600, 28,300 psi.

The next threshold criterion that can be checked is temperature. If the highest temperature of *both* load states in a load state pair is less than 300°F, then the temperature threshold criterion is satisfied and that load state pair can be excluded from environmental considerations. The same also applies for oxygen content.

If the flow rate information is available for both load states in a load state pair, then the threshold criterion on flow rate can also be used to eliminate appropriate load state pairs from consideration of environmental effects.

4.3 NB-3600 Analysis

The load state pair screening conducted in the preceding subsection narrows down the load state pairs for which the environmental correction need to be applied. Beyond this point, the application of the environmental correction factors will be somewhat different for NB-3600 and NB-3200 fatigue evaluations. This section describes the procedures applicable to NB-3600 fatigue evaluations.

The next step in the NB-3600 fatigue evaluation process (Figure 4-1) is determining the appropriate values of temperature, strain rate, and oxygen concentration (for carbon and low-alloy steels) for each of these load state pairs. Once the appropriate values of these parameters has been determined for a load state pair, the environmental correction factor F_{en} can be determined by using one of the applicable equations (3-11 through 3-15) in Section 3. Partial fatigue usage, including environmental effects for that load state pair, is equal to the existing partial fatigue usage times the correction factor F_{en}.

Total fatigue usage, including the environmental effects, is obtained by summing these partial fatigue usages and adding to this sum the partial fatigue usages of load state pairs that were screened out (see Figure 4-1).

A key parameter in calculating F_{en} is strain rate. The sophistication in calculating this parameter depends on the details of the available information on temperature transients. Therefore, two approaches are outlined. The first one assumes that only the T_a, T_b, ΔT_1, and ΔT_2 information is available. The second approach is based on the availability of detailed elapsed time versus temperature information for a transient. Subsection 4.3.2 describes the details of these approaches.

4.3.1 Determining Temperature

As discussed later in Subsection 4.3.2, it is the strain rate during the tensile phase, rather than the compressive phase, that is important from the viewpoint of environmental fatigue damage. For example, a step-down temperature transient produces tensile stresses at the inside surface of a component that is typically in contact with the fluid. Therefore, in determining an appropriate value of temperature for a load state pair, the load state associated with the step-down transient is the one to consider.

Because the metal temperature is typically changing during a transient, the choices for temperature T are:

- Maximum temperature during the transient
- Average temperature during the transient
- Temperature at the time when the maximum stress occurs

The last option might not be appropriate because the maximum or minimum stress usually occurs at low temperatures, while a significant part of the tensile stress might have developed at higher temperatures. Reference 2-19 used the maximum temperature calculated for the times of maximum and minimum stresses, if known; otherwise, the maximum temperature for the load state pair was used.

The use of average temperature during the transient is also somewhat questionable, because any averaging must also take into account the strain rate variation.

For the analyses in this subsection, the maximum temperature for the load pair was used conservatively. When an incremental approach to calculating F_{en} was used, as described later, the instantaneous metal temperatures and strain rates were used to obtain an instantaneous damage parameter F_{en}.

4.3.2 Determination of Strain Rate

Two approaches were studied to account for strain rate effects. In the first approach, information generally supplied in the Class 1 NB-3600 fatigue evaluation (i.e., load state, pressure, component moments, design cycles, T_a, T_b, ΔT_1, ΔT_2, etc.) can be used to calculate an average strain rate. In the second approach, the results of the one-dimensional heat transfer analysis can be used to calculate an effective damage factor F_{en}, based on temperature and strain rate variations throughout the transient.

Both the Japanese and the Argonne test results show that it is the strain rate during the tensile phase, rather than the compressive phase, that is important from the viewpoint of environmental fatigue damage. Figure 4-2 shows a slide from Reference 4-2 illustrating this point. Generally, tensile stresses are produced on the inside surface of the pipe during a step-down temperature transient (i.e., the fluid temperature drops as the transient progresses in time). Conversely, a step-up temperature transient produces compressive stresses. Therefore, we are interested in the fraction of S_a of a load state pair that pertains to the load set with the positive strain rate.

Average Strain Rate

The thermally induced stresses in the piping are expected to be proportional to the temperature gradient quantities such as $|T_a - T_b|$, ΔT_1 and ΔT_2. Generally, the $|T_a - T_b|$, ΔT_1 and ΔT_2 values in defining a load set are selected at a point in a temperature transient where the composite sum $\{|T_a - T_b| + \Delta T_1 + \Delta T_2\}$ reaches a maximum. Also, it is very likely that a load state pair with significant alternating stress amplitude would consist of a load set with a step-down temperature transient paired with a step-up temperature transient load set, or vice versa. Therefore, it is reasonable to use this composite sum to determine the fraction of S_a of a load sets pair associated with increasing strain.

Based on the preceding discussion, the following approach was used to estimate strain rate. Let $|T_{a,t} - T_{b,t}|$, $\Delta T_{1,t}$, and $\Delta T_{2,t}$ be associated with a step-down temperature transient and $|T_{a,c} - T_{b,c}|$, $\Delta T_{1,c}$ and $\Delta T_{2,c}$ for the other load set, presumably the step-up temperature transient.

Now, define:
$$T_t = |T_{a,t} - T_{b,t}| + |\Delta T_{1,t}| + |\Delta T_{2,t}| \quad \text{(Eq. 4-10)}$$
$$T_c = |T_{a,c} - T_{b,c}| + |\Delta T_{1,c}| + |\Delta T_{2,c}| \quad \text{(Eq. 4-11)}$$

Then, the peak stress magnitude associated with the increasing strain is:

$$S_{p,t} = 2S_a\,[T_t/(T_t+T_c)] \quad \text{(Eq. 4-12)}$$

Now, assume that the elapsed time is t_t where T_t was determined (presumably, the maximum). Then, the average strain rate for this load state pair is:

$$\dot{\varepsilon} = \dot{\varepsilon}_t = S_{p,t}/(Et_t) \quad \text{(Eq. 4-13)}$$

The value of E could be assumed the same as that in the Code fatigue curve.

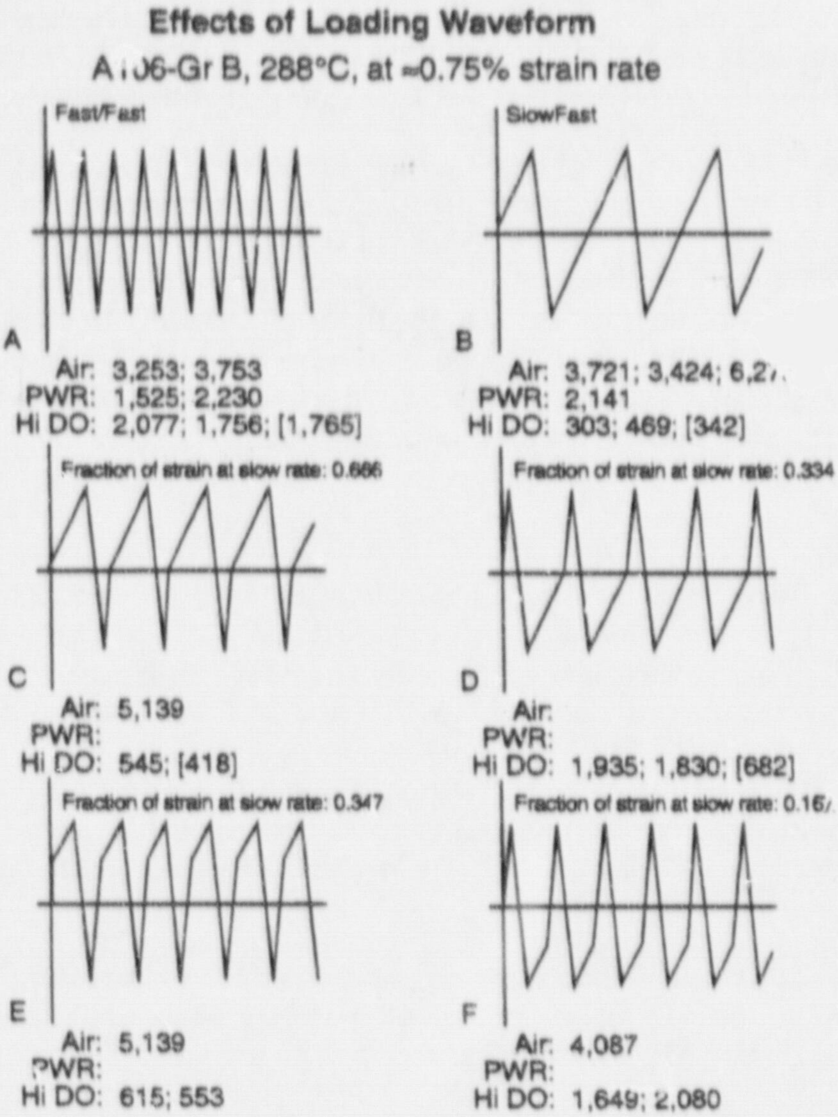


Figure 4-2
Effect of Strain Rate Variation during Tensile and Compressive Phases of Fatigue Cycling (Reference 4-2).

Effective Damage Factor

The highest temperature in the load set was used in the preceding approach to calculate an environmental factor F_{en} associated with a load state pair. Also, strain rate was obtained by averaging over the time period from the start of the transient to the time when the temperature stresses reach a peak. This approach is expected to yield a conservative value of F_{en}. However, when the detailed $|T_{a,i} - T_{b,i}|$, $DT_{1,i}$, and $DT_{2,i}$ information is available as a function of elapsed time from the start of the transient, it is possible to calculate an effective value of F_{en} that considers the variations in metal temperature and strain rate as the temperature transient progresses. This approach is expected to yield a less conservative value of F_{en}. The following assumptions are made in calculating the instantaneous strain rate:

- The peak stress value $S_{p,l}$ as calculated in Equation 4-12, is associated with composite temperature T_l. Stress at any other intermediate time point τ during the transient is obtained as:

$$S_{p,l} = T_\tau / T_l \quad \text{(Eq. 4-14)}$$

$$T_\tau = |T_{a,\tau} - T_{b,\tau}| + |\Delta T_{1,\tau}| + |\Delta T_{2,\tau}| \quad \text{(Eq. 4-15)}$$

- Temperature T to be used in the F_{en} is the instantaneous metal temperature, which at time τ can be obtained as:

$$T_{m,\tau} = \textit{larger of}\,(T_{a,\tau}, T_{b,\tau}) + \Delta T_{1',\tau}/2 + \Delta T_{2,\tau} \quad \text{(Eq. 4-16)}$$

The instantaneous strain rate $\dot{\varepsilon}_\tau$ between time points τ−Δτ and τ can then be calculated as:

$$\dot{\varepsilon}_\tau = [S_{p,\tau} - S_{p,\tau-\Delta\tau}]/(\Delta\tau E) \quad \text{(Eq. 4-17)}$$

The F_{en} can then be incrementally calculated from the start of the transient until the metal temperature reaches 300°F (defined as t_{300}):

$$F_{en,300} = (1/t_{300}) \int^{t_{300}} exp(+0.384-0.00133T_{m,\tau} + 0.554S^*T_{m,\tau}{}^*O^*\dot{\varepsilon}_\tau{}^*)d\tau \quad \text{(Eq. 4-18)}$$

The above formulation is for carbon steel piping. A similar expression for stainless steel piping can be also developed. The application of this approach is described in the next section.

4.3.3 Determination of Oxygen Concentration

The oxygen concentration DO is a parameter in calculating F_{en} for the carbon and low-alloy steels. The DO value can be conservatively taken as the maximum of applicable values for the load states constituting a load state pair. In view of the discussion in the preceding subsection, the use of DO level associated with the step-down transient is justified when the DO levels differ considerably between the two load states.

4.3.4 Determining Corrected Fatigue Usage

Once the appropriate values of temperature, strain rate, and dissolved oxygen (for carbon and low-alloy steels) are determined for a load state pair, the environmental correction factor F_{en} for that load state pair can be calculated using one of the equations (3-11 through 3-15). If the effective damage approach is used, then the equation (4-18) can be used to calculate the effective value of F_{en} for a load state pair. Partial fatigue usage associated with a load state pair from the previous Code calculations should be multiplied by F_{en} to obtain the new value of partial fatigue usage. Total fatigue usage, including environmental effects, is obtained by summing these partial fatigue usages and then adding to this sum the partial fatigue usages of load state pairs that were screened out (see Figure 4-1).

4.4 NB-3200 Analysis

The approach for an NB-3200 detailed analysis would be similar to that outlined in the preceding subsection, the only major difference being the area of strain rate determination for the NB-3600 approach.

4.4.1 Determining Temperature

The approach is essentially the same as that for NB-3600 analysis.

4.4.2 Determining Strain Rate

The information generally available in an NB-3200 fatigue evaluation is a set of three peak principal stresses or six peak stress components (three direct stresses and three shears) for each of the load states in a load state pair. These stress components reflect the sum total of stresses from internal pressure, plant transient, and applied mechanical loadings, i.e., the forces and the bending moments from the connected components. The analyst can identify the load set associated with the positive strain rate (i.e., increasing tensile stress or rising load) by looking at the dominant peak stress components. From this peak stress information, one can then calculate peak stress intensity $S_{p,i,l}$ associated with this load set. The effective strain rate is obtained by dividing this intensity with E and the elapsed time in seconds from the start of the transient when peak stress intensity occurs. This value should be multiplied by 100 to obtain the strain rate in % per second.

4.4.3 Determining Oxygen Concentration

The approach is essentially the same as that for the NB-3600 analysis.

4.4.4 Determining Corrected Fatigue Usage

The approach is essentially the same as that for the NB-3600 analysis.

4.5 References

[4-1] ASME Code Section III. Nuclear Components. 1992.

[4-2] Fatigue of Carbon and Low-alloy Steels in LWR Environments. Presentation by O.K. Chopra to PVRC W/G on S/N Data Analysis. June 5, 1995.

5

APPLICATION CASE STUDIES

5.1 NB-3600 Application

5.1.1 BWR Feedwater Piping

Figure 5-1 shows a mathematical model of the BWR feedwater piping system under consideration. Table 5-1 shows the details of a conventional NB-3600-type piping fatigue evaluation at node P71. The piping material is carbon steel. Pipe geometry and stress index information is provided in Table 5-1A. Table 5-1B contains a summary of all load state data included in the Class 1 Design Report. Generally, this data is available to the stress analyst. In this example, there are 53 load states identified with the following details:

- Load state number
- Number of cycles
- Internal pressure
- Three component moments
- Average temperature on the *a* side (TAS)
- Average temperature on the *b* side (TBS)
- Linear temperature gradient ΔT_1 (DT1)
- Non-linear temperature gradient ΔT_2 (DT2)

The fatigue usage calculation information for various load state pairs is contained in Table 5-1C. In all, there are 31 load state pairs. For this location, the total fatigue usage for all 31 load state pairs is 0.1409.

In Table 4-1, the threshold alternating stress level for environmental effects in carbon steels is ≤ 30 ksi. When compared to the alternating stress for each load state pair in Table 5-1C, load state pairs 3 through 11 exceed the 30 ksi threshold screening criteria. Therefore, the fatigue usage for the remaining load state pairs need not be corrected.

Because the dissolved oxygen level in BWR feedwater system piping is typically 0.2 ppm, none of the load state pairs will satisfy the dissolved oxygen threshold criterion of 0.1 ppm. Figure 5-2 shows temperature profiles of thermal transients associated with the load states constituting the nine load state pairs. A review of Figure 5-2 indicates that one load state pair (30-40) has the highest temperature in both load sets at less than the threshold value of 300°F. Accordingly, this load state pair was eliminated from consideration of environmental fatigue effects. Thus, in this case, the environmental effects need to be accounted for in 8 out of the 31 load state pairs in the design report. These load state pairs are shown in Table 5-2.

Table 5-1b
BWR Feedwater Piping Load State Data (Sheet 1 of 2)

LOAD SETS	DESCRIPTION	NO. OF CYCLES	PRESSURE	MA/MRA	MB/MRB	MC/MRC	TAS	TBS	DT1	DT2
0	DESIGN (9)		1250.	49058	61582	200956				
1	FATIGUE (14)	120.	0.	6590	42500	89900	70.000	70.000	0.	0.
2	FATIGUE	40.	1100.	331590	283500	147400	416.388	416.381	8.275	1.167
3	FATIGUE	90.	10.	-39010	1200	95780	129.679	129.678	0.771	0.074
4	FATIGUE	90.	1161.	-39910	-17800	262900	70.365	70.365	-0.863	-0.094
5	FATIGUE	40.	1050.	-24910	-82500	751900	551.678	551.678	0.482	0.
6	**FATIGUE**	**40.**	**1050.**	**-50510**	**-98500**	**782900**	**518.000**	**526.000**	**-19.000**	**-4.000**
7	FATIGUE	270.	1050.	147142	218940	451152	551.693	551.693	0.483	0.
8	**FATIGUE**	**270.**	**1053.**	**112590**	**62800**	**490900**	**487.000**	**508.000**	**-90.000**	**-18.000**
9	FATIGUE	270.	1053.	-50510	-98500	782900	52.205	52.208	-3.643	-0.556
10	FATIGUE	270.	1100.	331590	283500	147400	420.368	420.367	1.615	0.171
11	FATIGUE	12400.	1063.	264590	218500	249900	360.843	360.845	-1.390	-0.213
12	FATIGUE	12400.	1100.	331590	283500	147400	420.137	420.155	1.390	0.213
13	**FATIGUE**	**10.**	**1078.**	**-35110**	**-75500**	**748900**	**168.000**	**229.000**	**-99.000**	**-19.600**
14	**FATIGUE**	**10.**	**1078.**	**331590**	**283500**	**147400**	**386.000**	**364.000**	**47.000**	**9.800**
15	FATIGUE	10.	1115.	374058	302582	262456	421.000	421.000	0.	0.
16	FATIGUE	70.	1100.	149590	104900	427900	261.291	261.298	-13.843	-2.286
17	FATIGUE	70.	1078.	331590	283500	147400	409.709	409.702	13.843	2.286
18	FATIGUE	110.	1276.	373058	300582	291256	421.000	421.000	0.	0.
19	FATIGUE	110.	1276.	222590	173500	348900	355.000	368.000	-46.000	-10.000
20	FATIGUE	110.	1050.	224590	178500	293900	320.000	320.000	0.	0.
21	FATIGUE	110.	945.	56930	4732	850740	272.000	283.000	-35.000	-7.000
22	FATIGUE	110.	119.	-28510	-40500	420900	70.000	70.000	0.	0.
23	**FATIGUE**	**110.**	**119.**	**253058**	**219582**	**-74956**	**117.000**	**106.000**	**39.000**	**8.000**
24	**FATIGUE**	**110.**	**1051.**	**415810**	**368776**	**28120**	**472.635**	**472.634**	**0.503**	**0.**
25	FATIGUE	191.	119.	15150	43810	89113	120.364	120.364	-0.506	0.
26	FATIGUE	110.	1100.	393623	390080	389830	421.000	421.000	0.	0.
27	FATIGUE	111.	1051.	195090	146600	624900	270.997	270.997	-2.549	-0.270
28	FATIGUE	4107.	1050.	-26510	350500	802800	473.000	457.000	20.000	6.000

Table 5-1b
BWR Feedwater Piping Load State Date (Sheet 2 of 2)

LOAD SETS	DESCRIPTION	NO. OF CYCLES	PRESSURE	MA/MRA	MB/MRB	MC/MRC	TAS	TBS	DT1	DT2
29	FATIGUE	4107.	1050.	-24910	-82500	751900	344.000	357.000	-15.000	-6.000
30	**FATIGUE**	**80.**	**50.**	**-44110**	**-100500**	**770900**	**156.000**	**166.000**	**-50.000**	**-50.000**
31	FATIGUE	80.	50.	165590	154500	146600	197.000	196.000	71.000	22.000
32	FATIGUE	45.	26.	-60310	-19600	127300	50.048	50.048	-0.072	0.
33	FATIGUE	80.	1276.	373058	300582	291256	421.000	421.000	0.	0.
34	**FATIGUE**	**80.**	**1016.**	**98230**	**54500**	**762900**	**336.000**	**365.000**	**-72.000**	**-14.000**
35	FATIGUE	80.	1016.	110590	65000	483900	405.000	359.000	27.000	6.000
36	FATIGUE	270.	1053.	229590	182500	306900	219.000	213.000	11.000	3.000
37	FATIGUE	80.	1100.	110590	65000	483900	498.000	511.000	-72.200	-15.000
38	**FATIGUE**	**9.**	**640.**	**-7810**	**-25500**	**427900**	**205.000**	**247.000**	**-139.000**	**-41.000**
39	FATIGUE	111.	50.	-50310	-52800	396900	65.000	66.000	-7.000	-2.000
40	**FATIGUE**	**111.**	**50.**	**166590**	**166500**	**47500**	**113.000**	**102.000**	**110.000**	**28.000**
41	FATIGUE	111.	1051.	61590	4200	880900	270.000	270.000	0.	0.
42	FATIGUE	60.	1100.	473597	390080	389830	421.000	421.000	0.	0.
43	FATIGUE	60.	1100.	189583	176920	-95030	421.000	421.000	0.	0.
44	FATIGUE	570.	1100.	374058	302582	258456	421.000	421.000	0.	0.
45	FATIGUE	570.	1100.	289121	264417	36343	421.000	421.000	0.	0.
46	FATIGUE	760.	1100.	352824	293041	202928	421.000	421.000	0.	0.
47	FATIGUE	760.	1100.	310355	273958	91871	421.000	421.000	0.	0.
48	FATIGUE	4800.	1100.	361318	296857	225139	421.000	421.000	0.	0.
49	FATIGUE	4800.	1100.	301861	270142	69660	421.000	421.000	0.	0.
50	FATIGUE	6400.	1100.	346454	290178	186269	421.000	421.000	0.	0.
51	FATIGUE	6400.	1100.	316725	276821	108530	421.000	421.000	0.	0.
52	FATIGUE	120.	1100.	487167	429690	480810	421.000	421.000	0.	0.
53	FATIGUE	120.	1100.	176013	137310	-186010	421.000	421.000	0.	0.

Table 5-1c
BWR Feedwater Piping Load State Pair Fatigue Usage

LOAD STATE PAIR	I	J	EQ 11 (SP)	EQ 10 (SN)	EQ 12 (SE)	EQ 13 (SX)	KE	EQ 14 (SALT)	RS/ /3SM	DT1/ ALWDT1	DESIGN CYCLES	ALLOW CYCLES	USAGE FACTOR
1	42	43	23058.	23058.	0.	[illegible]	1.00	11529.	0.436	0.	60.	1000000.	0.0001
2	52	53	30378.	30378.	0.	8281.	1.00	15189.	0.574	0.	60.	291861.	0.0002
3	**13**	**40**	**89440.**	**77934.**	**29520.**	**24545.**	**1.95**	**87048.**	**1.473**	**0.255**	**10.**	**869.**	**0.0115**
4	**38**	**40**	**80494.**	**63814.**	**17694.**	**18984.**	**1.41**	**56856.**	**1.206**	**0.303**	**9.**	**2916.**	**00.003**
5	**34**	**40**	**78404.**	**68251.**	**27812.**	**21857.**	**1.56**	**81957.**	**1.290**	**0.221**	**80.**	**2218.**	**0.0361**
6	30	40	73164.	54309.	30689.	10421.	1.05	43448.	1.027	0.195	12.	6720.	0.0018
7	**14**	**30**	**70773.**	**56317.**	**31576.**	**19477.**	**1.13**	**41666.**	**1.065**	**0.118**	**10.**	**7609.**	**0.0013**
8	**24**	**30**	**66618.**	**54531.**	**38048.**	**16335.**	**1.06**	**37976.**	**1.031**	**0.061**	**58.**	**10022.**	**0.0058**
9	**6**	**23**	**63140.**	**60239.**	**32448.**	**20649.**	**1.28**	**40331.**	**1.139**	**0.071**	**40.**	**8381.**	**0.0048**
10	**8**	**23**	**63052.**	**56767.**	**18615.**	**21546.**	**1.16**	**36137.**	**1.073**	**0.157**	**70.**	**11867.**	**0.0059**
11	**8**	**31**	**58971.**	**49302.**	**13820.**	**20866.**	**1.00**	**31353.**	**0.932**	**0.196**	**80.**	**19243.**	**0.0042**
12	1	8	48695.	44344.	15932.	21849.	1.00	24347.	0.838	0.109	120.	41983.	0.0029
13	21	32	46617.	44924.	28133.	18756.	1.00	23308.	0.849	0.042	45.	47998.	0.0009
14	21	25	46200.	44508.	29303.	17565.	1.00	23100.	0.841	0.042	65.	49339.	0.0013
15	9	24	43225.	43091	38471.	10349.	1.00	21613.	0.815	0.005	52.	68072.	0.0008
16	25	37	42917.	39291.	15604.	20265.	1.00	21458.	0.743	0.089	80.	70535.	0.0011
17	25	23	42763.	41313.	29845.	17021.	1.00	21381.	0.781	0.025	46.	71802.	0.0006
18	19	28	39081.	35213.	20993.	12433.	1.00	19541.	0.666	0.091	110.	108733.	0.0010
19	9	17	38516.	37829.	32003.	10251.	1.00	19258.	0.715	0.021	70.	114592.	0.0006
20	26	39	38255.	37771.	21744.	19502.	1.00	19127.	0.714	0.009	110.	117439.	0.0009
21	2	9	37839.	37422.	32003.	10484.	1.00	18919.	0.707	0.015	40.	122159.	0.0003
22	33	39	37343.	36859.	21147.	21107.	1.00	18671.	0.697	0.010	[illegible]	128107.	0.0000
23	9	10	36833.	36657.	32003.	10504.	1.00	18417.	0.693	0.006	108.	134608.	0.0008
24	10	29	35968.	34477.	30367.	9559.	1.00	17984.	0.652	0.021	162.	146637.	0.0011
25	12	29	35954.	34452.	30367.	9561.	1.00	17977.	0.651	0.020	3945.	146856.	0.0269
26	12	28	35300.	33901.	28769.	9950.	1.00	17650.	0.641	0.023	3951.	156895.	0.0252
27	22	33	34793.	34793.	20681.	20545.	1.00	17397.	0.658	0.	79.	165280.	0.0005
28	18	22	34793.	34793.	20681.	20545.	1.00	17397.	0.658	0.	31.	165280.	0.0002
29	12	41	33975.	33924.	31845.	9460.	1.00	16988.	0.641	0.002	111.	180073.	0.0006
30	5	12	32267.	32216.	30367.	9378.	1.00	16134.	0.609	0.001	40.	221601.	0.0002
31	12	35	31441.	30042.	17574.	13350.	1.00	15721.	0.568	0.032	80.	249459.	0.0003

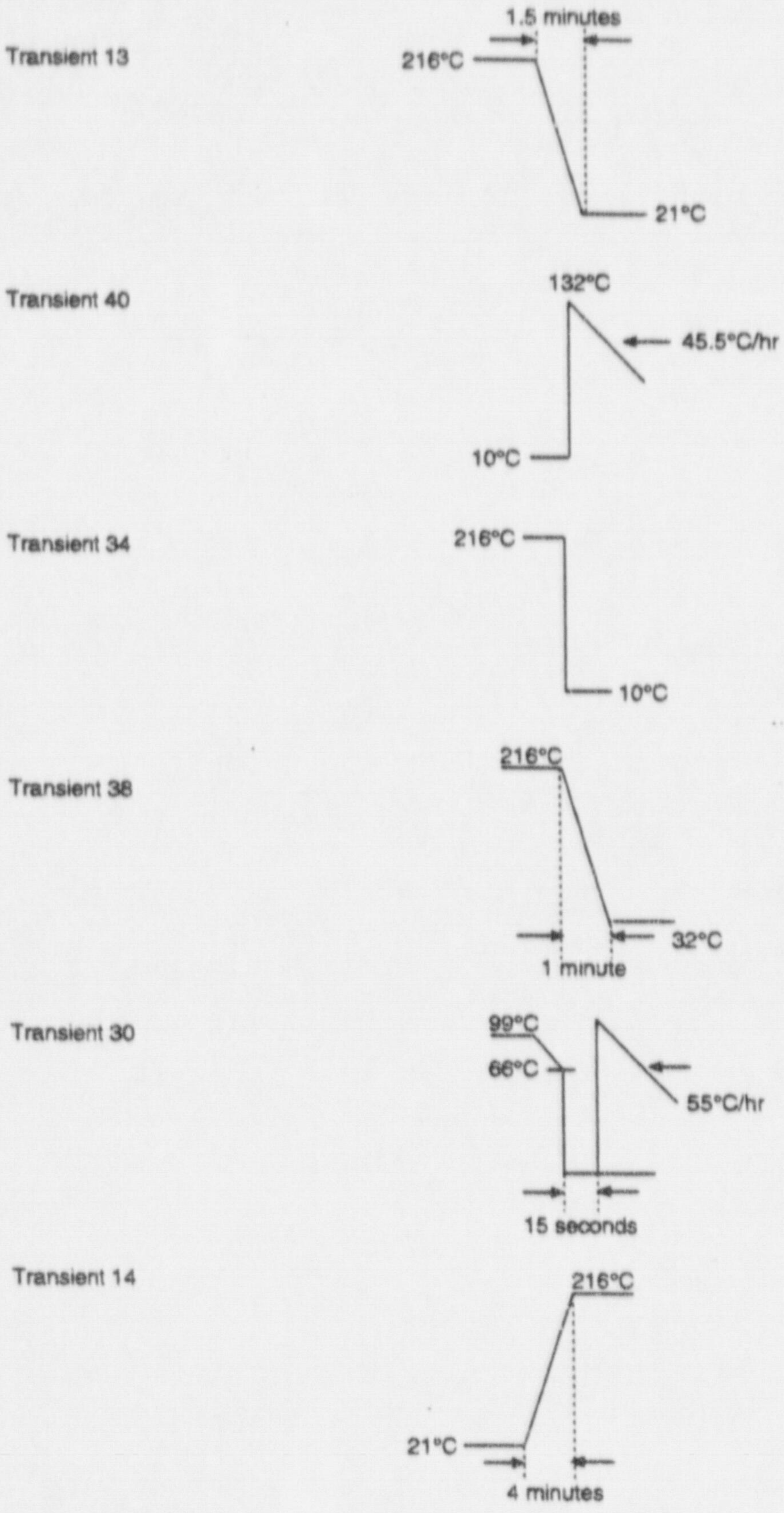
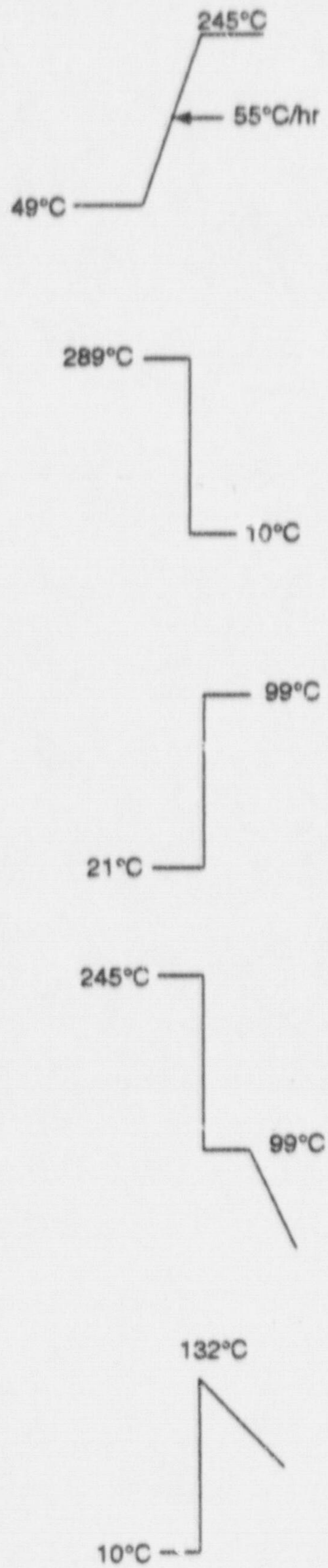


Figure 5-2
Temperature Profiles of Significant Transients.

Transient 24



Transient 6

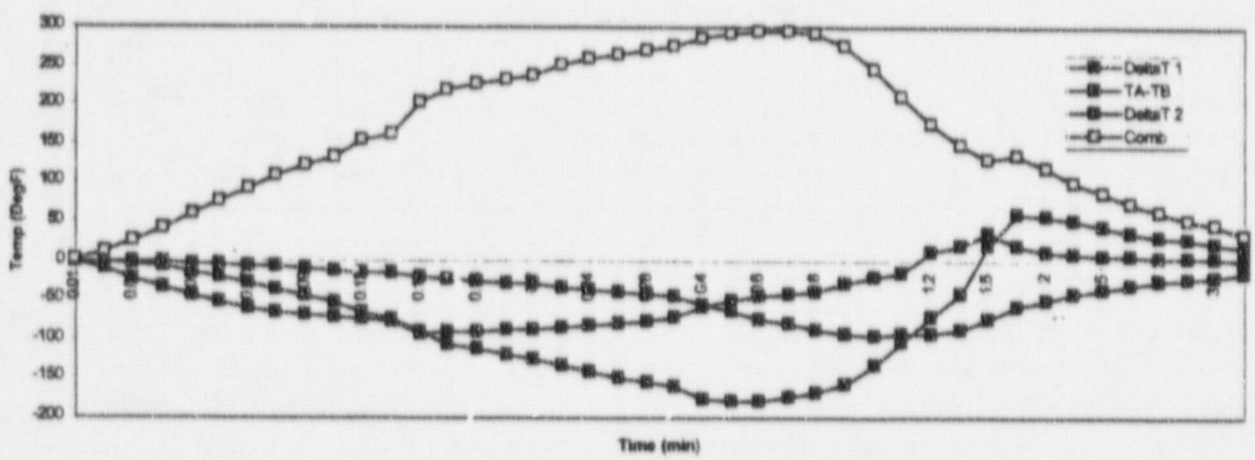
Transient 23

Transient 8

Transient 31

Figure 5-2 (continued)
Temperature Profiles of Significant Transients.

Now, consider the first load state pair, 13-40, and determine the F_{en} factor. Load state 13 ir this pair is associated with a step-down transient and, thus, was used to determine the strain rate for this load state pair. Figure 5-3 graphically shows the output results of a one-dimensional heat transfer computer run to determine the appropriate $|T_a - T_b|$, ΔT_1, and ΔT_2 values for transient or load state 13. This figure also shows the plot of the calculated value of composite temperature T_p, which, as desc·ibed earlier, is equal to $(|T_a - T_b| + |\Delta T_1| + |\Delta T_2|)$. Typical practice is to pick the T_a, T_b, ΔT_1, and ΔT_2 values where the composite temperature value reaches maximum. In this case, the composite tempe ature val ue reached maximum at time equal to 1.501 minutes, and, therefore, the T_a, T_b, ΔT_1, and ΔT_2 values at this point were used to define load state 13.



Fluid Temperature Profile:	Time (min.)	Temp (F)
	0.0	420.0
	1.5	70.0
	4.0	70.0
Thickness (a) = 1.03 in.	Thickness (b) = 1.34 in	

Material: Carbon Steel

Figure 5-3
Output of One-dimensional Heat Transfer Analysis for Transient 13.

Table 5-2
Strain Rate Calculation for Significant Load State Pairs

Load State			ΔT_1	ΔT_2	T_a	T_b	T_t	S_p (psi)	$S_{p,t}$	Time (min)	Str. Rate
13	40	I	-99	-19.6	168	229.0	179.6	174096	95154	1.5	0.0035
		J	110	28	113	102.0	149				
38	40	I	-139	-41	205	247.0	222	113712	68043	1	0.0038
		J	110	28	113	102.0	149				
34	40	I	-72	-14	336	365.0	115	123914	53978	0.33	0.0091
		J	110	28	113	102.0	149				
14	30	I	47	9.8	386	364.0	78.8	83332	48551	0.25	0.0108
		J	-50	-50	156	166.0	110				
24	30	I	0.5	0	472.6	472.6	0.5	75952	75608	0.25	0.0168
		J	-50	-50	156	166.0	110				
6	23	I	-19	-4	516	526.0	33	80662	29251	0.25	0.0065
		J	39	8	117	106.0	58				
8	23	I	-90	-18	487	508.0	129	72274	49857	0.25	0.0111
		J	39	8	117	106.0	58				
8	31	I	-90	-18	487	508.0	129	62706	36274	0.25	0.0081
		J	71	22	197	196.0	94				

Table 5-2 shows the strain rate calculation for each of the eight load states pairs. To further illustrate this, a detailed discussion of the strain rate calculation for load state pair 13-40 follows. The composite temperature of load set 13 is 179.6°F, and that of load set 40 is 149°F. Again, these values were obtained from the T_a, T_b, ΔT_1, and ΔT_2 information given in the load set definition of Table 5-1B. The alternating stress amplitude for this load state pair is given as 87048 psi, see Table 5-1C. Therefore, the peak stress range for this load state pair is:

$$S_p = 2 \bullet S_a$$

$$= 2 \bullet 87048 \text{ psi}$$

$$S_p = 174096 \text{ psi}$$

The tensile portion of peak stress range associated with load state 13 is calculated using Equation 4-12:

$$S_{p,t} = 2 \bullet S_a \, [T_t/(T_t + T_c)] \qquad \text{(Eq. 5-1)}$$

$$= [174096] \bullet [179.6/(179.6+149)] \text{ psi}$$

$$S_{p,t} = 95154 \text{ psi}$$

Because the composite temperature reaches a maximum at 1.5 minutes from the start of transient 13, the strain rate is then calculated using Equation 4-13:

$$\varepsilon = \varepsilon_t = S_{p,t}/(E \bullet t_r) \quad \text{(Eq. 5-2)}$$

$$= [95154/(30\text{x}10^6 \bullet 1.5\text{x}60)] \bullet 100$$

$$\varepsilon_t = 0.0035 \text{ \% per second}$$

The strain rates for the other load state pairs were similarly calculated and are shown in Table 5-2.

The strain rate values shown in Table 5-2 were then used to calculate the environmental fatigue correction factor F_{en} using Equation 3-11. This calculation for load state pair 13-40 is:

$$F_{en} = exp\ (+0.384 - 0.00133T - 0.554S^*T^*O^*\dot{\varepsilon}^*) \quad \text{(Eq. 5-3)}$$

The values of various parameters for load state pair 13-40 are the following:

T = 421°F

O = 0.2 ppm

$\dot{\varepsilon}$ = 0.0035%/sec

Based on the preceding values and Equation 3-8, the following values are obtained for S^*, T^*, O^*, and ε^*:

S^* = S = 0.01

T^* = [T-300]/1.8 = 67.2°C

O^* = O = 0.2

$\dot{\varepsilon}^*$ = ln(ε) = ln (0.0035) = -5.6481

When these values of the parameters are substituted in the preceding equation for F_{en}, a value of 1.677 is obtained. The partial fatigue usage factor for this load state pair is multiplied by the calculated value of F_{en} to obtain the new partial fatigue usage reflecting the environmental effects:

$$U_{en\ (13\text{-}40)} = U_{air\ (13\text{-}40)} \bullet F_{en} \quad \text{(Eq. 5-4)}$$

$$= 0.0115 \bullet 1.677$$

$$= 0.0193$$

Note that the existing partial fatigue usage for load state pair 13-40 based on Code (air) fatigue curve is listed in the last column of Table 5-1C. Similar calculations were performed for the remaining seven load state 2 pairs, as shown in Table 5-3. Cumulative fatigue usage (CUF) for these load state pairs is now corrected by totaling all partial usage factors. CUF increased from 0.0727 to 0.1204, or by a factor of 1.66.

Table 5-3
F_{en} Calculation for Significant Load Pairs

Sulfur (%) = 0.01, S^* = 0.01, E (ksi) = 30000

Load Set

I	*J*	*Sa* (ksi)	T_I	T_J	*T*	*T**	*O*	*O**	Str. Rate %/sec	*epsdt**	*Fn*	*Ua*	*Uen*
13	40	87.0	421	270	421	67.2	0.2	0.2	0.0035	-5.6481	1.677	0.0115	0.0193
38	40	56.9	421	270	421	67.2	0.2	0.2	0.0038	-5.5780	1.669	0.0031	0.0052
34	40	62.0	421	270	421	67.2	0.2	0.2	0.0091	-4.7009	1.563	0.0361	0.0564
14	30	41.7	421	270	421	67.2	0.2	0.2	0.0108	-4.5292	1.543	0.0013	0.0020
24	30	35.0	473	270	473	96.1	0.2	0.2	0.0168	-4.0863	1.638	0.0058	0.0095
6	23	40.3	552	210	552	140.0	0.2	0.2	0.0065	-5.0359	2.184	0.0048	0.0105
8	23	36.1	473	210	473	96.1	0.2	0.2	0.0111	-4.5027	1.712	0.0059	0.0101
8	31	31.4	473	270	473	96.1	0.2	0.2	0.0081	-4.8207	1.771	0.0042	0.0074
										Total =		0.0727	0.1204

The corrected fatigue usage for all 31 load state pairs (CUF_{env}) can now be calculated:

$$CUF_{en} = CUF_{air} + (0.1204 - 0.0727) \quad \text{(Eq. 5-6)}$$

$$CUF_{en} = 0.1409 + 0.0477$$

$$CUF_{en} = 0.1886$$

The F_{en} value for the load state pair 13-40 was also calculated using the effective damage approach outlined in Subsection 4.2.5. Table 5-4 shows the details of this calculation. The calculations are carried to the point where the calculated metal temperature (column 10) reaches the threshold value of 300°F. The last column shows the calculated value of the cumulative average value of F_{en}. It is seen that the value of F_{en} using this approach is 1.38, compared to the earlier calculated value of 1.677. This is indicative of the conservatism that the effective damage approach can remove from the simplified calculations, such as those shown in Table 5-3.

Table 5-4
F_{en} Calculation for Load State Pair (13-40) Using Effective Damage Approach

Time (min)	DT1	TA	TB	DELT AB	DELT2	COM BIN.	strs (ksi)	Strain Rate (%/sec)	Metal Temp (F)	T*	epsdt*	Fn*dt	Fn
0.000	0.0	420.0	420.0	0.0	0.0	0.0	0.0		420.0	66.7			
0.010	-0.4	419.9	420.0	0.0	-1.3	1.7	2.0	0.0121	418.5	65.8	-4.4120	0.0153	1.53
0.019	-1.3	419.7	419.9	-0.1	-2.4	3.9	4.3	0.0150	416.7	64.9	-4.2027	0.0135	1.51
0.029	-2.6	419.5	419.7	-0.2	-3.4	6.3	6.5	0.0134	414.9	63.9	-4.3105	0.0150	1.51
0.041	-4.7	419.0	419.4	-0.4	-4.6	9.6	9.5	0.0146	412.5	62.5	-4.2244	0.0179	1.50
0.051	-6.3	418.5	419.1	-0.6	-5.3	12.2	11.9	0.0129	410.7	61.5	-4.3530	0.0150	1.50
0.060	-8.1	418.1	418.8	-0.7	-5.9	14.7	13.7	0.0140	408.8	60.5	-4.2696	0.0133	1.50
0.070	-9.9	417.5	418.5	-0.9	-6.5	17.3	15.8	0.0123	407.0	59.4	-4.3971	0.0149	1.50
0.079	-11.7	417.0	418.1	-1.1	-7.1	19.9	17.8	0.0134	405.1	58.4	[illegible]	0.0133	1.50
0.089	-13.6	416.4	417.7	-1.3	-7.6	22.5	19.8	0.0118	403.3	[illegible]	-4.4415	0.0148	1.49
0.102	-16.1	415.5	417.1	-1.6	-8.2	25.9	22.3	0.0118	400.9	56.0	-4.4413	0.0192	1.49
0.114	-18.6	414.6	[illegible]	-1.9	-8.7	29.2	24.8	0.0124	398.4	54.7	-4.3901	0.0176	1.49
0.130	-21.7	413.3	415.6	-2.3	-9.4	33.4	27.8	0.0113	395.4	53.0	-4.4874	0.0235	1.49
0.149	-25.4	[illegible]	414.5	-2.8	-10.1	38.2	31.3	0.0109	391.7	51.0	-4.5164	0.0277	1.48
0.171	29.5	409.7	413.1	-3.4	-10.8	43.7	35.1	0.0103	417.1	65.1	-4.5749	0.0326	1.48
0.180	-31.2	408.8	412.5	-3.7	-11.0	46.0	36.7	0.0104	385.8	47.7	-4.5642	0.0135	1.48
0.190	-32.9	407.8	[illegible]	-4.0	-11.3	48.2	38.2	0.0092	384.1	46.7	-4.6908	0.0145	1.48
0.199	-34.5	406.9	411.2	-4.3	-11.6	50.4	39.7	0.0100	382.3	45.7	-4.6058	0.0129	1.48
0.221	-38.3	404.5	409.5	-5.0	-12.2	55.5	43.1	0.0092	378.2	43.4	-4.6871	0.0315	1.48
0.240	-41.3	402.4	408.1	-5.6	-12.7	59.6	45.9	0.0087	374.7	41.5	-4.7391	0.0271	1.47
0.258	-44.3	400.2	406.5	-6.3	-13.1	63.7	48.6	0.0089	371.2	39.6	-4.7257	0.0254	1.47
0.280	-47.6	397.6	404.6	-7.1	-13.6	68.3	51.6	0.0081	367.2	37.3	-4.8164	0.0310	1.46
0.299	-50.3	395.2	403.0	-7.7	-14.1	72.1	54.0	0.0077	363.7	35.4	-4.8672	0.0266	1.46
0.321	-53.3	392.4	400.9	-8.6	-14.5	76.4	[illegible]	[illegible]	359.8	33.2	-4.9336	0.0306	1.45
0.339	-55.8	389.9	399.1	-9.3	-14.8	79.9	58.8	0.0072	356.4	31.3	-4.9313	0.0248	1.45
0.361	-58.5	386.9	397.0	-10.1	-15.2	83.9	61.3	0.0066	352.5	29.2	-5.0184	0.0302	1.44
0.379	-60.8	384.2	395.1	-10.9	-15.6	87.2	63.3	0.0066	349.1	27.3	-5.0144	0.0245	1.44
0.401	-63.3	381.1	392.8	-11.7	-15.9	91.0	65.5	0.0061	345.2	25.1	-5.1042	0.0297	1.44
0.419	-65.3	378.3	390.8	-12.5	-16.2	94.1	67.3	0.0061	341.9	23.3	-5.0994	0.0241	1.43
0.440	-67.6	375.0	388.4	-13.4	-16.6	97.6	69.4	0.0058	338.0	21.1	-5.1431	0.0279	1.43
0.459	-69.5	372.1	386.3	-14.2	-16.9	100.5	71.1	0.0053	334.6	19.2	-5.2387	0.0251	1.42
0.480	-71.6	368.7	383.8	-15.1	-17.1	103.8	72.8	0.0050	330.8	17.1	-5.2961	0.0275	1.42
0.501	-73.6	365.2	381.2	-16.0	-17.4	106.9	74.6	0.0049	327.0	15.0	-5.3158	0.0273	1.41
0.549	-77.7	357.1	375.2	-18.0	-18.0	113.7	78.2	0.0046	318.3	10.2	-5.3881	0.0615	1.40
0.600	-81.7	348.2	368.5	-20.2	-18.5	120.4	81.8	0.0041	309.1	5.0	-5.4943	0.0639	1.39
0.651	-85.1	339.1	361.5	-22.4	-19.0	126.5	84.7	0.0034	300.0	0.0	-5.6732	0.0624	1.38
0.701	-88.1	329.9	354.4	-24.5	-19.4	132.0	87.3	0.0032	290.9	0.0	-5.7520	0.0606	1.36
0.751	-90.8	320.4	347.0	-26.6	-19.8	137.2	89.7	0.0028	281.9	0.0	-5.8639	0.0610	1.35
0.799	-93.1	311.3	339.9	-28.6	-20.0	141.7	91.6	0.0024	273.4	0.0	-6.0406	0.0590	1.35

Table 5-4 (continued)
F_{en} Calculation for Load State Pair (13-40) Using Effective Damage Approach

Time (min)	DT1	TA	TB	DELTA B	DELT2	COMB IN.	strs (ksi)	Strain Rate (%/sec)	Metal Temp (F)	*T**	*epsdt**	*Fn*dt*	*Fn*
0.851	-95.1	301.1	331.8	-30.8	-20.3	146.2	93.4	0.0020	264.0	0.0	-6.2047	0.0643	1.34
0.900	-96.8	291.3	324.0	-32.8	-20.5	150.1	94.3	0.0018	255.1	0.0	-6.3018	0.0610	1.33
0.949	-98.3	281.4	316.1	-34.7	-20.6	153.6	96.1	0.0014	246.4	0.0	-6.5471	0.0614	1.33
1.000	-99.5	271.0	307.7	-36.7	-20.8	157.0	97.1	0.0012	237.2	0.0	-6.7202	0.0643	1.33
1.099	-101.3	250.6	291.1	-40.5	-20.9	162.7	98.5	0.0008	219.6	0.0	-6.9078	0.1265	1.32
1.200	-102.2	229.7	273.9	-44.2	-20.9	167.3	99.1	0.0004	201.9	0.0	-6.9078	0.1308	1.32
1.300	-102.2	209.0	256.8	-47.8	-20.6	170.6	98.8	-0.0002	185.0	0.0	-6.9078	0.1311	
1.401	-101.4	188.2	239.5	-51.3	-20.3	173.0	97.8	-0.0006	168.5	0.0	-6.9078	0.1341	
1.501	-99.2	168.1	222.9	-54.8	-19.5	173.5	95.2	-0.0015	153.8	0.0	-6.9078	0.1342	
1.601	-88.5	151.1	207.7	-56.6	-15.2	160.4	81.9	-0.0079	148.2	0.0	-6.9078	0.1347	
1.700	-75.7	137.5	194.2	-56.7	-12.9	145.2	69.9	-0.0073	143.4	0.0	-6.9078	0.1339	
1.801	-64.2	126.2	181.7	-55.[illegible]	-10.9	130.6	59.2	-0.0063	138.7	0.0	-6.9078	0.1370	
1.901	-54.7	116.8	170.4	-5[illegible].5	-9.3	117.6	50.5	-0.0052	133.7	0.0	-6.9078	0.1362	
1.999	-47.0	109.4	160.5	-51.1	-8.0	10[illegible].2	43.4	-0.0043	128.9	0.0	-6.9078	0.1339	
2.200	-34.8	97.8	143.0	-45.2	-5.9	85.9	32.2	-0.0034	119.6	0.0	-6.9078	0.2766	
2.500	-22.5	86.9	122.7	-35.8	-3.9	62.2	20.8	-0.0023	107.6	0.0	-6.9078	0.4165	
2.751	-15.8	81.3	110.0	-28.7	-2.7	47.3	14.7	-0.0015	99.3	0.0	-6.9078	0.3506	
2.999	-11.4	77.7	100.4	-22.7	-2.0	36.0	10.5	-0.0010	92.7	0.0	-6.9078	0.3481	
3.250	-8.2	75.3	93.0	-17.6	-1.4	27.2	7.6	-0.0007	87.5	0.0	-6.9078	0.3537	
3.500	-5.9	73.7	87.3	-13.6	-1.0	20.5	5.5	-0.0005	83.3	0.0	-6.9078	0.3534	
3.750	-4.3	72.7	83.1	-10.4	-0.8	15.5	4.1	-0.0004	80.2	0.0	-6.9078	0.3542	
4.000	-3.2	71.9	79.9	-8.0	-0.6	11.7	3.0	-0.0003	77.7	0.0	-6.9078	0.3548	

Note: The material is carbon steel. The values of stress indices, E, Alpha and Poisson's ratio are the same as those in Figure 5-3.

5.1.2 Recirculation System Piping

A BWR/4 recirculation piping system was analyzed in Reference 2-18. Figure 5-4 shows the mathematical model of the piping system. The piping material is Type 304 stainless steel. The location chosen for fatigue evaluation was the residual heat removal (RHR) system return tee where the calculated fatigue usage factor was found to be high. The fatigue usage calculation, using the anticipated cycles (Table 5-137 of Reference 2-18), was chosen for the application of methodology developed in Section 4. Table 5-5 lists the alternating stress amplitudes and the strain rates used in that evaluation. A revised version of stainless steel interim fatigue curve was used to determine CUF. Reference 2-18 reported a CUF of 3.256.

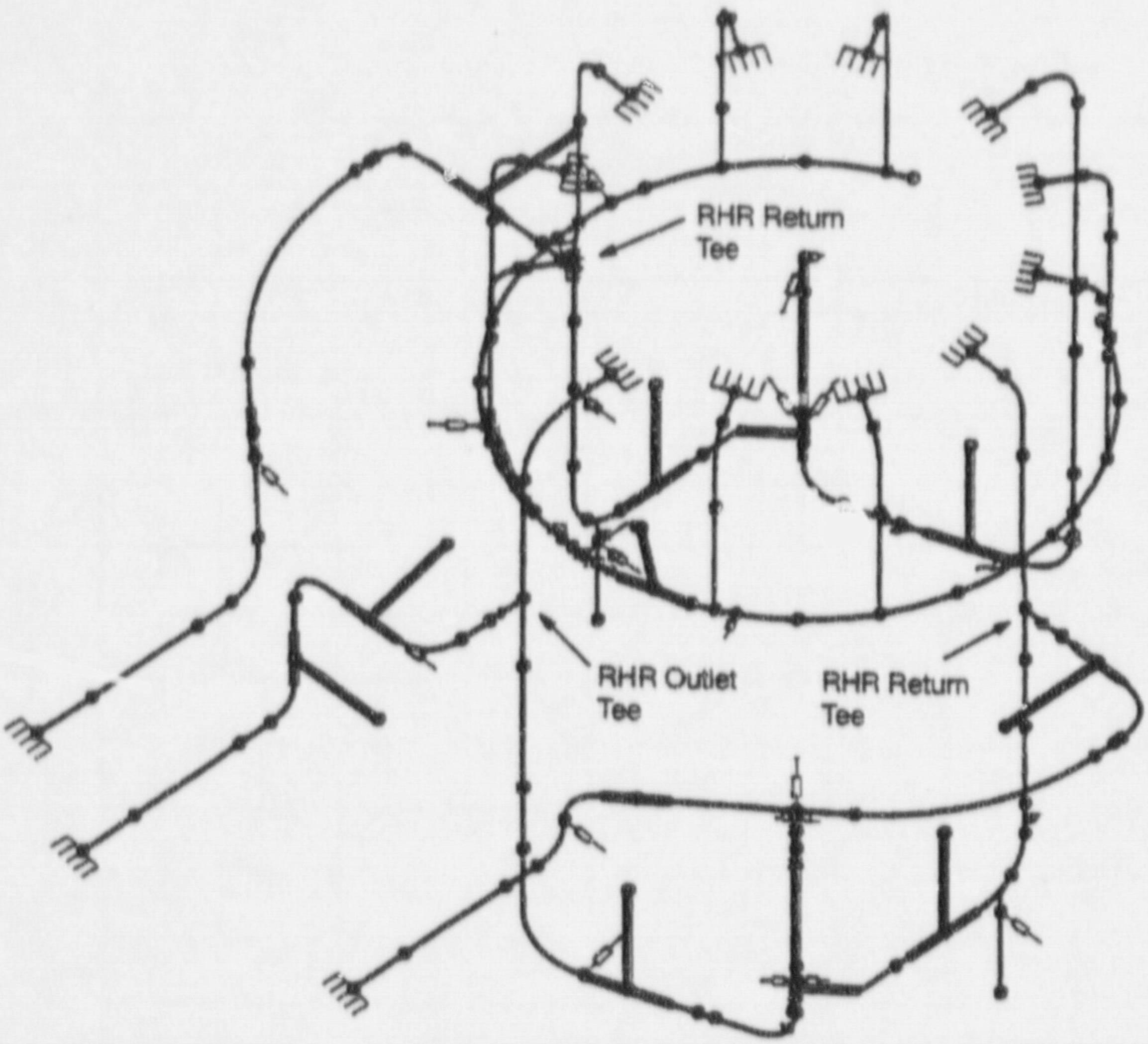


Figure 5-4
Mathematical Model o: VR/4 Recirculation Piping System.

To make an equal comparison, the alternating stress magnitudes and calculated values of strain rates for various load state pairs were assumed to be same as those used in the Reference 2-18 analysis.

Table 5-5
CUF Results for Example Recirculation Piping System

Load Pair	S_{alt} (ksi)	n	Current Code Fatigue Usage		Proposed approach Fatigue Usage		
			N	U_a	Strain Rate (%/sec)	F_{en}	U_{en}
Composite Loss E/OBE	182.76	10	266	0.0376	0.022	2.388	0.0898
Composite Loss A/RHR B	161.69	10	384	0.026	0.019	2.435	0.0633
Turbine Roll A/RHR B	144.89	160	535	0.299	0.017	2.472	0.739
RHR A/OBE	133.56	40	693	0.0577	0.016	2.492	0.144
RHR A/ Turbine Roll A	116.13	12	1086	0.011	0.014	2.537	0.028
RHR A/ Comp. Loss C	107.48	10	1412	0.0071	0.013	2.562	0.018
RHR A/ Comp. Loss D	100.12	10	1796	0.0056	0.012	2.59	0.014
RHR A/ Comp. Loss G	99.65	10	1825	0.0055	0.012	2.59	0.014
RHR A/Turb. Trip-Scrams B	94.26	88	2227	0.0395	0.011	2.62	0.103
Turb. Trip B/ Shutdown	63.86	10	10107	0.001	0.001	3.613	0.004
Turb. Trip A/ Null & Cooldown	62.87	10	10905	0.001	0.001	3.613	0.004
Turbine Trip-Scrams / Shutdown	59.20	160	14611	0.011	0.001	3.613	0.04
Turbine Trip-Scrams / Cooldown	57.14	36	17358	0.0021	0.001	3.613	0.007
Turbine Roll B/Null	56.85	172	17793	0.01	0.001	3.613	0.036
Warmup/Composite Loss F	55.42	10	20146	0.0005	0.001	3.613	0.002
Hydrotest Down/ Startup	50.64	68	31786	0.002	0.001	3.613	0.007
Reduction to Power/ Cooldown	50.56	139	32041	0.0043	0.001	3.613	0.016

Table 5-5 (continued)
CUF Results for Example Recirculation Piping System

Load Pair	S_{alt} (ksi)	n	Current Code Fatigue Usage		Proposed Approach Fatigue Usage		
			N	U_a	Strain Rate (%/sec)	F_{en}	U_{en}
Reduction to Power/ Warmup	50.43	26	32460	0.0008	0.001	3.613	0.003
Warmup/Startup	50.42	104	32494	0.003	0.001	3.613	0.011
	46.76	25	47562	0.0005	0.001	3.613	0.002
	42.83	10	76633	0.0001	0.001	3.613	0.0004
	42.74	58	77520	0.0007	0.001	3.613	0.002
	41.82	10	87342	0.0001	0.001	3.613	0.004
Total				0.526			1.351

Now consider the first load state pair in Table 5-5 with a S_{alt} of 182.76 ksi and strain rate of 0.022%/second. The F_{en} for this load state pair was calculated using Equation 3-13. The only variable in that equation is $\dot{\varepsilon}^*$. The value of $\dot{\varepsilon}^*$ was obtained using the strain rate of 0.022%/second:

$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$$

$$= \ln(0.022)$$

$$\dot{\varepsilon}^* = -3.8167$$

The F_{en} was then calculated as follows:

$$F_{en} = \exp(+0.359 - 0.134\dot{\varepsilon}^*) \quad \text{(Eq. 5-7)}$$

$$= \exp(+0.359 - 0.134 \bullet [-3.8167])$$

$$F_{en} = 2.388$$

Given the S_a value of 182.76 and the number of cycles at 10, the partial fatigue usage for this load state pair based on the 1992 Code fatigue curve was calculated as 0.0376. The corrected partial fatigue usage for this load state pair was then obtained by multiplying this value with F_{en}:

$$U_{en} = U_{air} \bullet F_{en} \quad \text{(Eq. 5-8)}$$

$$= 0.0376 \bullet 2.388$$

$$= 0.0898$$

Similar calculations were repeated for other load state pairs in Table 5-5. The CUF based on the 1992 Code fatigue curve was determined to be 0.526. Table 5-5 shows the calculated value CUF using the proposed approach as 1.351. This represents an increase by a factor of (1.351/0.526) or 2.57 compared to an increase by a factor of (3.256/0.526) or 6.19 based on Reference 2-18.

Note that the fatigue usage factor at the RHR tee is high due to conservatisms built into the NB-3600 procedures. A fatigue usage calculation in Reference 5-1 for a similar recirculation line to RHR branch connection using both the NB-3600 and NB-3200 methods clearly illustrate this. It was reported that for one of the load states pair (28-9), the calculated fatigue usage based on the NB-3600 procedures was 0.43 versus 0.0002 when the NB-3200 procedures were used. Although such dramatic reductions in calculated fatigue usages are not always possible, it does illustrate that selective use of NB-3200 methods might help reduce the calculated values of fatigue usage factors.

5.1.3 PWR Surge Line

In Section 5.2.3 of Reference 2-18, Ware, et al., considered a PWR surge line elbow for evaluating fatigue usage. Table 5-32 of that reference presented the results of their evaluation using the anticipated number of cycles. The same case is considered here and the fatigue usage was calculated using the proposed methodology. The surge line material is SA-376 Type 316 stainless steel. For consistency, the strain rate was assumed as 0.001%/second for all of the load state pairs, as in Reference 2-18. The calculated fatigue usage factor in Reference 2-18 was 1.345. A revised version of stainless steel interim fatigue curve was used in that evaluation.

Table 5-6 shows the results of the evaluation using the proposed methodology. The calculation procedure for F_{en} was essentially the same as that described in the preceding subsection. The last three load state pairs listed in Reference 2-18 were not included in Table 5-6 because their contribution to the total fatigue usage was insignificant. A review of Table 5-6 indicates that the calculated value of the cumulative fatigue usage based on the proposed methodology is 0.425, versus the reported value of 1.345 in Reference 2-18.

Table 5-6
CUF Results for Surge Line Elbow

Load Pair	S_{alt} (ksi)	n	Current Code Fatigue Usage		Proposed Approach Fatigue Usage		
			N	U_a	Strain Rate (%/sec)	F_{en}	U_{en}
Stratif./Loss of Flow with Reactor Trip	59.56	2	14187	0.0001	0.001	3.613	0.0004
Stratif./Loss of Flow with Loss of Load	58.29	1	15755	-	0.001	3.613	-
Stratif./Loss of Flow w/o Loss of Load	57.01	37	17552	0.002	0.001	3.613	0.007
Stratification/Loss of Load	55.45	40	20090	0.002	0.001	3.613	0.007
Stratification/ Reactor Trip	54.25	70	22440	0.003	0.001	3.613	0.011
Stratification/ Stratification	50.44	71	32430	0.0022	0.001	3.613	0.008
Stratification/ Reactor Trip	49.19	67	36815	0.0018	0.001	3.613	0.006
Stratification/ Low Pressure	45.47	5	55210	-	0.001	3.613	-
Stratification/ Plant Unloading	44.89	202	59240	0.0034	0.001	3.613	0.012
Stratification/ Stratification	36.99	17570	170080	0.103	0.001	3.613	0.372
Stratification/ Leak Test A	33.31	150	319215	0.0005	0.001	3.613	0.002
Stratification/ Hydrotest	32.66	2	361010	-	0.001	3.613	-
Total				0.118			0.425

5.2 NB-3200 Application

For the NB-3200 application, a feedwater nozzle safe end fatigue evaluation presented in Reference 2-18 was considered. The same case is used here to calculate a new fatigue usage factor based on the proposed methodology.To make a direct comparison with the CUF determined in Reference 2-18, the alternating stresses, strain rates, and temperatures for the various load state pairs were assumed to be the same as those in that reference. The safe end material is SA-508 carbon steel. The CUF determined in Reference 2-18 was 1.73.

Table 5-7
CUF Results for a Feedwater Nozzle Safe End

Load Pair	S_{alt} (ksi)	n	Current Code Fatigue Usage		Proposed Approach Fatigue Usage			
			N	U_s	Temp (°C)	Strain Rate (%/sec)	F_{en}	U_{en}
Turbine Roll A/TG Trip A	82.27	120	1024	0.117	200	0.028	1.515	0.177
Turbine Roll A /Hot Standby A	72.60	90	1429	0.063	200	0.026	1.524	0.096
Hot Standby A /Null	64.41	142	1967	0.072	200	0.026	1.524	0.110
Shutdown A /Null	38.98	555	9272	0.060	200	0.002	1.886	0.113
Turbine Roll A /Turbine Trip A	29.28	10	23830	0.0004	200	0.001	1.0*	0.0004
Turbine Roll B/ TG Trip B	20.85	120	81350	0.001	200	0.001	1.0*	0.001
TG Trip B/Null	19.21	98	115630	0.0008	200	0.001	1.0*	0.0008
Turbine Trip B /Null	17.56	10	159810	-	288	0.001	1.0*	-
OBE/Null	17.44	10	163810	-	288	0.001	1.0*	-
Hot Standby B /Null	13.85	222	444850	0.0005	288	0.001	1.0*	0.0005
Shutdown B /Null	13.43	666	523970	0.001	288	0.001	1.0*	0.001
Startup/Null	13.33	120	560450	0.0002	288	0.001	1.0*	0.0002
Total				0.316				0.50

* *The alternating stress S_a meets the threshold criteria.*

The results of CUF calculations using the proposed approach are shown in Table 5-7. The CUF using the 1992 Code fatigue curve is 0.312 as shown in Table 5-7. The following illustrates the partial fatigue usage calculation using the proposed approach. Consider the first load state pair in Table 5-7. The temperature associated with this load state is 200°C and the strain rate is 0.028%/second. The F_{en} for this load state pair was calculated using Equation 3-11. The parameters were as follows:

S = 0.015

T = 200°C

$\dot{\varepsilon}$ = 0.028%/sec

O = 0.2 ppm

Using the preceding values, the parameters that go into the expression for F_{en} were obtained using Equation 3-8:

$$S^* = 0.015$$

$$T^* = 50$$

$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$$

$$= \ln(0.028)$$

$$= -3.5755$$

$$O^* = 0.2$$

The F_{en} was calculated using Equation 3-11 for carbon steels as follows:

$$F_{en} = \exp(+0.384 - 0.00133T - 0.554S^*T^*O^*\dot{\varepsilon}^*) \quad \text{(Eq. 5-9)}$$

$$= \exp(0.384 - 0.00133 \bullet 50 - 0.554 \bullet 0.015 \bullet 50 \bullet 0.2 \bullet [-3.5755])$$

$$= 1.515$$

The partial fatigue usage for this load state pair based on the 1992 Code fatigue curve was earlier calculated as 0.117. The corrected partial fatigue usage for this load state pair was then obtained by multiplying this value by F_{en}:

$$U_{en} = U_{air} \bullet F_{en} \quad \text{(Eq. 5-10)}$$

$$= 0.117 \bullet 1.515$$

$$= 0.177$$

Similar calculations were repeated for other load state pairs in Table 5-7. The CUF incorporating the environmental effects is shown as 0.497 in Table 5-7. It is seen that the increase in calculated CUF using the proposed approach is considerably less than when using the interim curves.

In connection with the feedwater nozzle and safe end fatigue usage factors, it is noteworthy that the fatigue usage based on monitoring the actual plant transients is generally considerably lower than that based on the design transients. For example, based on fatigue monitoring by General Electric of a Japanese BWR for two fuel cycles, the 40-year CUF for the feedwater nozzle was estimated at only 0.0074, compared to the design basis value of 0.387 [Reference 5-2]. Similarly, it was noted in Reference 2-19 that for 12 startups and 11 shutdowns at a BWR, the computed feedwater nozzle CUF based on fatigue monitoring was about 1/30th of the design basis CUF.

5.3 References

[5-1] H.L. Hwang, J.R., and D.M. Bosi. "Fatigue Usage Factor Evaluation for an Integrally Reinforced Branch Connection using NB-3600 and NB-3200 Analysis Methods. ASME PVP. Volume No. 313-2. 1995.

[5-2] T. Sakai, K. Tokunaga, G.L. Stevens, and S. Ranganath. "Implementation of Automated, On-line Fatigue Monitoring in a Boiling Water Reactor." ASME PVP. Volume 252. 1993.

6

RECOMMENDED ASME SECTION III CHANGES

This section presents suggested changes in the appropriate articles of ASME Section III to provide stress analysts with enabling words to include the environmental effects in the Code fatigue evaluations conducted according to NB-3600 and NB-3200. The evaluation procedures could be incorporated in the form of a non-mandatory appendix to the Code. A suggested format of such an appendix is provided in the Appendix to the report.

6.1 NB-3600

Paragraph NB-3610 specifies the general requirements of piping design. A subparagraph NB-3614 worded as follows might be added to provide enabling words.

NB-3614 Environmental Effects

When the environmental effects on the fatigue analysis required by NB-3650 are considered significant, such effects may be accounted for by using the methods described in Appendix XX.

The other location that needs to be modified is another subparagraph, NB-3653.8, which might be added as follows:

NB-3653.8 Consideration of Environmental Effects

When the environmental effects are considered significant, the cumulative fatigue damage may be calculated using the procedures of Appendix XX.

6.2 NB-3200

The procedure for fatigue analysis in NB-3200 is contained in NB-3224.4(e), "Procedure for Analysis for Cyclic Loading." Paragraph (5) of NB-3224.4 (e) stipulates six steps for calculating cumulative fatigue damage when there are two or more types of stress cycles that produce significant stresses. Add the following step to NB-3224.4(e):

Step 7: When the environmental effects on the fatigue life are considered significant, such effects may be accounted for by using the methods described in Appendix XX.

6.3 Non-mandatory Appendix Overview

At the end of this report is a non-mandatory Appendix that might be added to ASME Section III. The procedures in the Appendix are consistent with the environmental correction factor approach outlined in Section 4 of the report. The piping or vessel stress analysts will then have a choice of either using the procedures outlined in this non-mandatory Appendix or using equivalent procedures to correct the Code CUF for environmental effects, where such effects are judged significant.

7

SUMMARY

Pressure-retaining components in the light water reactor (LWR) primary systems are designed to meet the requirements of Section III of the ASME Boiler and Pressure Vessel Code or an equivalent Code. The Class I rules of Section III require a fatigue evaluation for the transient stresses that occur during normal/upset condition operation. The fatigue design curves in Section III are based on the cyclic life observed in strain-controlled fatigue tests conducted in the air environment and include either a factor of two on stress or 20 on cycles over the mean curves. The effects of high-temperature reactor water environment were not explicitly considered, although a factor of 4 in the factor of 20 on cyclic life was attributed to atmosphere.

Although there have been relatively few corrosion fatigue failures in materials typically used in the LWR applications, the laboratory data generated in various test programs (e.g., EPRI-sponsored testing at GE, NRC-sponsored testing at Argonne, and testing conducted in Japan) indicate that fatigue lives shorter than the Code design values are possible, especially under low-frequency loading conditions in oxygenated water environments at elevated temperatures.

The laboratory testing by Argonne and in Japan identified strain rate, temperature, strain amplitude, and oxygen content as significant variables affecting fatigue-initiation life. The laboratory testing has generally been with one or a combination of significant variables held at a specified fixed value during the test. However, during the course of a typical plant transient, generally, the temperature and the strain rate are continuously varying but the stress analyses are not detailed enough to evaluate the values of these variables. Furthermore, it is unreasonable to burden the piping or vessel stress analysts to require such a detailed evaluation. Therefore, there is a need for simplified, but not overly conservative, procedures for ASME Section III, NB-3600- and NB-3200-type analyses in which reactor water environment effects need to be accounted for. The basic approach used in this report was to take the existing fatigue usage and multiply it by an environmental correction factor F_{en} to obtain a new fatigue usage reflecting the environmental effects.

A review of the available laboratory test data and previous studies indicated that, currently, two approaches are available: the Higuchi-Iida approach and the NUREG/CR-5999 approach proposed by Argonne. The Argonne also proposed a statistical characterization in the form of a mathematical expression for the cyclic fatigue-initiation life with significant variables, such as strain rate and temperature as the parameters. The materials covered were carbon and low-alloy steels, stainless steels, and Alloy 600. These expressions were recast in this report to produce mathematical expressions for

F_{en}. This represented the third approach. A comparison of the F_{en} values predicted by the three approaches as a function of dissolved oxygen in reactor water showed that the major differences are in the dissolved oxygen range of 0.2 to 0.5 ppm. A review of recent data from Japan and earlier EPRI-sponsored testing of blunt notch CT specimens indicated that predictions based on the Argonne statistical characterization are more consistent with this data. Therefore, F_{en} factors developed in this report from the Argonne statistical characterization were used for subsequent implementation in the NB-3600 and NB-3200 fatigue analyses. The threshold values of significant parameters developed by the PVRC committee were also discussed and adopted.

The most important parameter was identified as the strain rate for a load state pair. For the NB-3600 fatigue evaluations, an approach was described to determine the strain rate. Also, an effective damage approach was described which removes conservatism in the calculated value of F_{en}. The proposed approach was applied to several example cases such as feed water piping, recirculation piping, feedwater safe end and surge line. The results indicated that there is generally a modest increase in the calculated fatigue usage, which is considerably less than that resulting from using the NURG/CR-5999 interim curves.

The report also describes the proposed changes in Section III fatigue-evaluation procedures that might provide analysts with enabling words to refer to a non-mandatory appendix to account for environmental fatigue effects. An example of the non-mandatory appendix is included as an appendix to this report.

Non-mandatory Appendix X

FATIGUE EVALUATIONS INCLUDING ENVIRONMENTAL EFFECTS

X-1000 Scope

This appendix provides methods for performing fatigue usage factor evaluations of reactor coolant system and primary pressure boundary components when the effects of reactor water on fatigue-initiation life are judged to be significant.

X-1100 Environmental Fatigue Correction

The evaluation method uses as its input the partial fatigue usage factors U_1, U_2, U_3, ...U_n, determined in Class I fatigue evaluations. In the Class I design-by-analysis procedure, the partial fatigue usage factors are calculated for each type of stress cycle in paragraph NB-3222.4(e)(5). For Class I piping products designed using the NB-3600 procedure, Paragraph NB-3653 provides the procedure for calculating partial fatigue usage factors for each of the load state pairs

The cumulative fatigue usage factor, U_{en}, considering the environmental effects, is calculated as:

$$U_{en} = U_1 \bullet F_{en\,1} + U_2 \bullet F_{en\,2} + U_3 \bullet F_{en\,3} \ldots U_i \bullet F_{en\,i} \ldots. + U_n \bullet F_{en\,n}$$

where, $F_{en,i}$ is the environmental fatigue correction factor for the ith stress cycle (NB-3200) or load state pair (NB-3600).

X-1200 Environmental Factor Definition

The F_{en} factors are to be calculated using the expressions below.

Carbon Steel

$$F_{en} = exp\,(+0.384 - 0.00133T - 0.554S^*T^*O^*\dot{\varepsilon}^*) \qquad \text{(Eq. 1)}$$

Low-alloy Steel

$$F_{en} = exp\,(+0.766 - 0.00133T - \text{[illegible]}S^*T^*O^*\dot{\varepsilon}^*) \qquad \text{(Eq. 2)}$$

Stainless Steels Except 316NG

$$F_{en} = exp\,(+0.359 - 0.134\dot{\varepsilon}^*) \quad \text{(Eq. 3)}$$

Type 316NG Stainless Steel

$$F_{en} = exp\,(-0.023 - 0.134\dot{\varepsilon}^*) \quad \text{(Eq. 4)}$$

Alloy 600

$$F_{en} = 1.49 \quad \text{(Eq. 5)}$$

X-1300 Evaluation Procedures

For some types of stress cycles or load state pairs, any one or more than one environmental parameters are below the threshold value for significant environmental fatigue effects. The value of the environmental fatigue correction factor F_{en} for such types of stress cycles or load state pairs will be equal to 1.0. Article X-2000 provides procedures for threshold criteria evaluation.

The procedures for the evaluation of F_{en} factors for design by analysis and for Class I piping products fatigue evaluations are provided in X-3000.

X-1400 Nomenclature

The symbols adopted in this appendix are defined as follows:

E = Young's Modulus, psi

F_{en} = Environmental correction factor applied to fatigue usage calculated using Code fatigue curves

O = Oxygen content of fluid (ppm)

O^* = Transformed oxygen content

S = Sulfur content of carbon and low-alloy steels, weight %

S^* = Transformed sulfur content

S_{alt} = Alternating stress amplitude, psi

T = Temperature (°C)

T^* = Transformed temperature

T_a = Average temperature on side a during a temperature transient

T_b = Average temperature on side b during a temperature transient

T_c = Sum of $|T_a\text{-}T_b|$, $|\Delta T_1|$, and $|\Delta T_2|$ for temperature transient producing compressive stresses at the component surface in contact with fluid

T_m = Metal temperature during a temperature transient at surface in contact with fluid

T_t = Sum of $|T_a\text{-}T_b|$, $|\Delta T_1|$, and $|\Delta T_2|$ for temperature transient producing tensile stresses at the component surface in contact with fluid

ΔT_1 = Linear temperature gradient through a component wall during a temperature transient

ΔT_2 = Nonlinear temperature gradient through a component wall during a temperature transient

t_t = Elapsed time between the start of temperature transient and the time when T_t is reached, seconds

t_{300} = Elapsed time between the start of temperature transient and the time when the metal surface in contact with fluid reaches 300°F, seconds

U_{em} = Cumulative fatigue usage factor including the environmental effects

U_i = Cumulative fatigue usage factor for load pair *i* obtained by using Code fatigue curves

$\dot{\varepsilon}$ = Strain rate, %/second

$\dot{\varepsilon}^*$ = Transformed strain rate

ARTICLE X-2000

ENVIRONMENTAL FATIGUE THRESHOLD CONSIDERATIONS

X-2000 Scope

This article provides procedures for screening out types of stress cycles or load state pairs for which any one or more than one environmental parameters are below the threshold value for significant environmental fatigue effects. The value of the environmental fatigue correction factor F_{en} for such types of stress cycles or load state pairs will be equal to 1.0.

X-2100 Strain Range Threshold

(a) Calculate the strain range, ε_i associated with a type of stress cycle or load state pair *i* by multiplying the alternating stress intensity $S_{alt\,i}$ by 2 and dividing by the modulus of elasticity *E*. The value of *E* shall be obtained from the applicable design fatigue curves of Figures I-9.0.

(b) If the value of ε_i calculated in Step (a) for a type of stress cycle or load state pair is less than or equal to 0.1, that type of stress cycle or load state pair satisfies the threshold criterion for strain range and the value of $F_{en\,i}$ is 1.0. No further evaluation with respect to other threshold values need be made for this type of stress cycle or load state pair.

X-2200 Strain Rate Threshold

A type of stress cycle or the load state pair that involves seismic load state satisfies the strain rate threshold criterion for strain rate and the value of $F_{en\,i}$ is 1.0. No further evaluation with respect to other threshold values need be made for this type of stress cycle or load state pair.

X-2300 Temperature Threshold

(a) Define the effective temperature *T* associated with a type of stress cycle or load state pair *i* as equal to the higher of the highest temperatures in the two transients or load states constituting the type of stress cycle or load state pair.

(b) If the temperature calculated in Step X-2300(a) is less than or equal to 300°F (or 150°C), the stress cycle or load state pair satisfies the threshold criterion for temperature and the value of $F_{en\,i}$ is 1.0.

X-2400 Dissolved Oxygen Threshold

(a) Define the effective dissolved oxygen content *DO* associated with a type of stress cycle or load state pair *I* as equal to the higher of the highest oxygen content in the two transients or load states constituting the type of stress cycle or load state pair.

(b) If the value of *DO* determined in Step X-2400(a) for a type of stress cycle or load state pair is less than or equal to 0.05 ppm, that type of stress cycle or load state pair satisfies the threshold criterion and the value of $F_{en\,i}$ is 1.0.

ARTICLE X-3000

ENVIRONMENTAL FACTOR EVALUATION

X-3100 Scope

This article provides procedures for calculating the F_{en} factors for types of stress cycles (NB-3200) or load state pairs (NB-3600). Only the types of stress cycles or load state pairs that do not meet the threshold criteria of X-2000 need to be considered for F_{en} calculation.

X-3200 Evaluation Procedure for Design By Analysis

X-3210 Determination of Transformed Strain Rate

The strain rate (%/sec) for a stress cycle is determined as:

$$\dot{\varepsilon} = S_{range\,i} \bullet 100/E \bullet t_{max}$$

where, $S_{range\,i}$ is the stress difference range for cycle i as determined in NB-3224.4(e)(5) and the t_{max} is the time in seconds when the stress difference reaches a maximum from the start of the temperature transient. This calculation is performed only for the step-down temperature transient in the stress cycles constituting a pair. The transformed strain rate ε^* is obtained as:

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 1\%/sec)$$

$$\dot{\varepsilon}^* = ln(\dot{\varepsilon}) \qquad (0.001 \leq \dot{\varepsilon} \leq 1\%/sec)$$

$$\dot{\varepsilon}^* = ln(0.001) \qquad (\dot{\varepsilon} < 0.001\%/sec)$$

X-3220 Determination of Transformed Temperature

The temperature T associated with a type of stress cycle i as equal to the higher of the highest temperatures in the two transients constituting the type of stress cycle. The transformed temperature T^* is obtained as:

$$T^* = 0 \qquad (T < 150°C)$$

$$T^* = T-150 \qquad (T > 150°C)$$

X-3230 Determination of Transformed DO for Carbon and Low-alloy Steels

The effective dissolved oxygen content DO associated with a type of stress cycle i is equal to the higher of the highest oxygen content in the two transients constituting the type of stress cycle. The transformed DO, O^* is obtained as follows:

$O^* = 0$ (DO<0.05 ppm)

$O^* = DO$ (0.05 ppm ≤ DO ≤ 0.5 ppm)

$O^* = 0.5$ (DO > 0.5 ppm)

X-3240 Determination of Transformed Sulfur for Carbon and Low-alloy Steels

The sulfur content S in terms of weight percent migh be obtained from the certified material test report or an equivalent source. If the sulfur content is unknown, then its value will be assumed as 0.015%. The transformed sulfur S^* is obtained as:

$S^* = S$ (0<S<0.015 wt%)

$S^* = 0.015$ (S>0.015 wt%)

X-3250 Determination of F_{en}

The environmental correction factor $F_{en\,i}$ for a type of stress cycle and the cumulative fatigue usage factor will be calculated using equations given in X-1200.

X-3260 Determination of F_{en} Based on Damage Approach

Procedure similar to that described in X-3660 may be used to remove some of the conservatism built into the $F_{en\,i}$ determined in X-3250.

X-3600 Evaluation Procedure for Piping

X-3610 General Requirements

The procedures in this article use the input information and the partial fatigue usage results from the NB-3650 fatigue evaluation. The example of specific load state information needed is internal pressure and the three moment components, $|T_a - T_b|$, ΔT_1 and ΔT_2. When the detailed results of one-dimensional transient heat transfer analyses are available in the form of time history of $|T_a - T_b|$, ΔT_1, and ΔT_2, such results might be used to reduce conservatisms in the calculated values of environmental correction factor.

X-3610 Determination of Transformed Strain Rate

The strain rate (%/sec) for a stress cycle is determined as:

$$\dot{\varepsilon} = 2 \bullet S_{alt\,i} \bullet [T_t/(T_t + T_c)]/(E \bullet t_t)$$

where $S_{alt\,i}$ is the alternating stress intensity for load state pair I calculated in NB-3653.3. This calculation is performed only for the step-down temperature transient in a load state pair. The transformed strain rate $\dot{\varepsilon}^*$ is obtained as:

$\dot{\varepsilon}^* = 0$ $(\dot{\varepsilon} > 1\%/sec)$

$\dot{\varepsilon}^* = ln(e)$ $(0.001 \le \dot{\varepsilon} \le 1\%/sec)$

$\dot{\varepsilon}^* = ln(0.001)$ $(\dot{\varepsilon} < 0.001\%/sec)$

X-3620 Determination of Transformed Temperature

The temperature T associated with a load state pair is equal to the higher of the highest temperatures in the two transients constituting the load state pair. The transformed temperature T^* is obtained as the following:

$T^* = 0$ $(T < 150°C)$

$T^* = T-150$ $(T > 150°C)$

X-3630 Determination of Transformed DO for Carbon and Low-alloy Steels

The effective dissolved oxygen content DO associated with a load state pair i is equal to the higher of the highest oxygen content in the two transients constituting the load state pair. The transformed DO, O^* is obtained as:

$O^* = 0$ $(DO < 0.05\ ppm)$

$O^* = DO$ $(0.05\ ppm \le DO \le 0.5\ ppm)$

$O^* = 0.5$ $(DO > 0.5\ ppm)$

X-3640 Determination of Transformed Sulfur for Carbon and Low-alloy Steels

The sulfur content S in terms of weight percent may be obtained from the certified material test report or an equivalent source. If the sulfur content is unknown, then its value will be assumed as 0.015%. The transformed sulfur, S^* is obtained as follows:

$S^* = S$ $(0 < S < 0.015\ wt\%)$

$S^* = 0.015$ $(S > 0.015\ wt\%)$

X-3650 Determination of F_{en}

The environmental correction factor $F_{en,i}$ will be calculated using equations given in X-1200.

X-3660 Determination of F_{en} Based on Damage Approach

When the detailed results of one-dimensional transient heat transfer analyses are available in the form of time history of $|T_a - T_b|$, ΔT_1 and ΔT_2, such results may be used to reduce conservatisms in the calculated values of F_{en}. The following expression or equivalent shall be used:

$$F_{en,300} = (1/t_{300}) \int [t_{300}/exp(+0.384-0.00133T_{m,\tau} + 0.554S^{*}T_{m,\tau}{}^{*}O^{*}\dot{\varepsilon}_{\tau}{}^{*})]d\tau$$

The preceding value of F_{en} may be used in lieu of the F_{en} value calculated in X-3650.

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