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October 3, 2011

Mr. Michael J. Case
Director
Division of Engineering
Office of Nuclear Regulatory Research
The United Sates Nuclear Regulatory Commission

Dear Mr. Case

This is to respond to your letter dated June 6, 2011 requesting the delivery of our Environmental Fatigue Data for the updating of your Regulatory Guide 1.207 formulated in 2008.

First of all let us express our apology for the time taken so long to meet your request due to the administrative reasons despite that your continuous interest in this Data was perceived as the great honor to our organization. Now we are pleased to inform you that data you requested is being exposed and provided to you by CDROM as attached. This is the dataset embedded behind the report JNES-SS-1005 translated into English from the original Japanese Report JNES-SS-0701.

Correlation of Environmental Fatigue has been developed by JNES based on the dataset collected by JNES itself and literature data collected by other organizations. We have also identified the sources of those data and included the information this time.

We hope we share the same understanding between you and us that our data is provided to NRC based on the spirit of the Implementing Agreement between the United States Nuclear Regulatory Commission and the Japan Nuclear Energy Safety Organization in the Area of Material-Related Research signed September 21 of 2007 and moreover as is mentioned in your letter, we expect that you will cite the name of JNES whenever appropriate and our data will not be delivered to the third party.

Finally we are really hoping that our cooperation would be maintained and further enlarged to the new horizon related to the material behavior.

Sincerely Yours

Naoyuki Hasegawa
Director General

JNES-SS-1005

Nuclear Power Generation Facilities

Environmental Fatigue Evaluation Method for Nuclear Power Plants

JNES-SS Report

March 2011

Nuclear Energy System Safety Division
Japan Nuclear Energy Safety Organization

Preface

This JNES-SS report is "Environmental Fatigue Evaluation Guide for Nuclear Power Generation Facilities" that summarizes the results on environmental fatigue evaluation derived from the final technical results of EFT project, "Environmental Fatigue Testing of Materials for Nuclear Power Generation Facilities". This EFT project was advanced by commission to the Japan Power Engineering and Inspection Corporation (JAPEIC) from Ministry of International Trade and Industry (MITI) (from April 1994 to September 2003), and subsequently by subsidies to the Japan Nuclear Energy Safety Organization (JNES) from MITI (from December 2003 to March 2007).

As for the equation to evaluate the environmental fatigue life for nuclear power generation facilities in the past, "Environmental Fatigue Evaluation Guide" was proposed in March 2000 as the mid-term results of EFT project. In September 2000, based on this guide, the Nuclear Power Generation Safety Management Division of the Agency for Natural Resources and Energy, MITI issued "Guidelines for Evaluating Fatigue Initiation Life Reduction in the LWR Environment" as a notification on ageing measures for nuclear power plants (12 Safety Management No.11). In June 2002, the Thermal and Nuclear Power Engineering Society (TENPES) issued "Guidline on Environmental Fatigue Evaluation for Nuclear Power Generation Facilities" (called "the TENPES Guideline") that would provide specific and practical evaluation method in application of this guideline for actual plants. Subsequently, JNES SS Report, "The Environmental Fatigue Evaluation Guide for Nuclear Power Generation Facilities" (JNES-SS-0503) was issued in 2005 on the basis of the results summarized in EFT project until March 2004. Based on this report, the new Code, "Codes for Nuclear Power Generation Facilities; Environmental Fatigue Evaluation Method for Nuclear Power Plants" (JSME S NF1-2006) was issued by the Japan Society of Mechanical Engineers (JSME).

This report is to provide the final proposal of the equation to evaluate the environmental fatigue life that has been reviewed and revised, including the newest data obtained in EFT project.

The major items revised from JNES-SS-0503 mentioned above are shown below:

(1) Reference fatigue curve in air at the room temperature

- The reference fatigue curve was developed, involving the newest data for each of carbon steel, low-alloy steel, stainless steel, and nickel-chromium-iron alloy.

(2) Environmental fatigue life correction factor (F_{en})

- The equation to evaluate F_{en} for the dissolved oxygen concentration, $DO > 0.7$ ppm was added for carbon steels and stainless steels.

- The transient conditions in the BWR environment were added as the conditions for applying the equation to evaluate F_{en} for carbon steels and stainless steels.
- The equation to evaluate F_{en} in the BWR environment was revised for austenitic stainless steels.
- The equation to evaluate F_{en} for nickel-chromium-iron alloy was changed to the new equation.

(Note for English version)

This JNES SS Report entitled “JNES-SS-1005 Nuclear Power Generation Facilites, Enviromental Fatigue Evaluation Method for Nuclear Power Plants” is translated into English from original JNES-SS-0701 in Japanese. A part of the contents of JNES-SS-0701 was changed to facilitate understanding the contents and to provide additional information on environmental fatigue activites. The key equations, however, were not changed from JNES-SS-0701.

Nuclear Power Generation Facilities

Environmental Fatigue Evaluation Method for Nuclear Power Plants

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Chapter 1 Scope

1.1 Scope of Application

This document is applicable in the items provided in the following (1) through (3).

(1) Subjects to be evaluated

When fatigue evaluation is performed for components of light water reactor plant, this guideline is applicable in evaluation of environmental effect on the materials exposed to high temperature water.

(2) Materials

This document is applicable for materials such as carbon steel, low alloy steel, austenitic stainless steel and nickel-chromium-iron alloy used for the light water reactor.

(3) Environmental conditions

Temperature and water chemistry shall be in the ranges of design and operating conditions of the light water reactor.

1.2 Conditions of Application

The evaluation based on this guideline requires the relevant evaluation conditions needed for fatigue evaluation without consideration of environmental conditions, such as transient conditions for structures and components to be evaluated, stresses and the number of cycles due to transients, and combination of transients.

Chapter 2 Symbols

C	: Constant to calculate F_{en}
DO	: Dissolved oxygen concentration (ppm)
F_{en}	: Environmental fatigue life correction factor ($=N_A/N_W$)
$F_{en,i}$	: F_{en} at the i^{th} stress cycle in n cycles
$F_{en,sc}$	: F_{en} using the factor multiplication method
$F_{en,simp}$	: F_{en} using the simplified method
$F_{en,det}$	: F_{en} using the detailed method
N_A	: Fatigue life in air at room temperature (cycles)
N_W	: Fatigue life in water (cycles)
O^*	: Parameter of dissolved oxygen concentration
S	: Sulfur content in steel (%)
S^*	: Parameter of sulfur content
T	: Temperature (°C)
T^*	: Parameter of temperature
U	: Cumulative fatigue usage factor without environmental effects
U_{en}	: Cumulative fatigue usage factor with environmental effects
U_i	: Cumulative fatigue usage factor without environmental effects at the i^{th} stress cycle in n cycles
$\dot{\varepsilon}$	: Strain rate[1] (%/s)
$\dot{\varepsilon}^*$	: Parameter of strain rate
ε_{max}	: Maximum strain (%)
ε_{min}	: Minimum strain (%)

1 Only positive strain rates (time periods with continuously increasing strains) are considered when calculating environmental fatigue effects.

Chapter 3 Method to Evaluate Environmental Effects

This chapter indicates the methods to evaluate environmental fatigue life of structures and components that are exposed to the reactor cooling water of BWR and PWR, and PWR secondary system water. The environmental fatigue life correction factor, F_{en} defined in 3.1 shall be used to evaluate the effect of the environment.

3.1 Definition of F_{en}

The F_{en} is the factor of the reduction effect of fatigue life in high temperature water environment and is defined as the value obtained by dividing the fatigue life in air with a particular strain amplitude by the fatigue life in the reactor cooling water or PWR secondary system water with the same strain amplitude according to equation (3.1-1): detailed methods are described in 3.3.

$$F_{en}=\frac{N_A}{N_W} \tag{3.1-1}$$

The cumulative fatigue usage factor with environmental effects, U_{en} can be expressed by using F_{en} in the following equation (3.1-2):

$$U_{en} = U \times F_{en} = \sum_{i=1}^{n} U_i \times F_{en,i} \tag{3.1-2}$$

Where, U_i and $F_{en,i}$ are the cumulative fatigue usage factor without environmental effects at the ith stress cycle in n cycles and the environmental fatigue life correction factor at the i^{th} stress cycle in n cycles, respectively.

3.2 Environmental Effects Threshold

This section indicates the conditions of the environmental effects threshold. Environmental effects are not considered when the following criteria are satisfied and evaluation of F_{en}=1.0 is applicable.

(1) Strain amplitudes

The threshold strain amplitudes are as follows:

For carbon steels and low-alloy steels 0.042 % or less

For austenitic stainless steels and nickel-chromium-iron alloys, 0.11% or less

(2) Load conditions

F_{en} is influenced by the environment at the strain rate due to thermal transient and pressure fluctuation of the actual plant. Regarding the seismic loads, since F_{en} is not influenced by the environment because of sufficiently fast strain rate, consideration of the environmental effect is not required.

3.3 F_{en} Definitions for Various Materials

3.3.1 Carbon and Low-Alloy Steels and the Welds

$$\ln(F_{en}) = 0.00822\,(0.772 - \dot{\varepsilon}^*) S^* \times T^* \times O^* \qquad (3.3.1\text{-}1)$$

Where

[If DO≦0.7ppm]

$\dot{\varepsilon}^* = \ln(2.16)$ $(\dot{\varepsilon} > 2.16\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.0004 \le \dot{\varepsilon} \le 2.16\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(0.0004)$ $(\dot{\varepsilon} < 0.0004\%/\mathrm{s})$

$S^* = \ln(12.32) + 97.92 \times S$

$T^* = 0.0358 \times T$ $(T < 50℃)$

$T^* = \ln(6)$ $(50 \le T \le 160°\mathrm{C})$

$T^* = \ln(0.398) + 0.0170 \times T$ $(T > 160℃)$

$O^* = \ln(3.28)$ $(DO < 0.02\,\mathrm{ppm})$

$O^* = \ln(70.79) + 0.7853 \times \ln(DO)$ $(0.02 \le DO \le 0.7\,\mathrm{ppm})$

[If DO>0.7ppm]

$\dot{\varepsilon}^* = \ln(2.16)$ $(\dot{\varepsilon} > 2.16\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.0001 \le \dot{\varepsilon} \le 2.16\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(0.0001)$ $(\dot{\varepsilon} \le 0.0001\%/\mathrm{s})$

$S^* = \ln(12.32) + 97.92 \times S$

$T^* = 0.0358 \times T$ $(T < 50℃)$

$T^* = \ln(6)$ $(50 \le T \le 160°\mathrm{C})$

$T^* = \ln(0.398) + 0.0170 \times T$ $(T > 160℃)$

$O^* = \ln(53.5)$ $(DO > 0.7\,\mathrm{ppm})$

Transient condition: In the BWR environment, this equation is applied for the thermal transient, and when the strain rate is higher than 0.004 %/s on the condition of peak retaining pressure assumed in the transients with elastic follow-up such as internal pressure, the strain rate is treated as 0.004 %/s.

3.3.2 Austenitic Stainless Steels and the Welds

(1) In the BWR plant environment:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^* \qquad (3.3.2\text{-}1)$$

Where,

$C = 0.992$

$\dot{\varepsilon}^* = \ln(2.69)$ ($\dot{\varepsilon} > 2.69\%/s$)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.00004 \le \dot{\varepsilon} \le 2.69\%/s$)

$\dot{\varepsilon}^* = \ln(0.00004)$ ($\dot{\varepsilon} < 0.00004\%/s$)

$T^* = 0.000969 \times T$

Transient conditions: In the BWR environment, this equation is applied for the thermal transients, and when the peak retaining pressure is assumed, the strain rate is treated as the lower fatigue rate threshold.

(2) In the PWR plant environment and the PWR plant secondary system environment:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^* \qquad (3.3.2\text{-}2)$$

Where,

$C = 3.910$

$\dot{\varepsilon}^* = \ln(49.9)$ ($\dot{\varepsilon} > 49.9\%/s$)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.0004 \le \dot{\varepsilon} \le 49.9\%/s$)
(Stainless steel except cast stainless steels)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.00004 \le \dot{\varepsilon} \le 49.9\%/s$)
(Cast stainless steels)

$\dot{\varepsilon}^* = \ln(0.0004)$ ($\dot{\varepsilon} < 0.0004\%/s$)
(Stainless steel except cast stainless steels)

$\dot{\varepsilon}^* = \ln(0.00004)$ ($\dot{\varepsilon} < 0.00004\%/s$)
(Cast stainless steels)

$T^* = 0.000782 \times T$ ($T \le 325°C$)

$T^* = 0.254$ ($T > 325°C$)

3.3.3 Nickel-Chromium-Iron Alloys and the Welds

(1) In the BWR plant environment:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^* \qquad (3.3.3\text{-}1)$$

Where,

$C = -0.112$

$\dot{\varepsilon}^* = \ln(0.894)$ ($\dot{\varepsilon} > 0.894\%/s$)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.00004 \leq \dot{\varepsilon} \leq 0.894\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(0.00004)$ $(\dot{\varepsilon} < 0.00004\%/\mathrm{s})$

$T^* = 0.000343 \times T$

(2) In the PWR plant environment and the PWR plant secondary system environment:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^* \tag{3.3.3-2}$$

Where,

$C = 2.94$

$\dot{\varepsilon}^* = \ln(19.0)$ $(\dot{\varepsilon} > 19.0\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.0004 \leq \dot{\varepsilon} \leq 19.0\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(0.0004)$ $(\dot{\varepsilon} < 0.0004\%/\mathrm{s})$

$T^* = 0.000397 \times T$

Chapter 4 Methods to calculate F_{en}

4.1 Methods to calculate F_{en} for the Transients

4.1.1 Determination of Time Segments to be Evaluated

The equation in Section 3.3 provides F_{en} in terms of constant values such as strain rate, temperature and dissolved oxygen concentration. However, during plant operating transients, strain rate and temperatures are not constant and F_{en} is constantly changing. The environmental effect is highly dependent on strain rate when strain rate is positive. So the environmental fatigue evaluation is conducted at the range. It is necessary to identify all of the time segments where the strain is increasing. The incremental strain range is divided into the appropriate number of incremental time segments and F_{en} is calculated for each time segment.

There are the evaluation methods to consider a total of incremental strain range as one time segment (simplified method) and to divide into several time segments (detailed method). Each parameter in calculating F_{en} in the transients is set as described below:

(1) Strain Rate

The average strain rate of each time segment shall be used in the calculation. The lower thresholds of strain rate can be used for the most conservative evaluation (the lower threshold of strain rate: 0.0004 %/s at $DO < 0.7$ ppm and 0.0001 %/s at $DO >$ 0.7 ppm for carbon steel and lowalloy steel, 0.00004 %/s for PWR cast stainless steel and BWR stainless steel, 0.0004 %/s except PWR cast steel, 0.00004 %/s for BWR-and 0.0004 %/s for PWR nickel-chrome-iron alloy) .

(2) Temperature

The maximum metal temperature at the surface of the structure exposed to the environment during the time segment being evaluated is used. The maximum temperature for the concerned transient or the maximum service temperature can be alternatively used.

(3) Dissolved Oxygen Concentration (in case of carbon steels and low alloy steels)

The maximum dissolved oxygen concentration in the reactor cooling water or PWR secondary system water in contact with the material during the time segment being evaluated is used. The maximum dissolved oxygen concentration for the concerned transient or the maximum value assumed for the concerned component can be alternatively used.

(4) Sulfur Content (in case of carbon steels and low-alloy steels)

The maximum sulfur content specified in the material certificate report (mill sheet) or purchase specification for the item shall be used. Or the maximum value set in the Rules on Materials for Nuclear Facilities can be used.

4.1.2 Calculation of F_{en}

Calculation of F_{en} is made with the methods to provide large and simplified F_{en}, and also accurate and complicated F_{en} based on the selection of strain rate, temperature and dissolved oxygen concentration. Specifically, three methods for determining F_{en} are available with varying degrees of complexity and conservatism as mentioned below.

① Factor multiplication method

The simplest and most conservative method, F_{en} is based on use of the limiting values (design conditions) for each variable without the need for identifying time periods with positive strain rates.

② Simplified method

This method requires identification of time periods within stress cycles where the strain rates are positive and evaluating them each as a single time segment without further subdivision. A stress cycle is typically composed of two transients and a transient may have more than one time segment where strain rate is positive.

③ Detailed method

This method requires identification of time periods within stress cycles where the strain rates are positive, then dividing each time period into smaller time segments for evaluation.

In the actual evaluation, any of these three kinds or combination of these methods is also usable. Or, for the case that evaluation is made for combination with the transient conditions such as the evaluation at the design stage, either one of three methods may be used for each of combinations to obtain each cumulative fatigue usage factor, and the overall cumulative fatigue usage factors, U_{en} for subjected evaluation part may be obtained by summing up the total cumulative fatigue factors obtained.

(1) Evaluation using the factor multiplication method

For the factor multiplication method, the cumulative fatigue usage factor, U, at a point without environmental effects is multiplied by the maximum F_{en} (in this case called $F_{en,sc}$) for that location

$$U_{en} = U \times F_{en,sc} \tag{4.1-1}$$

This method is the simplest, but may calculate extremely large F_{en}. The values used to calculate $F_{en,sc}$ by the factor multiplication method are as follows:

- Strain rate: The lower thresholds of strain rate are shown in (lower threshold of strain rate in 4.1.1(1).

- Temperature: the maximum service temperature or higher, over the lifetime of the structure. Alternatively, the maximum temperature during each transient may be used.

- Dissolved oxygen concentration: The maximum dissolved oxygen concentration or higher, over the lifetime of the structure and components. Alternatively, the maximum dissolved oxygen concentration during each transient may be used.

The $F_{en,sc}$ equations for various materials and reactor type are listed in items (a) through (c) below.

(a) Carbon and low-alloy steels and their welds

① In the BWR plant environment:

$$F_{en,sc} = \exp(0.07066 \times S^* \times T^* \times O^*) \quad (DO \leq 0.7 \text{ ppm}) \qquad (4.1\text{-}2)$$

$$F_{en,sc} = \exp(0.08205 \times S^* \times T^* \times O^*) \quad (DO > 0.7 \text{ ppm})$$

$$S^* = \ln(12.32) + 97.92 \times S$$

$$T^* = 0.0358 \times T \quad (T < 50℃)$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160\ °C)$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160℃)$$

$$O^* = \ln(3.28) \quad (DO < 0.02 \text{ ppm})$$

$$O^* = \ln(70.79) + 0.7853 \times \ln(DO) \quad (0.02 \leq DO \leq 0.7 \text{ ppm})$$

$$O^* = \ln(53.5) \quad (DO > 0.7 \text{ ppm})$$

② In the PWR plant secondary system environment:

$$F_{en,sc} = \exp(0.08393 \times S^* \times T^*) \qquad (4.1\text{-}3)$$

$$S^* = \ln(12.32) + 97.92 \times S$$

$$T^* = 0.03584 \times T \quad (T < 50\ °C)$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160\ °C)$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160℃)$$

(b) Austenitic stainless steels and their welds

① In the BWR plant environment:

$$F_{en,sc} = \exp(11.119 \times T^*) \qquad (4.1\text{-}4)$$

$$T^* = 0.000969 \times T$$

② In the PWR plant environment:

$$F_{en,sc} = \exp(11.734 \times T^*)$$

(Stainless steel except cast stainless steels)

(4.1-5)

$F_{en,sc} = \exp(14.037 \times T^*)$ (Cast stainless steels)

$T^* = 0.000782 \times T$ ($T \leq 325$℃)

$T^* = 0.254$ ($T > 325$℃)

(c) Nickel-chromium-iron alloys and their welds

① In the BWR plant environment:

$$F_{en,sc} = \exp(10.015 \times T^*) \quad (4.1\text{-}6)$$

$$T^* = 0.000343 \times T$$

② In the PWR plant environment

$$F_{en,sc} = \exp(10.764 \times T^*) \quad (4.1\text{-}7)$$

$$T^* = 0.000397 \times T$$

(2) Evaluation using the simplified method

For the purpose of this explanation, two transients are used to demonstrate the simplified method. This method is to be applied respectively until all cycles of all transients have been included in the evaluation. To perform an evaluation using the simplified method, $F_{en,simp,A}$ and $F_{en,simp,B}$ shall be calculated respectively for two transients (A and B), which constitute the stress cycle used in the calculation of a fatigue usage factor. As shown in Figure 4.1-1, the time segments evaluated for each transient are those where strain is increasing (i.e. from ε_{min} to ε_{max}). After defining the strain rate, temperature and dissolved oxygen concentration in these time segments according to 4.11, values of F_{en} are calculated using the equations from 3.3. The resulting $F_{en,simp,A}$ and $F_{en,simp,B}$ are produced for each transient.

$F_{en,simp}$ of a stress cycle shall be calculated using equation (4.1-8). However, as an alternative, the larger of $F_{en,simp,A}$ or $F_{en,simp,B}$ may be used.

$$F_{en,simp} = \frac{F_{en,simp,A} \times (\varepsilon_{max,A} - \varepsilon_{min,A}) + F_{en,simp,B} \times (\varepsilon_{max,B} - \varepsilon_{min,B})}{(\varepsilon_{max,A} - \varepsilon_{min,A}) + (\varepsilon_{max,B} - \varepsilon_{min,B})} \quad (4.1\text{-}8)$$

The cumulative fatigue usage factor at a point is calculated using equation (4.1-9).

$$U_{en} = \sum_{i=1}^{n} U_i \times F_{en,simp,i} \quad (4.1\text{-}9)$$

Where, $F_{en,simp,i}$ is for the i^{th} stress cycle in n cycles.

(3) Evaluation using the detailed method

For the purpose of this explanation, two transients are used to demonstrate the detailed method. This method is to be applied respectively until all cycles of all transients have been included in the evaluation. To perform an evaluation using the detailed method, $F_{en,det,A}$ and $F_{en,det,B}$ shall be calculated for two transients (A and B), which constitute the stress cycle used in the calculation of a fatigue usage factor, similar to the simplified method specified in 4.1.2 (2). As shown in Figure 4.1-2, the range (ε_{min} to ε_{max}) where strains continuously increase is divided into n-number time segments to be evaluated. Then, values of F_{en} are calculated for each time segment using the equations in 3.3 after defining the strain rate, temperature and dissolved oxygen concentration in these time segments according to 4.1.1. Although this method is the most complicated, it calculates more accurate F_{en}. Smaller the time segment is divided into, more accurate F_{en} is.

$F_{en,det}$ in each transient shall be calculated using equation (4.1-10).

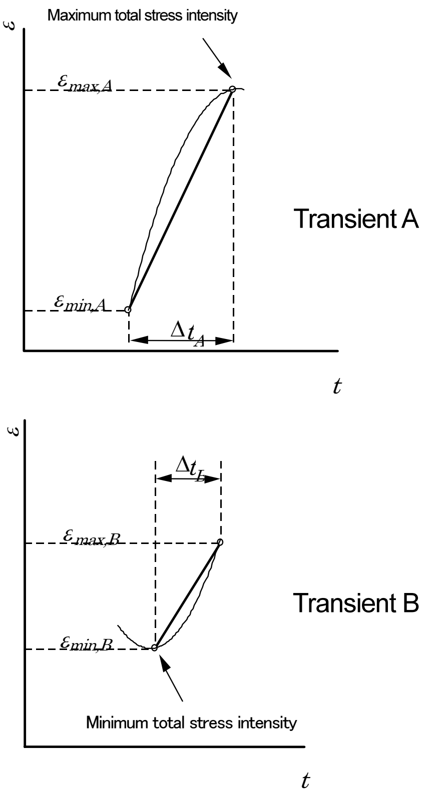
$$F_{en,det} = \sum_{k=1}^{n} F_{en,k} \frac{\Delta\varepsilon_k}{\varepsilon_{max} - \varepsilon_{min}} \tag{4.1-10}$$

$F_{en,det}$ in the stress cycle shall be calculated using equation (4.1-11)

$$F_{en,det} = \frac{F_{en,det,A} \times (\varepsilon_{max,A} - \varepsilon_{min,A}) + F_{en,det,B} \times (\varepsilon_{max,B} - \varepsilon_{min,B})}{(\varepsilon_{max,A} - \varepsilon_{min,A}) + (\varepsilon_{max,B} - \varepsilon_{min,B})} \tag{4.1-11}$$

The cumulative fatigue usage factor shall be calculated using equation (4.1-12).

$$U_{en} = \sum_{i=1}^{n} U_i \times F_{en,det,i} \tag{4.1-12}$$



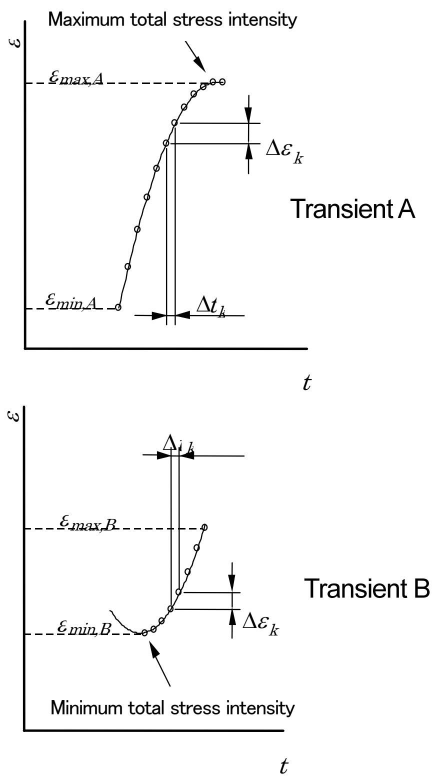
Strain rate during transient A:

$$\dot{\varepsilon}_A = \frac{\varepsilon_{max,A} - \varepsilon_{min,A}}{\Delta t_A}$$

Strain rate during transient B:

$$\dot{\varepsilon}_B = \frac{\varepsilon_{max,B} - \varepsilon_{min,B}}{\Delta t_B}$$

Figure 4.1-1 Strain Rate Calculated Using the Simplified Method



Strain rate in an incremental time segment, k:

$$\dot{\varepsilon}_k = \frac{\Delta\varepsilon_k}{\Delta t_k}$$

Environmental fatigue life correction factor during transient A:

$$F_{en\ det,A} = \sum_{k=1}^{m} F_{en,k} \frac{\Delta\varepsilon_k}{\varepsilon_{max,A} - \varepsilon_{min,A}}$$

Environmental fatigue life correction factor during transient B:

$$F_{en\ det,B} = \sum_{k=1}^{n} F_{en,k} \frac{\Delta\varepsilon_k}{\varepsilon_{max,B} - \varepsilon_{min,B}}$$

Figure 4.1-2 Strain Rate and Environmental Fatigue Life Correction Factor Calculated Using the Detailed Method

4.2 Fatigue Evaluation Method for Vessels

To evaluate the fatigue for vessels, the factor multiplication method specified in 4.2.1, the simplified method in 4.2.2 or the detailed method in 4.2.3 may be used. These three methods may be applied singly or in combination.

4.2.1 Evaluation Using the Factor Multiplication Method

Evaluation using the factor multiplication method shall be performed in accordance with the procedure specified in 4.1.2 (1).

4.2.2 Evaluation Using the Simplified Method

Evaluation using the simplified method shall be performed in accordance with the procedure specified in 4.1.2 (2). Generally, the incremental strain rate is determined based on the histories of strain and temperature during transients for vessel that are calculated by the analysis. Since the environmental effect is established by the incremental strain, the increase and decrease of strains should be discriminated. The fatigue evaluation is performed by calculating the allowable number of stress cycles for the difference between the maximum and the minimum stress intensities, while the environmental fatigue life correction factor, F_{en}, is determined by the strains histories corresponding to the history of difference in stress intensities. In this case, the positive or negative sign of strains should be determined, because the sign for the diference between the maximum and the minimum stress intensities is not defined.

$F_{en,simp,i}$ for vessels shall be calculated by either of the following two methods:

(1) Identify the time during each transient when the stress intensity is largest, then assign the sign of the largest principal stress at that point and time to the strain (refer to Figure 4.2-1).

(2) Calculate $F_{en,simp,i}$ assuming the stress intensity is positive, repeating the calculation with stress intensity negative, then select the larger of the two for $F_{en,simp,i}$.

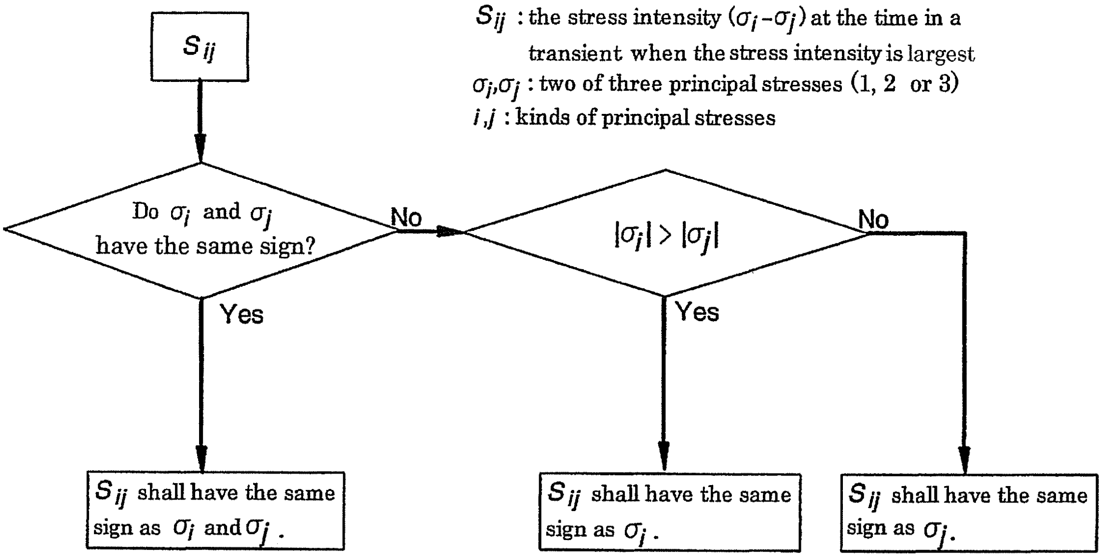


Figure 4.2-1 Flow Chart for Determining Sign of Stress Intensity (Principal Stress Difference) in the Individual Transients

4.2.3 Evaluation Using the Detailed Method

Evaluation using the detailed method shall be performed in accordance with the procedure specified in 4.1.2 (3). The strain rate used in calculating $F_{en,det,i}$, shall be determined in the same manner as described in 4.2.2

4.3 Fatigue Evaluation Method for Piping

To evaluate the fatigue in piping, either of the factor multiplication method described in 4.3.1, the simplified method in 4.3.2 or the detailed method in 4.3.3 may be used. These three methods may be applied singly or in combination.

In case of piping, since calculation of strain rates used is complicated in evaluation using simplified method and detailed method, the evaluation for combination of each transient is usually performed in the order of procedures of evaluation using the factor multiplication method, the simplified method and the detailed method.

Piping may be evaluated in accordance with the method used for vessels described in 4.2 when the time history of strain changes is known.

4.3.1 Evaluation Using the Factor Multiplication Method

Evaluation using the factor multiplication method shall be performed in accordance with the procedure specified in 4.1.2 (1).

4.3.2 Evaluation Using the Simplified Method

Evaluation using the simplified method shall be performed in accordance with the procedure specified in 4.1.2 (2).

The following steps shall be used to calculate the strain rate for piping. Stresses for piping are usually calculated with the equation on the basis of the maximum of pressure difference and the maximum of temperature difference. The equation to calculate the double amplitude of peak stress, S_p, is defined in equation (4.3-1). Refer to the JSME Design and Construction Rules PPB-3532. S_p in each of transients is used for calculation of strain rate.

Regarding the combination of transients to be evaluated, the bending moment term (M term) and the temperature difference terms (ΔT_1, ΔT_2 and $T_a - T_b$) of equation (4.3-1) shall be evaluated to determine which is dominant. When the M term is dominant, the strain rate shall be assumed to be equal to the linearized strain rate of the "start up" transient. When either one of the temperature difference terms (ΔT_1, ΔT_2 and $T_a - T_b$) is dominant, the strain rate shall be obtained based on the assumption that the strains increase linearly from the minimum to the maximum value. In this case, these minimum and maximum strain values shall be of the most dominant term among the terms ΔT_1, ΔT_2 and $T_a - T_b$ for the transient being evaluated.

$$S_P = \underbrace{\frac{K_1 C_1 P_0 D_0}{2t}}_{P\text{term}} + \underbrace{\frac{K_2 C_2 M}{Z_i}}_{M\text{term}} + \underbrace{\frac{K_3 E\alpha|\Delta T_1|}{1.4}}_{\Delta T_1\text{ term}} + \underbrace{K_3 C_3 E_{ab}|\alpha_a T_a - \alpha_b T_b|}_{T_a - T_b\text{ term}} + \underbrace{\frac{E\alpha|\Delta T_2|}{0.7}}_{\Delta T_2\text{ term}} \qquad (4.3\text{-}1)$$

4.3.3 Evaluation Using the Detailed Method

Evaluation using the detailed method shall be performed in accordance with the procedure specified in 4.1.2 (3).

This method is applicable for cases when the ΔT terms are dominant in equation (4.3-1). $F_{en,det}$ can be calculated by the method described in equation (4.3-1) by focusing on the history in a transient with a larger difference in temperature among the combination of the transients of the most dominant term among the terms ΔT_1, ΔT_2 and $T_a - T_b$, for the transient being evaluated, and dividing the range of increasing strain into incremental time segments.

4.4 Fatigue Evaluation Method for Pumps

The method to evaluate fatigue for vessels, specified in 4.2, can be applied for pumps.

4.5 Fatigue Evaluation Method for Valves

To evaluate fatigue for valves, either of the factor multiplication method specified in 4.5.1, the simplified method in 4.5.2 or the detailed method in 4.5.3 may be used. These three methods may be applied singly or in combination.

Since calculation of strain rates for valves used is complicated in evaluation using the simplified method and the detailed method, the evaluation is usually performed for combination of each transient in the order of procedures of evaluation using the factor multiplication method, the simplified evaluation method and the detailed evaluation method.

The evaluation for valves may be performed in accordance with the method to evaluate fatigue for vessels described in 4.2 when the time history of strains for the valve has been obtained in the same manner as is used for vessels.

4.5.1 Evaluation Using the Factor Multiplication Method

Evaluation using the factor multiplication method shall be performed in accordance with the procedure specified in 4.1.2 (1).

4.5.2 Evaluation Using the Factor Multiplication Method

Evaluation using the simplified method shall be performed in accordance with the procedure specified in 4.1.2 (2).

The following steps shall be taken to calculate the strain rate to be used in the evaluation for valves.

Refer to the JSME Design and Construction Rules VVB-3360 for the symbols in equation (4.5-1) and the JSME Design and Construction Rules VVB-3370 for definitions of symbols in equation (4.5-2).

(1) For the start up and shut down transient:

The strain rate ($S_p/\Delta t$) shall be calculated by doubling S_ℓ in equation (4.5-1) to give S_p, and then dividing by the duration of the “start up” transient.

$$S_\ell = 2Ps\left(\frac{ri}{te} + 0.5\right) + \frac{Pe}{2} + \alpha E C_3 \Delta T + 1.3 Q_T \qquad (4.5\text{-}1)$$

(2) For transients other than the start up and shut down transient:

The strain rate ($S_p/\Delta t$) shall be calculated by determining strain from equation (4.5-2), and then dividing by the duration of the transient being evaluated.

$$S_p = 4\Delta P fm\left(\frac{ri}{te} + 0.5\right) + \alpha E \Delta T f\,(C_3 C_4 + C_5) \qquad (4.5\text{-}2)$$

4.5.3 Evaluation Using the Detailed Method

Evaluation using the detailed method shall be performed in accordance with the procedure specified in 4.1.2 (3)

The time history such as temperature, pressure and so on obtained for the simplified method specified in 4.3.2, may be used to calculate $F_{en,det}$ in accordance with 4.1.2 (3) using equations (4.5-1) and (4.5-2).

4.6 Fatigue Evaluation Method for Core Support Structures

The method to evaluate fatigue for vessels, specified in 4.2, may be applied to the evaluation of the core support structures.

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Environmental Fatigue Evaluation Method for Nuclear Power Plants

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Chapter 1 Scope

1.1 Scope of Application

A reduction in the fatigue life of components in simulated reactor cooling water environments was first recognized in Japan and reported to the nuclear industry [1, 2]. Subsequently, the Environmental Fatigue Data Committee (EFD) of the Thermal and Nuclear Power Engineering Society (TENPES) and the Committee on Environmental Fatigue Testing (EFT) of the Japan Power Engineering and Inspection Corporation (JAPEIC) (From 1994 to September 2003) and Japan Nuclear Energy Safety Organization (JNES) (From October 2003 to March 2007) investigated the environmental fatigue.

In September 2000, the Nuclear Power Generation Safety Management Division of the Agency for Natural Resources and Energy, Ministry of International Trade and Industry (MITI) issued "Guidelines for Evaluating Fatigue Initiation Life Reduction in the Light Water Reactor (LWR) Environment" (hereafter, called "the MITI Guidelines") [3]. These guidelines include an equation to evaluate environmental fatigue and require electric utilities to consider the environmental effects in their Plant Life Management (PLM) activities. However, the MITI Guidelines do not include specific and practical techniques for evaluating environmental fatigue under actual plant conditions. Accordingly, TENPES took on the task to produce one. In 2002 TENPES issued the "Guidelines on Environmental Fatigue Evaluation for LWR Component" [4, 5] (hereafter, called "the TENPES Guidelines") based on the techniques developed by the EFD Committee.

In EFT Project, JNES SS Report "the Environmental Fatigue Evaluation Guide (EFEG)" was issued in March 2006 by reviewing the equations for the environmental fatigue life correction factor, F_{en}, specified in the MITI Guidelines, and the techniques for evaluating environmental fatigue specified in the TENPES Guidelines [6] . And based on the new code called Environmental Fatigue Evaluation Method (EFEM), was established in the JSME Codes for Nuclear Power Generation Facilities – Environmental Fatigue Evaluation Method for Nuclear Power Plants (JSME S NF1-2006, EFEM-2006) [7], which was issued in July 2006.

The environmental fatigue life equations that have been proposed in the past are reevaluated and revised, including the newest data obtained in the EFT project. This guideline is to provide the final proposal of the equations.

Environmental fatigue evaluations have been conducted as part of the evaluation at plant design stage, the Periodic Safety Review (PSR) for operating plants, Plant Life Management (PLM) programs and for the purpose of investigating the causes of fatigue failure. This guideline is designed specifically for these purposes.

(1) Subjects to be evaluated

This guideline provides a detailed procedure for considering environmental effects on fatigue in LWR environments. Therefore, this guideline only applies to components exposed to reactor cooling water (BWR and PWR) and the PWR plant secondary system environment.

(2) Materials

The materials addressed by this guideline include carbon steel, low-alloy steel, austenitic stainless steel (hereafter, called "stainless steel"), and nickel- chromium-iron alloy with fatigue data for these materials in simulated reactor cooling water environments has been collected and equations for evaluating fatigue life of these materials have been established.

(3) Environmental conditions

This guideline is based on the investigations performed by the EFD Committee at TEMPES and EFT Project at JNES, which considered a wide range of conditions covering actual water chemistry and temperature conditions from Japanese BWR and PWR plants. This guideline applies to BWR and PWR plants operating in Japan, as well as other plants operating within ranges of similar temperature and water chemistry. This guideline should not be applied to the plants under conditions that deviate from the design conditions such as the temperature and water chemistry as mentioned above.

1.2 Condition for Application

This guideline adopts the cumulative environmental fatigue usage factor, U_{en} , obtained by multiplying the cumulative fatigue usage factor, U, calculated from the design fatigue curve based on fatigue data in air, by the environmental fatigue correction factor, F_{en}. Therefore, in order to evaluate in accordance with this guide, it is assumed that the U is available and that appropriate data for stresses, number of cycles and operating conditions are available.

It is recognized that the conventional fatigue design method includes conservative elements. The report published from EPRI, "Evaluation of Conservatisms and Environmental Effects in ASME Code, Section Ⅲ, Class 1 Fatigue Analysis" (SAND-0187) indicates that the fatigue evaluation for class 1 vessel and piping includes conservatism described in Table E-1.2-1. The fatigue evaluation to consider the environmental effects is more severe as compared with the evaluation not to consider the environmental effects, but it is possible to aim at more detailed and rational fatigue evaluation to mitigate the severity, referring to the conservatism described in Table E-1.2-1.

Table E-1.2-1 Evaluation of the Conservatism and Environmental Effect in ASME Code Class 1 Fatigue Analysis: (Conservatism of Fatigue Evaluation)

	Items	Contents
Determination of design transients	Conservative grouping of design transients	Since the design transients can be conservatively grouped, the cumulative fatigue usage factor is enlarged.
	Step-wise transient changes	Stepwise change of transient temperature increases values of secondary stress and peak stress, and leads to enlargement of *UF.*
Analysis methods	Detailed stress models	More accurate generating stress can be obtained by changing to the detailed FEM from the interaction method as an algorithm of generating stress. The interaction method is axisymmetric and is used for calculating pressure and stress resulting from the temperature change to the axial direction. Since the average temperature only can be analyzed to the radial direction, the stress generated due to linear and non-linear temperature change must be calculated by other methods (usually using the equation). The stresses calculated by the equation are conservative and higher because of assumed complete constraint of thermal expansion.
	Conservative thermal parameters	・Heat transfer analysis may be conducted using constant heat transfer coefficient. Since the more conservative values are chosen in the actual heat transfer coefficients generated, the higher stresses are calculated. ・Fluid temperature in the analysis is assumed to be stepwise changed.
	Heat transfer analysis at the discontinuous parts of piping configuration	When heat transfer analysis is conducted with the specified equation, the average temperature is calculated at the welds of components with different thickness, assuming only the heat current to the radial direction. Therefore, the higher average temperature is calculated at the thinner thickness side, and temperature difference, $/T_a\text{-}T_b/$, is overestimated. $/T_a\text{-}T_b/$ can be decreased by FEM analysis.
Application of ASME Code and conservatism included in the Code itself	Elasto-plastic analysis (1)	*Sm* value used for *Ke* calculation is determined based on the maximum allowable operating temperature, and becomes conservative value.
	Elasto-plastic analysis (1)	The peak stress is generally generated earlier than primary + secondary stress. Although times when the maximum of both stresses generate are different, *Ke* is currently calculated based on the maximum primary + secondary stress, and is applied to the maximum peak stress intensity.
	Elasto-plastic analysis (1)	Excessive *Ke* is calculated by *Ke* equation developed under the conservative assumption.
	Difference of time phase of stress	In piping, each stress range for ΔT_1、ΔT_2、and $T_a\text{-}T_b$ is simply summed up. Since the time when each of the maximum values generates is different, respectively, the stress value can be reduced, if the time history of stress is evaluated in detail.
others	Fatigue monitoring	More accurate *UF* evaluation can be made by use of actual transient cycles (usually less as compared with the number of design transient cycles). Accuracy for thermal stratification evaluation is more improved by change from the enveloping condition base to individual actual measurement results.

Chapter 2 Symbols

The following symbols are used in this explanation other than symbols described in chapter 2 of the text.

$F_{en,asr}$: Environmental fatigue life correction factor evaluated by the mean strain rate

$F_{en,tbi}$: Environmental fatigue life correction factor evaluated by the time based integral method

$F_{en,sbi}$: Environmental fatigue life correction factor evaluated by the strain based integral method

F_{encal} : Predictive F_{en} calculated by the modified rate approach method

F_{entest} : Environmental fatigue life correction factor F_{en} obtained by the test results

$F_{en,s(f)}$: Environmental fatigue life correction factor for low rate (high rate)

N_{25} : Fatigue time defined as the number of cycles when the load at time of the maximum strain due to tension in the strain controlled fatigue test is falling by 25% from the load value at one half (1/2) of the number of cycles at that time.

N_{25W} : N_{25} in water

N_{WP} : Predicted value of N_{25} in water

$\Delta\varepsilon_{S(f)}$: Incremental strain of lower (higher) strain rate (%)

$\Delta t_{S(f)}$: Incremental strain time of lower (higher) strain rate(s)

$\dot{\varepsilon}_{S(f)}$: Lower (higher) strain rate (%/s)

Chapter 3 Method to Evaluate Environmental Effects

3.1 Definition of F_{en}

The fatigue failure evaluation considering the light water reactor (LWR) environment is roughly divided into two methods. One is the method to establish a fatigue design curve in consideration of various conditions. This method is not realistic to create the curve for every condition because of having numerical conditions. Therefore, it will be realistic to determine typical curves for severest condition, intermediate condition, and mild condition. Another is a method to use the environmental fatigue life correction factor, F_{en} [8-11]. F_{en} is a factor that indicates to what degree the fatigue life in environment is reduced compared with the life in air at room temperature, and is defined by the equation (E- 3.1-1).

$$F_{en} = N_A / N_W \quad \text{(E- 3.1-1)}$$

F_{en} is a function depending on material, strain rate, temperature, dissolved oxygen concentration and so on, and can be calculated, if these parameters are determined.

The fatigue failure evaluation for Class 1 components in the current Design and Construction Rule is prescribed in PVB-3114 or PVB-3122. The partial cumulative fatigue usage factor, U_i is obtained by applying stress cycles from a combination of two transients and the number of assumed cycles on the design fatigue curve, and then the cumulative fatigue usage factor is calculated by linearly summing up these U_i for all stress cycles. Therefore, the cumulative fatigue usage factor is expressed by the following equation:

$$U_{air} = U_1 + U_2 + U_3 + U_i + \ldots.. + U_n \quad \text{(E- 3.1-2)}$$

If the conditions, such as strain rate, temperature, and dissolved oxygen concentration, are determinend for each stress cycle, F_{en} value for each stress cycle can be calculated. The cumulative fatigue usage factor, U_{en} for the environment can be calculated by linear sum-up of the partial cumulative fatigue usage factor, U_i, for each stress cycle muliplied by $F_{en,i}$ for the stress cycle. This equation is expressd with the following equation:

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

(E- 3.1-3)

3.2 Environmental Effects Threshold

(1) Strain amplitude

Environmental effects vanish for small strains [1, 2, 10-14]. In other words, high temperature water conditions are not a sufficient condition to influence high cycle fatigue limit.

The relation between strain amplitude and fatigue life in high temperature water for carbon steel, low alloy steel, and stainless steel is shown in Figures E-3.2-1, 3.2-2 and 3.2-3, respectively. The data of small amplitude are not so many because of requiring much test time. The fatigue strength in high temperature near the fatigue limit are not seen to be below the fatigue strength in air in any figure. In another word, the fatigue curve in high temperature has trend only to shift leftward but not to shift downward. Based on such a phenomenon, each equation to evaluate F_{en} mentioned later has determined the lower limits (the threshold values) of strain amplitude at which the environmental effects vanish. These values are 0.042% for carbon steel and low alloy steel [15], and 0.11% for stainless steel [13]. 0.042 % for carbon steel and low alloy steel is strain amplitude equivalent to that at 10^6 cycles in the current design fatigue curve. The design fatigue curve is usually determined in consideration of the maximum influence of mean stress. However, there is no test result considering the mean stress in available fatigue data in high temperature obtained in the past. Therefore, the minimum value of the current fatigue design curve is used taking conservatism into consideration. Under an assumption of no effect of mean stress in the current design fatigue curve for the stainless steel, the fatigue limit strain amplitude of 0.11% in air at room temperature was defined as the threshold of environmental effect threshold strain amplitude. In addition, since the same design fatigue curve as the curve for stainless steel is currently used for nickel-chromium-iron alloy, the environmental effect threshold strain amplitude was determined the same 0.11% as that of stainless steel.

(2) Load conditions

Environmental effects vanish for large strain rates [1, 2, 10-14]. According to the F_{en} equation in next section, F_{en} is saturate at $F_{en} = 1.0$ as the strain rate increases. Consideration of environmental effects is usually required for the thermal transient phenomenon to be a target of fatigue evaluation because of the slow strain rate, but seismic loading cycles are excluded from the environmental fatigue evaluation, because seismic loading cycles are characterized by high strain rate of short duration.

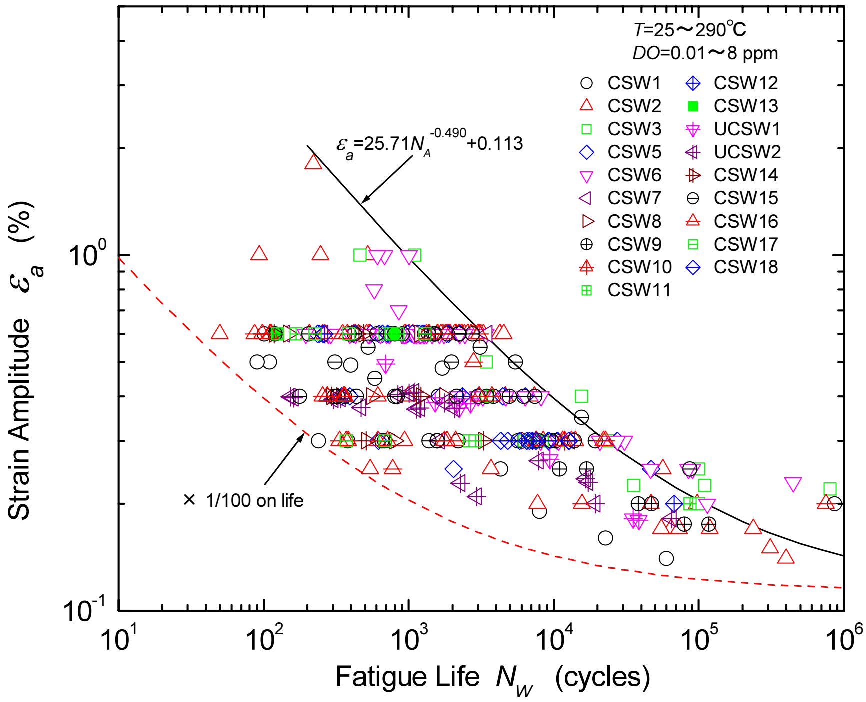


Figure E-3.2-1 Fatigue Data for Carbon Steel in High Temperature Water

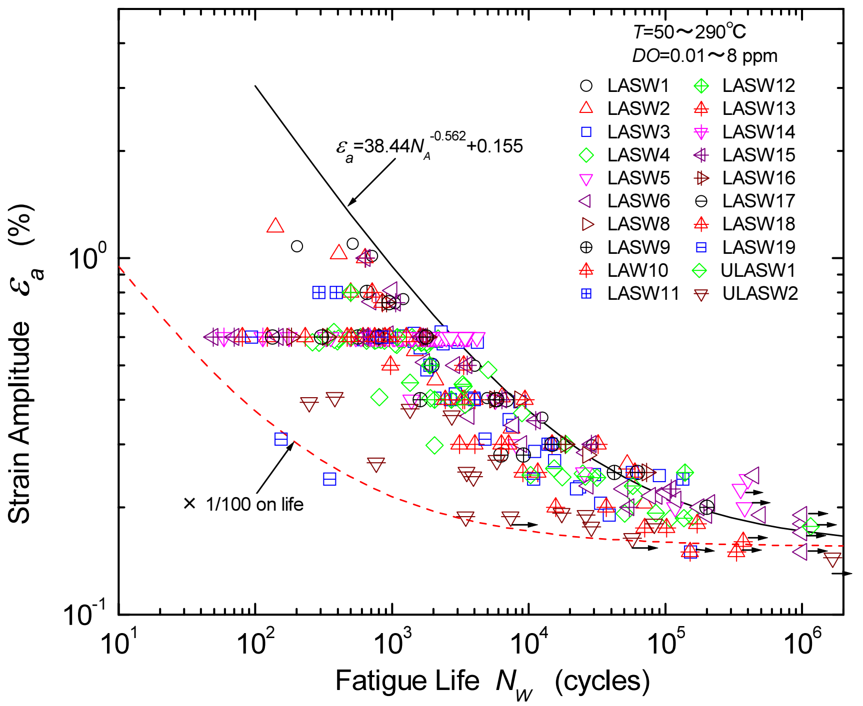


Figure E- 3.2-2 Fatigue Data for Low Alloy Steel in High Temperature

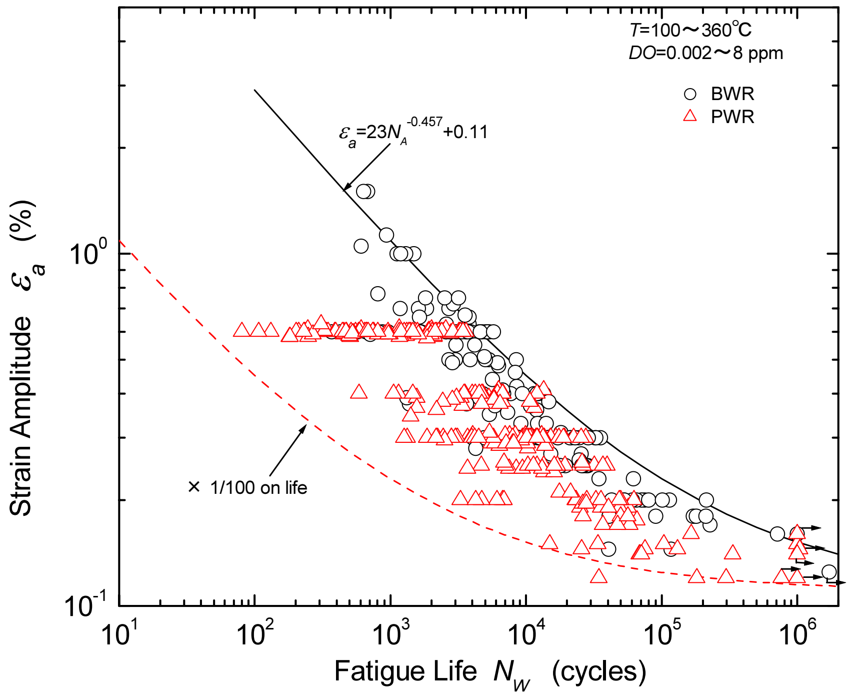


Figure E-3. 2-3 Fatigue Data for Stainless Steel in High Temperature Water

3.3 F_{en} Definition for Various Materials

Low cycle fatigue life of structural material in simulated reactor coolant water decreases depending on the parameter such as the strain rate, temperature and so on.

A great number of tests have been conducted mainly in Japan to identify and quantify the effects of environmental parameters. As a result, equations have been developed to calculate the environmental fatigue life correction factor, F_{en} for materials used in LWR applications. The important parameters for carbon and low-alloy steels are strain rate, temperature, dissolved oxygen concentration, and the sulfur content of the material. The important parameters for stainless steel and nickel-chromium-iron alloys are strain rate and temperature [10, 13].

Based on the experimental results of EFT [16] , the Agency for Natural Resources and Energy (ANRE) issued the MITI Guidelines in September 2000 [3]. Subsequently, based on the data on stainless steel which had been accumulated by the EFT project, equations to evaluate F_{en} for stainless steel in the BWR environment were proposed, followed by revised equations for F_{en} in the PWR environment [11, 14, 17]. The EFT annual report of 2004 [18] and JNES-SS report [6] included a total review of the equations to evaluate F_{en} for carbon and low-alloy steels, the revision of the lower strain rate threshold for cast stainless steel (lower by an order) and new equations for nickel-chromium-iron alloy. These results were also published in the 2006 ASME PVP Conferences [19, 20].

In EFT project, the environmental fatigue life equation (F_{en} equation) was further reviewed for each material based on data and finding newly obtained in 2006, and the final equation was developed. This guideline provides finally proposed environmental fatigue life equation in the EFT project. Table E-3.3-1 compares the equations proposed in March 2000 (MITI guideline in 2000), in March 2005 (JSME Rule in 2006), and March 2007 (finally proposed equation).

The JSME Code Committees established EFEM-2006 in July 2006 (JSME S NF1-2006) [7] utilizing the new information from EFT project [6].

Similar F_{en} equations for carbon, low-alloy and stainless steels were proposed by Argonne National Laboratory (ANL) in the USA [21, 22]. The U.S. NRC issued the Regulatory Guide 1.207 and NUREG/CR-6909 in February 2007 [39]. There are no significant differences between the Japanese and USA models since most of the database utilized by ANL was provided by Japan. However, the Japanese model is based on additional data generated in Japan over the past ten years.

Specific differences are:

- The ANL model uses separate equations for carbon and low-alloy steels while the Japanese model uses identical equations for these materials. However, the difference between ANL model's separate equations tends to become smaller as they are revised and there are few differences in the latest version.

- There are minor differences in curve fitting for the four major effects (i.e., strain rate, sulfur content, temperature and oxygen concentration) between the ANL and Japanese models.
- The Japanese model specifies different equations for stainless steel in PWR and BWR environments while the ANL model uses identical equations.
- The ANL model applies its own design fatigue curve, in which design factor for life cycles is changed from 20 to 12.

Table E-3.3.1 compares the original MITI Guidelines, the Japanese model and the ANL model.

The U. S. Pressure Vessel Research Council (PVRC) established the Committee on Cyclic Life and Environmental Effects (CLEE) with support from Japan in 1991. The Committee worked until the end of fiscal year 2003 ending all activities in March 2004 after issuing WRC Bulletin 487 "PVRC's Position on Environmental Effects on Fatigue Life in LWR Applications" [40]. The PVRC F_{en} equations for carbon and low-alloy steels eliminated the constant terms from the ANL equations, which were developed around 2000, and added moderation factors of 1.7 for carbon steel and 2.5 for low-alloy steel. The F_{en} equation for stainless steel was the same as that in the ANL model (without a moderation factor), which was established around 2000.

3.3.1 Carbon and Low-Alloy Steels and the Welds

<Fatigue data used for evaluation>
The data used for evaluation are all strain-controlled data. The fatigue data in air are finally 128 data with 15 heats, 288 data with 28heats for carbon steels and low-alloy steels respectively. The fatigue strength curve in room temperature air is determined utilizing these data.

The fatigue data in simulated light water reactor environment were used for the evaluation are 606 for carbon steels and 477 for low alloy steels. The fatigue curve for simulated light water reactor environment has been determined utilizing these data.

(1) Reference fatigue curve in air

Figures E-3.3.1-1 and E-3.3.1-3 show the fatigue data in air at the room temperature for carbon steel and stainless steel proposed in March 2000 and the approximate curve obtained with Stromyer method and its equation. Those fatigue data at the present time are also shown in Figures 3.3.1-2 and 3.3.1-4. The latter figures show the comparison between the approximate curve and its equation at the present time and those at the time of March 2000. Although the number of data at the present time is increased about three times for the carbon steel and by about 30 % for the low alloy steel, respectively, the approximate curves are almost similar. Accordingly, the fatigue curve proposed in March 2000 has been determined to be used for the fatigue curve in air at the room temperature for any steel. These equations are expressed with the equations E-3.3.1-1 and 3.3.1-2.

$$\varepsilon_a = 25.71 N_A^{-0.490} + 0.113 \quad \text{(Carbon Steel)} \qquad \text{(E-3.3.1-1)}$$

$$\varepsilon_a = 38.44 N_A^{-0.562} + 0.155 \quad \text{(Low Alloy Steel)} \qquad \text{(E-3.3.1-2)}$$

(2) Effects of sulfur contents

The fatigue life reduction in the simulated LWR environment is evaluated with the environment fatigue life correction factor, F_{en}. F_{en} is defined as the ratio of the life in air at the room temperature to the life in the environment for the same strain amplitude, as expressed with the equation E-3.3.1-3.

$$F_{en} = N_A / N_W \qquad \text{(E-3.3.1-3)}$$

The fatigue data for the conditions of the lower rates ($\dot{\varepsilon} \leqq 0.01$ %/s), the high temperature (T=289 °C) and the high dissolved oxygen concentrations (DO>0.7ppm) having significant environmental effect are chosen from the fatigue data in the high temperature water for the carbon steel and low-alloy steel. For the data other than for the strain rate of 0.001%/s, F_{en} for the strain rate equivalent to 0.001 %/s is calculated with the equation E-3.3.1-4. Figure E-3.3.1-5 shows the relation in the semi-logarithmic scale between these F_{en} and sulfur contents.

$$\ln(F_{en(0.001\%/s)}) = \ln(N_A / N_W) \times (\ln(0.001)/\ln(\dot{\varepsilon})) \qquad \text{(E-3.3.1-4)}$$

Figure E-3.3.1-5 shows all data for base materials of carbon steel and low alloy steel, and those weld metals, separately. As shown in the figure, there is no great difference between data of carbon steel and low alloy steel, but data of weld metal are definitely different from those of base material. Especially, $F_{en\,(0.001\%/s)}$ of weld metal is significantly small as compared with data of base materials, and the environmental effects are small, probably because fine sulfide particles distribute in the weld metal. When fatigue strengths of weld metals are higher than those of base materials, the fatigue fracture of structures may be evaluated on the basis of base material, because the fatigue fracture is controlled by the base materials. The number of data points of base materials is different for each heat and strain rate. To equalize this influence, the average value is taken for each heat and strain rate, and one datum is given for each heat and strain rate. All data for carbon steel and low-alloy steel are shown together in Figure E- 3.3.1-6.

The relation between F_{en} and sulfur content is shown as a solid line in Figure EF-3.3.1-6.

The MITI Guidelines curve, shown as a dashed line in the same figure, has a smaller slope since it is based on only carbon steel data.

The logarithm of $F_{en\,(0.001\%/s)}$ appears to increase linearly with sulfur content. The difference in the F_{en} slope between carbon steels and low alloy steels was judged to be small leading to the linear relation shown by equation E-3.3.1-5.

$$\ln(F_{en(0.001\%/s)}) = \ln(13.41) + 97.92S \qquad \text{(E-3.3.1-5)}$$

The relation between F_{en} and sulfur content is shown as a solid line in Figure EF-3.3.1-6. The MITI Guidelines curve, shown as a dashed line in the same figure, has a smaller slope because the curve is based on the carbon steel data only.

(3) Effects of strain rate

Sulfur contents have a great influence on the fatigue life of steels in high temperature water environment. Different sulfur contents in steel specimens were converted to a sulfur content of 0.015% by using equation E-3.3.1-6 so as to cover as much data as possible to evaluate the effect of strain rate on F_{en}.

$$F_{en(S=0.015\%)} = F_{en(S)}/\exp(97.92\times(S-0.015)) \qquad \text{(E-3.3.1-6)}$$

For carbon steels and low-alloy steels, the data obtained at high temperature (289 °C), high dissolved oxygen concentration (DO > 0.7 ppm) and strain rate over 0.0004%/s were collected to determine the influence of strain rate. The effect of strain rate on $F_{en\,(S=0.015\%)}$ for carbon steels and Low-alloy steels is shown in Figure 3.3.1-7.

Significant dispersion of data is seen definitely as shown in the figure. $F_{en\,(S=0.015\%)}$ increases almost linearly with decrease of strain rate, and difference between carbon steel and low alloy steel is almost not seen. To equalize the influence of different number of data for each heat and strain rate, the average values of $F_{en\,(S=0.015\%)}$ for strain rate of each of carbon steels and low alloy steels are taken and plotted as shown in Figure E-3.3.1-8. Equation E-3.3.1-7 was developed as a result of linear approximation of these data.

$$\ln(F_{en(S=0.015\%)}) = \ln(1.49) - 0.518\ln(\dot{\varepsilon}) \qquad \text{(E- 3.3.1-7)}$$

The relation obtained by the proposed line in 1999 (same as the MITI Guidelines) is shown by a dashed line. Compared with the dashed line obtained by the MITI Guidelines, F_{en}=1.0 is delivered at $\dot{\varepsilon}$ =2.16 %/s in the solid line with a slightly smaller slope.

Several heat and test conditions were selected for available data of strain rates below 0.0001%/s, and the relation between strain rates and F_{en} is shown in Figure E-3.3.1-9.

Those data both for carbon and low-alloy steels were divided into two groups according to the DO concentration. One group contains data at DO concentrations ranging from 1 to 8 ppm and the other group has data at a low DO concentration of 0.2ppm.For both groups of data, F_{en} reaches a threshold at lower strain rates. The threshold of strain rate for the group with higher DO concentrations is 0.0001 %/s while that for the group with a lower DO concentration is much higher at 0.0004 %/s.

On the evaluation in 2004, the threshold of strain rate was set at 0.0004 %/s regardless of DO concentration because of lack of data regarding lower strain rates.

This is revised as follows in this guideline:
$F_{en\,(S=0.015\%)}$ at the higher dissolved oxygen (DO) concentration above 0.7 ppm are averaged for each of carbon steel, low alloy steel and strain rate, and the averaged values are plotted with strain rates by logarithm-logarithm as shown in Figure E-3.3.1-10. However, in this guideline, the threshold of lower strain rates at high DO concentrations above 0.7 ppm is changed to 0.0001 %/s.

There is no necessity that the strain rate in the environment becomes less than unity (1.0), although F_{en} decreases as the strain rate increases. Accordingly, a linear relation shown by the equation E-3.3.1-7 is assumed in the range between 0.0001 %/s and 2.16 %/s, while thresholds are assumed at $F_{en\,(S=0.015\%)}$=1.0 when strain rates are at or above 2.16 %/s, and $F_{en\,(S=0.015\%)}$=176.4 (obtained by substituting $\dot{\varepsilon} = 0.0001\ \%/s$ in equation E-3.3.1-7) .

Considering the above results, while the slope of the line remains unchanged as compared with the proposal of 2004, the threshold of lower strain rates remains unchanged as 0.0004 %/s at $DO \leq 0.7$ ppm and changes to 0.0001 %/s at $DO > 0.7$ ppm.

(4) Effects of temperature

F_{en} data obtained by converting them into those equivalent to high dissolved oxygen concentration ($DO >$ 0.7 ppm), sulfur content of 0.015 % and strain rate of 0.001 %/s for carbon and low-alloy steels are plotted in Figure E-3.3.1-11. This data shows a rising trend with temperature. The trend line for temperature above 150 °C was determined by a least squares fit regardless of steel type and is defined by equation E-3.3.1-8.

$$\ln(F_{en}) = \ln(0.355) + 0.0175T \quad \text{for } 150\ °\text{C} < \text{T} \qquad \text{(E- 3.3.1-8)}$$

When the data are averaged between 50 °C and 150 °C, the resultant $F_{en\,(S=0.015\%)}$ is equal to 6.0. The intersection of the result delivered by equation E-3.3.1-8 and F_{en}= 6.0 occurs at 160 °C. At a temperature 289 °C, F_{en} =53.5, from equation E- 3.3.1-8. Therefore, equation E-3.3.1-8 is adjusted so that the line passes through the intersections (160 °C, F_{en} = 6.0) and (289 °C, F_{en} = 53.5) to produce equation E-3.3.1-9:

$$\ln(F_{en}) = \ln(0.398) + 0.0170T \quad \text{(E- 3.3.1-9)}$$

The figure indicates a horizontal line of $F_{en\,(S=0.015\%)}$=6.0 between 50 and 160 °C, and a straight line of equation E-3.3.1-9 above 160 °C. For temperatures at or below 50 °C, $F_{en(S=0.015\%)}$ decreases again as temperature decreases. Similar to stainless steel, assuming that $F_{en\,(S=0.015\%)}$ equals 1.0 at 0 °C and taking into account the data on carbon steel at 25 °C, the assumption of a line connecting the points (50 °C, F_{en} = 6.0) and (0 °C, F_{en} = 1.0) is valid. The recommended relation between $F_{en\,(S=0.015\%)}$ and temperature is shown by the solid line (three straight lines) in Figure E-3.3.1-11

The proposal 1999 (same as the MITI Guidelines equation), shown by the dashed line in the figure, assumes that $F_{en\,(S=0.015\%)}$ has a minimum value of 5.30 at temperatures below 180 °C. Although the MITI Guidelines assumed the same $F_{en\,(S=0.015\%)}$ for room temperature, after 2004, the value of $F_{en\,(S=0.015\%)}$ has changed as mentioned above.

(5) Effects of dissolved oxygen concentration

Figure E-3.3.1-12 shows the logarithmic relation between F_{en} and dissolved oxygen concentration (DO) for carbon and low-alloy steels at high temperature (289 °C), sulfur content of 0.015 % and strain rate of 0.001 %/s. This data shows a rising trend with dissolved oxygen. A few data for low alloy steel are available in the transition zone, and the data dispersion is also large. Accordingly, the linear slope in the transition zone was determined using a great number of carbon steel data. The data shows an approximate linear change in the range of DO between 0.03 and 0.5 ppm although there is significant dispersion in the data. Therefore, the trend line of the data in this range was determined by a least squares fit and is defined by equation E- 3.3.1-10.

$$\ln(F_{en(S=0.015\%)}) = \ln(71.99) + 0.772\ln(DO) \quad \text{(E- 3.3.1-10)}$$

The threshold of F_{en} at high DO is assumed to be 53.5, which can be derived by substituting $\dot{\varepsilon} = 0.001\%/s$ in equation E-3.3.1-7. The threshold of F_{en} at low DO is assumed to be 3.28, which is derived by averaging the data on carbon and low-alloy steels with DO of 0.01 ppm or less. The intersection between the line expressed by equation E-3.3.1-10 and F_{en} = 53.5 corresponds approximately to DO = 0.7 ppm while the intersection of the line and F_{en} = 3.28 corresponds approximately to DO = 0.02 ppm. The line expressed by equation E-3.3.1-11 does not require a high level of rigidity since there is significant dispersion of data in the transition zones. For easier application, equation E-3.3.1-10 is adjusted so the line passes through the points (F_{en}=53.5, DO = 0.7 ppm) and (F_{en} = 3.28, DO = 0.02 ppm). The resulting equation is E-3.3.1-11:

$$\ln(F_{en(S=0.015\%)}) = \ln(70.8) + 0.785\ln(DO) \quad \text{for } 0.02\text{ppm} < DO < 0.7\text{ppm}$$

(E- 3.3.1-11)

In Figure E-3.3.1-12, the recommended curve is shown as a solid line consisting of a horizontal line (DO < 0.02 ppm at F_{en} =3.28); a sloped line defined by equation E-3.1.1-11; and another horizontal line (DO > 0.7 ppm at F_{en} =53.5). These 3 lines represent the revised relation for F_{en} as a function of DO for carbon steel and low-alloy steel. The proposal 1999 (the same as the MITI Guidelines equation), shown by the dashed line in the figure, specified the transition zone between 0.03 and 0.5 ppm instead of the new values of 0.02 and 0.7 ppm. The change mentioned above was made in the proposal 1999.

(6) Effects of water flow rate

The fatigue life of carbon steel in high temperature water of the BWR environment depends on the flow rate [23, 36, 37]. The relation between F_{en} and flow rate for carbon steel and low-alloy steel is shown in Figures E-3.3.1-13and EF-3.3.1-14, respectively. For both types of steels, F_{en} highly depends on the flow rate and tends to become smaller with a high flow rate under the condition with a high dissolved oxygen concentration for the materials containing high sulfur for which F_{en} becomes larger. However, the flow rate has little effect on F_{en} for the materials containing less sulfur for which F_{en} remains lower in nature or under the condition with low dissolved oxygen concentrations. Accordingly, it can be considered that the flow rate has no effect on F_{en} in reactor cooling water of PWR and has only a little effect on F_{en} in BWR where dissolved oxygen concentration is 0.2 ppm in reactor cooling water and 0.05 ppm in feed-water [23, 36]. The current F_{en} equation, which was formulated based on the data with lower flow rates, results in a conservative evaluation under a high flow rate condition in a consistent manner. Therefore, the effect of flow rate is not considered in this evaluation method.

(7) Effects of strain holding

In the high temperature water environment, the fatigue life of carbon and low-alloy steels is reduced due to strain holding at the peak (local maximum value) [23, 26]. The relation between F_{en} and strain hold time for carbon and low-alloy steels is shown in Figures E-3.3.1-15 and 3.3.1-16, respectively. In these figures, three different symbols, open, half solid and solid represent the test results under the strain holding at peak, peak minus 0.03 % and peak minus 0.06 %, respectively. In addition, a dotted line represents F_{en} at a strain rate of 0.004 %/s without holding while a dashed and dotted line represents F_{en} at a strain rate of 0.4 %/s without holding. As shown in Figure E-3.3.1-15, the fatigue life reduction due to strain holding at the peak is significant at higher strain rates while it becomes smaller as the strain rate decreases with little fatigue life reduction at 0.004 %/s or less. The extent of fatigue life reduction depends on the hold time. The fatigue life reduction tends to be saturated as the hold time becomes longer. The threshold is close to the life at a strain rate of 0.004 %/s. Regarding carbon steel, the effect of strain holding is negligible at 0.004 %/s or lower strain rates. The fatigue life reduction due to strain holding in low-alloy steel is smaller than that in carbon steel.

Although the fatigue life is reduced due to strain holding at the peak (local maximum value),when strain was held at 0.06 % below the peak strain after overshoot show no fatigue life reduction although tensile stresses corresponding to the yield point still remain. From these results, the effect of strain holding in the actual plant should be addressed as follows. Since the peak thermal stress generated by thermal transient is not considered to exceed the yield stress significantly, there is no necessity of taking the effect of strain holding into consideration.

Considering the above results, the evaluation should be performed assuming a strain rate of 0.004 %/s for strain rates exceeding 0.004 %/s while considering fatigue life reduction due to strain holding when the strain is at the peak and held under the internal pressure condition that accompanies elastic follow-up.

(8) Applicability of F_{en} equation for high strength materials

The environmental fatigue tests were also performed for the representative high strength materials to be used in the LWR pressure boundary including carbon steel STS480 and low-alloy steel SQV2B although they are not so widely used. The test results confirmed that the environmental effects are not significant for these high strength materials. Therefore, it is considered that the F_{en} equations in this code are applicable to all carbon steel and low-alloy steel that are generally used in the LWR pressure boundary.

(9) Equations to calculate F_{en}

The basic equation to calculate F_{en} is equation E-3.3.1-7, which defines the relation between F_{en} and strain rate. Equation E-3.3.1-7 can be rewritten as shown in equation E-3.3.1-12

$$\ln(F_{en}) = \{\ln(1.49)/0.518 - \ln(\dot{\varepsilon})\}0.518 \qquad \text{(E-3.3.1-12)}$$

F_{en} from equation E-3.3.1-12 equals 53.5 when the strain rate is 0.001 %/s, sulfur content is 0.015 %, temperature is 289 °C and dissolved oxygen concentration is greater than or equal to 0.7 ppm. Equations E-3.3.1-7, E-3.3.1-9 and E-3.3.1-11 were determined so that F_{en}=53.5 could be achieved with the above parameter conditions. However, equation E-3.3.1-5 which expresses the relation between F_{en} and S has not been adjusted. When equation E-3.3.1-5 is modified so that the relation of equation E-3.3.1-6 is moistened and S equals 0.015 % when F_{en} equals 53.5 without changing the gradient, the equation results in equation E-3.3.1-13 shown below:

$$\ln(F_{en}) = \ln(12.32) + 97.92S \quad \text{(E-3.3.1-13)}$$

When equation E-3.3.1-12 is multiplied by the effects of parameters, the result is equation E-3.3.1-14 which expresses the equation to calculate F_{en} for carbon and low-alloy steels.

$$\ln(F_{en}) = \{\ln(1.49)/0.518 - \dot{\varepsilon}^*\}0.518\{S^*/\ln(53.5)\}\{T^*/\ln(53.5)\}\{O^*/\ln(53.5)\}$$

$$= 0.00822(0.772 - \dot{\varepsilon}^*)S^*T^*O^* \quad \text{(E- 3.3.1-14)}$$

Where,

If $DO \leq 0.7$ ppm,

$\dot{\varepsilon}^* = \ln(2.16)$	$(\dot{\varepsilon} > 2.16\%/\text{s})$
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$	$(0.0004 \leq \dot{\varepsilon} \leq 2.16\%/\text{s})$
$\dot{\varepsilon}^* = \ln(0.0004)$	$(\dot{\varepsilon} < 0.0004\%/\text{s})$
$S^* = \ln(12.32) + 97.92S$	
$T^* = 0.0358T$	$(T < 50°\text{C})$
$T^* = \ln(6)$	$(50 \leq T \leq 160°\text{C})$
$T^* = \ln(0.398) + 0.0170T$	$(T > 160°\text{C})$
$O^* = \ln(3.28)$	$(DO < 0.02\text{ ppm})$
$O^* = \ln(70.79) + 0.7853\ln(DO)$	$(0.02 \leq DO \leq 0.7\text{ ppm})$

Where,

If $DO > 0.7$ ppm

$\dot{\varepsilon}^* = \ln(2.16)$	$(\dot{\varepsilon} > 2.16\%/\text{s})$
$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$	$(0.0001 \leq \dot{\varepsilon} \leq 2.16\%/\text{s})$
$\dot{\varepsilon}^* = \ln(0.0001)$	$(\dot{\varepsilon} < 0.0001\%/\text{s})$
$S^* = \ln(12.32) + 97.92S$	
$T^* = 0.0358T$	$(T < 50°\text{C})$
$T^* = \ln(6)$	$(50 \leq T \leq 160°\text{C})$
$T^* = \ln(0.398) + 0.0170T$	$(T > 160°\text{C})$
$O^* = \ln(53.5)$	$(DO > 0.7\text{ ppm})$

This equation is applicable for following scope:

Materials:	All of carbon steel, low alloy steel, and these welds currently used at LWR pressure boundary
Strain amplitudes:	Exclude 0.042 % or less.
Load conditions:	Exclude seismic load.
Transient conditions:	This equation is used for thermal transient in BWR environment. When the strain rate is higher than 0.004 %/s

under transient with elastic follow-up such as internal pressure and condition of assumed strain holding, the evaluation is made using the strain rate of 0.004 %/s.

The predicted fatigue life is obtained by dividing the fatigue life in air at room temperature by F_{en} calculated using this proposed equation for each test condition. Comparison of this predicted fatigue life with the test result in the environment is shown in Figure E-3.3.1-17 for carbon steel, and in Figure E-3.3.1-18 for low alloy steel.

Either case of carbon steel and low alloy steel could be almost predicted in the range of a factor 5, but some data deviated from this range was exceptionally in a portion of both materials. Data of short life that deviate to the conservative side are for high flow rate, weld metal and low alloy steel SQV2B. These data have low environmental susceptibility as mentioned above. Some data points are seen at the longer life region and deviate to the conservative side. This is assumed due to fatigue life extended by dynamic strain aging effect in the lower strain amplitude region. Contrary to above materials, some data for low alloy steel deviate to the non-conservative side in the long life region. A portion of these data is considered to be for old U.S. materials of low quality. A number of data at the conservative side was seen especially around 100 ℃ of mid-temperature in the simulated PWR environment. Since F_{en} under these conditions is small because of lower temperature and lower dissolved oxygen concentration, the environmental correction is not almost contributed. Therefore, the fatigue strength as material characteristics is assumed to be lower. However, data of fatigue life reduction exceeding a factor 5 are limited in small strain amplitude region and is not practical, and the margin is determined by stress amplitude. Accordingly, it is considered that this level of life reduction is adequately covered by the stress margin of 2 in the design fatigue curve.

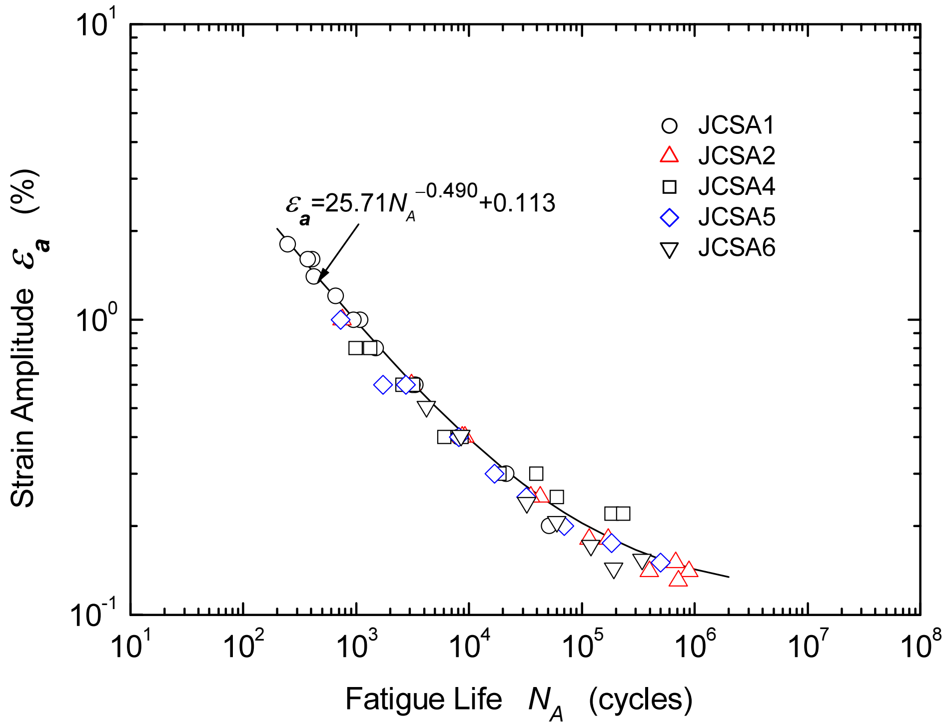


Figure E-3.3.1-1 Fatigue Curve in Air at Room Temperature for Carbon Steel (1999 Version)

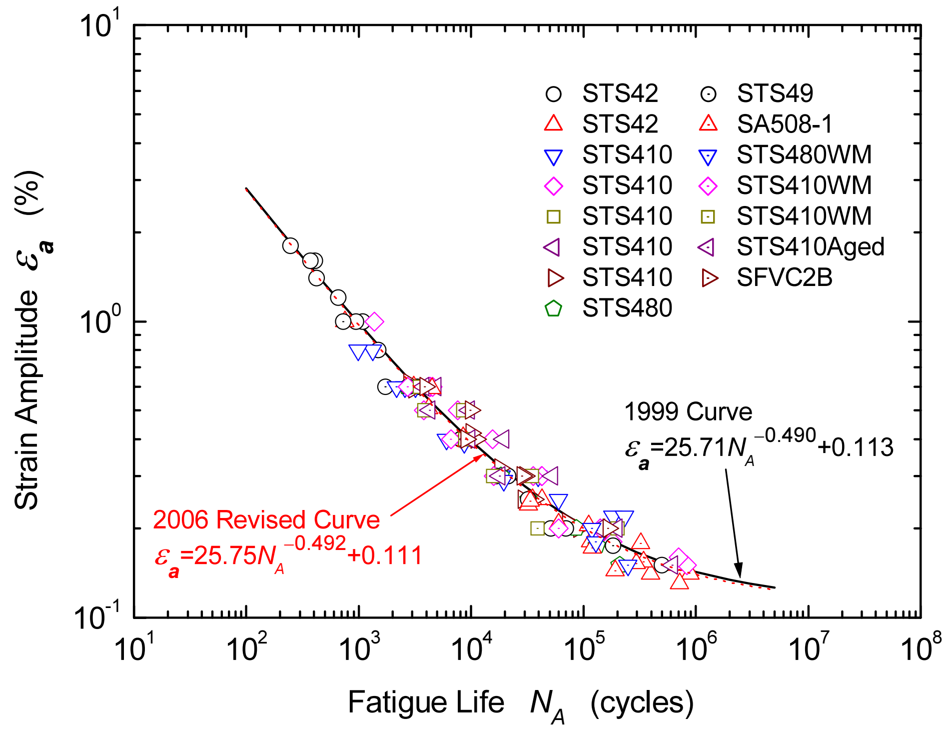


Figure E-3.3.1-2 Fatigue Curve in Air at Room Temperature for Carbon Steel (2006 Version)

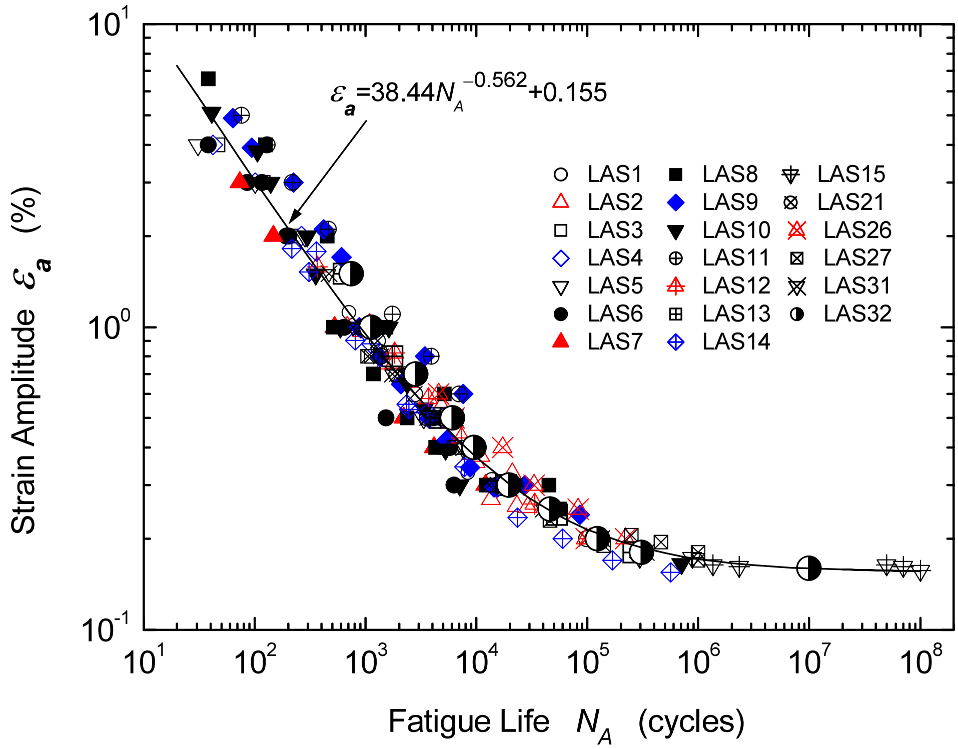


Figure E-3.3.1-3 Fatigue Curve in Air at Room Temperature for Low-Alloy Steel (1999 Version)

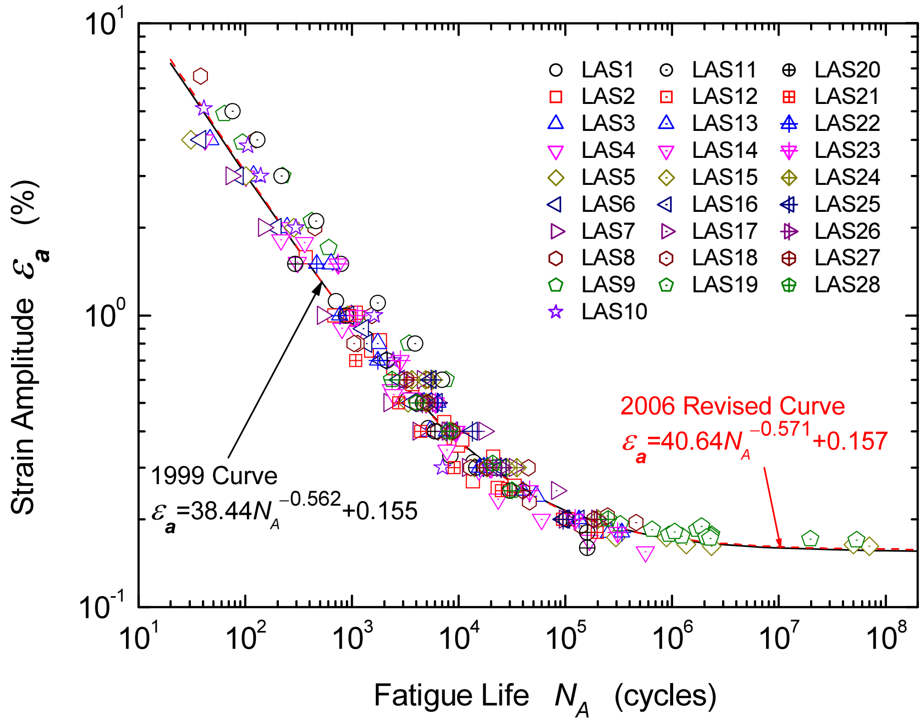


Figure E-3.3.1-4 Fatigue Curve in Air at Room Temperature for Low-alloy Steel (2006 Version)

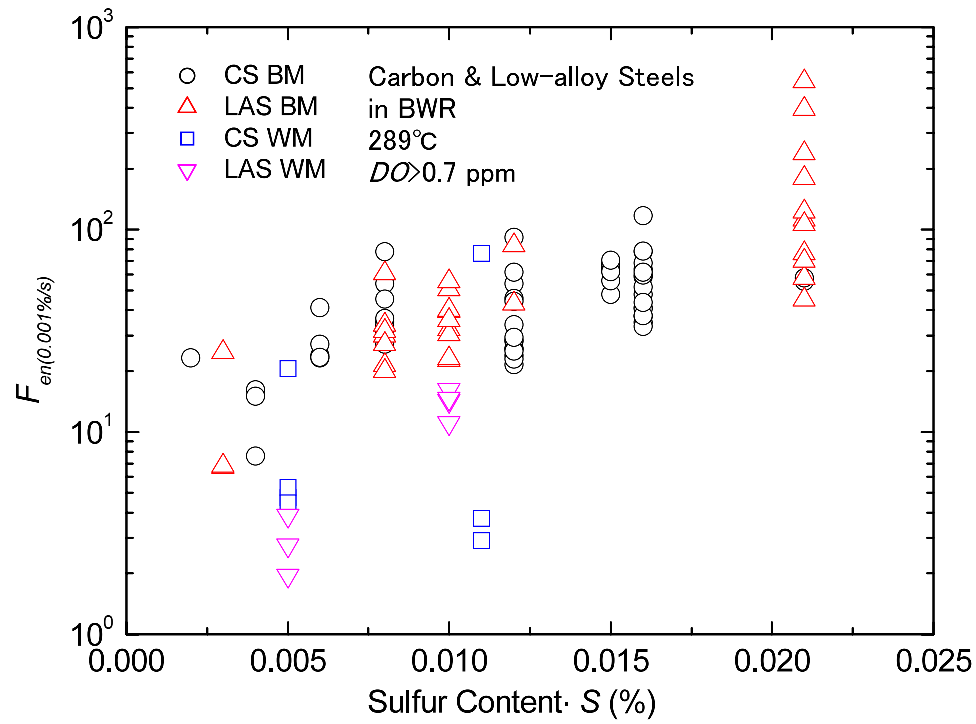


Figure E-3.3.1-5 Relation between F_{en} and Sulfur Content for Carbon Steel/Low-Alloy Steel (All Data)

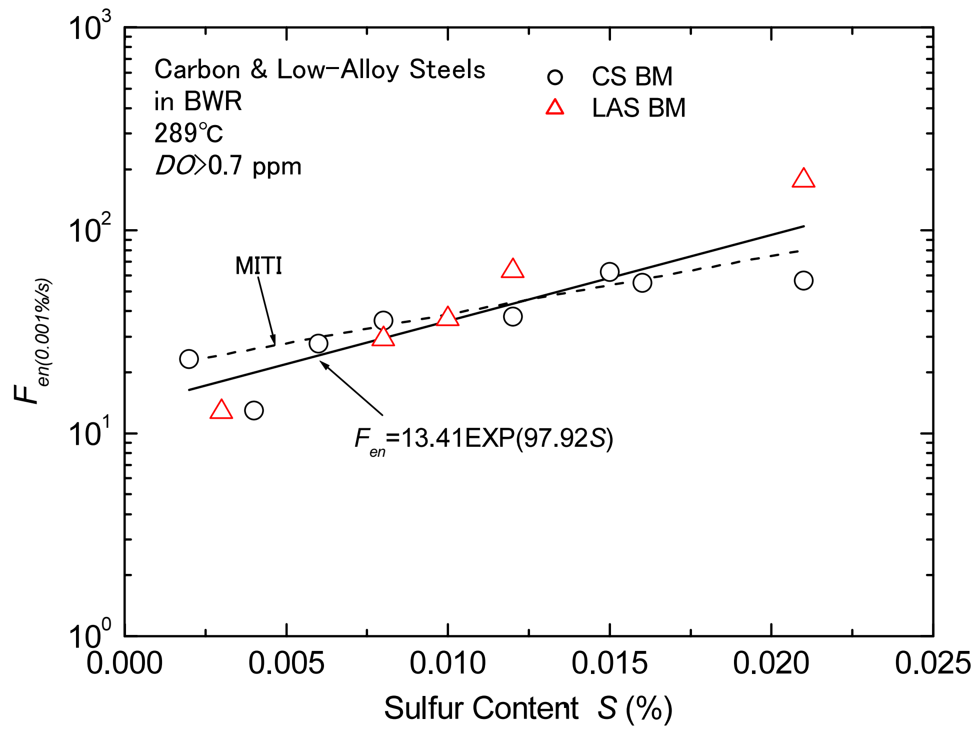


Figure E-3.3.1-6 Relation between F_{en} and Sulfur Content for Carbon Steel/low-Alloy Steel (Average Value except Weld Metal)

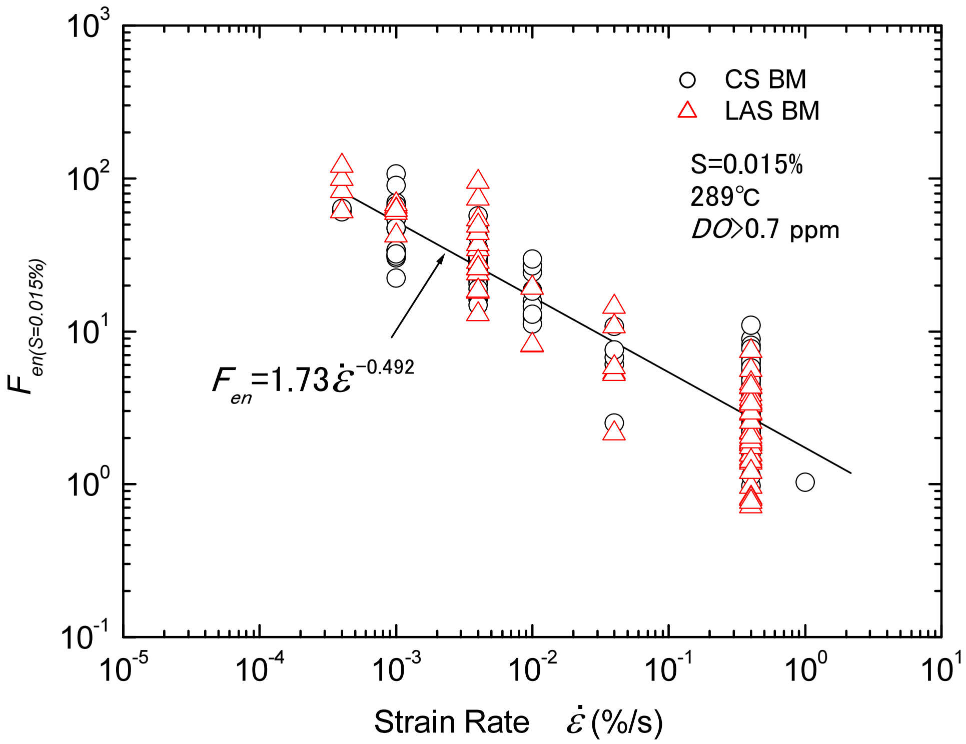


Figure E- 3.3.1-7 Relation between F_{en} and Strain Rate for Carbon Steel/Low Alloy Steel $\varepsilon \geqq 0.0004\%$ (All Data)

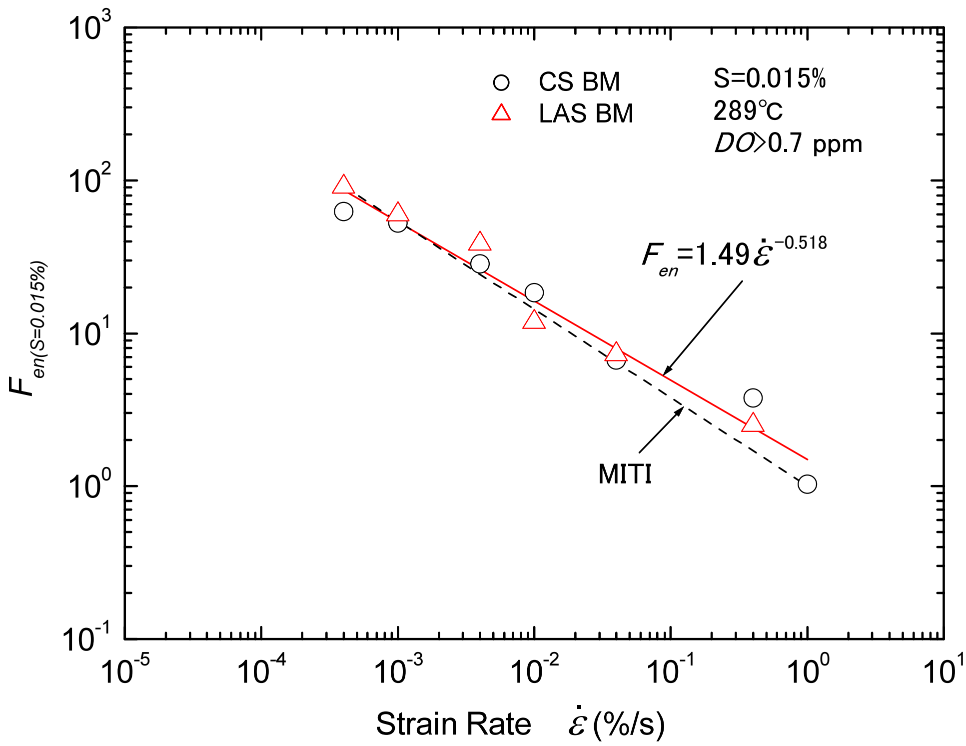


Figure E-3.3.1-8 Relation between F_{en} and Strain Rate for Carbon Steel/ Low-Alloy Steel ($\dot{\varepsilon} \geq 0.0004\%/s$ Average Value)

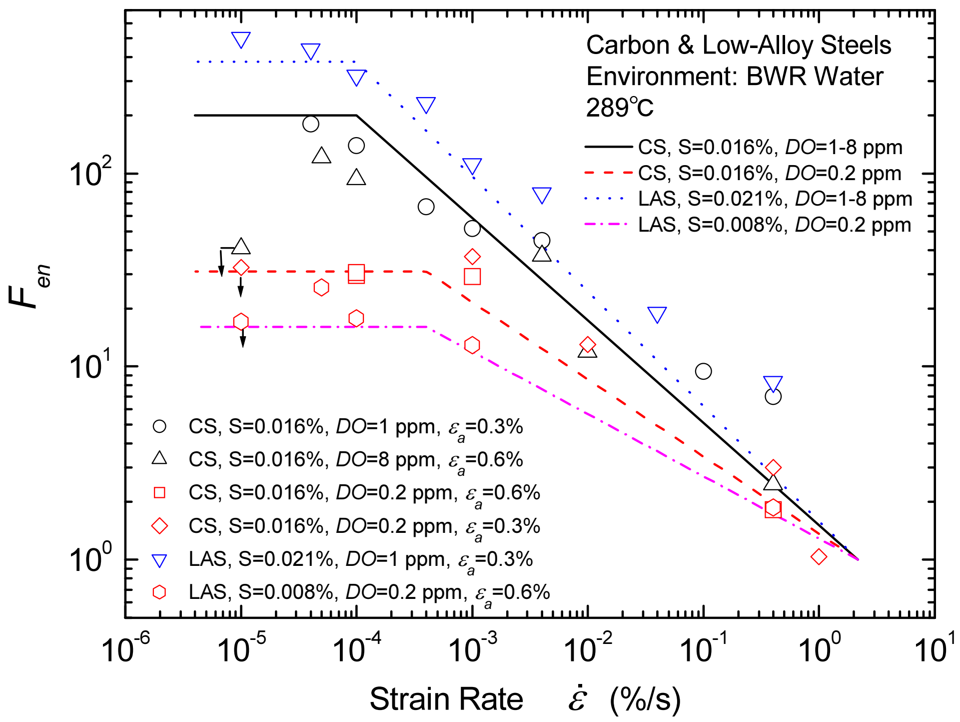


Figure E-3.3.1-9 Relation between F_{en} and Strain Rate for Carbon Steel/Low-Alloy Steel (Strain Rate Threshold at Lower Rate Region)

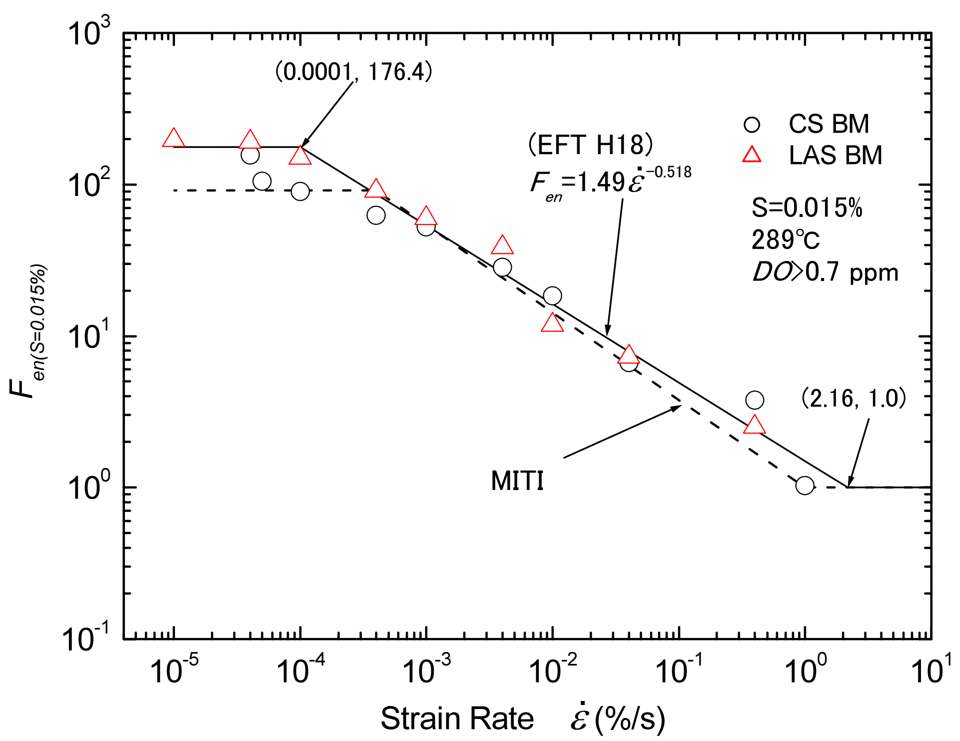


Figure E- 3.3.1-10 Relation between F_{en} and Strain Rate for Carbon Steel/Low-Alloy Steel (Threshold Value)

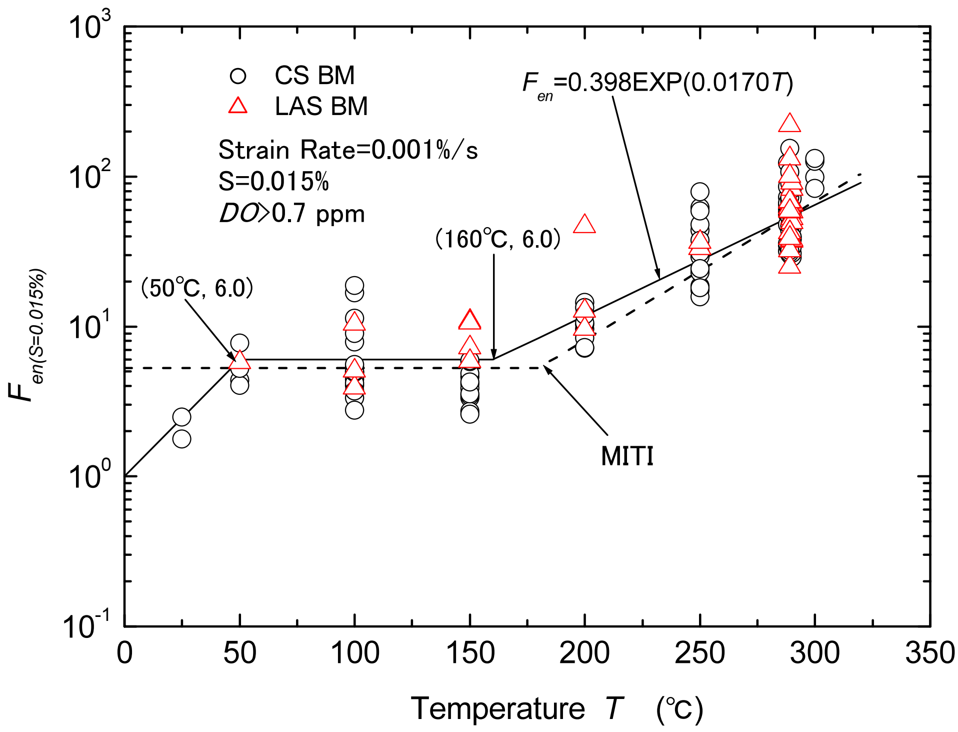


Figure E- 3.3.1-11 Relation between F_{en} and Temperature for Carbon Steel/ Low Alloy Steel (Trend Lines in Entire Temperature Region)

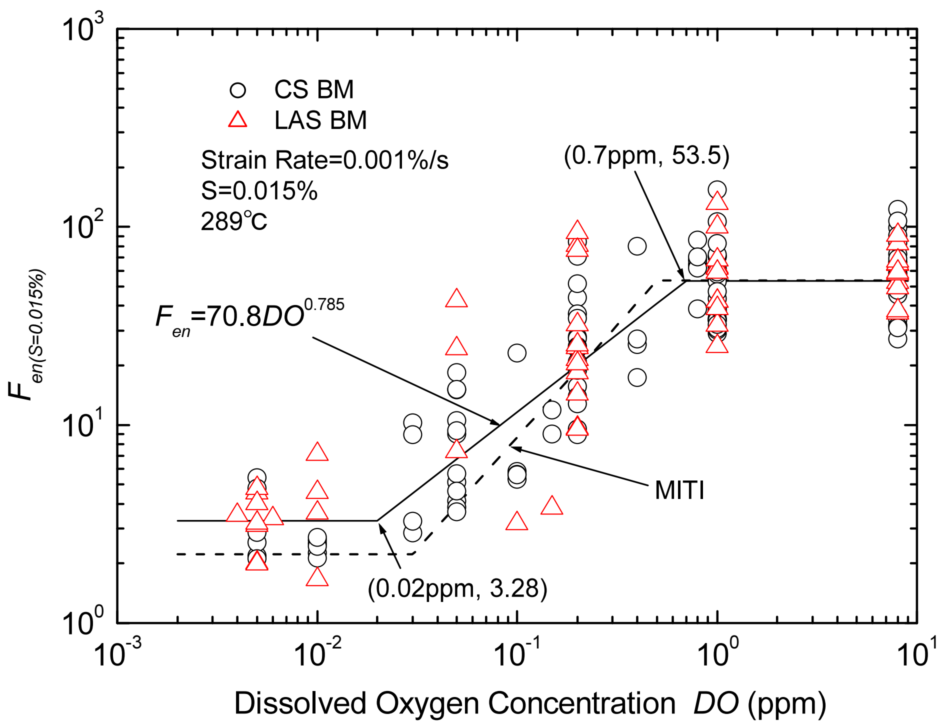


Figure E- 3.3.1-12 Relation between F_{en} and Dissolved Oxygen Concentration for Carbon Steel/Low-Alloy Steel (Trend Lines in Entire Region)

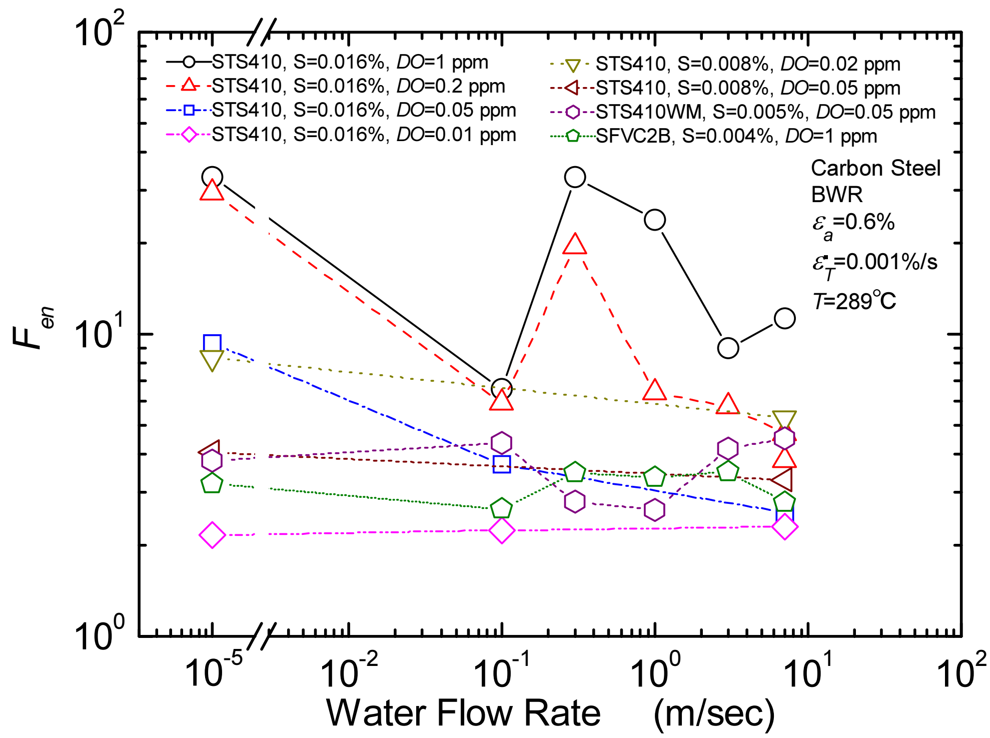


Figure E-3.3.1-13 Relation between F_{en} and Water Flow Rate for Carbon Steel

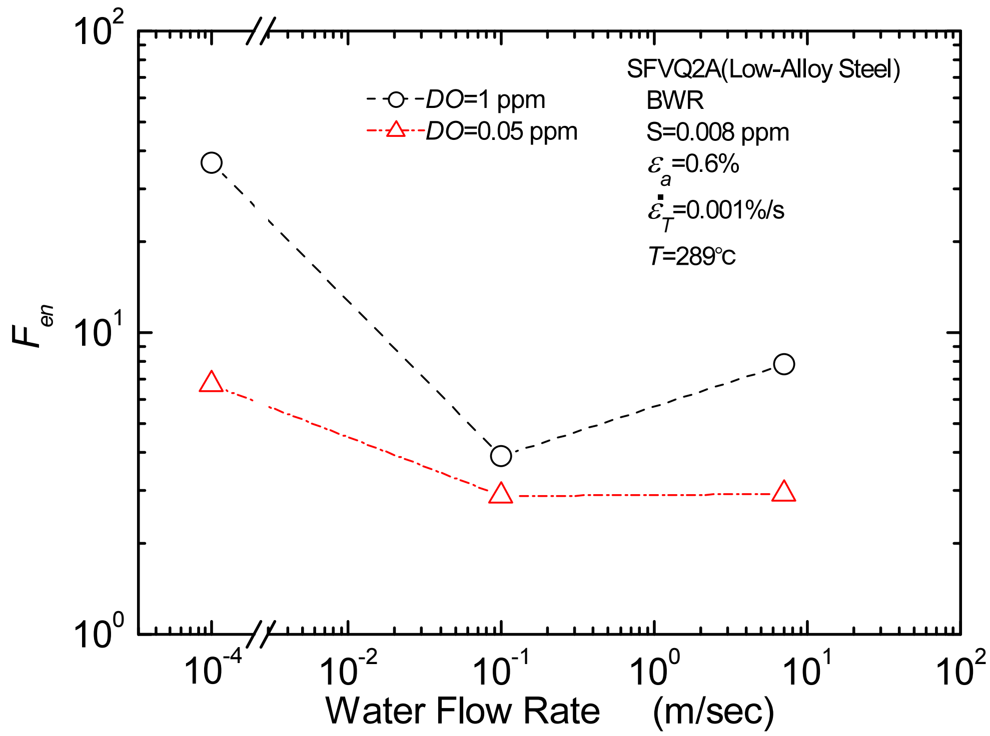


Figure E 3.3.1-14 Relation between F_{en} and Water Flow Rate for Low-Alloy Steel

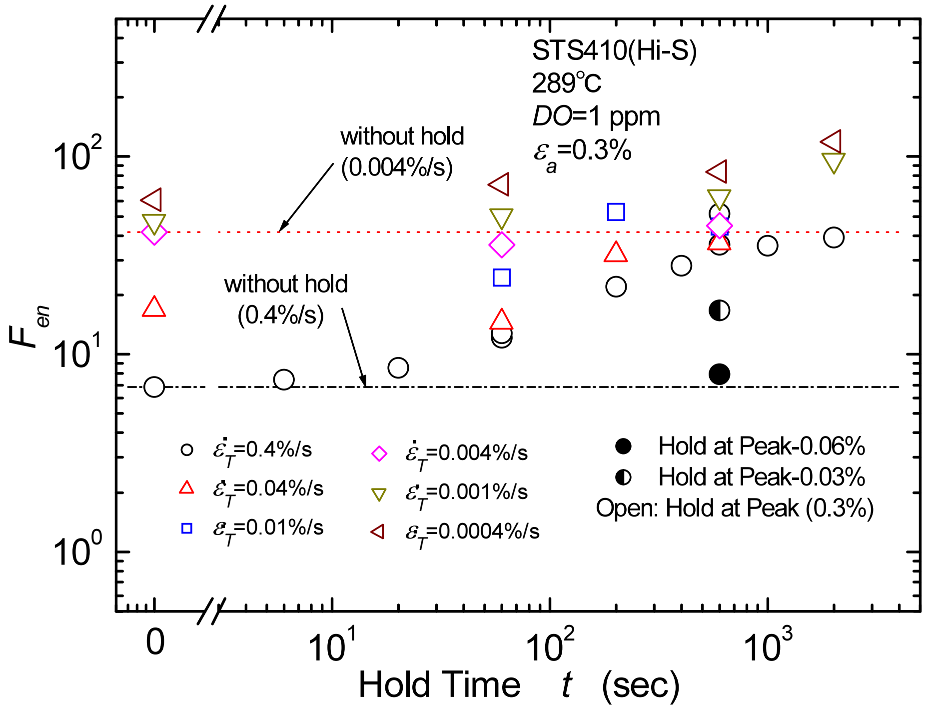


Figure E-3.3.1-15 Relation between F_{en} and Strain Hold Time for Carbon Steel

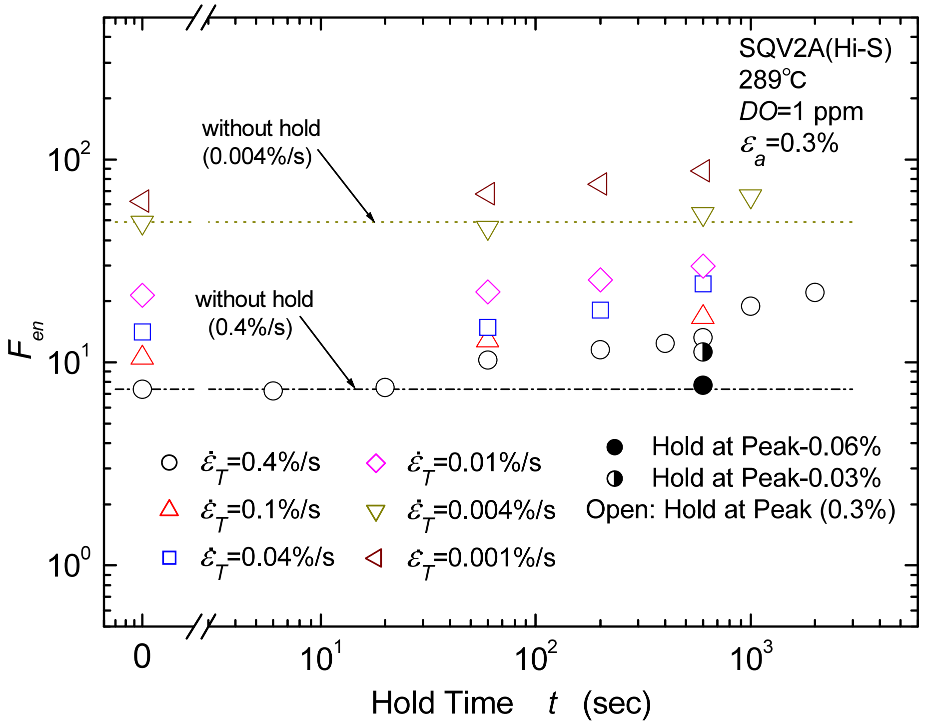


Figure E-3.3.1-16 Relation between F_{en} and Strain Hold Time for Low-Alloy Steel

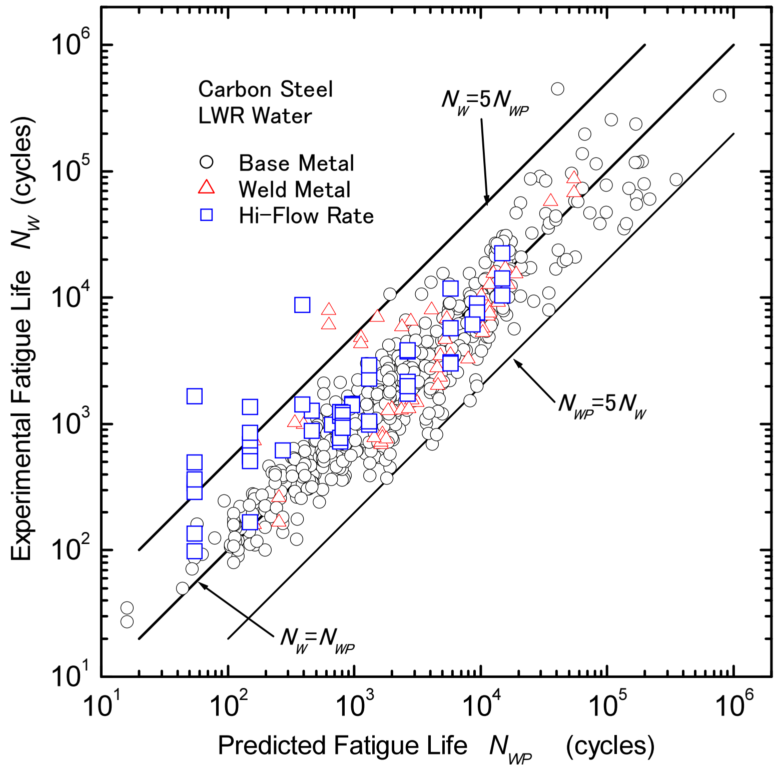


Figure E- 3.3.1-17 Comparison between Experimental and Predicted Values of Simulated LWR Environmental Fatigue Life for Carbon Steel

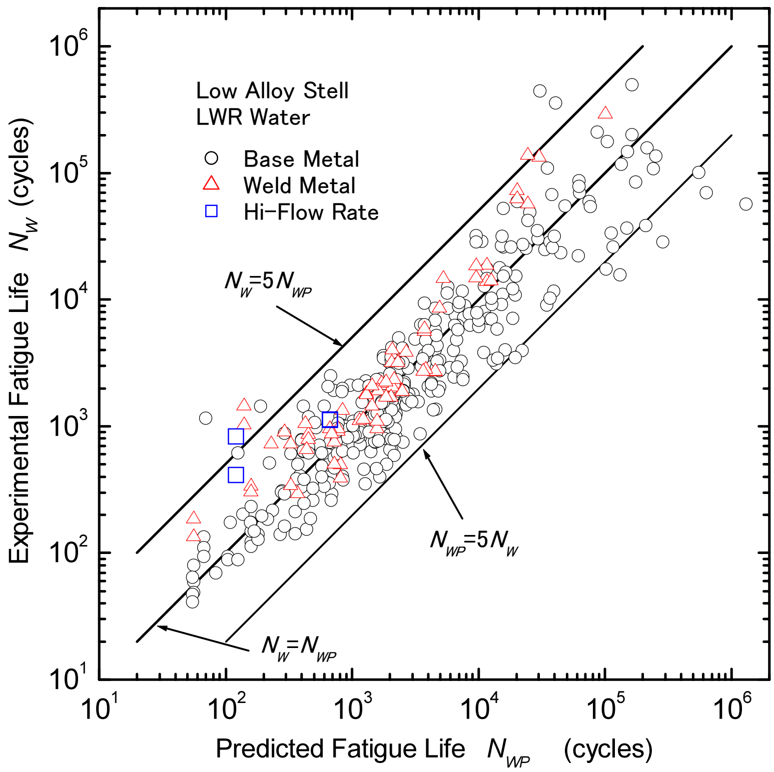


Figure E- 3.3.1-18 Comparison between Experimental and Predicted Values of Simulated LWR Environmental Fatigue Life for Low-Alloy Steel

3.3.2 F_{en} of Austenitic Stainless Steel and the Welds

After the first fatigue life equation for austenitic stainless steel was proposed in 2001 [17], the strain rate threshold for cast steel was reevaluated in 2004 [6, 18], and was again reevaluated in 2005 [23]. Finally, data of extremely lower strain rates for type 316NG in BWR environment, higher flow rates for type 304 and so on were added, and the following proposal was made.

<Fatigue data used for evaluation>
All data used for evaluation was provided by the strain controlled fatigue test. Domestic data in Japan only were used for data in air, which are 567 data between room temperature and 400 °C. 302 data in air at the room temperature only were available except data for cast steel, and 403 data were available, if data for cast steel and higher temperature up to 325 °C were included.

The number of fatigue data in the simulated LWR environment including domestic data in Japan and ANL data in U.S. are 216 for simulated BWR environment and 380 for simulated PWR environment. The fatigue life equation in simulated LWR environment was reevaluated using these data.

(1) Reference fatigue curve in air

The fatigue data in air at room temperature for types 316 and 304 are shown in Figure E-3.3.2-1. The approximate curve of data and its equation, Tsutsumi curve proposed in 2001 and its equation [17], and the current ASME design fatigue curve were indicated together in the figure. The approximate curve of data based on Stromyer's method was almost the same as Tsutsumi curve. Although not indicated here, these curves are almost equal to the equation of Jaske-O'Donnell proposal [24] or Chopra proposal [21]. In Figure E-3.3.2-2, data for cast steel and high temperature of 325 C are added to Figure E-3.3.2-1. Similarly in this figure, approximate curve of data and equation, Tsutsumi curve proposed in 2001 and equation, and current ASME design fatigue curve were also indicated. The fatigue strength of the latter approximate curve is a little lower in the long life region.

The evaluation of environmental fatigue data has been conventionally made based on the fatigue curve in air at room temperature. The approximate curve of data in air at room temperature that have been obtained until now is almost the same as Tsutsumi curve used as conventional basis, as shown in Figure E-3.3.2-1. Therefore, it is determined to use Tsutsumi curve as the reference curve in the future. Tsutsumi curve is expressed with the following equation.

$$\varepsilon_a = 23.0\, N_A^{-0.457} + 0.11 \qquad \text{(E-3.3.2-1)}$$

(2) Effects of strain rate

In JNES-SS-0503, the relation between F_{en} and the strain rates for all data except those for the cast stainless steel was calculated with the method of least squares under the assumption that effect of different materials on F_{en} was not significant except for the cast stainless steel. As a result, the trend lines were remained because those lines were not different from the conventional ones [23], while the trend lines for cast stainless steel were calculated independently [23].

Since the issuance of JNES-SS-0503, a large number of data regarding the effects of strain rates under the BWR plant environment at a high flow rate and low strain rates for 316NG material have been accumulated, and it was verified that the fatigue life reduction in high flow rate water was higher than those in stagnant water [35, 36] and that the fatigue life reduction was not saturated at lower strain rates for 316 NG material [35]. Considering those results, JNES-SS-0503 has been reviewed. Materials were classified into type 316 NG, 304, its associated weld metal and cast stainless steels. Figure E-3.3.2-3 shows the relation between average F_{en} and strain rate at 289°C in stagnant simulated BWR water for each type of material. The data obtained from a single point were eliminated since its weight was too small compared to the average. All the trend lines shown in this figure are calculated by a least-squares method. They consist of a trend line representing the data on each material excluding those under high flow rates, a trend line on all the data including those under high flow rates and a JSME EFEM 2006 trend line representing the data excluding those for cast steel and under high flow rates [6, 18]. While a trend line for cast steel is located at a rather higher position, the other trend lines seem to be almost overlapped. The fatigue life for 316 NG, 304 and 304 L stainless steels obtained from the tests in high flow rate water, which is apparently lower than that in stagnant water, will be separately treated. In stead, average F_{en} values in high flow rates (1～10m/s) for each type of material were obtained and then three points of data were plotted at a strain rate of 0.001 %/s. The data in high flow rates at the three points were applied in calculating a trend line representing all the data. The equations used to obtain the above mentioned trend lines for each material and for all data, and the trend line of JNES-SS-0503 are shown below [6, 7, 18]:

- Type 316NG (BWR): $F_{en} = 1.33\ \dot{\varepsilon}^{-0.236}$ (E-3.3.2-2)
- Type 304 (BWR): $F_{en} = 1.75\ \dot{\varepsilon}^{-0.202}$ (F-3.3.2-3)
- SS Weld Metal (BWR): $F_{en} = 1.03\ \dot{\varepsilon}^{-0.281}$ (E- 3.3.2-4)
- Cast SS (BWR): $F_{en} = 1.94\ \dot{\varepsilon}^{-0.282}$ (E- 3.3.2-5)
- All data trend line (BWR) $F_{en} = 1.32\ \dot{\varepsilon}^{-0.280}$ (E- 3.3.2-6)
- Conventional trend line (BWR) $F_{en} = 1.32\ \dot{\varepsilon}^{-0.235}$ (E- 3.3.2-7)

As a conclusion, it was determined to place the above “trend line for all data including those under high flow rates" as the basis for the future evaluations. This trend line has a greater slope than the conventional trend line proposed in the JNES-SS-0503 version and F_{en} tends to become significantly larger for lower strain rates.

For 316NG and cast stainless steel both of which data were obtained to the extent of very low strain rate under the simulated BWR environment at 289 C, the relation between F_{en} and strain rate is shown in Figure E-3.3.2-4. The figure also includes the trend line for all data shown in Figure E-3.3.2-3 and equation E-3.1.3.5-6. Regarding the strain rate threshold, data for 316 NG is not saturated at 0.0004 %/s of the threshold proposed in the JNES-SS-0503 version, and thus it is necessary to lower the threshold by one order to 0.00004 %/s. Although the data for cast stainless steel seem to stop at 0.0004 %/s, it was determined to lower the threshold to 0.00004 %/s from the conservative viewpoint since F_{en} is higher at 0.0004 %/s. Regarding SUS304 which has no data for lower strain rates, the strain rate threshold is set at 0.00004 %/s like other materials. Although weld metal indicates a threshold at 0.0004 %/s, no evaluation is conducted for weld metal alone. Therefore, the strain rate threshold of 0.00004 %/s is applied to all stainless steel materials subject to the BWR environment.

Figure E-3.3.2-5 indicates the trend line defined in this guideline version 2007 and the data for all types of stainless steel in the simulated BWR environment at 289 °C. The figure also shows the trend line defined by 2003 proposal [6, 7, 18]. The trend line in this guideline 2007 version shows significantly large F_{en} in the lower strain rate region.

Stainless steel materials subject to the simulated PWR environment were also classified into types 316,/304 and associated weld metal and cast stainless steel like those in BWR environment. The relation between the averaged F_{en} for each material and strain rates in the simulated PWR environment at 325 °C is shown in Figure E-3.3.2-6. The figure also indicates the trend lines for the individual stainless steels obtained by a least squares fit, a trend line for all data and_the guideline 2003 version [6, 7, 18]. In deriving the trend line, the data at 0.0004 %/s or higher strain rates for non-cast stainless steel and the data at 0.00004 %/s or higher strain rates for cast stainless steel were subjected to the evaluation. Lower strain rates for which the environmental effects are determined to be saturated are excluded from the evaluation. As shown in the figure, there is a little difference between materials. The equations to derive the trend lines [37] for each material and all data and the JNES-SS-0503 version [6, 7, 18] are shown below:

- Type 316 (PWR)： $F_{en} = 2.18\dot{\varepsilon}^{-0.315}$ (E-3.3.2-8)
- Type 304 (PWR)： $F_{en} = 3.02\dot{\varepsilon}^{-0.286}$ (E-3.3.2-9)

- Weld metal (PWR) : $F_{en} = 2.25\dot{\varepsilon}^{-0.223}$ (E-3.3.2-10)
- Cast SS (PWR) : $F_{en} = 1.95\dot{\varepsilon}^{-0.297}$ (E-3.3.2-11)
- Trend line for all data (PWR) : $F_{en} = 2.50\dot{\varepsilon}^{-0.257}$ (E-3.3.2-12)
- JNES-SS-0503 version (PWR): $F_{en} = 2.70\dot{\varepsilon}^{-0.254}$ (E-3.3.2-13)

Comparing with the JNES-SS-0503 version, the present trend line has little change, in particular for low strain rates for which F_{en} is large. Therefore, it was concluded that the EFEM 2006 version is still valid.

The relation between F_{en} and strain rate for materials other than cast stainless steel in the simulated PWR environment at 325 °C is shown in Figure E-3.3.2-7. The figure also indicates the JNES-SS-0503 version. As can be seen in this figure, the JNES-SS-0503 version's threshold of lower strain rate of 0.0004 %/s is still applicable to the materials other than cast stainless steel. Similarly, the trend line representing the relation between F_{en} and strain rate for cast stainless steel and the JNES-SS-0503 version [6, 18] are shown in Figure E-3.3.2-8 [6, 7, 18]. The JNES-SS-0503 version's threshold of lower strain rate of 0.00004 %/s is applicable to cast stainless steel.

In Figure E-3.3.2-9, data representing all types of stainless steels in the simulated PWR environment at 325 °C are shown with the JNES-SS-0503 trend line. The figure also indicates the trend line for all the data defined above. With little difference between these lines, it was decided to adopt equation of the JNES-SS-0503 version for PWR.

(3) Effects of temperature

Utilizing the data obtained from tests conducted by changing temperature in the BWR simulated environment, the relation between $F_{en\,(0.001\%/s)}$ at a strain rate of 0.001 %/s and temperature is shown in Figure E-3.3.2-10. The data for lower strain rates below 0.01 %/s were also used for the evaluation by converting them into that equivalent to a strain rate of 0.001 %/s by using equation E-3.3.2-14.

$$\ln(F_{en(0.001\%/s)}) = \ln(N_A/N_W)(\ln(0.001)/\ln(\dot{\varepsilon})) \quad \text{(E-3.3.2-14)}$$

The vertical axis of the figure is $F_{en\,(0.001\%/s)}$ in the case that the fatigue data of which strain rate was converted to 0.001 %/s are included in it. The trend line in Figure E-3.3.2-6 was not obtained by fitting against data but derived by connecting F_{en} =9.14 (289 °C), which was obtained by substituting $\dot{\varepsilon} = 0.001\%/s$ into equation E-3.3.2-6, and F_{en}=1.0 (0 °C). The straight line shown in the figure can be expressed by the following equation:

(Relation between F_{en} and temperature in BWR environment for stainless steels)

$$\ln(F_{en\,(0.001\%/s)}) = 0.00765\,T \qquad \text{(E-3.3.2-15)}$$

The relation between $F_{en(0.001\%/s)}$ at a strain rate of 0.001 %/s and temperature in the simulated PWR environment is shown in Figure E-3.3.2-11 like that in BWR environment. The data for lower strain rates below 0.01 %/s were also used for the evaluation by converting them into that equivalent to a strain rate of 0.001 %/s by using the equation E-3.3.2-11. The trend line in Figure E-3.3.2-11 was not obtained by fitting against data, and indicates the comparison with the equation proposed in 2001. The data show that the F_{en} equation is almost valid [6, 18]. Therefore, the relation between F_{en} and temperature in PWR environment remains unchanged.

(4) Effects of dissolved oxygen concentration

Figure E-3.3.2-12 shows the relation between $F_{en\,(0.001\%/s)}$ and dissolved oxygen concentration (DO) in the simulated BWR environment at 289 °C and strain rate of 0.001 %/s. The data for lower strain rates below 0.004 %/s were also used for the evaluation by converting them into that equivalent to a strain rate of 0.001 %/s by using the equation E-3.3.2-14. In this figure, $F_{en\,(0.001\%/s)}$ shows a rising trend as dissolved oxygen concentrations decrease for stainless steel while the data for other materials have large scatter and there is no clear dependency on the dissolved oxygen concentration. The horizontal lines represent the averaged values for non-cast stainless steel base metal, weld metal and cast stainless steel. It was concluded that the policy described in JNES-SS-0503 that there was no effect of dissolved oxygen concentration would be maintained.

Figure E-3.3.2-13 shows the relation between F_{en} and dissolved oxygen concentration in simulated PWR environment at 325 °C and strain rate of 0.01 %/s. With data on low strain rates with different dissolved oxygen concentrations at only 4 points, a comparison was made with the data at a similar strain rate of 0.01 %/s only. The number of data points was the same as that in JNES-SS-0503. The horizontal lines represent the averaged values for individual materials. Although F_{en} of type 304 is higher than type 316, it is determined that there is no effect of dissolved oxygen concentration on F_{en}. Accordingly, it was concluded that there was no effect of dissolved oxygen concentration both in PWR and BWR.

(5) Effects of water flow rate

The fatigue life of stainless steel in the BWR environment depends on the water flow rate [35, 36]. Figure E-3.3.2-14 shows the relation between F_{en} and flow rate in the BWR environment for three types of stainless steels (types 316 NG, 304 and 304 L). Contrary to carbon steel, F_{en} for stainless steel becomes larger at higher flow rates (That means the life of stainless steel becomes shorter under higher flow rates). The extent of increase in F_{en} at high flow rate depends on material and the largest is for type 304 and the smallest for type 316 NG. With large data scatter, it is impossible to quantify the dependency on the flow rate. From the qualitative view point, it can be said that F_{en} apparently becomes larger in water at a flow rate higher than a certain level compared with that in stagnant water. Under such circumstances it is difficult to include the flow rate as a parameter in the evaluation method. However, it is not negligible since the elimination of flow rates may result in a non-conservative evaluation result. Therefore, as described in the above item (2), it was decided that the 3 averaged F_{en} at a strain rate of 0.001 %/s and a high flow rate exceeding 1m/s for 3 types of stainless steels are incorporated into the data group which is used to determine the relation between F_{en} and strain rate.

Figure E-3.3.2-15 shows the relation between F_{en} and flow rate for stainless steel in PWR environment. As can be seen in this figure, F_{en} has no dependency on flow rate in PWR environment [23, 35].

(6) Effects of sensitization and thermal ageing

As shown in Figure E-3.3.2-16, the effect of sensitization of stainless steel on F_{en} in BWR environment can be seen. The figure shows the relation between F_{en} and strain rate for type 304 base metal subject to solution heat treatment (1,100 °C × (30min./25mm)→water quenching) and subject to sensitizing heat treatment (750°C × 100min→furnace quenching→400 °C×1,700 h→air quenching) in BWR environment. The figure also shows a trend line for type 304 (equation E-3.3.2-6). As can be seen in this figure, the data for both types of materials are present close to the trend line with a little difference between them although F_{en} for sensitized material is slightly higher than that of solution treated material. Therefore, it is concluded that the sensitization has no effect on F_{en} in BWR environment. Although many fatigue tests were carried out for thermal aged materials in LWR water, the effect of thermal aging on environmental fatigue is not clear.

(7) Effects of stress (strain) holding

The fatigue life of stainless steel in hot water of BWR is reduced due to strain holding at the peak [35, 38]. Figure E-3.3.2-17 shows the relation between F_{en} and strain hold time for stainless steel in BWR environment. In the figure, three different symbols, open, half solid and solid represent the test results under the strain holding at peak, peak minus 0.03 % and peak minus 0.06 %, respectively. The solid and half solid symbols were tested considering ordinary thermal transients in which the strain is held at a value slightly below the peak after overshoot. In addition, F_{en} at 0.004 %/s strain rate without holding is shown with a dotted line. As shown in the figure, contrary to the case of carbon steel, the fatigue life reduction due to strain holding at the peak is significant at lower strain rates and fatigue life reduction disappears at 0.004 %/s or higher strain rates. The extent of fatigue life reduction depends on the hold time. The fatigue life reduction tends to be saturated as the hold time becomes longer. However the fatigue life reduction is not saturated even at 2,000 seconds hold time.

Solid and half solid symbols where strain was held at 0.06 % below the peak strain after overshoot show no fatigue life reduction although tensile stresses corresponding to the yield point remain. It can be concluded that when the process transfers from increasing strain to holding strain, the fatigue life reduces while no fatigue life reduction occurs when the process transfers from strain decreasing to strain holding. Considering the above results, the evaluation should be performed by setting a saturated strain rate while considering fatigue life reduction due to strain holding when the strain is at the peak and held under the high temperature and pressure conditions.

Figure E-3.3.2-18 shows the relation between F_{en} and strain hold time for stainless steel in PWR environment. As shown in this figure, F_{en} for stainless steel in PWR environment is independent from the effect of strain holding.

(8) Proposal of equation for fatigue life (Equations to calculate F_{en})

It was determined that the F_{en} equation in JNES-SS-0503 for stainless steel in PWR environment would remain unchanged while the equation for BWR environment would be revised. In JNES-SS-0503, fatigue data for cast stainless steel in BWR environment were excluded from the evaluation. Considering new data showing fatigue life reduction of type 316NG at extremely low strain rates and fatigue life reduction of type 304 in high flow rate water, which have been accumulated since the issuance of JNES-SS-0503, the trend lines were re-evaluated including cast stainless steel data. The F_{en} equations for stainless steel in BWR and PWR environments respectively are defined as follows.

The basic equations represent the relation between F_{en} and strain rate by equation E-3.3.2-6 for BWR environment. These can be expressed in the form of the following general equation E-3.3.2-16:

$$\ln(F_{en}) = \{\ln(1.32)/0.280 - \ln(\dot{\varepsilon})\}0.280 \qquad \text{(E-3.3.2-16)}$$

Multiplying equation E-3.3.2-16 by the effects of temperature, which is a ratio of equation E-3.3.2-15 vs. logalism, ln(9.14), of F_n at 289 °C and 0.001 %/s, results in equation E-3.2-17:

$$\ln(F_{en}) = \{\ln(1.32)/0.280 - \ln(\dot{\varepsilon})\}0.280 \times 0.00765T/\ln(9.14) \qquad \text{(E-3.3.2-17)}$$

Adding this equation, F_{en} for stainless steels is expressed as shown below:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^* \qquad \text{(E-3.3.2-18)}$$

C, $\dot{\varepsilon}^*$ and T^* for each reactor type and steel type are shown below:

(In the BWR plant environment)

$C = 0.992$

$\dot{\varepsilon}^* = \ln(2.69)$ $(\dot{\varepsilon} > 2.69\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.00004 \le \dot{\varepsilon} \le 2.69\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(0.00004)$ $(\dot{\varepsilon} < 0.00004\%/\mathrm{s})$

$T^* = 0.000969 \times T$

(In the PWR plant environment)

$C = 3.910$

$\dot{\varepsilon}^* = \ln(49.9)$ $(\dot{\varepsilon} > 49.9\%/\mathrm{s})$

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.0004 \le \dot{\varepsilon} \le 49.9\%/\mathrm{s})$
(Stainless steel except cast Stainless steels)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ $(0.00004 \le \dot{\varepsilon} \le 49.9\%/\mathrm{s})$
(Cast stainless steels)

$\dot{\varepsilon}^* = \ln(0.0004)$ $(\dot{\varepsilon} < 0.0004\%/\mathrm{s})$
(Stainless steel except cast Stainless steels)

$\dot{\varepsilon}^* = \ln(0.00004)$ $(\dot{\varepsilon} < 0.00004\%/\mathrm{s})$
(Cast stainless steels)

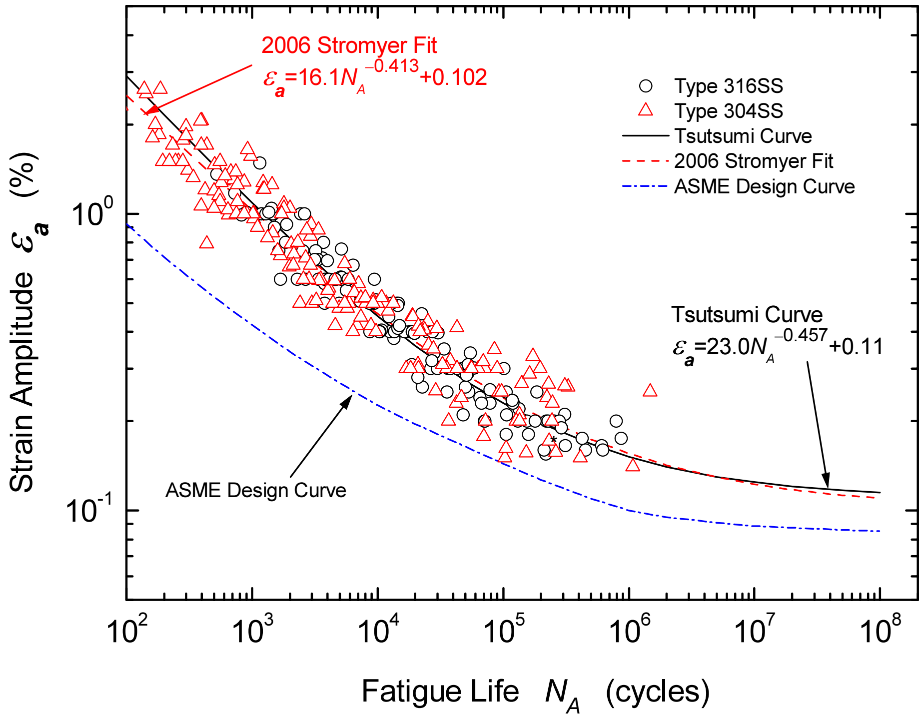
$T^* = 0.000782 \times T$ $(T \le 325°\mathrm{C})$

$T^* = 0.254$ $(T > 325°\mathrm{C})$

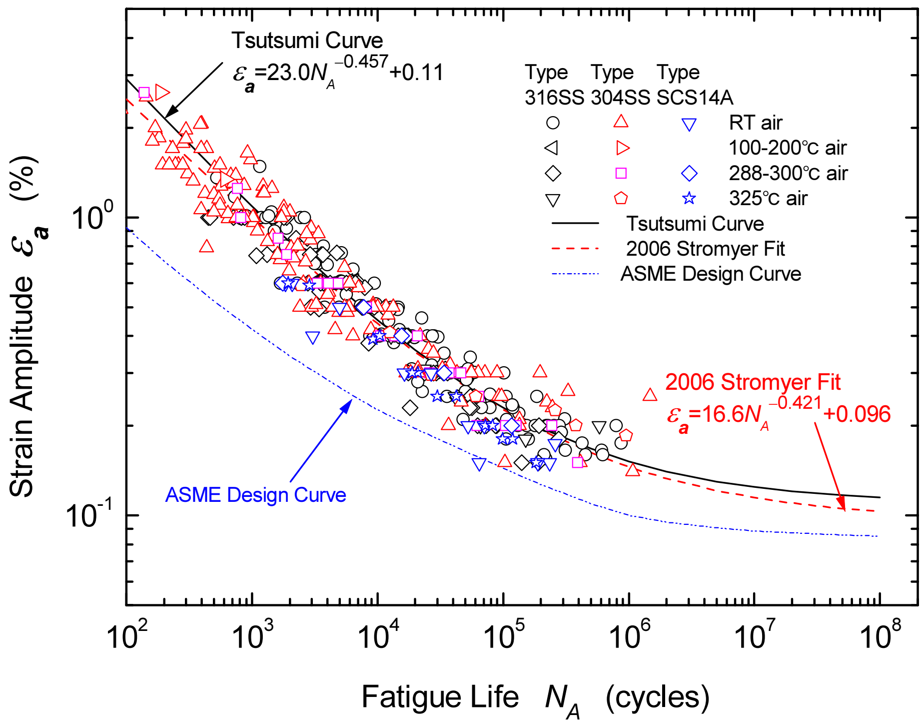
The scope covered by this equation is shown below:.

Material:	All stainless steels currently used at LWR pressure boundary and these welds.
Strain amplitude:	Exclude 0.11 % or less.
Load conditions:	Exclude seismic load.
Transient conditions:	This equation is used for thermal transient in the BWR environment. When peak holding in the transients with elastic follow up such as pressure is assumed, the strain rate is treated as the threshold of lower strain rate.

F_{en} was calculated by this equation for each test condition, and the predicted fatigue life was obtained by dividing the fatigue life in air at room temperature by F_{en}. Figure E-3.3.2-19 shows the comparison of the predicted fatigue life with the test result in the BWR environment, and Figure E-3.3.2-20 shows the same comparison in the PWR environment, respectively. Any case including the high flow rate data could be predicted almost in the range of a factor 5, but a potion of data deviated to the non-conservative side from this range was seen at long life region. All of these data are for long life of the strain amplitude below 0.15 %. In the region where the strain amplitude is small, the design fatigue curve was originally determined by the margin of not 20 of life but 2 of stress amplitude. Accordingly, it is considered that this level of life reduction is adequately covered with stress margin of 2 of the design fatigue curve.



Fatigue E-3.3.2-1 Curve in Air at Room Temperature for Austenitic Stainless Steel (2006 Version)



Fatigue E-3.3.2-2 Curve in Air for Austenitic Stainless Steel (2006 Version)

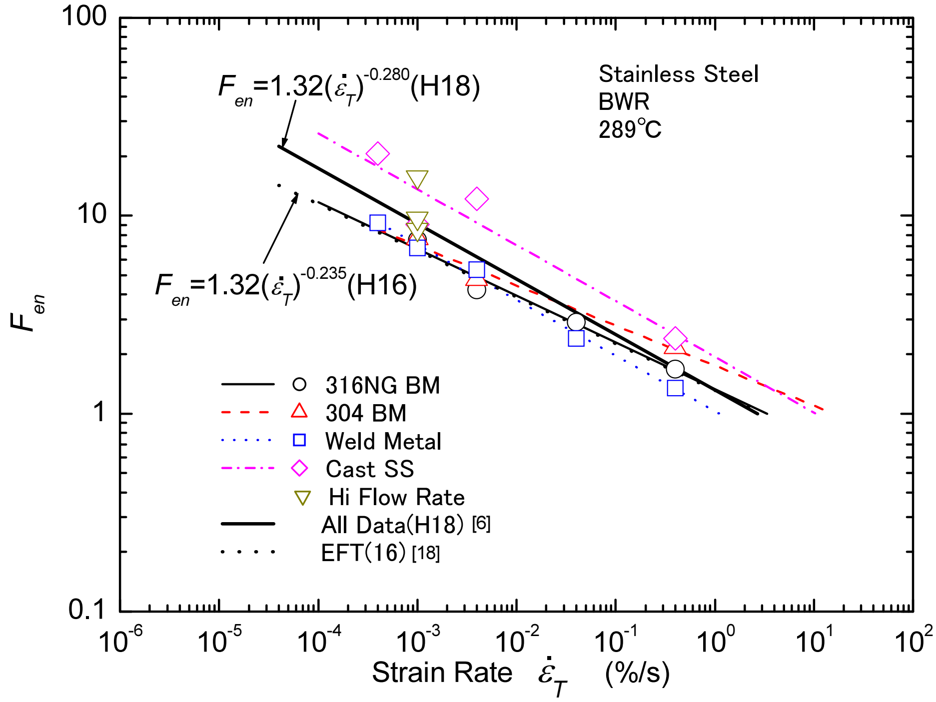


Figure E-3.3.2-3 Relation between F_{en} and Strain Rate of Stainless Steel (BWR, Average Value Evaluation)

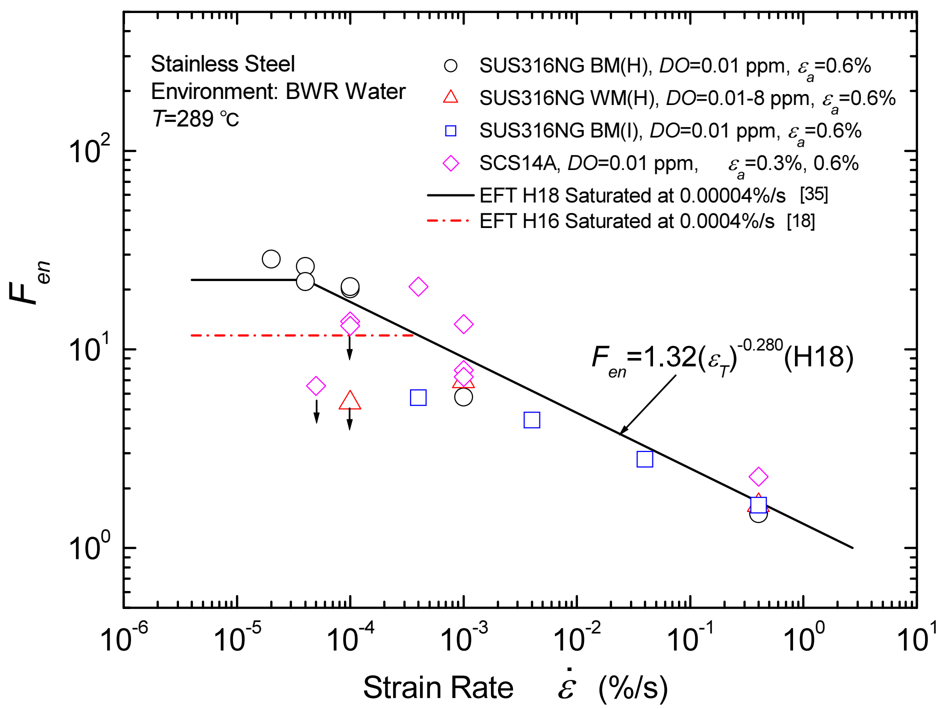


Figure E-3.3.2-4 Relation between F_{en} and Strain Rate for Stainless Steel (Threshold of Lower Strain Rate)

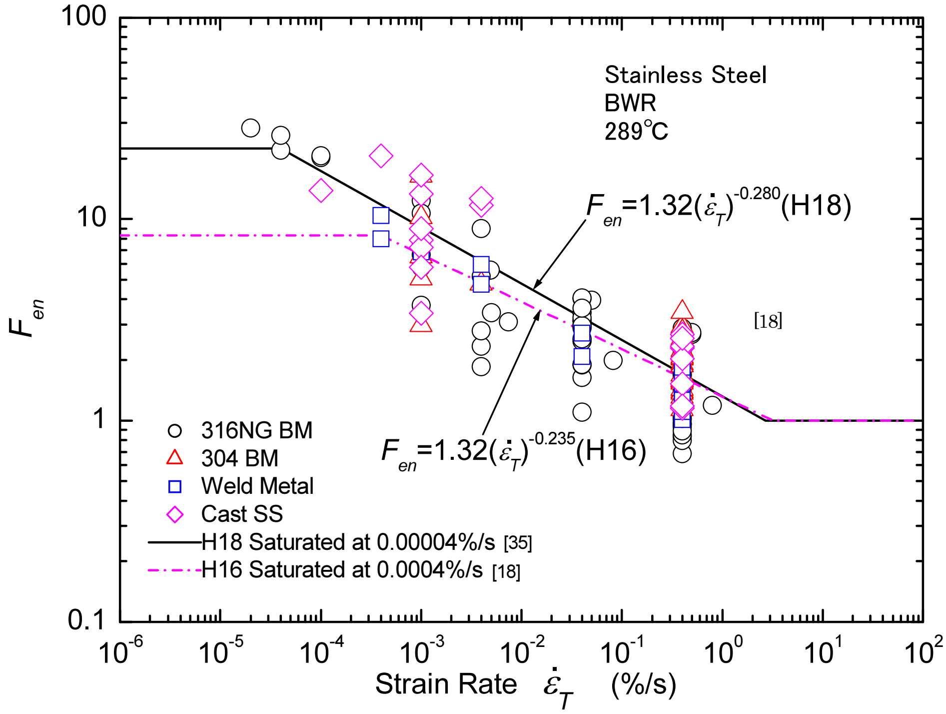


Figure E-3.3.2-5 Relation between F_{en} and Strain Rate for Stainless Steel (BWR, All Data and Proposed Lines)

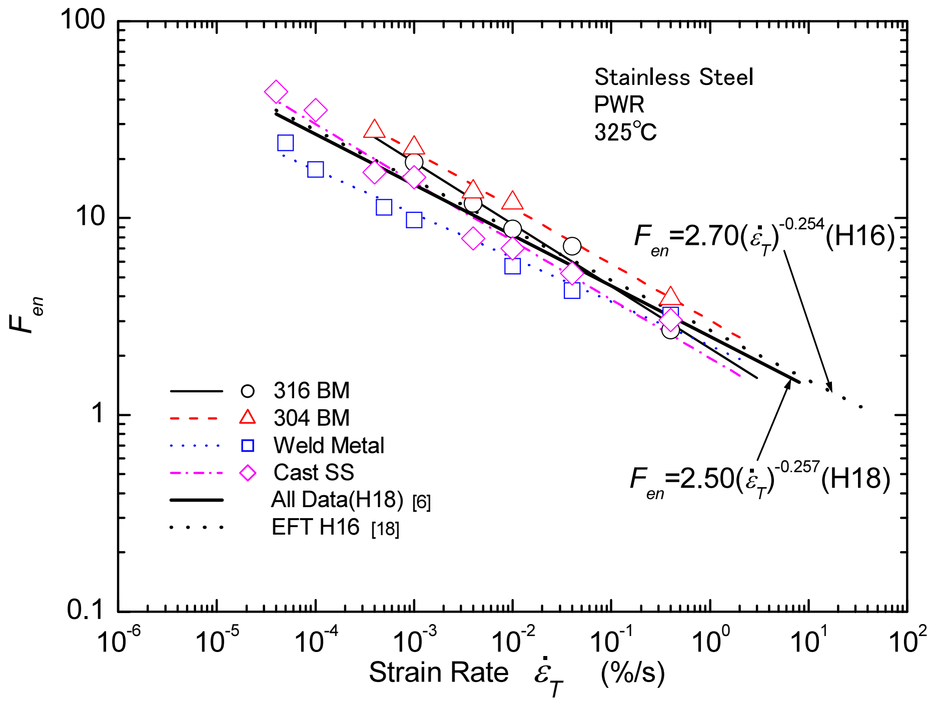


Figure E-3.3.2-6 Relation between F_{en} and Strain Rate for Stainless Steel (PWR, Average Value Evaluation).

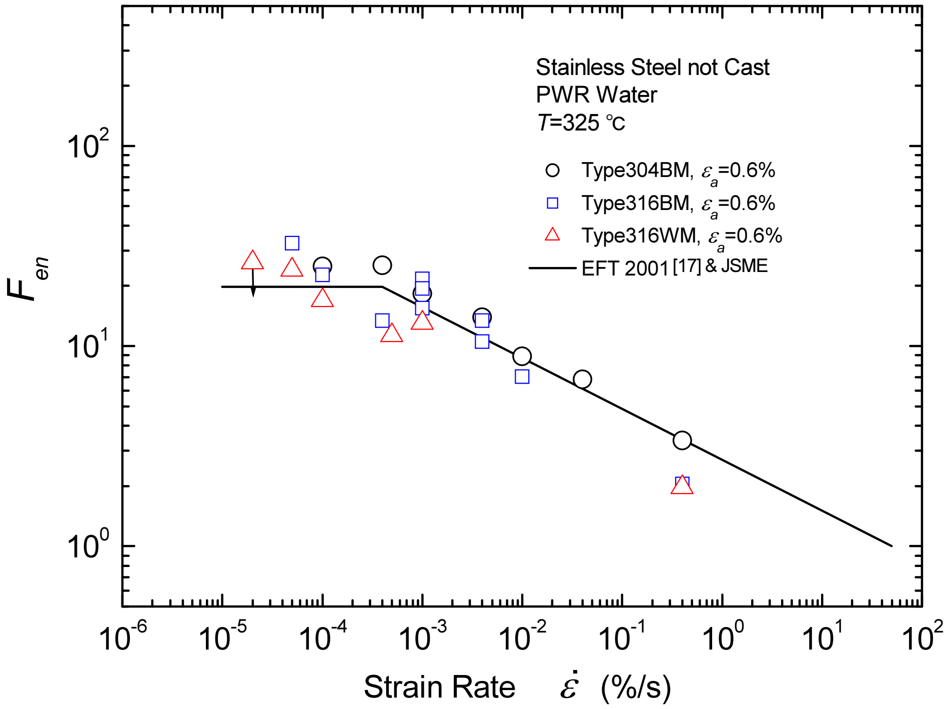


Figure E-3.3.2-7 Relation between F_{en} and Strain Rates for Stainless Steel (PWR, Non-Cast Steel, Threshold of Lower Strain Rate)

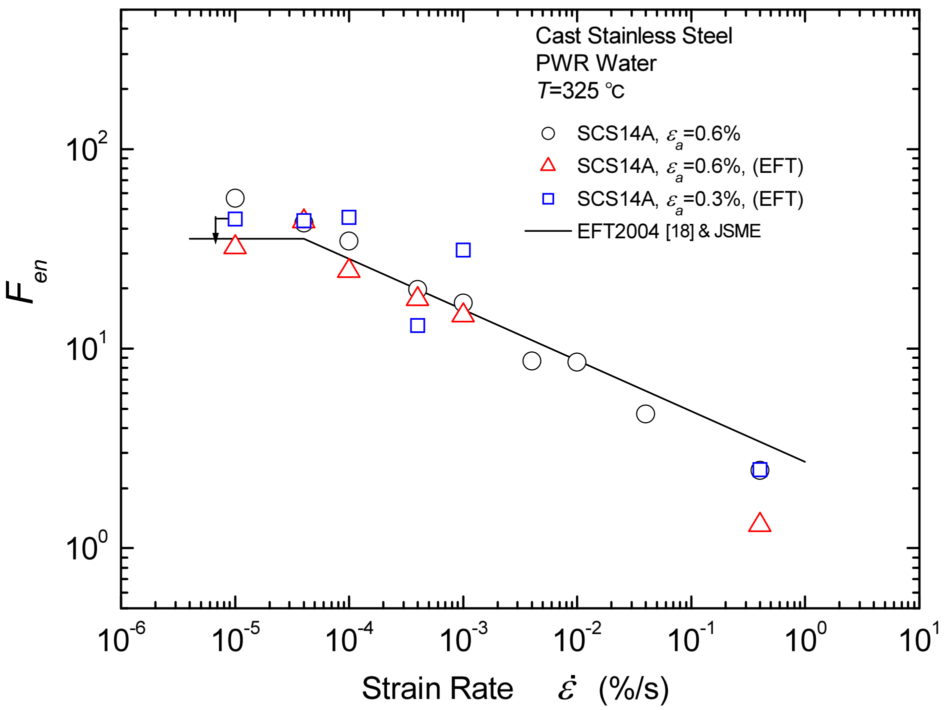


Figure E-3.3.2-8 Relation between F_{en} and Strain Rates for Stainless Steel (PWR, Cast Steel, Threshold of Lower Rate Strain Rate)

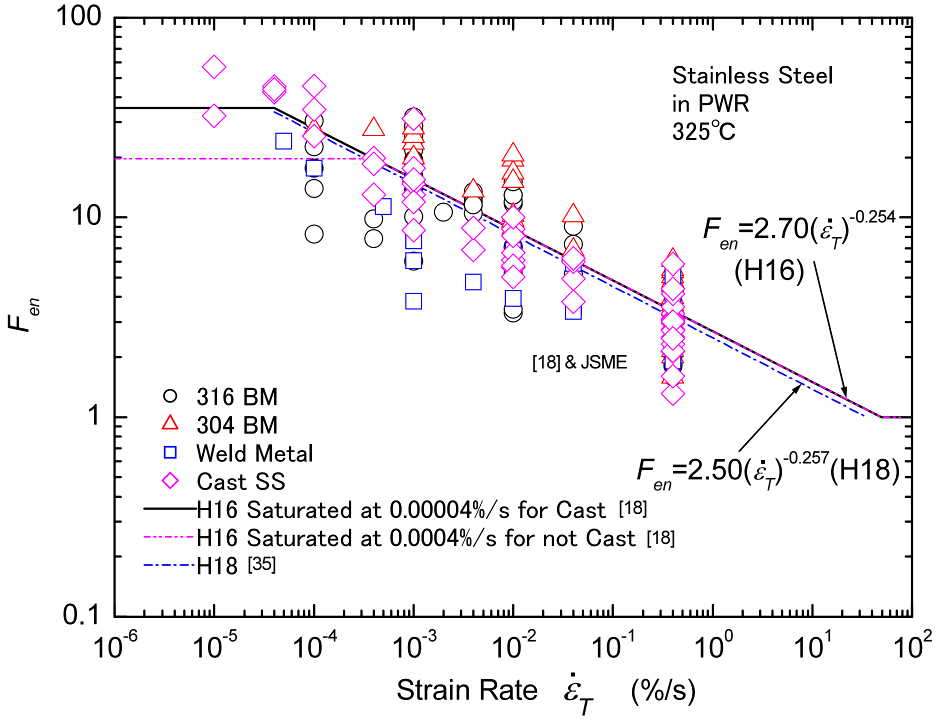


Figure E-3.3.2-9 Relation between F_{en} and Strain Rate for Stainless Steel (PWR, All Data and Proposed Lines).

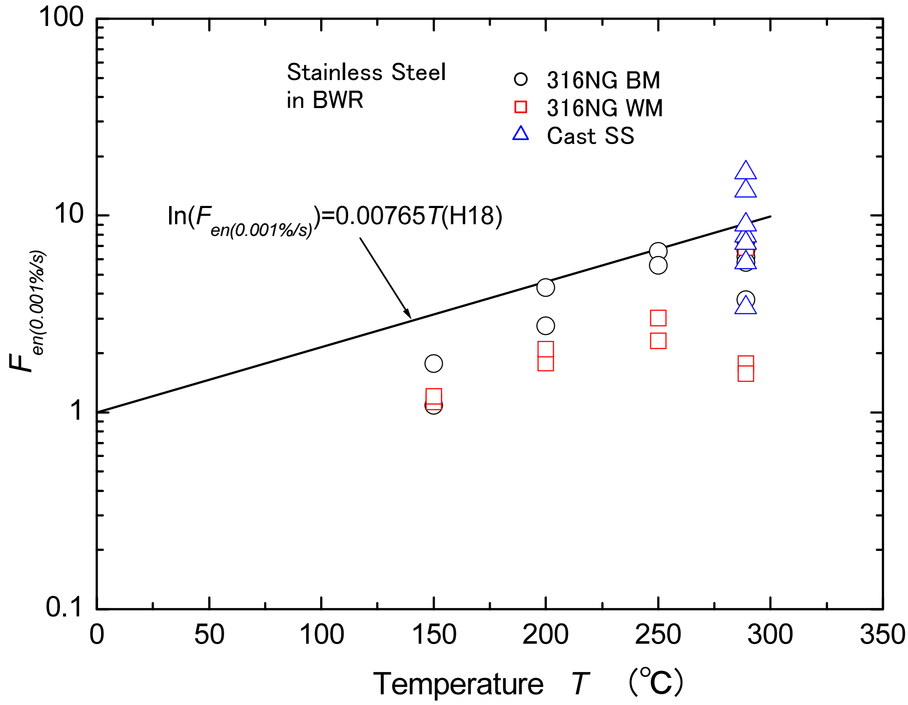


Figure E-3.3.2-10 Relation between $F_{en\ (0.001\%/s)}$ and Temperature for Stainless Steel (BWR)

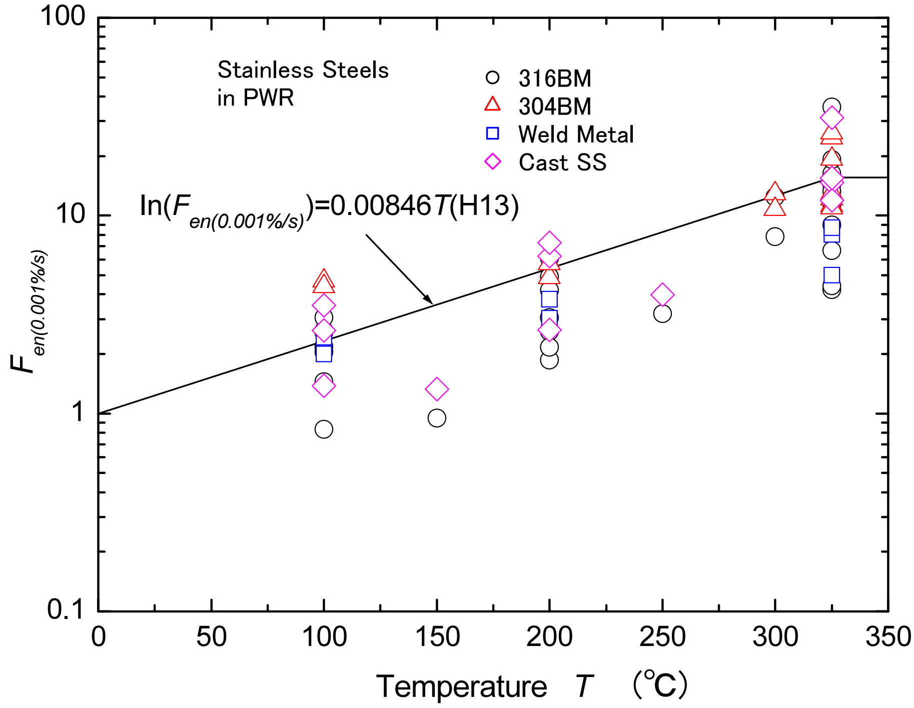


Figure E- 3.3.2-11 Relation between $F_{en\ (0.001\%/s)}$ and Temperature for Stainless Steel (PWR)

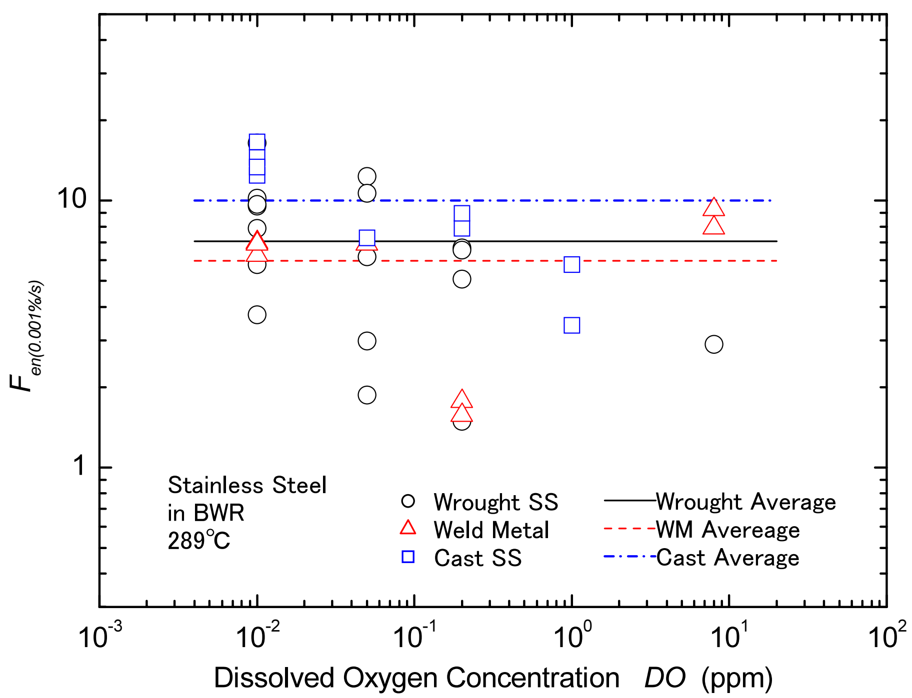


Figure E- 3.3.2-12 Relation between $F_{en\ (0.001\%/s)}$ and Dissolved Oxygen Concentration for Stainless Steel (BWR)

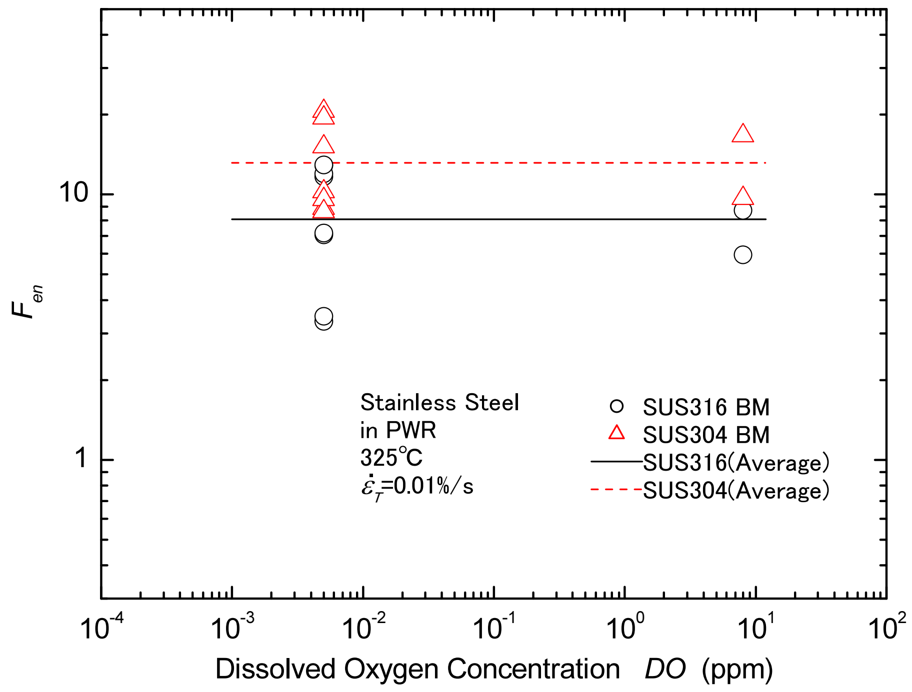


Figure E- 3.3.2-13 Relation between F_{en} and Dissolved Oxygen Concentration of Stainless Steel (PWR)

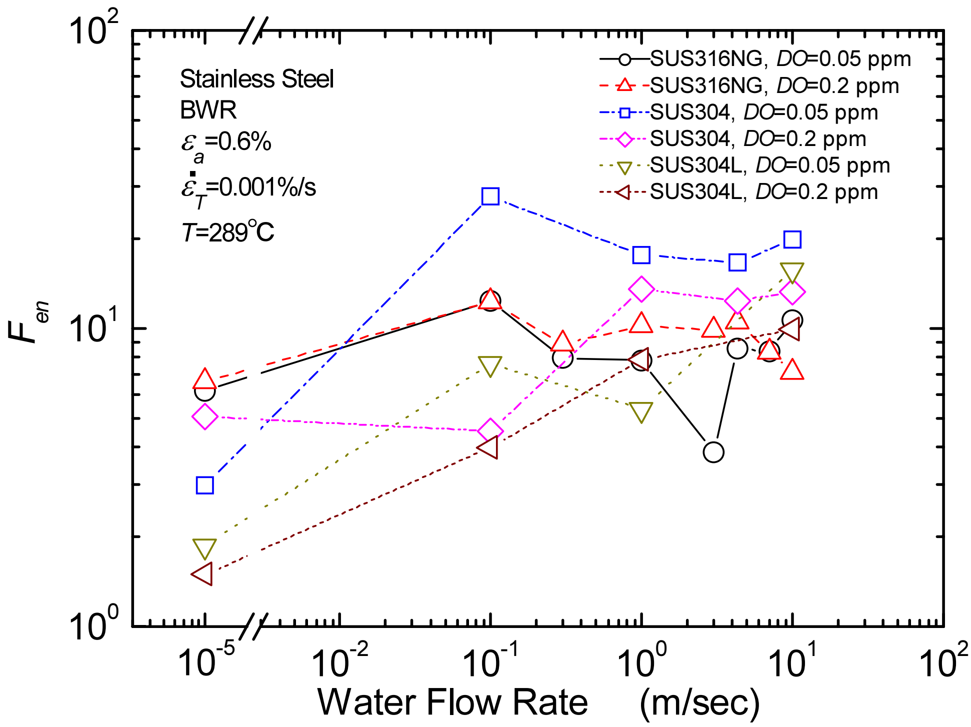


Figure E- 3.3.2-14 Relation between F_{en} and Water Flow Rate for Stainless Steel (BWR)

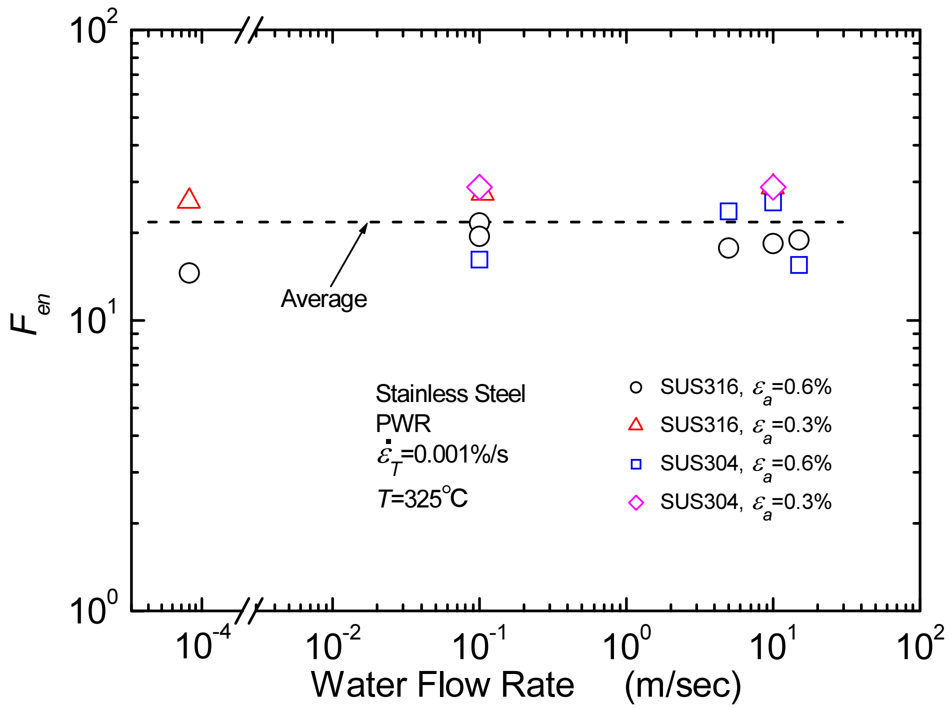


Figure E-3.3.2-15 Relation between F_{en} and Water Flow Rate for Stainless Steel (PWR)

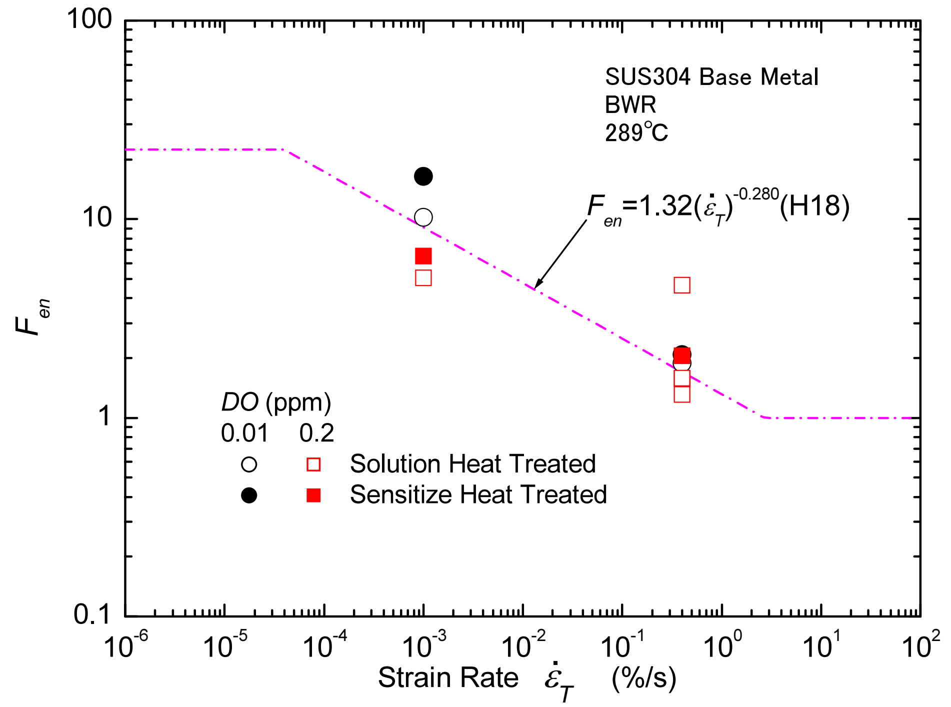


Figure E-3.3.2-16 Effect of Sensitization on Relation between F_{en} and Water Flow Rate for Stainless Steel

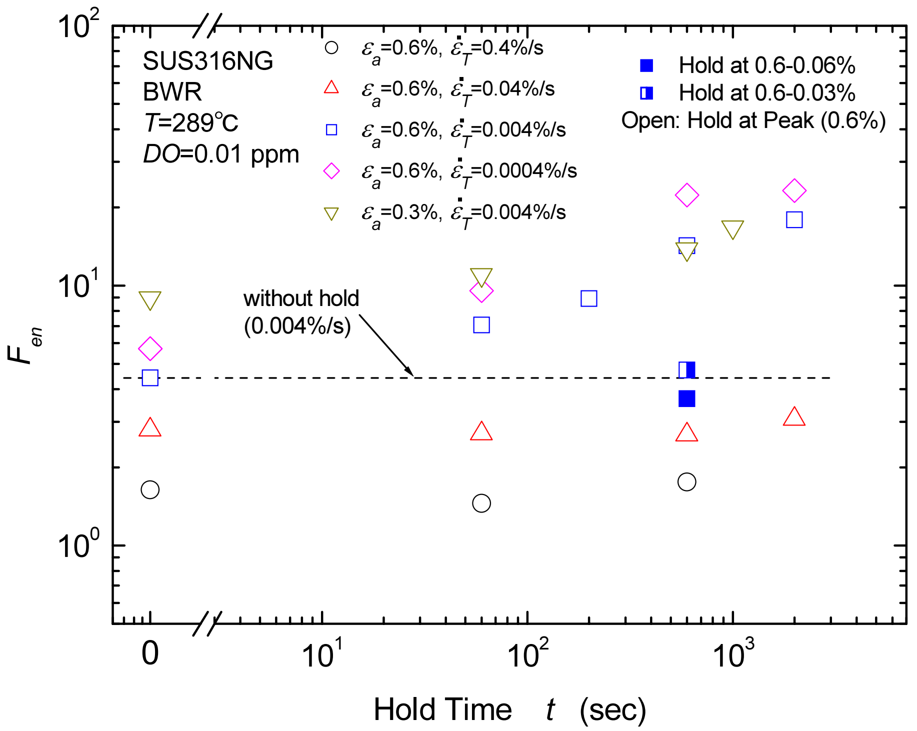


Figure E- 3.3.2-17 Relation between F_{en} and Strain Hold Time for Stainless Steel (BWR)

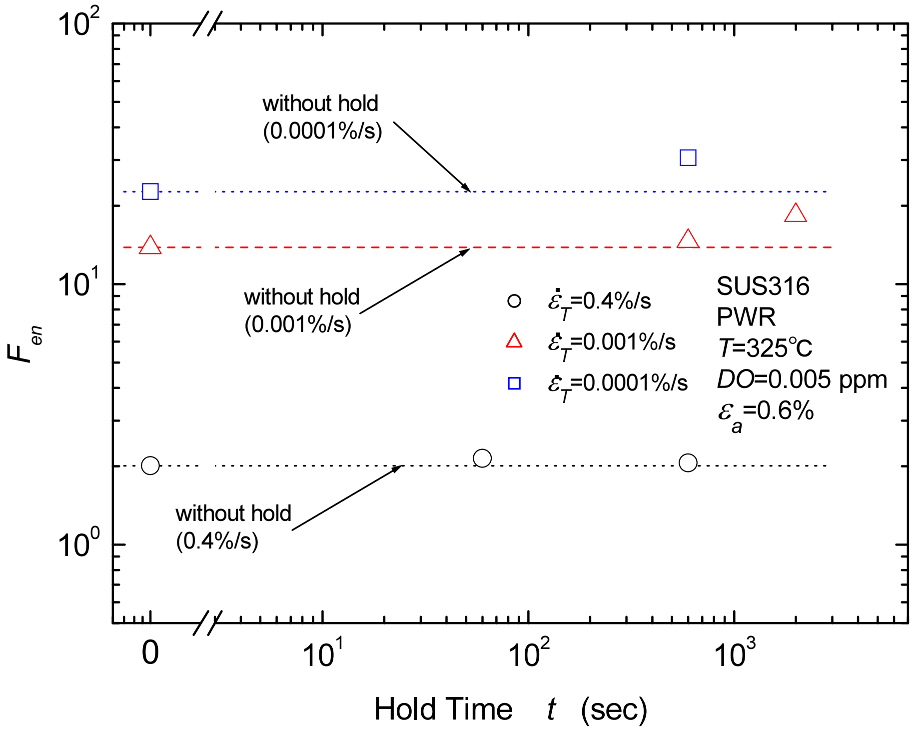


Figure E- 3.3.2-18 Relation between F_{en} and Strain Hold time for Stainless Steel (PWR)

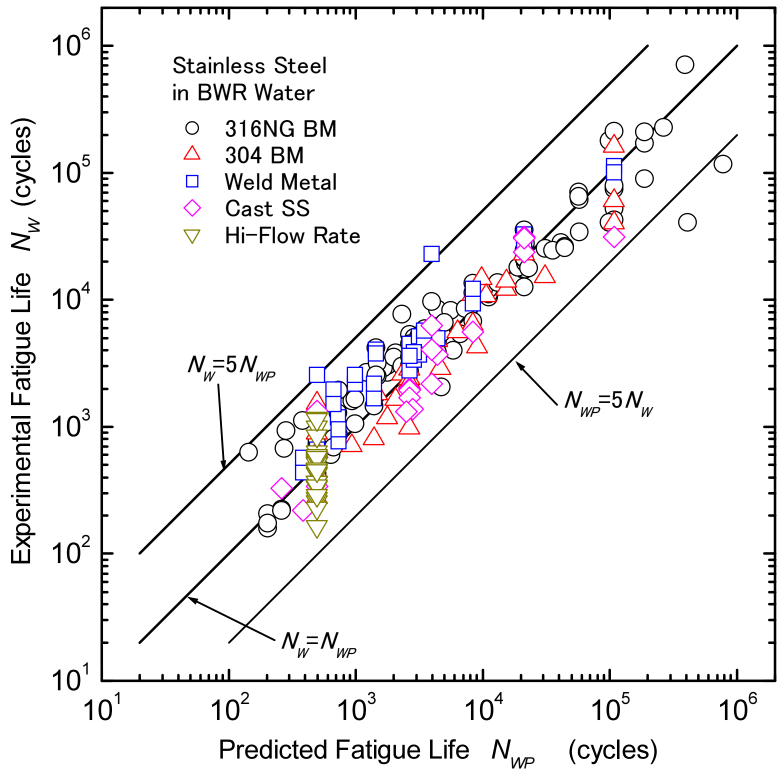


Figure E- 3.3.2-19 Comparison between Experimental and Predicted Values in Simulated BWR Environment

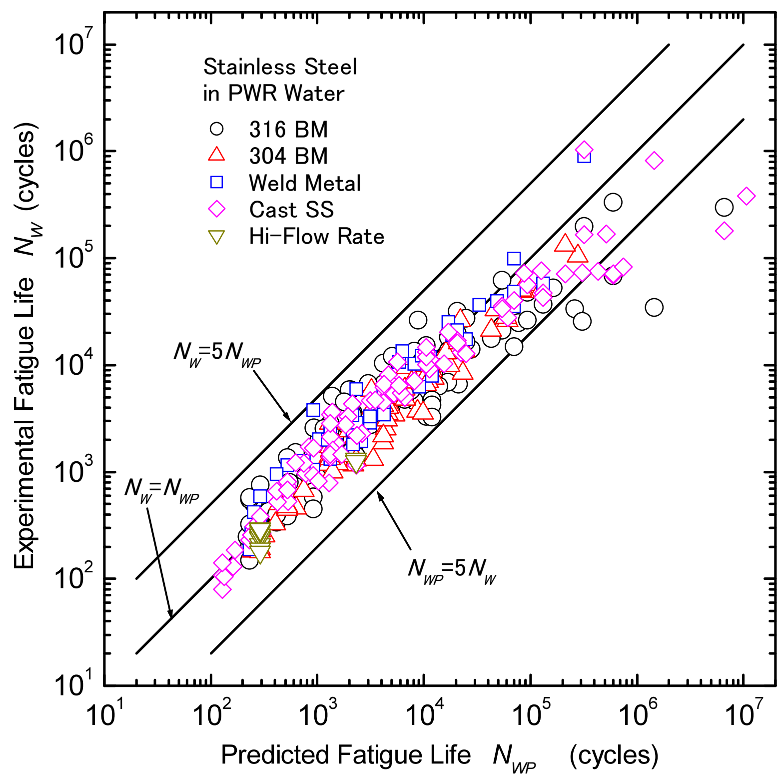


Figure E -3.3.2-20 Comparison between Experimental and Predicted Values in Simulated PWR Environment

3.3.3 F_{en} of Nickel-Chromium-Iron Alloy and the Welds

The equation to calculate F_{en} for nickel-chromium-iron alloys defined in 2004 was re-evaluated considering the data newly accumulated [35].

<Fatigue data used for evaluation>
All data used for evaluation were obtained from the strain controlled fatigue test. Domestic data in Japan only were used for data in air, and 83 data with 8 heats were collected. 7 data with one heat of them were collected at 289 °C and the other at the room temperature.

The data in simulated BWR environment were collected at temperature of 289 °C except 3 data at 200 °C, and the dissolved oxygen concentration was selected in the range of 0.01-8 ppm. For all data in the PWR environment, the temperature was selected in the range of 100-325 °C and the dissolved oxygen concentration was 0.005 ppm.

(1) Reference fatigue curve in air

The curve is determined only with data in air at room temperature. The relation between strain amplitude and data of life in air at room temperature are shown Figure E-3.3.3-1. In the figure, the approximate line obtained by Stromeyer!s method and Tsutsumi curve for all the data are indicated together. These equations are shown below:

"Fatigue curve in air at room temperature for nickel-chromium-iron alloy" [35]

$$\varepsilon_a = 19.0\, N_A^{-0.450} + 0.118 \qquad \text{(E-3.3.3-1)}$$

"Tsutsumi curve for stainless steel"

$$\varepsilon_a = 23.0\, N_A^{-0.457} + 0.11 \qquad \text{(E-3.3.3-2)}$$

As shown in the figure, the overall fatigue curve in air at the room temperature for the nickel-chromium-iron alloy is in good agreement with Tsutumi curve for stainless steel, although the fatigue strength is slightly lower at the large strain amplitude region. After this, this curve calculated by equation E-3.3.3-1 is defined as the reference curve in air.

(2) Effect of strain rate

The data on fatigue life in simulated BWR environment are plotted in Figure E-3.3.3-2 to show the relation between the fatigue life and strain amplitude according to the strain rate [20]. The figure also indicates a trend line representing the data in air at room temperature. With a minor decline in the fatigue strength of nickel-chromium-iron alloys in simulated BWR environment, many data are located above the in–air curve for higher strain rates, in particular for smaller strain amplitudes.

Similarly the data on fatigue life in simulated PWR environment are plotted in Figure E-3.3.3-3 to show the relation between the fatigue life and strain amplitude according to the strain rate [20]. The figure also indicates a trend line of equation E-3.3.3-1 representing the data in air at room temperature. With a larger decline in fatigue strength of nickel-chromium-iron alloys in simulated PWR environment compared with that in simulated BWR environment, few data were above the in-air curve.

Figure E-3.3.3-4 shows the relation between F_{en} and strain rate in simulated BWR environment. In plotting this figure, the data for strain amplitude of 0.25 % or less were eliminated since the fatigue strength tends to become higher in BWR environment than in air for relatively low strain amplitudes as can be seen in Figure E-3.3.2-2. The data for alloy 600 conventional, alloy 600 modified (Nb added for resisting to SCC) and type 182 weld metal are plotted separately in this figure. Since no clear differences were detected in the behavior of these materials, it was determined to deal these data as the similar ones. Although relatively large data scatter is present, the logarithmic linear relation was derived from the least squares fit of the data and is shown as the solid line in the figure and equation E-3.3.3-3.

$$\ln(F_{en}) = \ln(0.989) - 0.099\ln(\dot{\varepsilon}) \qquad \text{(Alloy 600, BWR)} \qquad \text{(E-3.3.3-3)}$$

The slope of this line is significantly smaller than those for other materials, which suggests that the fatigue life of nickel- chromium -iron alloys is less sensitive to the BWR environment.

Figure E-3.3.3-5 shows the relation between F_{en} and strain rate in simulated PWR environment. The data for alloy 600 base material, type 132 weld metal, alloy 690 base material and type 152 weld metal are plotted separately. Effects of PWR water on fatigue life of alloy 690 and type 152 weld metal were clearly less, compared to alloy 600 and type 132 weld metal though essentially the same for base and weld metals. Considering that nickel-chromium-iron alloys have low sensitivity to the environment, it was decided to obtain the trend line without distinguishing 690 from 600. Previous results for all materials indicated the linear relation between F_{en} and strain rate as shown in Figure E-3.3.3-5. The logarithmic linear relation was derived from the least squares fit and shown as the solid line in the figure and equation E-3.3.3-4.

$$\ln(F_{en}) = \ln(1.46) - 0.129\ln(\dot{\varepsilon}) \qquad \text{(600/690 alloy PWR)} \qquad \text{(E-3.3.3-4)}$$

The degree of slope of this line is between that for Alloy 600 and stainless steel in BWR environment.

The threshold of higher strain rate was obtained in the same way as that for other materials. Considering that there is no possibility of F_{en} being less than 1 as shown in Equation_E-3.3.3-3, the points where the lines derived from Equations E-3.3.3-3 and E-3.3.3-4 respectively intersect with F_{en}=1 are defined as the threshold of higher strain rates. These points are located at (0.898, 1) and (19.0, 1) on the coordinate axis. The threshold of lower strain rates was set at 0.0004 %/s for PWR and 0.00004 %/s for BWR respectively similar to those of rolled stainless steel since the amount of data was not sufficient to perform the evaluation.

Figure E-3.3.3-6 compares the relation between F_{en} and strain rate for nickel-chromium-iron alloys in PWR and BWR environments. The figure also shows the relation between F_{en} and strain rate for austenitic stainless steel in BWR and PWR environment. As can be seen in the figure, the declining rate of fatigue life of nickel-chromium-iron alloys under elevated temperature water is lower than that of stainless steel by several factors. Therefore, it is concluded that nickel-chromium- iron alloys have lower sensitivity to the environment than stainless steel.

(3) Effects of temperature

One datum was obtained at 200 °C in BWR environment while three data at 200 °C and one datum at 100 °C in PWR environment were obtained from the environmental fatigue tests, which were conducted by changing the temperature at lower strain rates where F_{en} can be evaluated. The strain rate is 0.001 %/s for all the data. The relation between F_{en} and strain rate is shown in Figure EF-3.3.3-7 [26,30]. It was assumed that F_{en} = 1.0 at 0 °C as was assumed for stainless steel. F_{en} at 289 °C or 325 °C was obtained by substituting 0.001 %/s for the strain rate into equations E-3.3.3-3 and E-3.3.3-4. The straight lines for BWR and PWR environment can be expressed by the following equations, respectively:

$$\ln(F_{en}) = 0.00233\,T \qquad \text{(Alloy 600 BWR)} \qquad \text{(E-3.3.3-5)}$$

$$\ln(F_{en}) = 0.00391\,T \qquad \text{(Alloy 600/690 PWR)} \qquad \text{(E-3.3.3-6)}$$

Figure E-3.3.3-7 compares the nickel-chromium-iron alloy curves with those of austenitic stainless steel in PWR and BWR environment for reference.

(4) Effects of dissolved oxygen concentration

Figure E-3.3.3-8 shows the relation between $F_{en\,(0.001\%/s)}$ and dissolved oxygen concentration (DO) for nickel-chromium-iron alloys at strain rate of 0.001 %/s. The data were obtained from the tests conducted by changing dissolved oxygen concentration in simulated BWR environment. The data for lower strain rates below 0.001 %/s were also used for the evaluation by converting them into that equivalent to a strain rate of 0.001 %/s by using the equation E-3.3.3-7.

$$\ln(F_{en(0.001\%/s)}) = \ln(N_A/N_W)(\ln(0.001)/\ln(\dot{\varepsilon})) \qquad \text{(E-3.3.3-7)}$$

The horizontal line in Figure E-3.3.3-8 represents the averaged value ($F_{en\ (0.001\%/s)}$= 1.94). As shown in the figure, F_{en} for nickel-chromium-iron alloys does not depend on the dissolved oxygen concentration.

(5) Equation proposed for fatigue life (Equation to calculate F_{en})

The basic equations E-3.3.3-3 and E-3.3.3-4, which express the relation between F_{en} and strain rate, can be expressed by the following general equation E-3.3.3-8:.

$$\ln(F_{en}) = \ln(A) - B\ln(\dot{\varepsilon}) = \{\ln(A)/B - \ln(\dot{\varepsilon})\}B \qquad \text{(E-3.3.3-8)}$$

The equations E-3.3.3-5 and E-3.3.3-6, which represent the relation between F_{en} and temperature, can be expressed by the following general equation E-3.3.3-9:

$$\ln(F_{en}) = F \times T \qquad \text{(E-3.3.3-9)}$$

Multiplying equation E-3.3.3-8 by the effects of temperature results in equation E-3.3.3-10:

$$\ln(F_{en}) = \{\ln(A)/B - \ln(\dot{\varepsilon})\}B(FT/FT_{max}) = \{\ln(A)/B - \ln(\dot{\varepsilon})\}(B/T_{max})T \qquad \text{(E-3.3.3-10)}$$

Where T_{max} is 289 °C for BWR and 325 °C for PWR. Assuming that $\ln(A)/B = C$, and $\ln(\dot{\varepsilon}) = \dot{\varepsilon}^*$, $(B/T_{max}) \times T = T^*$, equation E-3.3.3-10 can be expressed by equation E-3.3.3-11:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*)T^* \qquad \text{(E-3.3.3-11)}$$

C, $\dot{\varepsilon}^*$ and T^* for each reactor type are shown below:

(Alloy 600 in BWR plant environment)

$C = -0.112$

$\dot{\varepsilon}^* = \ln(0.894)$ ($\dot{\varepsilon} > 0.894\%/s$)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.00004 \le \dot{\varepsilon} \le 0.894\%/s$)

$\dot{\varepsilon}^* = \ln(0.00004)$ ($\dot{\varepsilon} < 0.00004\%/s$)

$T^* = 0.000343 \times T$

(Alloy 600/690 in PWR plant environment)

$C = 2.94$

$\dot{\varepsilon}^* = \ln(19.0)$ ($\dot{\varepsilon} > 19.0\%/s$)

$\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.0004 \le \dot{\varepsilon} \le 19.0\%/s$)

$\dot{\varepsilon}^* = \ln(0.0004)$ ($\dot{\varepsilon} < 0.0004\%/s$)

$T^* = 0.000397 \times T$

The scope covered by this equation is shown below:

Material: All nickel-chromium-iron alloys and these welds currently used at LWR pressure boundary

Strain amplitude: Except 0.11% or less

Load conditions: Except seismic load

F_{en} was calculated by the equation E-3.3.3-11 for each test condition, and the predicted fatigue life was obtained by dividing the fatigue life in air at room temperature by F_{en}. Figure E-3.3.3-9 shows the comparison of the predicted fatigue life with the test result in the BWR environment, and Figure E-3.3.2-10 shows the same comparison in the PWR environment, respectively. In simulated BWR environment where the environmental effect was originally small and test data were largely scattered, the data had large dispersion and were at conservative side at the long life region. In simulated PWR environment, alloy 600 data were slightly at the non-conservative side and alloy 690 data were slightly at the conservative side, but the difference between both materials was not significant. Therefore, if both data are treated as the same, it is judged that any special problem will not occur.

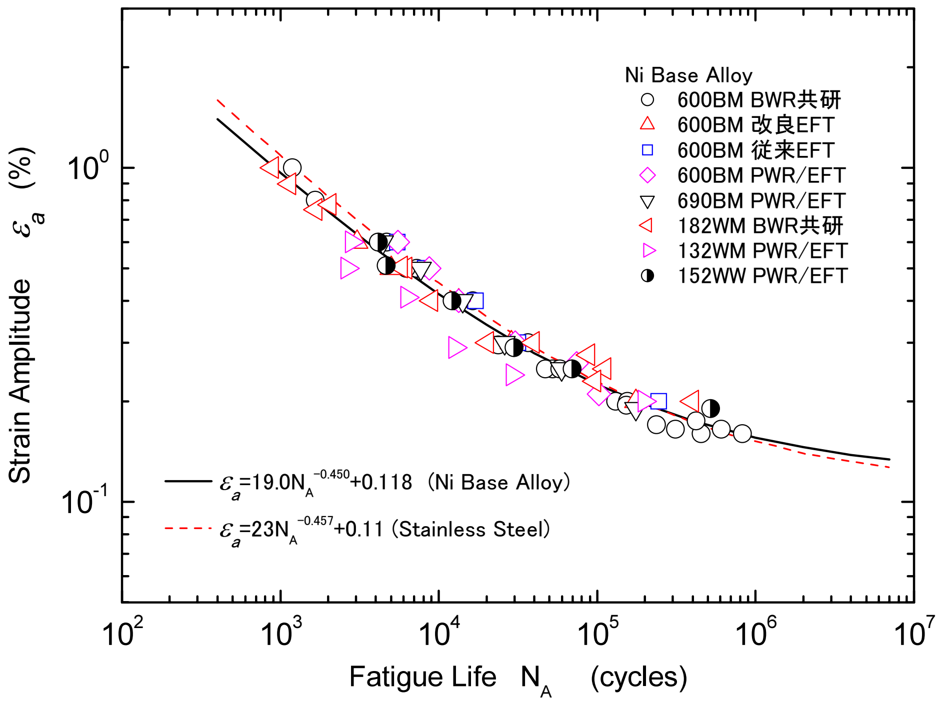


Figure E-3.3.3-1 Fatigue Curve for Nickel-Chromium-Iron Alloy in Air at Room Temperature (the same as 2004 Version)

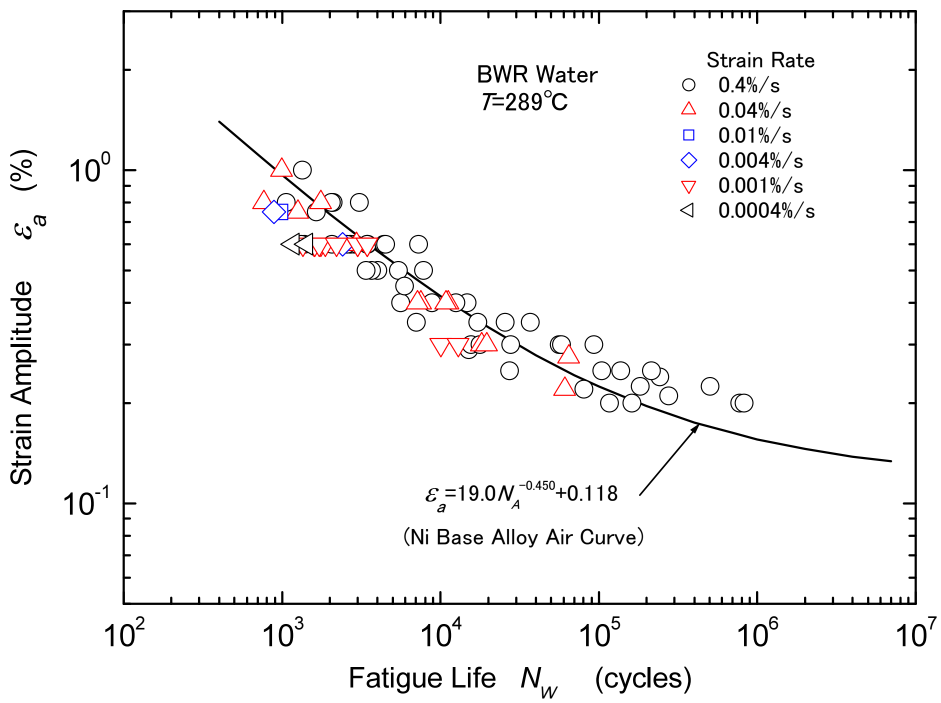


Figure E-3.3.3-2 Fatigue Date for Nickel-Chromium-Iron Alloy in Simulated BWR Environment

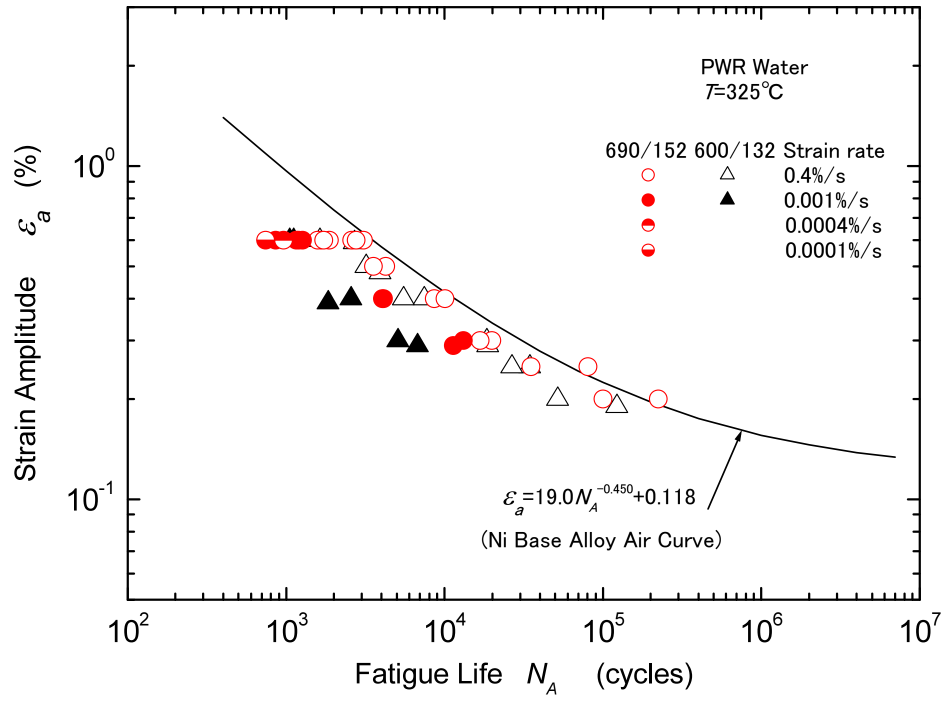


Figure E-3.3.3-3 Fatigue Date for Nickel-Chromium-Iron Alloy in Simulated PWR Environment

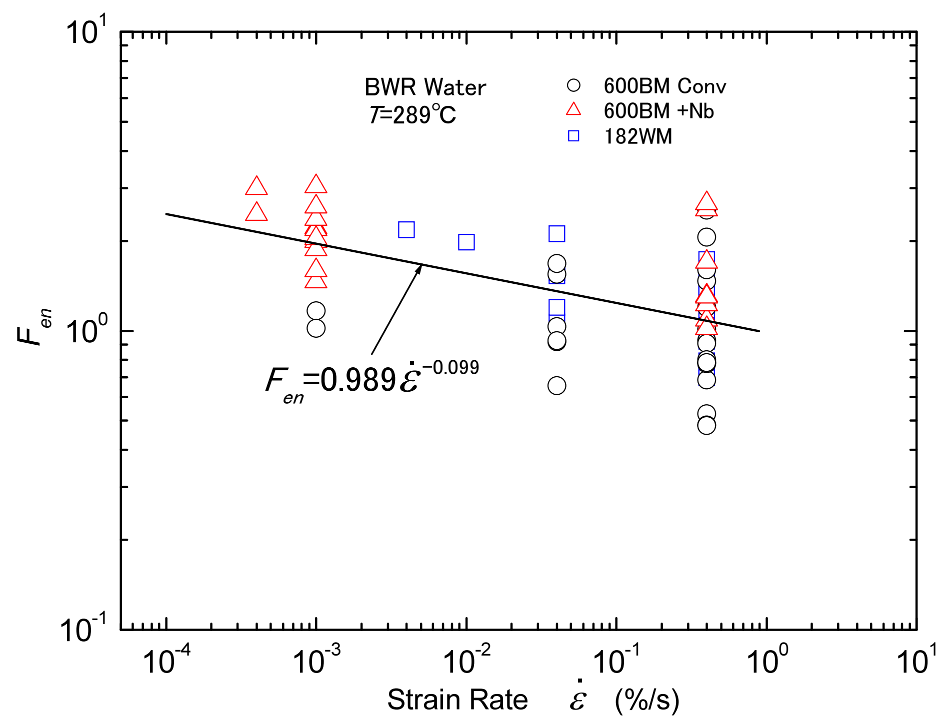


Figure E-3.3.3-4 Relation between F_{en} and Strain Rate for Nickel-Chromium-Iron Alloy in Simulated BWR Environment

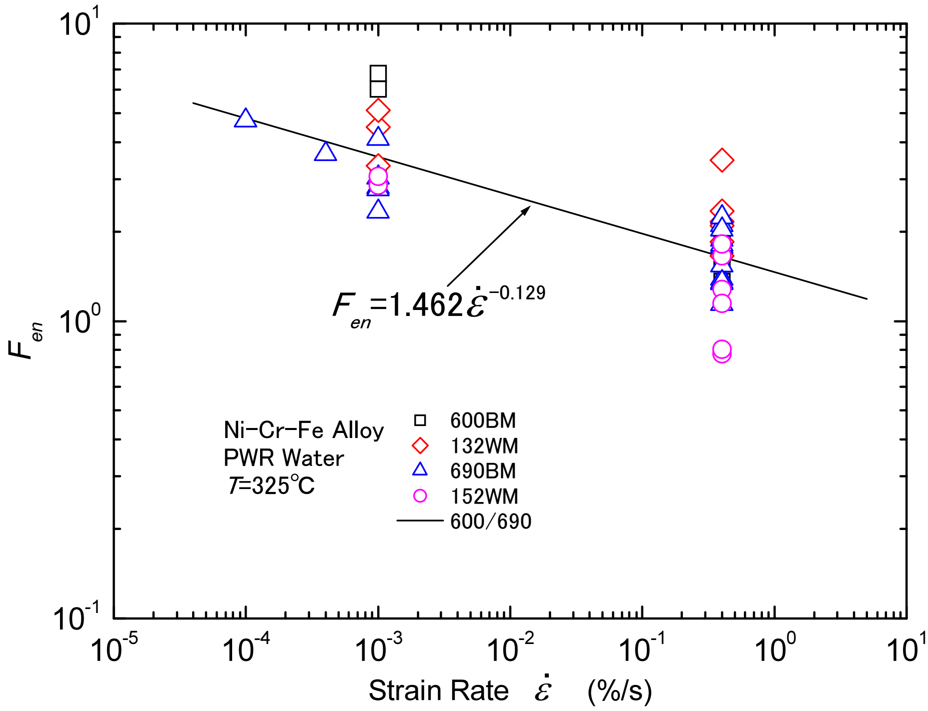


Figure E-3.3.3-5 Relation between F_{en} and Strain Rate for Nickel-Chromium-Iron Alloy in Simulated PWR Environment

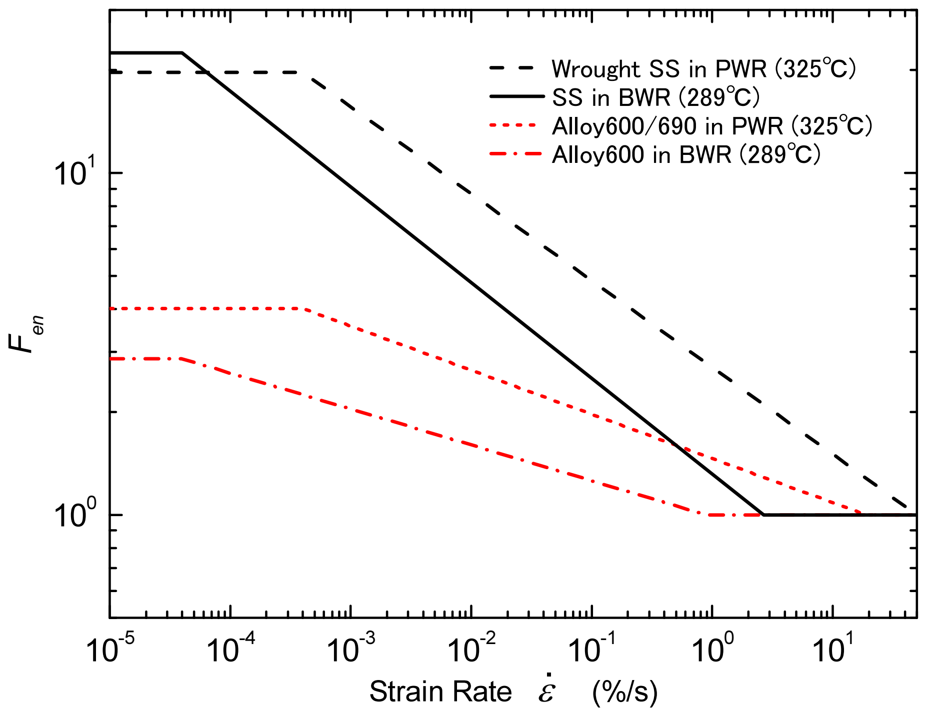


Figure E-3.3.3-6 Relation between F_{en} and Strain Rate for Nickel-Chromium-Iron Alloy in Simulated LWR Environment (Comparison with Stanless Steel)

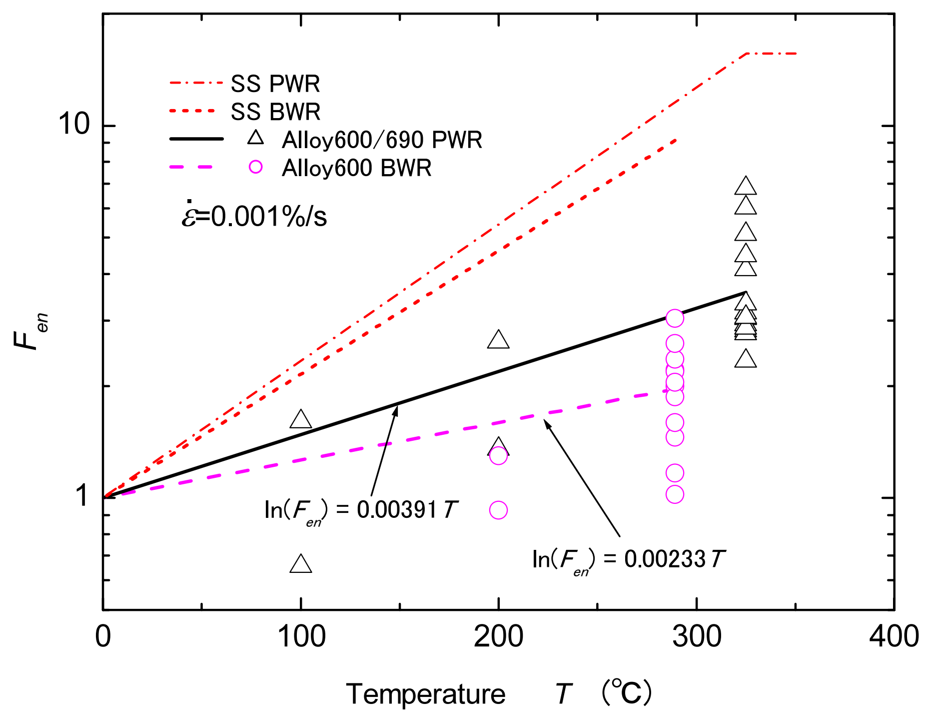


Figure E-3.3.3-7 Relation between F_{en} and Temperature for Nickel-chromium-iron Alloy in simulated LWR Environment (Comparison with Stainless Steel)

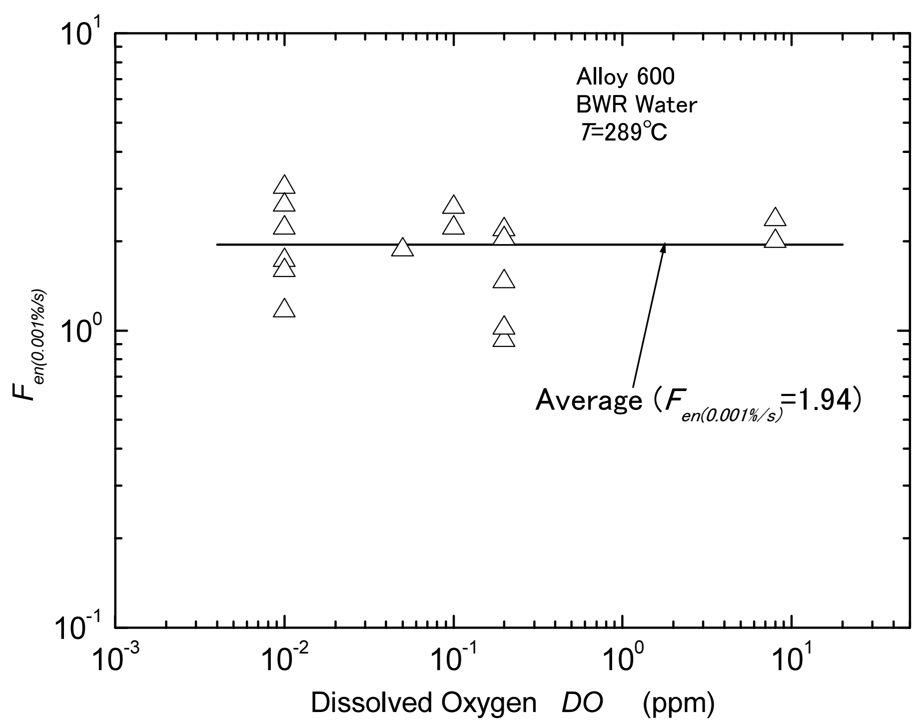


Figure E-3.3.3-8 Relation between F_{en} and Dissolved Oxygen Concentration for Nickel-chromium-iron Alloy in Simulated BWR Environment

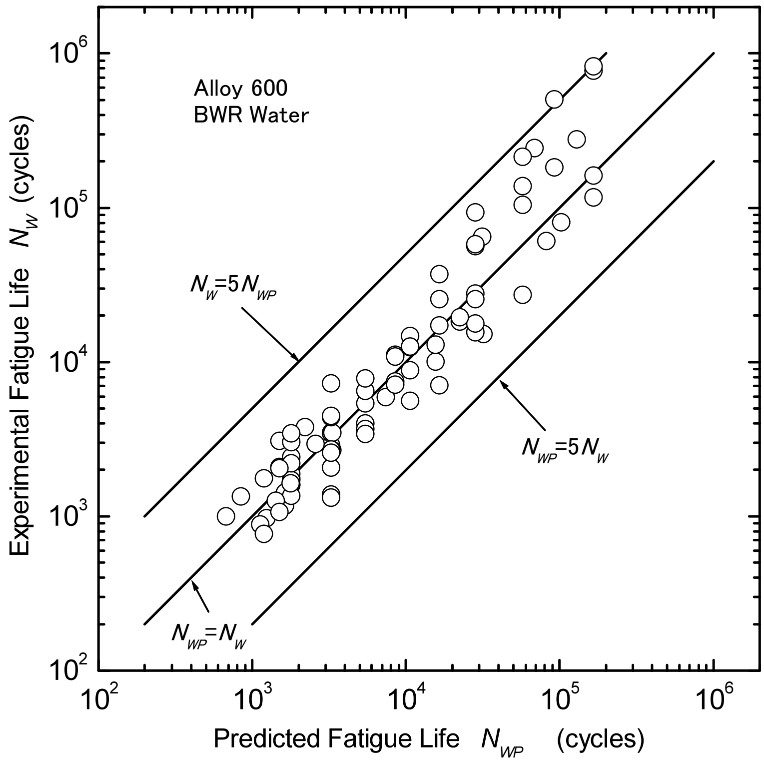


Figure E-3.3.3-9 Relation between Experimental and Predicted values of Fatigue Life for Nickel-Chromium-Iron Alloy in Simulated BWR Environment

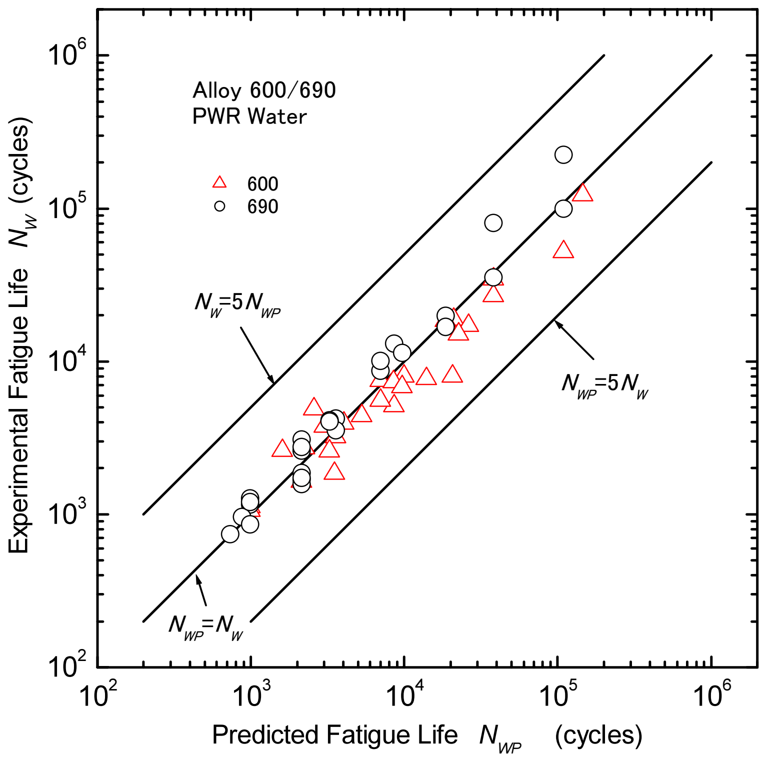


Figure E-3.3.3-10 Relation between Experimental and Predicted values of Fatigue Life for Nickel-Chromium-Iron Alloy in Simulated PWR Environment

Table E-3.1-1 Comparison of Equations to Calculate F_{en} for Carbon and Low-Alloy Steels

ANL model (NUREG/CR6909)	JNES-SS-0503	JNES-SS-0701
Carbon and Low-alloy Steels	Carbon and Low-alloy Steels	Carbon and Low-alloy Steels
[Carbon Steel] $\ln(F_{en}) = 0.632 - 0.101 \times \dot{\varepsilon}^* S^* T^* O^*$ [Low-alloy Steel] $\ln(F_{en}) = 0.702 - 0.101 \times \dot{\varepsilon}^* S^* T^* O^*$ $\dot{\varepsilon}^* = 0$ ($\dot{\varepsilon} > 1.0\%/s$) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.001 \leq \dot{\varepsilon} \leq 1.0\%/s$) $\dot{\varepsilon}^* = \ln(0.001)$ ($\dot{\varepsilon} < 0.001\%/s$) $S^* = 0.001$ ($S \leq 0.001\%$) $S^* = S$ ($0.001 < S \leq 0.015\ \%$) $S^* = 0.015$ ($S > 0.015\%$) $T^* = 0$ ($T < 150°C$) $T^* = T - 150$ ($150 \leq T \leq 350°C$) $O^* = 0$ ($DO \leq 0.04$ ppm) $O^* = \ln(DO / 0.04)$ ($0.04 < DO \leq 0.5$ ppm) $O^* = \ln(12.5)$ ($DO > 0.5$ ppm) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.07\%$) [Ref.] Best Fit Curve for Fatigue life in Air Carbon Steel : $\ln(N_A) = 6.583 - 1.975 \ln(\varepsilon_a - 0.113)$ ($\varepsilon_a = 28.0\ N_A^{-0.506} + 0.113$) Low-alloy Steel : $\ln(N_A) = 6.449 - 1.808 \ln(\varepsilon_a - 0.151)$ ($\varepsilon_a = 35.4\ N_A^{-0.553} + 0.151$)	$\ln(F_{en}) = 0.00822(0.7721 - \dot{\varepsilon}^*) S^* T^* O^*$ $\dot{\varepsilon}^* = \ln(2.16)$ ($\dot{\varepsilon} > 2.16\%/s$) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.0004 \leq \dot{\varepsilon} \leq 2.16\%/s$) $\dot{\varepsilon}^* = \ln(0.0004)$ ($\dot{\varepsilon} < 0.0004\%/s$) $S^* = \ln(12.32) + 97.92 \times S$ $T^* = 0.03584 \times T$ ($T < 50°C$) $T^* = \ln(6)$ ($50 \leq T \leq 160°C$) $T^* = \ln(0.3977) + 0.01696 \times T$ ($T > 160°C$) $O^* = \ln(3.28)$ ($DO < 0.02$ ppm) $O^* = \ln(70.79) + 0.7853 \times \ln(DO)$ ($0.02 \leq DO \leq 0.7$ ppm) $O^* = \ln(53.5)$ ($DO > 0.7$ ppm) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.042\%$ or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air Carbon Steel : $\varepsilon_a = 25.71\ N_A^{-0.490} + 0.113$ Low-alloy Steel : $\varepsilon_a = 38.44\ N_A^{-0.562} + 0.155$	$\ln(F_{en}) = 0.00822(0.772 - \dot{\varepsilon}^*) S^* T^* O^*$ [If $DO \leq 0.7$ ppm] $\dot{\varepsilon}^* = \ln(2.16)$ ($\dot{\varepsilon} > 2.16\%/s$) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.0004 \leq \dot{\varepsilon} \leq 2.16\%/s$) $\dot{\varepsilon}^* = \ln(0.0004)$ ($\dot{\varepsilon} < 0.0004\%/s$) $S^* = \ln(12.32) + 97.92 \times S$ $T^* = 0.0358 \times T$ ($T < 50°C$) $T^* = \ln(6)$ ($50 \leq T \leq 160°C$) $T^* = \ln(0.398) + 0.0170 \times T$ ($T > 160°C$) $O^* = \ln(3.28)$ ($DO < 0.02$ ppm) $O^* = \ln(70.79) + 0.7853 \times \ln(DO)$ ($0.02 \leq DO \leq 0.7$ ppm) [If $DO > 0.7$ ppm] $\dot{\varepsilon}^* = \ln(2.16)$ ($\dot{\varepsilon} > 2.16\%/s$) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ ($0.0001 \leq \dot{\varepsilon} \leq 2.16\%/s$) $\dot{\varepsilon}^* = \ln(0.0001)$ ($\dot{\varepsilon} < 0.0001\%/s$) $S^* = \ln(12.32) + 97.92 \times S$ $T^* = 0.0358 \times T$ ($T < 50°C$) $T^* = \ln(6)$ ($50 \leq T \leq 160°C$) $T^* = \ln(0.398) + 0.0170 \times T$ ($T > 160°C$) $O^* = \ln(53.5)$ ($DO > 0.7$ ppm) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.042\%$ or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air Carbon Steel : same as on the left Low-alloy Steel : same as on the left

Table E-3.1-2 Comparison of Equations to Calculate Fen for Stainless Steels and Nickel-Chromium-Iron Alloys

ANL model (NUREG/CR6909)	JNES-SS-0503	JNES-SS-0701
Stainless Steels	Stainless Steels	Stainless Steels
$\ln(F_{en}) = 0.734 - \dot{\varepsilon}^* T^* O^*$ $\dot{\varepsilon}^* = 0$ ($\dot{\varepsilon} > 0.4$%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/0.4)$ ($0.0004 \leq \dot{\varepsilon} \leq 0.4$%/s) $\dot{\varepsilon}^* = \ln(0.0004/0.4)$ ($\dot{\varepsilon} < 0.0004$%/s) $T^* = 0$ (T<150°C) $T^* = (T-150)/175$ ($150 \leq T < 325$°C) $T^* = 1$ ($T \geq 325$°C) $O^* = 0.281$ (all DO levels) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.10$%) [Ref.] Best Fit Curve for Fatigue life in Air $\ln(N_A) = 6.891-1.920\ln(\varepsilon_a-0.112)$ ($\varepsilon_a=36.2\ N_A^{-0.521}+0.112$)	$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^*$ C=1.182 (BWR) C=3.910 (PWR) $\dot{\varepsilon}^* = \ln(3.26)$ (BWR : $\dot{\varepsilon}$>3.26%/s) $\dot{\varepsilon}^* = \ln(49.9)$ (PWR : $\dot{\varepsilon}$>49.9%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ (BWR exc. Cast: $0.0004 \leq \dot{\varepsilon} \leq 3.26$%/s) (BWR Cast: $0.00004 \leq \dot{\varepsilon} \leq 3.26$%/s) (PWR exc. Cast: $0.0004 \leq \dot{\varepsilon} \leq 49.9$%/s) (PWR Cast: $0.00004 \leq \dot{\varepsilon} \leq 49.9$%/s) $\dot{\varepsilon}^* = \ln(0.0004)$ (exc. Cast : $\dot{\varepsilon} < 0.0004$%/s) $\dot{\varepsilon}^* = \ln(0.00004)$ (Cast : $\dot{\varepsilon}$ <0.00004%/s) $T^* = 0.000813 \times T$ (BWR) $T^* = 0.000782 \times T$ (PWR : $T \leq 325$°C) $T^* = 0.254$ (PWR : T>325℃) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.11$% or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air $\varepsilon_a=23.0\ N_A^{-0.457}+0.11$	$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^*$ C = 0.992 (BWR) C = 3.910 (PWR) $\dot{\varepsilon}^* = \ln(2.69)$ (BWR: $\dot{\varepsilon}$ >2.69%/s) $\dot{\varepsilon}^* = \ln(49.9)$ (PWR: $\dot{\varepsilon}$ >49.9%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ (BWR : $0.00004 \leq \dot{\varepsilon} \leq 2.69$%/s) (PWR exc. Cast: $0.0004 \leq \dot{\varepsilon} \leq 49.9$%/s) (PWR Cast : $0.00004 \leq \dot{\varepsilon} \leq 49.9$%/s) $\dot{\varepsilon}^* = \ln(0.0004)$ (PWR exc. Cast : $\dot{\varepsilon} < 0.0004$%/s) $\dot{\varepsilon}^* = \ln(0.00004)$ (BWR : $\dot{\varepsilon}$ <0.00004%/s) (PWR Cast : $\dot{\varepsilon}$ <0.00004%/s) $T^* = 0.000969 \times T$ (BWR) $T^* = 0.000782 \times T$ (PWR: $T \leq 325$°C) $T^* = 0.254$ (PWR: T>325℃) $F_{en} = 1.0$ ($\varepsilon_a \leq 0.11$% or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air same as on the left
Nickel-Chromium-Iron Alloys	Nickel-Chromium-Iron Alloys	Nickel-Chromium-Iron Alloys
$\ln(F_{en}) = -\dot{\varepsilon}^* T^* O^*$ $\dot{\varepsilon}^* = 0$ ($\dot{\varepsilon} > 5.0$%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon}/5.0)$ ($0.0004 \leq \dot{\varepsilon} \leq 5.0$%/s) $\dot{\varepsilon}^* = \ln(0.0004/5.0)$ ($\dot{\varepsilon} < 0.0004$%/s) $T^* = T/325$ ($T < 325$°C) $T^* = 1$ ($T \geq 325$°C) $O^* = 0.09$ (NWC BWR water) $O^* = 0.16$ (PWR or HWC BWR water) [Ref.] Best Fit Curve for Fatigue life in Air same as Stainless Steels	$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^*$ C= 0.5878 (BWR) C= 3.262 (PWR) $\dot{\varepsilon}^* = \ln(1.80)$ (BWR : $\dot{\varepsilon}$ >1.80%/s) $\dot{\varepsilon}^* = \ln(26.1)$ (PWR : $\dot{\varepsilon}$ >26.1%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ (BWR: $0.0004 \leq \dot{\varepsilon} \leq 1.80$%/s) (PWR: $0.0004 \leq \dot{\varepsilon} \leq 26.1$%/s) $\dot{\varepsilon}^* = \ln(0.0004)$ ($\dot{\varepsilon} < 0.0004$%/s) $T^* = 0.000339 \times T$ (BWR) $T^* = 0.0004028 \times T$ (PWR) F_{en}=1.0 ($\varepsilon_a \leq 0.11$% or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air $\varepsilon_a=16.259\ N_A^{-0.4271}+0.1085$	$\ln(F_{en}) = (C - \dot{\varepsilon}^*) \times T^*$ C= -0.112 (BWR) C= 2.94 (PWR) $\dot{\varepsilon}^* = \ln(0.894)$ (BWR : $\dot{\varepsilon}$ >0.894%/s) $\dot{\varepsilon}^* = \ln(19.0)$ (PWR : $\dot{\varepsilon}$ >19.0%/s) $\dot{\varepsilon}^* = \ln(\dot{\varepsilon})$ (BWR: $0.00004 \leq \dot{\varepsilon} \leq 0.894$%/s) (PWR: $0.0004 \leq \dot{\varepsilon} \leq 19.0$%/s) $\dot{\varepsilon}^* = \ln(0.00004)$ (BWR: $\dot{\varepsilon}$ <0.00004%/s) $\dot{\varepsilon}^* = \ln(0.0004)$ (PWR: $\dot{\varepsilon}$ < 0.0004%/s) $T^* = 0.000343 \times T$ (BWR) $T^* = 0.000397 \times T$ (PWR) F_{en}=1.0 ($\varepsilon_a \leq 0.11$% or seismic loading) [Ref.] Best Fit Curve for Fatigue life in Air $\varepsilon_a=19.0\ N_A^{-0.450}+0.118$

Chapter 4 Methods to calculate Fen

4.1 Determination of Time Segments to be Evaluated

4.1.1 Determination of Each Parameter in the Transients

Section3.3 provides F_{en} in terms of constant values such as strain rate, temperature and dissolved oxygen concentration. However, during plant operating transients strain rate and temperatures are not constants and F_{en} is constantly changing. The environmental effect is a strong function of strain rate when strain rate is positive. So when evaluating fatigue at the point, it is necessary to identify all of the time segments where the strain is increasing (i.e. from ε_{min} to ε_{max}). The incremental strain range is divided into the appropriate number of incremental time segments and F_{en} is calculated for each time segment. In the simplified method, the incremental strain range is seen as one time segment during a transient while the detailed method divides the incremental strain range into several time segments.

(1) Strain rates

A number of two-steps change fatigue tests were performed to develop the method to evaluate change of the strain rate. As shown in Figure E-4.1-1, the strain waveform in the incremental process of strain rate was divided in two steps, and the strain rate was changed. The higher strain rate in the test was 0.4 %/s, and the lower strain rate was 0.004 %/s. Two steps of change from the higher to the lower strain rate and the reverse change were performed. The higher condition in the decreasing process of strain rate was constant. F_{en} may be calculated by the following three models:

① Mean strain rate model:

F_{en} is based on the average strain rate. F_{en} is calculated by the following equation for the two-speed gear testing

$$F_{en,asr} = ((\Delta\varepsilon_s + \Delta\varepsilon_f)/(\Delta t_s + \Delta t_f))^{-P} \quad \text{(E-4.1-1)}$$

Where, $P = (\ln(F_{en,s}) - \ln(F_{en,f}))/(\ln(\dot{\varepsilon}_f) - \ln(\dot{\varepsilon}_s))$

② Time based integral model:

F_{en} for individual stain rates weighted with the loading time is integrated. (The method, which was proposed by Mehta [25], can be expressed with equation E-4.1-2):

$$F_{en,tbi} = (1/t_{T,th}) \int_0^{t_{T,th}} \{F_{en}(t)\} \mathrm{d}t \quad \text{(E-4.1-2)}$$

Fen is calculated by the following equation in the two- speed fatigue test

$$F_{en,tbi} = (F_{en,s} \times \Delta t_s + F_{en,f} \times \Delta t_f)/(\Delta t_s + \Delta t_f) \quad \text{(E-4.1-3)}$$

③ Strain based integral model:

F_{en} for individual strain rates weighted with strain gains is integrated. (The method, which was proposed by Kishida et al. [26] and Higuchi et al. [27, 28] can be expressed with Equation E-4.1-4). This is called the modified rate approach.

$$F_{en,sbi} = \int_{\varepsilon_{min}}^{\varepsilon_{max}} \{F_{en}(\varepsilon')/(\varepsilon_{max} - \varepsilon_{min})\} d\varepsilon \qquad \text{(E-4.1-4)}$$

F_{en} is calculated by the following equation in the two-speed fatigue test.

$$F_{en,sbi} = (F_{en,s} \times \Delta\varepsilon_s + F_{en,f} \times \Delta\varepsilon_f)/(\Delta\varepsilon_s + \Delta\varepsilon_f) \qquad \text{(E-4.1-5)}$$

F_{en} is obtained by above three models using F_{en} for each of constant higher and lower strain rate in the two-speed fatigue test. The comparison of this result with the test result for carbon steel is shown in Figure E-4.1-2 [29, 30] and for stainless steel in Figure E-4.1-3 [29, 30].

The time based integral model did not correlate with the test results for either material. In particular, the calculated results for small changes in strain at lower strain rates are excessively conservative. The strain based integral model showed the best correlation with the test results although slightly conservative. The mean strain rate model was consistently conservative.

Considering the above results, it is concluded that:

- Calculation by the time based integral model is not suitable for evaluating F_{en},
- Results calculated using the mean strain rate model consistently provide conservative evaluations of F_{en},
- The strain based integral model is the most accurate of the three methods.

In detailed evaluation, the time segment is divided into several small time segments, and the method using the strain based integral model is used.

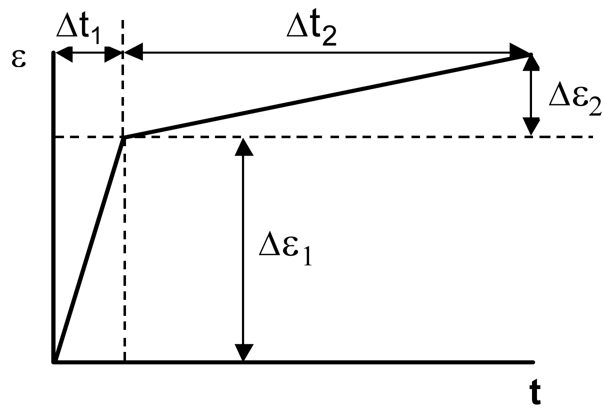


Figure E-4.1-1 Example of Strain Waveform Obtained by Two Steps Strain Rate Fatigue Tests

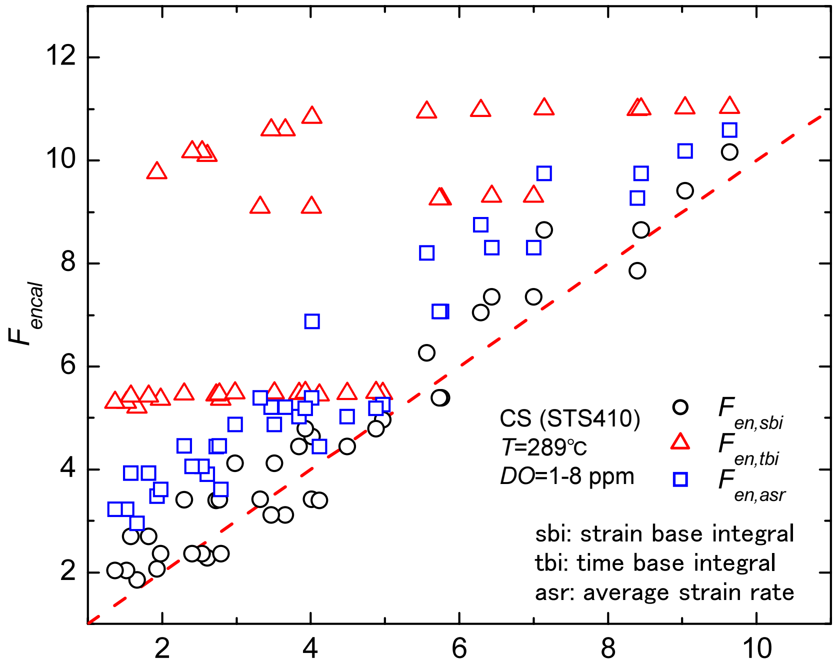


Figure E-4.1-2 Effects of Evaluation Techniques on the Relation between F_{encal}-F_{entest} in Two-Speed Fatigue Tests (Carbon Steel)

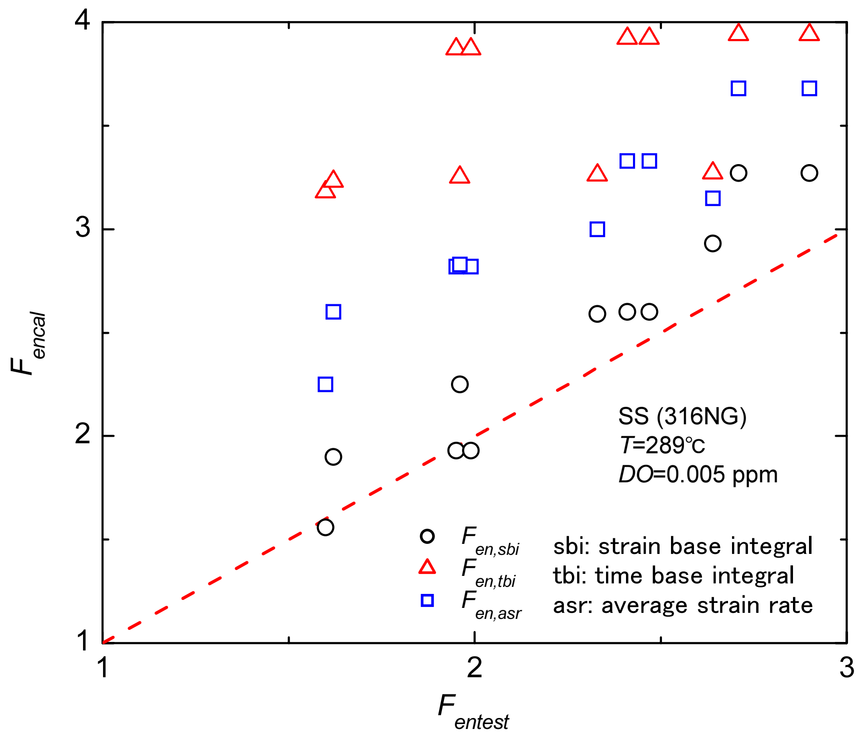


Figure E-4.1-3 Effects of Evaluation Techniques on the Relation between F_{encal}-F_{entest} in Two-Speed Fatigue Tests (Stainless Steel)

(2) Temperature

The modified rate approach method has been proposed for evaluating continuous temperature change like the transients occurring in actual plants. This method is basically similar to the strain based integral model used when the strain rate is changed. Temperature effects are incorporated into this model by including the mean or maximum temperature in each time segment [31~33]. This method can be expressed with equation E-4.1-6:

$$F_{en} = \sum_{i}^{n} \{F_{en}(\varepsilon'_i , T_i) \times \Delta\varepsilon_i / (\varepsilon_{max} - \varepsilon_{min})\} \quad \text{(E-4.1-6)}$$

Since the environmental effect is larger at higher temperatures, the maximum temperature in the time segment being evaluated is used for conservatism.

Use of the maximum temperature during the transient or the maximum service temperature in the component enables a conservative but more simplified evaluation.

(3) Dissolved oxygen concentration

Experimentally supporting data is not available for method to evaluate the effect of changes in the dissolved oxygen concentration. The environmental effects become larger as dissolved oxygen concentration is higher. Therefore, changes in the dissolved oxygen concentration are dealt with in the same way as temperature. That is, the maximum dissolved oxygen concentration in the relevant time segment is used to calculate F_{en}. Use of the maximum dissolved oxygen concentration in the stress cycle is conservative. Use of the maximum dissolved oxygen concentration during the transient or the maximum value in the component enables a conservative but more simplified evaluation.

(4) Sulfur content

The environmental effects become larger as the sulfur content in carbon and low-alloy steels becomes higher. Therefore, if a mill sheet for the relevant material is available, it should be used. If not available, the use of either the maximum sulfur content specified in the material purchase specifications or that in the Rules on Materials for Nuclear Facilities for the relevant material enables a simplified but conservative evaluation.

(5) Other influence factors

① Surface roughness

Regarding the effect of surface toughness on the fatigue life in high temperature water, the data have not been almost published. There are available data in Japan indicating that the fatigue life in high temperature water of the carbon steel specimens with rough surface was reduced below a half compared with the specimens with smooth surface, while ANL reported that the similar result was obtained for stainless steels. It is judged from these results that the effect of surface roughness (fatigue reduction) in high temperature water is practically equal compared with the effect in air. This effect of surface roughness is contained in the design factor of 2 in stress and 20 in life of the current fatigue design curve.

② Effects of dimension

The pipe test data performed in GE are available as those for the large sized test [29]. The life reduction in this test is significantly large. However, this test results are old and have uncertain points to calculate the stresses. Therefore it is difficult to find out the effect of dimension in high temperature water. Since any advantageous point for large size, in particular, is not recognized compared with the result in air, the effect of dimension is treated as equal to in air. The effect of dimension is contained in the design factor of 2 in stress and 20 in life of the current fatigue design curve.

4.1.2 Calculation of F_{en}

In conducting fatigue evaluations, the environmental effects can be estimated by calculating the changes in the strain rate and temperature from the evaluations based on the changes of temperature and stress over time during a transient. However, the evaluation to determine the changes in the strain rate over time generally involves a complicated procedure. In this regard, three options are provided. For example, for the part where the cumulative fatigue usage factor without the environmental effect is known and small, a simplified method can verify the factor subject to the environmental effect to be below one (1).

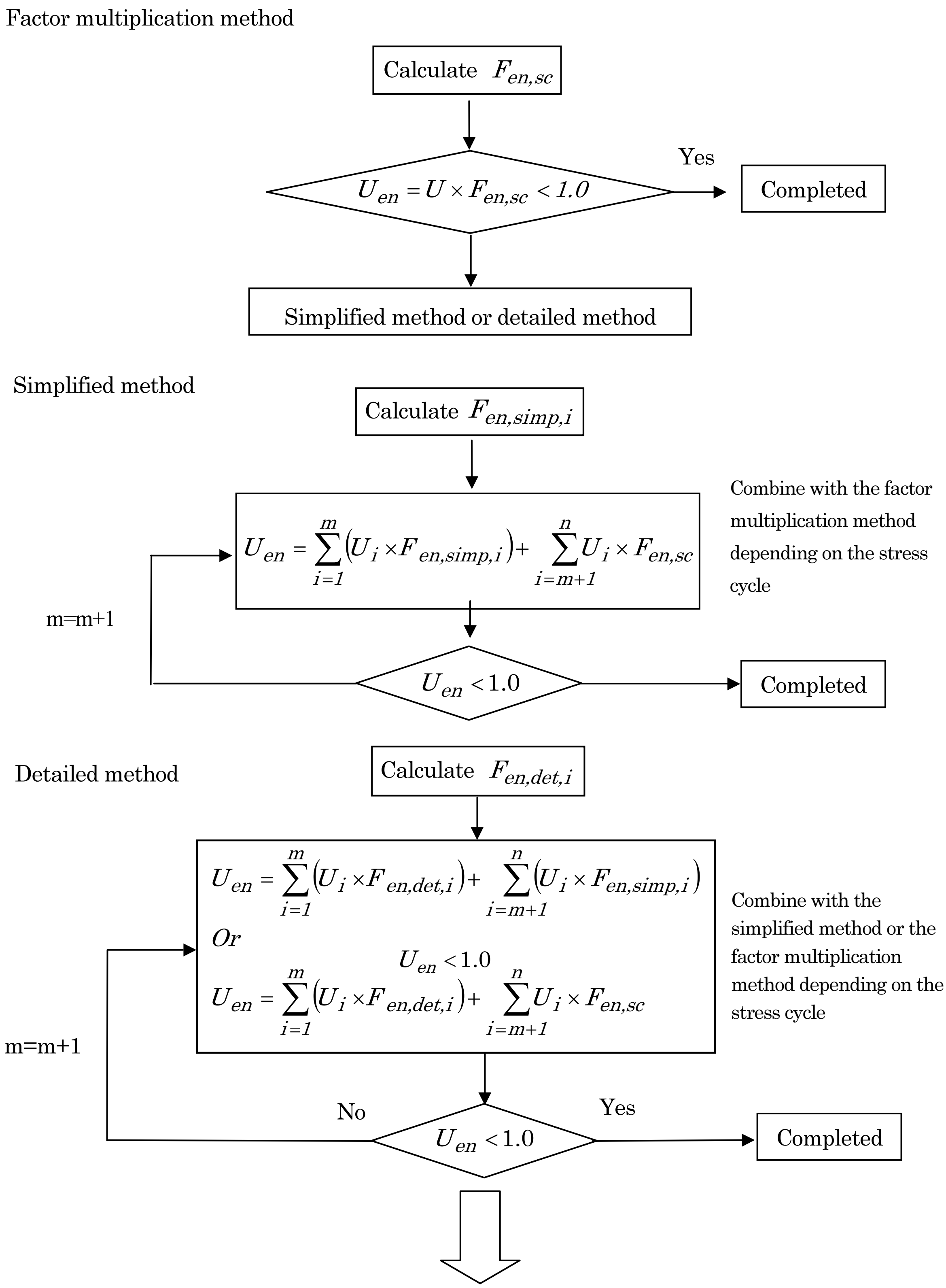
The significant environmental effects on the strain rates are generally complicated to calculate. Since there is an upper limit of the environmental effects, conservative evaluation results can be obtained by multiplying the cumulative fatigue usage factor by F_{en} indicating the environmental effects based on the maximum effects of strain rate. The factor multiplication method, which is described in Section 4.1.2 (1) was developed according to this concept.

Calculation of the strain rate for each time segment is complicated during the transients, because F_{en} is a function of temperature and strain rate. Use of the mean or average strain rate method as shown earlier produces a conservative result for F_{en}. Taking this into account, a simplified method which uses the mean strain rate, maximum temperature and maximum dissolved oxygen concentration during a transient is provided as described in Section 4.1.2 (2).

To calculate more accurate F_{en}, the detailed method divides the strain history during the transient into a numbers of time segments and calculates F_{en} for individual time segments using the temperature and strain rate for each time segment, is provided as described in section4.1.2 (3).

Any combination of the above methods will give conservative results, so it is permitted to apply these different methods to each section in a stress cycle as judged convenient by the analyst.

If the results of the factor multiplication method do not meet the allowable limit, the simplified method and then the detailed method may be used progressively to perform analyses in a more detailed manner. This evaluation sequence is shown in Figure E-4.1-4.



Consider possible application of other techniques if $U_{en} < 1.0$ is not achieved.

Figure E-4.1-4 Environmental Fatigue Evaluation Procedures

(1) Evaluation using the factor multiplication method

The factor multiplication method is applicable when cumulative fatigue usage factors without environmental effects are known for the application of the construction permit submitted during the plant construction phase. For example, the method may be applied to the fatigue evaluation conducted as a part of Plant Life Management (PLM) activities.

With this method, a value of F_{en} is determined for all operating conditions and is multiplied by the cumulative fatigue usage factor. The value of F_{en} is based on the maximum values of the applicable environmental factors, including strain rate, temperature, dissolved oxygen concentration, and material sulfur content.

$F_{en,sc}$ is based on the following environmental factors:

①Carbon and low-alloy steels and their welds in the BWR environment

The strain rate is set at 0.0004 %/s when $DO \leq 0.7$ ppm and at 0.0001 %/s when $DO > 0.7$ ppm. The maximum values of dissolved oxygen concentration, temperature and sulfur content in the relevant component are used.

② Carbon and low-alloy steels and their welds in the PWR secondary system environment

The strain rate is set at 0.0004 %/s and the dissolved oxygen concentration at 0.005 ppm (5 ppb). The maximum temperature and sulfur content in the relevant component are used.

③Austenitic Stainless steels and their welds

The strain rate is set at 0.00004 %/s in the BWR environment and at 0.0004 %/s in the PWR environment except for cast steel and 0.00004 %/s for cast steel in the PWR environment. There is no dependency on the dissolved oxygen concentration or sulfur content except for temperature. The maximum temperature in the relevant component is used.

④ Nickel-chromium-iron alloys and their welds

The strain rate is set at 0.00004 %/s in the BWR environment and at 0.0004 %/s in the PWR environment. The maximum temperature in the relevant component is used as a function of temperature only as well as that of stainless steel.

(2) Evaluation using the simplified method

As described in Explanation 4.1.1(1)①for a transient where strain rate changes, use of the mean strain rate for the transient being evaluated is conservative. The following assumptions apply when the Simplified Method is used.

Strain rate : mean strain rate over the full range of the evaluated transient $(=(\varepsilon_{max} - \varepsilon_{min}) / \Delta t)$

Temperature: maximum (or higher) temperature over the full range of the evaluated transient.

Dissolved oxygen concentration: maximum (or higher) dissolved oxygen concentration over the full range of the evaluated transient.

The simplified method calculates $F_{en,simp,A}$ and $F_{en,simp,B}$ for stress cycles resulting from two transients (A,B).

(3) Evaluation using the detailed method

The simplified method assumes the range in which strain continuously increases during each transient (ε_{min} to ε_{max}) as one time segment. On the other hand, the detailed method divides the range in which strain continuously increases into n-number of time segments and calculates F_{en} for each time segment. In spite of its complexity, the detailed method leads to a more realistic value for F_{en} . The accuracy of the calculation is improved as the number of incremental time segments increases. The strain rate, temperature and dissolved oxygen concentration in the incremental time segments are defined as follows:

Strain rate: mean strain rate over the incremental time segment ($\Delta\varepsilon / \Delta t$)

Temperature: maximum (or higher) temperature in the incremental time segment.

Dissolved oxygen concentration: maximum (or higher) dissolved oxygen concentration in the incremental time segment.

4.2 Fatigue Evaluation Method for Vessels

Different methods are specified for vessels, piping, pumps, valves and core support structures. Sections 4.2, 4.3, 4.4, 4.5 and 4.6 describe the method to evaluate the environmental effects for vessels, piping, pumps, valves and core support structures, respectively. Although the evaluation method for vessels generally becomes complicated compared with other components such as piping, the stresses can be calculated more accurately than those based on the evaluation method for piping with the large margin. In the JSME Design and Construction Rules for nuclear power reactor facilities, piping and so on are allowed to be designed and evaluated using the stress analysis methods for vessels. Similarly, the environmental effects for piping, pumps, valves and core support structures may be evaluated in the same manner as the vessel.

(1) Evaluation using the factor multiplication method

The cumulative fatigue usage factor with the most conservative environmental effect is determined for vessel. This value is obtained by multiplying the cumulative fatigue usage factor in air, U, for the relevant vessel part by $F_{en,sc,}$ which is calculated by the method described in 4.1.2 (1), considering the maximum environmental effect

(2) Evaluation using the simplified method

Strain and temperature histories during a transient for vessels have been determined by analyses. Since it is impossible to define the strain rate while strain rate is positive based on these data alone, a new method to define the strain rate is needed.

In the fatigue analysis, fatigue usage factor is evaluated by calculating the allowable stress cycles in terms of the difference between the maximum and minimum stress intensities. In order to determine the environmental fatigue life correction factor, $F_{en,}$ strains corresponding to the stress intensities are determined to define the strain histories, considering the history of difference in stress intensities. In this method, a positive or negative sign is not defined for the difference between maximum and minimum stress intensities. Accordingly, the sign for strains is not defined either. To determine whether strains are rising or declining, the signs of the principal stresses are applied to strains. That is, two principal stresses, which provide the basis of the stress intensity when peak stress intensities reach the ultimate value, are compared, and the sign of the principal stress with a larger contribution (i.e., larger absolute value) is defined as the sign of the stress intensity during the relevant transient. The same sign is also applied to strains.

Rather than tracing the sign of the principal stress with a larger contribution to define the sign of strains, $F_{en,simp,i}$ may also be calculated for positive and negative values of stress intensities for each transient, and the larger value with either positive or negative sign can be defined as the final $F_{en,simp,i}$. The cumulative fatigue usage factor with the environmental effect is calculated by the linear sum-up of the partial cumulative fatigue usage factor in air, U_i, for each stress cycle at the vessel part multiplied by $F_{en,simp,i}$, which can be calculated in accordance with the method described in 4.1.2 (2)

(3) Determination using detailed method

The incremental strain range during a transient determined by the same technique as that of the simplified method mentioned above is divided into several time segments. $F_{en,det.i}$ for each stress cycle are calculated by the technique described in 4.1.2 (3). Then, the cumulative fatigue usage factor with the environmental effect for a vessel is calculated by linear sum-up of the partial cumulative fatigue usage factor, $U_{i,}$ for each stress cycle multiplied by this $F_{en,det,i}$.

4.3 Fatigue Evaluation Method for Piping

The simplified method for piping calculates the environmental fatigue life correction factor, F_{en}, from the strain rate value for each transient, and evaluates the cumulative fatigue usage factor. This method is similar to the simplified method for the vessel, but it is different in terms of use of transient change time when calculating the strain rate. In the simplified method for piping, the strain rate of the peak stress intensity divided by each transient time was used.

4.4 Fatigue Evaluation Method for Pumps

The Design and Construction Rules for nuclear power reactor facilities by JSME describe that "the pump casing generally has complicated configurations, thus it is difficult to perform calculations of a simplified pump casing. In addition, three-dimensional analyses have technological difficulties at present. Therefore, in view of previous achievements, it seems to be valid to require the design by rules instead of the design by stress analysis which does not have established methods". Based on this concept, the required minimum thickness of the pressure boundary and the required configurations in terms of strength are defined and the fatigue evaluation of pumps is not conducted in the ordinary design.

However, when the stress analysis for pumps is conducted as for Class 1 vessels in accordance with PMB-3210 of the Design and Construction Rules for nuclear power reactor facilities by JSME, cumulative fatigue usage factor and strain histories for pumps may be obtained in the same way they are for Class 1 vessels. In such cases, the evaluation method for vessels can be applied to the environmental effects evaluation for pumps.

4.5 Fatigue Evaluation Method for Valves

The structural design of valves utilizes the simplified stress analysis method, which introduces stress indices, and generally does not obtain time histories of strain or stress. Therefore in the simplified evaluation of valves, strain rate is calculated by dividing strains, which are obtained from stresses calculated by the equation used in the fatigue evaluation specified by the Design and Construction Rules for nuclear power reactor facilities by JSME, by the time of the transient.

However, VVB-3360 and VVB-3370 of the Design and Construction Rules for nuclear power reactor facilities by JSME specify different equations to calculate stresses for the start up and shut down phase and other transients (e.g., step-wise transient) to be used in the fatigue evaluation of valves. Therefore, different equations to calculate F_{en} are defined for the start up and shut down phase and other transients. The start up and shut down phase includes leak tests.

VVB-3360 of the Design and Construction Rules for nuclear power reactor facilities by JSME has a special provision for valves in the start up and shut down phase. The provision specifies that the allowable number of cycles corresponding to peak stress amplitude on the surface of the valve body should be 2,000 or over. Since stresses generated during the start up and shut down phase are low in general, and if the cumulative fatigue usage factor has been calculated taking into account the environmental effects including the start up and shut down phase and other transients, the provision does not require an evaluation with environmental effects.

4.6 Fatigue Evaluation Method for Core Support Structures

The core support structures are subject to the same stress analysis and strength evaluation as for Class 1 vessels. Therefore, the evaluation methods for vessels may be applied.

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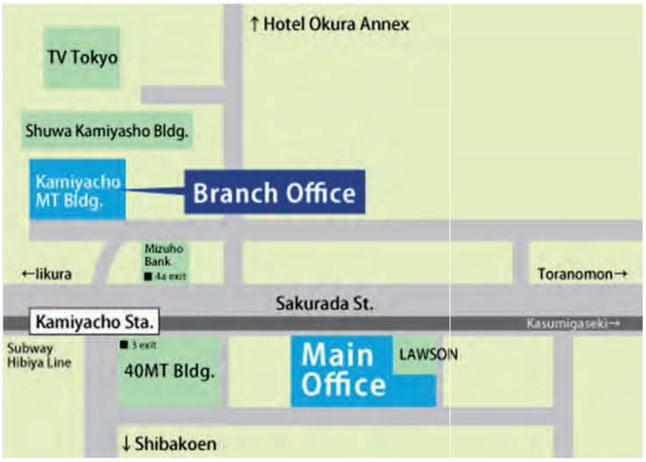

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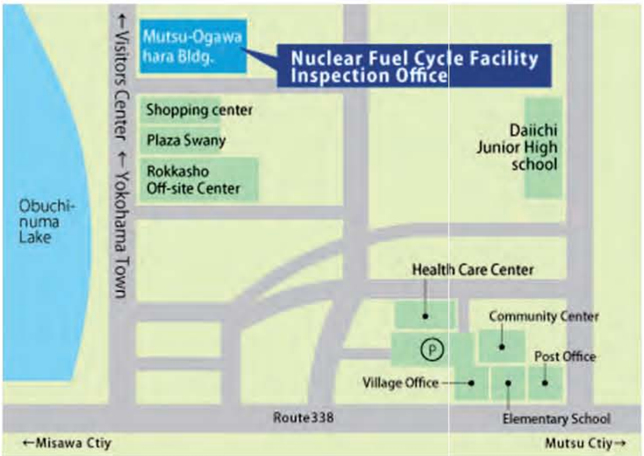

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