Summary of Environmental Fatigue Analysis Results for the US-APWR Class 1 Components

Non-Proprietary Version

July 2010

Revision History

Revision	Page	Description
0	All	Original Issue

MITSUBISHI HEAVY INDUSTRIES, LTD.
16-5, Konan 2-chome, Minato-ku
Tokyo 108-8215 Japan

Abstract

This report complies with the USNRC Regulatory Guide 1.207 for environmental fatigue analysis of ASME Class 1 components and has been prepared in support of the US-APWR DCD Review process.

The environmental fatigue analysis method used in this report is based on the method authorized in NUREG/CR-6909 which is consistent with the requirement of Regulatory Guide 1.207.

This report provides the environmental fatigue results for the US-APWR Class 1 components, including the Reactor Vessel (RV), Control Rod Drive Mechanism (CDRM), Steam Generator (SG), Pressurizer (PZR), Reactor Coolant Loop (RCL) Piping, and the Reactor Coolant Pump (RCP).

The environmental fatigue analyses for other Class 1 piping systems are documented in a separate report.

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List of Acronyms

The following list defines the acronyms used in this document.

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
CRDM	Control Rod Drive Mechanism
CUF	Cumulative Usage Factor
CVCS	Chemical and Volume Control System
DCD	Design Control Document
DO	Dissolved oxygen
DVI	Direct Vessel Injection
FEA	Finite Element Analysis
JSME	Japan Society of Mechanical Engineering
LAS	Low Alloy Steel
LH	Latch Housing
LWR	Light Water Reactor
PZR	Pressurizer
PWR	Pressurized Water Reactor
RCL	Reactor Coolant Loop
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
R.G or RG	Regulatory Guide
RT	Room Temperature
RTH	Rod Travel Housing
RV	Reactor Vessel
RVCH	Reactor Vessel Closure Head
SIS	Safety Injection System
SG	Steam Generator
SS	Stainless Steel
USNRC	U.S. Nuclear Regulatory Commission

1 INTRODUCTION

This report complies with the USNRC Regulatory Guide 1.207 (Reference 1) for environmental fatigue analysis of ASME Class 1 components (Reference 2) and has been prepared in support of the US-APWR DCD Review process.

The pressure boundary parts in contact with the primary coolant are evaluated for fatigue incorporating the life reduction effects of the light-water reactor (LWR) environment, particularly the water environment of the Pressurized Water Reactor (PWR).

The environmental fatigue analysis method used in this report determines fatigue usage factors using the ASME Code fatigue analysis procedure along with the new fatigue curves developed by the Argonne National Laboratory (ANL) and the environmental correction factor (F_{en}) described in NUREG/CR-6909 (References 1 and 3).

This report provides the environmental fatigue results for the US-APWR Class 1 components, including the Reactor Vessel (RV), Control Rod Drive Mechanisms (CRDM), Steam Generators (SG), Pressurizer (PZR), Reactor Coolant Loop (RCL) Piping, and the Reactor Coolant Pumps (RCP). The environmental fatigue analyses for other Class 1 piping systems are documented in a separate report (Reference 17).

2 SELECTION OF COMPONENTS AND PARTS FOR ANALYSES

The pressure boundary locations in contact with the primary coolant including regions protected by cladding are listed in Table 2-1 along with the cumulative usage factors in air derived from the stress analysis results for the US-APWR Class1 components (See Reference 11 to Reference 16). By using the results of the ASME fatigue analysis with new fatigue curve developed by ANL (hereafter referred to as NUREG design fatigue curve) it is possible to demonstrate that many areas in contact with the primary coolant easily meet the environmental fatigue limits. That is the purpose of this section.

Table 2-1 identifies the parts, their material, maximum alternating stress intensity used to enter design fatigue curve, Ke multiplier per NB-3228.5, maximum cumulative usage factor based on the ASME design fatigue curve in air, and cumulative usage factor based on the NUREG design fatigue curve in air (Reference 3) at the limiting locations exposed to the primary coolant.

Per Reference 4, parts with cladding are evaluated for environmental effects by applying the analytical method to the underlying low alloy steel material. Neglecting the cladding is consistent with the ASME Code fatigue procedure.

NUREG/CR-6909, Appendix A (Reference 3) specifies an environmental correction factor F_{en}.
The nominal environmental correction factor $F_{en,nom}$ is defined as follows:

$$\ln\left(F_{en,nom}\right) = \ln\left(N_{air,RT}\right) - \ln\left(N_{water}\right)$$

Where:

$N_{air,RT}$ = Fatigue life (number of cycles) in air, at room temperature

N_{water} = Fatigue life (number of cycles) in water, at the service temperature

The factor ($F_{en,nom}$) for Carbon and Low-Alloy Steels, Austenitic Stainless Steels, and Ni-Cr-Fe Alloys are given in the following equations respectively from Reference 3:

For Low-Alloy Steels

$$F_{en,nom} = \exp\left(0.702 - 0.101\, S^*\, T^*\, O^*\, \dot{\varepsilon}^*\right)$$

A threshold value of 0.07% for strain amplitude for the Low-Alloy steel is defined. Thus,

$$F_{en,nom} = 1.0 \quad \text{for } \varepsilon_a \leq 0.07\%$$

For Austenitic Stainless Steels

$$F_{en\,nom} = \exp\left(0.734 - T^*\, O^*\, \dot{\varepsilon}^*\right)$$

For Ni-Cr-Fe Alloys

$$F_{en\ nom} = \mathbf{exp}\left(-T^* \ \dot{\varepsilon}^* \ O^*\right)$$

For austenitic stainless steels and Ni-Cr-Fe alloys, a threshold value of 0.1% for strain amplitude is defined. Thus,

$$F_{en,nom}=1 \text{ for } \varepsilon_a \leq 0.10\%$$

Where transformed sulfur content (S^*), transformed temperature (T^*), transformed dissolved oxygen (O^*) and transformed strain rate ($\dot{\varepsilon}^*$) are:

For low alloy steels

$S^*=0.001$	S $\leq$ 0.001 Wt.%
S^*=S	S $\leq$ 0.015 Wt.%
S^*=0.015	S > 0.015 Wt.%
T^*=0	T < 150°C
T^*=T-150	T=150 - 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
$\dot{\varepsilon}^*$=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

For austenitic stainless steels

T^*=0	T < 150°C
T^*=(T-150)/175	150 $\leq$ T < 325 °C
T^*=1	T $\geq$ 325 °C
$\dot{\varepsilon}^*$=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
O^*=0.281	All DO levels

For Ni-Cr-Fe alloys

T^*=T/325	T < 325°C
T^*=1	T $\geq$ 325 °C
$\dot{\varepsilon}^*$=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
O^*=0.16	PWR water

2.1 LOW ALLOY STEEL EVALUATION

2.2 AUSTENITIC STAINLESS STEELS & NI-CR-FE ALLOY EVALUATION

Table 2-1 Fatigue Results for the Limiting Locations exposed to Primary Coolant

Component & Part			Material Type	Max Salt' (ksi)	Ke	ASME (air) Max U[1)]	NUREG (air) Max U[2)]	Upper Bound F_{en} U[3)]	Detailed Analysis Needed[4)]
RV									
CRDM									
PZR									

Table 2-1 Fatigue Results for the Limiting Locations exposed to Primary Coolant

Component & Part		Material Type	Max Salt' (ksi)	Ke	ASME (air) Max U1)	NUREG (air) Max U2)	Upper Bound F_{en} U3)	Detailed Analysis Needed4)
SG								
RCL Piping								
RCP								

Figure 2.1-1 Location for Environmental Fatigue Evaluation for DVI Nozzle of RV

Figure 2.1-2 Location for Environmental Fatigue Evaluation for Spray Nozzle of PZR (109 degrees sector model)

Figure 2.1-3 Location for Environmental Fatigue Evaluation for Surge Nozzle of PZR (30 degrees sector model)

Figure 2.1-4 Location for Environmental Fatigue Evaluation for Charging Nozzle of RCL Piping

Figure 2.1-5 Location for Environmental Fatigue Evaluation for Accumulator Tank Nozzle of RCL Piping

Figure 2.1-6 Location for Environmental Fatigue Evaluation for Pump Casing Lugs of RCP

Figure 2.1-7 Location for Environmental Fatigue Evaluation for Discharge Nozzle of RCP

Figure 2.1-8 Location for Environmental Fatigue Evaluation for Diffuser Flange of RCP

3 SUMMARY OF RESULTS AND CONCLUSION

The fatigue evaluation is based on the US-APWR operating transients defined in the component design specifications for a plant-operating period of 60 years. The most limiting results for environmental fatigue for each component are listed in Table 3-1. None of the cumulative usage factors exceeds the allowable limit of 1.0.

From the results summarized in this report, it is concluded that the US-APWR Class 1 components satisfy the USNRC Regulatory Guide 1.207 requirements for environmental fatigue as well as the ASME Section III requirements for fatigue.

Table 3-1 Summary of Environmental Fatigue Results at the most Limiting Locations

Component	Location	Material	ASME Fatigue Usage in air U 1)	NUREG (LWR) Environmental Fatigue U_{en}
RV				
CRDM				
PZR				
SG				
RCL Piping				
RCP				

4 NOMENCLATURE

ε_a	Strain amplitude
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}^*$	Transformed strain rate
ε_R	Strain range
$\varepsilon_x, \varepsilon_y, \varepsilon_z$	Strain components
$\gamma_{xy}, \gamma_{yz}, \gamma_{zx}$	Shear strain components
E	Modulus of elasticity of the material
$F_{en,nom}$	Nominal environmental fatigue correction factor
$F_{en\ i}$	Environmental fatigue correction factor for "i" th stress cycle
K_e	S_a multiplier for fatigue (per ASME NB-3228.5)
ni	Specified number of cycle
Ni	Allowable number of stress cycles
O^*	Transformed dissolved oxygen
RT	Room temperature
S^*	Transformed sulfur content
T^*	Transformed temperature
S_a	Stress amplitude or Alternating stress that is used to enter design fatigue curve
S.I. or SI	Stress Intensity
Salt	Alternating stress intensity adjusted by an appropriate K_e multiplier
Salt'	Alternating stress intensity (Salt) adjusted by the modulus of elasticity ratio that is used to enter design fatigue curve.
Sp	Peak stress intensity range
U	Cumulative usage factor in air
U_i	Usage factor in air
U_{en}	Cumulative usage factor in LWR environment
$U_{en\ i}$	Usage factor in LWR environment

5 ASSUMPTION AND OPEN ITEMS

5.1 ASSUMPTION

When the cumulative environmental usage factor based on Equation A.20 of NUREG/CR-6909 exceeds the allowable, usage factors were re-calculated based on total strain by elastic-plastic analysis and added to the remaining elastically calculated usage factors. This assumption is reasonable, since in all cases, such plasticity is a local condition that does not produce a significant change in the load path during plastic behavior. Elastic-plastic analysis is permitted for fatigue evaluations in ASME NB-3228.4.This assumption was applied for the RCL Piping Charging Nozzle and the RCP Diffuser Flange environmental fatigue evaluations.

5.2 OPEN ITEMS

There are no open items.

6 ACCEPTANCE CRITERIA

The usage factors are calculated based on the ASME procedure with the NUREG design fatigue curves, provided in NUREG/CR-6909, Appendix A, Figures A.1, A.2, and A.3 (Reference 3). Theses usage factors are multiplied by F_{en} to obtain the cumulative usage factor in the LWR environment. The cumulative usage factor in the LWR environment U_{en} is not permitted to exceed the limit of 1.0.

$$U_{en} = U_1 \cdot F_{en,1} + U_2 \cdot F_{en,2} + U_3 \cdot F_{en,3} + U_i \cdot F_{en,i} ..... + U_n \cdot F_{en,n} \leq 1.0$$

7 CALCULATION

7.1 GENERAL METHODOLOGY

Figure 7.1-1 Environmental Fatigue Analysis Flow

7.1.1 F_{EN} Calculation

1) The modified rate approach is expressed in the following formula.

$$F_{en} = \sum_{k=1}^{n} F_{en,nom,k}\left(\dot{\varepsilon}_k, T_k\right)\frac{\Delta\varepsilon_k}{\varepsilon_{\max} - \varepsilon_{\min}}$$ …………… [Eq. (30) of NUREG/CR-6909]

Because environmental effects on fatigue life occur primarily during the tensile loading cycle (i.e., increasing strain portion), these calculations are performed only for the increasing strain portion of the paired strain range.

Where

n	:	Total number of strain increments
k	:	Subscript for the k-th increment
$F_{en,nom,k}\left(\dot{\varepsilon}_k, T_k\right)$	:	Nominal correction factor for the k-th increment
$\dot{\varepsilon}_k$	:	Strain rate for the k-th increment
T_k	:	Temperature for the k-th increment
$\Delta\varepsilon_k$	:	Increment of strain (%) for the k-th increment
$\varepsilon_{\max}$ $\varepsilon_{\min}$	:	Maximum, minimum strain (%) for the integration range

2) F_{en} for transient pair A-B (Reference 9)

$$F_{en,i} = \frac{F_{en}^{A}\left(\varepsilon_{\max}^{A} - \varepsilon_{\min}^{A}\right) + F_{en}^{B}\left(\varepsilon_{\max}^{B} - \varepsilon_{\min}^{B}\right)}{\left(\varepsilon_{mx}^{A} - \varepsilon_{\min}^{A}\right) + \left(\varepsilon_{\max}^{B} - \varepsilon_{\min}^{B}\right)}$$

Where

$F_{en,i}$	: Environmental correction factor for i-th stress cycle or transient pair
F_{en}^{A}	: F_{en} for Transient A calculated by Eq. (30) of NUREG/CR-6909
F_{en}^{B}	: F_{en} for Transient B calculated by Eq. (30) of NUREG/CR-6909
$\varepsilon_{\max}^{A}$ $\varepsilon_{\min}^{A}$	: Maximum, minimum strain (%) for the integration range for transient A
$\varepsilon_{\max}^{B}$ $\varepsilon_{\min}^{B}$	: Maximum, minimum strain (%) for the integration range for transient B

3） Calculate the environmental usage factor using Equation A.20 of NUREG/CR-6909:

$$U_{en} = \sum_{1}^{n} U_i \cdot F_{en,i}$$ ……………………………. [Eq. A.20 of NUREG/CR-6909]

Where

U_{en}: Cumulative usage factor in LWR environment.

U_i: Usage factors in air with the NUREG design fatigue curve for i-th stress cycle or transient pair.

7.1.2 Fatigue Evaluation by Elastic-Plastic Analysis

The ASME Code NB-3228.3 and NB-3228.4 (c) state how to analyze fatigue using a total strain by plastic analysis.

NB-3228.3: *"Plastic analysis is a method of a structural analysis by which the structural behavior under given loads is computed by considering the actual material stress-strain relationship and stress redistribution, and it may include either strain hardening or change in geometry, or both."*

NB-3228.4 (c): "*In evaluating stresses for comparison with fatigue allowables, the numerically maximum principal total strain range shall be multiplied by one-half the modulus of elasticity of the material (Section II, Part D, Subpart 2, Tables TM) at the mean value of the temperature of the cycle."*

7.1.2.1 Principal Total Strain range

NB-3228.4 (c) defines the alternating stress (S_a) in terms of the numerically maximum principal total strain range (ε_R) for comparison with fatigue allowables:

$$S_a = \frac{1}{2} E \varepsilon_R$$

The principal strain ranges are derived from the difference in the components of strains for the stress cycle (transient pairings: A-B);

$$(\varepsilon_x)_R = (\varepsilon_x)_A - (\varepsilon_x)_B \qquad (\varepsilon_y)_R = (\varepsilon_y)_A - (\varepsilon_y)_B \qquad (\varepsilon_z)_R = (\varepsilon_z)_A - (\varepsilon_z)_B$$

$$(\gamma_{xy})_R = (\gamma_{xy})_A - (\gamma_{xy})_B \qquad (\gamma_{yz})_R = (\gamma_{yz})_A - (\gamma_{yz})_B \qquad (\gamma_{zx})_R = (\gamma_{zx})_A - (\gamma_{zx})_B$$

$$\begin{pmatrix} \varepsilon_{R1} \\ \varepsilon_{R2} \\ \varepsilon_{R3} \end{pmatrix} \Leftarrow \begin{pmatrix} (\varepsilon_x)_R & \frac{1}{2}(\gamma_{xy})_R & \frac{1}{2}(\gamma_{zx})_R \\ \frac{1}{2}(\gamma_{xy})_R & (\varepsilon_y)_R & \frac{1}{2}(\gamma_{yz})_R \\ \frac{1}{2}(\gamma_{zx})_R & \frac{1}{2}(\gamma_{yz})_R & (\varepsilon_z)_R \end{pmatrix}$$

The principal total strain range used for fatigue is the largest of the three principal strain ranges ($\varepsilon_{R1}, \varepsilon_{R2}, \varepsilon_{R3}$).

$$\varepsilon_R = \mathbf{max}(|\varepsilon_{R1}|, |\varepsilon_{R2}|, |\varepsilon_{R3}|)$$

7.1.2.2 Elastic-Plastic Analysis by Finite Element Code

The elastic-plastic analysis was performed using the ABAQUS finite element code which is capable of modeling elastic-plastic material behavior and geometric nonlinearities. Since the fatigue phenomenon is due to cyclic operation with stabilized local strain, the analysis was performed with no geometric nonlinearities. A linear kinematic hardening model with the bi-linear strain–stress relationship was used.

The elastic-plastic analysis for a full stress cycle consisted of analyzing two different transients that were combined by inserting appropriate load steps between the end of the first transient and the beginning of the second transient.

Since the structural action for fatigue requires shakedown, the elastic-plastic analysis was continued until shakedown was evident, then the total strain used in the fatigue calculation was taken from the last cycle of the analysis.

Reference10 indicates that a stabilized cyclic stress strain curve is appropriate for the material model in the elastic-plastic analysis and that a linear kinematic hardening model, which ABQUS supports, can be used for cyclic loading.

7.2 INPUT

7.2.1 Input for Environmental Fatigue Analysis based on Elastic Analysis

The stress and the temperature time histories at each location evaluated for environmental fatigue were taken from the outputs for Technical Reports of Stress Analysis Results (See References 11, 13, 14 and 16).

7.2.2 Input for Environmental Fatigue Analysis based on Elastic-Plastic Analysis

7.2.2.1 Material Properties

The material properties documented in Technical Reports for Stress Analysis Results were used in the calculations (See References 14 and 16).

7.2.2.2 Stress-Strain Curve for Elastic-Plastic Analysis

The bi-linear stress-strain curves are developed for Type 316 and Type 304 stainless steels and used for the elastic-plastic analyses.

8 COMPUTER PROGRAMS USED

Table 8-1 provides a brief description of each of the computer programs used.

Table 8-1 Computer Program Description

No.	Program Name	Version	Description
1	ABAQUS	6.7-1	ABAQUS is a general purpose finite element computer program that performs a wide range of linear and nonlinear engineering simulations
2	CLASS2D, CLASS3D	4	CLASS2D and CLASS3D are MHI programs for classifying the stresses for axisymmetric and 3D solid models and for coordinate transformation
3	EDITSTRS	4	EDITSTRS is an MHI program that creates input file for the stress evaluation programs
4	EVALSECO	5	EVALSECO is an MHI program that performs the primary plus secondary stress evaluation, the ASME fatigue evaluation, and creates an input file based on elastic analysis for the EVALIRAMJ program.
5	EVALSEFAV	5	EVALSEFAV is an MHI program that performs the primary plus secondary stress evaluation, the ASME fatigue evaluation, and creates an input file based on plastic analysis for the EVALIRAMJ program.
6	EVALIRAMJ	3	MHI program that performs the environmental fatigue evaluation

All these computer programs were verified and validated in compliance with the MHI quality assurance program. The computer programs were validated using one of the methods described below. Verification tests demonstrate the capability of the computer programs to produce valid results for test problems encompassing the range of permitted usage defined by the program documentation.

- Hand calculations
- Known solution for similar or standard problem
- Acceptable experimental test results
- Published analytical results
- Results from other similar verified programs

9 ENVIRONMENTAL FATIGUE ANALYSIS RESULTS

9.1 RV

9.1.1 DVI Nozzle of the RV

Table 9.1.1-1 Fatigue Usage based on ASME Design Fatigue Curve for RV DVI Nozzle (SS) at Location SCL-12-IN (see Fig. 2.1-1)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air) Ui

Table 9.1.1-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RV DVI Nozzle (SS) at Location SCL-12-IN

Transient [1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.2 PZR

9.2.1 Spray Line Nozzle of the PZR

Table 9.2.1-1 Fatigue Usage based on ASME Design Fatigue Curve for PZR Spray Line Nozzle (SS) at Location SCL-13-IN (see Fig. 2.1-2)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air) Ui

Table 9.2.1-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for PZR Spray Line Nozzle (SS) at Location SCL-13-IN

Transient [1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.2.2 Surge Nozzle of the PZR

Table 9.2.2-1 Fatigue Usage based on ASME Design Fatigue Curve for PZR Surge Nozzle (SS) at Location SCL-12-IN (see Fig. 2.1-3)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air) Ui

Table 9.2.2-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for PZR Surge Nozzle (SS) at Location SCL-12-IN

Transient 1)		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

Table 9.2.2-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for PZR Surge Nozzle (SS) at Location SCL-12-IN

Transient [1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.3 RCL PIPING

9.3.1 Charging Nozzle of the RCL Piping

Table 9.3.1-1 Fatigue Usage based on ASME Design Fatigue Curve for RCL Piping Charging Nozzle (SS) at Location SCL-01-A-IN (see Fig. 2.1-4)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air) Ui

Table 9.3.1-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RCL Piping Charging Nozzle (SS) at Location: SCL-01-A-IN

Transient [1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.3.2 Accumulator Tank Nozzle of the RCL Piping

Table 9.3.2-1 Fatigue Usage based on ASME Design Fatigue Curve for RCL Piping Accumulator Tank Nozzle (SS) at Location SCL-08-B-IN (see Fig. 2.1-5)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air) Ui

Table 9.3.2-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RCL Piping Accumulator Tank Nozzle (SS) at Location SCL-08-B-IN

Transient[1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.4 RCP

9.4.1 Pump Casing Lug of the RCP

Table 9.4.1-1 Fatigue Usage based on ASME Design Fatigue Curve for RCP Pump Casing Lug No.3 (SS) at Location A05F-IN (see Fig. 2.1-6)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air)Ui

Table 9.4.1-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RCP Pump Casing Lug No.3 (SS) at Location A05F-IN

Transient [1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.4.2 Discharge Nozzle of the RCP

Table 9.4.2-1 Fatigue Usage based on ASME Design Fatigue Curve for RCP Discharge Nozzle (SS) at Location H09B-IN (see Fig. 2.1-7)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air)Ui

Table 9.4.2-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RCP Discharge Nozzle (SS) at Location H09B-IN

Transient[1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

9.4.3 DIFFUSER FLANGE OF THE RCP

Table 9.4.3-1 Fatigue Usage based on ASME Design Fatigue Curve for RCP Diffuser Flange at Location DF08-IN (see Fig. 2.1-8)

Transient Pair[1)]		S_P ksi	K_e	Salt ksi	Salt' ksi	ni	ASME (air) Ni	ASME (air)Ui

Table 9.4.3-2 Fatigue Usage based on NUREG/CR-6909 and Environmental Fatigue Usage for RCP Diffuser Flange (SS) at Location DF08-IN

Transient[1)]		Salt' ksi	ni	NUREG (air) Ni	NUREG (air) Ui	F_{eni}	NUREG (LWR) U_{eni}
A	B						

10 REFERENCES

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16. "Summary of Stress Analysis Results for the US-APWR Reactor Coolant Loop Piping", MUAP-09010 Rev.1 May 2009.
17. "Summary of Environmental Fatigue Analysis Results for the US-APWR Reactor Coolant Loop Branch Piping", MUAP-10016 Rev.0 July 2010.

APPENDIX A: REVISED POINTS FROM TECHNICAL REPORTS

The environmental fatigue analysis is based on the fatigue analysis results which are shown in Technical Reports (Reference 11 to 16). However, in several parts, the fatigue analysis results are revised from Technical Reports. This appendix shows the revised results.

A.1 RV DVI nozzle

Table A1-1 DVI Nozzle Result Summary

Condition	Part	Stress-to-Allowable Ratio					Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress	Fatigue	
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Design							
Level A / Level B							
Level C							
Level D							

Table A1-1 DVI Nozzle Result Summary

Condition	Part	Stress-to-Allowable Ratio					Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress	Fatigue	
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Test							

A.2 RCL Piping Surge Nozzle

Table A2-1 Surge Nozzle Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue Usage Factor	Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q		
Design							
Level A/B							
Level C							
Level D							

A.3 RCP

CASING LUGS, DISCHARGE NOZZLE AND SUCTION NOZZLE

MAIN FLANGE AND No.1 & No.2 SEAL HOUSING

RESULTS FOR DIFFUSER FLANGE

HEAT EXCHANGER TUBING SEAL WATER INJECTION NOZZLE

A.3.1 RESUNLTS FOR CASING LUGS

Table A3-1-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_L	P_L+P_b
Design			
Level D			
Test			

Table A3-1-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_L+P_b+Q'
Level A/B		

Table A3-1-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-1-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-1-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A		

A.3.2 RESULTS FOR DISCHARGE NOZZLE

Table A3-2-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m or P_L	P_m+P_b
Design			
Level D			
Test			

Table A3-2-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-2-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-2-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-2-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A		

A.3.3 RESULTS FOR SUCTION NOZZLE

Table A3-3-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m or P_L	P_m+P_b
Design			
Level D			
Test			

Table A3-3-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-3-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-3-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-3-5 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A		

A.3.4 RESULTS FOR MAIN FLANGE

Table A3-4-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m or P_L	P_m+P_b
Design			
Level D			
Test			

Table A3-4-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-4-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-4-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-4-5 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Bearing Stress
Design		
Level A/B		
Level C		
Test		

A.3.5 RESULTS FOR No.1 & No.2 SEAL HOUSING

Table A3-5-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m	P_m+P_b
Design			
Level D			
Test			

Table A3-5-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-5-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-5-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-5-5 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Bearing Stress
Design		
Level A/B		
Level C		
Test		

A.3.6 RESULTS FOR DIFFUSER FLANGE

Table A3-6-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m	P_m+P_b
Design			
Level D			
Test			

Table A3-6-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q'
Level A/B		

Table A3-6-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-6-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

Table A3-6-5 Summary of Bearing Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Bearing Stress
Design		
Level A		
Level B		
Test		

Table A3-6-6 Summary of Thermal Ratchet evaluations

Condition	Part	Stress-to-Allowable Ratio
		Thermal Stress
Level A		

A.3.7 RESULTS FOR HEAT EXCHANGER TUBING

Table A3-7-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m or P_L	P_m+P_b
Design			
Level D			
Test			

Table A3-7-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-7-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-7-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

A.3.8 RESULTS FOR SEAL WATER INJECTION NOZZLE

Table A3-8-1 Summary of Primary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio	
		P_m or P_L	P_m+P_b
Design			
Level D			
Test			

Table A3-8-2 Summary of Primary plus Secondary Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		P_m+P_b+Q
Level A/B		

Table A3-8-3 Summary of Fatigue evaluations

Condition	Part	Usage Factor
Level A/B		

Table A3-8-4 Summary of Triaxial Stress evaluations

Condition	Part	Stress-to-Allowable Ratio
		Triaxial Stress
Design		
Test		

APPENDIX B: CORRESPONDENCE TABLES BETWEEN TRANSIENT NAMES AND MARKS

This appendix shows the correspondence between transient names and marks for each part which the environmental fatigue evaluations are shown in chapter 9.

B.1 RV

Table B1-1 Reactor Vessel Design Transients (1/2)

Mark	Transient		Remark
1A1	Plant heat-up (50°F/h)		
1B1	Plant cooldown (100°F/h)		Includes Transient for Loss of offsite power with natural circulation cooldown (10 times) and Safe shutdown (1 time)
1C1	Ramp load increase between 15% and 100% of full power (5% or full power per minute)		
1C2	Ramp load increase between 50% and 100% of full power (5% or full power per minute)		
1D1	Ramp load decrease between 15% and 100% of full power (5% or full power per minute)		
1D2	Ramp load decrease between 50% and 100% of full power (5% or full power per minute)		
1E1	Step load increase of 10% of full power		
1F1	Step load decrease of 10% of full power		
1G1	Large step load decrease with turbine bypass		
1H1, 1H2	Steady-state fluctuations and load regulation	i) Steady state fluctuations	
		ii) Load regulation	
1I1	Main feedwater cycling		
1J1	Refueling		
1K1	Ramp load increase between 0% and 15% of full power		
1L1	Ramp load decrease between 0% and 15% of full power		
1M1	RCP startup		
1N1	RCP shutdown		
1O1	Core lifetime extension		
1P1	Primary leakage test		
1Q1	Turbine roll test		
OBE	Operating-basis earthquake		
0ST	Flange opening / closing		

Table B1-1 Reactor Vessel Design Transients (2/2)

Mark	Transient		Remark
2A1	Loss of load		
2B1	Loss of offsite power		
2C1	Partial loss of reactor coolant flow		
2D1 to 2D4	Reactor trip from full power	i) With no inadvertent cooldown	
		ii) With cooldown and no safety injection	
		iii) With cooldown and safety injection	
2E1	Inadvertent RCS depressurization		
2F1	Control rod drop		
2G1	Inadvertent safeguards actuation		
2H1	Emergency feedwater cycling		
2I1	Cold over-pressure		
2J1	Excessive feedwater flow		Covered by Transient for reactor trip from full power ii)
2K1	Loss of offsite power with natural circulation cooldown		Covered by Transient for plant cooldown
2L1	Partial loss of emergency feedwater		
2M1	Safe Shutdown		

B.2 PZR

Table B2-1 Pressurizer Design Transients (1/2)

Mark	Transient		Remark
1A1 to 1A6	Plant heat-up		
1B1 to 1B9, 1BA to 1BC	Plant cooldown		
1C1	Ramp load increase between 15% and 100% of full power (5% of full power per minute)		
1C2	Ramp load increase between 50% and 100% of full power (5% of full power per minute)		
1D1	Ramp load decrease between 15% and 100% of full power (5% of full power per minute)		
1D2	Ramp load decrease between 50% and 100% of full power (5% of full power per minute)		
1E1	Step load increase of 10% of full power		
1F1	Step load decrease of 10% of full power		
1G1	Large step load decrease with turbine bypass		
1H1, 1H2	Steady-state fluctuation and load regulation	i)Steady-state fluctuation	
		ii)Load regulation	
1I1	Main feedwater cycling		
1M1	Reactor Coolant Pump startup		
1N1	Reactor Coolant Pump shutdown		
1P1	Primary leakage test		
1Q1	Turbine roll test		
1R1	Boron Concentration		

Table B2-1 Pressurizer Design Transients (2/2)

Mark	Transient		Remark
2A1	Loss of load		
2B1	Loss of offsite power		
2C1	Partial loss of reactor coolant flow		
2D1 to 2D4	RT from full power	i) With no inadvertent cooldown	
		ii) With cooldown and no safety injection	
		iii) With cooldown and safety injection	
2E1, 2E2	Inadvertent RCS depressurization	i) Umbrella case	
		ii) Inadvertent auxiliary spray	
2F1	Control rod drop		
2G1	Inadvertent safeguards actuation		
2H1	Emergency feedwater cycling		
2I1 to 2I3	Cold over-pressure	i) mass input	
		ii) heat input	
2J1	Excessive feedwater flow		Be covered with the transient of Reactor trip from full power ii)
2K1	Loss of offsite power with natural circulation cooldown -		Be covered with the transient of Plant cooldown
2L1	Partial loss of emergency feedwater		Use the figure of the transient of Loss of offsite power.
2M1	Safe shutdown		Be covered with the transient of Plant cooldown

B.3 RCL Piping

Table B3-1 RCL Piping Accumulator Tank Nozzle (1/2)

<table>
<tr><th>Level</th><th>Mark</th><th colspan="2">Transient</th></tr>
<tr><td rowspan="21">A</td><td>2U1</td><td colspan="2">Plant heat-up</td></tr>
<tr><td>2V1</td><td colspan="2">Plant cooldown</td></tr>
<tr><td>1C1</td><td colspan="2">Ramp load increase between 15% and 100% of full power
(5% of full power per minute)</td></tr>
<tr><td>1C2</td><td colspan="2">Ramp load increase between 50% and 100% of full power
(5% of full power per minute)</td></tr>
<tr><td>1D1</td><td colspan="2">Ramp load decrease between 15% and 100% of full power
(5% of full power per minute)</td></tr>
<tr><td>1D2</td><td colspan="2">Ramp load decrease between 50% and 100% of full power
(5% of full power per minute)</td></tr>
<tr><td>1E1</td><td colspan="2">Step load increase of 10% of full power</td></tr>
<tr><td>1F1</td><td colspan="2">Step load decrease of 10% of full power</td></tr>
<tr><td>1G1</td><td colspan="2">Large step load decrease with turbine bypass</td></tr>
<tr><td>1H1</td><td rowspan="2">Steady state fluctuation and load regulation</td><td>Steady-state fluctuation</td></tr>
<tr><td>1H2</td><td>Load regulation</td></tr>
<tr><td>1I1</td><td colspan="2">Main feedwater cycling</td></tr>
<tr><td>1J1</td><td colspan="2">Refueling</td></tr>
<tr><td>1K1</td><td colspan="2">Ramp load increase between 0 and 15% of full power</td></tr>
<tr><td>1L1</td><td colspan="2">Ramp load decrease between 0 and 15% of full power</td></tr>
<tr><td>1M1</td><td colspan="2">Reactor Coolant Pump startup</td></tr>
<tr><td>1N1</td><td colspan="2">Reactor Coolant Pump shutdown</td></tr>
<tr><td>1O1</td><td colspan="2">Core lifetime extension</td></tr>
<tr><td>1P1</td><td colspan="2">Primary leakage test</td></tr>
<tr><td>1Q1</td><td colspan="2">Turbine roll test</td></tr>
</table>

Table B3-1 RCL Piping Accumulator Tank Nozzle (2/2)

Level	Mark	Transient		
B	2A1	Loss of load		
	2B1	Loss of offsite power	w/o emergency feedwater	
	2B2		with emergency feedwater	
	2C1	Partial loss of reactor coolant flow	inactive loop	
	2C2		active loop	
	2D1	RT (reactor trip) from full power	i) with no inadvertent cooldown	
	2D2		ii) with cooldown and no safety injection	faulted loop
	2D3			intact loop
	2D4		iii) with cooldown and safety injection	
	2E1	Inadvertent RCS depressurization		
	2F1	Control rod drop	case A	
	2F2		case B	
	2G1	Inadvertent safeguards actuation		
	2H1	Emergency feedwater cycling		
	2I1	Cold over-pressure	mass input	
	2I2		heat input	active loop
	2I3			inactive loop
	2J1	Excessive feedwater flow		
	2K1	Loss of offsite power with natural circulation cooldown		
	2L1	Partial loss of emergency feedwater		
	2M1	Safe shutdown		
	2T1	Inadvertent operation of accumulator		

Table B3-2 Transients of RCL Piping Charging Nozzle(1/2)

Level	Mark	Transient	
A	1A1	Plant heat-up	
	1B1	Plant cooldown	
	1C1	Ramp load increase between 15% and 100% of full power (5% of full power per minute)	
	1C2	Ramp load increase between 50% and 100% of full power (5% of full power per minute)	
	1D1	Ramp load decrease between 15% and 100% of full power (5% of full power per minute)	
	1D2	Ramp load decrease between 50% and 100% of full power (5% of full power per minute)	
	1E1	Step load increase of 10% of full power	
	1F1	Step load decrease of 10% of full power	
	1G1	Large step load decrease with turbine bypass	
	1H1	Steady state fluctuation and load regulation	Steady-state fluctuation
	1H2		Load regulation
	1I1	Main feedwater cycling	
	1J1	Refueling	
	1K1	Ramp load increase between 0 and 15% of full power	
	1L1	Ramp load decrease between 0 and 15% of full power	
	1M1	Reactor Coolant Pump startup	
	1N1	Reactor Coolant Pump shutdown	
	1O1	Core lifetime extension	
	1P1	Primary leakage test	
	1Q1	Turbine roll test	

Table B3-2 Transients of RCL Piping Charging Nozzle(2/2)

Level	Mark	Transient		
B	2A1	Loss of load		
	2B1	Loss of offsite power	w/o emergency feedwater	
	2B2		with emergency feedwater	
	2C1	Partial loss of reactor coolant flow	inactive loop	
	2C2		active loop	
	2D1	RT (reactor trip) from full power	i) with no inadvertent cooldown	
	2D2		ii) with cooldown and no safety injection	faulted loop
	2D3			intact loop
	2D4		iii) with cooldown and safety injection	
	2E1	Inadvertent RCS depressurization		
	2F1	Control rod drop	case A	
	2F2		case B	
	2G1	Inadvertent safeguards actuation		
	2H1	Emergency feedwater cycling		
	2I1	Cold over-pressure	mass input	
	2I2		heat input	active loop
	2I3			inactive loop
	2J1	Excessive feedwater flow		
	2K1	Loss of offsite power with natural circulation cooldown		
	2L1	Partial loss of emergency feedwater		
	2M1	Safe shutdown		
	2N1 to 2N5	Letdown shut off and re-initiated		
	2O1, 2OA	Charging shut off and re-initiated (Maintenance of a regenerating heat exchanger)		
	2O2 to 2O4	Charging shut off and re-initiated (Safety injection)		
	2Q1 to 2Q9, 2QA to 2QJ	Charging flow 50% step increase and return		
	2R1	Letdown flow 50% step decrease and return		
	2S1	Letdown flow 100% step increase and return		

B.4 RCP

Table B4-1 Transients of Casing Lugs

Mark	Transient
1A1	Plant heat-up (50°F/Hr)
1B1	Plant cooldown (100°F/Hr)
1F1	Step load decrease of 10% of full power
1G1	Large step load decrease with turbine bypass
1J1	Refueling
1P1	Primary leakage test
1P2	Primary leakage test
1Q1	Turbine roll test
2A1	Loss of load
2B1	Loss of offsite power (with emergency feed water)
2B2	Loss of offsite power (without emergency feed water)
2D4	Reactor trip from full power (with cooldown and safety injection)
2E1	Inadvertent RCS depressurization
2F2	Control rod drop (with emergency feed water and ECCS)

Table B4-2 Transients of Discharge Nozzle

Mark	Transient
1A1	Plant heat-up (50°F/Hr)
1B1	Plant cooldown (100°F/Hr)
1G1	Large step load decrease with turbine bypass
1J1	Refueling
1P1	Primary leakage test
1P2	Primary leakage test
1Q1	Turbine roll test
2A1	Loss of load
2B1	Loss of offsite power (with emergency feed water)
2B2	Loss of offsite power (without emergency feed water)
2D4	Reactor trip from full power (with cooldown and safety injection)
2E1	Inadvertent RCS depressurization
2F2	Control rod drop (with emergency feed water and ECCS)
2G1	Inadvertent safeguard actuation
0ST1	Zero stress

Table B4-3 Transients of Diffuser Flange

Mark	Transient
1A1	Plant heat-up (50°F/Hr)
1B1	Plant cooldown (100°F/Hr)
1D1	Ramp load decrease between 15% and 100% of full power (5% of full power per minute)
1F1	Step load decrease of 10% of full power
1G1	Large step load decrease with turbine bypass
1J1	Refueling
1P1	Primary leakage test
1P2	Primary leakage test
1Q1	Turbine roll test
2A1	Loss of load
2B1	Loss of offsite power (with emergency feed water)
2B2	Loss of offsite power (without emergency feed water)
2D4	Reactor trip from full power (with cooldown and safety injection)
2E1	Inadvertent RCS depressurization
2F2	Control rod drop (with emergency feed water and ECCS)
2G1	Inadvertent safeguard actuation
2I1	Cold over pressure (mass input case)
2I2	Cold over pressure (heat input case in active loop)
2I3	Cold over pressure (heat input case in non-active loop)
0ST1	Zero stress
HYD001	Hydro test (3107 psig)
PRE001	Pre-load

APPENDIX C Environmental Fatigue Analysis Method Summary