



Materials Reliability Program: Environmentally Assisted Fatigue Handbook (MRP-483), Guidance for Service Life Extension and New Design

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T. Damiani

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3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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The following organizations, under contract to EPRI, prepared this report:

MPR Associates, Inc.
320 King St.
Alexandria, VA 22314

Principal Investigators
R. Keating
S. McKillop

Mitsubishi Heavy Industries, Ltd.
1-1-1, Wadasaki-cho, Hyogo-ku
Kobe, Japan, 652-8585

Principal Investigator
S. Asada

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ABSTRACT

Environmentally Assisted Fatigue (EAF) is a degradation mechanism that can impact materials exposed to light water reactor (LWR) environments in nuclear power plants (NPP). This degradation has been seen in materials when tested for fatigue life and exposed to LWR water chemistry conditions. The relationship between the life of a component and the magnitude and frequency of the cyclic loading is determined within structural codes through the fatigue-life curve, or S-N curve. Historically, the curves were determined by testing in air environments and adjustment factors were applied to account for a variety of effects not explicitly accounted for in the testing. One effect that was not originally explicitly accounted for in testing was exposure to LWR coolant during operation.

Initial EAF testing indicated that the effects of LWR environments were potentially more severe than the original adjustment factors and could significantly reduce the fatigue resistance of materials. Based on the conditions in an operating plant, the primary concern is the reduction in low cycle fatigue life of piping and pressure vessels. This reduction in fatigue life of pressure boundary components in LWR environments as compared to air is referred to as EAF.

This handbook is a compendium of research and regulatory documents, assessment methods, and strategies intended to aid utility engineers in implementing a systematic fatigue management program for which EAF must be considered. The handbook focuses on the U.S. and Japanese research and regulatory history, along with application of environmental penalty factors (F_{en}) in international structural safety codes for primary pressure boundary components such as pipes and pressure vessels. The content addresses EAF both for license renewals and new reactor designs. It also includes guidelines for how to address locations with high predicted EAF through refinements in the EAF analysis and/or in the underlying component fatigue analyses.

Keywords

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F_{en}

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PRIMARY AUDIENCE: Utility engineers, both domestic and international, responsible for fatigue management program implementation or fatigue analysis to support license renewal.

SECONDARY AUDIENCE: Design engineers for new plants and design engineering, maintenance, and in-service inspection program management in operating domestic and international nuclear power facilities.

KEY RESEARCH QUESTION

What are the industry recognized methods, tools, and guidance to address environmentally assisted fatigue (EAF) and how are those methods developed and proactively implemented in domestic and international comprehensive fatigue management programs at nuclear power facilities?

RESEARCH OVERVIEW

EPRI published the initial Fatigue Management Handbook (MRP-235) in 1994 and it has been revised several times to ensure that it provides the most up to date and pertinent content and reference documents available. Membership comments about the size and usability of the Fatigue Management Handbook have led to efforts to once more revise the document and provide guidance for specific fatigue mechanisms (i.e., thermal, vibration, low cycle fatigue) in separate handbooks. This handbook is focused on Environmentally Assisted Fatigue (EAF). The EAF handbook provides a compilation of terminology, bases, and reference documents that are needed to prioritize the methods and tools available to assess EAF of a component. Implementing the guidance in this handbook will result in a systematic fatigue management program that addresses environmental effects for operating nuclear plants or the development of sound fatigue management approaches related to environmental effects for new reactor designs.

KEY FINDINGS

- Section 1 of this handbook provides introductory information on the role of the environment on fatigue evaluations, including a primer on metal fatigue, the currently available design rules for general fatigue, and the significance of accommodating EAF in design.
- Section 2 contains the history of EAF, including relevant research, regulatory positions, and industry guidance, focused not only domestically but also on the significant contributions from Japan and other international stakeholders.
- Sections 3 and 4 address the testing completed (Section 3) to develop the EAF correlations (Section 4), commonly referred to as F_{en} . The F_{en} value serves as a correction for the reactor coolant environments and is applied to the in-air fatigue usage.
- Section 5 provides detailed strategies and approaches for managing EAF systematically, which allows users to identify the most resource efficient approaches to address EAF through either analytical methods or an active fatigue monitoring program.
- Section 6 summarizes the current ongoing research topics related to EAF to understand the near-term gaps in the analysis approaches and available analytical methods.

WHY THIS MATTERS

This handbook provides tools to help utilities proactively implement a comprehensive fatigue management program to address EAF. Such a program will enable utility engineers:

- to identify methods and strategies to manage specific components and locations susceptible to EAF,
- to implement a systematic approach to EAF that considers the available data, which may be different between existing and new nuclear power plants, and
- to select resource-conscious measures to balance analytical and/or experimental approaches versus monitoring strategies to address EAF.

Since the nuclear community is global, the EAF research has also been conducted on a global scale. The initial research for EAF began in Japan in the early 1980s and the research has been furthered through international collaboration to fully characterize EAF. A key goal of the research is to not only maintain technical accuracy in accounting for its effects, but to also ensure safe operations of current and new nuclear facilities. Documenting the methods and history of this extensive body of research is important to ensure future knowledge transfer and understanding of this complex degradation mechanism.

HOW TO APPLY RESULTS

Pursuing industry-wide standards and methods to evaluate EAF requires an understanding of the history, technical basis, and strategies for resource-conscious management of this degradation mechanism. This research can be applied to components by utilities looking for license amendment requests or for new LWR designs. In many cases, based on the developed threshold and detailed evaluation methods, it is possible to identify components susceptible to EAF and implement mitigation techniques to prevent failure. However, it is often not practical or possible to implement wide-scale programs evaluating and monitoring every location in a reactor coolant environment. While each situation is unique, the systematic approaches defined in this handbook are intended to assist utilities in identifying the most fruitful and cost-effective approach(es) to mitigate and/or minimize the impact of EAF in order to meet regulatory requirements for extended operations or new reactor designs.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- International research technical conferences (for example, International Cooperative Group on Environmentally Assisted Cracking [ICG-EAC], ASME Pressure Vessel and Piping Conference)
- Materials Reliability Program (MRP) and Boiling Water Reactor Vessel and Internals Program (BWRVIP) meetings
- Standards Development Organization Committee Meetings (for example, ASME Boiler and Pressure Vessel Code Committee meetings for Working Group on Environmental Fatigue Evaluation Methods [EFEM], where JSME regularly reports and collaborates on EAF methodologies and approaches).

EPRI CONTACTS: Thomas Damiani, Principal Technical Leader, tdamiani@epri.com

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ACRONYM AND VARIABLE DEFINITIONS

AMP	Aging Management Program
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
B&PV	Boiler and Pressure Vessel
BNCS	ASME Board of Nuclear Codes and Standards
BSI	British Standards Institute
BWR	Boiling Water Reactor
BWRVIP	Boiling Water Reactor Vessels and Internals Project
CUF	In-air Cumulative Usage Factor
CUF_{en}	LWR Environment Cumulative Usage Factor
CYS	Cyclic Yield Strength
DFC	Design Fatigue Curve
DO	Dissolved Oxygen (ppm)
EAF	Environmentally Assisted Fatigue
EDF	Électricité de France
EFD	Environmental Fatigue Data
EFEM	Environmental Fatigue Evaluation Method
EFT	Environmental Fatigue Testing
EPRI	Electric Power Research Institute
FAP	Fatigue Action Plan
F_{en}	Environmental Fatigue Multiplier
GALL	Generic Aging Lessons Learned
HCF	High Cycle Fatigue
HWC	Hydrogen Water Chemistry
ICPVT	International Conference on Pressure Vessel Technology
IGALL	International GALL Report
IGSCC	Intergranular Stress Corrosion Cracking
ISI	Inservice Inspection
JAPEIC	Japan Power Engineering and Inspection Corporation
JNES	Japan Nuclear Energy Safety Organization
JSME	Japan Society of Mechanical Engineering

JWES	Japan Welding Engineering Society
K_e	simplified elastic-plastic penalty factor
K_e^*	alternate simplified elastic-plastic penalty factor
LCF	Low Cycle Fatigue
LWR	Light Water Reactor
METI	Ministry of Economy, Trade and Industry
MITI	Ministry of International Trade and Industry
MRA	Modified Rate Approach
MRP	Materials Reliability Program
NISA	Nuclear and Industrial Safety Agency
NPP	Nuclear Power Plant
NRA	Nuclear Regulatory Authority
NRC	Nuclear Regulatory Commission
NWC	Normal Water Chemistry
PLM	Plant Life Management
ppm	Parts Per Million
PSR	Periodic Safety Review
PVRC	Pressure Vessel Research Council
PWR	Pressurized Water Reactor
S	Sulfur Content (wt%)
SDO	Standards Development Organization
SIA	Structural Integrity Associates
S-N	Stress or Strain Versus Number of Cycles (fatigue curve)
SNW	Strain-Life Weighted
SS	Stainless Steels
SWT	Smith-Watson-Topper
T	Temperature (°F or °C)
TENPES	Thermal and Nuclear Power Engineering Society
U_i	In-air Partial Fatigue Usage Factor
WEC	Westinghouse Electric Company
ε	strain (%)
$\dot{\varepsilon}$	strain rate (%/s)

CONTENTS

ABSTRACT	V
EXECUTIVE SUMMARY	VII
1 INTRODUCTION	1-1
1.1 Metal Fatigue Primer	1-2
1.2 Design Rules for Fatigue	1-4
2 HISTORY OF ENVIRONMENTALLY ASSISTED FATIGUE	2-1
2.1 U.S. History.....	2-1
2.1.1 U.S. NRC	2-1
2.1.2 U.S. Industry Efforts	2-4
2.2 Japanese History	2-5
3 SUMMARY OF FATIGUE DATA.....	3-1
3.1 Fatigue Strain vs. Life Behavior in LWR Environments	3-2
3.1.1 EAF on Carbon and Low Alloy Steels	3-2
3.1.1.1 Effect of Temperature on Carbon and Low Alloy Steel Fatigue	3-2
3.1.1.2 Effect of Dissolved Oxygen on Carbon and Low Alloy Steel Fatigue.....	3-3
3.1.1.3 Effect of Sulfur Content on Carbon and Low Alloy Steel Fatigue.....	3-3
3.1.2 EAF on Austenitic Stainless Steels	3-3
3.1.2.1 Effect of Temperature on Austenitic Stainless Steel Fatigue	3-4
3.1.2.2 Effect of Dissolved Oxygen on Austenitic Stainless Steel Fatigue.....	3-4
3.1.3 EAF on Nickel-Based Alloys	3-4
3.1.3.1 Effect of Temperature on Nickel-Based Alloy Fatigue.....	3-4
3.1.3.2 Effect of Dissolved Oxygen on Nickel-Based Alloy Fatigue	3-5
3.1.4 Impact of Strain Rate and Amplitude on Environmental Effects	3-5
3.1.5 Effect of LWR Environments on Corrosion Fatigue Summary	3-6
3.2 Fatigue Strain vs. Fatigue Life Behavior in Air.....	3-7

4 EAF CORRECTION FACTORS	4-1
4.1 NUREG/CR-6909, Revision 1 F_{en} Correlations.....	4-2
4.1.1 Carbon and Low-Alloy Steels.....	4-2
4.1.2 Austenitic Stainless Steels.....	4-3
4.1.3 Nickel-Based Alloy Steels	4-4
4.2 JNES-SS-0701/JSME S NF1-2009.....	4-4
4.2.1 Carbon and Low Alloy Steels and Associated Welds	4-5
4.2.2 Austenitic Stainless Steels and their Associated Welds	4-5
4.2.3 Nickel-Based Alloys and their Associated Welds.....	4-6
4.2.4 Threshold for Environmental Effects	4-7
 5 STRATEGY FOR IMPLEMENTATION OF ENVIRONMENTALLY ASSISTED FATIGUE	 5-1
5.1 Step 1: Collect EAF Evaluation Inputs.....	5-8
5.1.1 Current Licensing Basis Inputs for Existing Plants.....	5-8
5.1.2 EAF Inputs for New Designs	5-9
5.2 Step 2: Identify Limiting Locations for EAF Evaluation	5-9
5.2.1 Existing Plants.....	5-9
5.2.2 New Plants	5-10
5.3 Step 3: Refine F_{en}	5-13
5.3.1 Dissolved Oxygen Content.....	5-19
5.3.2 Sulfur in Carbon and Low-Alloy Steels.....	5-20
5.3.3 Metal Temperature.....	5-21
5.3.4 Strain Rate	5-22
5.3.5 Integrated Temperature and Strain Rate Approaches	5-27
5.3.5.1 Simplified Method.....	5-27
5.3.5.2 Modified Rate Approach (MRA)	5-29
5.4 Step 4: Reduce the CUF	5-31
5.4.1 Remove Conservatism in Simplified Elastic-Plastic Penalty Factor, K_e	5-31
5.4.2 Alternative Simplified Elastic-Plastic Penalty Factor, K_e	5-32
5.4.3 Thickness and Gradient Factors for Piping Fatigue Analyses	5-35
5.4.4 Perform Adjustments to Base Fatigue Analysis	5-36
5.4.4.1 Redefine Transient Groupings	5-36
5.4.4.2 Refinements to the Original Analysis Methodology.....	5-37
5.4.4.3 Use of Inelastic Analysis Approaches	5-37

5.5	Step 5: Identify Fatigue Management Strategies for EAF.....	5-38
5.5.1	Existing Plants.....	5-38
5.5.1.1	Fatigue Monitoring.....	5-38
5.5.1.2	Flaw Tolerance/Growth Evaluation	5-38
5.5.1.3	Repair or Replace Components	5-39
5.5.2	New Plants	5-39
6	EAF FUTURE RESEARCH	6-1
6.1	Refined Fatigue Curves	6-1
6.2	Advanced Analytical Approaches	6-2
6.2.1	Strain-Life Weighted Approach	6-2
6.2.2	Piping and Valve Strain Rate Refinements	6-2
6.2.3	Total Life	6-2
6.2.4	Surface Finish Effects	6-3
6.2.5	Fatigue Curves that directly account for Environmental Effects.....	6-4
6.3	Additional Laboratory Testing	6-4
6.3.1	EAF Component Testing.....	6-4
6.3.2	Multi-axial Fatigue Testing	6-4
6.3.3	Updated F_{en} Correlations for Stainless Steels.....	6-5
7	REFERENCES	7-1
A	SAMPLE PROBLEMS	A-1
A.1	Sample Problem 1 – Update existing CUF calculation to apply NUREG/CR-6909, Revision 1 Fatigue Curves (Stainless Steel).....	A-1
A.2	Sample Problem 2 - Applying CUF_{en} reduction steps to a Stainless Steel EAF evaluation	A-4
A.2.1	Step 1: Collect Design Inputs.....	A-4
A.2.2	Step 2: Bounding CUF_{en} Calculation and F_{en} Screening	A-5
A.2.3	Step 3: Refine F_{en}	A-5
A.2.4	Step 4: Refine in-air Fatigue Usage	A-8
A.3	Sample Problem 3 - Calculating Refined F_{en} Based on Average Temperature and Modified Rate Approach (Stainless Steel).....	A-9
A.3.1	Average Temperature Approach.....	A-9
A.3.2	Modified Rate Approach.....	A-9
B	F_{EN} EQUATIONS USED IN U.S. PLANT LICENSE RENEWAL APPLICATIONS.....	B-1

B.1	NUREG/CR-5704	B-1
B.2	NUREG/CR-6583	B-1
B.3	NUREG/CR-6909, Revision 0.....	B-2
B.3.1	Carbon and Low Alloy Steels	B-2
B.3.2	Austenitic Stainless Steels	B-3
B.3.3	Ni-Cr-Fe Alloys.....	B-3
C	JAPANESE METHODS FOR ADDRESSING EAF	C-1
C.1	TENPES Guideline	C-1
C.2	MITI Guideline	C-14
C.3	JNES-SS-1005	C-15
C.3.1	F_{en} expressions	C-15
C.3.2	EAF Evaluation Method (General)	C-18
C.3.3	EAF Evaluation Method for Vessels.....	C-21
C.3.4	EAF Evaluation Method for Piping	C-23
C.3.5	EAF Evaluation Method for Pumps	C-24
C.3.6	EAF Evaluation Method for Valves	C-24
C.3.7	Evaluation Method for Core Support Structures	C-24
C.3.8	EAF Tests in the EFT Project.....	C-24
C.4	JSME Environmental Fatigue Evaluation Method.....	C-50
C.4.1	2006 Edition (First Edition of JSME S NF1).....	C-50
C.4.2	2009 Edition	C-54
C.4.3	Future Edition.....	C-54
D	EPRI BWRVIA WATER CHEMISTRY DISCUSSION AND EXAMPLE.....	D-1
E	HISTORICAL EPRI REFERENCE LIST	E-1
F	STRATEGIES WHEN FATIGUE ANALYSIS IS NOT AVAILABLE	F-1
F.1	B31.1 Piping Analyses.....	F-1
F.2	Reactor Internals	F-1

LIST OF FIGURES

Figure 1-1 S-N Fatigue Data for Engineering Materials	1-3
Figure 1-2 S-N Fatigue Data for Engineering Materials	1-4
Figure 2-1 Historical Timeline of EAF in the U.S. Nuclear Industry	2-8
Figure 2-2 Relation Between Total Strain Amplitude and Fatigue Life for Carbon Steel Piping Material in Pure Water at 250°C and 8 ppm DO	2-10
Figure 2-3 Fatigue Test Equipment for Carbon Steel Piping Material in Pure Water at 250°C and 8 ppm DO	2-10
Figure 2-4 Relation Between Total Strain Amplitude and Fatigue Life for 304 Austenitic Stainless Steel in Pure Water at 300°C and 8 ppm DO	2-11
Figure 2-5 Fatigue Test Equipment for 304 Austenitic Stainless Steel in Pure Water at 300°C and 8 ppm DO	2-11
Figure 2-6 Fatigue Test Data for Carbon Steel in Various Test Conditions	2-12
Figure 2-7 Relation of Fatigue Life Ratio ($= N_{25(\text{water})}/N_{25(\text{air})}$) Fatigue Test Data for Carbon Steel in Various Test Conditions	2-12
Figure 2-8 Comparison of Strain Rate Dependency Obtained by Surface Observation and Fatigue Tests	2-13
Figure 2-9 Comparison of Temperature Dependency Obtained by Surface Observation and Fatigue Tests	2-13
Figure 3-1 Comparison of Carbon Steel Fatigue Design Curves in Air [1]	3-9
Figure 3-2 Comparison of Low-Alloy Steel Fatigue Design Curves in Air [1]	3-9
Figure 3-3 Comparison of Austenitic Stainless Steel and Nickel-Based Alloy Steel Fatigue Design Curves in Air [1]	3-10
Figure 5-1 Screening Strategy for Evaluating Environmentally Assisted Fatigue for Existing LWR Designs	5-3
Figure 5-2 Screening Strategy for Evaluating Environmentally Assisted Fatigue for New LWR Designs	5-4
Figure 5-3 Strategies to Refine F_{en}	5-5
Figure 5-4 Strategies to Refine CUF	5-6
Figure 5-5 Strategies for Fatigue Management	5-7
Figure 5-6 F_{en} vs Temperature for Carbon and Low Alloy Steels, <0.04 ppm DO	5-14
Figure 5-7 F_{en} vs Temperature for Carbon and Low Alloy Steels, 0.3 ppm DO	5-15
Figure 5-8 F_{en} vs Temperature for Carbon and Low Alloy Steel, >0.5 ppm DO	5-16
Figure 5-9 F_{en} vs Temperature for Austenitic Stainless Steel, <0.1 ppm DO	5-17
Figure 5-10 F_{en} vs Temperature for Nickel-based Alloy Steels, <0.1 ppm DO	5-18

Figure 5-11 Correlation of F_{en} based on Strain Rate for Carbon and Low Alloy Steels with $DO < 0.04$ ppm and Sulfur Content > 0.015	5-24
Figure 5-12 Correlation of F_{en} based on Strain Rate for Austenitic Stainless Steel with $DO < 0.1$ ppm.....	5-25
Figure 5-13 Correlation of F_{en} based on Strain Rate for Nickel-based Alloy Steel with DO < 0.1 ppm	5-26
Figure 5-14 Determination of Strain Rate for the Simplified Method	5-28
Figure 5-15 Determination of Strain Rate for the Simplified Method for Overlapping Strain Ranges	5-28
Figure 5-16 Determination of Strain Rate for the MRA	5-30
Figure 5-17 Determination of Strain Rate for the MRA for Overlapping Strain Ranges.....	5-30
Figure 5-18 K_e^* for Carbon Steel	5-33
Figure 5-19 K_e^* for Low Alloy Steel.....	5-34
Figure 5-20 K_e^* for Stainless Steel.....	5-35
Figure A-1 Fatigue Curve Comparison: ASME 2004 Edition vs. NUREG/CR-6909, Revision 1	A-3
Figure A-2. Time History Temperature and Stress Profiles for Stainless Steel Component.....	A-10
Figure C-1 Determining the Sign of the Stress Difference	C-12
Figure C-2 Determining Strain Rate for the Simplified Method.....	C-12
Figure C-3 Determining Strain Rate and F_{en} for the Detailed Method.....	C-13
Figure C-4 Monotonically Increasing Strain History (For the Startup Condition)	C-13
Figure C-5 Determining Strain Rate for the Simplified Method	C-22
Figure C-6 Determining Strain Rate and F_{en} for the Detailed Method.....	C-23
Figure C-7 Relation Between F_{en} and Strain Rate for Austenitic Stainless Steels with F_{en} Expressions (PWR)	C-33
Figure C-8 Relation Between F_{en} and Strain Rate for High Nickel Alloys with F_{en} Expressions (PWR).....	C-33
Figure C-9 Relation Between F_{en} and Strain Rate for Carbon and Low Alloy Steels with F_{en} Expressions	C-49
Figure C-10 Relation Between F_{en} and Strain Rate for Austenitic Stainless Steels with F_{en} Expressions (BWR)	C-49
Figure C-11 Relation Between F_{en} and Strain Rate for High Nickel Alloys with F_{en} Expressions (BWR).....	C-50
Figure C-12 Concept of the New Design Fatigue Curve.....	C-58
Figure C-13 Flowchart of the New Fatigue Analysis Method	C-59
Figure C-14 Scheme of Relation between DFC and BFC Considering Design Factors	C-60
Figure C-15 Design Fatigue Curve for SFVQ1A (equivalent to SA-508 Gr. 3 Cl. 1).....	C-60
Figure C-16 Design Fatigue Curve for SUS F316 (equivalent to SA-182 F316)	C-61
Figure C-17 The Best-Fit Curve for Base Metal 316SS from the EFT Project.....	C-61
Figure C-18 Developed F_{en} Expressions for SS Base Metal.....	C-62

Figure C-19 Comparison of F_{en} Expressions	C-62
Figure C-20 Comparison of Experimental Fatigue Lives vs. Estimated Fatigue Lives	C-63
Figure C-21 Parameter Survey of Initial Flaw Depth for Crack Growth	C-63
Figure C-22 Proposed Flaw Tolerance Approach.....	C-64
Figure D-1 Reactor Pressure Vessel Thermal Regions and Zone Identification.....	D-2
Figure D-2 Radiolysis Model Region and Circuit Identification [52]	D-3

LIST OF TABLES

Table 2-1 History of Japanese EAF Methods	2-9
Table 5-1 Required Inputs for EAF Evaluation for Existing LWRs	5-8
Table 5-2 Required Inputs for EAF Evaluation for New LWRs	5-9
Table 5-3 Maximum F_{en} and Acceptable CUF	5-12
Table 5-4 Qualitative assessment of transient thermal ramp rates on Strain Rate and F_{en}	5-23
Table 6-1 List of Candidate Materials for Discrete Fatigue Curves	6-1
Table A-1. Alternating Stress Design Results (Used as Inputs)	A-2
Table A-2. Fatigue Analysis Results Comparison.....	A-3
Table A-3. CUF (Step 1)	A-4
Table A-4. CUF_{en} with $F_{en} = 1.0$ Refinement and Maximum F_{en} (Step 2)	A-5
Table A-5. CUF_{en} with F_{en} Refinements (Step 3)	A-7
Table A-6. CUF_{en} with K_e Refinements (Step 4).....	A-8
Table A-7. Summary of Results for Refined F_{en}	A-9
Table A-8. Input Data and Substep Calculations for F_{en} based on MRA	A-11
Table C-1 Chemical Compositions of Materials for PWR Environments (Carbon and Low Alloy Steels, Austenitic Stainless Steels)	C-27
Table C-2 Chemical Compositions of Materials for PWR Environments (High Nickel Alloys)	C-28
Table C-3 Mechanical Properties of Materials for PWR Environments	C-29
Table C-4 Fundamental Fatigue Test Matrix for PWR Primary Side (2 pages)	C-30
Table C-5 Fundamental Fatigue Test Matrix for PWR Secondary Side	C-32
Table C-6 Chemical Compositions of Materials for BWR Environments (Carbon and Low Alloy Steels)	C-34
Table C-7 Chemical Compositions of Materials for BWR Environments (Austenitic Stainless Steels)	C-35
Table C-8 Chemical Compositions of Materials for BWR Environments (High Nickel Alloys)	C-35
Table C-9 Mechanical Properties of Materials for BWR Environments (Carbon and Low Alloy Steels)	C-36
Table C-10 Mechanical Properties of Materials for BWR Environments (Austenitic Stainless Steels and High Nickel Alloys).....	C-37
Table C-11 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (Low S))	C-38
Table C-12 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Weld (Low S)).....	C-38

Table C-13 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (High S))	C-39
Table C-14 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Weld (High S)).....	C-39
Table C-15 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (Extra High S)).....	C-40
Table C-16 Fundamental Fatigue Test Matrix for BWR Conditions (SFVC2B).....	C-40
Table C-17 Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2B)	C-41
Table C-18 Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2B Weld)	C-42
Table C-19 Fundamental Fatigue Test Matrix for BWR Conditions (316NG)	C-43
Table C-20 Fundamental Fatigue Test Matrix for BWR Conditions (316NG Weld).....	C-44
Table C-21 Fundamental Fatigue Test Matrix for BWR Conditions (304).....	C-45
Table C-22 Fundamental Fatigue Test Matrix for BWR Conditions (SCS14A).....	C-45
Table C-23 Fundamental Fatigue Test Matrix for BWR Conditions (Alloy 600).....	C-46
Table C-24 Fundamental Fatigue Test Matrix for BWR Conditions (Conventional Alloy 600)	C-46
Table C-25 Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Thermal Aged).....	C-47
Table C-26 Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2A Thermal Aged).....	C-47
Table C-27 Fundamental Fatigue Test Matrix for BWR Conditions (SQV2B).....	C-48
Table C-28 Fundamental Fatigue Test Matrix for BWR Conditions (304L).....	C-48
Table C-29 Factors of Data Scatter	C-64
Table D-1: IGSCC Mitigation Types [81].....	D-1
Table E-1: List of EAF-Related Reports Published by EPRI.....	E-2

1

INTRODUCTION

Environmentally Assisted Fatigue (EAF) is a corrosion fatigue mechanism generally associated with exposure of components to light water reactor (LWR) environments. While EAF can impact all manner of components and materials exposed to LWR environments in a nuclear power plant (NPP), in the context of this handbook, EAF refers to the impact of environment on pressure boundary materials and components. Corrosion fatigue results from the effect of cyclic loading in a corrosive environment. The available data indicate that LWR environments introduce the degradation mechanisms of slip oxidation/dissolution and hydrogen-induced cracking that potentially increase both fatigue crack initiation and fatigue crack growth rates. Cracks formed by corrosion-assisted fatigue mechanisms are usually wider and less uniform in appearance because of the metal removed by corrosion. Initiation may occur at multiple sites. Microscopically, the cracks are typically transgranular, wide, oxide-filled, and blunt-tipped, with irregular crack profiles and signs of discontinuous propagation. As with fatigue cracks in air, the crack orientation is generally normal to the predominant stress field. However, corrosion-assisted fatigue cracks are more likely to form branches that follow grain boundaries in the metal [1].

To date, there has been no documented instance of a fatigue failure in an operating LWR plant for anticipated service loadings where LWR coolant environmental effects were the primary cause. However, laboratory tests have shown that a reduction in fatigue life (as represented by the stress or strain versus life (S-N) curve) can occur under certain conditions. While the effects of an operational wetted environment, as opposed to laboratory testing conditions, were considered in the development of the American Society of Mechanical Engineers (ASME) Code fatigue curves, the factors on the fatigue curve were not conservative enough to account for the full effect of the LWR environment [2, Appendix W, W-2700, 2021 Edition].

Several aspects of a component's environment may affect the fatigue susceptibility (both initiation and flaw propagation rate). These include, but are not limited to, chemistry of the adjacent fluid, neutron flux, cyclic strain rate, and temperature. EAF evaluation, within the context of this report, is focused primarily on the influence of water chemistry environments on crack initiation of pressure boundary components and the associated regulatory requirements pertaining to either initial licensing or existing license renewal.

The most widely accepted method to explicitly evaluate environmental effects involves the application of an additional factor, F_{en} , which is applied to the constituent values that make up the fatigue cumulative usage factor (CUF), resulting in a cumulative usage factor in environment, CUF_{en} . A CUF_{en} less than 1.0 considering the design transients and primary water chemistry means the component is not expected to initiate a crack of engineering significance. EAF must be addressed for new plant design as well as for life extension evaluations in older plants [3].

The history, research, tools, and application of EAF for license renewals and in new LWR designs are discussed in detail in this handbook:

- Chapter 2 contains the history of EAF, including relevant research, regulatory positions, and industry guidance, focused not only domestically but on the significant contributions from Japan and other international stakeholders.
- Chapters 3 and 4 address the testing completed (Chapter 3) to develop the EAF correlations (Chapter 4), commonly referred to as F_{en} . The F_{en} value serves as a correction for the reactor coolant environments and is applied to the in-air fatigue usage.
- Chapter 5 provides detailed strategies and approaches for managing EAF systematically, which allows users to identify the most resource efficient approaches to address EAF. EAF may be managed by methods to reduce the CUF_{en} through analytical methods and/or an active fatigue monitoring program, or via flaw tolerance methods coupled with inspections. Implementation of these strategies may differ between new design and license renewal application.
- Chapter 6 summarizes the current on-going research topics related to EAF to understand the near-term gaps in the analysis approaches and available analytical methods.

1.1 Metal Fatigue Primer

The American Society of Testing and Materials (ASTM) defines fatigue as the process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at a location which may culminate in cracks or complete fracture after enough fluctuations [4]. The study of fatigue failures has been the subject of ongoing research for well over a century. Many factors have led us to our current understanding of fatigue, and by correlation, its effect on the operability and life of nuclear power plant components.

For analysis purposes, predictions of fatigue failures are evaluated by using the stress or strain versus life (S-N) curve. Figure 1-1 shows typical test data collected to generate an S-N curve [5]. The results of the strain cycle testing are plotted on a log-log diagram of alternating stress amplitude versus fatigue life. The total cyclic strain range, $\Delta\epsilon_t$, is multiplied by the elastic modulus of the material, E , to produce a nominal stress range, ΔS_t . Since the total strain range consists of equal amplitudes of positive and negative strains, the alternating stress amplitude, S_{alt} , is defined as $\Delta S_t/2$. The conversion of strain to stress is done so that fatigue evaluations are completed on a stress-basis typical of other stress analyses and evaluations (e.g., ASME limits for elastic analysis are evaluated to stress intensity limits). For a given stress in a component, the number of predicted fatigue cycles to failure can be identified from the S-N curve and used in design [2].

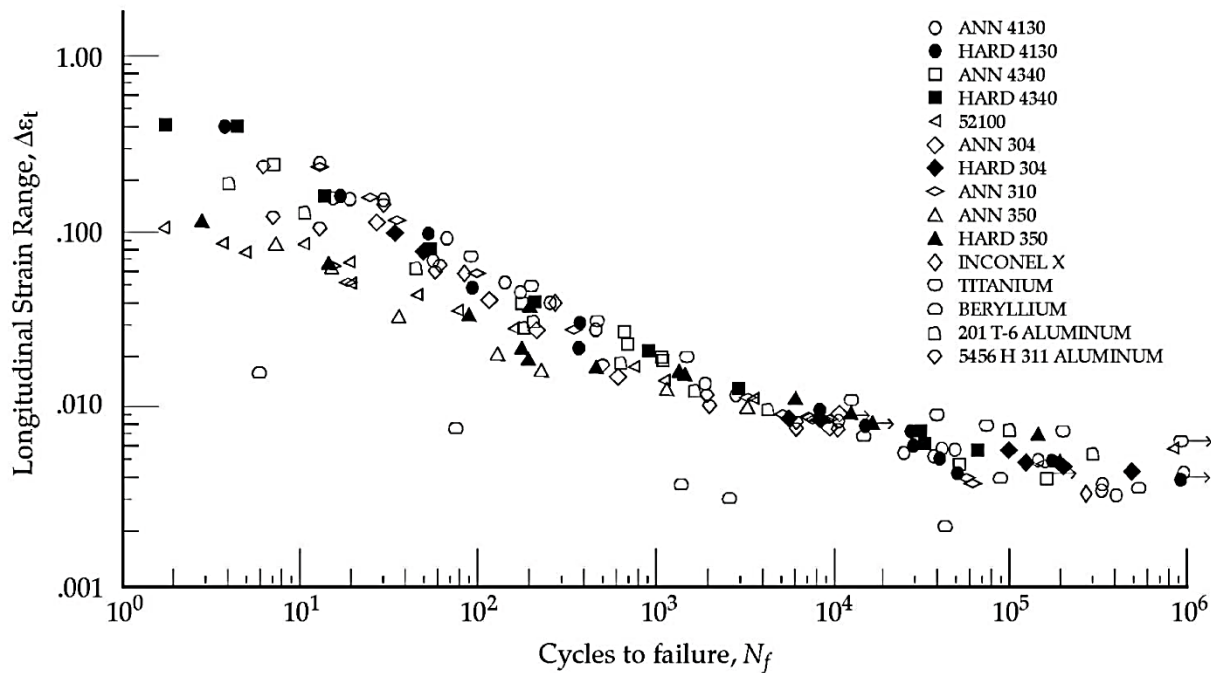


Figure 1-1
S-N Fatigue Data for Engineering Materials

(Reprinted from S.S. Manson, "Thermal Stress and Low Cycle Fatigue," McGraw-Hill Co., 1966.)

When assessing fatigue of components, there are two general categories of fatigue which are important in nuclear power plant design and analysis: low cycle fatigue (LCF) and high cycle fatigue (HCF). These regimes, as well as the transition regime, are shown in Figure 1-2 [5]. There are substantive differences between the two regimes in terms of the major factors controlling fatigue life.

- At the extreme low cycle end of the S-N curve ($< 1,000$ cycles), the strains are in the plastic range (that is, stress levels are well above the yield strength of the material) with the elastic strain amplitude being negligible by comparison. In this regime, crack initiation occurs with relatively few cycles and then most of the specimen life is in crack propagation where a small, initiated crack grows to a size which can fracture the specimen. A major mechanism that can cause low cycle fatigue (high strains) in nuclear power plants is thermal transient loading.
- At the other end of the curve ($> 10^5$ cycles), high cycle fatigue is seen to be well-characterized in terms of only the elastic strain amplitude. Since stress levels are below yield, little or no plastic straining occurs with numbers of cycles typically in the millions. Once a crack initiates in a HCF situation, component failure is usually soon to follow, generally occurring rapidly and without warning since observable cracks do not occur until very late in component life. Nuclear plant high cycle fatigue concerns are generally associated with high-speed rotating or reciprocating equipment, vibrational, or local thermal cycling due to hot and cold fluid stratification and mixing or due to thermal striping. A large percentage of the fatigue failures which have occurred in the industry are attributable to this phenomenon,

because it is generally not addressed or addressed to only a limited extent in the design process.

- Between these extremes ($10^3 < N < 10^5$ cycles) is a transition regime in which both the elastic and plastic strain amplitudes are of significance. Nuclear power plant design fatigue applications lie in this transitional regime, as the design basis for major plant heat-up/cool-down cycles is typically in the hundreds, and the other types of cycles (scrams, pump trips, and so on) combine to produce total numbers of design basis cycles in the thousands or tens of thousands.

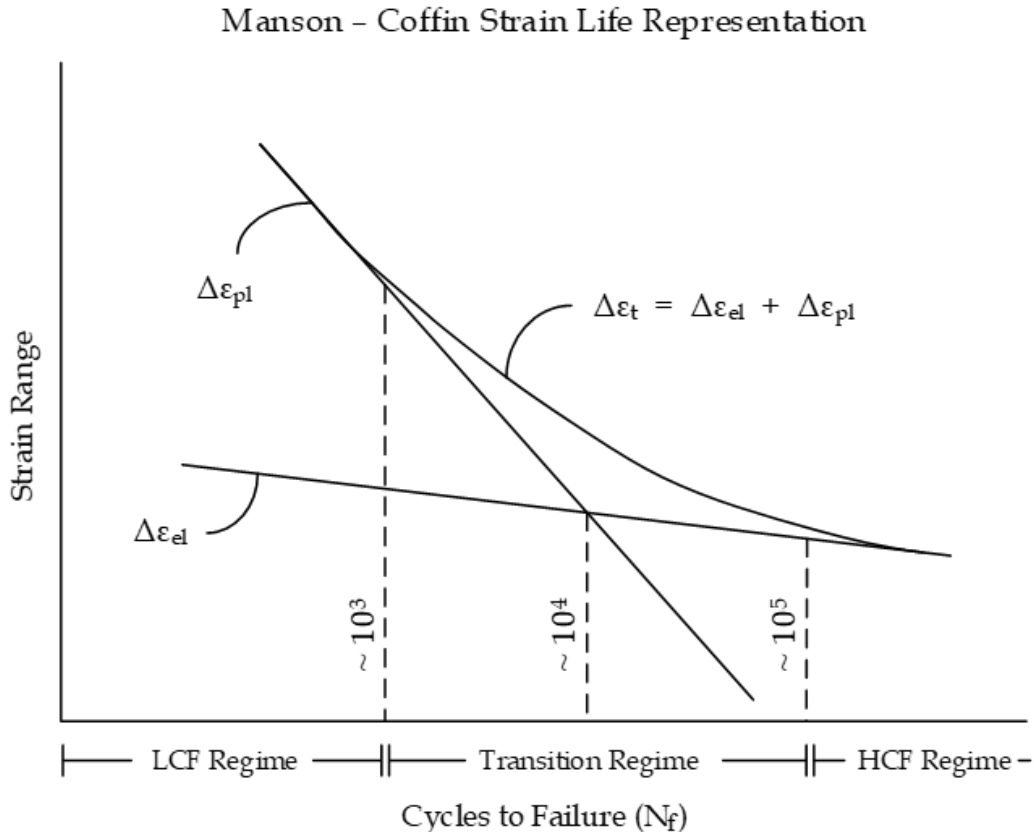


Figure 1-2
S-N Fatigue Data for Engineering Materials

(Reprinted from S.S. Manson, "Thermal Stress and Low Cycle Fatigue," McGraw-Hill Co., 1966.)

1.2 Design Rules for Fatigue

The 1963 Edition of Section III [2] was the first ASME Code to recognize that self-limiting (secondary) and localized stresses can have a significant influence on component performance and should be considered. It also recognized that the allowable stresses for secondary and local stresses should be higher than for primary stresses. It is important to recognize that for some operating power plants, the fatigue design, especially for piping, predates the ASME Code. For

piping design, ASME B31.7-1969 [6] was used prior to ASME Section III, Class 1, Subarticle NB-3600 which was first published in the 1971 Edition [2], and some early plants used ASME B31.1 for piping [7], which does not require *CUF* calculation. There have been numerous revisions and updates to the Code since its initial publication or alternatives to Section III may have been used in the original design basis, but the underlying design philosophy is consistent, and thus this guidance is applicable.

When detailed fatigue evaluations are required by either the Code or the Design Specification, the operating pressure and temperature transients are required to be specified in the design specification. Commonly, Class 1 and Class CS components are evaluated for fatigue. In some instances, Class 2 or Class MC may also be evaluated for fatigue if the expected cyclic loading is significant. Typically, Class 3 components are not evaluated for fatigue. An Owner may require a fatigue evaluation in the Design Specification even if it is not required by the governing design code if fatigue is a credible degradation mechanism. The ASME Boiler and Pressure Vessel Code, Section III [2], hereafter referred to as the ASME Code, provides the applicable fatigue curves, specified by groups of materials.

As specified in the ASME Code with details provided in the EPRI Low Cycle Fatigue Handbook (MRP-481) [8], the fatigue analysis procedure consists of the following steps:

- Determine the stress histories for all normal, test, and upset service conditions. Select one or more controlling component location(s) for evaluation. For piping components, the analysis is typically conducted for all welds and fitting locations.
- From the stress histories for all service conditions, calculate stress differences in accordance with ASME Code for all identified stress cycles. A stress cycle is defined as the change in stress from an initial value to an algebraic maximum value and an algebraic minimum value, and then return to the initial value. The stress history locations of each maxima and minima value that make up the stress differences correspond to different transients identified within the design specification. These are also referred to as load set pairs.
- From the identified stress differences, determine the alternating stress amplitude (S_{alt}) for each stress cycle. This must include stress concentration effects. Also, any additional strain due to plasticity must be accounted for in the analysis using the simplified elastic plastic correction factor (K_e) or another method.
- Modify S_{alt} to account for service loading temperature by multiplying it by the ratio of the modulus of elasticity on the fatigue curve, divided by the modulus of elasticity used in the stress analysis.
- Determine the allowable number of cycles (N_{allow}) for the S_{alt} values determined for each stress cycle using a fatigue curve, such as given in ASME Code Section III Appendix I.
- For the load set pairs identified as part of the stress cycle, a number of applied cycles, n_i , is defined. The fatigue usage for each stress cycle is determined by n_i/N_{allow} . Determine fatigue usage contributions for all load set pairs.

- The cumulative fatigue usage factor, CUF , is determined by the summation of usages for all load set pairs:

$$CUF = \sum_{i=1}^M \frac{n_i}{N_i}$$

where,

n_i = number of applied cycles for transient load set pair, i

N_i = number of allowable cycles for transient load set pair, i

M = total number of sets of transient load set pairs

In the fatigue analysis process, a component meets the design criterion if the maximum CUF for all analysis locations is less than or equal to 1.0.

In nuclear power plants, the fatigue mechanisms that have either contributed to cracking and/or leakage during operation or are of concern for long-term aging management are low cycle fatigue, thermal fatigue, vibration fatigue, and EAF. Guidance related to low cycle fatigue, high cycle thermal fatigue, and vibration fatigue are addressed in separate handbooks ([8], [9], [10]).

2

HISTORY OF ENVIRONMENTALLY ASSISTED FATIGUE

Japan was the first country in the world to initiate EAF research, beginning to study this degradation mechanism in the early 1980s with the first journal article being released in 1982. Japan's research spurred extensive research that is still on-going today. The collaborative, global study of this phenomenon has resulted in improvements to the fatigue evaluation factors that account for environmental effects. The international cooperation to characterize and predict this degradation mechanism ensures public and worker health and safety.

While the history of EAF is vast, within the context of this report the history focuses on the U.S. Nuclear Regulatory Commission (NRC) regulations and guides related to EAF and supplemental U.S. industry sponsored documents to implement these requirements. An abridged summary of the key historical Japanese EAF methods development work provides additional context to the U.S. industry's response to EAF.

2.1 U.S. History

The timeline of the industry efforts paralleled those of the Regulators. A timeline of the major U.S. milestones related to EAF is shown in Figure 2-1. An overview of the history of EAF in the U.S. followed by discussion on each of the significant publications are summarized in this section.

2.1.1 U.S. NRC

Nuclear plants in the U.S. were originally licensed by the U.S. NRC for 40 years of operation. Most U.S. utilities have submitted applications to the NRC and have been approved to extend operation to 60 years, and several have applied to extend their licenses for an additional 20 years (80 years total). Plants are required by federal law to manage the aging effects, including, but not limited to, environmentally assisted fatigue of systems, structures, and components in the scope of license renewal. Part 54 to Title 10 of the U.S. Code of Federal Regulations (10CFR54) specifies the "Requirements for Renewal of Operating Licenses for Nuclear Power Plants" [11].

During rulemaking activities related to license renewal in the early 1990s, the NRC found that the licensing basis for fatigue design of metal components differed considerably across the domestic operating fleet. In response, the NRC developed the Fatigue Action Plan (FAP) to assess the safety significance of fatigue on the domestic operating fleet [12]. The NRC FAP also assessed the effects of LWR water environments on fatigue life since preliminary testing at that time indicated that the effects of LWR environments could significantly reduce the fatigue resistance of materials [13]. Although the NRC concluded in a probabilistic risk study in NUREG/CR-6674 [14] that the effect of a reactor water environment is not a safety issue, the probability of leakage was predicted to increase for operation past 40 years. EPRI Report 3002018260 titled "PWR Subsequent License Renewal Environmentally Assisted Fatigue Database" [15] provides a detailed description of the required program scope, required utility

actions and evaluations, and operating experience related to license renewal and extension applications.

The staff previously evaluated two approaches to EAF: developing new fatigue curves specific to light-water environments and the use of an environmental factor, F_{en} , to adjust the CUF calculated with the design curves. The NRC and the industry converged on the environmental factor approach given it can more easily be adapted to fit evolving industry needs [16].

NRC reports NUREG-1801, “Generic Aging Lessons Learned (GALL) Report” [17, 18, 19] (applicable to 60-year license renewals) and NUREG-2191, “Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report” [20] (applicable to 80-year license renewals), identify acceptable aging management programs, including programs for fatigue and cyclic operation (Chapter X.M1 in both reports).

The GALL-SLR Report contains the NRC’s current considerations of environmental effects for license renewals at the time of this report. A plant’s Aging Management Program (AMP) provides an approach and basis for managing structures and components that are subject to fatigue or cycle-based time-limited aging analyses to meet licensing commitments. Part of the AMP is monitoring and assessing environmental effects on fatigue for critical components. The GALL-SLR Report states that environmental effects on fatigue may be evaluated using the guidance in Regulatory Guide (RG) 1.207, Revision 1 [3], which references as the technical basis NUREG/CR-6909, Revision 1 [1], or other subsequent NRC-endorsed alternatives.

Regulatory Guide 1.207, Revision 1 describes methods and procedures that the NRC considers acceptable to determine the fatigue lives of components evaluated by a cumulative usage factor (CUF) calculation to account for the effects of LWR water environments.

NUREG/CR-6909, Revision 1 is a comprehensive and consolidated reference that supports the development of the recommended environmental factors. The report summarizes the work performed at Argonne National Laboratory (ANL) based on the available industry research on fatigue of piping and pressure vessel steels in LWR environments. This report has been endorsed by the NRC as a method for addressing environmental effects in fatigue analyses for both license extensions and new reactor designs and is the technical basis for Regulatory Guide 1.207. There are some updates in NUREG/CR-6909, Revision 1 that plants may consider when applying for subsequent license renewals, even if previous evaluations were completed to earlier endorsed regulatory guides. There are also some challenges associated with this guidance, particularly for stainless steel components, because of the revised fatigue curves that have been implemented.

To satisfactorily address EAF for longer term operation, utilities must perform, or commit to performing, the following:

- Demonstrate that the cumulative EAF usage (CUF_{en}) for all components remains less than 1.0 for the licensed life of the plant.
- If it cannot be demonstrated that the CUF_{en} remains less than 1.0 for the licensed life of the plant, corrective action must be taken prior to the time when the CUF_{en} exceeds 1.0. Some acceptable options for corrective action are:
 - Perform refined fatigue analysis or fatigue monitoring to remove excess conservatism and lower CUF_{en} : Use guidance from EPRI Low Cycle Fatigue Handbook (MRP-481) [8], which provides strategies on fatigue licensing basis monitoring activities for the current licensing basis and the extended operating period, to develop fatigue management and EAF assessment approaches that are compliant with plant technical specifications and regulatory guidance.
 - Perform inspections and flaw tolerance evaluations using an NRC-approved approach that accounts for environmental effects on crack growth. ASME Code, Section XI, Nonmandatory Appendix L [21] provides one method of flaw tolerance that may be used.
 - A flaw tolerance evaluation consists of performing a baseline inspection of the component to verify the absence of flaws, and then determining the time required for a postulated flaw, initially sized at the detection threshold of the inspection, to reach, but not exceed, an allowable flaw size. The time obtained from the flaw tolerance assessment identifies the time for the next inspection. The reinspections can be continued as long as no flaws are detected. This approach is a viable alternative to produce an acceptable analysis for regulatory approval when refined CUF_{en} calculations are unsuccessful. In many cases, inspections of components with high CUF or CUF_{en} values are already performed as part of the 10-year inservice inspection (ISI) program, therefore, inspections may not be an additional burden. For extended plant operation, reactor water environmental effects must be included in the postulated crack growth laws for any Appendix L evaluation. To-date, many flaw tolerance evaluations have been submitted to and accepted by the NRC on a plant-specific basis for successful management of EAF during the period of extended operation.
 - Repair or replace the component to re-start or mitigate fatigue damage.
- Include a discussion of the efforts to address EAF and the results in the application for a renewed operating license.

The NRC Staff expects that the effects of the environment on fatigue are addressed in licensing applications associated with new reactor (either new nuclear reactor construction permits or operating licenses under U.S. Code of Federal Regulations, Title 10, “Energy” (10 CFR), Part 50, “Domestic Licensing of Production and Utilization Facilities” [22] or design certifications and combined licenses under 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants” [23]. Originally, Regulatory Guide 1.207, Revision 0 [24] titled “Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environments for New Reactors”

was limited in scope to new reactor designs. With the publication of Regulatory Guide 1.207, Revision 1, a consistent methodology is available for both new reactors seeking new licenses and existing reactors seeking license renewals.

2.1.2 U.S. Industry Efforts

The U.S. industry efforts were coordinated largely through EPRI, the ASME Section III Code Committee activities, and international researchers. Efforts included the EPRI EAF Expert Panel that developed the EPRI Report 1025823 titled “Guidelines for Addressing Environmental Effects in Fatigue Usage Calculations” [25] in 2012, where the details of the approaches for applying the F_{en} formulas to fatigue evaluations were developed by a group of industry participants. This filled the gap left by NUREG F_{en} formulas with no application guidelines (except for some mention of modified rate approach) and informed ongoing development of ASME Code Cases through Working Group Environmental Fatigue Evaluation Methods, and even the example problem in NUREG/CR-6909, Revision 1. An extensive history of EPRI publications, guides, and research related to EAF is documented in Appendix E and many of the international publications are referenced throughout this report or in the references cited in NUREG/CR-6909, Revision 1.

The current EPRI guidance and research centers around the following recently released reports that further qualify critical responses to EAF:

- EPRI Report 3002018262, Revision 1 “Environmentally Assisted Fatigue Screening Methods” [26]: EPRI Report 3002018262 provides processes for three EAF screening methods to consistently identify the most limiting locations for management of EAF effects on Class 1 reactor coolant pressure boundary components wetted with primary coolant. These methods reduce the efforts involved with plant assessment by focusing efforts on the most limiting locations through uniform processes.
- EPRI Report 3002018260, Revision 0, “Pressurized Water Reactor Subsequent License Renewal Environmentally Assisted Fatigue Database” [15]: EPRI Report 3002018260 provides findings from the collection of PWR EAF CUF_{en} results applicable to 60 and 80 years of operation. This data is critical to understanding how EAF affects license renewals of PWRs and provides a picture of work needed to address EAF in these cases.
- EPRI Report 3002021227, “BWRVIP-343: BWR Subsequent License Renewal Environmentally Assisted Fatigue Database” [27]: BWRVIP-343 provides a compilation of available EAF evaluations for those boiling water reactor (BWR) units that have performed EAF component assessments for extended operations. This includes most of the U.S. BWRs that have submitted 60-year license renewal applications (LRAs) and a non-U.S. BWR that has performed EAF evaluations to satisfy local regulatory requirements.
- EPRI Report 3002013214, “Environmentally Assisted Fatigue (EAF) Knowledge Gap Analysis: Update and Revision of the EAF Knowledge Gaps” [28]: The original Knowledge Gap Assessment (EPRI report 1023012) was produced in 2011 and provided a list of gaps in the nuclear industry’s understanding of EAF developed by the EPRI EAF Expert Panel. EPRI Report 3002013214 provides an update and refinement of the existing Knowledge Gaps (as they were previously defined in EPRI report 1023012) to reflect the significant additional worldwide research efforts over the past decade.

The industry efforts are also shaping the work in the ASME Codes and Standards. Beginning in the early 1990s, the ASME Board on Nuclear Codes and Standards (BNCS) and the Pressure Vessel Research Council (PVRC) collaborated to examine the existing worldwide fatigue strain vs. life (S-N) data and develop recommendations for the ASME in response to the Japanese and U.S. NRC research. Over the years, the ASME continued to study and evolve the fatigue design rules and ultimately formed the Section III Working Group on Environmental Fatigue Evaluation Methods. Members of the initial committees included EAF global experts, including the EPRI Environmental Fatigue Expert Panel. The Working Group charter, which is still in effect today, evaluates recognized methods of assessing cyclic life of Class 1 components that are subject to a wetted environment and proposes ASME Code changes to incorporate the state-of-the-art research as Code Revisions, Appendices, and/or Code Cases. The actions of this committee support the operating fleet and the advanced light water fleet.

2.2 Japanese History

Japan was the first country to initiate EAF research, and the history of Japanese EAF research is explained below and summarized in Appendix C.

Higuchi, et al. reported EAF test results for carbon steel piping material, JIS STS42, in pure water at 250°C and a *DO* content of 8 parts per million (ppm) with strain-controlled fatigue tests in 1982 [29]. Figure 2-2 shows the relationship between strain amplitude and fatigue life. The fatigue lives in a water environment clearly show the dependency on strain rate. In this series of EAF testing, round bar specimens were used in an autoclave as shown in Figure 2-3.

Endo, et al. reported EAF test results for 304 austenitic stainless steel in pure water at 300°C and 8 ppm *DO* with strain-controlled fatigue tests in 1985 [30]. Figure 2-4 shows the relations between strain amplitude and fatigue life. The fatigue lives in a water environment also clearly show the dependency on strain rate. In this series of EAF testing, hollow cylindrical specimens were used without an autoclave as shown in Figure 2-5.

Some of the EAF test results produced lower fatigue lives compared to air fatigue design curves that were established in industry codes, such as ASME and JSME. At this point, EAF causing a significant reduction in fatigue life was new knowledge for the nuclear industry. Higuchi, et al. presented the EAF test results for carbon steel in oxygenated high temperature water at the 6th International Conference on Pressure Vessel Technology (ICPVT) in 1988 [31], and Kanasaki presented the EAF test results for 304 stainless steel in PWR environments at the Pressure Vessel Research Council (PVRC) Autumn Meeting in 1996 [32]. Higuchi et al. reported that the fatigue life in high temperature oxygenated pure water decreased remarkably with decreasing strain rate, and the dependencies of temperature and dissolved oxygen content were obtained for carbon steel and low alloy steel as shown in Figure 2-6 and Figure 2-7. Kanasaki reported the dependency on strain rate and temperature as shown in Figure 2-8 and Figure 2-9. These studies led to the world nuclear industry beginning to realize the importance of the EAF issue.

The nuclear industry community of Japan recognized the necessity to develop an environmental fatigue evaluation method, so the Environmental Fatigue Data (EFD) Committee (Chair: Emeritus Professor Kunihiro Iida) in the Thermal and Nuclear Power Engineering Society (TENPES) was established from 1993 to 1995. During this time, additional fatigue data for EAF were obtained from utility projects and those data were provided to the EFD Committee.

Subsequent to the EFD Committee, a national project called the Environmental Fatigue Testing (EFT) Project was started in 1994 by the Japan Power Engineering and Inspection Corporation (JAPEIC), as directed by the Japanese Ministry of International Trade and Industry (MITI). The Japan Nuclear Energy Safety Organization (JNES) succeeded the EFT Project from October 2003, as directed by the Nuclear and Industrial Safety Agency (NISA) in the Ministry of Economy, Trade and Industry (METI). The EFT Project continued until March 2007 (end of 2006).

In 1999, the Resources and Energy Agency of MITI required Japanese utilities to perform Plant Life Management (PLM) Aging Evaluations as a part of their Periodic Safety Reviews (PSRs) for aged nuclear power plants with more than 30 years of operation. The 1999 report of the EFT Project described that EAF data for carbon, low alloy, and austenitic stainless steels were obtained, and the fatigue lives in LWR environments were lower than those in air. As a result, MITI mandated performance of EAF evaluations in the PLM Aging Evaluations using, “The Guideline for Evaluating Fatigue Initiation Life Reduction in LWR Environment” (MITI Guideline) in September 2000 [33].

It is noted that the MITI Guideline included empirical evaluation equations for EAF, but it did not include any detailed procedure to apply the evaluation equations. The utilities and the plant suppliers needed a detailed procedure for EAF evaluation.

In response to this request from the industrial side, TENPES organized the Committee on Environmental Fatigue Evaluation Guidelines in April 2001. Based on the evaluation method developed by the EFD Committee, a guideline for EAF evaluation called the TENPES Guideline was established incorporating the environmental multiplier, or F_{en} , expressions from the MITI Guideline and the evaluation method for EAF developed by the EFD Committee in June 2002 [34]. This guideline was the first prototype of the “ F_{en} method” in Japan; the F_{en} method is now widely used worldwide for evaluating EAF effects.

After that, environmental fatigue evaluations were regularly conducted as a part of PSRs, and there was an increased demand to revise the TENPES Guideline. In response to this demand, the JSME Main Committee on Power Generation Facility Codes established the Subgroup on Environmental Fatigue reporting to the Subcommittee on Nuclear Power. This subgroup started in April 2004 and developed the JSME S NF1 “Environmental Fatigue Evaluation Method for Nuclear Power Plants” (hereinafter called “JSME Environmental Fatigue Evaluation Method”) [35].

The first edition of the JSME Environmental Fatigue Evaluation Method was published in the 2006 Edition of the JSME Code. The latest JNES report for the EFT Project at that time was published as JNES-SS-0503 [36] and the results of that report were incorporated into this edition of the JSME Environmental Fatigue Evaluation Method [37].

The second edition of the JSME Environmental Fatigue Evaluation Method was published in the 2009 Edition of the JSME Code [38], and this edition incorporated the final JNES report for the EFT Project, JNES-SS-0701 [39] that was developed based on the final project report of the EFT Project [40]. JNES-SS-1005 [41] was subsequently published as the English translation of JNES-SS-0701.

It is noted that the environmental fatigue data for the EFT Project were transmitted to the U.S. NRC and incorporated into the NRC’s EAF research activities in NUREG/CR-6909, Revision 1.

Because the fatigue testing in the EFT Project is useful for understanding NUREG/CR-6909, Revision 1, the EFT Project test program is explained later in this report.

The third edition of the JSME Environmental Fatigue Evaluation Method has been approved by the JSME Main Committee for the 2022 edition of the JSME code for application to existing plants. The following three technical revisions have been added:

- New design fatigue curves using tensile strength as a variable;
- New F_{en} expression for austenitic stainless steels in PWR environments; and
- Flaw tolerance approach.

The necessity of a new fatigue analysis method to obtain accurate fatigue life was recognized in Japan, and the Design Fatigue Curve (DFC) Subcommittee was established in the Atomic Energy Research Committee in the Japan Welding Engineering Society (JWES) from August 2011 to March 2013 (Phase 1) [42 and 43]. The DFC Subcommittee Phase 2 followed from April 2013 to March 2016 and proposed a new fatigue analysis method [44]. To optimize the JSME Environmental Fatigue Evaluation Method, the Subgroup on Fatigue Evaluation that succeeded the Task Group on Fatigue Evaluation reviewed the new fatigue analysis method developed by the DFC subcommittees and decided to incorporate the new design fatigue curves with some revisions into the JSME Environmental Fatigue Evaluation Method [45].

The F_{en} expression for austenitic stainless steels in PWR environments in the JSME Environmental Fatigue Evaluation Method (2009 Edition) shows relatively high F_{en} values in the high strain rate region. The strain rate for $F_{en} = 1$ is 49.9 %/s, while it is 2.69 %/s for BWR environments. To confirm environmental effects at high strain rates for austenitic stainless steels in PWR environments, the Japanese PWR Group performed a series of environmental fatigue tests and developed F_{en} expressions for austenitic stainless steels (base metals, welds, and cast stainless steels) for PWR environments [46]. The Subgroup on Fatigue Evaluation reviewed the three F_{en} expressions that were developed and decided to employ the F_{en} expression for base metals because it is the most conservative among the three F_{en} expressions, and the EAF test data used in the F_{en} expression of the 2009 Edition were confirmed to be conservatively estimated by the combination of the employed F_{en} expression and the revised design fatigue curve [45].

The flaw tolerance approach incorporated into the JSME Environmental Fatigue Evaluation Method is a total fatigue life approach. First, a fatigue usage factor, including environmental effects (CUF_{en}), is calculated. Then, a postulated crack is assumed at the time when $CUF_{en} = 1.0$, after which, a fatigue crack growth analysis and fracture mechanics evaluation are performed [47].

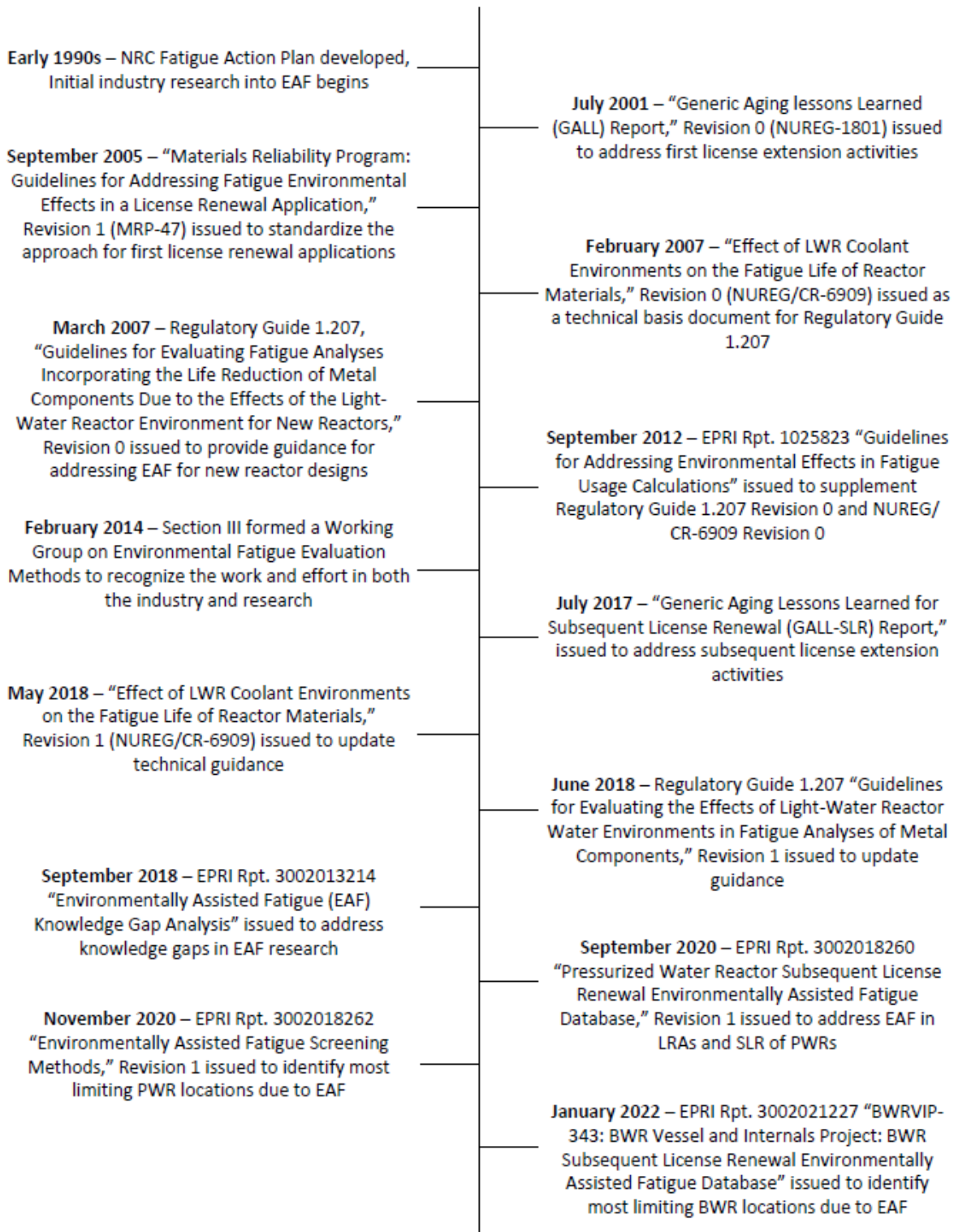
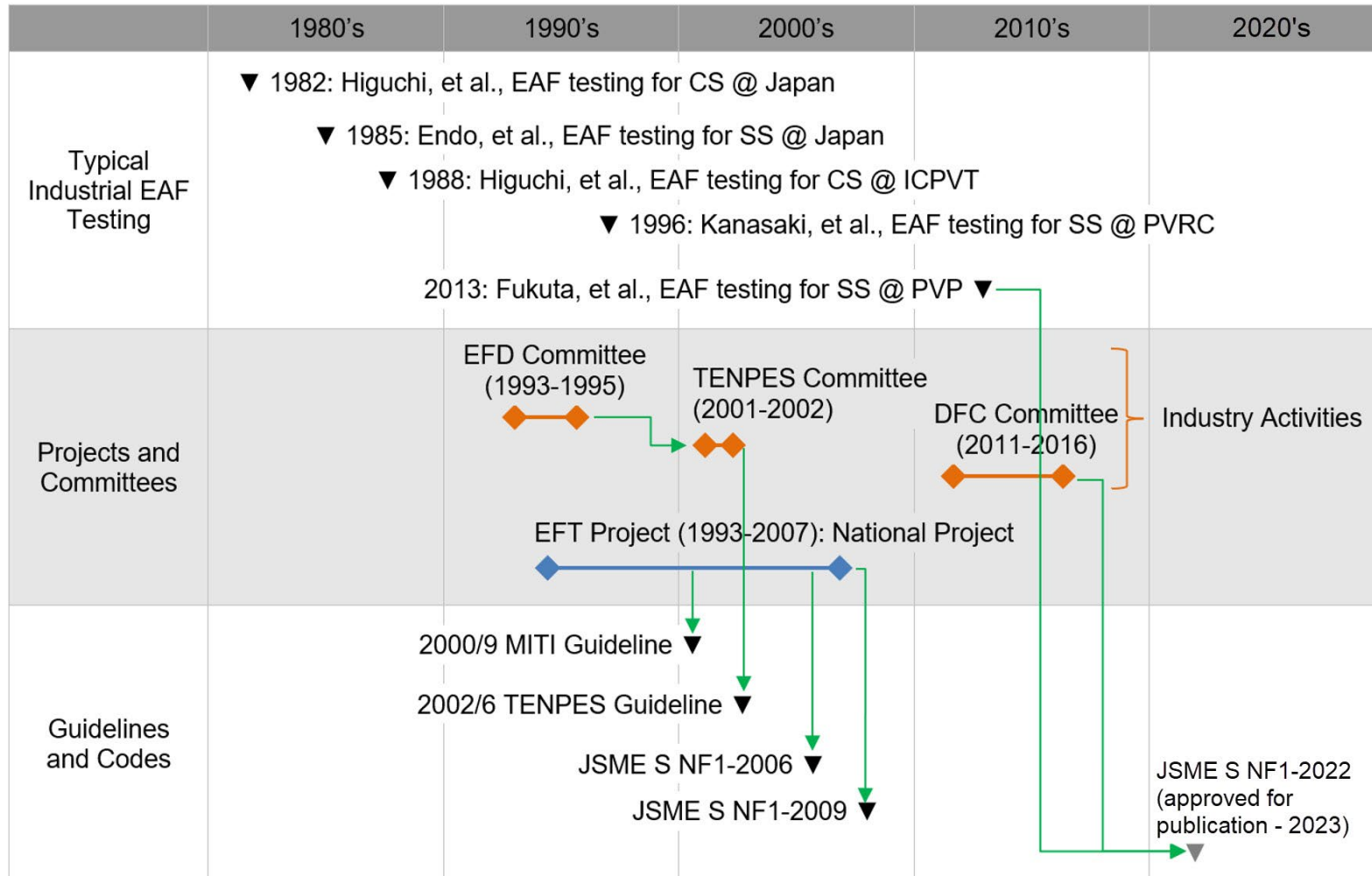


Figure 2-1
Historical Timeline of EAF in the U.S. Nuclear Industry

Table 2-1
History of Japanese EAF Methods



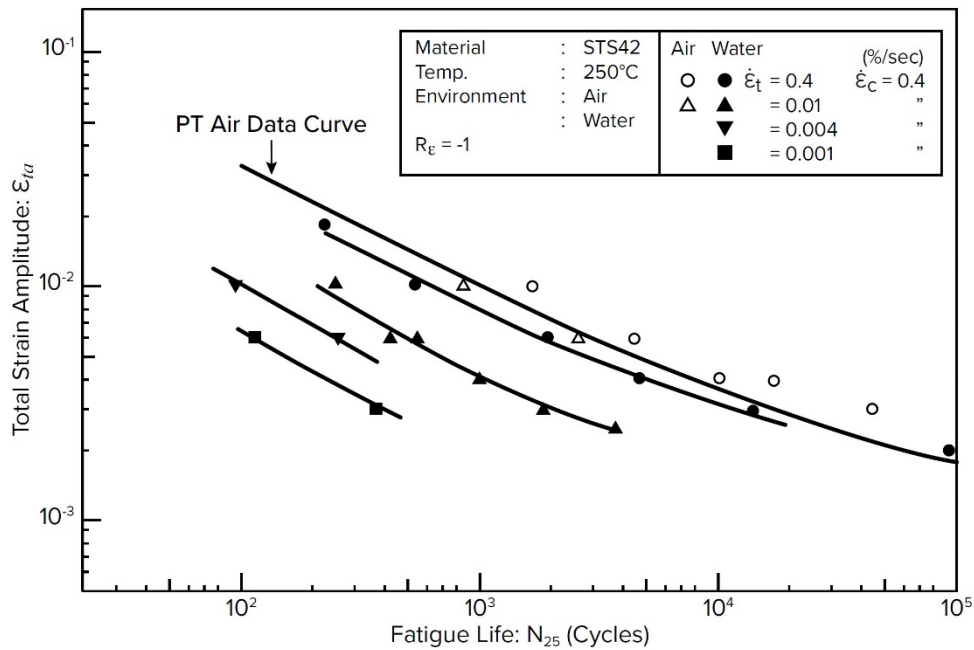


Figure 2-2
Relation Between Total Strain Amplitude and Fatigue Life for Carbon Steel Piping Material in Pure Water at 250°C and 8 ppm DO

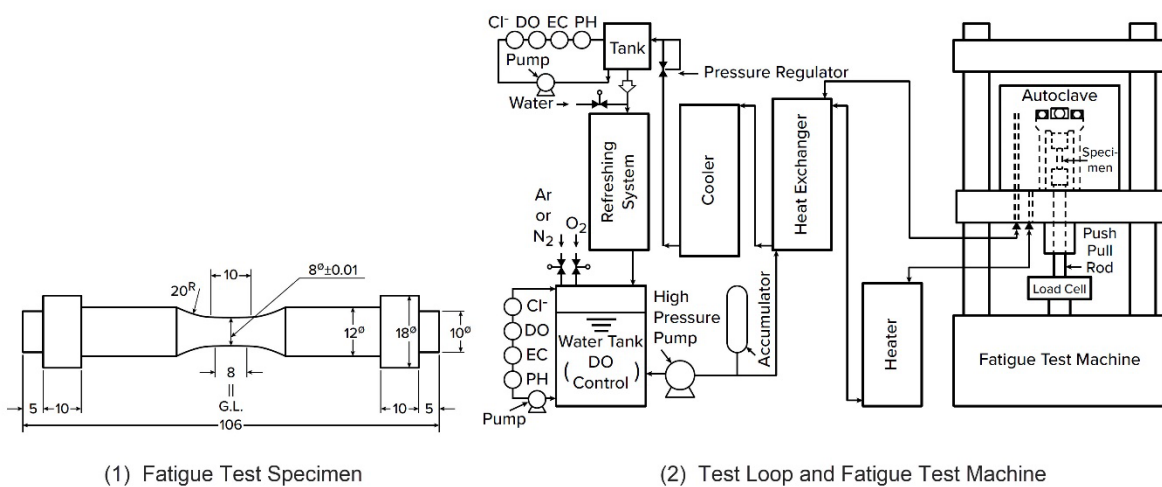


Figure 2-3
Fatigue Test Equipment for Carbon Steel Piping Material in Pure Water at 250°C and 8 ppm DO

(Figure 2-2 and Figure 2-3 reprinted from [29] by permission of the Iron and Steel Institute of Japan. All rights reserved.)

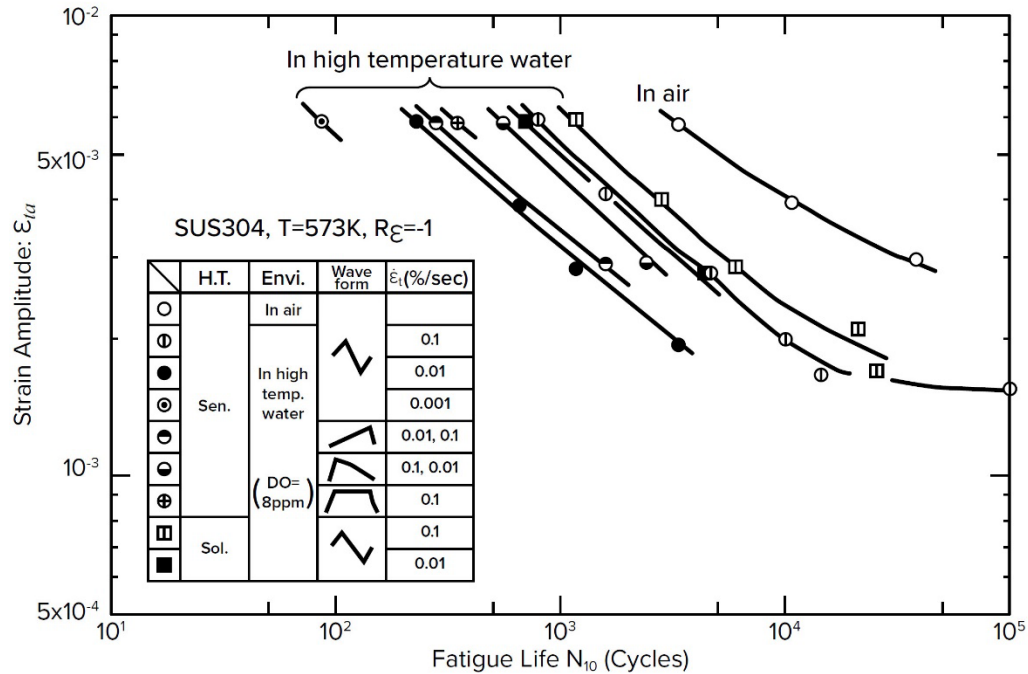


Figure 2-4
Relation Between Total Strain Amplitude and Fatigue Life for 304 Austenitic Stainless Steel in Pure Water at 300°C and 8 ppm DO

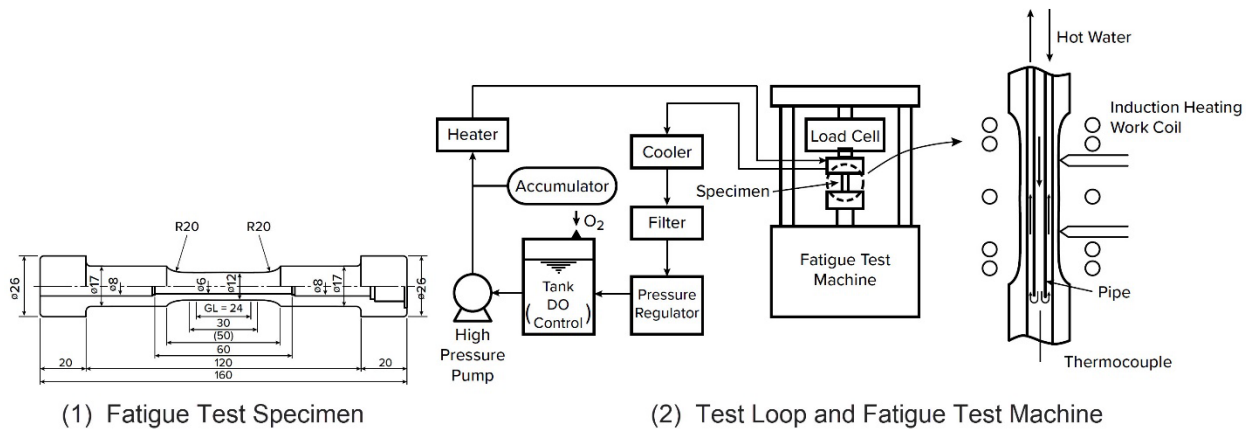


Figure 2-5
Fatigue Test Equipment for 304 Austenitic Stainless Steel in Pure Water at 300°C and 8 ppm DO

(Figure 2-4 and Figure 2-5 reprinted from [30] by permission of the Japan Materials Society Editorial Committee. All rights reserved.)

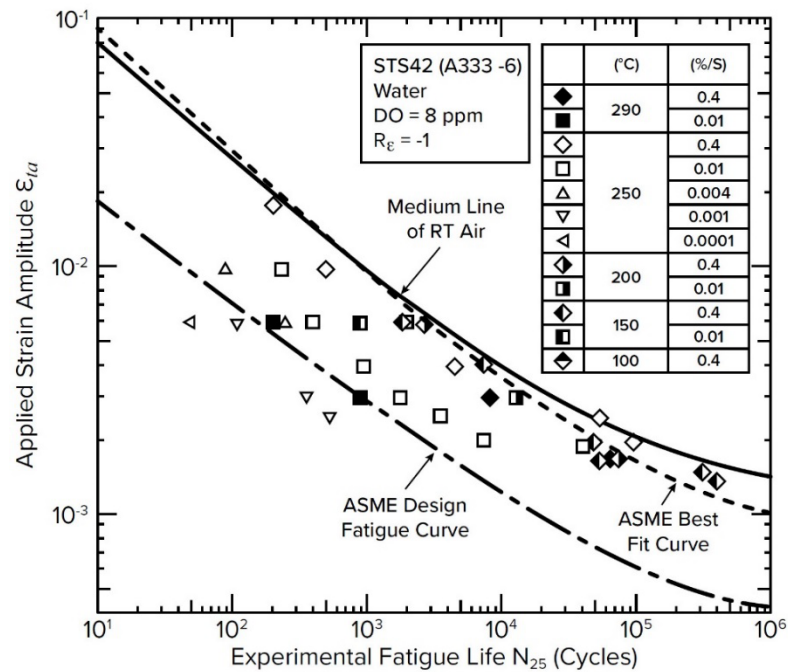


Figure 2-6
Fatigue Test Data for Carbon Steel in Various Test Conditions

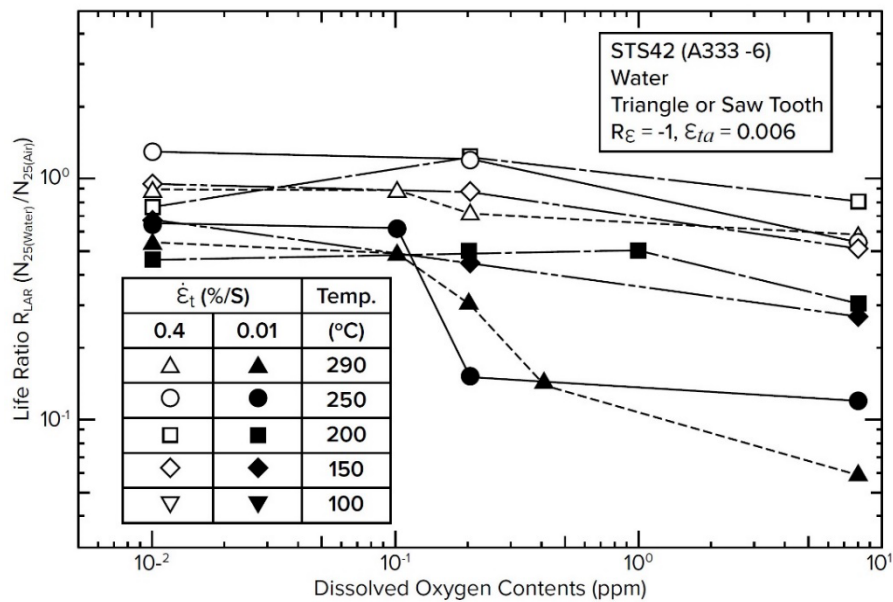


Figure 2-7
Relation of Fatigue Life Ratio (= $N_{25(water)}/N_{25(Air)}$) Fatigue Test Data for Carbon Steel in Various Test Conditions

(Figure 2-6 and Figure 2-7 reprinted from [31] by permission of Elsevier Books. All rights reserved.)

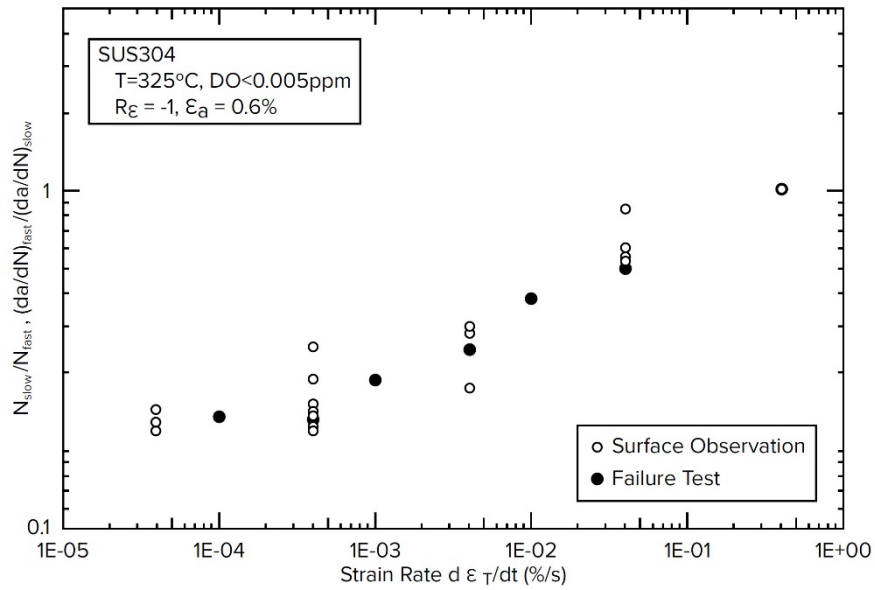


Figure 2-8
Comparison of Strain Rate Dependency Obtained by Surface Observation and Fatigue Tests

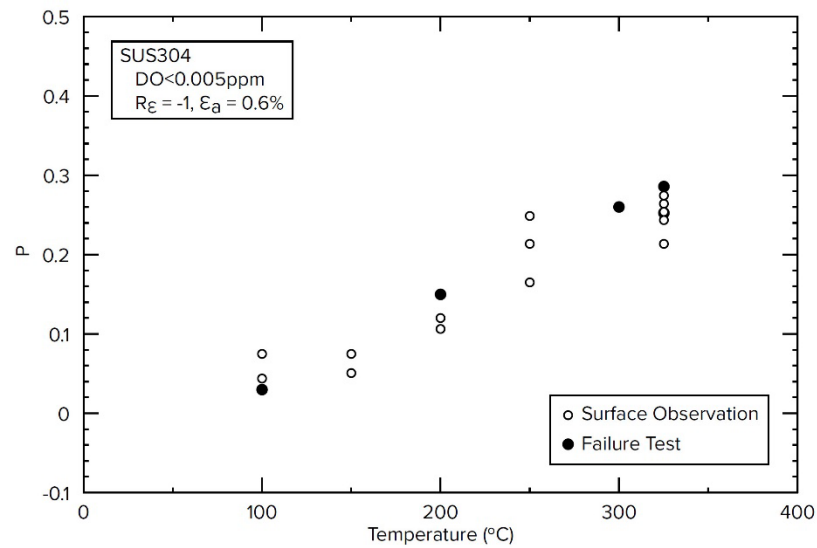


Figure 2-9
Comparison of Temperature Dependency Obtained by Surface Observation and Fatigue Tests

3

SUMMARY OF FATIGUE DATA

To obtain the original ASME Section III [2] fatigue curves, best-fit curves to the experimental fatigue data without environmental effects were decreased by an adjustment factor of either two on stress (which affects the HCF portion of the S-N curve) or 20 on cycles (which affects the LCF portion of the S-N curve), whichever is more limiting. These adjustment factors are not safety factors and were intended to account for uncertainties to cover scatter of data, size effect, surface finish, and atmosphere (environment). NUREG/CR-6909 summarizes the historic division of the adjustment factor of 20 found in the ASME Section III criteria document as follows:

Scatter of data (minimum to mean)	2.0
Size effect	2.5
Surface finish, atmosphere, and so on	4.0

NUREG/CR-6909, Revision 1 [1] contains background information related to each of the subfactors, which is summarized herein unless otherwise cited. The subfactor of 4.0 was meant to account for a combination of effects, including the atmosphere or environment seen by the fatigue test specimens. The subfactor was determined to be insufficient to bound the degradation seen in LWR environments as shown by the testing documented in NUREG/CR-6909. Under certain laboratory environmental and loading conditions, the fatigue life of small-scale, polished laboratory specimens in reactor water relative to those in air can be a factor of approximately 15 lower for austenitic stainless steels, a factor of approximately four lower for nickel-base alloys, and a factor of more than 50 lower for carbon and low-alloy steels in highly oxygenated water.

The fatigue life models for estimating fatigue in LWR environments are based on an analysis comparing the S-N data in air to the S-N data in LWR environments. These fatigue life models form the basis for the environmental fatigue correction factor (F_{en}) method for incorporating the effects of LWR environments into ASME Code Section III fatigue evaluations. Since F_{en} is a multiplier on the air curves, the use of the F_{en} requires in-air design fatigue curves that do not contain an implicit correction for environment that was originally part of the fatigue curve subfactors. This avoids potentially double counting the environment penalty.

Section 3.1 provides a summary of the fatigue data available that is used to establish F_{en} as of the publication of this report, focusing on a summary of the NRC-sponsored research performed by ANL to review a large body of domestic and international materials testing on corrosion fatigue, including data from the Japanese testing discussed in Section 2.2. This research has formed the basis for the F_{en} factors applied to the fatigue curves proposed in NUREG/CR-6909, Revision 1. Section 3.2 provides a summary of the research on the in-air fatigue curves since these are necessary to appropriately calculate the contributions of the environment.

3.1 Fatigue Strain vs. Life Behavior in LWR Environments

ANL researched the effects of LWR environments on the fatigue behavior in carbon, low alloy, austenitic stainless, and nickel-based (Ni-Cr-Fe) alloy steels. Failure during fatigue testing of these materials is defined as a 25% reduction in load in small-scale, polished laboratory specimens with an average gauge diameter of about 0.2 to 0.375 in (5.1 to 9.5 mm). This corresponds to the formation of surface cracks and their growth to an engineering depth of 0.118 in (3 mm) deep. This 25% load drop crack depth is defined for these materials as the mean fatigue life, which is then reduced by factors to develop the S–N design fatigue curves in the ASME Code, Section III, Appendix I [2]. Fatigue life has conventionally been divided into two stages: Stage I = crack initiation, expressed as the number of cycles required to nucleate microcracks on the material's surface; and Stage II = crack propagation, expressed as the number of cycles required to propagate the surface cracks to an engineering relative size for which linear elastic fracture mechanics would be applicable. Because of the use of 25% load drop to define crack initiation in the fatigue design curves, the curves have some amount of Stage II included. The database was normalized to be consistent with the 25% load drop criterion.

During cyclic loading of polished cylindrical laboratory test specimens, surface cracks 0.4 mils (10 μm) or longer form early in life, that is, less than 10% of the test life, at surface irregularities either already in existence or produced by slip bands, grain boundaries, second-phase particles, and so on. Thus, fatigue life defined by the ASME Code fatigue curves may be considered to constitute propagation of cracks from 0.4 to 118 mils (10 to 3000 μm) long.

Based on the S–N data comparison, the key parameters affecting the fatigue lives of these materials in LWR environments were determined to be temperature, strain rate and strain amplitude, *DO* level in the water and, for carbon and low-alloy steels, the sulfur content of the steels. In addition, this comparison determined that environmental effects on fatigue lives are only significant when the key parameters meet certain threshold values. When any one of the key parameters does not satisfy its threshold condition, the environmental effects are moderate (e.g., less than a factor of 2 decrease in fatigue lives). The threshold values for each key parameter are discussed in more detail in Section 4.

3.1.1 EAF on Carbon and Low Alloy Steels

The carbon and low-alloy steel corrosion fatigue database consists of data from approximately 1,174 tests, which represented 638 tests on carbon steels and 536 tests on low-alloy steels. Carbon steels included in the ANL evaluation represented approximately twenty-one heats of A106 Grades B and C, A333 Grade 6, A508 Grade 1, A226 Class 4, and A516–G70 steels. The low alloy steel tests included twenty heats of A302 Grade B, A508 Grades 2 and 3, A533 Grade B, 15MnNi63, and 17MnMoV64 steels. All the LWR data sources for carbon and low alloy steels are summarized in Table 4-1 of NUREG/CR-6909, Revision 1.

3.1.1.1 Effect of Temperature on Carbon and Low Alloy Steel Fatigue

The change in the fatigue life for two heats of A333 Grade 6 carbon steel, with test temperature at *DO* levels of less than 0.05 and greater than 1 ppm, was evaluated in tests where the applied strain amplitude was above and strain rate was below their respective critical thresholds. The two heats had a fatigue life of 2,993 cycles in air. The results indicated a threshold temperature of 302°F (150°C), above which the environment decreased fatigue life if the *DO* level in the water

was also above the critical level of 0.05 ppm. In the temperature range of 302 to 608°F (150 to 320°C), the logarithm of fatigue life was found to decrease linearly with temperature; the decrease in life was greater at higher temperatures and *DO* levels. Only a moderate decrease in fatigue life was observed in water at temperatures below the threshold value of 302°F (150°C) or at *DO* levels less than or equal to 0.05 ppm. Under these conditions, fatigue life in water was a factor of approximately two lower than in air.

3.1.1.2 Effect of Dissolved Oxygen on Carbon and Low Alloy Steel Fatigue

The dependence of fatigue life of carbon steel on the *DO* content in water was also investigated. Tests were conducted with the test temperature, applied strain amplitude, and sulfur content in the steel above the critical threshold values and the strain rate below the critical threshold values. The results indicated that the fatigue life was not further affected below a minimum *DO* level of 0.04 ppm or above a maximum *DO* level of 0.5 ppm. For *DO* levels between 0.04 and 0.5 ppm, fatigue life decreased logarithmically with the *DO* level.

In low *DO* PWR or hydrogen water chemistry (HWC) BWR environments (*DO* levels below 0.04 ppm) the environmental effects on the fatigue life of carbon and low-alloy steels were found to be insignificant where strain rates are greater than or equal to 1%/s. In contrast, environmental enhancement of crack growth rates has been observed in low alloy steels even in low *DO* water. This apparent inconsistency of fatigue S-N data with the crack growth rate data was attributed to differences in the local environment at the crack tip. The initiation of environmentally assisted enhancement of crack growth rates in low alloy steels requires a critical level of sulfides at the crack tip. The development of this critical sulfide concentration requires a minimum crack extension of 13 mils (0.33 mm) and crack growth rates in the range of 1.8×10^{-2} to 5.95×10^{-5} in/h (1.3×10^{-4} to 4.2×10^{-7} mm/s). These conditions were not achieved within the majority of the available fatigue S-N tests. Thus, environmental effects on fatigue life are expected to be insignificant in low *DO* environments for carbon and low alloy steels.

3.1.1.3 Effect of Sulfur Content on Carbon and Low Alloy Steel Fatigue

The sulfur content of the materials and their morphologies are the most important material-related parameters that determine susceptibility of low alloy steels to environmentally enhanced fatigue crack growth rates. A critical concentration of S^{2-} or HS^- ions is required at the crack tip for environmental effects to occur. Both the corrosion fatigue crack growth rates and the threshold stress intensity factor, ΔK_{th} , are a function of the sulfur content in the range 0.003 to 0.019 wt.%. The probability of environmental enhancement of fatigue crack growth rates in pre-cracked specimens fabricated from low alloy steel appears to diminish markedly for *S* contents less than 0.005 wt.%.

3.1.2 EAF on Austenitic Stainless Steels

The austenitic stainless steel corrosion fatigue database consists of data from approximately 683 tests that included 193 tests on eleven heats of Type 304 stainless steel, 255 tests on eight heats of Type 316 stainless steel, 115 tests on seven heats of CF-8M cast austenitic stainless steels, and 120 tests on six compositions of stainless steel weld metals. The database included both low-carbon and high-carbon grades of Types 304 and 316 stainless steels. For all stainless steel data, 15% of the tests were conducted at temperatures of 212–392°F (100–200°C), 39% at 482–554°F

(250–290°C), 44% at 572–617°F (300–325°C), and 1% (10 tests) at 680°F (360°C). All the LWR data sources for stainless steels are summarized in Table 4-2 of NUREG/CR-6909, Revision 1.

3.1.2.1 Effect of Temperature on Austenitic Stainless Steel Fatigue

The results of tests evaluating the effect of test temperature on fatigue lives of austenitic stainless steels at two strain amplitudes and two strain rates suggested a threshold temperature of 212°F (100°C), above which the environment decreased the fatigue life in low *DO* water if the strain rate was below 0.4%/s. This strain rate was the threshold strain rate in NUREG/CR-6909, Revision 0 [48] but has been modified to be 7%/s in Revision 1 based on a reanalysis of the data [1]. In the range of 212–617°F (100–325°C), the logarithm of fatigue life decreased linearly with temperature. Environmental effects either did not occur or were insignificant at temperatures below the threshold value of 212°F (100°C).

3.1.2.2 Effect of Dissolved Oxygen on Austenitic Stainless Steel Fatigue

In contrast to the behavior of carbon and low alloy steels, the fatigue lives of austenitic stainless steels decreased significantly in low *DO* water (that is, less than 0.05 ppm). In low *DO* water, the fatigue lives were not influenced by the material composition or heat treatment. However, the fatigue lives continued to decrease with decreasing strain rate in the range of 7–0.0004%/s and increasing temperature in the range of 212–617°F (100–325°C).

For a high-carbon Type 304 stainless steel, environmental effects in high-*DO* water were insignificant for mill annealed material, that is, non-sensitized steel, whereas the effects of the environment were the same for sensitized material in high- and low-*DO* water. For low-carbon Type 316NG stainless steels, some effects of strain rate were apparent in high-*DO* water, although they were smaller than those in low-*DO* water.

3.1.3 EAF on Nickel-Based Alloys

The nickel-based alloy steel corrosion fatigue database consists of data from approximately 162 tests, including 87 tests on five heats of Alloy 600, 21 tests on two heats of Alloy 690, and 54 tests on six heats of Ni-Cr-Fe alloy weld metals that included Alloys 82, 182, 132, and 152. Out of these, seven tests were conducted at 212°F (100°C), one test at 129°F (54°C), ten tests at 392°F (200°C), 88 tests at 552°F (289°C), ten tests at 599°F (315°C), and 47 tests at 617°F (325°C). All the LWR data sources for nickel-base alloy steels are summarized in Table 4-3 of NUREG/CR-6909, Revision 1.

3.1.3.1 Effect of Temperature on Nickel-Based Alloy Fatigue

The results of limited testing of Alloy 600 in PWR environments at three different strain amplitudes as a function of temperature indicated a decrease in fatigue lives with increasing temperature. Because of very limited fatigue data for nickel-based (Ni-Cr-Fe) alloys, as discussed below, the effects of temperature on the fatigue lives of these materials were also assumed to be similar to those observed in austenitic stainless steels. Environmental effects on fatigue lives below a threshold temperature of 122°F (50°C) were insignificant. In addition, it was assumed that a slow strain rate applied during the tensile-loading cycle (that is, up ramp with increasing strain) was primarily responsible for the environmentally assisted reduction in fatigue

lives. Slow rates applied during both tensile- and compressive-loading cycles (that is, up and down ramps) did not further decrease fatigue lives compared with those observed for tests with only a slow tensile loading cycle. Thus, loading and environmental conditions during the tensile-loading cycle are important for an environmentally assisted reduction in the fatigue lives of Ni-Cr-Fe alloys. In addition, the available fatigue ε - N data for Ni-Cr-Fe alloys in LWR environments did not define the threshold strain amplitude, below which, environmental effects on fatigue lives did not occur.

3.1.3.2 Effect of Dissolved Oxygen on Nickel-Based Alloy Fatigue

Test results indicated that the effects of environment are greater in low *DO* PWR water than in high *DO* BWR water. However, under similar loading and environmental conditions, the extent of the effects of environment were considerably less for the Ni-Cr-Fe alloys compared to that for austenitic SSs. In general, environmental effects on fatigue lives were the same for wrought and weld Ni-Cr-Fe alloys.

3.1.4 Impact of Strain Rate and Amplitude on Environmental Effects

The variations in fatigue life in air due to the effects of strain rate were generally accounted for in the subfactor for “data scatter and material variability” in carbon and low alloy steels or were deemed inconsequential to in-air fatigue for stainless steels [1]. The research indicated that strain rate had a much more significant effect in the water environment than anticipated and is one of the primary factors influencing F_{en} . Specifically, in a primary water environment:

- **Carbon and Low Alloy Steels.** The effects of strain rate on the fatigue lives were determined to be significant when other key threshold conditions (e.g., strain amplitude, temperature, and *DO* content), were satisfied.¹ When any one of the threshold conditions was not satisfied (e.g., if *DO* values less than 0.04 ppm for a PWR environment or temperatures less than 150°C were present), the effects of strain rate were consistent with those observed in air. When all threshold conditions were satisfied, the fatigue lives of carbon and low-alloy steels decreased logarithmically with decreasing strain rate. [1, Section 4.1.2]
- **Stainless Steels.** In low-*DO* PWR environments, the fatigue lives of austenitic SSs decreased with decreasing strain rates below approximately 7%/s; the effects of environment on fatigue lives saturated at approximately 0.0004%/s. Environmental effects did not occur at strain rates greater than 7%/s (i.e., $F_{en} = 1$). In combination with sufficiently high temperature, decreases in the strain rate from 7 to 0.0004%/s reduced the fatigue lives by more than a factor of 10. In high-*DO* water at 288°C, the effects of strain rate were less pronounced than they were in low-*DO* water. [1, Section 4.2.2]
- **Nickel-based (Ni-Cr-Fe) Alloy Steels.** Given the limited available data, the effects of strain rate on Ni-Cr-Fe alloys were assumed to be similar to those for austenitic SSs and the effects were assumed to saturate at a strain rate of 0.0004%/s. [1, Section 4.3.2]

¹ Satisfied in this context means that the conditions are within the specified ranges determined from the testing and reflected in the F_{en} equations in Section 4.

For these materials, minimum strain amplitude threshold values (see Section 4 and 5.2.2) are required for the environmentally induced decrease in fatigue lives to occur.

3.1.5 Effect of LWR Environments on Corrosion Fatigue Summary

The fatigue S-N data for carbon, low alloy, wrought and cast austenitic stainless, and Ni-Cr-Fe alloy steels were evaluated by ANL to define the effects of key material, loading and environmental parameters on the fatigue lives of these alloys. The fatigue lives of these materials decrease in LWR environments for polished, small-scale laboratory specimens; the magnitude of the reduction depends on temperature, strain rate, *DO* content of the water, and, for carbon and low alloy steels, the sulfur content of the steel. For all these materials, environmental effects on fatigue life are significant only when critical parameters (for example, temperature, strain rate, *DO* level and strain amplitude) meet certain threshold values. Environmental effects are insignificant when any one of the threshold conditions is not satisfied. For all materials, environmental effects on fatigue life occur primarily during the tensile loading cycle and at strain levels greater than the threshold value.

In summary:

- **Carbon and Low Alloy Steels.** The corrosion fatigue data in LWR environments indicate a significant decrease in fatigue life of carbon and low alloy steels in small-scale, polished laboratory specimens when five key threshold conditions are satisfied simultaneously: service temperature and *DO* in the water are above a minimum threshold, the loading strain rate is below a threshold value or the strain amplitude is above a certain threshold value, and the sulfur content is above a certain threshold (the effect of sulfur content depends on the bulk *DO* level in the water). Although the microstructures and cyclic-hardening behavior of carbon and low alloy steels are significantly different, environmental degradation of fatigue life for these steels is nearly identical. For both steels, environmental effects on fatigue life are moderate, that is, a factor of approximately two lower, if any one of the key threshold conditions is not satisfied.
- **Austenitic Stainless Steels.** The fatigue lives of cast and wrought austenitic stainless steels decrease in LWR environments compared to those in air. The fatigue life in small-scale, polished laboratory specimens decreased significantly when three threshold conditions are satisfied simultaneously: applied strain range and service temperature are above minimum threshold levels, and the loading strain rate is below a threshold value. The *DO* content of the water and, to some extent, the composition and heat treatment of the steel are also important parameters for environmental effects on fatigue life. A minimum threshold strain amplitude is required (see Section 4.1.2) for an environmentally assisted decrease in the fatigue life of stainless steels. This strain amplitude was found to be independent of material type (weld or base metal) and temperature in the range of 482–617°F (250–325°C). Strain rate and temperature have a strong effect on fatigue life of stainless steels in LWR environments. Fatigue life decreases with decreasing strain rate below 7%/s; the effect saturates at 0.0004%/s. Similarly, the fatigue S-N data suggest a threshold temperature of 212°F (100°C); in the range of 212–617°F (100–325°C), the logarithm of life decreases linearly with temperature. For some stainless steels, fatigue life is longer in high-*DO* water than in low-*DO* PWR environments. Although the fatigue life in air of Type 316NG stainless steel is slightly longer than that of Types 304 and 316 stainless steels, the effects of LWR

environments are comparable for wrought Types 304, 316 and 316NG stainless steels. The available data indicate that the fatigue life of cast austenitic stainless steels in both low-*DO* and high-*DO* environments is comparable to that of wrought stainless steels in low-*DO* environments.

- **Nickel-based (Ni-Cr-Fe) Alloy Steels.** The fatigue data for Ni-Cr-Fe alloy steels in LWR environments is limited. Similar to carbon, low alloy, and austenitic stainless steels, the fatigue lives of Ni-Cr-Fe alloys and their weld metals are also decreased in LWR environments for small-scale, polished laboratory specimens. For example, the fatigue life of these alloys decreases logarithmically with decreasing strain rate. The test results indicate that environmental effects on the fatigue life of Ni-Cr-Fe alloys are strongly dependent on key parameters such as strain rate, temperature, and the *DO* level in water. Similar to stainless steels, the effect of a water environment on the fatigue life of Ni-Cr-Fe alloys is greater in the low *DO* PWR environment than in the high *DO* BWR environment. However, under similar loading and environmental conditions, the extent of the effects of environment is considerably less for the Ni-Cr-Fe alloys than for austenitic stainless steels. In general, environmental effects on fatigue life are the same for wrought and weld nickel-based alloys.

3.2 Fatigue Strain vs. Fatigue Life Behavior in Air

The original ASME Code Section III fatigue curves were based primarily on strain-controlled fatigue tests of small, polished specimens at room temperature in air environments. Best-fit curves to the experimental test data were first adjusted to account for mean stress effects using the modified Goodman relationship, followed by reducing the mean stress adjusted curves by factors of 2 on stress or 20 on cycles. These factors were intended as “adjustment factors” that were applied to the experimental laboratory data to obtain estimates of the fatigue lives of actual reactor components (i.e., not factors of safety to overall component life). The adjustment factors addressed things like surface finish and environment (which was underestimated). The best-fit curves for the various materials provided an estimate of the fatigue life that would lead to failure in 50% of the population under a given loading.

NUREG/CR-6909 includes the database compiled by the Pressure Vessel Research Council (PVRC) that was used to develop the ASME Code Section III design fatigue curves. In addition, the database was significantly expanded to include the Japan Nuclear Energy Safety Organization (JNES) data summarized in JNES-SS-1005, “Environmental Fatigue Evaluation Method for Nuclear Power Plants,” [41] and data obtained from open literature fatigue S-N test results on several heats of carbon and low-alloy steels tested in BWR environments. In general, the expanded database was obtained from smooth cylindrical gauge specimens that were tested under strain-control with fully reversed loading. In nearly all tests, fatigue life was defined as the number of cycles necessary for the tensile stress to drop 25% from its peak or steady-state value.

Based on the expanded database, ANL redeveloped best-fit curves for each material. Consistent with the approach used to develop the original ASME Code Section III fatigue curves, the best-fit curves were corrected for mean stress effects by using the modified Goodman relationship. The effects of temperature, strain rate, sulfide morphology, cyclic strain hardening behavior, heat-to-heat variability, and surface finish were all considered in development of the best-fit curves. The primary differences between the NUREG/CR-6909 in air fatigue curves and the original ASME Code Section III design fatigue curves are summarized below:

1. Different adjustment factors

The original ASME Section III fatigue curves included an adjustment factor of 20 on cycles for carbon and low-alloy steels and austenitic SSs to account for the effects of material variability and data scatter, specimen size, surface finish, and loading history. In the ANL curve development documented in NUREG/CR-6909, Revision 1, the factor of 20 on cycles in the original ASME Section III fatigue curves was determined to be conservative by at least a factor of 1.7 when environmental effects were not considered. This, combined with the revised mean curve development, resulted in modified ‘in-air’ design fatigue curves, using an adjustment factor of 12 on cycles instead of the traditional factor of 20. These revised curves can now be used in determining an explicit correction for environment. Per Regulatory Guide 1.207 [3], the fatigue design curves for carbon and low-alloy steels and austenitic stainless from either NUREG/CR-6909, Revision 1 or Section III Appendix I of the 2013 Edition (or later) of the ASME Code may be used to determine the fatigue lives of those materials.

2. Consistent austenitic SS test database and fatigue curve

The original ASME Code Section III fatigue curve for austenitic SSs was not consistent with the fatigue S-N data collected during the ANL research that was originally documented in NUREG/CR-6909, Revision 0. The fatigue lives predicted by the original ASME Code Section III mean air curves were longer than those obtained from experiments. The updated ASME Section III fatigue curves incorporated the refined data into the austenitic stainless steel fatigue curve in Section III, Mandatory Appendix I, 2009 Edition.

3. Extension of carbon/low-alloy steel fatigue curve from 10^6 to 10^{11} cycles

NUREG/CR-6909, Revision 0 extended the fatigue design air curve for carbon and low-alloy steels from 10^6 to 10^{11} cycles. Subsequently, the updated ASME Section III fatigue curves for carbon and low-alloy steels were extended in the 2011 Edition from 10^6 to 10^{11} cycles with a technical basis that is consistent with NUREG/CR-6909, Revision 1. The methodology used to extend the updated ASME Section III fatigue curves contained additional conservatism in this high cycle regime to account for more recent vibration data compared to Revision 0 of NUREG/CR-6909.

The differences between the original ASME fatigue curves prior to the 2009 Code Edition and the NUREG/CR-6909, Revision 1 curves are shown in Figures 3-1 through 3-3 below. When conducting an EAF evaluation using F_{en} calculated from NUREG-6909, the partial usage factors should be based on the NUREG/CR-6909 fatigue curves, rather than the original or updated ASME fatigue curves.



Key Point

For austenitic stainless steel, the NUREG/CR-6909 curves are substantially more conservative in the transition region compared to the Section III fatigue curve prior to the 2009 Addenda, potentially resulting in up to a factor of 10 decrease in fatigue life. Therefore, it is vitally important to assess the fatigue curves used in the CUF calculation relative to those specified for the development of the F_{en} factor to ensure the EAF evaluation is correct.

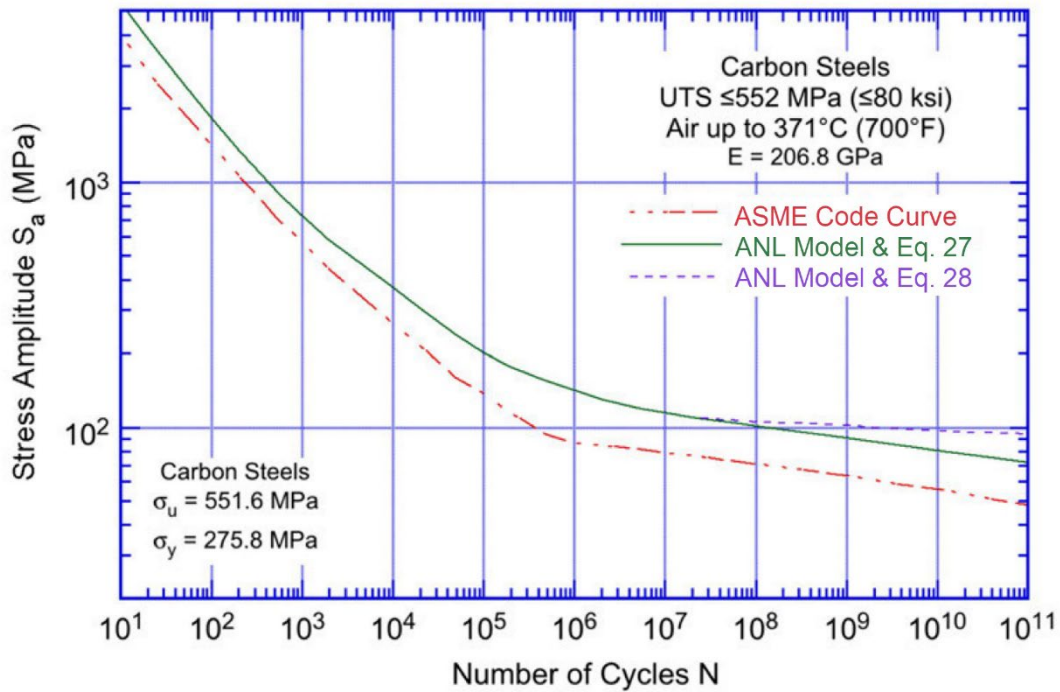


Figure 3-1
Comparison of Carbon Steel Fatigue Design Curves in Air [1]

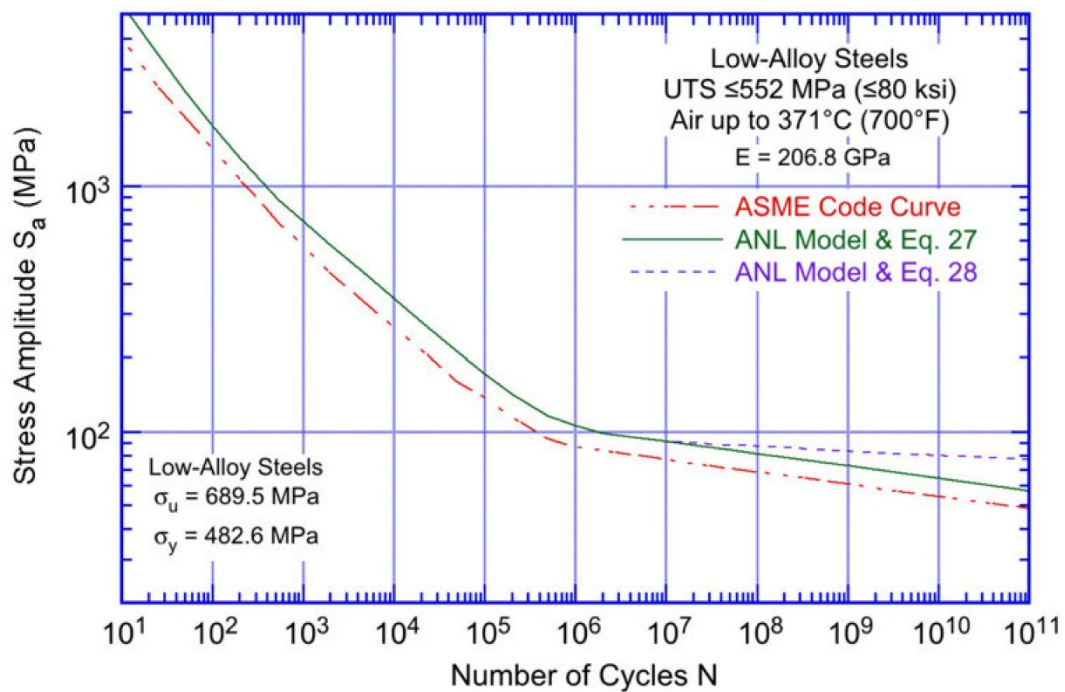


Figure 3-2
Comparison of Low-Alloy Steel Fatigue Design Curves in Air [1]

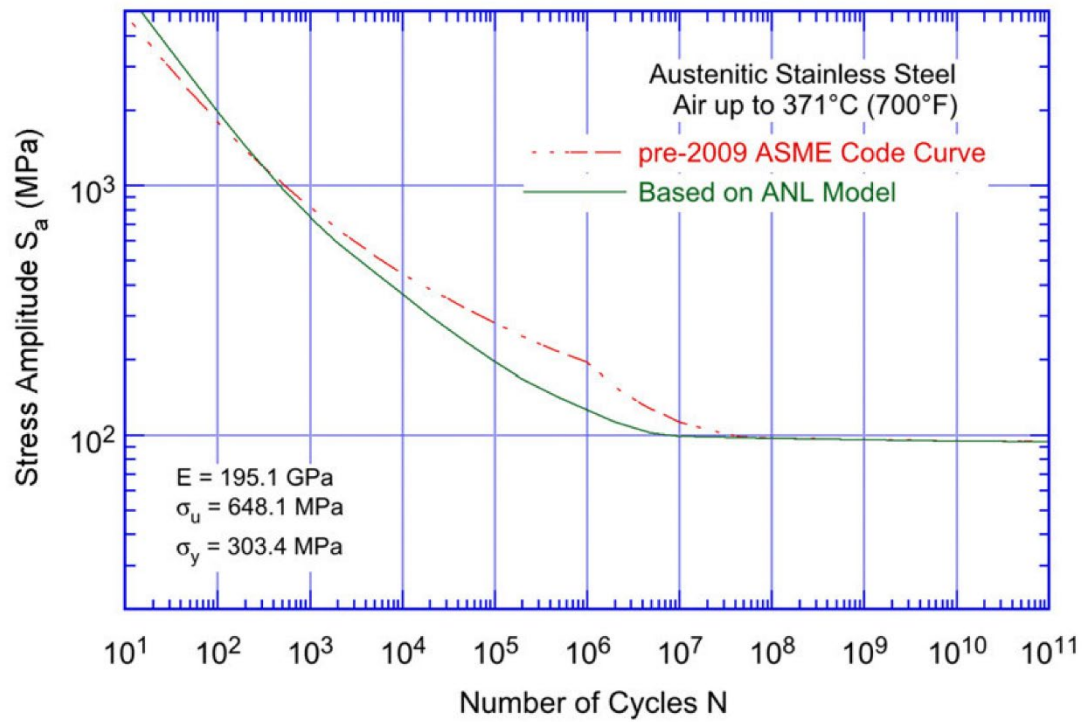


Figure 3-3
Comparison of Austenitic Stainless Steel and Nickel-Based Alloy Steel Fatigue Design
Curves in Air [1]

4

EAF CORRECTION FACTORS

Over the years, various methods have been proposed to assess the effect of LWR environment on the fatigue life of components in the primary coolant pressure boundary system. The latest and most common methods for addressing EAF are discussed in this section, based on developments in the United States and Japan. In both countries, the effects of LWR environments are accounted for by multiplying the partial fatigue usage factor by the environmental fatigue correction factor, F_{en} . The cumulative fatigue usage factor considering the environmental effects, CUF_{en} , is generally expressed as follows:

$$CUF_{en} = \sum_{i=1}^n (U_i * F_{en,i}) \quad \text{Eq. 4-1}$$

where,

i = transient stress cycle pair number from the design specification

n = the total number of transient stress cycle pairs

U_i = partial in air usage factor from the i^{th} transient stress cycle pair

$F_{en,i}$ = Environmental correction factor for the i^{th} transient stress cycle pair

CUF_{en} can be conservatively approximated by using a bounding F_{en} value. The simplest and most conservative approximation is to apply the maximum F_{en} value based on the correlations presented for each material below. That expression is:

$$CUF_{en} = CUF * F_{en,max} \quad \text{Eq. 4-1a}$$

This method is applicable to any component, or portion of a component, that is exposed to primary coolant and has been evaluated for CUF . Such components may include vessels, piping, pumps, valves, and reactor internals components.

The F_{en} correlations and methodologies from NUREG-6909, Revision 1 [1] and JNES-SS-0701/JSME S NF1 [35] are described in Sections 4.1 and 4.2, respectively. Other correlations available for international use, such as RCC-M-2017 Edition Section VI- RPP No. 3, KTA, and various ASME Code Cases are not discussed in this handbook. While each of the methods has different F_{en} expressions and does result in different F_{en} factors, it is difficult to examine the relative comparison of the F_{en} on EAF without also comparing the base in-air fatigue curves. However, in each formulation, temperature, dissolved oxygen, strain rates, and if applicable, sulfur content, are the key inputs governing EAF. Therefore, the approaches described in Section 5 may be used with any F_{en} formulation even though this report focuses mainly on the US and Japanese F_{en} approaches.

4.1 NUREG/CR-6909, Revision 1 F_{en} Correlations

The current technical basis for the environmental fatigue correction factor approach is provided in NUREG/CR-6909, Revision 1. The key parameters that influence fatigue life in these environments are temperature, the dissolved oxygen (DO) in the water, strain rate and amplitude, and, for carbon and low-alloy steels, the sulfur content of the steel. In general, F_{en} increases with increasing temperature and decreasing strain rate. The impact of dissolved oxygen content is material dependent, with increasing DO being detrimental to carbon and low-alloy steels but beneficial to austenitic stainless steel. The following sections provide the current expressions for F_{en} that have been developed based on the ANL fatigue life models for carbon and low alloy steels, austenitic stainless steels, and nickel-based alloys. Previous versions of F_{en} that have been used U.S. license renewals are documented in Appendix B. The following parameters are used in the calculation of F_{en} :

- S is the sulfur content of the steel in wt. %
- T is the metal surface temperature in °C
- DO is the dissolved oxygen content of the water in ppm
- $\dot{\epsilon}$ is the strain rate in %/s

4.1.1 Carbon and Low-Alloy Steels

The F_{en} expressions for carbon and low-alloy steels are given in Equations (A.2) to (A.7) of NUREG/CR-6909, Revision 1 as:

$$F_{en} = \exp([0.003 - 0.031\dot{\epsilon}^*] S^* T^* O^*) \quad \text{Eq. 4-2}$$

where,

$$S^* = 2.0 + 98 S \quad (S \leq 0.015 \text{ wt } \%)$$

$$S^* = 3.47 \quad (S > 0.015 \text{ wt } \%)$$

$$T^* = 0.395 \quad (T < 150^\circ\text{C})$$

$$T^* = (T - 75)/190 \quad (150^\circ\text{C} \leq T \leq 325^\circ\text{C})$$

$$O^* = 1.49 \quad (DO < 0.04 \text{ ppm})$$

$$O^* = \ln(DO/0.009) \quad (0.04 \text{ ppm} \leq DO \leq 0.5 \text{ ppm})$$

$$O^* = 4.02 \quad (DO > 0.5 \text{ ppm})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 2.2\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/2.2) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 2.2\%/s)$$

$$\dot{\epsilon}^* = \ln(0.0004/2.2) \quad (\dot{\epsilon} < 0.0004\%/s)$$

In addition, a threshold value of either 0.07% for strain amplitude (one-half the strain range for the cycle) or a stress amplitude of 21.0 ksi [145 MPa] is defined, below which environmental

effects on the fatigue lives of these steels may not occur (i.e., $F_{en} = 1.0$). However, this threshold should not be applied in the formulation of a modified rate approach to F_{en} calculation, as discussed in Section 4.4 of NUREG/CR-6909, Revision 1.

4.1.2 Austenitic Stainless Steels

The F_{en} expressions for wrought and cast austenitic stainless steels are given in Equations (A.8) to (A.13) of NUREG/CR-6909, Revision 1 as:

$$F_{en} = \exp(-T^* \dot{\epsilon}^* O^*) \quad \text{Eq. 4-3}$$

where,

$$T^* = 0 \quad (T < 100^\circ\text{C})$$

$$T^* = (T - 100)/250 \quad (100^\circ\text{C} \leq T \leq 325^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 7\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/7) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 7\%/s)$$

$$\dot{\epsilon}^* = \ln(0.0004/7) \quad (\dot{\epsilon} < 0.0004\%/s)$$

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

$$O^* = 0.29$$

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

$$O^* = 0.29 \text{ (sensitized high carbon wrought and cast SSs)}$$

$$O^* = 0.14 \text{ (all other wrought SSs)}$$

In addition, a threshold value of either 0.1% for strain amplitude (one-half the strain range for the cycle) or a stress amplitude of 28.3 ksi (195 MPa) is defined, below which, environmental effects on the fatigue lives of these steels may not occur (i.e., $F_{en} = 1.0$). However, this threshold should not be applied in the formulation of a modified rate approach to F_{en} calculation, as discussed in Section 4.4 of NUREG/CR-6909, Revision 1.

4.1.3 Nickel-Based Alloy Steels

The F_{en} expressions for nickel-based alloy steels, except Inconel 718, are given in Equations (A.14) to (A.18) of NUREG/CR-6909, Revision 1 as:

$$F_{en} = \exp(-T^* \dot{\epsilon}^* O^*) \quad \text{Eq. 4-4}$$

where,

$$T^* = 0 \quad (T < 50^\circ\text{C})$$

$$T^* = (T-50)/275 \quad (50^\circ\text{C} \leq T \leq 325^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 5\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/5) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 5\%/s)$$

$$\dot{\epsilon}^* = \ln(0.0004/5) \quad (\dot{\epsilon} < 0.0004\%/s)$$

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

$$O^* = 0.14$$

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

$$O^* = 0.06$$

In addition, a threshold value of either 0.1% for strain amplitude (one-half the strain range for the cycle) or a stress amplitude of 28.3 ksi (195 MPa) is defined, below which, environmental effects on the fatigue lives of these steels may not occur (i.e., $F_{en} = 1.0$). However, this threshold should not be applied in the formulation of a modified rate approach to F_{en} calculation, as discussed in Section 4.4 of NUREG/CR-6909, Revision 1. This F_{en} expression is not applicable for Inconel 718 because of lack of data. [1, Appendix A]

4.2 JNES-SS-0701/JSME S NF1-2009

The current technical basis for the environmental fatigue correction factor approach in Japan is provided in JNES-SS-0701 (in Japanese) [39], which is based on the EFT Project [40] final report. JNES-SS-1005 [41] is the English translation of JNES-SS-0701. This report formed the basis for the current JSME guidance on environmental fatigue, which is the 2009 version of JSME S NF1 [35].

(The equations in Section 4.2 are reprinted from [39, 41] by permission of the Japan Nuclear Regulatory Authority. All rights reserved.)

4.2.1 Carbon and Low Alloy Steels and Associated Welds

$$\ln(F_{en}) = 0.00822(0.722 - \dot{\epsilon}^*) \times S^* \times T^* \times O^* \quad \text{Eq. 4-5}$$

where:

For $DO \leq 0.7$ ppm

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

For $DO > 0.7$ ppm

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

Transient conditions: In BWR environments, the F_{en} expression is applied to thermal transients. Also, for transients that have elastic follow-up due to pressure maintaining its peak value, the strain rate is assumed equal to 0.004 %/s when the strain rate is greater than 0.004 %/s.

4.2.2 Austenitic Stainless Steels and their Associated Welds

BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. 4-6}$$

where:

$$C = 0.992$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 2.69 \%/\text{s})$$

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

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

Transient conditions: In BWR environments, the F_{en} expression is applied to thermal transients. Also, for transients that have elastic follow-up due to pressure maintaining its peak value, the strain rate is assumed equal to the lower threshold strain rate.

PWR environments and PWR plant secondary system environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. 4-7}$$

where,

$$C = 3.910$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 49.9 \%/\text{s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 49.9 \%/\text{s for Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.0004) \quad (\dot{\epsilon} < 0.0004 \%/\text{s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.00004) \quad (\dot{\epsilon} < 0.00004 \%/\text{s for Cast SS})$$

$$T^* = 0.000782 \times T \quad (T \leq 325 \text{ }^\circ\text{C})$$

$$T^* = 0.254 \quad (T > 325 \text{ }^\circ\text{C})$$

4.2.3 Nickel-Based Alloys and their Associated Welds

BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. 4-8}$$

where,

$$C = -0.112$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 0.894 \%/\text{s})$$

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

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

PWR environments and PWR plant secondary system environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. 4-9}$$

where,

$$C = 2.94$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 19.0 \%/\text{s})$$

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

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

4.2.4 Threshold for Environmental Effects

The threshold strain amplitudes are as follows:

- 0.042 % or less for carbon and low alloy steels
- 0.11 % or less for austenitic stainless steels and high nickel alloys

Seismic loads are exempted from environmental fatigue evaluation because strain rates during such events are sufficiently high that the effects of EAF are negligible.

5

STRATEGY FOR IMPLEMENTATION OF ENVIRONMENTALLY ASSISTED FATIGUE

This section provides strategies for implementing EAF analyses and options for addressing high EAF usages for both existing plants and new reactor designs, as the regulatory and code options differ depending on the plant. The following topics are discussed:

- Development of the scope for an EAF evaluation (Section 5.1)
- Application of simplified screening approaches (Section 5.2)
- Strategies to reduce the calculated EAF usage (Sections 5.3 and 5.4)
- Strategies to manage high EAF usage (Section 5.5)

Fatigue evaluation procedures, such as those in the ASME Section III Code, are based on the determination of a CUF . A factor to account for the effect of the environment, F_{en} , is applied to the CUF or the partial usage factors (U_i) calculated in an air environment to determine the cumulative fatigue usage in primary water environment, known as CUF_{en} .

It can be challenging to demonstrate an acceptable CUF_{en} at end-of-life for some components and locations, and the calculations required for a detailed CUF_{en} analysis can be time consuming and analytically laborious. A cost-benefit analysis approach is helpful in determining a resource conscious approach to ensure success is achieved in addressing this degradation mechanism. For existing plants, it is not required to conduct detailed evaluations of the entire plant. There are existing strategies to screen plant locations to determine the most limiting locations from an EAF perspective and then focus detailed EAF evaluations on those locations only. For new construction applications, the detailed stress analyses are readily available or in the course of preparation, so techniques that require detailed calculations can more easily be completed as part of the design process.

Analysts generally first approach CUF_{en} calculations by conducting very simple bounding analyses. Typically, this means using the highest possible value for F_{en} across all transient stress cycle pairs. Components, or portions of components, that are acceptable using this bounding approach require no additional analysis. For evaluating stainless steel components in existing NPPs, this approach is generally not an option because of the significant changes to the fatigue curve, as seen in Figure 3-3. It is often the case that CUF values are available, but the underlying fatigue tables with detailed information are not and can be challenging to obtain.

Components that do not meet the CUF_{en} limit of ≤ 1.0 using a bounding approach may be acceptable through a more detailed calculation of F_{en} , or by reanalyzing the underlying ASME alternating stress and partial usage factors to remove or reduce conservatism. A combination of approaches may also be used depending on the circumstances. The initial strategy for EAF evaluation is to calculate CUF_{en} without requiring subsequent fatigue analyses using the data

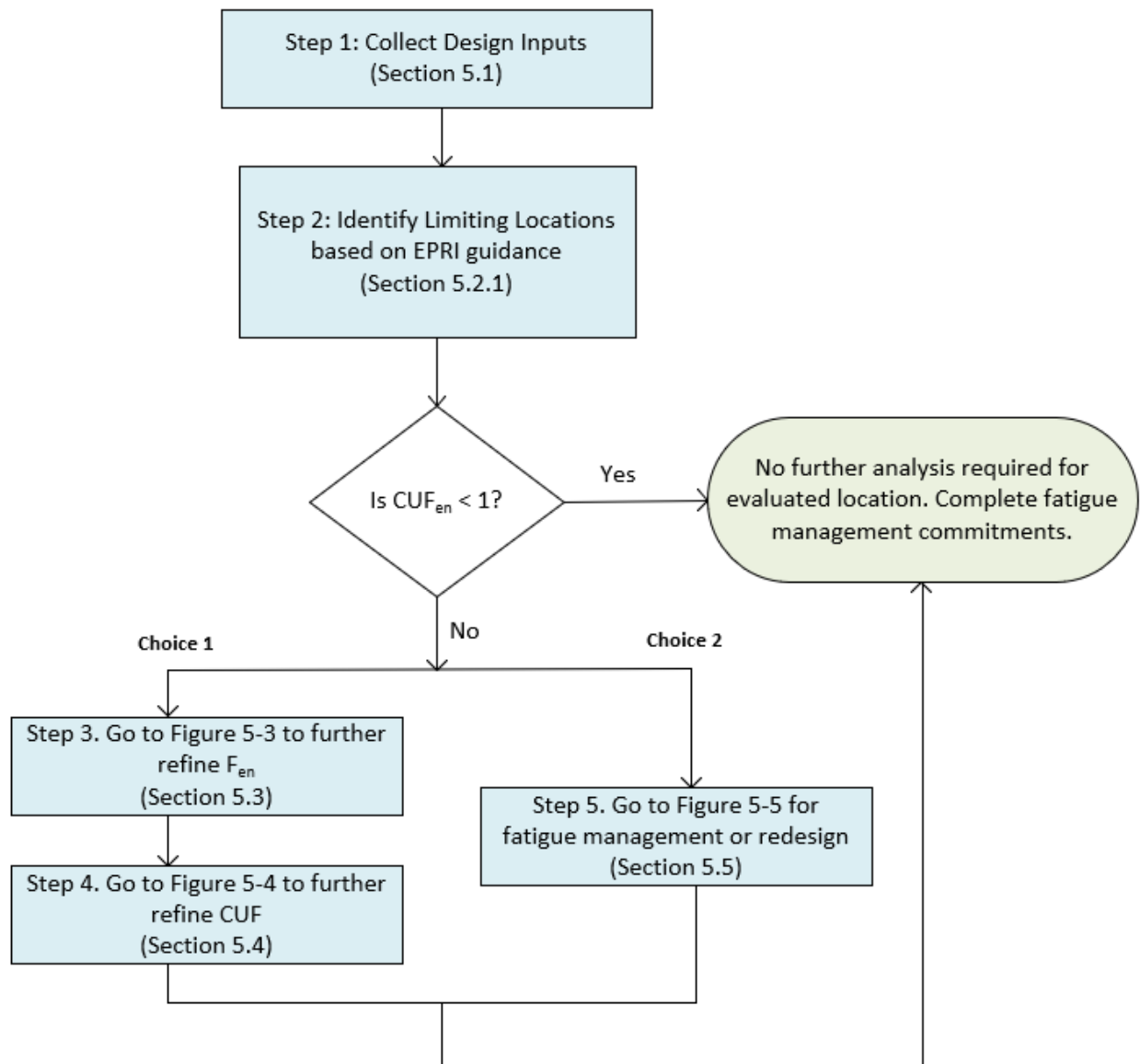
readily available in a typical Design Report or fatigue calculation. Using this data, a detailed evaluation can reduce the F_{en} factor to a potentially acceptable level. Such strategies can be applied to the total CUF or to only those partial usage factors that make up the most significant contribution to the CUF . If a detailed F_{en} approach is not successful, the underlying ASME fatigue analysis can be reevaluated to reduce conservatism in the underlying air fatigue CUF calculation.

Recommended strategies for assessing EAF for existing reactor designs and for new reactors are summarized in Figure 5-1 and Figure 5-2, respectively. The proposed approaches of addressing EAF through analysis or plant operational programs are consistent with regulatory expectations both in the US and internationally. In the US, refer to NRC reports NUREG-1801, “Generic Aging Lessons Learned (GALL) Report” [18, 19] (applicable to 60-year license renewals) and NUREG-2191, “Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report” [20] (applicable to 80-year license renewals) for fatigue and cyclic operation for additional detailed guidance (Chapter X.M1 in both reports).

These strategies refer to recommended approaches for reducing the value of F_{en} (Figure 5-3) and for reducing the underlying ASME in air fatigue usage (Figure 5-4). Figure 5-3 and Figure 5-4 provide a recommended strategy and are not considered a detailed procedure. These strategies are generally organized to first recommend those approaches requiring the least analytical effort; however, the most effective approach to assessing EAF can be system and component dependent, and the ordering should consider items such as potential areas of conservatism, dominant loadings, the existing analysis level of refinement, etc. when determining how to proceed. Acceptability may be achieved by using any of these strategies or any combination of different strategies outlined in this section. As discussed above, there are different regulatory and ASME Code limitations for new and existing reactors; therefore, the approaches to address EAF are different.

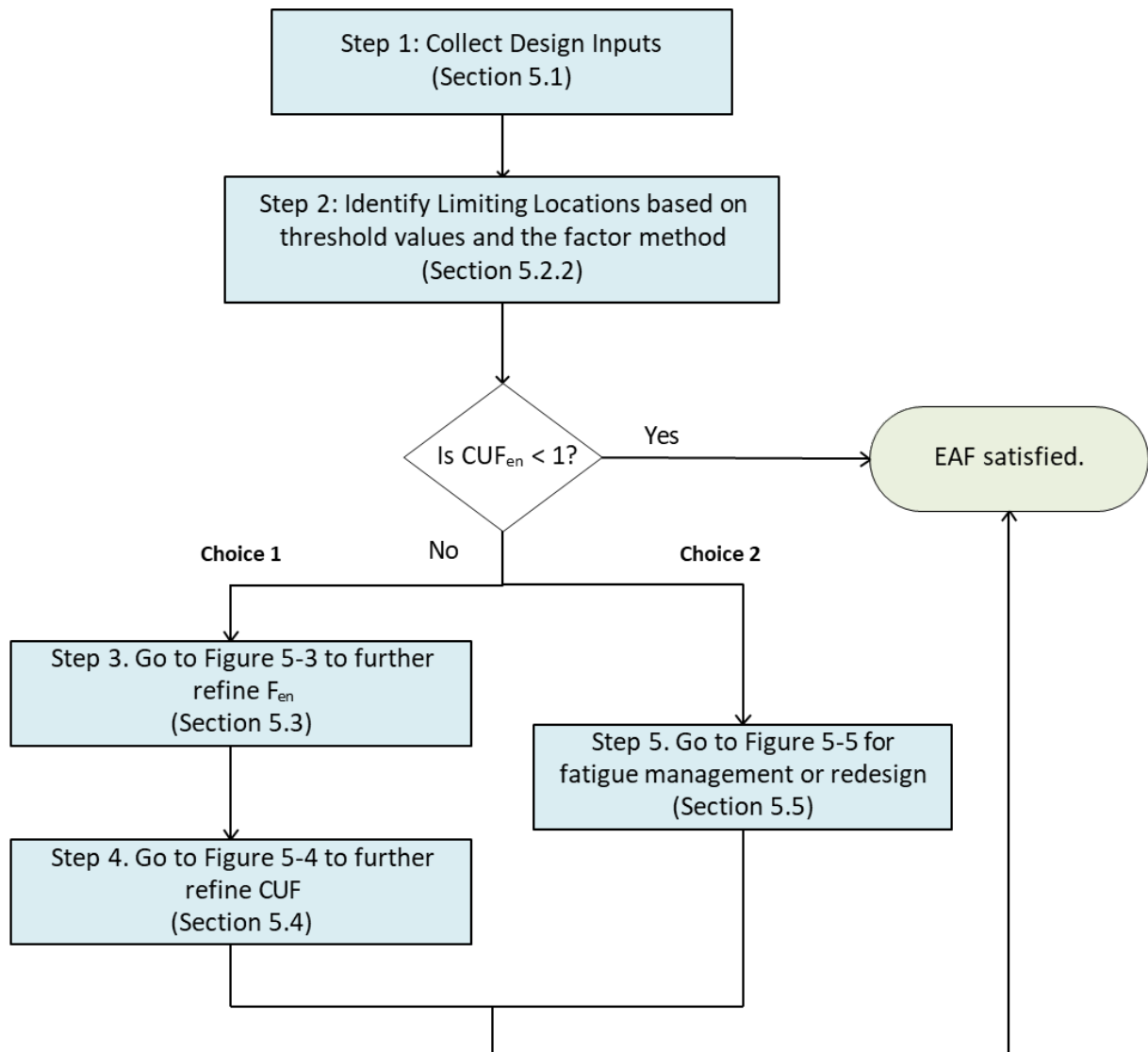
The options available when CUF_{en} cannot be shown through analysis to be less than 1.0 are shown in Figure 5-5. These include, for existing designs development, a fatigue management program (including potential on-line monitoring), flaw tolerance evaluations with periodic inspections, or for new designs, refinement of thermal transients and/or component re-design.

The steps outlined in Figures 5-1 through 5-5 are explained in the following sections.



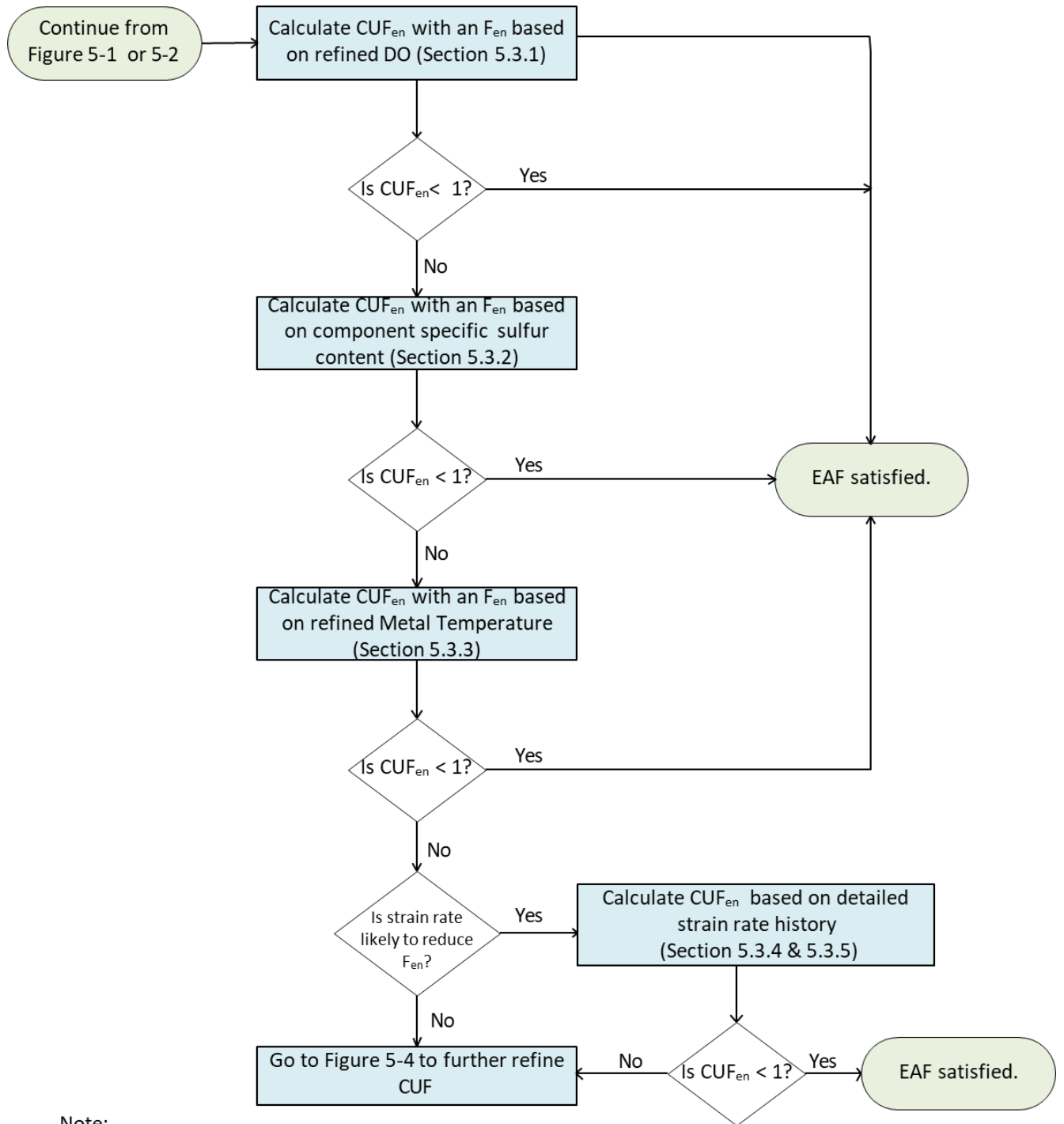
Note: Steps 3 & 4 may be ordered based on specifics of analysis.

Figure 5-1
Screening Strategy for Evaluating Environmentally Assisted Fatigue for Existing LWR Designs



Note: Steps 3 & 4 may be ordered based on specifics of analysis

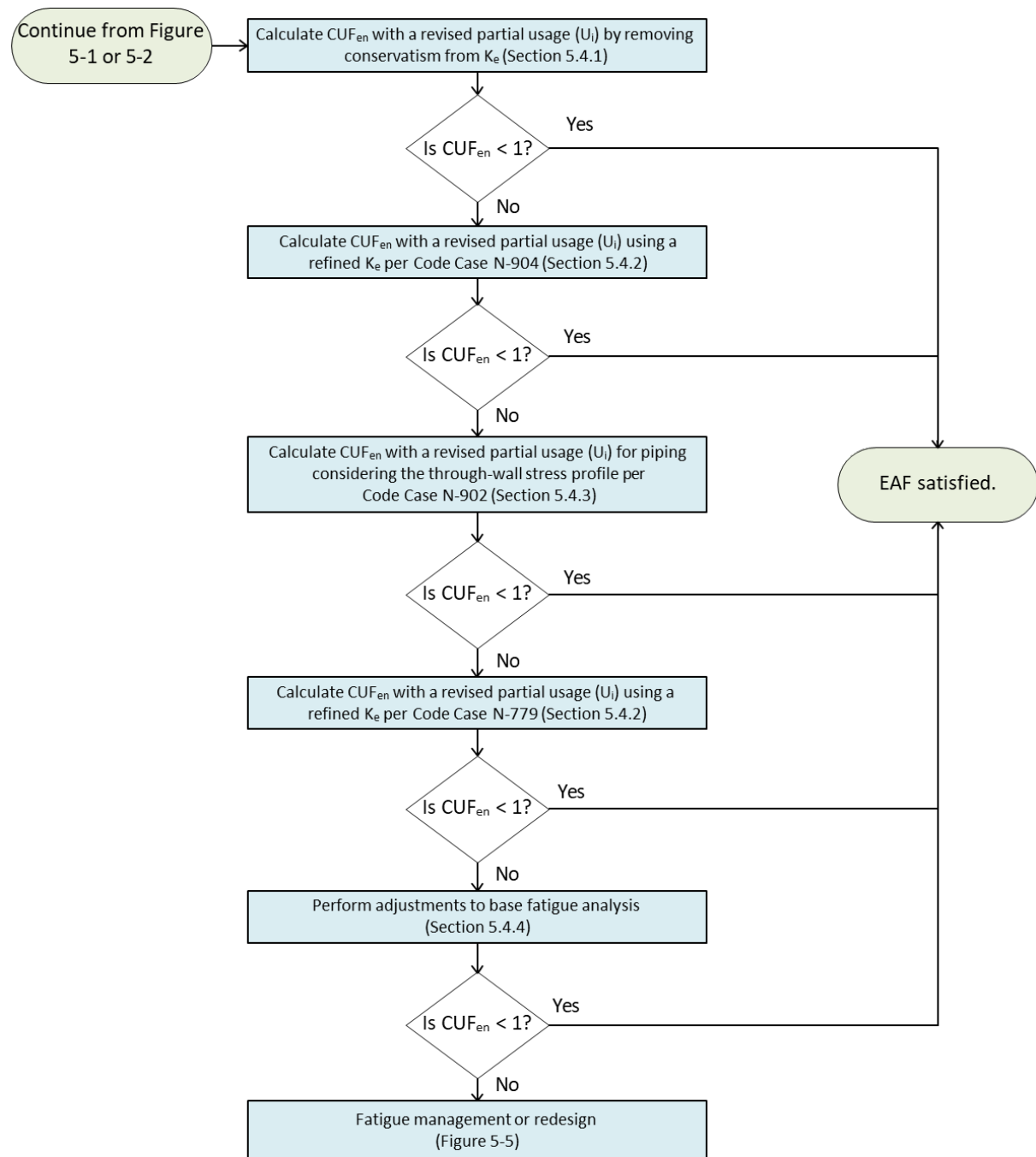
Figure 5-2
Screening Strategy for Evaluating Environmentally Assisted Fatigue for New LWR Designs



Note:

1. May approach strategies in any order.
2. May consider refinements to CUF in conjunction with or before any of these strategies.

Figure 5-3
Strategies to Refine F_{en}



Note:

1. May approach strategies in any order.
2. For piping, fatigue requirements changed after the 1977 Edition, Summer 1979 Addenda and may result in significant benefit if later Code editions are used (See Section 5.4.1 for further discussion).
3. For U.S. plants, Code Cases not approved (including those not yet reviewed) by the NRC may be permitted however, detailed technical justification is required.

Figure 5-4
Strategies to Refine CUF

Operating Plants

- Fatigue Monitoring Program
- Recalculate CUF using projected cycles for the extended operating period instead of current licensing basis cycles.
- Recalculate F_{en} values based on the use of actual plant transient pressure and temperature data.
- Perform a flaw tolerance evaluation and implement periodic inspections (e.g., ASME Section XI, Appendix L).
- Repair / Replacement

New Plant Designs

- Redefine thermal transients.
- Use Code Case N-919 [49] to demonstrate $CUF_{en} < 1$ for 10 years and commit to operating plant fatigue assessment requirements.
- Redesign the component.

Note: For US plants, Code Cases not approved (including those not yet reviewed) by the NRC may be permitted however, detailed technical justification is required.

Figure 5-5
Strategies for Fatigue Management

5.1 Step 1: Collect EAF Evaluation Inputs

The inputs needed to perform an EAF Evaluation include the fatigue analysis (*CUF*), *DO* of the primary water coolant, sulfur content of the metal for carbon and low alloy steels, and the temperature and strain time histories for all transients applicable to the metal component. For these inputs, conservative values based on bounding inputs from NUREG/CR-6909, Revision 1 may be used if detailed inputs are not readily available. Refinements may then be made based on the considerations discussed in Sections 5.3 and 5.4 of this report.

5.1.1 Current Licensing Basis Inputs for Existing Plants

The required inputs from the current licensing basis for an existing plant performing an EAF evaluation are listed in Table 5-1 below.

Table 5-1
Required Inputs for EAF Evaluation for Existing LWRs

Input	Source	Note
<i>CUF</i> based on NUREG-6909, Rev 1 fatigue curves Design Fatigue Table	Design Report Associated backup calculations	Required Input from Design Report The fatigue curves must be from NUREG/CR-6909 or equivalent as discussed in Section 3.2. For ASME B31.1 piping and reactor internals where a fatigue analysis was not completed as part of the design basis calculations, see guidance in Appendix F.
Dissolved Oxygen in LWR Coolant	Operational Procedures Plant Operational Historical Data Chemistry Procedures NUREG/CR-6909, Rev 1	It can be challenging to collect historic plant operation data and using bounding NUREG/CR-6909, Rev 1 values or operational procedures are likely most efficient.
Sulfur Content of Metal	Certified Material Test Report (CMTR) ASME Code material specifications NUREG/CR-6909, Rev 1	Using bounding NUREG/CR-6909, Rev 1 values are likely most efficient if CMTRs are not readily available.
Metal Temperature	Design Report Associated backup calculations NUREG/CR-6909, Rev 1	Temperature vs time data is typically available in the Design Reports so using bounding NUREG/CR-6909, Rev 1 values is not the only option.
Strain Rate	Design Report Associated backup calculations NUREG/CR-6909, Rev 1	Using bounding NUREG/CR-6909, Rev 1 values are likely most efficient since detailed strain rates are not typically included in design reports and may require rerunning analyses to obtain information.

In the case of operating plants, the *CUF* is likely based on fatigue curves that contain the original design margins with partial subfactors that comprise the original Code factors of 2 and 20. It

may be necessary to adjust the current licensing basis ASME Code calculated CUF to use S-N curves based on air environments using NUREG/CR-6909 or more recent ASME Code versions (beginning with the 2009 Addenda). Existing alternating stresses S_{alt} (or allowable cycles) and the number of cycles for each transient stress cycle pair from the current licensing basis are used, but the allowable cycles are recalculated using the appropriate S-N curves and extended design cycles for the new licensing basis. An example of this process is provided in Example Problem 1 in Appendix A.

5.1.2 EAF Inputs for New Designs

The required inputs from the current licensing basis for a new plant performing EAF evaluations are listed in Table 5-2 below.

Table 5-2
Required Inputs for EAF Evaluation for New LWRs

Input	Source	Note
CUF based on NUREG-6909, Rev 1 fatigue curves or equivalent Design Fatigue Table	Design Report Associated Backup Calculations	Required Input from Design Report The fatigue curves must be from NUREG/CR-6909 or equivalent as discussed in Section 3.2.
Dissolved Oxygen in LWR Coolant	Design Specification Operational Procedures NUREG/CR-6909, Rev 1	Information available in plant system-level design documents should be used in lieu of bounding NUREG/CR-6909, Rev 1 input values.
Sulfur Content of Metal	Design Specification ASME material specification ASTM Specification NUREG/CR-6909, Rev 1	Information available in Material Specification and/or the Design Specification may be used in lieu of a bounding value NUREG-6909, Rev 1.
Metal Temperature	Design Report Associated Backup Calculations NUREG/CR-6909, Rev 1	Temperature vs time data is typically available in the Design Reports so using bounding NUREG/CR-6909, Rev 1 values are not the only option.
Strain Rate	Design Report Associated Backup Calculations	Detailed strain rates may be available through finite element analyses (e.g., ANSYS or ABAQUS runs) so refinements based on strain rate are feasible.

5.2 Step 2: Identify Limiting Locations for EAF Evaluation

There are strategies available to screen plant locations to determine those locations that are limiting and then focus evaluations on those locations only. These approaches are different for existing plants and new designs as discussed below.

5.2.1 Existing Plants

Initially, for license renewal, NUREG/CR-6260 [50] established six locations (by plant design and vintage) that were expected to be representative of components that had higher CUF values and/or were important from a risk perspective. Plants are expected to demonstrate the validity of the NUREG/CR-6260 locations or augment the list with additional locations to cover any locations that may be more limiting for EAF than the NUREG/CR-6260 locations on a plant-specific basis [19 and 20].

EPRI's EAF Screening Report [26] provided the following three EAF screening methods for use in nuclear power plants:

- Structural Integrity Associates (SIA) EAF Screening Method
- Westinghouse Electric Company (WEC) EAF Screening Method
- Électricité de France (EDF) EAF Screening Method

These screening methods are intended to identify limiting fatigue locations, including consideration of the locations previously identified in NUREG/CR-6260, to manage the effects of EAF on ASME Class 1 reactor coolant pressure boundary components throughout plant extended operating periods. The purpose of these screening methods is to reduce the overall number of component locations requiring a detailed EAF assessment, while still meeting the regulatory requirements to determine those EAF locations that are limiting in their plants.

EDF, SIA, and WEC have developed methods for screening the primary coolant-wetted Class 1 reactor coolant pressure boundary (RCPB) fatigue-sensitive components in a plant by ranking them in terms of CUF_{en} and then determining a set of leading locations, or Sentinel Locations, such that every plant component is covered by one or more Sentinel Locations. The basis for this approach is to first group components into common thermal zones, or transient sections. CUF_{en} values for the sampled locations in NUREG/CR-6260 can be compared to Sentinel Locations within the same transient section or thermal zone. Sentinel Location CUF_{en} values in thermal zones without corresponding locations from NUREG/CR-6260 can be screened relative to whether they are greater than or less than unity. The EPRI EAF Screening Report contains the detailed procedures for these approaches.

For the SIA and WEC methods, the F_{en} factors considered are conservative, but offer a simplified screening approach that does not require extensive reanalysis. If the CUF_{en} is greater than 1.0 after applying the conservative screening methods, two of the options to evaluate EAF and satisfy the GALL or GALL-SLR are to enter the location into the Fatigue Monitoring program or to further refine the analysis to demonstrate CUF_{en} is less than 1.0. Approaches and options to further refine the analysis as discussed in Section 5.3 and 5.4 of this report.

5.2.2 New Plants

For EAF in new plants, all applicable locations should be evaluated. The guidelines and methods for screening susceptible locations are applicable to new plant designs. These methods may be applicable either before or after design CUF calculations have been completed. As discussed in Section 3.1, environmental effects on fatigue lives are significant when key parameters are above or below certain threshold values. When any one of the key parameters does not satisfy its threshold condition, the F_{en} is 1.0. Based on the threshold values for temperature and strain rate provided in Section 4, which are from NUREG/CR-6909, Revision 1, Appendix A, F_{en} is equal to 1.0 for the following conditions for carbon and low alloy steels, austenitic stainless steels, and nickel based-alloy steels. Consequently, an EAF analysis is not required under these conditions.

- Any material: If the location is not in contact with primary reactor coolant, then F_{en} is 1.0. The equations for F_{en} are limited to temperatures up to 325°C (617°F). This maximum temperature was developed based on the available testing and covers most LWR environments. Additional guidance is under development regarding the effects due to temperatures above 325°C.
- Carbon and Low Alloy Steels: F_{en} is equal to 1.0 when any of the following is true:
 - Strain amplitude (alternating strain) is less than or equal to 0.07%, or
 - Stress amplitude (alternating stress) is less than or equal to 145 MPa (21 ksi).
- Austenitic stainless steels: F_{en} is equal to 1.0 when any of the following is true:
 - Service temperatures are less than 100°C (212°F), or
 - Strain rates are greater than 7% per second, or
 - Strain amplitude (alternating strain) is less than or equal to 0.10%, or
 - Stress amplitude (alternating stress) is less than or equal to 195 MPa (28.3 ksi)
- Nickel-based alloy steels: F_{en} is equal to 1.0 when any of the following is true:
 - Service temperatures are less than 50°C (122°F), or
 - Strain rates are greater than 5% per second, or
 - Strain amplitude (alternating strain) is less than or equal to 0.10%, or
 - Stress amplitude (alternating stress) is less than or equal to 195 MPa (28.3 ksi).
- Cladding: ASME Code Section III NB-3122 prescribes the treatment of cladding with respect to meeting structural design limits. Fatigue and EAF evaluations are not explicitly required for the cladding. An EAF evaluation of the base metal is required. If cladding is considered structural, then an EAF evaluation of the cladding is required.

Therefore, when F_{en} equals 1.0, provided the CUF is less than 1.0, then the CUF_{en} is also less than 1.0.

Table 5-3
Maximum F_{en} and Acceptable CUF

Material	Maximum Temperature Threshold	Minimum Strain Rate Threshold (%/s)	Sulfur (wt%)	DO Content (ppm) ⁽²⁾		Maximum F_{en} ⁽³⁾	Maximum Acceptable CUF ⁽⁴⁾
Carbon and Low Alloy Steels ⁽¹⁾	617°F [325°C]	0.0004	0.015	PWR	< 0.04	6.28	0.16
			0.015	BWR	> 0.5	142	0.007
Austenitic Stainless Steels	617°F [325°C]	0.0004	--	PWR and BWR	< 0.1	12.8	0.08
Nickel-based Alloy Steels	617°F [325°C]	0.0004	--	PWR and BWR	< 0.1	3.75	0.26

Notes:

- 1) Maximum F_{en} for carbon and low alloy steels is provided for high sulfur (>0.015 wt.%).
- 2) DO content for typical PWR environment and typical Normal Water Chemistry BWR environment, which bounds the hydrogen water chemistry DO content. It is necessary to review plant chemistry records to ensure applicability and conservatism of the stated DO content. See Section 5.3.1 for additional discussion.
- 3) F_{en} factor calculated in accordance with NUREG/CR-6909, Revision 1.
- 4) The existing fatigue evaluation is acceptable if the ASME Code CUF , which was determined with the fatigue curves presented in NUREG/CR-6909, is less than or equal to the maximum acceptable CUF .

When the environmental conditions are above the stated threshold values, the simplest screening approach is to conservatively calculate a single value of F_{en} , denoted $F_{en, factor}$, based on the most severe conditions for any of the analyzed transients and limiting DO, sulfur, temperature, and strain rate parameters in NUREG/CR-6909, Revision 1 that is multiplied by CUF .

$$CUF_{en} = CUF \times F_{en, factor} \quad \text{Eq. 5-1}$$

This approach internationally is known as the ‘factor method’. The factor method is not explicitly described in NUREG/CR-6909; however, it is a reasonable and graded approach to evaluate the impact of F_{en} on existing designs. As discussed, exact calculations of F_{en} can be laborious, but result in lower values, while simple approaches are analytically quick, but result in higher values of F_{en} and thus higher CUF_{en} . The factor method is the simplest and most conservative approach. If the CUF is sufficiently low, application of simple and conservative values of F_{en} may be acceptable. Components, or portions of components, that are acceptable with this bounding approach require no further analysis.

In general, F_{en} increases with increasing temperature, decreasing strain rate, and increasing sulfur content. For carbon steel, F_{en} increases with increasing oxygen content. For stainless and nickel-based steels, F_{en} increases with decreasing oxygen content. The maximum F_{en} factor for each material is summarized in Table 5-3, which is based on the threshold values for temperature, strain rate, sulfur, and dissolved oxygen content, provided in Section 4.1.

For context, the last column of Table 5-3 is the maximum acceptable CUF determined using NUREG-6909, Revision 1 maximum F_{en} values. Therefore, a CUF that is less than or equal to the CUF in the last column will always be acceptable for EAF. For example, if the calculated

CUF for a location on the wetted surface of a carbon steel component in typical PWR water chemistry of less than 0.04 ppm DO is less than 0.16, that location is always acceptable for EAF.

For Table 5-3, the DO content ranges are taken from NUREG/CR-6909, Revision 1. See additional discussion in Section 5.3.1 on DO content and methods to verify and refine the DO content, as necessary.

5.3 Step 3: Refine F_{en}

Detailed calculations may be made for F_{en} based on the temperature, DO content, sulfur, and strain rate from the relationships detailed in Section 4. The general trends for F_{en} vs these parameters for the identified materials are shown in Figure 5-6 through Figure 5-10. Refinement of the constituent inputs to the F_{en} equations from additional data or a better understanding of plant operations can serve to minimize the impact of F_{en} on the overall CUF_{en} calculation. The strategies to reduce F_{en} in the order of increasing complexity are:

1. DO Content
2. Sulfur (Carbon steel and low alloy steel only)
3. Metal Temperature
4. Strain Rate

All the suggested approaches can be used concurrently, or in any order, but the suggestion is to start with the least resource intensive options that provide the largest potential reduction in F_{en} , which are provided first in this report. Additionally, guidance is given when each of these strategies could work for existing PWRs, BWRs, and new plant designs in the following subsections. For example, for low alloy steels in BWRs, understanding the strain rate, while most analytically intensive, may be the most fruitful in gaining reductions in F_{en} since the DO content and sulfur are fixed and temperature may not provide a significant enough reduction in F_{en} . Additionally, considering options to reduce CUF as discussed in Section 5.4 may be considered prior to more detailed strain rate calculations, should those be less resource intensive and offer a larger reduction in CUF , which in turn reduces CUF_{en} . Appendix A of this report provides examples of how to implement approaches to reduce F_{en} and recalculate CUF_{en} .

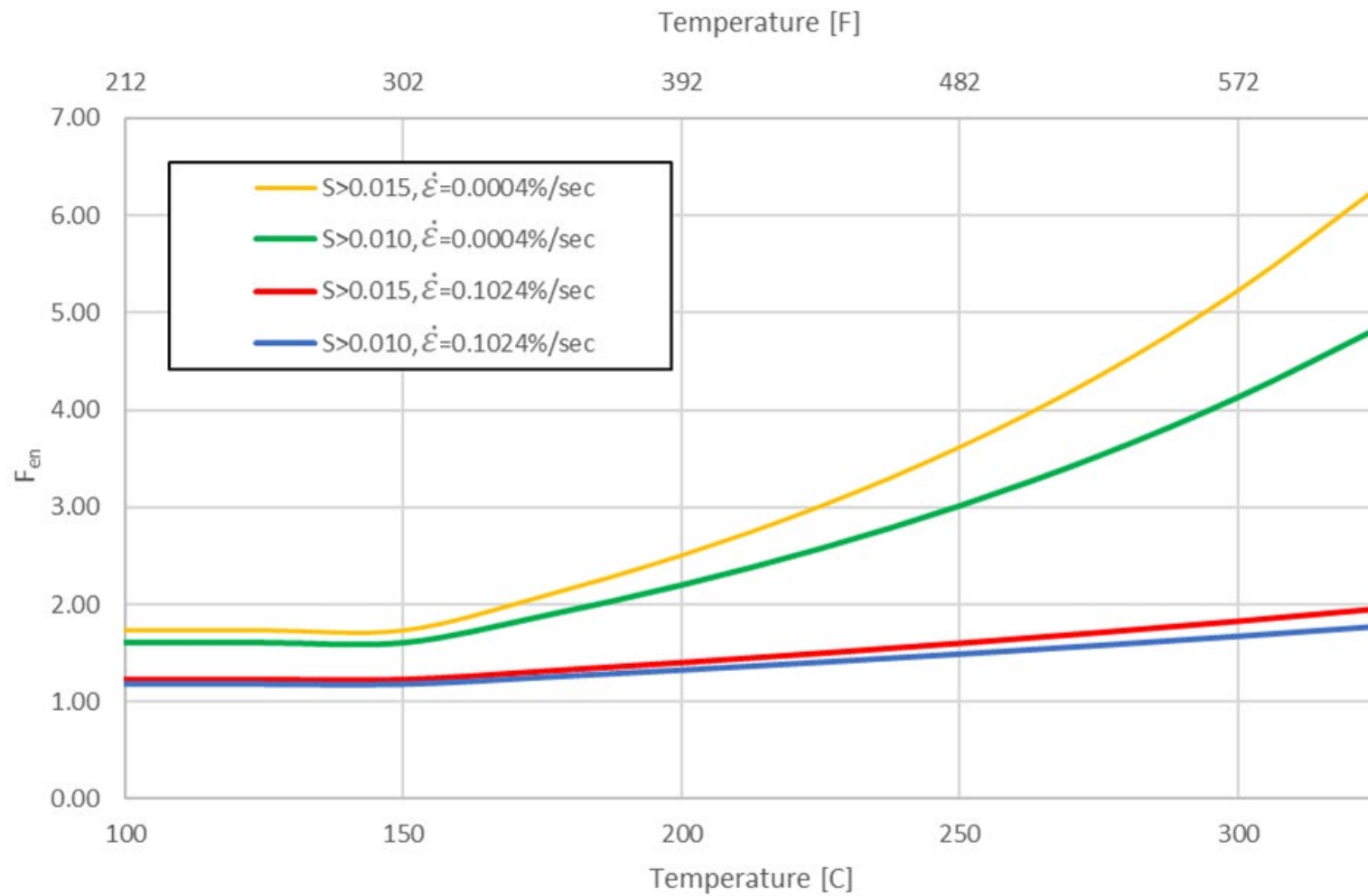


Figure 5-6
 F_{en} vs Temperature for Carbon and Low Alloy Steels, <0.04 ppm DO

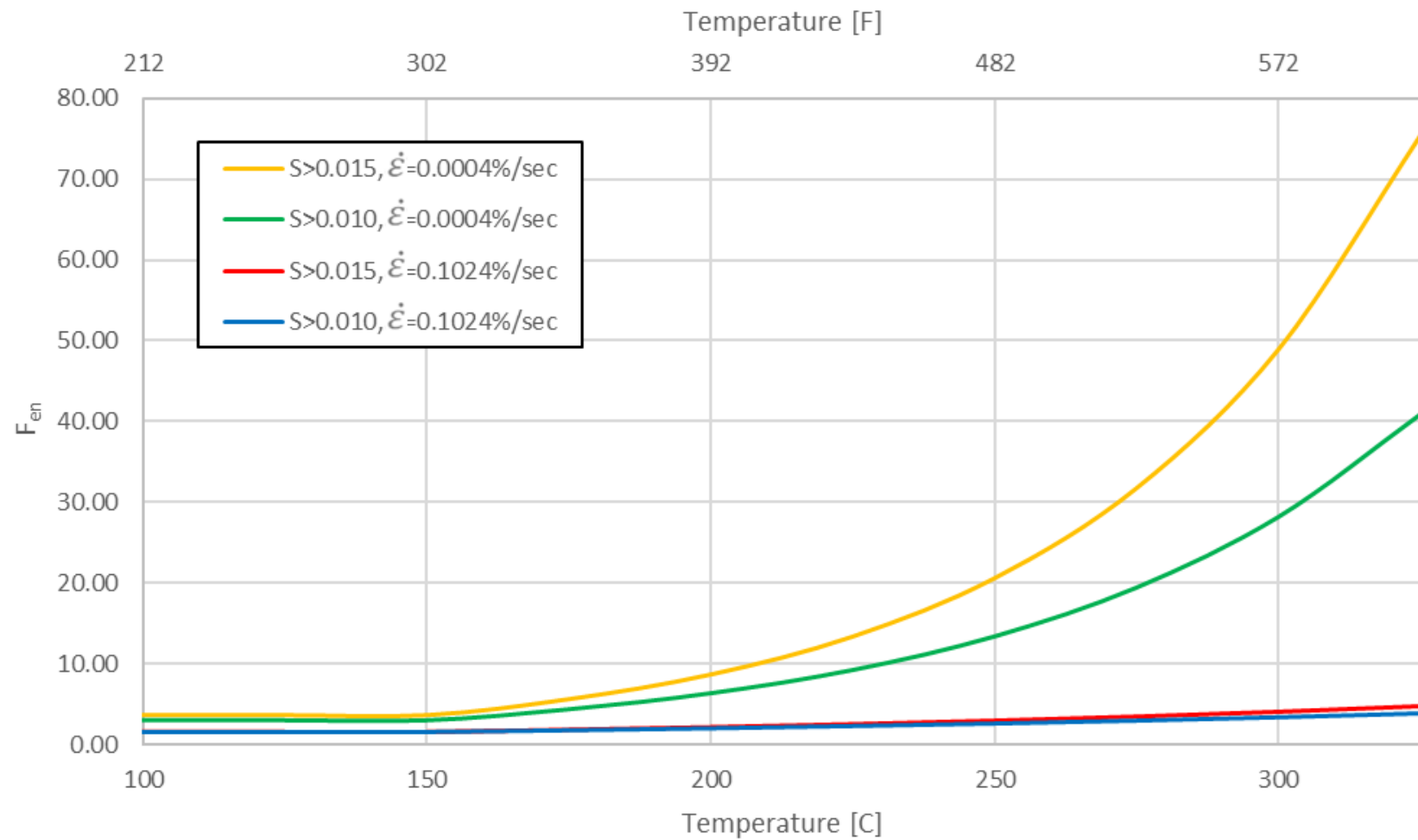


Figure 5-7
 F_{en} vs Temperature for Carbon and Low Alloy Steels, 0.3 ppm DO

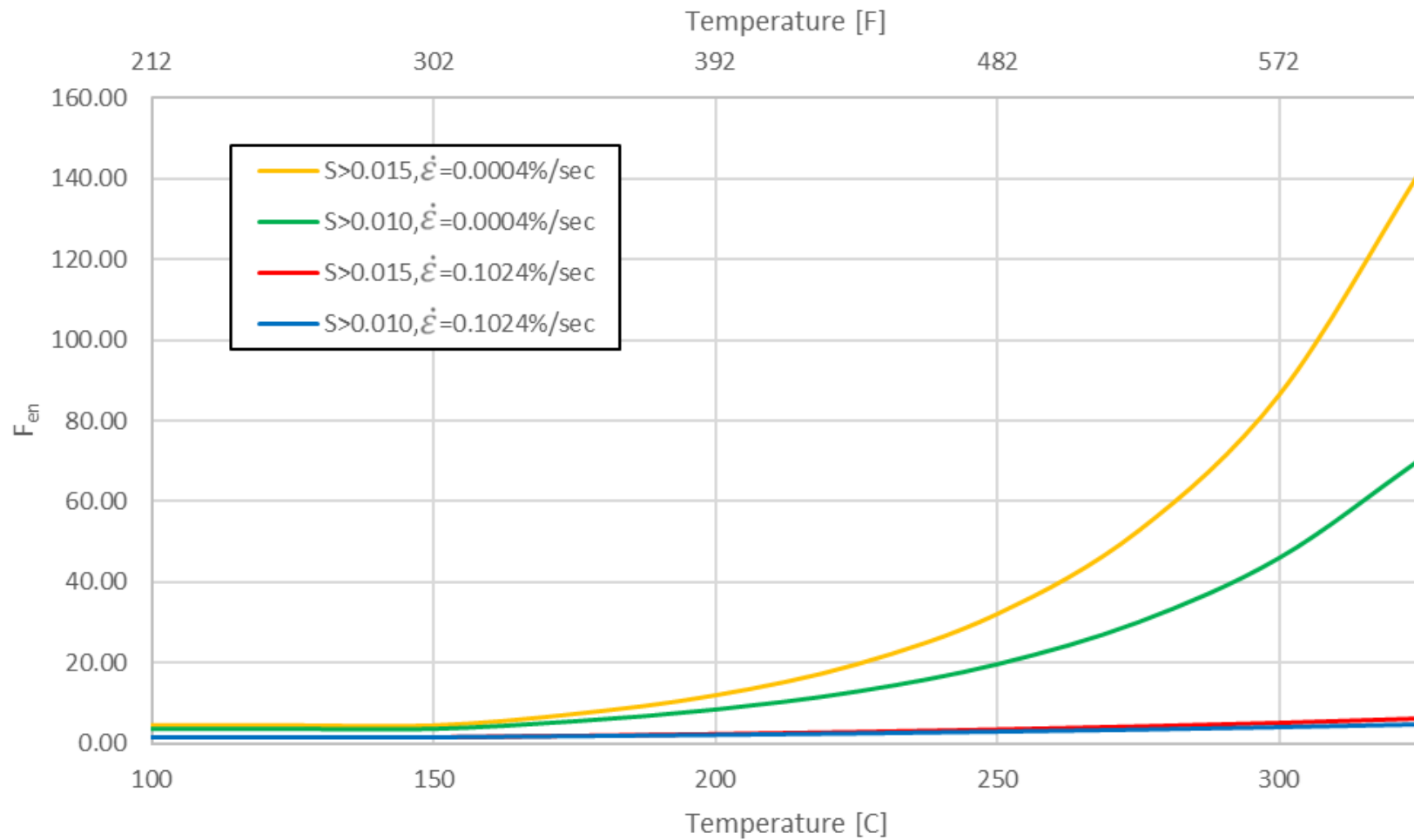


Figure 5-8
 F_{en} vs Temperature for Carbon and Low Alloy Steel, >0.5 ppm DO

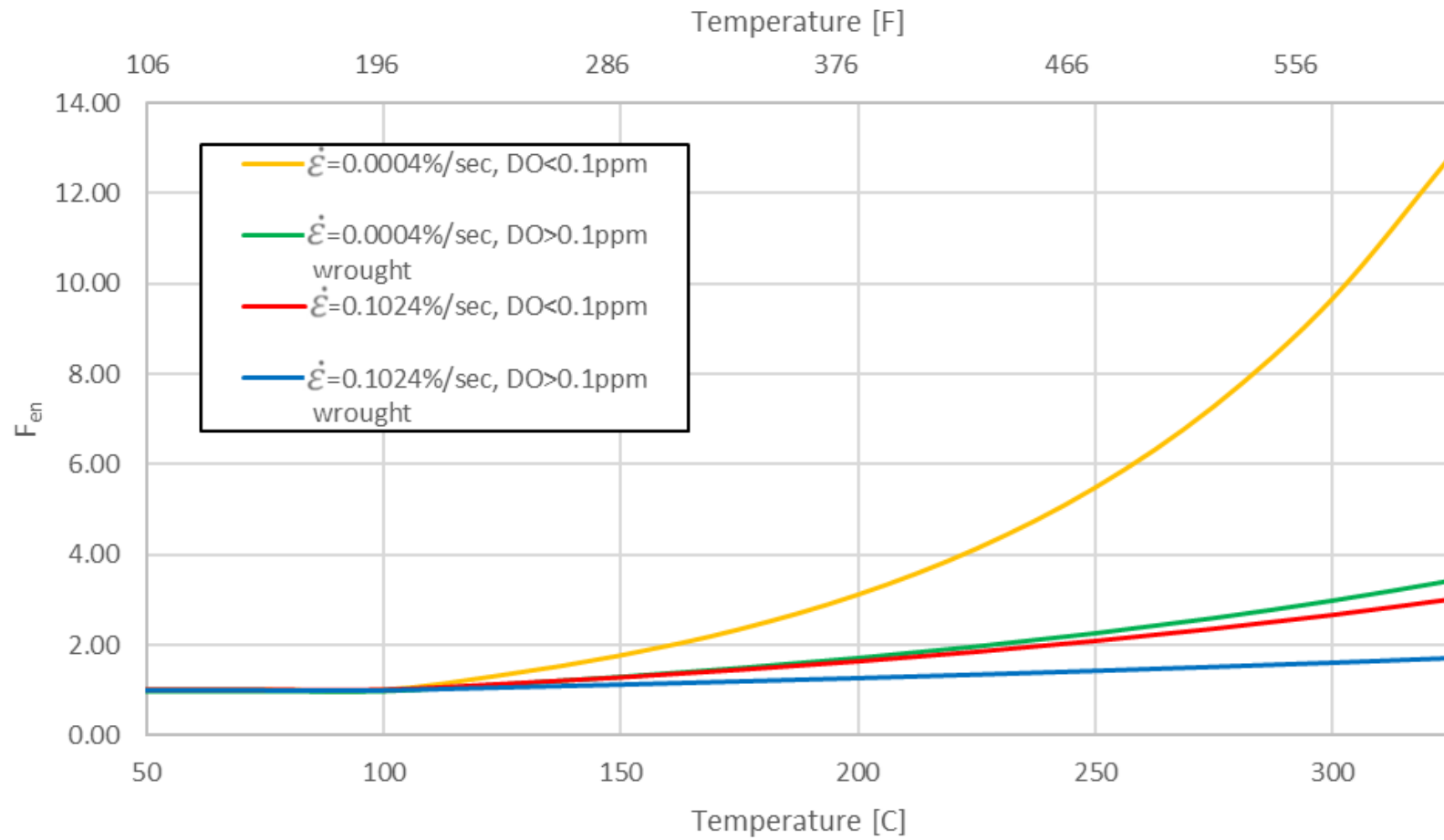


Figure 5-9
 F_{en} vs Temperature for Austenitic Stainless Steel, <0.1 ppm DO

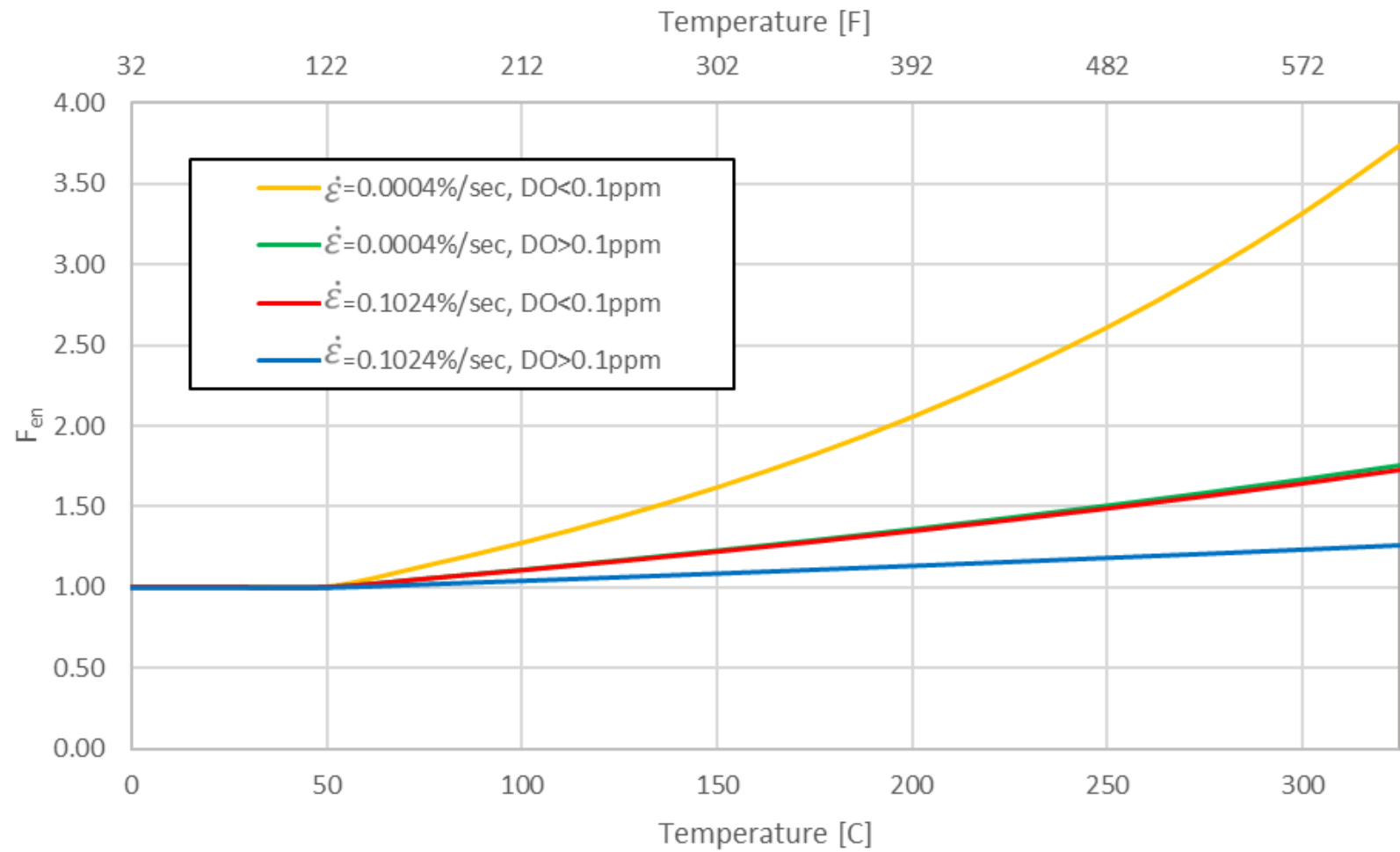


Figure 5-10
 F_{en} vs Temperature for Nickel-based Alloy Steels, <0.1 ppm DO

5.3.1 Dissolved Oxygen Content

The DO content varies by reactor type (PWR vs BWR) and DO content has a different effect on EAF in carbon and low alloy steel compared to stainless and nickel-based alloy steels. Therefore, it is necessary to review plant chemistry records to ensure applicability and conservatism of the DO content selected for the F_{en} calculation.

In operating PWRs, operations DO is not always < 0.04 ppm. It is typically higher following refueling, and during plant heatup becomes low at around 250°F. Therefore, in justifying a maximum F_{en} of 6.28 when using NUREG/CR-6909, Revision 1 for ferritic materials in PWRs, it is necessary to review plant chemistry records to ensure conservatism for these outlier conditions. With NUREG/CR-6583 [51], it was always possible to assume that DO content was below the lower threshold by the time the coolant reached the temperature threshold; therefore, F_{en} was always a fixed value in PWRs for ferritic materials.

Similarly, DO content is not fixed in operating BWRs and is quite a complex issue. It varies significantly from one location to another and from one operating practice (normal water chemistry) to another (noble metal chemistry, hydrogen water chemistry, etc. and degree of mitigation availability). Experience shows a bounding value will be too severe to demonstrate $CUF_{en} < 1.0$ since, as shown in Table 5-3, the F_{en} is more than 100. Determining applicable DO content levels for water chemistry for BWRs can be completed using the EPRI BWRVIA model [52], which determines applicable DO levels in various regions of the plants, and for different time periods, including early life (normal water chemistry), and later in life (Noble Metal Chemical Addition, Hydrogen Water Chemistry, On-Line NobleChem, etc.). Additional background and discussion related to BWR DO content is provided in Appendix D.

For the operating fleet, the dissolved oxygen content of the coolant is specific to a given system and typically cannot be easily modified to manage this active degradation mechanism; however, in some cases, analyses may have used bounding values for convenience and options to refine DO content calculations can yield significant reductions in F_{en} . The following trends can be observed:

1. For carbon steel and low-alloy steel, the value of F_{en} increases with increasing oxygen content. Since this effect is so large, the initial screening already incorporates typical DO for PWRs. The F_{en} is almost 24 times larger at a DO level of 0.5 ppm to that at 0.04 ppm. The F_{en} is two times larger at a DO level of 0.5 ppm to that at 0.3 ppm.
2. For austenitic stainless steel and nickel-based alloys, the value of F_{en} increases with decreasing oxygen content. The coefficient based on the dissolved oxygen depends on whether the oxygen concentration is above or below 0.1 ppm, with the lower concentration resulting in a larger F_{en} value. If the oxygen concentration is unknown, the constant based on the lower concentration should be used to calculate F_{en} . At slow strain rates and the maximum metal temperature, the maximum F_{en} based on DO less than 0.1 ppm is three to four times greater than the F_{en} for DO greater than 0.1 ppm.

In existing plants, this modification of F_{en} will not typically be worthwhile for PWRs if the initial screening used a DO of 0.04 ppm or less. The DO content is typically 0.04 ppm or less if standard primary water chemistry guidance is followed. For example, a value of 0.005 ppm, nearly an order of magnitude below the threshold value, is typical based on EPRI published

primary water chemistry guidelines [26, Section 4.1.4]. Therefore, the resources to determine the actual DO for the plant are likely not warranted.

However, for BWRs, if the maximum DO is used in the screening and a lower DO content is known from plant procedures and/or operating history, refining the DO content is simple to implement and can result in a significant reduction in F_{en} . A plant with a license extension must monitor dissolved oxygen content during the period of license extension to ensure that the environmental fatigue (F_{en}) evaluations remain valid.

For new light water reactors, the dissolved oxygen content of the primary coolant in which the component sits should be provided in design documentation, such as the Design Specification, and may result in a reduction in F_{en} .

5.3.2 Sulfur in Carbon and Low-Alloy Steels

The sulfur content of carbon and low alloy steels is specific to a material specification or the actual heat and cannot be modified, unless the material has not yet been manufactured. In general, F_{en} increases with increasing sulfur content up to 0.015 wt% sulfur.

As an example, the material specification for SA-508, Grade 3 low alloy steels, typically used in reactor pressure vessels, has a 0.025 wt% maximum permitted sulfur. As this is above 0.015 wt%, the variable (S^*) used in the calculation of F_{en} is 3.47. If sulfur is limited by the Design Specifications to 0.01 wt%, S^* is reduced to 2.98.

The relative contribution of sulfur content on F_{en} vs temperature is shown in Figure 5-6, Figure 5-7, and Figure 5-8. These figures contrast trends in F_{en} for sulfur contents at and below the maximum value of 0.015 wt% for different strain rates and DO values. The following trends are identified:

- Dissolved Oxygen:
 - The ratio of F_{en} between the sulfur content of 0.015 and 0.01 wt % increases as the DO level increases for a given strain rate and temperature.
 - For a DO of 0.04 ppm or less, the change of 0.005 wt% in sulfur results in little change in F_{en} at low temperatures and a reduction of 20% in F_{en} at higher temperatures, when F_{en} is significant.
 - For a DO of 0.3 ppm or higher, the change of 0.005 wt% in sulfur results in little change in F_{en} at low temperatures and a reduction by a factor of two in F_{en} at higher temperatures, when F_{en} is significant. There is significant value in determining the actual sulfur content above a DO of 0.3 ppm if there is a significant usage because it can reduce F_{en} by about half.
- Strain Rate:
 - The effect of sulfur content is negligible for ‘fast’ transients where the strain rate exceeds 0.1024%/sec.
 - For the slower transients, refining the sulfur content can significantly reduce F_{en} by close to a factor of two at higher temperatures.

Because the ASME/ASTM material specification permits sulfur concentrations up to 0.025%, for existing plants, obtaining the sulfur data may be resource intensive as operating plants must retrieve CMTRs or non-destructive chemical analysis must be performed in potentially inaccessible or high radiation areas. Therefore, this may not be a viable approach to significantly impact F_{en} for PWRs, but could be advantageous in BWRs if the DO is lower than 0.5 ppm but higher than 0.04 ppm.

For new light water reactors, the sulfur content should be specified in design documentation, such as the Design Specification or the applicable Material Specifications. To credit a lower sulfur content in the F_{en} calculation, sulfur content must be specified and controlled when melting the heat of material. Incorporating this data should be easily accessible such that F_{en} can be reduced without much additional effort.

5.3.3 Metal Temperature

Fatigue pairings for a partial usage factor are the difference between a minimum stress state and a maximum stress state. Commonly, the minimum and maximum stress states correspond to different metal temperatures as they occur at different times in a single transient or between different transients. As seen in Figure 5-6 through Figure 5-10, F_{en} is highly dependent on temperature.

There are two approaches to reduce F_{en} focused on temperature alone:

- Use the Maximum Transient Temperature: If the maximum temperature used in a bounding calculation or an initial screening is less than 617°F [325°C], the F_{en} may be easily and conservatively based on the maximum temperature of the metal.
- Use the Average Temperature: F_{en} may be based on the average of the high and low metal temperatures corresponding to the two stress states of the surface in contact with the reactor water. The temperature for each transient should be selected in accordance with Section 4.4 of NUREG/CR-6909, Revision 1. When the strain rate is constant and the temperature response is linear, the F_{en} may be calculated based on the average temperature as defined in [1, Section 4.4, pg. A-6].

Per guidance in NUREG/CR-6909, an average temperature should only be used if it has been demonstrated that it yields a comparable or conservative estimate of F_{en} compared to the F_{en} obtained using the modified rate approach and should be justified on a case-by-case basis. The U.S. NRC has shown significant interest when licensees have used the average temperature approach to establish a F_{en} value. While it is permitted in accordance with the guidance of NUREG/CR-6909, there is potential for additional detailed justification that could be requested [53, 54, 55].



Key Information Point

Analysts should weigh the effort of computing a detailed F_{en} using methods like the MRA (See Section 5.3.4) versus the effort of providing sufficient justification that may be required (e.g., cost associated with requests for additional information could include licensing, executive affidavits, legal counsel, etc.).

Calculation of F_{en} using the Average Temperature for a simplified transient is illustrated in Sample Problem A.3.

Since the fatigue analysis includes the transient stress cycle pairs, the effects of temperature can be accounted for in both the operating plants and the new designs without significant resources if the detailed information is readily available. The new F_{en} is calculated on a per pairing basis and can be applied to each individual partial usage. Then, the sum of each of the partial usages multiplied by the respective F_{en} is the total CUF_{en} .

To illustrate the impact that temperature has on F_{en} , take an austenitic stainless steel component in a PWR environment with a slow and constant strain rate, with minimum and maximum metal temperatures at the two stress states of 302°F [150°C] and 572°F [300°C] as an example. Using the maximum temperature results in a F_{en} of 9.7, while using the average temperature of 437°F [225°C] results in a F_{en} of 4.1.

Integrated approaches that simultaneously account for the effects of temperature and strain can be implemented. The MRA approach is discussed in Section 5.3.5. The integrated approaches are more detailed but can offer significant benefit.

5.3.4 Strain Rate

The strain rate used in F_{en} calculations is determined as the strain difference over the increasingly tensile² portion of the transient divided by the time duration of the tensile strain change. Unlike the other key parameters associated with the environmental fatigue correction factor, the strain rate for a given transient pairing is difficult to calculate and not typically reported in an older ASME Design Report. In general, the environmental fatigue correction factor increases with decreasing (i.e., slower) strain rates, meaning slow transients result in a higher F_{en} . Consequently, it is always conservative to assume the minimum (slowest) strain rate when calculating the environmental fatigue correction factor. While it is simpler and more conservative to just assume a transient is slow, such an assumption can have a significant impact on calculation of F_{en} .

Figure 5-11, Figure 5-12 and Figure 5-13 show the F_{en} factors based on strain rate for carbon and low alloy steels, stainless steels, and nickel-based alloy steels. While strain rate does have a significant impact on F_{en} , the calculational effort to determine strain rate can be significant depending on the availability of information. However, the F_{en} factors decrease rapidly with increasing strain rates and are only large below strain rates of 0.5%/s. Fast transients, like earthquakes, translate to a relatively simple calculation to determine strain rate, and the benefit is great in doing such a calculation.

For context, strain rates above 0.5%/s are typically associated with loadings induced by effects other than temperature changes. For example, a seismic event that occurs at 10 Hz (i.e., 0.1 seconds per cycle) and results in a stress of 30 ksi [207 MPa], has a strain rate of approximately

² Increasingly tensile in this context refers to the portion of the stress/strain cycle with positive strain rate. This applies even when the stress history is compressive. This is discussed in greater detail in section 5.3.5 and [23] along with Sample Problem 3 in Appendix A.

1%/s. Using a strain rate of 1%/s opposed to 0.0004%/s has a non-negligible impact on the F_{en} factor.

There is also benefit, especially for the carbon steel and low-alloy steel F_{en} factors, at strain rates greater than 0.0004%/s. Table 5-4 provides a qualitative assessment of transient thermal ramp rates with relative potential effects on F_{en} . To have a relatively fast strain rate from a thermal transient, the temperature change rate must be very fast (i.e. $\sim 100^\circ\text{F}/\text{sec}$ [$55.6^\circ\text{C}/\text{sec}$]). For example, cold water injection events are likely occurring as a fast strain rate. For most plant operational thermal transients, the strain rates are much slower, and the full effect of F_{en} will likely be applicable. For a transient around $100^\circ\text{F}/\text{min}$ [$55.6^\circ\text{C}/\text{min}$], the strain rate may be approaching the threshold limit of 0.0004%/sec where the effect on the F_{en} may become beneficial. For a $100^\circ\text{F}/\text{hour}$ [$55.6^\circ\text{C}/\text{hour}$] is well below the threshold of 0.0004%/s where F_{en} will not be affected. These thermal ramp rate examples are provided to be advisory, as the actual strain rate depends on the geometry, material, elasticity, heat transfer coefficients, and coefficients of thermal expansion. Additional details on the effects of ramp rates to F_{en} are available MRP-218 [56] and PVP2020-21545 [57]. A generic parametric study was performed in MRP-218 to characterize limiting transient ramp rates with respect to environmental fatigue usage for a range of piping geometry and material configurations. PVP2020-21545 describes parametric study results to optimize thermal hydraulic and stress response modeling assumptions with respect to transient rates and downstream effects on environmental fatigue results in both design and monitoring fatigue evaluations.

Thermal shock events also tend to be major contributors to fatigue usage because of the high thermal stress and high K_e . Approaches to reduce high K_e factors are addressed below in Section 5.4, which can reduce the CUF value apart from consideration of EAF. Additionally, reduced K_e values are also used in conjunction with the strain rate approaches in Section 5.3.5. These effects, considered either separately or in combination, when applied for a specific pairing, could provide a significant benefit. For thermal non-shock events, analysts are cautioned that the benefit of a more rigorous strain rate calculation may not be worth the effort unless there is confidence that the transient is at least relatively fast.

Table 5-4
Qualitative assessment of transient thermal ramp rates on Strain Rate and F_{en}

Thermal Ramp Rate ^[1]	Anticipated Strain Rate	Effect on F_{en}
100°F per second	Fast	Significant
100°F per minute	Medium	Potential
100°F per hour	Slow	Little/No Benefit

Note:

1. A temperature change of $\Delta 100^\circ\text{F}$ is equivalent to a temperature change of $\Delta 55.6^\circ\text{C}$.

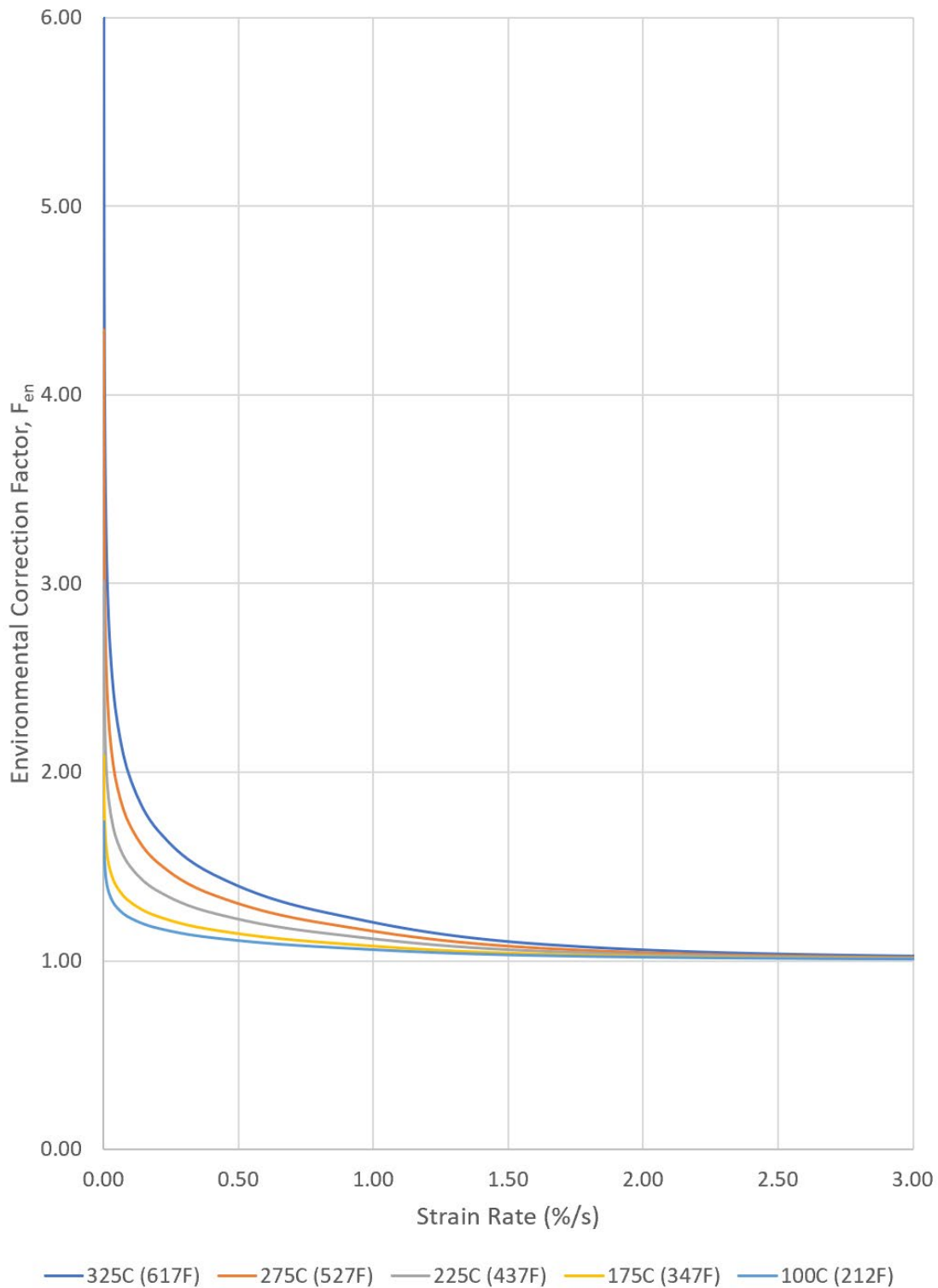


Figure 5-11
Correlation of F_{en} based on Strain Rate for Carbon and Low Alloy Steels with $DO < 0.04$ ppm and Sulfur Content > 0.015

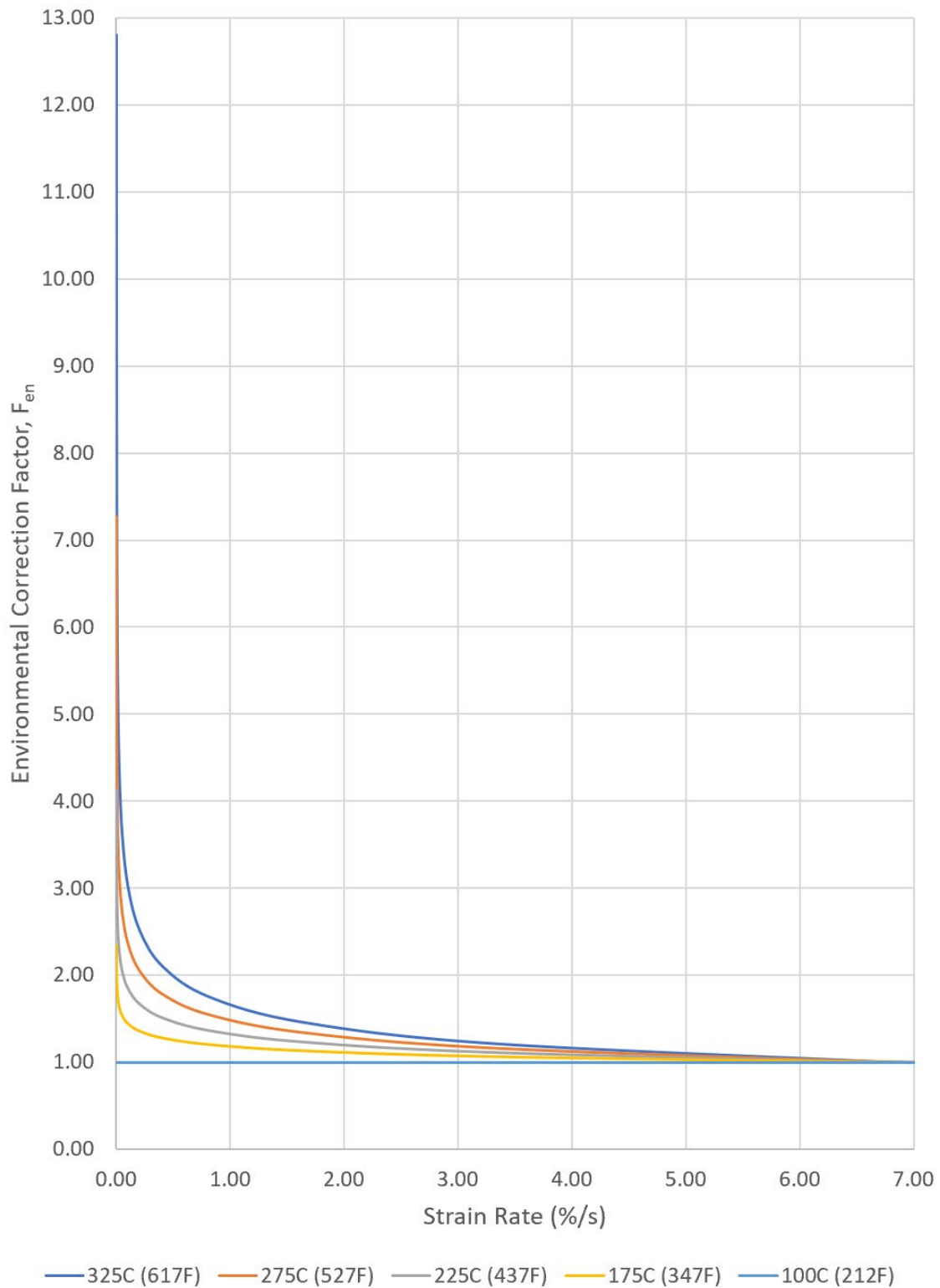


Figure 5-12
Correlation of F_{en} based on Strain Rate for Austenitic Stainless Steel with $DO < 0.1$ ppm

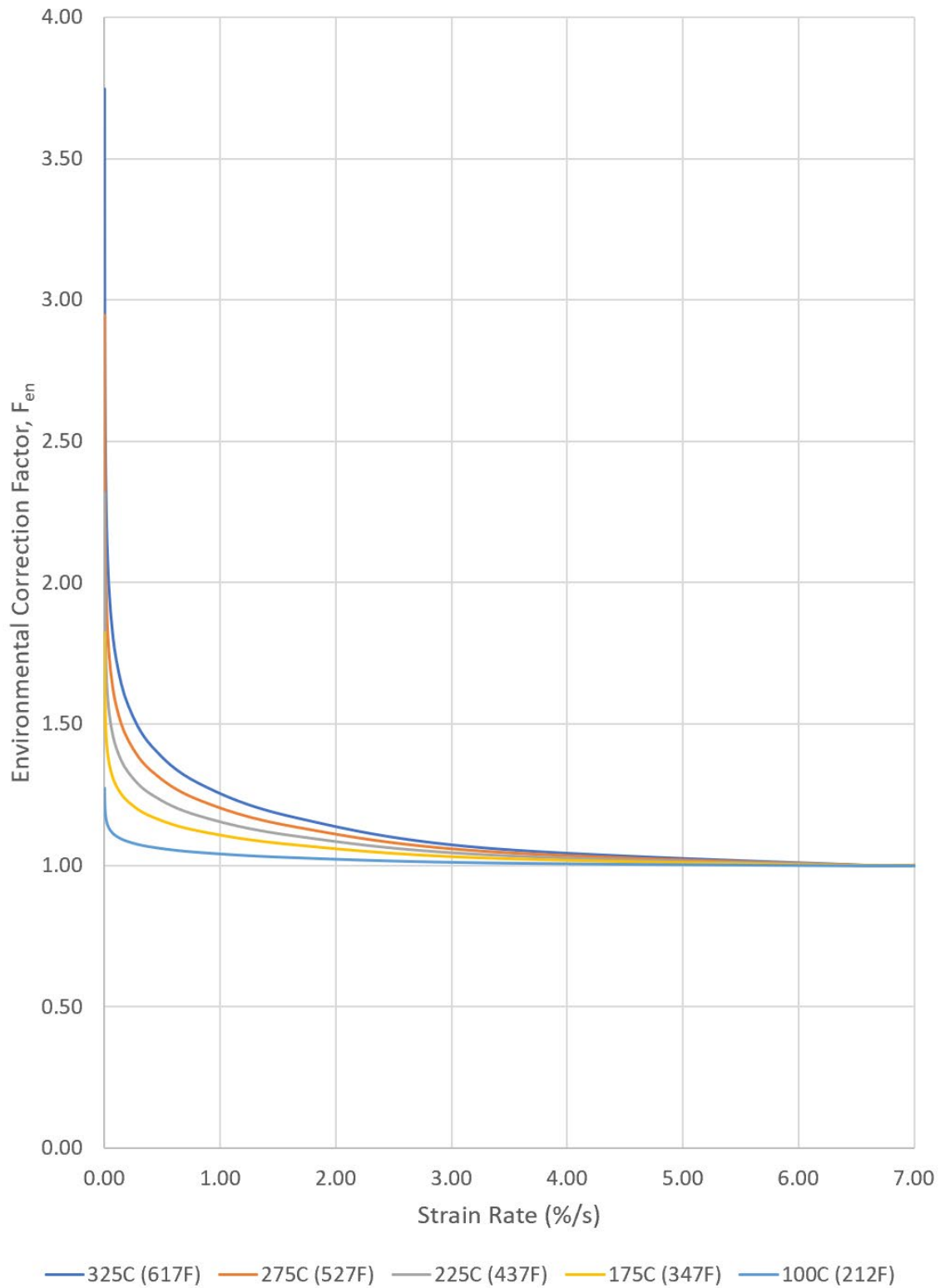


Figure 5-13
Correlation of F_{en} based on Strain Rate for Nickel-based Alloy Steel with $DO < 0.1$ ppm

5.3.5 Integrated Temperature and Strain Rate Approaches

If a more refined environmental fatigue correction factor is determined to be economical, guidance for developing strain rates is provided in Code Case N-884 [58] for components analyzed according to the design by analysis rules in ASME Section III, Appendix XIII or, for Code versions prior to 2017, Subarticle NB-3200. References to Appendix XIII in this handbook cover both. This guidance consists of the following two methods:

- Simplified Method
- Modified Rate Approach

Regardless of the method, the full strain history for the transients is required. The strain history can be calculated from the stress component history. The time history of the six stress components (σ_i , τ_i) is recommended because they have directionality (+/-). Additional guidance is provided in Section 2100 of Code Case N-884. The figures in this Section represent directional strain determined from the stress components, as specified in Code Case N-884.

The guidance in Code Case N-884 is only applicable for components designed to the rules in Appendix XIII or NB-3200. Strain rate guidance for piping is currently under development. Consequently, determining strain rate for piping is currently limited to methods in Code Case N-792-1 [59]. As an alternative, the piping can be re-evaluated using Appendix XIII methods.

5.3.5.1 Simplified Method

The simplified method is discussed in Section 2210 of Code Case N-884. This method accounts for both the strain rate and temperature difference between the two transients contributing to the stresses in a fatigue pair. The strain rates for each transient (ϵ_a and ϵ_b as shown in Figure 5-14) are first calculated by dividing the range between the minimum and maximum strain values by the change in time. The temperatures associated with the minimum and maximum stresses in the fatigue pair are used as described in Section 5.3.3. When the strain range in the two transients overlap as shown in Figure 5-15, the overlapped region may be subtracted from the total strain range and time duration from either transient to determine the conservative strain rate.

Using these strain rates along with the other key environmental parameters discussed above, a F_{en} factor is calculated for each transient ($F_{en,simp,a}$ and $F_{en,simp,b}$). The effective environmental fatigue correction factor for each transient is then calculated in accordance with the Equations in Section 4.

Then a combined F_{en} factor ($F_{en,simp}$) is determined from the strain ranges for the identified transients based on the F_{en} factors for each portion of the load step ($F_{en,simp,A}$, $F_{en,simp,B}$) and the associated minimum and maximum strain for each portion (ϵ_{min} to ϵ_{max}), as shown in Equation (5-2) and Equation (5-3).

$$F_{en,simp} = \frac{F_{en,simp,A} \times (\epsilon_{max,A} - \epsilon_{min,A}) + F_{en,simp,B} \times (\epsilon_{max,B} - \epsilon_{min,B})}{(\epsilon_{max,A} - \epsilon_{min,A}) + (\epsilon_{max,B} - \epsilon_{min,B})} \quad \text{Eq. 5-2}$$

$F_{en,simp}$ is then applied to the usage factor (U_i) for the specific load combination (i) and all load combinations are added:

$$CUF_{en} = \sum_{i=1}^n U_i \times F_{en\ simp,i}$$

Eq. 5-3

The Simplified Method is similar to the Multilinear Strain-Based Method in NUREG/CR-6909.

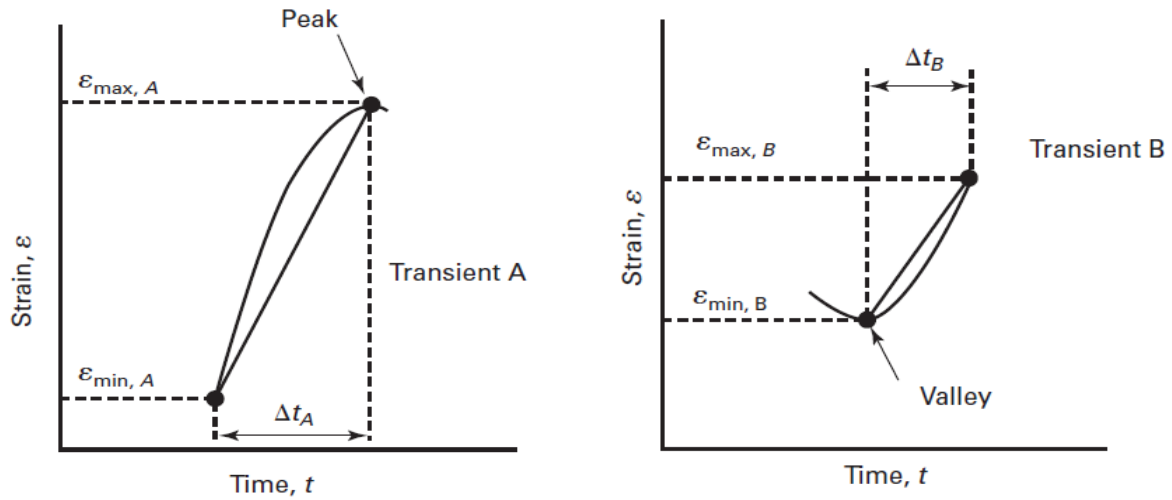


Figure 5-14
Determination of Strain Rate for the Simplified Method

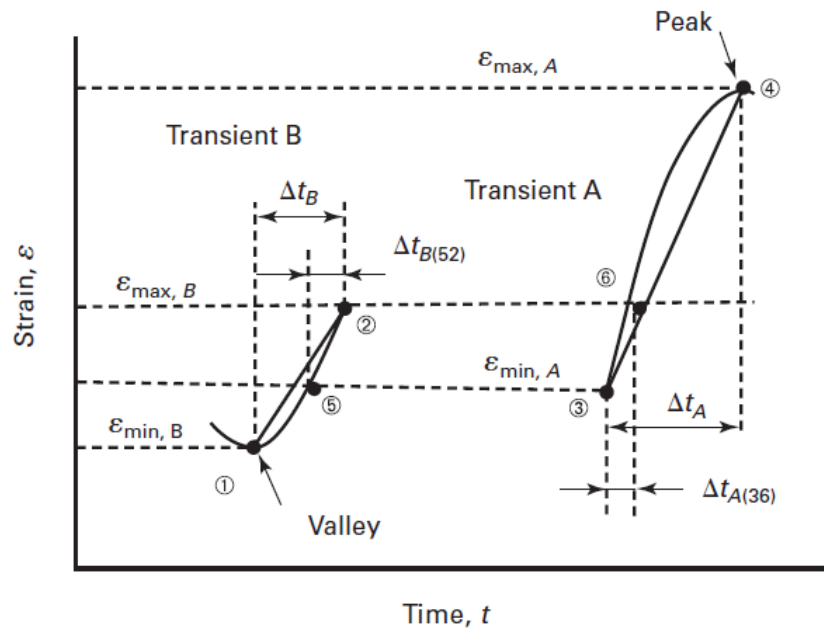


Figure 5-15
Determination of Strain Rate for the Simplified Method for Overlapping Strain Ranges

5.3.5.2 Modified Rate Approach (MRA)

The MRA is provided in Section 2220 of Code Case N-884. This approach is a more refined version of the simplified method in which the transient stress/strain histories are divided into smaller increments over the portion of the transients with an increasing strain rate (also referred to as increasingly tensile; see footnote in Section 5.3.4). Discretization of the strain histories for MRA is shown in Figure 5-16 and Figure 5-17. For each increment, an incremental F_{en} , denoted $F_{en,k}$ in Equation 5-4 below, is calculated through an incremental strain rate using the average value of the temperature across the increment and applicable values of DO and S , respectively. Equation 5-4 shows the summation of the incremental F_{en} values over the discretized portions of each transient with a determined number of segments for each transient, denoted m_A and m_B .

$$F_{en\ mra,A} = \frac{\sum_{k=1}^{m_A} F_{en,k} \Delta \epsilon_{k,A}}{\sum_{k=1}^{m_A} \Delta \epsilon_{k,A}},$$

$$F_{en\ mra,B} = \frac{\sum_{k=1}^{m_B} F_{en,k} \Delta \epsilon_{k,B}}{\sum_{k=1}^{m_B} \Delta \epsilon_{k,B}}$$
Eq. 5-4

The combined F_{en} factor ($F_{en,mra}$) for the pair of transients is calculated as follows:

$$F_{en,mra} = \frac{F_{en,mra,A} \times (\sum_{k=1}^{m_A} \Delta \epsilon_{k,A}) + F_{en,mra,B} \times (\sum_{k=1}^{m_B} \Delta \epsilon_{k,B})}{(\sum_{k=1}^{m_A} \Delta \epsilon_{k,A}) + (\sum_{k=1}^{m_B} \Delta \epsilon_{k,B})}$$
Eq. 5-5

CUF_{en} is then calculated by:

$$CUF_{en} = \sum_{i=1}^n U_{,i} \times F_{en,mra,i}$$
Eq. 5-6

In comparison to the simplified strain rate approach, this method requires more detailed information from the analysis. To gain the benefit of this method, the increments considered for the discretization may need to be decreased. Also, use of MRA requires consideration of the entirety of the increasing portion of the strain history. Strain amplitude threshold values, as noted in Section 4.1, should not be applied with MRA.

The Japanese approach to accounting for strain rate is documented in Appendix C. It is conceptually similar to the approach documented in NUREG/CR-6909 and Code Case N-884.

$$F_{en-n} = \sum_{k=1}^k F_{en,k} \frac{\Delta \epsilon_k}{\epsilon_{max} - \epsilon_{min}}$$

Calculation of F_{en} using the MRA for a simplified transient is illustrated in Sample Problem A.3.

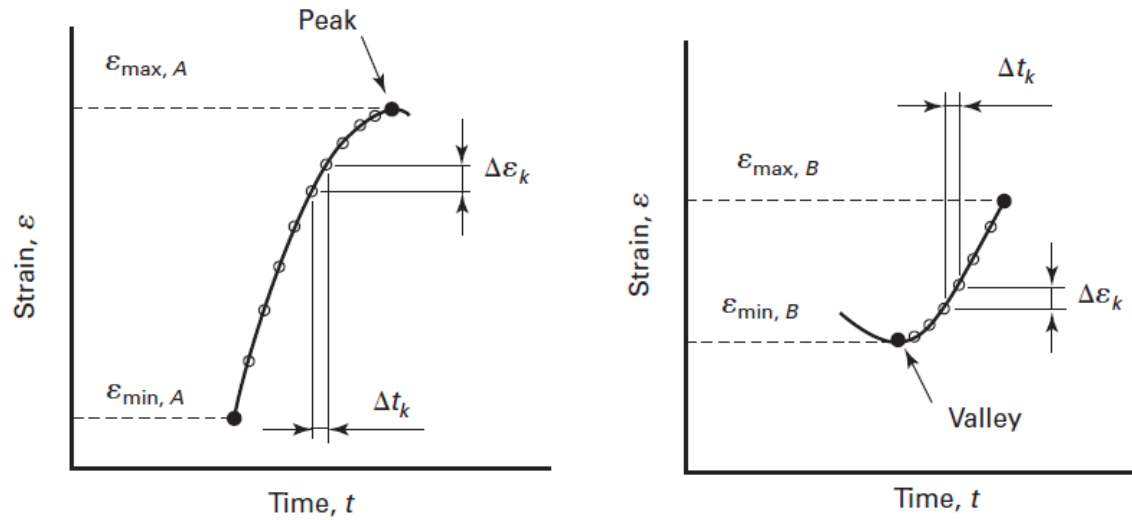


Figure 5-16
Determination of Strain Rate for the MRA

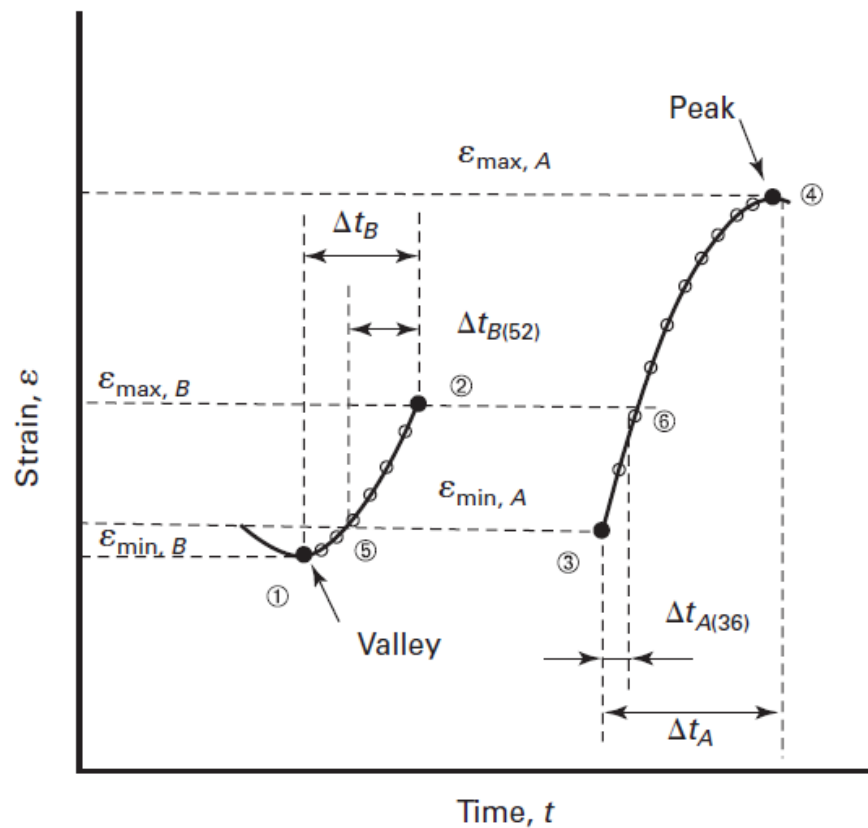


Figure 5-17
Determination of Strain Rate for the MRA for Overlapping Strain Ranges

5.4 Step 4: Reduce the CUF

Detailed calculations may be used to reduce the CUF , which will reduce the CUF_{en} . The first three methods presented in this section may require only recalculation of the transient stress cycle pair parameters using the existing inputs, and not a stress reanalysis (reestablishing the fatigue pairings) or access to a significant amount of transient data. The two methods, the alternative simplified elastic-plastic penalty factor and the thickness and gradient factor, can be combined if needed.

The approaches defined below may also be combined with the approaches to reduce F_{en} from above. It is noted that if the transients are regrouped or redefined, as outlined in Section 5.4.4.1 below, any temperature or strain rate refinements would need to be recalculated based on the new pairings.

The methods presented in this section are based on an elastic stress analysis and identified to reduce conservatism in fatigue evaluations to accommodate the additional impact of environmental effects. Additional methodologies such as refined modeling and transient definition, transient regrouping and/or cycle count refinement, and using inelastic analysis may also be performed as methods to reduce the CUF . Guidance for these methods is summarized below and detailed in Section 4 of the EPRI Low Cycle Fatigue Handbook (MRP-481) [8].

5.4.1 Remove Conservatism in Simplified Elastic-Plastic Penalty Factor, K_e

The methods in ASME Code Section III are generally based on linear elastic stress analysis. To account for plastic cycling, Section III provides simplified rules using an elastic-plastic correction factor, K_e , when the primary plus secondary stress intensity range exceeds $3S_m$. This factor is primarily driven by the primary plus secondary stress intensity (P+Q) range and currently has a maximum value of 3.33 for stainless steels and 5.0 for carbon steels. While the simplified elastic-plastic analysis rules are easy to apply, and avoid more complicated nonlinear analysis, the application of the K_e correction factor, particularly for thermal stress events, can produce overly conservative stress results.

The original plants often have stress analyses completed to older editions of Section III and B31.7. As outlined in NUREG/CR-6260 [50], there are several conservatisms that could exist in the original calculations to consider in reducing K_e , and thus reduce CUF and CUF_{en} . Two often used approaches are:

- Utilize change in piping fatigue requirements: Changes to the NB-3600 piping rules in the 1977 edition, Summer 1979 addenda to remove the ΔT_I term result in a decrease in the primary plus secondary stress range equation (Equation 10) that is used to establish K_e . If the primary plus secondary stress intensity range used to calculate K_e decreased, K_e will decrease, decreasing CUF and CUF_{en} .
- Determine S_m based on transient temperatures when calculating K_e : Section III permits K_e to be calculated based on the maximum transient temperature, or even the average transient temperature if no mechanical loads are present. If S_m used to calculate K_e was determined based on design temperature, a slight reduction in K_e , and thus CUF and CUF_{en} , would be realized for a lower temperature that results in a higher S_m .

- Remove conservatism in stress concentration factor/fatigue strength reduction factor: In some cases, for ease of calculation, a single, conservative stress concentration factor/fatigue strength reduction factor was used for all locations. Applying location-specific stress concentration factor/fatigue strength reduction factor may reduce the alternating stress at the locations of interest and reduce CUF and CUF_{en} .

5.4.2 Alternative Simplified Elastic-Plastic Penalty Factor, K_e

The maximum value of K_e correction factor is based on testing of a tapered flat bar in tension, which resulted in yielding of the entire cross section. The background on this testing is documented in EPRI Report 3002014122 [60]. Since the P+Q range typically includes displacement-controlled stresses, such as thermal expansion moments and secondary stresses from through-wall thermal gradients, yielding is limited to local areas. Consequently, the K_e values from the Code may be conservative by as much as a factor of 2 on stress, especially where the thermal stresses due to temperature transients contribute too much of the P+Q range. Because the fatigue curves are logarithmic, this could result in an overestimate of the usage by a factor of 10 to 30, depending on the stress amplitude.

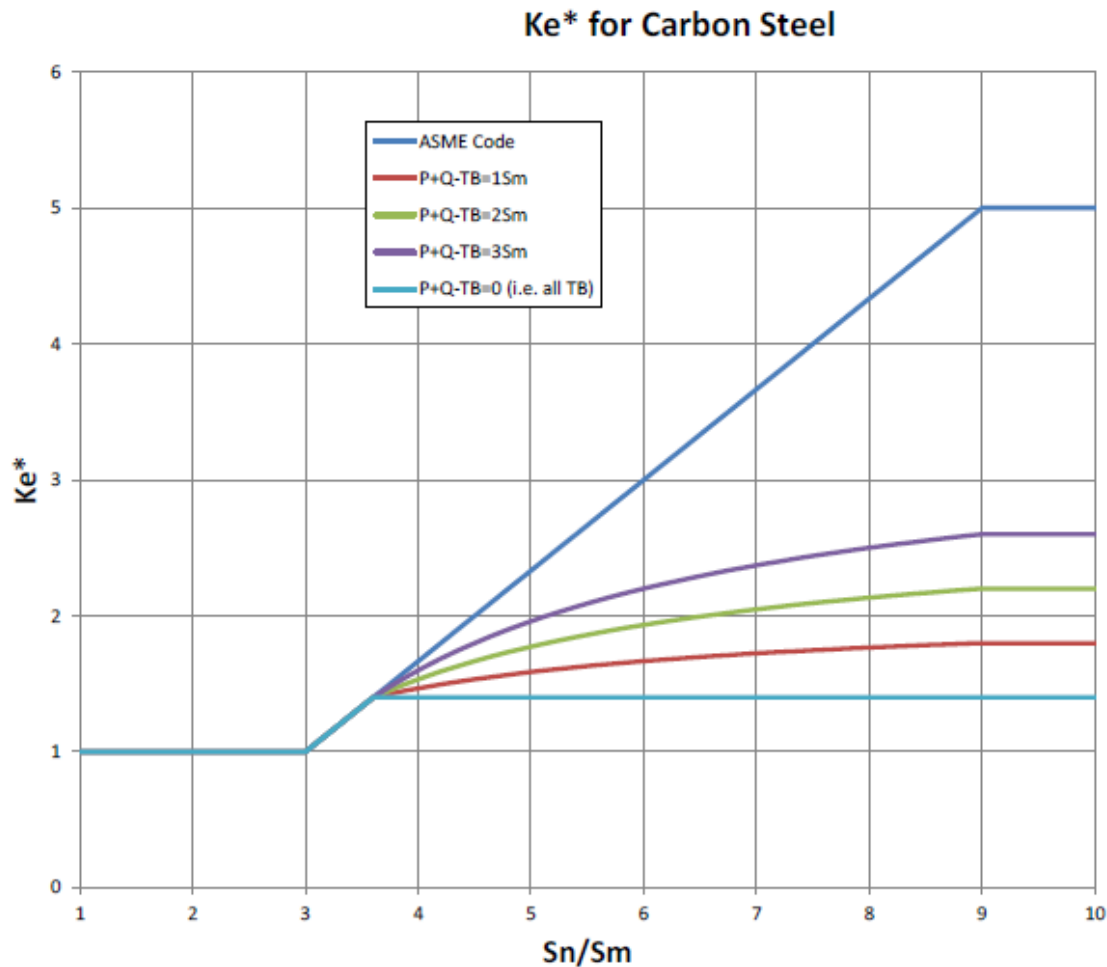
Alternative methods for determining more realistic K_e factors are provided in Code Case N-779 [61] and Code Case N-904 [62]. Code Case N-779 offers an alternative approach to calculating the simplified elastic plastic correction factor, K_e , to be used in a fatigue analysis of NB-3200, NE-3200, NG-3200 and NB-3600 components. The alternate calculation approach separates out the effects of thermal stresses and non-thermal stresses by applying the traditional K_e factor to the non-thermal stresses and alternate factors, K_v and K_n , to the thermal stresses to determine the alternating stress used in the fatigue curve. Code Case N-779 has been approved by the U.S. NRC for use with code editions Summer 1979 addenda and later [63], but is more complex and may require new stress calculations to implement.

Code Case N-904 offers a simplified approach that relies only on information which typically exists in ASME Code stress reports. The technical basis and sample problems for Code Case N-904 are documented in EPRI Report 3002014122 [60], but it has not yet been approved by the NRC for generic use. One may pursue use of the Code Case with the NRC on a specific basis. This methodology is applicable to three different sets of components and structures: (1) Vessels and piping components analyzed using Mandatory Appendix XIII or NB-3200, (2) Piping components analyzed to NB-3600 requirements, and (3) Core support structures. The penalty factor calculated with this methodology is referred to as K_e^* .

Plots of K_e^* for unnotched carbon steels, low alloy steel, and stainless steel components are provided in Figure 5-18 through Figure 5-20 to illustrate the potential reductions ([60], Figures 6-1 through 6-3, respectively). The plots include K_e^* for various values of the range of primary plus secondary membrane plus bending stress intensity, excluding thermal bending stresses (P+Q-TB). As shown in the curves, K_e^* decreases as thermal bending stress increases (or P+Q-TB decreases). For comparison purposes, the plots also include the K_e correction factor based on the Code, which is significantly larger at higher stress ratios. For cases where thermal bending makes up all the P+Q range, K_e^* is only 1.4.

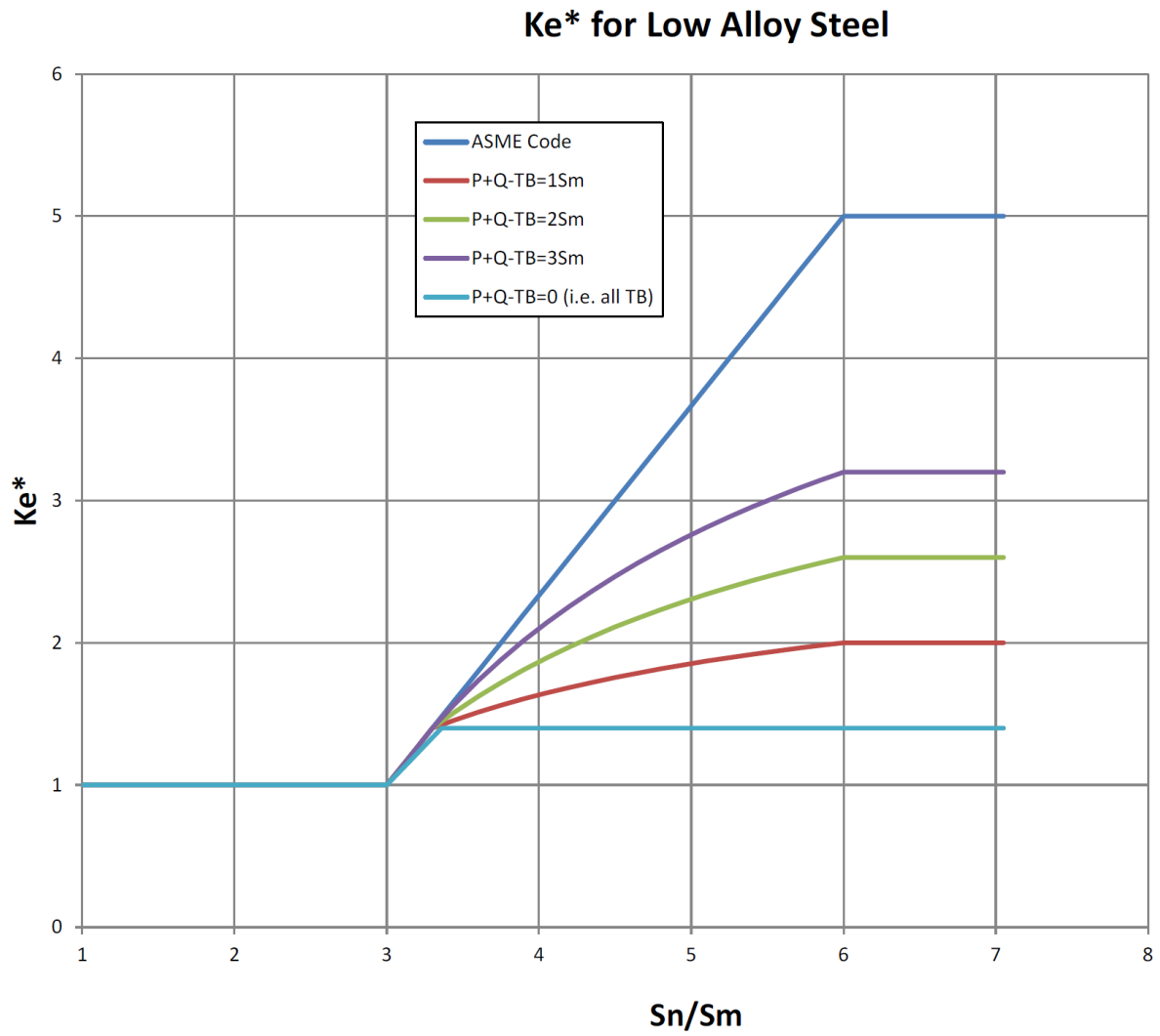
To illustrate the magnitude of this reduction, take a stainless steel component with primary plus secondary stress intensity (P+Q) range of $6S_m$ ($S_n/S_m = 6$ on the horizontal axis of Figure 5-20). As shown in Figure 5-20, K_e is 3.33 per the ASME Code. If the primary plus secondary

membrane plus bending stress intensity, excluding thermal bending stresses ($P+Q-TB$) is $2S_m$, then K_e^* is approximately 2.2. In this example, the elastic-plastic penalty factor and by extension, the alternating stress, is reduced by 33%. Assuming a typical elastically calculated alternating stress without K_e is 62 ksi [427 MPa], S_{alt} including K_e is 207 ksi [1427 MPa] while S_{alt} including K_e^* is 136 ksi [938 MPa]. Therefore, the allowable number of cycles increases from approximately 200 to 500, which decreases the usage by 60%. Note, the reductions in K_e^* are larger for carbon steel and result in even greater reductions in usages.



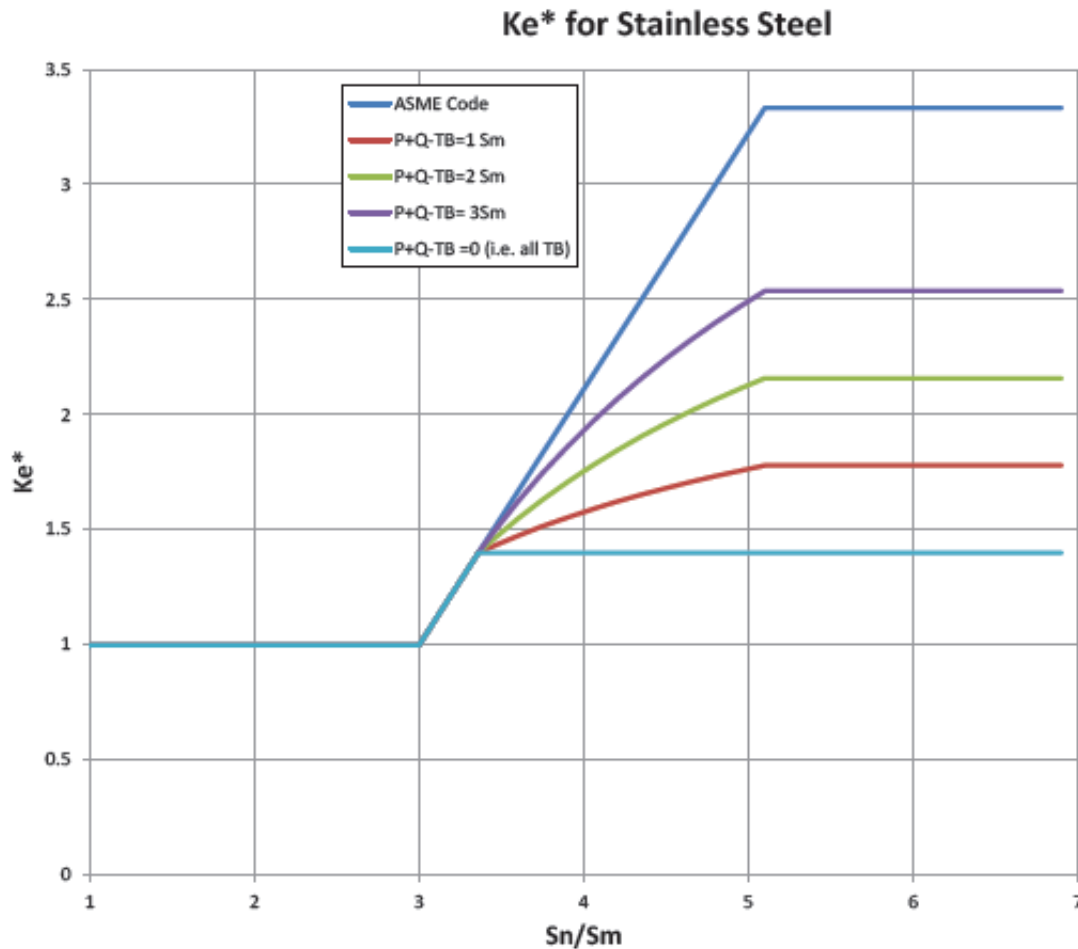
Note: TB is thermal bending stress

Figure 5-18
 K_e^* for Carbon Steel



Note: TB is thermal bending stress

Figure 5-19
K_e* for Low Alloy Steel



Note: TB is thermal bending stress

Figure 5-20
 K_e^* for Stainless Steel

5.4.3 Thickness and Gradient Factors for Piping Fatigue Analyses

Significant fatigue usage in some nuclear power plant piping components is generally driven by stress cycle pairs that include high-strain, low-cycle thermal transient events. Such pairs come from thermal shock events, such as those caused by cold-water injections into hot components. These thermal transients can create large stresses at the inside surface of a component and result in significant non-linear through-wall stress gradients. Under these conditions, crack growth rates will decrease as the crack grows through the pipe wall because of the significant drop-off in stress through the thickness. This results in longer time spent in crack propagation (Stage II life) fatigue life compared to the case when the stress is constant (membrane) through the thickness, such as the situation with laboratory test specimens.

Code Case N-902 [64] provides an alternative method for calculating the cumulative usage for ASME Class 1 piping components. The technical basis and sample problems for Code Case

N-902 are documented in EPRI Report 3002014121 [65], but the Code Case has not yet been approved by the NRC for generic use. One may pursue use of the Code Case with the U.S. NRC on a specific basis. This method includes application of fatigue usage adjustment factors that account for: 1) increased cyclic life associated with component wall thicknesses that differ from the size of standard fatigue test specimens used to develop the fatigue design curves (fatigue thickness factor, TF), and 2) the increased fatigue life associated with the presence of nonuniform pipe wall stress gradients (fatigue gradient factor, GF). These factors are a function of wall thickness, strain rate, and ratio of membrane and through-thickness bending stress range to total stress range. The cumulative usage factor, CUF , considering the thickness and gradient factors, is calculated using the following equation:

$$CUF = U_1TF_1GF_1 + U_2TF_2GF_2 + \dots + U_nTF_nGF_n \quad \text{Eq. 5-7}$$

Results documented in EPRI Report 3002014121 [65] indicate that the TF and GF factors result in significant reductions in calculated CUF , especially in thicker piping. Revised or enhanced stress analysis and fatigue calculations are not required to develop the TF and GF adjustment factors; however, detailed stress results from the piping calculation are required to determine the GF, which is a function of the ratio of membrane and through-thickness bending stress range to total stress range.

5.4.4 Perform Adjustments to Base Fatigue Analysis

If reducing K_e or accounting for more explicit stress distributions does not result in a CUF_{en} less than one, there is the possibility to remove conservatism in the details of the fatigue calculations. In general, these approaches require reanalysis, which can be resource intensive if original analysis inputs and files are not available.

While there may be minimal relief by accounting for refinements in material properties used in the thermal analysis or the modulus of elasticity for the fatigue curve, the main reanalysis technique used to reduce CUF is to redefine the transient groupings, refinements to the original analysis methodology, or use of inelastic analysis for fatigue. NUREG/CR-6260 [50] provides additional discussion on the items discussed here, as well as discussion on potential causes during reanalysis which could result in an increase, rather than a decrease, in the CUF .

5.4.4.1 Redefine Transient Groupings

Grouping transients is common practice in fatigue analyses. Grouping transients is the process by which similar transients are combined and analyzed as a bounding transient with the combined number of occurrences of each transient. This practice inherently introduces conservatism in a fatigue analysis but is generally accepted as it reduces the analytical effort of analyzing each transient separately. Consequently, ungrouping transients can reduce the CUF . The disadvantage of ungrouping transients is it requires a complete reanalysis.

The amount of conservatism introduced by this practice depends on the similarity of the transients grouped. The more similar the transients are to one another; the less conservatism is introduced. The issue with this practice arises when a transient that results in a large alternating stress with a few cycles is used to bound less severe transients with many cycles. In effect, the number of occurrences for this severe transient is being overrepresented and inflating the usage. In these scenarios, significant reductions in partial usages can be achieved by ungrouping or

separating these transients. In the case where the less severe transients contribute little to the overall usage, the usage can be approximated using just the number of cycles associated with the severe transient only.

The practice of grouping transients also needs to be assessed carefully because an approach that is conservative for determining a fatigue usage may not be conservative for calculating an F_{en} factor. To illustrate this idea, consider the example below. If grouped transients results in nonconservative F_{en} factors, the transients will need to be selectively ungrouped to apply a representative F_{en} factor.

- Fatigue is usually driven by fast thermal transients, so it would be acceptable to group a fast transient with a slow transient. However, the F_{en} for a fast transient would be smaller than the F_{en} for a slow transient.
- An instantaneous step change in temperature is mathematically bounding but increases the strain rate, which in turn, decreases the F_{en} factor.

Although regrouping or ungrouping of transients can reduce the usage significantly, it may take significant effort as it requires a reanalysis of the transients that were modified. Additional guidance on the ramp rate effects can be found in EPRI Report 1015014 (MRP-218) [56] and PVP2020-21545 [57].

Additionally, for operating plants, the number of occurrences for events may be modified based on updates in operating practices or revisions in the licensing documents. For example, if a hydrostatic test or operating basis earthquake has significant partial usage (U_i), there may be justification for reducing the number of these cycles considered in the analysis (See NUREG/CR-6260 [50], Section 4.3).

5.4.4.2 Refinements to the Original Analysis Methodology

The approaches and assumptions taken for the original analysis methodology to calculate the primary plus secondary membrane plus bending stress intensity range and the total stress intensity may be revisited. For example, the approach to the heat transfer coefficients, the assumed temperature step changes, or the damping used for dynamic loads such as operating basis earthquake could be revisited. In some instances, hand calculations with simplifying assumptions may have been used and a finite element analysis may remove some of this conservatism. For example, a finite element evaluation could be used for a nozzle that was previously analyzed as a piping branch connection.

5.4.4.3 Use of Inelastic Analysis Approaches

While inelastic analysis was included in Section III since the early 1970s, there is now sufficient precedence to perform inelastic analysis for component qualifications. Performing a fatigue analysis using inelastic analysis approaches would eliminate the need for the overly conservative K_e factor. If the limiting partial usage is easily identified, a plastic analysis for that one event could be used to replace the partial usage (U_i). This approach, while valid, is resource intensive. Additionally, if the stress cycling is well understood, it may be possible to compute the fatigue based on the accumulated strain for more than one transient pair, but can be very difficult since the fatigue in an inelastic analysis is dependent on the prior stress states (e.g., “path dependent”).

5.5 Step 5: Identify Fatigue Management Strategies for EAF

At any time in the process, a component may be placed into an aging management program (AMP) for existing plants; for example, the degradation effects may be managed through monitoring and non-destructive examinations performed at appropriate intervals to detect loss of performance and structural capacity. The strategies that are typically used for existing plants and recommended strategies for new plants are discussed in the following subsections.

5.5.1 Existing Plants

For existing plants applying for license extension, the GALL [19] and GALL-SLR [20] Reports discuss the fatigue monitoring, flaw tolerance/growth evaluations, and repair/replacement of components to address EAF in place of performing an EAF fatigue usage analysis.

5.5.1.1 Fatigue Monitoring

Design and licensing basis cycles for plant transients are developed to bound the actual transients experienced during operation. Fatigue monitoring supports the AMP to track the actual plant transient cycles (cycle counting) and pertinent severity data (i.e., pressure and temperature). By replacing the current licensing basis transients used in a component's analysis of record with more realistic transient cycles or by computing stress responses of components to the plant transient parameters, the fatigue monitoring approach removes the conservatism associated with design transients that inflates the calculated usages. Two ways in which fatigue monitoring can be used to manage or reduce fatigue usage include:

- Recalculating CUF using projected cycles for the extended operating period instead of design or current licensing basis cycles
- Recalculating CUF_{en} values based on the use of actual plant transient pressure and temperature data

Additional detail related to fatigue monitoring is documented in the Low Cycle Fatigue Handbook [8].

5.5.1.2 Flaw Tolerance/Growth Evaluation

Flaw tolerance evaluations can be used to establish inspection frequencies for components that exceed CUF_{en} fatigue limits, or to eliminate the need for CUF_{en} calculations. In many cases, inspections of components with high CUF_{en} values are already performed as part of the 10-year in-service inspection (ISI) program.

Flaw tolerance evaluations consist of performance of a baseline inspection of a component to verify the absence of flaws, and then determination of the time it takes for a postulated flaw, initially sized at the detection threshold of the inspection technique, to grow to an allowable flaw size. The amount of time it takes a postulated flaw to grow to an allowable flaw size determines the reinspection frequency. The re-inspections can be continued as long as no flaws are detected.

Guidance on the performance of fatigue flaw tolerance evaluations to determine acceptability for continued service of reactor coolant system and primary pressure boundary components and piping subjected to cyclic loadings is provided in ASME Code, Section XI, Nonmandatory Appendix L [21]. Appendix L explicitly allows for consideration of actual plant cycles and

measured plant data when characterizing the frequency and severity of transient loading. To account for reactor water environmental effects, the flaw tolerance evaluation must include the appropriate postulated crack growth laws. As of publication of this handbook, the latest crack growth laws for PWR materials and environments are provided in:

- ASME Code Case N-809 for stainless steels
- ASME Code Case N-643-2 and Section XI Appendix A for carbon and low alloy steels
- ASME Section XI, Nonmandatory Appendix C, Paragraph C-8411 for Ni-Cr-Fe Alloy steels (Alloy 600)

In addition to the list above, there is also work ongoing to consolidate all the crack growth laws into non-mandatory Appendix Y in Section XI for the 2023 version of the Code.

5.5.1.3 Repair or Replace Components

As an alternative to the above strategies for managing unacceptable EAF usage, a component can be repaired or replaced. Since fatigue is a time-dependent degradation mechanism, repair or replacement restarts the clock. In general, this strategy is more appropriate for components that have a lower capital cost and can be easily accessed in the plant. While this is an option, it is not often a viable or cost-effective option for items that are in contact with primary coolant.

5.5.2 New Plants

For a new plant, there are several options to consider if EAF cannot be met. The first option is redesigning the component, and while this is the most labor intensive in design, depending on the lifetime of the plant, this may be the most economical approach when considering the total cost to maintain and monitor a component over the life of the plant.

Another potential approach is to utilize a strategy such as that in ASME Code Case N-919 [49]. This Code Case permits the CUF_{en} to be less than 1.0 for a 10-year period if the CUF is demonstrated to be acceptable for the entire design life. The Code Case also requires establishment of an operating plant fatigue assessment that addresses the remaining portion of the service cycles specified in the Design Specification that is not included in the calculation of CUF_{en} . This Code Case has not yet been reviewed by the U.S. NRC.

6

EAF FUTURE RESEARCH

Research and methods for addressing EAF are areas of continuous improvement. This section summarizes the major improvements that are under development in ASME Section III and other international Standards Development Organizations (SDOs). These innovative approaches might be used to further refine EAF evaluations in the coming years. These approaches are under development, have not been reviewed or approved by regulating agencies, and are subject to change as future research and SDO feedback are incorporated.

6.1 Refined Fatigue Curves

As part of the ASME Fatigue Action Plan, there are efforts underway to refine the fatigue curves based on material types, instead of material groups. The list of materials is included in Table 6-1 [66]. Additionally, the committee is determining if additional data is available to support the ASME Section III Division 5 community, because while they are not concerned with primary water environments, the environmental effects may be unknown so refined data could be useful.

Like the efforts by ASME to update the design fatigue curves, efforts are underway in JSME to update the design fatigue curves used for fatigue analysis in air environments. The new curves are based on best-fit curves to the experimental fatigue data with factors to account for data scatter. The effect of surface finish is considered as a fatigue strength reduction factor, K_{sf} , that is applied to the total stress intensity. The effect of mean stress is considered using the Smith-Watson-Topper (SWT) approach, rather than the Modified Goodman approach that is typically used. Details of the JSME's approach are included in Appendix C.4.

Table 6-1
List of Candidate Materials for Discrete Fatigue Curves

SA-182 F316	SA-336 Gr. F1	SA-333 Gr 6
SA-376 GR TP316	SA-358 Cl 1 Type 304	SB 167 Inconel
SA- 213 TP304	SA-376 TP304	SB 564 Inconel
SA-106 Gr B	SA-376 TP316	SA-193, Grade B8M
SA-106 Gr C	SA-508 Class 2a	SA-479, Type 316
SA-155 GR KCF-70	SA-508 Class 2	SA-479, Type XM-19
SA-182 F304	SA-516 Gr 70	SB-637, Grade 688, Type 1
SA-182 F304N	SA-533 Gr A Cl 2	Alloy 718 (UNS N07718)
SA-182 TP316L	SA-533 Gr B Cl 1	SB-637, Type 2 or 3 (UNS N07750)
SA-312 TP304	SA-403 WP304	AMS 5698G, AMS 5699G (UNS N07750)
SA-312 TP316	SA-403 WP316	

6.2 Advanced Analytical Approaches

6.2.1 Strain-Life Weighted Approach

The correlations used to develop F_{en} are predominantly based on testing conducted with constant temperature and strain rate. Service conditions result in more complex loading conditions, with both strain rate and temperature varying through the cycle. To account for this, NUREG/CR-6909 recommends a modified rate approach, which breaks down the cycle into a number of strain increments and then integrates them to provide the F_{en} for the cycle.

Testing conducted with varying temperature and strain rates indicate that the modified rate approach may not accurately capture these complex loading conditions. In particular, the modified rate approach does not predict a difference in life when the temperature is varied in-phase or out-of-phase with the strain waveform, or when the slow portion of the strain rate is moved from the top to the bottom of the waveform [67].

The Strain-Life Weighted (SNW) approach is intended to improve the modified rate approach to accurately account for the simultaneous effects of changes in strain rates and temperatures. Specifically, the F_{en} contribution of each increment is weighted based on the position in the cycle (with more weighting applied to increments approaching the maximum stress value of the cycle). Early estimates show a notable reduction in calculated F_{en} factors with this method for some cases, as compared to the modified rate approach. As of the publication of this Handbook, the SNW approach has been balloted within the ASME Section III Standards Committee with approval expected for the publication of the next version of the Code in 2024. It is currently limited to austenitic stainless steels because of the availability of test data.

6.2.2 Piping and Valve Strain Rate Refinements

A Code Case to determine the strain rate for environmental fatigue evaluation for Class 1 piping (NB-3600) and valves (NB-3500) is under development. This Code Case is intended to be used in combination with Code Case N-792 [59] with the environmental fatigue correction factor, F_{en} , method. This guidance is being developed after it was concluded that the general guidance provided in Code Case N-884 [58] could not be implemented because typical fatigue analysis equations, solution methods, and outputs do not easily provide the necessary stress history to determine strain rate for the Code Case N-884 approach. The Code Case in development is intended to be a simpler and more efficient approach to disposition piping and avoid having to perform costly design by analysis evaluations for these components. The simplified equations used to determine the stress intensity range for piping and valves, which consists of a moment, pressure, temperature, and temperature difference term, is the primary cause for the conservatism. Once completed, this Code Case is expected to reduce the conservatism that is currently included in the strain rate calculations in Code Case N-884, which will reduce the overall impact of EAF on piping and valve analyses.

6.2.3 Total Life

Total-life approaches are being proposed and worked in both the ASME and the JSME Committees. They are jointly seeking to incorporate fatigue approaches based on fracture mechanics that explicitly consider the time it takes for both crack initiation and crack growth. Code Case N-919 [49] is a codified total-life approach within the ASME Code to design with a

focus on a 10-year life. The other methodology under development is focusing on a general approach to incorporate fracture mechanics methodology as an appropriate means of design fatigue life predictions.

The procedure involves four main stages: determining the life to initiate the defect, identifying an initiated defect size, calculating the fatigue crack growth period, and determining a limiting safe defect size. There are three main approaches that can be used to characterize the limiting safe defect size:

- Linear Elastic Fracture Mechanics – LEFM is generally applicable to high strength, low toughness metals where the failure mode is characterized well by comparing the maximum stress intensity factor (SIF) to the toughness.
- Limit load – Limit load is generally applicable to low strength, high toughness materials where the failure mode is characterized well by comparing the loading over the remaining ligament to the material flow strength (average of yield and ultimate strengths).
- Elastic Plastic Fracture Mechanics – EPFM is generally applicable to the intermediate case where the brittle and ductile failure modes interact.

A JSME task group developed a flaw tolerance approach, also referred to as Total Fatigue Life, that assumes that a crack forms at $CUF_{en} = 1.0$. The approach is based on crack aspect ratios developed based on experience at Japanese nuclear power plants and a probabilistic fracture mechanics code. A similar approach is under discussion in the ASME Section III Working Group on Environmental Fatigue Evaluation Methods.

The current area of discussion for use of fracture mechanics evaluations in fatigue design is the characterization of the initial defect and the appropriate margins in the crack growth curves. In Section XI, Division 1, the flaw evaluations are typically completed once a flaw is identified. There are discussions on the appropriate methods to encompass plausible defect sizes and orientations to use as a valid input into the fatigue crack growth models. If the initial defect information is not appropriate, then the fracture mechanics evaluation, and thus the design fatigue life, is not appropriate.

It should be emphasized that these proposed total life evaluations do not advocate for installing a new component with known defects; instead, they offer an alternative method for evaluating and defining the fatigue life of a component using fracture mechanics approaches.

6.2.4 Surface Finish Effects

As discussed in NUREG/CR-6909, Revision 1 [1, Section 4.1.12 for carbon and low-alloy steels, Section 4.2.14 for stainless], the effects of surface finish are inconclusive; however, the current air curves include a surface finish sub-factor in the overall factor of 12 on cycles. Separate research has indicated that the surface finish effect in water environments is less than that in air for some conditions. As such, the factor for surface finish effects is not fully characterized and requires further research, as identified in the Fatigue Gap Analysis as Knowledge Gap 12 [28]. It is hypothesized that in water there is a threshold for surface finish effects that is currently being studied. A proposed Code Case limiting the impact of F_{en} for certain surface finishes is in development within ASME. The limiting value is referred to as F_{en-} .

threshold, and the method was documented in PVP2017-65367 [68]. Additional work on surface finish and the impact on the design fatigue curve is also ongoing with both ASME and JSME.

6.2.5 Fatigue Curves that directly account for Environmental Effects

There are two approved Section III Code Cases pertaining to environmental effects on fatigue usage: Code Case N-761 [69] and Code Case N-792 [59]. However, the U.S. NRC has not approved either Code Case for use: Code Case N-761 because of insufficient technical basis, and Code Case N-792 because the fatigue curves do not reflect the latest available data [70]. The ASME Code Committees are actively working to update Code Case N-792 to reflect the stated concerns and incorporate improvements into the approach. Code Case N-761 is not currently under further consideration within ASME.

6.3 Additional Laboratory Testing

6.3.1 EAF Component Testing

Nearly all of the testing has been performed on small, simple specimens and is then correlated to actual components. EPRI is currently leading an effort to conduct testing on realistic components with plant-representative transients [71 and 72]. The hypothesis is that testing using components and/or component-like features under plant-representative loading conditions will provide additional insights on the current EAF models for both fatigue crack initiation and propagation that have been developed from small-scale specimens tested under mechanical loading conditions. EPRI identified this as Knowledge Gap 33 in the EAF Knowledge Gap Assessment [28]. The aim for the test program is to better correlate conventional small-scale, uniaxial testing and full-sized component testing.

The planned EPRI test loop from 2018 was designed to subject various component geometries, including straight pipe, multiple-stepped pipe, and small components with wetted-surface notches to thermal strains without mechanical loading. The planned test transients are thermal shocks, moderate ramp rates, and slow ramp rates.

6.3.2 Multi-axial Fatigue Testing

Considering the complexities of multi-axial loading in both NPP and mock-up components, reproducing multi-axial loading indicative of NPP components in small-scale laboratory test specimens in a LWR environment can be undertaken to better understand the EAF effects on components. The development of a test program and test facility to conduct such research is a complex task to undertake that requires a substantial development effort. To manage and mitigate the risks for such a test program, a small-scale laboratory testing methodology capable of producing effective data to study EAF under multi-axial cyclic loading is proposed within the EPRI Small-Scale Multi-Axial Fatigue Testing report is documented in [72]. The two main recommendations based on the evaluation presented in this report are to (1) study environmentally assisted multi-axial fatigue initiation based on cruciform specimens combined with X-Shaped specimens and (2) study of environmentally-assisted multi-axial fatigue crack growth based on cruciform specimens combined with compact tension shear/compact tension shear rotation specimens. EPRI is currently considering this testing approach.

6.3.3 Updated F_{en} Correlations for Stainless Steels

The Japanese PWR group conducted experiments to investigate the environmental effects at high strain rates for austenitic stainless steels. Based on the experimental data, F_{en} expressions were developed for base metals, welds, and cast stainless steels. The group found that the F_{en} factors for base metals were most conservative, and these expressions are recommended for inclusion in the JSME code (See Appendix C.4.3).

7

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A

SAMPLE PROBLEMS

This appendix includes the following sample problems to provide examples of how to implement the guidance in this handbook.

- Sample Problem 1 – Update existing CUF calculation to apply NUREG/CR-6909, Revision 1 Fatigue Curves (Stainless Steel).
- Sample Problem 2 – Applying CUF_{en} reduction steps to a Stainless Steel EAF evaluation.
- Sample Problem 3 – Calculating Refined F_{en} Based on Average Temperature or Modified Rate Approach (Stainless Steel)

These sample problems only cover the most current accepted procedure, both for ASME and NUREG/CR-6909. Older editions of the code vary some, as well as the original NUREG/CR-6909, but the overall process and procedures are the same. For older versions, use the analogous references.

A.1 Sample Problem 1 – Update existing CUF calculation to apply NUREG/CR-6909, Revision 1 Fatigue Curves (Stainless Steel)

This sample problem shows how to update an existing CUF calculation at a single location with the updated fatigue curves provided in NUREG/CR-6909, Revision 1. To complete an EAF evaluation, a reconciliation or an update of the fatigue analysis is necessary if the fatigue usage is calculated based on S-N curves that are not consistent with NUREG/CR-6909, Revision 1. Updating the calculations is part of Step 1 in the process described in Section 5, which is to collect the necessary input data.

The input for this example problem is a fatigue analysis conducted according to ASME Code NB-3200, 2004 Edition with the alternating stress listed in Table A-1. To prepare for applying F_{en} factors, the fatigue usage factors should be recalculated to reflect the applicable curve in NUREG/CR-6909, Revision 1.

The updated fatigue curves lead to a change in the number of allowed cycles for the updated analysis. However, the overall analysis methodology is unchanged.

The allowable cycles per transient pairing are determined from the S-N curves. Interpolation is required between the provided data points. The ASME Code prescribes logarithmic interpolation of the following form for fatigue curves (Section III, Mandatory Appendix I):

$$N = N_i \left(\frac{N_j}{N_i} \right)^{\log\left(\frac{S_i}{S}\right) / \log\left(\frac{S_i}{S_j}\right)} \quad \text{Eq. A-1}$$

where,

N = the number of allowable cycles at alternating stress of interest (S), and

N_i, N_j = the number of allowable cycles at next highest (S_i) and next lowest (S_j) alternating stress provided in the table, respectively.

Table A-2 shows the determination of the CUF from the fatigue analysis input Table A-1 using the previous (ASME Code, 2004 Edition, Mandatory Appendix I, Figures I-9.2.1 and I-9.2.2 Curve C) and current (ASME Code 2021 edition adopted from NUREG/CR-6909, Revision 1) stainless steel design fatigue curves. The difference in these fatigue curves are shown in Figure A-1. Equation A-1 is used to calculate the exact number of allowable cycles, as shown in Table A-2.

It is important to note that in the very low cycle region, the pre-2009 ASME curves are slightly more conservative than the NUREG/CR-6909, Revision 1 curves (See Figure 3-3), but in the transition region, the opposite is true. Therefore, if there are moderate alternating stresses with high numbers of cycles, switching fatigue curves can have a significant effect, as shown in this example.

Table A-1. Alternating Stress Design Results (Used as Inputs)

Transient Pairing		Cycles Used	$S_a^{(1)}$
Transient / Load Step	Transient / Load Step		
A/6	B/10	10	196,670 psi [1356 MPa]
A/6	C/8	8890	35,580 psi [245 MPa]
C/8	Steady State	8110	20,653 psi [142 MPa]

Note:

1. The total alternating stress, S_a , due to mechanical and thermal loads including modulus and plasticity corrections.

Table A-2. Fatigue Analysis Results Comparison

Transient Pairing		Cycles Used	2004 ASME Code Edition		2021 ASME Code Edition [1]	
Transient / Load Step	Transient / Load Step		Cycles Allowed	$U_i^{(1)}$	Cycles Allowed	$U_i^{(1)}$
A/6	B/10	10	213	0.0469	230	0.0435
A/6	C/8	8890	211,500	0.0420	42,611	0.2086
C/8	Steady State	8110	3,052,011	0.0027	493,094	0.0164
			CUF:	0.0916	CUF:	0.2686

Note(s):

1. Partial Usage = (Cycles Used / Cycles Allowed)

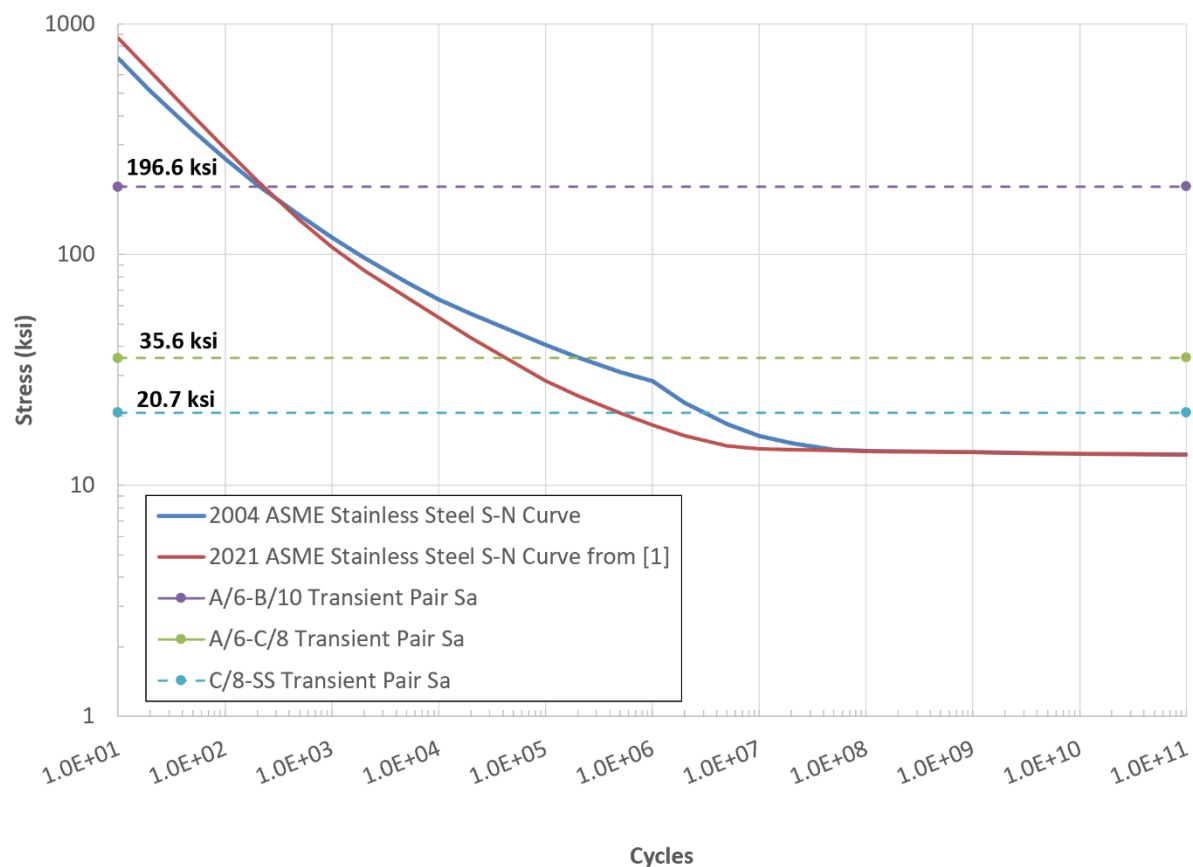


Figure A-1
Fatigue Curve Comparison: ASME 2004 Edition vs. NUREG/CR-6909, Revision 1

A.2 Sample Problem 2 - Applying CUF_{en} reduction steps to a Stainless Steel EAF evaluation

Purpose:

To demonstrate approaches for reducing F_{en} provided in Section 5.

A.2.1 Step 1: Collect Design Inputs

The fatigue results in Table A-3 are obtained from the Design Report for a particular location of interest for a new reactor design. The material is stainless steel. The fatigue evaluation was completed using the ASME Code, 2019 Edition for a Class 1 vessel. The EAF evaluation is to NUREG-6909, Revision 1. Since the stainless steel fatigue curves in Appendix I and NUREG/CR-6909, Revision 1 are identical, the partial usages do not need to be re-calculated based on a different S-N curve as is demonstrated in Sample Problem 1.

Table A-3. CUF (Step 1)

Transient Pairing			K_e	$S_a^{(1)}$ ksi (MPa)	$K_e * S_a^{(2)}$ ksi (MPa)	Cycle Used	Cycles Allowed	U_i
Transient / Load Step								
1	A/6	B/10	3.33	65.7 (453.2)	218.9 (1509.1)	12	181	0.0663
2	A/6	C/8	2.36	34.6 (238.6)	81.7 (563.1)	35	2,345	0.0149
3	D/8	Steady State	2.06	33.5 (231.1)	69.1 (476.2)	1,125	4,137	0.2719
4	E/5	Steady State	1.00	31.2 (215.4)	31.2 (215.4)	45	69,668	0.0006
5	F/14	Steady State	1.00	30.2 (208.5)	30.2 (208.5)	50	78,809	0.0006
6	G/3	Steady State	1.00	16.3 (112.1)	16.3 (112.1)	80,000	2,168,563	0.0369
							CUF:	0.3913

Notes:

1. The total alternating stress due to mechanical and thermal loads including modulus correction.
2. Total alternating stress intensity used for entering the design fatigue curve.

A.2.2 Step 2: Bounding CUF_{en} Calculation and F_{en} Screening

In Step 2, a bounding F_{en} is evaluated, along with application of potential screening criteria for F_{en} based on Section 5.2.2.

Maximum F_{en}

As described in Table 5-3, the maximum F_{en} is 12.8 for stainless steel. From the calculation below, the simplest method to apply the maximum F_{en} does not result in CUF_{en} less than 1.0.

$$CUF_{en} = 0.3913 \times 12.8 = 5.009$$

$F_{en} = 1.0$ Refinement

The screening criteria in Section 5.2 can be applied to screen a location that is not susceptible to fatigue. It can also be applied to individual transient pairings to determine if a F_{en} of 1.0 is appropriate. A F_{en} of 1.0 is applied to pairing 6 since the alternating stress is less than the alternating stress threshold of 28.3 ksi [195 MPa].

Step 2 Result:

The resulting CUF_{en} from this refinement is listed in Table A-4. However, since the CUF_{en} is greater than 1, continue to Step 3 refinement.

Table A-4. CUF_{en} with $F_{en} = 1.0$ Refinement and Maximum F_{en} (Step 2)

Transient Pairing			U_i	$F_{en,i}$	$U_{en,i} = U F_i \times F_{en,i}$
	Transient / Load Step	Transient / Load Step			
1	A/6	B/10	0.0663	12.8	0.8486
2	A/6	C/8	0.0149	12.8	0.1910
3	D/8	Steady State	0.2719	12.8	3.4808
4	E/5	Steady State	0.0006	12.8	0.0083
5	F/14	Steady State	0.0006	12.8	0.0081
6	G/3	Steady State	0.0369	1.0	0.0369
				CUF_{en}:	4.574

A.2.3 Step 3: Refine F_{en}

Transient pair 6 has the lowest F_{en} so further refinement is not possible. The 4th and 5th pairings will not be further refined since the partial usages are almost negligible even with the maximum F_{en} applied. Given the above considerations, further refinements to transient pairs 1, 2, and 3 are considered.

Dissolved Oxygen Content (Section 5.3.1)

A refinement to F_{en} based on Dissolved Oxygen content is not applicable since the PWR environment already accounts for the lowest DO content. The DO content adjustment is typically applicable to BWR environments or for PWR environments for carbon and low alloy steel. Note that a refinement in F_{en} resulting from DO content may be applied to all partial usages when it is applicable.

Sulfur Content Refinement (Section 5.3.2)

A refinement to F_{en} based on sulfur content is not applicable since the material is stainless steel. The sulfur content adjustment is only applicable to carbon and low alloy steels. Note that a refinement in F_{en} resulting from sulfur content may be applied to all partial usages when it is applicable.

Metal Temperature (Section 5.3.3)

The F_{en} of 12.8 is calculated based on the maximum EAF temperature of 617°F (325°C). The design information for the maximum metal temperature during the transient pair may be used to reduce F_{en} . The following maximum metal temperatures for the first three pairs and the recalculated F_{en} are provided in Table A-5.

Strain Rate (Section 5.3.4)

The strain rate for the transients with high partial usages will take significant effort to calculate since the original analysis runs are not available, so Step 4 will be pursued before considering a refinement of F_{en} based on strain rate. Note, a sample problem demonstrating strain rate refinements is not included in this report because comprehensive sample problems are provided in the technical basis documents and other industry technical publications cited in Section 5.3.4, such as in Appendix C of [1] and [25].

Step 3 Result:

The resulting CUF_{en} is listed in Table A-5. While the CUF has been significantly reduced by accounting for the effects of the maximum metal temperature during the transients, as opposed to the design or maximum environmental fatigue temperature, CUF_{en} is greater than 1 and it is not desired to proceed with detailed strain rate calculations so continue to Step 4 to attempt further refinements.

Table A-5. CUF_{en} with F_{en} Refinements (Step 3)

Transient Pairing			U_i	Max Metal Temp °F (°C).	$F_{en,i}$	$U_{en,i} = U_i \times F_{en,i}$
Transient / Load Step	Transient / Load Step	Transient / Load Step				
1	A/6	B/10	0.0663	570 (299)	9.54	0.6325
2	A/6	C/8	0.0149	482 (250)	5.47	0.0816
3	D/8	Steady State	0.2719	300 (149)	1.74	0.4731
4	See Table A-4					0.0083
5						0.0081
6						0.0369
					CUF_{en}:	1.2405

A.2.4 Step 4: Refine in-air Fatigue Usage

Analytical options to further reduce CUF_{en} are pursued. The focus is on those transient pairings with high K_e , like transient pairings 1, 2 and 3.

Refine K_e

There is substantial benefit from the refined K_e for the 1st pairings. From Code Case N-904, the modified K_e , K_e^* , is approximately 2.6 for the maximum permitted primary plus secondary membrane plus bending stress range minus thermal bending, P+Q-TB, of $3S_m$ (Figure 5-20). If the P+Q-TB stress range is known from the stress report, the K_e^* value can be further reduced.

Step 4 Result:

The resulting CUF_{en} is listed in Table A-6. The CUF has been significantly reduced and CUF_{en} is less than 1, which is acceptable. Therefore, the reevaluation of this location is complete.

Table A-6. CUF_{en} with K_e Refinements (Step 4)

Transient Pairing			K_e	$S_a^{(2)}$ ksi (MPa)	$K_e^* S_a^{(3)}$ ksi (MPa)	Cycle Used	Cycles Allowed	U_i	F_{en}	$U_{en,i} =$ $U_i \times F_{en,i}$
Transient / Load Step	Transient / Load Step	Transient / Load Step								
1	A/6	B/10	2.60	65.7 (453.2)	170.9 (1178.3)	12	320	0.0375	9.54	0.3578
2	A/6	C/8	See Table A-5							0.0816
3	D/8	Steady State								0.4786
4	E/5	Steady State								0.0083
5	F/14	Steady State								0.0081
6	G/3	Steady State								0.0369
									CUF_{en}:	0.9713

A.3 Sample Problem 3 - Calculating Refined F_{en} Based on Average Temperature and Modified Rate Approach (Stainless Steel)

When detailed stress and temperature results are available, an F_{en} based on the detailed transient data can be calculated. The intermediate steps to calculate an F_{en} using the average temperature (Section 5.3.4) and the modified rate approach (Section 5.3.5) are illustrated in Table A-8 for the temperature and stress profile in Figure A-2. In this example, the F_{en} calculated using the average temperature approach exceeds the F_{en} calculated using the MRA approach. The results are summarized in Table A-7. Example problems to calculate an F_{en} for more complex loading histories are found in [1].

Table A-7. Summary of Results for Refined F_{en}

F_{en}		Commentary
Permitted Average Temp	1.28	Using T_{ave} considering threshold temperature, as allowed by NUREG/CR-6909, Revision 1
True Average Temp	1.0	Using average temperature below threshold temperature, not allowed by NUREG/CR-6909, Revision 1
MRA	1.14	Using detailed MRA, as allowed by NUREG/CR-6909, Revision 1

A.3.1 Average Temperature Approach

Since the strain rate is linear at 1.11539E-5 %/sec (See Step 1) and the temperature profile is linear with an average value of 121.5°C (the average of 143°C and 100°C), the F_{en} based on the average temperature approach is 1.28.

When establishing the average temperature, temperatures below 100°C are not considered because EAF is not a phenomenon below this threshold temperature. Calculating F_{en} using too low of an average temperature can underpredict the F_{en} . In this example, if the F_{en} were calculated based on the true average temperature of 99°C, then the F_{en} would be 1.0 and that would be non-conservative.

A.3.2 Modified Rate Approach

Step 1

Calculate the strain rate:

$$\dot{\epsilon}_i = \frac{\Delta\sigma}{E\Delta t}$$

In this example, the modulus is constant at 28.3 x 10⁶ psi.

Step 2

Calculate $F_{en,i}$ for each time step based on the temperature and strain rate at the time step using Equation 4-3.

Step 3

For each time step, calculate the change in strain rate (time steps are all of equal value):

$$\Delta \epsilon_i = \frac{\Delta \sigma}{E}$$

Step 4

Calculate the $F_{en,i} \Delta \epsilon_i$ for each time step.

F_{en} using MRA

Calculate the F_{en} using the MRA.

$$F_{en,MRA} = \frac{\sum F_{en,i} \Delta \epsilon_i}{\sum \Delta \epsilon_i} = 1.14$$

Example Transient with Linear Temperature and Linear Strain Rate

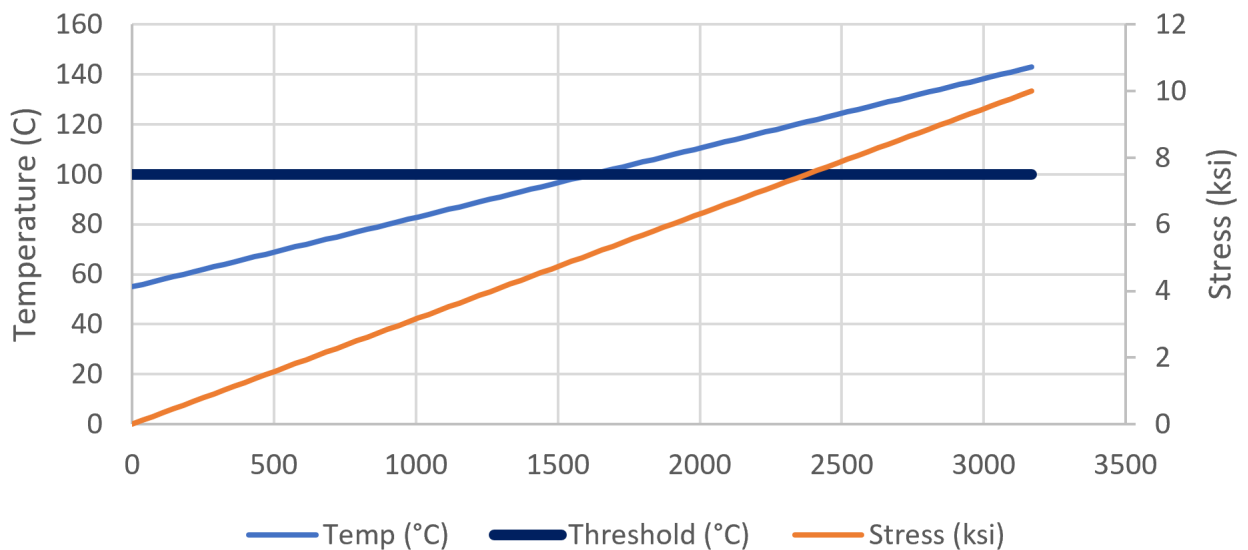


Figure A-2
Time History Temperature and Stress Profiles for Stainless Steel Component

Table A-8
Input Data and Substep Calculations for F_{en} based on MRA

Input Data			Step 1	Step 2	Step 3	Step 4
Time	Temp (°C)	Stress (ksi)	$\dot{\epsilon}$ (%/s)	$F_{en,i}$	$\Delta\epsilon$	$F_{en,i} \cdot \Delta\epsilon$
0	55	0				
36	56	0.113636	1.11539E-05	1	4.01542E-06	4.01542E-06
72	57	0.227273	1.11539E-05	1	4.01542E-06	4.01542E-06
108	58	0.340909	1.11539E-05	1	4.01542E-06	4.01542E-06
144	59	0.454545	1.11539E-05	1	4.01542E-06	4.01542E-06
180	60	0.568182	1.11539E-05	1	4.01542E-06	4.01542E-06
216	61	0.681818	1.11539E-05	1	4.01542E-06	4.01542E-06
252	62	0.795455	1.11539E-05	1	4.01542E-06	4.01542E-06
288	63	0.909091	1.11539E-05	1	4.01542E-06	4.01542E-06
324	64	1.022727	1.11539E-05	1	4.01542E-06	4.01542E-06
360	65	1.136364	1.11539E-05	1	4.01542E-06	4.01542E-06
396	66	1.25	1.11539E-05	1	4.01542E-06	4.01542E-06
432	67	1.363636	1.11539E-05	1	4.01542E-06	4.01542E-06
468	68	1.477273	1.11539E-05	1	4.01542E-06	4.01542E-06
504	69	1.590909	1.11539E-05	1	4.01542E-06	4.01542E-06
540	70	1.704545	1.11539E-05	1	4.01542E-06	4.01542E-06
576	71	1.818182	1.11539E-05	1	4.01542E-06	4.01542E-06
612	72	1.931818	1.11539E-05	1	4.01542E-06	4.01542E-06
648	73	2.045455	1.11539E-05	1	4.01542E-06	4.01542E-06
684	74	2.159091	1.11539E-05	1	4.01542E-06	4.01542E-06
720	75	2.272727	1.11539E-05	1	4.01542E-06	4.01542E-06
756	76	2.386364	1.11539E-05	1	4.01542E-06	4.01542E-06
792	77	2.5	1.11539E-05	1	4.01542E-06	4.01542E-06
828	78	2.613636	1.11539E-05	1	4.01542E-06	4.01542E-06
864	79	2.727273	1.11539E-05	1	4.01542E-06	4.01542E-06
900	80	2.840909	1.11539E-05	1	4.01542E-06	4.01542E-06
936	81	2.954545	1.11539E-05	1	4.01542E-06	4.01542E-06
972	82	3.068182	1.11539E-05	1	4.01542E-06	4.01542E-06
1008	83	3.181818	1.11539E-05	1	4.01542E-06	4.01542E-06
1044	84	3.295455	1.11539E-05	1	4.01542E-06	4.01542E-06
1080	85	3.409091	1.11539E-05	1	4.01542E-06	4.01542E-06

Sample Problems

Input Data			Step 1	Step 2	Step 3	Step 4
Time	Temp (°C)	Stress (ksi)	$\dot{\epsilon}$ (%/s)	$F_{en,i}$	$\Delta \epsilon_i$	$F_{en,i} \cdot \Delta \epsilon_i$
1116	86	3.522727	1.11539E-05	1	4.01542E-06	4.01542E-06
1152	87	3.636364	1.11539E-05	1	4.01542E-06	4.01542E-06
1188	88	3.75	1.11539E-05	1	4.01542E-06	4.01542E-06
1224	89	3.863636	1.11539E-05	1	4.01542E-06	4.01542E-06
1260	90	3.977273	1.11539E-05	1	4.01542E-06	4.01542E-06
1296	91	4.090909	1.11539E-05	1	4.01542E-06	4.01542E-06
1332	92	4.204545	1.11539E-05	1	4.01542E-06	4.01542E-06
1368	93	4.318182	1.11539E-05	1	4.01542E-06	4.01542E-06
1404	94	4.431818	1.11539E-05	1	4.01542E-06	4.01542E-06
1440	95	4.545455	1.11539E-05	1	4.01542E-06	4.01542E-06
1476	96	4.659091	1.11539E-05	1	4.01542E-06	4.01542E-06
1512	97	4.772727	1.11539E-05	1	4.01542E-06	4.01542E-06
1548	98	4.886364	1.11539E-05	1	4.01542E-06	4.01542E-06
1584	99	5	1.11539E-05	1	4.01542E-06	4.01542E-06
1620	100	5.113636	1.11539E-05	1	4.01542E-06	4.01542E-06
1656	101	5.227273	1.11539E-05	1.011398	4.01542E-06	4.06119E-06
1692	102	5.340909	1.11539E-05	1.022925	4.01542E-06	4.10747E-06
1728	103	5.454545	1.11539E-05	1.034584	4.01542E-06	4.15429E-06
1764	104	5.568182	1.11539E-05	1.046376	4.01542E-06	4.20164E-06
1800	105	5.681818	1.11539E-05	1.058302	4.01542E-06	4.24953E-06
1836	106	5.795455	1.11539E-05	1.070364	4.01542E-06	4.29796E-06
1872	107	5.909091	1.11539E-05	1.082564	4.01542E-06	4.34695E-06
1908	108	6.022727	1.11539E-05	1.094902	4.01542E-06	4.39649E-06
1944	109	6.136364	1.11539E-05	1.107382	4.01542E-06	4.4466E-06
1980	110	6.25	1.11539E-05	1.120003	4.01542E-06	4.49728E-06
2016	111	6.363636	1.11539E-05	1.132769	4.01542E-06	4.54854E-06
2052	112	6.477273	1.11539E-05	1.145679	4.01542E-06	4.60038E-06
2088	113	6.590909	1.11539E-05	1.158737	4.01542E-06	4.65282E-06
2124	114	6.704545	1.11539E-05	1.171944	4.01542E-06	4.70585E-06
2160	115	6.818182	1.11539E-05	1.185302	4.01542E-06	4.75948E-06
2196	116	6.931818	1.11539E-05	1.198811	4.01542E-06	4.81373E-06
2232	117	7.045455	1.11539E-05	1.212475	4.01542E-06	4.86859E-06
2268	118	7.159091	1.11539E-05	1.226294	4.01542E-06	4.92408E-06

Input Data			Step 1	Step 2	Step 3	Step 4
Time	Temp (°C)	Stress (ksi)	$\dot{\epsilon}$ (%/s)	$F_{en,i}$	$\Delta \epsilon_i$	$F_{en,i} \Delta \epsilon_i$
2304	119	7.272727	1.11539E-05	1.240271	4.01542E-06	4.98021E-06
2340	120	7.386364	1.11539E-05	1.254407	4.01542E-06	5.03697E-06
2376	121	7.5	1.11539E-05	1.268704	4.01542E-06	5.09438E-06
2412	122	7.613636	1.11539E-05	1.283164	4.01542E-06	5.15244E-06
2448	123	7.727273	1.11539E-05	1.297789	4.01542E-06	5.21117E-06
2484	124	7.840909	1.11539E-05	1.312581	4.01542E-06	5.27056E-06
2520	125	7.954545	1.11539E-05	1.327541	4.01542E-06	5.33064E-06
2556	126	8.068182	1.11539E-05	1.342672	4.01542E-06	5.39139E-06
2592	127	8.181818	1.11539E-05	1.357976	4.01542E-06	5.45284E-06
2628	128	8.295455	1.11539E-05	1.373453	4.01542E-06	5.51499E-06
2664	129	8.409091	1.11539E-05	1.389107	4.01542E-06	5.57785E-06
2700	130	8.522727	1.11539E-05	1.40494	4.01542E-06	5.64142E-06
2736	131	8.636364	1.11539E-05	1.420953	4.01542E-06	5.70572E-06
2772	132	8.75	1.11539E-05	1.437148	4.01542E-06	5.77075E-06
2808	133	8.863636	1.11539E-05	1.453528	4.01542E-06	5.83653E-06
2844	134	8.977273	1.11539E-05	1.470095	4.01542E-06	5.90305E-06
2880	135	9.090909	1.11539E-05	1.486851	4.01542E-06	5.97033E-06
2916	136	9.204545	1.11539E-05	1.503797	4.01542E-06	6.03838E-06
2952	137	9.318182	1.11539E-05	1.520937	4.01542E-06	6.1072E-06
2988	138	9.431818	1.11539E-05	1.538272	4.01542E-06	6.17681E-06
3024	139	9.545455	1.11539E-05	1.555805	4.01542E-06	6.24721E-06
3060	140	9.659091	1.11539E-05	1.573537	4.01542E-06	6.31841E-06
3096	141	9.772727	1.11539E-05	1.591472	4.01542E-06	6.39043E-06
3132	142	9.886364	1.11539E-05	1.609611	4.01542E-06	6.46326E-06
3168	143	10	1.11539E-05	1.627956	4.01542E-06	6.53693E-06
Sum:					0.000353357	0.000404447

B

F_{EN} EQUATIONS USED IN U.S. PLANT LICENSE RENEWAL APPLICATIONS

The expressions for F_{en} have changed over the years as the research and testing into EAF has progressed, along with changes in the regulatory guidance. Within the U.S., that guidance is found in revisions 0 through 2 of the GALL reports [17, 18, 19]. This appendix summarizes the various forms of F_{en} used by U.S. utilities in their license renewal applications. The equations below are from the following references:

- NUREG/CR-5704 [73] for austenitic stainless steels
- NUREG/CR-6583 [51] for carbon and low alloy steels
- NUREG/CR-6909, Revision 0 [48] for the above materials, along with nickel based alloys

B.1 NUREG/CR-5704

For austenitic stainless steels:

$$F_{en} = \exp(0.935 - T^* \dot{\epsilon}^* O^*) \quad \text{Eq. B-1}$$

where,

$$T^* = 0 \quad (T < 200^\circ\text{C})$$

$$T^* = 1 \quad (T \geq 200^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 0.4\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/0.4) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 0.4\%/s)$$

$$\dot{\epsilon}^* = \ln(0.0004/0.4) \quad (\dot{\epsilon} < 0.0004\%/s)$$

$$O^* = 0.260 \quad (DO < 0.05 \text{ ppm})$$

$$O^* = 0.172 \quad (DO \geq 0.5 \text{ ppm})$$

B.2 NUREG/CR-6583

For carbon steel:

$$F_{en} = \exp(0.585 - 0.00124T^* - 0.101S^*T^*\dot{\epsilon}^*O^*) \quad \text{Eq. B-2}$$

For low alloy steel:

$$F_{en} = \exp(0.929 - 0.00124T^* - 0.101S^*T^*\dot{\epsilon}^*O^*) \quad \text{Eq. B-3}$$

where,

$$S^* = S \quad (0 < S \leq 0.015 \text{ wt.}\%)$$

$$S^* = 0.015 \quad (S > 0.015 \text{ wt.}\%)$$

$$T^* = 0 \quad (T < 150^\circ\text{C})$$

$$T^* = T - 150 \quad (150^\circ\text{C} \leq T \leq 350^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 1 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.001 \text{ \%}/\text{s} \leq \dot{\epsilon} \leq 1 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(0.001) \quad (\dot{\epsilon} < 0.001 \text{ \%}/\text{s})$$

$$O^* = 0 \quad (DO < 0.05 \text{ ppm})$$

$$O^* = \ln(DO/0.04) \quad (0.05 \text{ ppm} \leq DO \leq 0.5 \text{ ppm})$$

$$O^* = \ln(12.5) \quad (DO > 0.5 \text{ ppm})$$

B.3 NUREG/CR-6909, Revision 0

B.3.1 Carbon and Low Alloy Steels

For carbon steel:

$$F_{en} = \exp(0.632 - 0.101S^*T^*\dot{\epsilon}^*O^*) \quad \text{Eq. B-4}$$

For low alloy steel:

$$F_{en} = \exp(0.702 - 0.101S^*T^*\dot{\epsilon}^*O^*) \quad \text{Eq. B-5}$$

where,

$$S^* = 0.015 \quad (DO > 1.0 \text{ ppm})$$

$$S^* = 0.001 \quad (DO \leq 1.0 \text{ ppm and } S \leq 0.001 \text{ wt.}\%)$$

$$S^* = S \quad (DO \leq 1.0 \text{ ppm and } 0.001 \text{ wt.}\% \leq S \leq 0.015 \text{ wt.}\%)$$

$$S^* = 0.015 \quad (DO \leq 1.0 \text{ ppm and } S > 0.015 \text{ wt.}\%)$$

$$T^* = 0 \quad (T < 150^\circ\text{C})$$

$$T^* = T - 150 \quad (150^\circ\text{C} \leq T \leq 350^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 1 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.001 \text{ \%}/\text{s} \leq \dot{\epsilon} \leq 1 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(0.001) \quad (\dot{\epsilon} < 0.001 \text{ \%}/\text{s})$$

$$O^* = 0 \quad (DO \leq 0.04 \text{ ppm})$$

$$O^* = \ln(DO/0.04) \quad (0.04 \text{ ppm} < DO \leq 0.5 \text{ ppm})$$

$$O^* = \ln(12.5) \quad (DO > 0.5 \text{ ppm})$$

B.3.2 Austenitic Stainless Steels

$$F_{en} = \exp(0.734 - T^* \dot{\epsilon}^* O^*) \quad \text{Eq. B-6}$$

where,

$$T^* = 0 \quad (T < 150^\circ\text{C})$$

$$T^* = (T - 150)/175 \quad (150^\circ\text{C} \leq T < 325^\circ\text{C})$$

$$T^* = 1 \quad (T \geq 325^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 0.4\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/0.4) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 0.4\%/s)$$

$$\dot{\epsilon}^* = \ln(0.0004/0.4) \quad (\dot{\epsilon} < 0.0004\%/s)$$

$$O^* = 0.281 \quad (\text{all } DO \text{ levels})$$

B.3.3 Ni-Cr-Fe Alloys

$$F_{en} = \exp(-T^* \dot{\epsilon}^* O^*) \quad \text{Eq. B-7}$$

where,

$$T^* = T/325 \quad (T < 325^\circ\text{C})$$

$$T^* = 1 \quad (T \geq 325^\circ\text{C})$$

$$\dot{\epsilon}^* = 0 \quad (\dot{\epsilon} > 5.0\%/s)$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}/5.0) \quad (0.0004\%/s \leq \dot{\epsilon} \leq 5.0 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(0.0004/5.0) \quad (\dot{\epsilon} < 0.0004 \text{ \%}/\text{s})$$

$$O^* = 0.09$$

(Normal Water Chemistry BWR Water)

$$O^* = 0.16$$

(PWR or Hydrogen Water Chemistry BWR Water)

C

JAPANESE METHODS FOR ADDRESSING EAF

This section explains the background and history of the Japanese environmentally assisted fatigue (EAF) methods. Several guidelines and methods for EAF have been published in Japan. The EAF guidelines and methods of the Thermal and Nuclear Power Engineering Society (TENPES), the Ministry of International Trade and Industry (MITI), the Japan Nuclear Energy Safety Organization (JNES), and the Japan Society of Mechanical Engineers (JSME) are explained.

The background and history for the Japanese methods for addressing EAF are provided in Section 2.2.

C.1 TENPES Guideline

The TENPES Guideline [74] employed the F_{en} expressions from the MITI Guideline and the detailed EAF evaluation method including the MRA developed by the EFD Committee. This was a prototype of the “ F_{en} method” in Japan. The TENPES Guideline was issued in June 2002 and replaced use of the MITI Guideline for the EAF evaluation in PSRs.

The outline of the TENPES Guideline is provided below.

1) F_{en} expressions

The F_{en} expressions are identical to those used in the MITI Guideline except for the threshold strain amplitude for carbon and low alloy steels. The MITI Guideline specifies the threshold strain amplitude for only austenitic stainless steels as 0.11%. The TENPES Guideline specifies the threshold for carbon and low alloy steels as 0.042%, which corresponds to the fatigue endurance limit of the design fatigue curve for carbon and low alloy steels in MITI Notification 501 (because any stress under the fatigue endurance limit is not required for fatigue analysis).

a) For carbon and low alloy steels and their associated welds:

$$\ln(F_{en}) = -(0.199 \times T^* \times O^* + 0.112) \times S^* \times \dot{\epsilon}^* \quad \text{Eq. C-1}$$

where,

$$\begin{aligned} \dot{\epsilon}^* &= 0 & (\dot{\epsilon} > 1.0 \%/\text{s}) \\ \dot{\epsilon}^* &= \ln(\dot{\epsilon}) & (1.0 \%/\text{s} \geq \dot{\epsilon} \geq 0.0004 \%/\text{s}) \\ \dot{\epsilon}^* &= \ln(0.0004) & (\dot{\epsilon} < 0.0004 \%/\text{s}) \\ T^* &= 0.00531 \times T - 0.7396 & (T \geq 180 \text{ }^\circ\text{C}) \\ T^* &= 0.216 & (T < 180 \text{ }^\circ\text{C}) \\ O^* &= 0 & (DO < 0.03 \text{ ppm}) \\ O^* &= \ln(DO/0.03) & (0.03 \text{ ppm} \leq DO \leq 0.5 \text{ ppm}) \\ O^* &= \ln(0.5/0.03) & (DO > 0.5 \text{ ppm}) \\ S^* &= 17.23 \times S + 0.777 \end{aligned}$$

b) For austenitic stainless steels and their associated welds in PWR environments:

$$\ln(F_{en}) = 1.233 - P \times \ln(\dot{\epsilon}^*/0.4) \quad \text{Eq. C-2}$$

where,

$$\begin{aligned} P &= 0.04 & (T \leq 100 \text{ }^\circ\text{C}) \\ P &= 9.33 \times 10^{-4} \times T - 0.053 & (100 \text{ }^\circ\text{C} < T \leq 325^\circ\text{C}) \\ P &= 0.25 & (T \geq 325 \text{ }^\circ\text{C}) \\ \dot{\epsilon}^* &= 0.4 & (\dot{\epsilon} > 0.4 \%/\text{s}) \\ \dot{\epsilon}^* &= \dot{\epsilon} & (0.0004 \%/\text{s} \leq \dot{\epsilon} \leq 0.4 \%/\text{s}) \\ \dot{\epsilon}^* &= 0.0004 & (\dot{\epsilon} < 0.0004 \%/\text{s}) \end{aligned}$$

c) For austenitic stainless steels and their associated welds in BWR environments:

Equation C-2 for austenitic stainless steels and their associated welds in PWR environments may be applied to BWR environments.

d) Ni-Cr-Fe alloys and their associated welds:

Equation C-2 for austenitic stainless steels and their associated welds in PWR environments may be applied to Ni-Cr-Fe alloys.

2) EAF Evaluation Method

The intent of the TENPES Guideline was to employ a detailed EAF evaluation method, while the MITI Guideline only provided F_{en} expressions. The EFD Committee developed the EAF evaluation method, and the TENPES finalized it and incorporated it into the TENPES Guideline. The EAF evaluation method includes the factor multiplication method, simplified method and detailed method known as the MRA Method. Also, procedures for vessels, piping, pumps, valves and core support structures were prescribed using those methods.

The outline of the EAF evaluation method is provided below.

a) Evaluation method for vessels

Vessels may be evaluated using the following three options developed by Kishida et al. [74] using the TENPES F_{en} equations.

- Factor Multiplication Method
- Simplified Method
- Detailed Method

(i) Factor Multiplication Method

The Factor Multiplication Method is the most conservative method among the three and multiplies a screening F_{en} factor to the total CUF in air as follows:

$$CUF_{en} = CUF \times F_{en\ SC} \quad \text{Eq. C-3}$$

where,

CUF_{en} = cumulative usage factor with environmental effects

CUF = original cumulative usage factor without environmental effects

$F_{en\ SC}$ = screening F_{en} factor calculated as follows:

Carbon and low alloy steels and their associated welds

The following F_{en} factors may be applied, where the F_{en} factor for BWR environments is obtained from Equation C-1 using $\dot{\epsilon} = 0.0004$ %/s (the saturation strain rate), and for PWR environments is obtained from Equation C-1 using $\dot{\epsilon} = 0.0004$ %/s (the saturation strain rate), $O^* = 0$ ($DO \leq 0.005$ ppm for PWR environments) and $T = 325$ °C (PWR typical operating temperature):

$$\text{For BWR, } F_{en\ SC} = \exp(1.557 \times T^* \times O^* \times S^* + 0.876 \times S^*) \quad \text{Eq. C-4}$$

where,

T^* , O^* , and S^* are used from Eq. C-1

T is set to the maximum temperature of the transients during the evaluated period or higher.

DO is set to the maximum DO during the evaluated period or higher.

S is set to the maximum value specified in the material code or the material purchase specification, or the value in the certified material test report.

$$\text{For PWR, } F_{enSC} = \exp(15.10 \times S + 0.681) \quad \text{Eq. C-5}$$

where,

S is set to the maximum value specified in the material code or the material purchase specification, or the value in the certified material test report.

Austenitic stainless steels and Ni-Cr-Fe alloys, and their associated welds

The following F_{en} factors may be applied, where the F_{en} factor is obtained from Equation C-2 using $\dot{\epsilon} = 0.0004$ %/s (the saturation strain rate):

$$F_{enSC} = \exp(1.233 + 6.908 \times P) \quad \text{Eq. C-6}$$

where,

$$P = 0.04 \quad (T \leq 100 \text{ }^{\circ}\text{C})$$

$$P = 9.33 \times 10^{-4} \times T - 0.053 \quad (100 \text{ }^{\circ}\text{C} < T < 325 \text{ }^{\circ}\text{C})$$

$$P = 0.25 \quad (T \geq 325 \text{ }^{\circ}\text{C})$$

T is set to the maximum temperature of the transients during the evaluated period or higher.

(ii) Simplified Method

The Simplified Method is a conservative method and uses the average strain rate for calculating the F_{en} factor for each load combination, i , in a fatigue calculation ($F_{en\text{ simp},i}$):

$$CUF_{en} = \sum_{i=1}^n U_{,i} \times F_{en\text{ simp},i} \quad \text{Eq. C-7}$$

$F_{en\text{ simp},i}$ is calculated using the following steps:

- A monotonically increasing strain history is applied to the F_{en} calculation because it affects EAF. The strain used to calculate the F_{en} factor is defined as the stress intensity divided by the modulus of elasticity, and a strain history is converted from the stress intensity history considering the plus/minus sign of the stress for a transient. It is noted that a stress intensity does not have a specific plus/minus sign. Therefore, the sign of the stress intensity shall be determined as shown in Figure C-1. This means that the principal stress with a larger absolute value is dominant and its sign is used for the sign of the stress intensity.
- Each strain history is obtained as shown in Figure C-2. The strain histories of Transient A and Transient B are combined as $\epsilon_{min,A} = \epsilon_{max,B}$, and the total strain history is obtained.

- The peak and the valley are connected with a straight line, and the average strain rate is determined as $\Delta\epsilon/\Delta t$.
- $F_{en\ simp,i}$ is calculated by substituting the average strain rate into Equation C-1 or Equation C-2. The parameters other than strain rate are set as follows:
 - The temperature is set to the maximum temperature for the pair of transients or higher. The design temperature may be conservatively used.
 - DO is set to the maximum value for the pair of transients or higher. The maximum DO value controlled in the plant may be conservatively used.
 - The following is employed for the material sulfur (S) value for the evaluated material:
 - The maximum value from the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.

(iii) Detailed Method (the MRA)

F_{en} is calculated by integrating the F_{en} value for each segment in a strain history which is called “the Modified Rate Approach” (MRA).

F_{en} by the MRA is defined as Equation C-8 and is practically calculated by Equation C-9:

$$F_{en} = \int_{\epsilon_{min}}^{\epsilon_{max}} \{F_{en}(\dot{\epsilon}_T)/(\epsilon_{max} - \epsilon_{min})\} d\epsilon \quad \text{Eq. C-8}$$

where,

$\dot{\epsilon}_T$ = strain rate for a monotonically increasing strain history

ϵ_{max} = the maximum strain for the pair of transients

ϵ_{min} = the minimum strain for the pair of transients

$$F_{en\ det,i} = \sum_{k=1}^m F_{en,k} \frac{\Delta\epsilon_k}{\epsilon_{max} - \epsilon_{min}} \quad \text{Eq. C-9}$$

where,

$F_{en\ det,i}$ = F_{en} for i^{th} transient pair

$F_{en,k}$ = F_{en} at k^{th} segment in a strain history. The F_{en} expression using Equation C-1 or Equation C-2 is applied. For each average strain rate, the temperature and DO values that are used are the minimum or lower value of strain rate and the maximum or higher value of temperature and DO .

$\Delta\epsilon_k$ = strain increment for k^{th} segment

ϵ_{max} = the maximum strain for the pair of transients

ε_{min} = the minimum strain for the pair of transients

The detailed method may be applied when a stress (strain) history for each transient is obtained. CUF_{en} is calculated as follows:

- The same as for the Simplified Method, where a monotonically increasing strain history is determined as shown in Figure C-3.
- The monotonically increasing strain history is divided into small segments. $F_{en,k}$ for the k^{th} segment is calculated using Equation C-1 or Equation C-2 assuming the strain rate, temperature, and DO are constant for the segment. The minimum or lower value of strain rate and the maximum or higher value of temperature and DO may be used for the segment.
- $F_{en\ det,i}$ is calculated by Equation C-9.
- CUF_{en} is calculated as follows:

$$CUF_{en} = \sum_{i=1}^n U_{,i} \times F_{en\ det,i} \quad \text{Eq. C-10}$$

b) Evaluation method for piping

Piping may be evaluated using the following three options:

- Factor Multiplication Method
- Simplified Method
- Detailed Method

The evaluation methods for vessels may be applied to piping when stress (strain) histories are available.

(i) Factor Multiplication Method

The Factor Multiplication Method is the most conservative method among the three and multiplies a screening F_{en} factor to the total CUF .

The Factor Multiplication Method for vessels is applied to piping.

(ii) Simplified Method

For the Simplified Method for piping, a strain rate for each pair of transients is determined, the F_{en} value is calculated, and then the CUF_{en} value is calculated. The Simplified Method for piping is basically similar to that for vessels, but a specific method for piping that is consistent with piping design by formula rules is employed to determine the strain rate.

In stress analyses for piping performed in accordance with the design code, the stress is generally calculated by a formula using the maximum pressure, the maximum difference of temperatures, and so on. The peak stress intensity range, S_p , for piping is defined in the design code as follows:

$$S_p = \underbrace{\frac{K_1 C_1 P_0 D_0}{2t}}_{\text{M term}} + \underbrace{\frac{K_2 C_2 M}{Z_t}}_{\Delta T_1 \text{ term}} + \underbrace{\frac{K_3 E \alpha |\Delta T_1|}{1.4} + K_3 C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b|}_{\text{T}_a\text{--T}_b \text{ term}} + \underbrace{\frac{E \alpha |\Delta T_2|}{0.7}}_{\Delta T_2 \text{ term}} \quad \text{Eq. C-11}$$

where,

K_1, K_2, K_3 = local stress indices for the specific component under investigation

C_1, C_2, C_3 = secondary stress indices for the specific component under investigation

P_0 = pressure for Service Levels A and B

D_o = outside diameter of pipe

t = nominal wall thickness of pipe

$t_a (t_b)$ = average wall thickness through the length $\sqrt{d_a t_a}$ ($\sqrt{d_b t_b}$)

$d_a (d_b)$ = inside diameter on side $a(b)$ of a gross structural discontinuity or material discontinuity

M = moment due to thermal expansion, thermal anchor movements and mechanical loads except dead weights

Z_i = section modulus

E = modulus of elasticity

E_{ab} = average modulus of elasticity of the two sides of a gross structural discontinuity or material discontinuity at room temperature

α = mean coefficient of thermal expansion

$\alpha_a (\alpha_b)$ = mean coefficient of thermal expansion on side $a(b)$ of a gross structural discontinuity or material discontinuity at room temperature

$T_a (T_b)$ = range of average temperature on side $a(b)$ of a gross structural discontinuity or material discontinuity. For generally cylindrical shapes, the averaging of T shall be over a distance of $\sqrt{d_a t_a}$ for T_a and over a distance of $\sqrt{d_b t_b}$ for T_b .

$|\Delta T_1|$ = absolute value of the range of the temperature difference between the temperature of the outside surface and the temperature of the inside surface of the piping product assuming a moment generating an equivalent linear temperature distribution

$|\Delta T_2|$ = absolute value of the range for that portion of the nonlinear thermal gradient through the wall thickness not included in ΔT_1

$F_{en\ sim p, i}$ is calculated using the following steps:

- For the pair of transients, the M and ΔT terms are compared, and the dominant term is determined.

- When the M term is greater than the ΔT_1 term, $F_{en\ simp,i}$ for the i^{th} transient pair is calculated using the F_{en} expression in Equation C-1 or Equation C-2 as follows:
 - The strain rate for the “Startup” transient is employed as the strain rate for the pair of transients to be evaluated, where the linear relation between strain and time is assumed as shown in Figure C-4.
 - The temperature is set to the maximum temperature for the pair of transients or higher. The design temperature may be conservatively used.
 - DO is set to the maximum value for the pair of transients or higher. The maximum DO value controlled in the plant may be conservatively used.
 - The following is employed for the S value for the evaluated material:
 - The maximum value of the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.
- When the ΔT term is greater than the M term, $F_{en\ simp,i}$ for the i^{th} transient pair is calculated using the F_{en} expression in Equation C-1 or Equation C-2 as follows:
 - The strain rate is calculated from the history of the ΔT_1 term for the transient for which the temperature difference is greatest for the pair of transients, assuming the variation from the minimum value to the maximum value is linear.
 - The temperature is set to the maximum temperature for the pair of transients or higher. The design temperature may be conservatively used.
 - DO is set to the maximum value in the pair of transients or higher. The maximum DO value controlled in the plant may be conservatively used.
 - The following is employed for the S value for the evaluated material:
 - The maximum value of the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.

CUF_{en} is calculated using Equation C-7 using the obtained $F_{en\ simp,i}$ values.

(iii) Detailed Method (the MRA)

The following Detailed Method for piping may be applied when the ΔT term is dominant in the Simplified Method for piping.

S_p depends on P , M , ΔT_1 , ΔT_2 and $T_a - T_b$. For the pair of transients under investigation, the transient for which the temperature difference for cooling is greater than that of the other transient is addressed. ΔT_1 , ΔT_2 , T_a and T_b of which histories are obtained using thermal analysis are substituted into the S_p calculation formula of Equation C-11 and the stress (strain) history is obtained.

Then, the obtained strain history is applied to the Detailed Method for vessels, and $F_{en\ det,i}$ and CUF_{en} are calculated.

c) Evaluation method for pumps

The evaluation methods for vessels may be applied to pumps.

d) Evaluation method for valves

Valves may be evaluated using the following three options:

- Factor Multiplication Method
- Simplified Method
- Detailed Method

The evaluation methods for vessels may be applied to valves when stress (strain) histories are available.

(i) Factor Multiplication Method

The Factor Multiplication Method is the most conservative method among the three and multiplies a screening F_{en} factor to the total CUF .

The Factor Multiplication Method for vessels is applied to valves.

(ii) Simplified Method

For the Simplified Method for valves, a strain rate for each pair of transients is determined, the F_{en} value is calculated, and then the CUF_{en} value is calculated. The Simplified Method for valves is basically similar to that for piping.

In stress analyses for valves performed in accordance with the design code, a stress is generally calculated by a formula using the maximum pressure, the maximum difference of temperatures, and so on, the same as for piping. The alternating stress intensity, S_{alt} ($= S_p/2$), for valves is stipulated in the design code as follows:

For startup and cooldown

$$\text{Inside of valve body: } S_{alt} = 2P_s \left(\frac{r_i}{t_e} + 0.5 \right) + \frac{P_e}{2} + \alpha E C_3 \Delta T + 1.3 Q_T \quad \text{Eq. C-12}$$

$$\text{Outside of valve body: } S_{alt} = 1.2 P_s \left(\frac{r_i}{t_e} + 0.5 \right) + P_e + 2\alpha E C_3 \Delta T \quad \text{Eq. C-13}$$

For other than startup and cooldown

$$S_{alt} = \frac{1}{2} \left\{ 4\Delta P_{fm} \left(\frac{r_i}{t_e} + 0.5 \right) + \alpha E \Delta T_f (C_3 C_4 + C_5) \right\} \quad \text{Eq. C-14}$$

where,

C_3, C_4, C_5 : stress indices specified in the design code

P_s : Standard Calculation Pressure defined in primary stress evaluation due to internal pressure in the design code

P_e : secondary stress due to piping reactions specified in the design code

ΔP_{fm} : specified range of pressure fluctuation except during startup and cooldown specified in the design code

Q_T : maximum thermal stress component caused by through-wall temperature gradient specified in the design code

ΔT : maximum magnitude of the difference in average wall temperature specified in the design code

ΔT_{fm} : specified range of temperature fluctuation except during startup and cooldown specified in the design code

r_i : inside radius of valve body at crotch region specified in the design code

t_e : valve body wall thickness adjacent to the crotch specified in the design code

E : modulus of elasticity

α : mean coefficient of thermal expansion

$F_{en\ simp,i}$ is calculated for startup and cooldown conditions and in other cases according to the following steps:

- $F_{en\ simp,i}$ for startup and cooldown conditions is calculated as follows:
 - The strain amplitude for startup is used.
 - S_p is determined as twice the S_{alt} obtained using Equation C-12, and the strain rate is obtained by dividing S_p by the time period for startup.
 - The temperature is set to the maximum temperature during startup and cooldown conditions or higher. The design temperature may be conservatively used.
 - DO is set to the maximum value during startup and cooldown conditions or higher. The maximum DO value controlled in the plant may be conservatively used.
 - The following is employed for the S value for the evaluated material:
 - The maximum value of the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.
- $F_{en\ simp,i}$ for other than startup and cooldown conditions is calculated as follows.
 - For the pair of transients, the transient for which temperature difference for cooling is greater is employed, and S_p is determined as twice the S_{alt} obtained using Equation C-14 for the employed transient. The strain rate is obtained by dividing S_p by the time period of the employed transient.
 - The temperature is set to the maximum temperature in the pair of transients or higher. The design temperature may be conservatively used.
 - DO is set to the maximum value in the pair of transients or higher. The maximum DO value controlled in the plant may be conservatively used.

- The following is employed for the S value for the evaluated material:
 - The maximum value of the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.
- CUF_{en} is then obtained by summing all $F_{en\ simp,i}$ values.

(iii) Detailed Method (the MRA)

The Detailed Method for piping may be applied when the temperature and pressure histories are available with the following conditions:

- Strain histories are calculated from temperature and pressure histories for startup and cooldown conditions and other than startup and cooldown conditions, and the strain rate for each segment is calculated. The lowest strain rate or lower may be applied to the strain rate for each segment.
- The temperature is set to the average temperature for each segment. The highest temperature or higher in each segment may be applied.
- DO is set to the average value at each segment. The highest DO value or higher in each segment may be applied.
- The following is employed for the S value for the evaluated material:
 - The maximum value of the material code, or the maximum value of the purchase specification.
 - The value in the certified material test report.

e) Evaluation method for core support structures

The evaluation methods for vessels may be applied to core support structures.

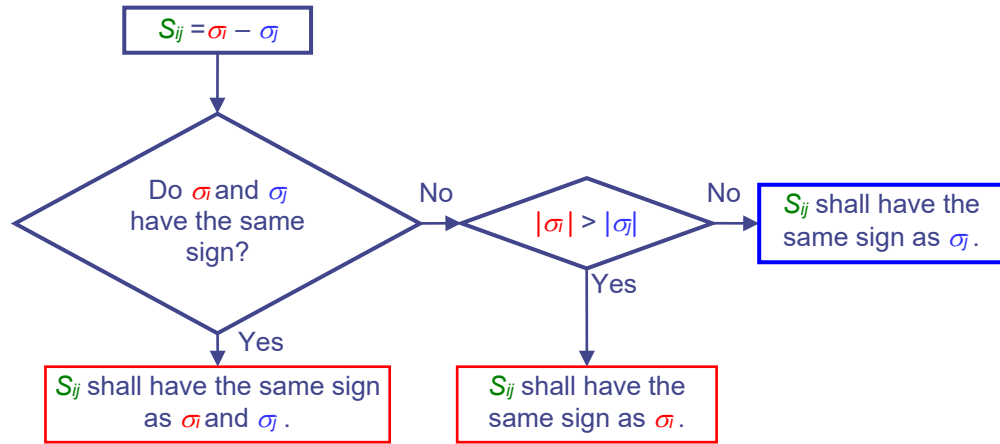


Figure C-1
Determining the Sign of the Stress Difference

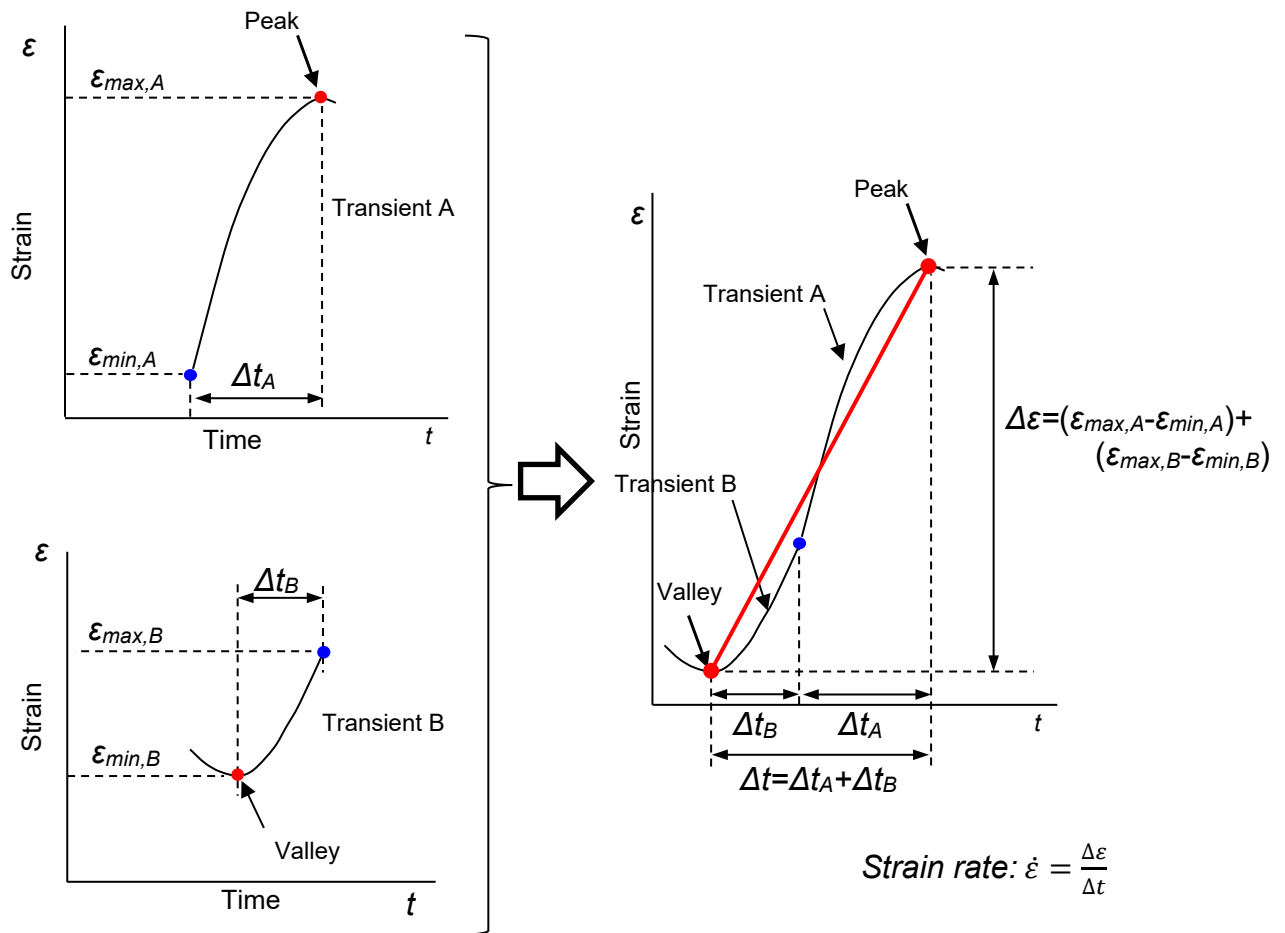


Figure C-2
Determining Strain Rate for the Simplified Method

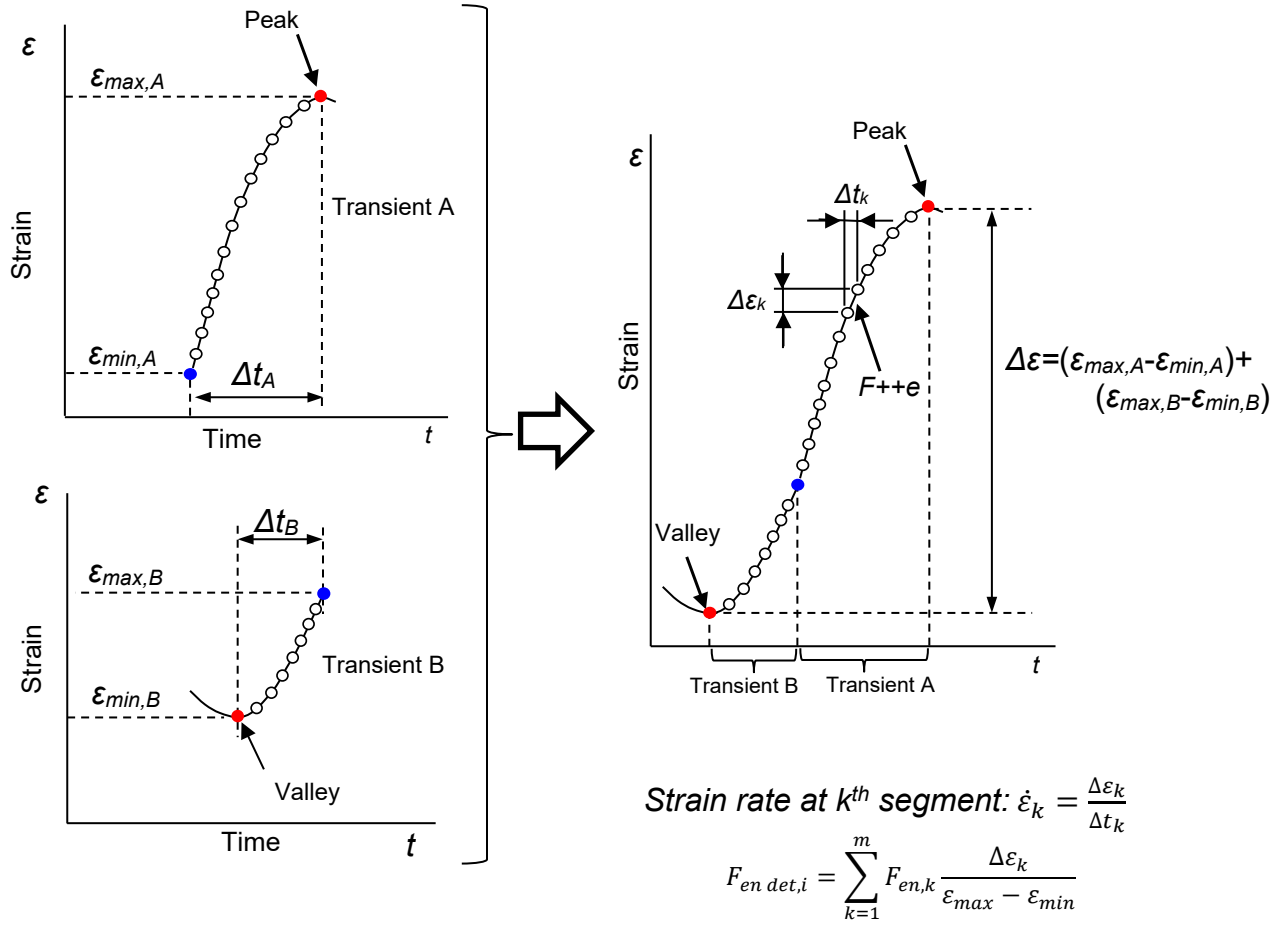


Figure C-3
Determining Strain Rate and F_{en} for the Detailed Method

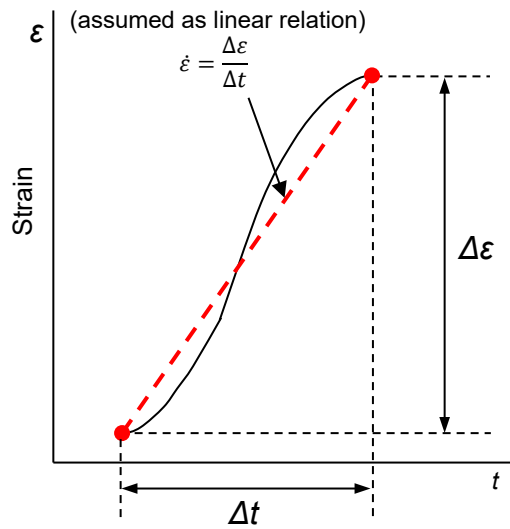


Figure C-4
Monotonically Increasing Strain History (For the Startup Condition)

(The equations and figures in Section C.1 are reprinted from [74] by permission of the Japan Thermal and Nuclear Power Engineering Society (TENPES). All rights reserved.)

C.2 MITI Guideline

MITI received the 1999 Report of the EFT Project that was founded by MITI, and the report indicated there was a reduction in the fatigue lives of carbon, low alloy, and austenitic stainless steels in the presence of an LWR environment. Based on this, MITI directed plants to perform EAF evaluation as a part of PLM Aging Evaluation using “the Guideline for Evaluating Fatigue Initiation Life Reduction in LWR Environment” (MITI Guideline) in September 2000.

The MITI Guideline specified only F_{en} expressions as follows. These F_{en} expressions from the MITI Guideline were incorporated into the TENPES Guideline.

a) For carbon and low alloy steels and their associated welds:

$$\ln(F_{en}) = -(\mathbf{0.199} \times \mathbf{T^*} \times \mathbf{O^*} + \mathbf{0.112}) \times \mathbf{S^*} \times \dot{\epsilon}^* \quad \text{Eq. C-15}$$

where:

$$\begin{aligned} \dot{\epsilon}^* &= 0 & (\dot{\epsilon} > 1.0 \text{ \%/s}) \\ \dot{\epsilon}^* &= \ln(\dot{\epsilon}) & (1.0 \text{ \%/s} \geq \dot{\epsilon} \geq 0.0004 \text{ \%/s}) \\ \dot{\epsilon}^* &= \ln(0.0004) & (\dot{\epsilon} < 0.0004 \text{ \%/s}) \\ T^* &= 0.00531 \times T - 0.7396 & (T \geq 180 \text{ }^\circ\text{C}) \\ T^* &= 0.216 & (T < 180 \text{ }^\circ\text{C}) \\ O^* &= \ln(DO/0.03) & (0.03 \text{ ppm} \leq DO \leq 0.5 \text{ ppm}) \\ O^* &= 0 & (DO < 0.03 \text{ ppm}) \\ O^* &= \ln(0.5/0.03) & (DO > 0.5 \text{ ppm}) \\ S^* &= 17.23 \times S + 0.777 \end{aligned}$$

b) For austenitic stainless steels and their associated welds:

$$\ln(F_{en}) = \mathbf{1.233} - \mathbf{P} \times \ln(\dot{\epsilon}^*/\mathbf{0.4}) \quad \text{Eq. C-16}$$

where:

$$\begin{aligned} P &= 0.04 & (T \leq 100 \text{ }^\circ\text{C}) \\ P &= 9.33 \times 10^{-4} \times T - 0.053 & (100 \text{ }^\circ\text{C} < T \leq 325 \text{ }^\circ\text{C}) \\ P &= 0.25 & (T \geq 325 \text{ }^\circ\text{C}) \\ \dot{\epsilon}^* &= 0.4 & (\dot{\epsilon} > 0.4 \text{ \%/s}) \end{aligned}$$

$$\dot{\varepsilon}^* = \dot{\varepsilon} \quad (0.0004 \% / s \leq \dot{\varepsilon} \leq 0.4 \% / s)$$

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

(Equations C-15 and C-16 reprinted from [33] by permission of the Japan Ministry of Economy, Trade, and Industry (METI), formerly named the Ministry of International Trade and Industry (MITI). All rights reserved.)

$F_{en} = 1.0$ when the strain amplitude $\leq 0.11 \%$, which corresponds to a stress of 195 MPa using an elastic modulus of $E = 177,000$ MPa because the environmental effect for this condition is negligible.

c) Scope and revision:

This guideline was to be applied to the fatigue analysis of aging plants.

Also, this guideline would be revised, if necessary, based on the results of study of additional data by future research programs.

The above F_{en} expression for austenitic stainless steels and their associated welds was obtained from experimental tests in PWR environments ($DO \leq 0.005$ ppm). Because the F_{en} in BWR environments ($DO > 0.005$ ppm) was still under study, the above F_{en} expression was applied to BWR environments until the results of study were available, which gives slightly conservative results.

C.3 JNES-SS-1005

JNES issued the final report of the EFT Project [40] and technical report JNES-SS-0701 [39] in April 2007. JNES-SS-1005 [41], which was a translated English version of JNES-SS-0701, was issued in March 2011.

It is noted that the Nuclear Regulatory Authority (NRA) of Japan formally provided the JNES EAF data summarized in JNES-SS-1005 to the U.S. NRC, and the NRC incorporated those data into NUREG/CR-6909, Revision 1 to update Regulatory Guide 1.207.

In this section, the EAF evaluation method of JNES-SS-1005 and the plan of experimental fatigue testing in the EFT Project are summarized.

(The equations and figures in Sections C.3.1 through C.3.7 are reprinted from [39, 41] by permission of the Japan Nuclear Regulatory Authority. All rights reserved.)

C.3.1 F_{en} expressions

All F_{en} expressions were fully revised from the MITI Guideline using the final test results of the EFT Project and documented in JNES-SS-1005 [41].

Threshold for Environmental Effects

The threshold strain amplitudes are as follows:

- 0.042 % or less for carbon and low alloy steels

- 0.11 % or less for austenitic stainless steels and high nickel alloys

Seismic loads are exempted from environmental fatigue evaluation because strain rates during seismic loads are sufficiently high that the effects of EAF are negligible.

For carbon and low alloy steels and their associated welds

$$\ln(F_{en}) = 0.00822(0.722 - \dot{\epsilon}^*) \times S^* \times T^* \times O^* \quad \text{Eq. C-17}$$

where:

[For $DO \leq 0.7$ ppm]

$$\dot{\epsilon}^* = \ln(2.16) \quad (\dot{\epsilon} > 2.16 \%/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 2.16 \%/\text{s})$$

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

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

$$T^* = 0.0358 \times T \quad (T < 50 \text{ }^\circ\text{C})$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160 \text{ }^\circ\text{C})$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160 \text{ }^\circ\text{C})$$

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

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

[For $DO > 0.7$ ppm]

$$\dot{\epsilon}^* = \ln(2.16) \quad (\dot{\epsilon} > 2.16 \%/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0001 \leq \dot{\epsilon} \leq 2.16 \%/\text{s})$$

$$\dot{\epsilon}^* = \ln(0.0001) \quad (\dot{\epsilon} < 0.0001 \%/\text{s})$$

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

$$T^* = 0.0358 \times T \quad (T < 50 \text{ }^\circ\text{C})$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160 \text{ }^\circ\text{C})$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160 \text{ }^\circ\text{C})$$

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

Transient conditions: In BWR environments, the F_{en} expression is applied to thermal transients. Also, for transients that have elastic follow-up due to pressure maintaining its

peak value, the strain rate is assumed equal to 0.004 %/s when the strain rate is greater than 0.004 %/s.

For austenitic stainless steels and their associated welds

(1) BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-18}$$

where:

$$C = 0.992$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 2.69 \text{ \%/s})$$

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

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

Transient conditions: In BWR environments, the F_{en} expression is applied to thermal transients. Also, for transients that have elastic follow-up due to pressure maintaining its peak value, the strain rate is assumed equal to the lower threshold strain rate.

(2) PWR environments and PWR plant secondary system environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-19}$$

where,

$$C = 3.910$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 49.9 \text{ \%/s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 49.9 \text{ \%/s for Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.0004) \quad (\dot{\epsilon} < 0.0004 \text{ \%/s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.00004) \quad (\dot{\epsilon} < 0.00004 \text{ \%/s for Cast SS})$$

$$T^* = 0.000782 \times T \quad (T \leq 325 \text{ }^\circ\text{C})$$

$$T^* = 0.254 \quad (T > 325 \text{ }^\circ\text{C})$$

Nickel-Chromium-Iron Alloys and their associated welds

(1) BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-20}$$

where,

$$C = -0.112$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 0.894 \%/\text{s})$$

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

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

(2) PWR environments and PWR plant secondary system environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-21}$$

where,

$$C = 2.94$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 19.0 \%/\text{s})$$

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

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

C.3.2 EAF Evaluation Method (General)

JNES-SS-1005 also specifies the following three methods that are nearly identical to the TENPES guideline:

- Factor Multiplication Method
- Simplified Method
- Detailed Method

Factor Multiplication Method

In the Factor Multiplication Method, the cumulative usage factor with environmental effects, CUF_{en} , is obtained by multiplying the cumulative usage factor in air, U , and the maximum F_{en} for the evaluation period, $F_{en,SC}$.

$$CUF_{en} = U \times F_{en,SC} \quad \text{Eq. C-22}$$

The values to calculate $F_{en,SC}$ are set as follows:

- Strain rate: the lowest threshold strain rate.
- Temperature: the design temperature for the evaluation period or higher. The maximum temperature of each transient may be conservatively used.
- DO : the maximum DO for the evaluation period or higher. The maximum DO of each transient may be conservatively used.

Specifically, the expressions for $F_{en,SC}$ are given for each material and reactor type as follows:

i) For carbon and low alloy steels and their associated welds

(1) BWR environments

$$F_{en,SC} = \exp(0.07066 \times S^* \times T^* \times O^*) \quad (DO \leq 0.7 \text{ ppm}) \quad \text{Eq. C-23}$$

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

where,

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

$$T^* = 0.0358 \times T \quad (T < 50 \text{ }^\circ\text{C})$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160 \text{ }^\circ\text{C})$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160 \text{ }^\circ\text{C})$$

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

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

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

(2) PWR environments

$$F_{en,SC} = \exp(0.08393 \times S^* \times T^*) \quad \text{Eq. C-24}$$

where,

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

$$T^* = 0.0358 \times T \quad (T < 50 \text{ }^\circ\text{C})$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160 \text{ }^\circ\text{C})$$

$$T^* = \ln(0.398) + 0.0170 \times T \quad (T > 160 \text{ }^\circ\text{C})$$

ii) For austenitic stainless steels and their associated welds

(1) BWR environments

$$F_{en} = \exp(11.119 \times T^*) \quad \text{Eq. C-25}$$

where,

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

(2) PWR environments and PWR plant secondary system environments

$$F_{en,SC} = \exp(11.734 \times T^*) \text{ for stainless steel except cast stainless steel} \quad \text{Eq. C-26}$$

$$F_{en,SC} = \exp(14.037 \times T^*) \text{ for cast stainless steel}$$

where,

$$T^* = 0.000782 \times T \quad (T \leq 325 \text{ }^\circ\text{C})$$

$$T^* = 0.254 \quad (T > 325 \text{ }^\circ\text{C})$$

iii) Nickel-Chromium-Iron Alloys and their associated welds

(1) BWR environments

$$F_{en,SC} = \exp(10.015 \times T^*) \quad \text{Eq. C-27}$$

where,

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

(2) PWR environments and PWR plant secondary system environments

$$F_{en,SC} = \exp(10.764 \times T^*) \quad \text{Eq. C-28}$$

where,

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

Simplified Method

The Simplified Method was updated from the TENPES Guideline.

As shown in Figure C-2, the Simplified Method of the TENPES Guideline is to combine the two transients and obtain the average strain rate from the combined curve.

Based on the discussions during the EFT Project, the determination of strain rate for the pair of transients was changed [76]. For two transients (Transient A and Transient B), $F_{en,simp,A}$ and $F_{en,simp,B}$ are calculated respectively as follows. As shown in Figure C-5, a strain history for which strain is continuously increasing (from ε_{min} to ε_{max}) is identified for each transient. The strain rates ($\dot{\varepsilon}_A$ and $\dot{\varepsilon}_B$) are determined as the average from ε_{min} to ε_{max} . $F_{en,simp,A}$ and $F_{en,simp,B}$ are calculated by the appropriate F_{en} expression from Equation C-17 to C-21 using the strain rates ($\dot{\varepsilon}_A$ and $\dot{\varepsilon}_B$) and the other appropriate parameters. Then, $F_{en,simp}$ for the transient pair stress cycle is calculated as follows. $F_{en,simp,A}$ or $F_{en,simp,B}$, whichever is greater, may be conservatively used as $F_{en,simp}$.

$$F_{en,simp} = \frac{F_{en,simp,A} \times (\varepsilon_{max,A} - \varepsilon_{min,A}) + F_{en,simp,B} \times (\varepsilon_{max,B} - \varepsilon_{min,B})}{(\varepsilon_{max,A} - \varepsilon_{min,A}) + (\varepsilon_{max,B} - \varepsilon_{min,B})} \quad \text{Eq. C-29}$$

CUF_{en} is then calculated as follows:

$$CUF_{en} = \sum_{i=1}^n U_i \times F_{en,simp,i} \quad \text{Eq. C-30}$$

Detailed Method

$F_{en,det,A}$ and $F_{en,det,B}$ for Transient A and Transient B, respectively, are calculated by the MRA, as shown in Figure C-6:

$$F_{en,det,A} = \sum_{k=1}^{m_A} F_{en,k} \frac{\Delta \varepsilon_k}{\varepsilon_{max,A} - \varepsilon_{min,A}}, F_{en,det,B} = \sum_{k=1}^{m_B} F_{en,k} \frac{\Delta \varepsilon_k}{\varepsilon_{max,B} - \varepsilon_{min,B}} \quad \text{Eq. C-31}$$

$F_{en,det}$ for the pair of transients is calculated as follows:

$$F_{en,det} = \frac{F_{en,det,A} \times (\varepsilon_{max,A} - \varepsilon_{min,A}) + F_{en,det,B} \times (\varepsilon_{max,B} - \varepsilon_{min,B})}{(\varepsilon_{max,A} - \varepsilon_{min,A}) + (\varepsilon_{max,B} - \varepsilon_{min,B})} \quad \text{Eq. C-32}$$

CUF_{en} is then calculated as follows:

$$CUF_{en} = \sum_{i=1}^n U_i \times F_{en,det,i} \quad \text{Eq. C-33}$$

C.3.3 EAF Evaluation Method for Vessels

Factor Multiplication Method

The Factor Multiplication Method described in Section C.3.2 above is applied.

Simplified Method

The Simplified Method described in Section C.3.2 above is applied. A strain history is converted from the stress intensity history considering the plus/minus sign for transient stress in accordance with Figure C-1.

Detailed Method

The Detailed Method described in Section C.3.2 above is applied. A strain history is converted from the stress intensity history considering the plus/minus sign for transient stress in accordance with Figure C-1.

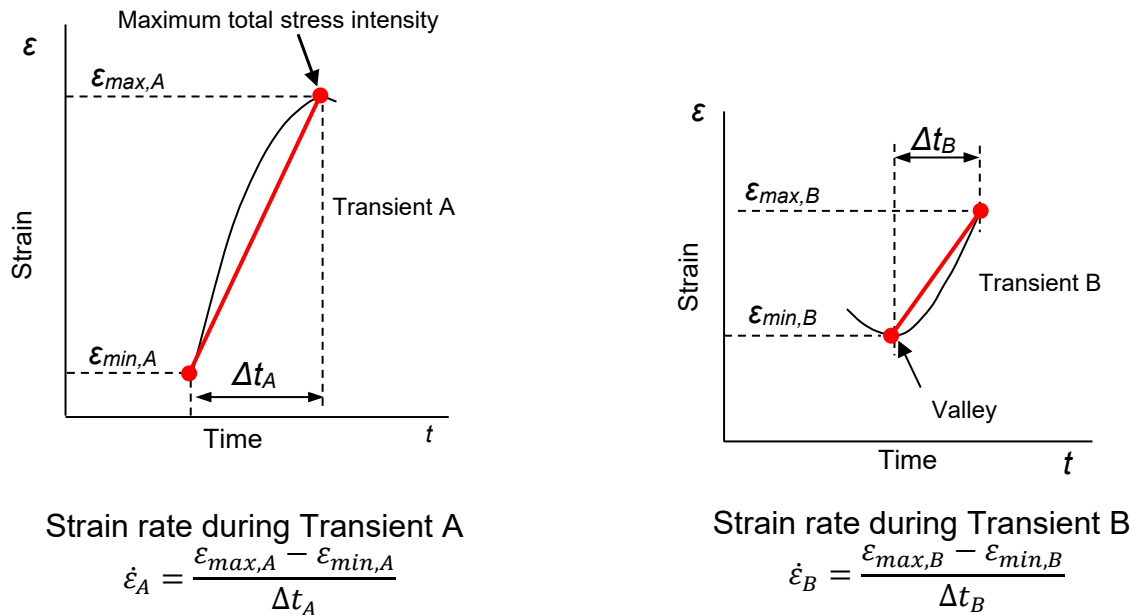
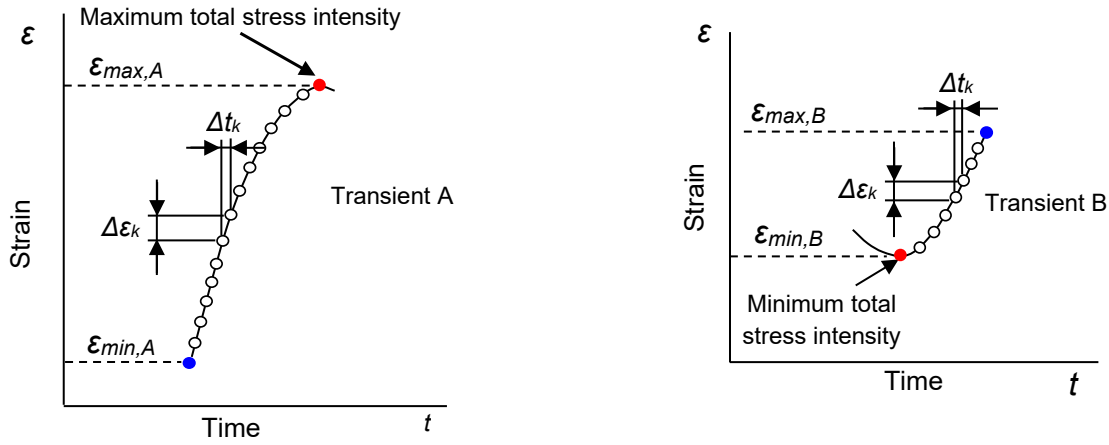


Figure C-5
Determining Strain Rate for the Simplified Method



Strain rate at k^{th} segment: $\dot{\varepsilon}_k = \frac{\Delta \varepsilon_k}{\Delta t_k}$

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

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

Figure C-6
Determining Strain Rate and F_{en} for the Detailed Method

C.3.4 EAF Evaluation Method for Piping

Factor Multiplication Method

The Factor Multiplication Method described in Section C.3.2 above is applied.

Simplified Method

The Simplified Method described in Section C.3.2 above is applied.

To obtain strain rates, Equation C-11 is used, and the dominant term is determined based on the M , ΔT_1 , ΔT_2 and $T_a - T_b$ terms.

When the M term is dominant, the strain rate is assumed to be equal to the linearized strain rate of the “startup” transient.

When one of the ΔT_1 , ΔT_2 or $T_a - T_b$ terms (temperature difference terms) is dominant, the transient with the greater temperature difference in the pair of transients for the dominant term is selected, and the strain rate for the selected transient is assumed to be linear from the minimum to the maximum.

Detailed Method

The Detailed Method described in Section C.3.2 above may be applied when any of the temperature difference terms is dominant. The transient with the greater temperature difference in the pair of transients for the dominant term is selected, and $F_{en, det}$ is calculated from the minimum to the maximum of the strain history in accordance with Section C.3.2 above.

C.3.5 EAF Evaluation Method for Pumps

The evaluation methods for vessels may be applied to pumps.

C.3.6 EAF Evaluation Method for Valves

Factor Multiplication Method

The Factor Multiplication Method described in Section C.3.2 above is applied.

Simplified Method

The Simplified Method described in Section C.3.2 above is applied.

Regarding strain rates, for startup and cooldown conditions, S_p is determined as twice the value of S_{alt} using Equation C-12, and the strain rate is obtained by dividing S_p by the time period of the startup event. For other than startup and cooldown conditions, S_p is determined as twice the value of S_{alt} using Equation C-14 for the employed transient, and the strain rate is obtained by dividing S_p by the time period of the employed transient.

Detailed Method

The Detailed Method described in Section C.3.2 above is applied.

When histories of temperature and pressure are available in b) above, the strain histories may be obtained from Equation C-12 or C-14, and $F_{en, det}$ is calculated from the obtained strain history in accordance with Section C.3.2 above.

C.3.7 Evaluation Method for Core Support Structures

The evaluation method for vessels may be applied to core support structures.

C.3.8 EAF Tests in the EFT Project

JNES-SS-1005 was developed based on the results from the EFT Project [40, 41]. In the EFT Project, a systematic fatigue test plan was developed to develop an EAF evaluation method for PWR and BWR environments. Outlines of the fatigue test plan and typical test results are introduced as follows.

For PWR environments, the materials employed were as follows:

- STS480 (Low S): Carbon steel piping
- STS480 weld
- STS480 (High S)

- SFVQ2A: Low alloy forging, equivalent to SA-508 Grade 2 Class 1
- SFVQ2A weld
- 316TP: 316 stainless steel piping
- 316 weld
- 304: 304 stainless steel plate
- 304 weld
- SCS14A: Cast stainless steel, equivalent to CF8M
- Alloy 690 (bar material)
- Alloy 690 weld
- Alloy 600 (bar material)

The chemical compositions of the above materials are tabulated in Table C-1 and Table C-2. The mechanical properties of the above materials are tabulated in Table C-3. The thermal aged conditions for SFVQ2A and SCS14 are evaluated at 325 °C for 60 years of operation. A series of fundamental fatigue tests was performed to develop F_{en} expressions for PWR environments, and the test matrixes are shown in Table C-4 for primary side materials and Table C-5 for secondary side materials. The total number of fatigue tests for austenitic stainless steels for primary side materials was 146 tests, that for high nickel alloys for primary side materials was 59 tests, and that for carbon and low alloy steels for secondary side materials was 107 tests.

Based on the fundamental fatigue tests, the F_{en} expressions for austenitic stainless steels in PWR environments and for high nickel alloys in PWR environments were developed.

As a typical result, the relation between F_{en} and strain rate in PWR primary environments for austenitic stainless steels is shown in Figure C-7, and for high nickel alloys in Figure C-8. These figures show that the developed F_{en} expressions are harmonious with the test data.

For BWR environments, the materials employed were as follows:

- STS410 (Low S): Carbon steel piping
- STS410 weld (Low S)
- STS410 (High S): Carbon steel piping
- STS410 weld (High S)
- STS410 (Extra High S): Carbon steel piping
- SFVC2B: Carbon steel forging, equivalent to SA-508 Grade 1A
- SFVQ2A: Low alloy forging, equivalent to SA-508 Grade 2 Class 1
- SFVQ2A weld
- SQV2B: Low alloy plate, equivalent to SA-533 Grade B Class 2
- 316NG: 316 stainless steel plate with extra control of C and N

- 316NG weld
- 304: 304 stainless steel plate
- 304L: 304L stainless steel plate
- SCS14A: Cast stainless steel, equivalent to CF8M
- Alloy 600 (plate)
- Conventional Alloy 600: SB-168

The chemical compositions for the above materials are tabulated in Table C-7, Table C-8 and Table C-9. The mechanical properties for the above materials are tabulated in Table C-9 and Table C-10. The thermal aged conditions for 304, Alloy 600, SCS14A, STS410 (Low S) and SFVQ2A are evaluated at 289°C for 80 years of operation.

A series of fundamental fatigue tests was performed to develop F_{en} expressions for BWR environments, and the test matrixes are shown in Table C-11 for STS410 (Low S), Table C-12 for STS410 Weld (Low S), Table C-13 for STS410 (High S), Table C-14 for STS410 Weld (High S), Table C-15 for STS410 (Extra High S), Table C-16 for SFVC2B, Table C-17 for SFVQ2B, Table C-18 for SFVQ2B Weld, Table C-19 for 316NG, Table C-20 for 316NG Weld, Table C-21 for 304, Table C-22 for SCS14A, Table C-23 for Alloy 600, Table C-24 for Conventional Alloy 600, Table C-25 for STS410 Thermal Aged, Table C-26 for SFVQ2A Thermal Aged, Table C-27 for SQV2B and Table C-28 for 304L. There were 400 total fatigue tests for carbon and low alloy steels, 173 tests for austenitic stainless steels, and 66 tests for high nickel alloys.

Based on the fundamental fatigue tests, the F_{en} expressions for carbon, low alloy, and austenitic stainless steels, and for high nickel alloys for BWR environments were developed.

As a typical result, the relation between F_{en} and strain rate for carbon and low alloy steels is shown in Figure C-9, for BWR environments for austenitic stainless steels is shown in Figure C-10, and for BWR environments for high nickel alloys is shown in Figure C-11. These figures show that the developed F_{en} expressions are harmonious with the test data.

Table C-1
Chemical Compositions of Materials for PWR Environments (Carbon and Low Alloy Steels, Austenitic Stainless Steels)

		Chemical Composition (%)								
		C	Si	Mn	P	S	Ni	Cr	Mo	V
STS480 ^(*) (Low S)	Spec. JIS G3455	≤ 0.33	0.10 – 0.35	0.30 – 1.50	≤ 0.035	≤ 0.035	—	—	—	—
	CMTR	0.24	0.27	1.27	0.022	0.006	—	—	—	—
STS480 Weld	Analyzed	0.075	0.33	1.39	0.007	0.004	0.48	—	—	—
STS480 (High S)	Spec. JIS G3455	≤ 0.33	0.10 – 0.35	0.30 – 1.50	≤ 0.035	≤ 0.035	—	—	—	—
	CMTR	0.21	0.24	1.25	0.003	0.02	—	—	—	—
	Analyzed	0.21	0.25	1.25	0.003	0.02	—	—	—	—
SFVQ2A ^(*)	Spec. JIS G3204	≤ 0.27	≤ 0.40	0.50 – 1.00	≤ 0.030	≤ 0.030	0.50 – 1.00	0.25 – 0.45	0.55 – 0.70	≤ 0.05
	CMTR	0.20	0.26	0.94	0.006	0.008	0.78	0.36	0.60	0.008
	Analyzed	0.21	0.27	0.95	0.007	0.009	0.77	0.36	0.59	<0.01
SFVQ2A Weld	Analyzed	0.10	0.22	1.13	0.008	0.004	0.84	0.08	0.49	—
316 TP	Spec. JIS G3459	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.040	≤ 0.030	10.00 – 14.00	16.00 – 18.00	2.00 – 3.00	—
	CMTR	0.04	0.37	1.55	0.025	≤ 0.001	12.55	16.50	2.10	—
316 Weld	Analyzed	0.07	0.4	1.82	0.011	0.006	12.5	18.5	2.19	—
304	Spec. JIS G4304	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	8.00 – 10.50	18.00 – 20.00	—	—
	CMTR	0.05	0.48	1.72	0.027	0.003	9.23	18.12	—	—
	Analyzed	0.053	0.5	1.73	0.023	0.002	8.28	18	—	—
304 Weld	Analyzed	0.034	0.71	1.93	0.022	0.007	9.78	19.6	0.08	—
SCS14A ^(*) (equivalent to CF8M)	Spec. JIS G5121	≤ 0.08	≤ 1.50	≤ 1.50	≤ 0.040	≤ 0.040	9.00 – 12.00	18.00 – 21.00	2.00 – 3.00	—
	CMTR	0.05	0.79	0.74	0.026	0.009	9.66	18.86	2.23	—
	Analyzed	0.048	0.78	0.74	0.024	0.007	9.54	18.5	2.19	—

(*) STS480: Carbon steel piping

(*) SFVQ2A: Low alloy forging (equivalent to SA-508 Grade 2 Class 1)

(*) SCS14A: Cast stainless steel (equivalent to CF8M)

Table C-2
Chemical Compositions of Materials for PWR Environments (High Nickel Alloys)

		Chemical Composition (%)								
		C	Si	Mn	P	S	Ni	Cr	Cu	Fe
Alloy 690	Spec. MITI 501	≤ 0.07	≤ 0.55	≤ 0.53	≤ 0.038	≤ 0.023	≥ 58.0	27.00 – 31.00	≤ 0.50	7.00 – 11.0
	CMTR	0.03	0.11	0.27	0.007	0.001	60.1	29.5	0.02	9.44
	Analyzed	<0.05	0.13	0.27	0.006	0.003	59.6	30.0	<0.01	9.72
Alloy 690 Weld	Analyzed	0.037	0.32	4.47	<0.005	0.001	55.6	29.2	<0.01	8.71
Alloy 600	Spec. JIS G4901	≤ 0.15	≤ 0.50	≤ 1.00	≤ 0.03	≤ 0.015	≥ 72.0	14.0 – 17.0	≤ 0.50	6.0 – 10.0
	CMTR	0.03	0.05	0.49	0.004	0.001	74.5	16.0	0.01	8.37
	Analyzed	0.024	0.10	0.51	≤ 0.005	≤ 0.001	72.7	15.9	≤ 0.01	8.22
Alloy 600 Weld	Analyzed	0.04	0.21	2.76	<0.005	0.004	72.5	15.0	<0.01	7.99

Table C-3
Mechanical Properties of Materials for PWR Environments

		Mechanical Properties							
		Room Temperature				325 °C			
		Yield Strength (0.2% Offset) (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)	Yield Strength (0.2% Offset) (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
STS480 (Low S)	Spec.	≥ 275	≥ 480	≥ 22	—	—	—	—	—
	CMTR	340	520	37	—	—	—	—	—
STS480 (High S)	CMTR	390	533	34	72	—	—	—	—
	Tested	356.5	538.5	29	60.15	245.5	613.5	26.6	46.85
STS480 Weld	Tested	526	577	28.3	74.5	427	663	27.2	45.6
SFVQ2A	Spec.	≥ 345	550 – 730	≥ 16	≥ 38	—	—	—	—
	CMTR	533	655	24	76	—	—	—	—
	Tested	571	653	24.9	77.3	460	641	22.2	73.0
SFVQ2A Thermal Aged	Tested	526	650	24.3	75.6	442	604	21.1	72.6
SFVQ2A Thermal Aged	Tested	594	657	23.7	74.4	525	717	23.6	57.7
316TP	Spec.	≥ 205	≥ 520	≥ 35	≥ 30	—	—	—	—
	CMTR	247	531	54	—	—	—	—	—
SUS316 Weld	Tested	473	566	46	69.8	385	422	23.4	71.0
304	Spec.	≥ 205	≥ 520	≥ 40	—	—	—	—	—
	CMTR	274	580	60	78	—	—	—	—
	Tested	276	601	58.2	80	164	476	45.7	77
304 Weld	Tested	414	578	384	52.0	324	417	25.9	51
SCS14A	Spec.	≥ 205	≥ 480	≥ 33	—	—	—	—	—
	CMTR	252	498	50	72.2	—	—	—	—
	Tested	242	497	44.5	75.4	140	385	37	52.3
SCS14A Thermal Aged	Tested	231.5	561	48.7	61.75	137	430	35.3	60.8
Alloy 690	Spec.	250 – 310	620 – 720	≥ 40	—	—	—	—	—
	CMTR	280	691	46	—	—	—	—	—
	Tested	259	689	45.2	60.2	193	571	46.3	58.3
Alloy 690 Weld	Tested	431	656	38.9	48.8	349	525	39.7	52.1
Alloy 600	Spec.	≥ 245	≥ 550	≥ 30	—	—	—	—	—
	CMTR	264	635	55	—	—	—	—	—
	Tested	247	660	42	74	200	621	44.2	69.7
Alloy 600 Weld	Tested	409	623	34.4	43.9	362	565	49.3	49.3

Table C-4
Fundamental Fatigue Test Matrix for PWR Primary Side (2 pages)

		Strain rate (%/s)							DO (ppm)	B (ppm)		Li (ppm)		DH (cc/kg)		Temperature (°C)				Strain Amplitude ε _a (%)	Number of Data			
		0.4	0.04	0.001	0.004	0.0004	0.0001	0.0004	0.00001	<0.005	500	1800	2	3.5	15	30	R.T.	100	200		325		Total	
316	Base Metal	X								X	X	X	X	X	X	X				X	0.12 – 0.6	10	55	
				X						X	X	X	X	X	X	X				X	0.2 – 0.6	9		
					X		X			X	X		X			X				X	0.2 – 0.6	6		
		X								X	X		X			X				X	0.1 – 0.2	2		
		X								[In-air]							X				0.18 – 0.6	6		
	Mean strain	Base Metal	X								X	X								X	0.2 – 0.6	8		
					X						X	X								X	0.2 – 0.6	5		
		Solid specimens	X		X						X	X								X	0.2 – 0.6	9		
	Weld	X									X	X		X			X		X	X	X	0.2 – 0.6		8
				X							X	X		X			X				X	0.2 – 0.6		3
		X		X						X	X		X			X		X	X		0.6	4		
					X	X	X	X		X	X		X			X				X	0.6	3		
X										X	X		X			X				X	0.1	1		
X										[In-air]							X				0.2 – 0.6	6		
304	Base Metal	X								X	X		X			X				X	0.3, 0.6	2	4	
				X							X	X		X			X				X	0.3, 0.6		2
	Weld	X									X	X		X			X				X	0.2 – 0.6	6	15
				X							X	X		X			X				X	0.2 – 0.6	3	
		X									[In-air]							X				0.2 – 0.6	6	

Table C-4 (continued)
Fundamental Fatigue Test Matrix for PWR Primary Side (2 pages)

		Strain rate (%/s)								DO (ppm)	B (ppm)		Li (ppm)		DH (cc/kg)		Temperature (°C)				Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	0.004	0.0004	0.0001	0.0004	0.00001	<0.005	500	1800	2	3.5	15	30	R.T.	100	200	325			Total
SCS14A	Base Metal	X								X	X		X			X		X	X	X	0.2 – 0.6	18	41
				X						X	X		X			X		X	X	X	0.3 – 0.6	9	
						X	X	X	XX	X	X		X			X				X	0.3, 0.6	8	
		X								[In-air]							X				0.2 – 0.6	6	
	Thermal Aged	X								X	X									X	0.4, 0.6	2	6
				X						X	X									X	0.4, 0.6	2	
		X								[In-air]							X				0.4, 0.6	2	
Alloy 600	Base Metal	X								X	X		X			X		X	X	X	0.2 – 0.6	12	27
				X						X	X		X			X		X	X	X	0.3 – 0.6	9	
		X								[In-air]											0.2 – 0.6	6	
	Weld	X								X	X		X			X				X	0.2 – 0.6	6	15
				X						X	X		X			X				X	0.3 – 0.6	3	
		X								[In-air]											0.2 – 0.6	6	
Alloy 690	Base Metal	X								X	X	X	X	X	X	X				X	0.2 – 0.6	10	25
				X		X	X			X	X	X	X	X	X	X				X	0.3 – 0.6	9	
		X								[In-air]											0.2 – 0.6	6	
	Weld	X								X	X		X			X				X	0.2 – 0.6	6	15
				X						X	X		X			X				X	0.3 – 0.6	3	
		X								[In-air]											0.2 – 0.6	6	

Table C-5
Fundamental Fatigue Test Matrix for PWR Secondary Side

		Strain rate (%/s)				DO (ppm)					Temperature (°C)						Strain Amplitude ε _a (%)	Number of Data	
		0.4	0.01	0.001	<0.001	0.005	0.1	0.15	0.2	>0.3	R.T.	100	150	200	250	290			Total
SFVQ2A	Base Metal	X				X						X	X	X	X	X	0.2 – 0.6	20	39
				X		X						X	X	X	X	X	0.3 – 0.6	13	
		X				[In-air]					X						0.2 – 0.6	6	
	Thermal Aged	Base Metal	X				X									X	0.4, 0.6	2	6
					X		X								X	0.4, 0.6	2		
			X				[In-air]					X					0.4, 0.6	2	
		Weld	X				X									X	0.2 – 0.6	6	15
					X		X									X	0.3 – 0.6	3	
			X				[In-air]					X					0.2 – 0.6	6	
STS480	Base Metal	X				X						X				X	0.15 – 0.6	14	26
				X		X						X				X	0.3 – 0.6	6	
		X				[In-air]					X					0.15 – 0.6	6		
		Weld	X				X									X	0.2 – 0.6	6	15
					X		X									X	0.3 – 0.6	3	
			X				[In-air]					X					0.2 – 0.6	6	
	High S	Base Metal	X				X									X	0.4, 0.6	2	6
					X		X									X	0.4, 0.6	2	
			X				[In-air]					X					0.4, 0.6	2	

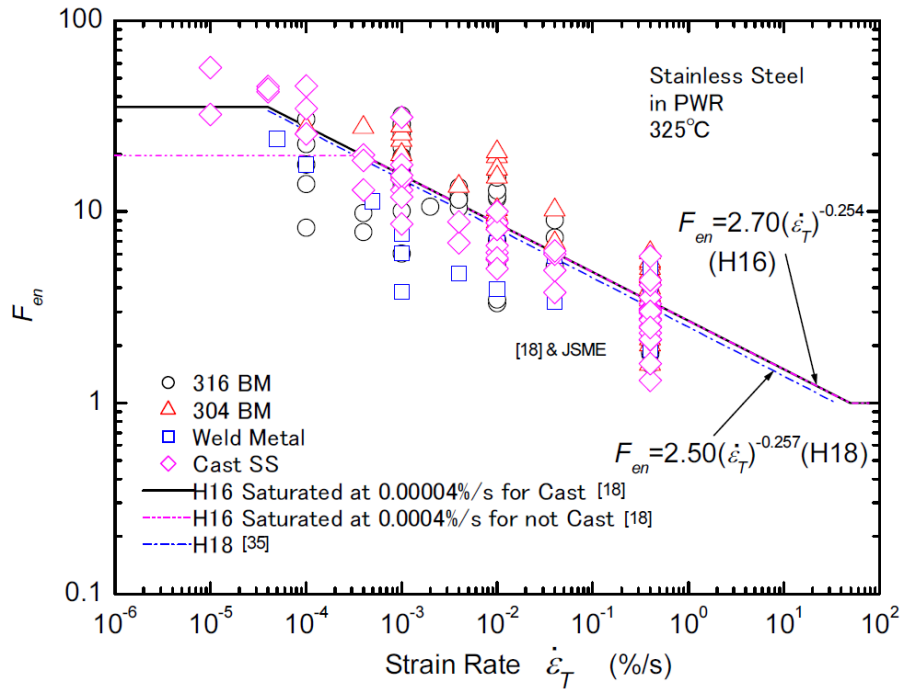


Figure C-7
Relation Between F_{en} and Strain Rate for Austenitic Stainless Steels with F_{en} Expressions (PWR)

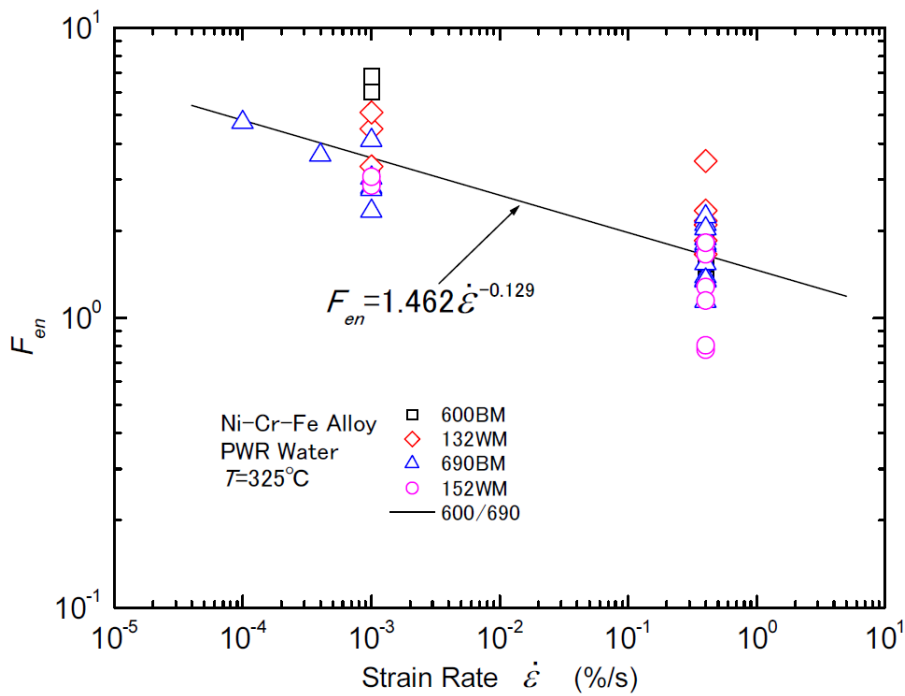


Figure C-8
Relation Between F_{en} and Strain Rate for High Nickel Alloys with F_{en} Expressions (PWR)

Table C-6
Chemical Compositions of Materials for BWR Environments (Carbon and Low Alloy Steels)

		Chemical Composition (%)								
		C	Si	Mn	P	S	Ni	Cr	Mo	V
STS410 ^(*) (Low S)	Spec. JIS G3455	≤ 0.30	0.10 – 0.35	0.30 – 1.40	≤ 0.035	≤ 0.035	—	—	—	—
	CMTR	0.21	0.27	1.29	0.010	0.008	—	—	—	—
	Analyzed	0.23	0.31	1.31	0.009	0.008	0.06	0.18	0.04	0.03
STS410 Weld (Low S)	Analyzed	0.06	0.36	1.41	0.010	0.004	0.50	0.03	0.01	—
STS410 (High S)	Spec. JIS G3455	≤ 0.30	0.10 – 0.35	0.30 – 1.40	≤ 0.035	≤ 0.035	—	—	—	—
	CMTR	0.20	0.26	1.14	0.01	0.016	—	—	—	—
	CMTR	0.23	0.25	1.14	0.007	0.022	0.04	0.16	0.03	0.04
STS410 Weld (High S)	Analyzed	0.06	0.36	1.33	0.010	0.010	0.49	0.03	0.01	—
STS410 (Extra High S)	Spec. JIS G3455	≤ 0.30	0.10 – 0.35	0.30 – 1.40	≤ 0.035	≤ 0.035	—	—	—	—
	CMTR	0.21	0.27	1.29	0.011	0.026	—	—	—	—
	Analyzed	0.22	0.29	1.26	0.010	0.020	0.08	0.18	0.02	0.04
SFVC2B ^{(*)2}	Spec. JIS G3202	≤ 0.30	≤ 0.35	0.70 – 1.35	≤ 0.030	≤ 0.030	—	—	—	—
	CMTR	0.19	0.23	1.24	0.005	0.004	—	—	—	—
	Analyzed	0.2	0.27	1.25	0.003	0.001	0.32	0.21	0.02	—
SFVQ2A ^{(*)3}	Spec. JISG3204	≤ 0.27	≤ 0.40	0.50 – 1.00	≤ 0.030	≤ 0.030	0.50 – 1.00	0.25 – 0.45	0.55 – 0.70	≤ 0.05
	CMTR	0.18	0.31	0.77	0.008	0.008	0.74	0.36	0.60	0.004
	Analyzed	0.18	0.30	0.73	0.007	0.007	0.75	0.34	0.62	<0.01
SFVQ2A Weld	Analyzed	0.09	0.19	1.44	0.013	0.006	0.80	0.05	0.47	<0.01
SQV2B ^{(*)4}	Spec. JISG3120	≤ 0.25	0.15 – 0.30	1.15 – 1.50	≤ 0.035	≤ 0.040	0.40 – 0.70	—	0.45 – 0.60	—
	CMTR	0.18	0.24	1.43	0.003	<0.001	0.66	—	0.57	—
	Analyzed	0.18	0.25	1.43	<0.005	<0.001	0.69	—	0.53	—

(*)1 STS410: Carbon steel piping

(*)2 SFVC2B: Low alloy forging (equivalent to SA-508 Grade 1A)

(*)3 SFVQ2A: Low alloy forging (equivalent to SA-508 Grade 2 Class 1)

(*)4 SQV2B: Low alloy plate (equivalent to SA-533 Grade B Class 2)

Table C-7
Chemical Compositions of Materials for BWR Environments (Austenitic Stainless Steels)

		Chemical Composition (%)								
		C	Si	Mn	P	S	Ni	Cr	Mo	V
316NG ^(*)	Spec. JIS G4304	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	10.00 – 14.00	16.00 – 18.00	2.00 – 3.00	—
	CMTR	0.011	0.52	0.91	0.017	0.004	11.18	16.26	2.17	—
	Analyzed	0.001	0.52	0.92	0.014	0.004	11.2	16.3	2.16	—
316NG Weld	Analyzed	0.017	0.43	1.86	0.011	0.005	12.01	19.49	2.39	—
304	Spec. JIS G4304	≤ 0.08	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	8.00 – 10.50	18.00 – 20.00	—	—
	CMTR	0.07	0.65	0.91	0.022	0.002	8.09	18.48	—	—
	Analyzed	0.07	0.62	0.92	0.022	0.002	8.19	18.59	—	—
304L	Spec. JIS G4304	≤ 0.03	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	9.00 – 13.00	18.00 – 20.00	—	—
	CMTR	0.017	0.29	1.19	0.024	0.002	9.15	18.05	—	—
	Analyzed	0.020	0.32	1.22	0.026	0.001	9.35	18.3	—	—
SCS14A (equivalent to CF8M)	Spec. JIS G5121	≤ 0.08	≤ 1.50	≤ 1.50	≤ 0.040	≤ 0.040	9.00 – 12.00	18.00 – 21.00	2.00 – 3.00	—
	CMTR	0.05	1.17	0.86	0.021	0.006	10.03	20.59	2.28	—
	Analyzed	0.06	1.27	0.78	0.022	0.009	9.82	20.8	2.22	—

(*) N of 316NG is not specified in JIS. N in the CMTR was 0.07%.

Table C-8
Chemical Compositions of Materials for BWR Environments (High Nickel Alloys)

		Chemical Composition (%)											
		C	Si	Mn	P	S	Ni	Cr	Fe	Ti	Nb	Ta	Cu
Alloy 600	Spec. JIS G4902	≤ 0.15	≤ 0.50	≤ 1.00	≤ 0.030	≤ 0.015	≥ 72.00	14.00 – 17.00	6.00 – 10.00	—	—	—	≤ 0.50
	CMTR	0.01	0.17	0.21	0.007	0.000	73.33	16.60	6.95	—	2.56		0.02
	Analyzed	0.01	0.18	0.21	0.005	<0.001	73.65	16.70	6.64	0.02	2.56	<0.01	0.02
Conventional Alloy 600	Spec. ASME SB- 168	≤ 0.15	≤ 0.50	≤ 1.00	—	≤ 0.015	≥ 72.00	14.00 – 17.00	6.00 – 10.00	—	—	—	≤ 0.50
	CMTR	0.07	0.34	0.37	—	0.001	74.15	15.41	9.46	—	—	—	0.20
	Analyzed	0.07	0.35	0.38	0.007	0.001	73.56	15.64	9.23	0.27	0.16	0.01	0.16

Table C-9
Mechanical Properties of Materials for BWR Environments (Carbon and Low Alloy Steels)

		Yield Strength (0.2% Offset) (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
STS410 (Low S)	Spec. JIS G3455	≥ 245	≥ 410	≥ 24	—
	CMTR	359	520	37	—
	Tested	321	552	31	76
STS410 Weld (Low S)	Tested	406	510	30	80
STS410 Thermal Aged (485 °C×500 h)	Tested	331	557	33	74
STS410 Thermal Aged (485 °C×1950 h)	Tested	318	538	33	75
STS410 Thermal Aged (485 °C×3900 h)	Tested	310	531	34	74
STS410 (High S)	Spec. JIS G3455	≥ 245	≥ 410	≥ 24	—
	CMTR	348	509	36	—
	Tested	356	541	33	76
STS410 Weld (High S)	Tested	397	496	37	79
STS410 (Extra High S)	Spec. JIS G3455	≥ 245	≥ 410	≥ 24	—
	CMTR	278	524	36	—
	Tested	404	563	30	73
SFVC2B	Spec. JIS G3202	≥ 245	490–640	≥ 18	≥ 38
	CMTR	347	501	36	77
	Tested	345	502	32	78
SFVQ2A	Spec. JIS G3204	≥ 345	550–730	≥ 16	≥ 38
	CMTR	510	637	27	74
	Tested	492	640	25	77
SFVQ2A Weld	Tested	474	570	28	76
SFVQ2A Thermal Aged (400 °C×2050 h)	Tested	492	644	26	79
SFVQ2A Weld (400 °C×2050 h)	Tested	466	629	26	75
SQV2B	Spec. JIS G3120	≥ 480	620 – 790	≥ 16	—
	CMTR	548	679	26	—
	Tested	528	668	26	75

Table C-10
Mechanical Properties of Materials for BWR Environments (Austenitic Stainless Steels and High Nickel Alloys)

		Yield Strength (0.2% Offset) (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
316NG	Spec. JIS G4304	≥ 205	≥ 520	≥ 40	—
	CMTR	252	558	62	85
	Tested	268	581	48	78
316NG Weld	Tested	484	622	29	60
304	Spec. JIS G4304	≥ 205	≥ 520	≥ 40	—
	CMTR	245	682	59	—
	Tested	219	686	61	73
304 Thermal Aged (400 °C× 1,700 h)	Tested	218	711	57	69
304L	Spec. JIS G4304	≥ 175	≥ 480	≥ 40	—
	CMTR	245	574	61	—
	Tested	214	598	64	84
SCS14A (CF8M)	Spec. JIS G5121	≥ 205	≥ 480	≥ 33	—
	CMTR	308	619	51	—
	Tested	253	535	46	76
SCS14A Thermal Aged (450 °C× 11,000 h)	Tested	252	646	23	35
Alloy 600	Spec. JIS G4902	≥ 240	≥ 550	≥ 30	—
	CMTR	279	677	54	—
	Tested	304	677	54	63
Alloy 600 Thermal Aged (400 °C× 2,000 h)	Tested	289	693	63	57
Conventional Alloy 600	Spec. ASME SB-168	≥ 240	≥ 550	≥ 30	—
	CMTR	303	696	39	—
	Tested	269	693	41	62

Table C-11
Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (Low S))

		Strain Rate (%/s)					DO (ppm)						Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.01	0.001	Extra Low	0.01	0.03	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
STS410	Base Metal, Low S S=0.008%	X										X					X	0.3, 0.4, 0.6	3	55
		X									X						X		3	
		X								X							X	0.25-0.6	9	
		X							X								X	0.3, 0.4, 0.6	3	
		X					X										X	0.6	1	
				X								X					X	0.3,0.4,0.6	3	
					X							X					X		4	
					X						X						X		3	
					X					X							X	0.3-0.6	8	
					X				X								X	0.3,0.4,0.6	4	
					X			X									X	0.3, 0.6	2	
					X		X										X	0.6	1	
					X						X					X		0.3	1	
					X						X					X			1	
					X				X							X			1	
					X					X									1	
					X					X					X				1	
					X				X						X				1	
					X						X								1	
					X						X			X					1	
		X							X								X	0.2	1	
			X							X							X	0.2	1	
		X					[In-air]						X					0.1-0.6	5	14
		X																0.1-0.6	6	
		X														X		0.3	1	
		X													X			0.3	1	
		X												X				0.3	1	

Table C-12
Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Weld (Low S))

		Strain Rate (%/s)				DO (ppm)				Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.01	0.001	Extra Low	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
STS410	Weld, Low S S=0.005 %	X							X					X	0.3, 0.6	2	21
		X						X						X		2	
		X					X							X	0.25-0.6	5	
		X				X								X	0.3, 0.6	2	
			X						X					X		2	
				X					X					X		2	
				X				X						X		2	
				X			X							X		2	
				X		X								X		2	
		X				[In-air]								X	0.1-0.6	5	11
		X								X						6	

Table C-13
Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (High S))

		Strain Rate (%/s)							DO (ppm)						Temperature (°C)					Strain Amplitude ε _a (%)	Number of Data		
		1	0.4	0.04	0.01	0.001	1E-4	5E-05	1E-05	0.01	0.03	0.05	0.2	1	8	R.T.	150	200	250		289	Total	
STS410	Base Metal, High S S=0.016%	X										X								X	0.3	1	59
			X											X						X	0.3, 0.4, 0.6	3	
			X										X							X	0.3, 0.4, 0.6	3	
			X										X							X	0.2-0.6	5	
			X									X								X	0.3, 0.4, 0.6	3	
			X							X										X	0.3, 0.6	2	
			X											X					X			1	
			X										X						X			1	
			X									X							X			1	
			X										X						X			1	
			X										X						X			1	
					X										X					X	0.3, 0.4, 0.6	3	
					X									X						X	0.3	1	
						X									X					X	0.3, 0.4, 0.6	3	
						X								X						X	0.2-0.6	6	
						X						X								X	0.3, 0.4, 0.6	3	
						X					X									X	0.3, 0.6	2	
						X					X									X	0.3, 0.6	2	
						X								X						X		1	
						X								X						X		1	
						X							X							X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
						X								X						X		1	
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X								X						X		1			
				X																			

Table C-14
Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Weld (High S))

		Strain Rate (%/s)					DO (ppm)				Temperature (°C)					Strain Amplitude ε _a (%)	Number of Data	
		0.4	0.04	0.01	0.001	Extra Low	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
STS410	Weld, High S S=0.011%	X								X					X	0.3	1	13
		X							X						X	0.3	1	
		X						X							X	0.2-0.6	5	
		X					X								X	0.3	1	
				X						X					X		1	
					X					X					X		1	
					X				X						X		1	
					X			X							X		1	
					X		X								X		1	
		X														X	0.1-0.6	5
X										X					X	6		

Table C-15
Fundamental Fatigue Test Matrix for BWR Conditions (STS410 (Extra High S))

		Strain Rate (%/s)				DO (ppm)				Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.01	0.001	Extra Low	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
STS410	Base Metal, Extra High S S=0.02%	X							X					X	0.3	1	12
		X						X						X		1	
		X					X							X	0.2-0.6	5	
		X				X								X	0.3	1	
				X					X					X		1	
				X				X						X		1	
				X			X							X		1	
				X		X								X		1	
		X				[In-air]				X					0.1-0.6	6	6

Table C-16
Fundamental Fatigue Test Matrix for BWR Conditions (SFVC2B)

		Strain Rate (%/s)					DO (ppm)				Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.01	0.001	Extra Low	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
SFVC2B	Base Metal S=0.004%	X								X					X	0.3	1	15
		X							X						X		1	
		X						X							X	0.2-0.6	5	
		X					X								X	0.3	1	
				X						X					X		1	
					X					X					X		1	
					X				X						X		1	
					X			X							X		1	
					X		X								X		1	
		X						X							X	0.2	1	
		X					[In-air]								X	0.1-0.6	5	11
		X									X						6	

Table C-17
Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2B)

		Strain Rate (%/s)						DO (ppm)				Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.01	0.001	0.0001	1.E-05	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
SFVQ2A	Base Metal, High S S=0.008%	X									X					X	0.3, 0.6	2	43
		X								X						X	0.3, 0.6	2	
		X							X							X	0.2-0.6	5	
		X						X								X	0.3, 0.4, 0.6	3	
		X								X						X	0.6	1	
		X							X							X		1	
		X						X								X		1	
		X								X					X			1	
		X							X						X			1	
		X						X							X			1	
				X							X					X	0.3, 0.6	2	
					X						X					X		2	
					X					X						X		2	
					X				X							X	0.6	2	
					X			X								X		3	
					X					X						X+		2	
					X				X							X+		2	
					X			X								X+		2	
					X					X					X			1	
					X				X						X		0.2	1	
					X				X							X		1	
					X				X							X		1	
						X			X							X	0.6	1	
							X		X							X		1	
		X						[In-air]								X	0.1-0.6	5	18
		X													X		0.6	1	
		X												X				1	
		X											X					1	
		X										X+					0.1-0.6	10	

Table C-18
Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2B Weld)

		Strain Rate (%/s)				DO (ppm)				Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	Extra Low	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
SFVQ2A	Weld, High S S=0.006 %	X							X					X	0.6	1	25
		X						X						X	0.6	1	
		X					X							X	0.2-0.6	5	
		X				X								X	0.6	1	
		X						X					X			1	
		X					X						X			1	
		X				X							X			1	
		X						X				X				1	
		X					X					X				1	
		X						X				X				1	
		X					X					X				1	
				X					X					X		1	
				X				X						X		1	
				X			X							X		1	
				X				X					X			1	
				X									X			1	
				X									X			1	
				X								X				1	
				X								X				1	
				X								X				1	
				X								X				1	
		X					X							X	0.2	1	
		X				[In-air]								X	0.1-0.6	5	11
		X								X						6	

Table C-19
Fundamental Fatigue Test Matrix for BWR Conditions (316NG)

		Strain Rate (%/s)						DO (ppm)					Temperature (°C)					Strain Amplitude ε _a (%)	Number of Data								
		(3)*	0.4	0.04	0.001	0.0001	2E-05	4E-05	0.01	0.05	0.2	1	8	R.T.	150	200	250		289	Total							
316NG	Base Metal	X								X			8						X	0.6	2	34					
			X							X									X	0.2~0.6	5						
			X							X									X	0.3, 0.6	2						
			X						X										X		2						
			X								X							X		0.6	1						
			X							X							X		1								
			X								X						X		1								
			X								X						X		1								
			X								X					X			1								
			X								X					X			1								
						X						X							X	0.3, 0.6	2						
						X					X								X		2						
						X				X									X		2						
						X						X							X	0.6	1						
						X					X								X		1						
						X						X						X			1						
						X					X							X			1						
						X						X					X				1						
						X					X						X				1						
							X			X									X	0.6	1						
							X			X									X		2						
									X	X									X		1						
								X		X									X		1						
				X						[In-air]									X	0.1~0.6	5		16				
			X																					X		0.6	1
			X																		X					0.6	1
			X																	X						0.1~0.6	6
			X																	X						0.6	2
			X																	X							

Table C-20
Fundamental Fatigue Test Matrix for BWR Conditions (316NG Weld)

		Strain Rate (%/s)				DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	0.0001	0.01	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
316NG	Weld	X						X							X	0.2-0.6	5	25
		X					X								X	0.6	1	
		X				X									X	0.6	1	
		X						X						X		0.6	1	
		X					X							X			1	
		X						X					X				1	
		X					X						X				1	
		X						X				X			X		1	
		X					X					X			X		1	
				X				X							X	0.3, 0.6 0.6	2	
				X				X							X		2	
				X		X									X		1	
				X				X						X		0.6	1	
				X			X							X			1	
				X				X					X				1	
				X			X						X				1	
				X				X				X					1	
				X			X					X					1	
				X			X					X					1	
					X					X					X		1	
		X				[In-air]									X	0.1-0.6	5	18
		X												X		0.6	1	
		X											X				1	
		X										X					1	
		X									X					0.1-0.6	10	

Table C-21
Fundamental Fatigue Test Matrix for BWR Conditions (304)

		Strain Rate (%/s)				DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	Extra Low	0.01	0.05	0.2	1	8	R.T.	150	200	250	289			Total
SUS304	Base Metal	X						X							X	0.2–0.6	5	15
		X					X								X	0.6	1	
		X				X									X		1	
				X			X								X		1	
				X			X								X		1	
				X		X									X		1	
		X						X							X	0.2	1	
	Base Metal, Thermal Aged	X						X							X	0.6	1	17
		X				X									X		1	
				X			X								X		1	
				X		X									X		1	
	Base Metal	X				[In-air]									X	0.1–0.6	5	17
		X									X							
		Base Metal, Thermal Aged	X									X						

Table C-22
Fundamental Fatigue Test Matrix for BWR Conditions (SCS14A)

		Strain Rate (%/s)						DO (ppm)						Temperature (°C)						Strain Amplitude ε _a (%)	Number of Data	
		0.4	0.01	0.001	0.0001	0.0004	5E-5	4E-5	0.01	0.05	0.2	1	8	R.T.	150	200	250	289	Total			
SCS14A	Base Metal	X									X							X	0.3, 0.6	2	24	
		X								X								X	0.2–0.6	5		
		X							X									X	0.3, 0.6	2		
				X							X								X	0.3, 0.6		2
				X							X								X	0.3, 0.6		2
				X					X										X			1
				X					X										X			2
					X				X										X	0.6		1
						X			X										X			1
							X		X										X			1
								X	X										X			1
	Base Metal, Thermal Aged	X									X								X	0.6	1	
		X							X										X		1	
				X							X								X		1	
				X					X										X		1	
	Base Metal	X							[In-air]									X	0.1–0.6	5	11	
		X							[In-air]					X						6		

Table C-23
Fundamental Fatigue Test Matrix for BWR Conditions (Alloy 600)

		Strain Rate (%/s)					DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	0.0004	0.0001	0.01	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
Alloy 600	Base Metal	X							X							X	0.2–0.6	5	30
		X							X							X	0.6	1	
		X					X									X	0.3, 0.6	2	
		X									X					X		2	
				X					X							X		2	
				X					X							X	0.6	1	
				X				X								X		1	
				X			X									X	0.3, 0.6	2	
				X							X					X		2	
					X		X									X	0.6	1	
						X			X							X		1	
					X		X									X		2	
		X					X							X				1	
				X			X							X				1	
		X							X					X				1	
	Base Metal, Thermal Aged	X							X							X	0.6	1	17
		X					X									X		1	
				X					X							X		1	
				X			X									X		1	
	Base Metal	X					[In-air]									X	0.1–0.6	5	
		X										X						6	
	Base Metal, Thermal Aged	X										X						6	

Table C-24
Fundamental Fatigue Test Matrix for BWR Conditions (Conventional Alloy 600)

		Strain Rate (%/s)				DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.01	0.001	Extra Low	0.01	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
Conventional Alloy 600	Base Metal	X						X							X	0.2–0.6	5	8
		X				X									X	0.6	1	
				X				X							X	0.6	1	
				X		X									X		1	
		X				[In-air]									X	0.1–0.6	5	11
		X									X						6	

Table C-25**Fundamental Fatigue Test Matrix for BWR Conditions (STS410 Thermal Aged)**

		Strain Rate (%/s)					DO (ppm)						Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.01	0.001	Extra Low	0.01	0.03	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
STS410 Base Metal, Low S S=0.008%	485 °C 500h	X								X							X	0.3, 0.6	2	18
				X						X							X		2	
					X					X							X		2	
	485 °C 1950h	X								X							X	0.3, 0.6	2	
				X						X							X		2	
					X					X							X		2	
	485 °C 3900h	X								X							X	0.3, 0.6	2	
				X						X							X		2	
					X					X							X		2	
	485 °C 500h	X					[In-air]						X					0.1-0.6	6	18
	485 °C 1950h	X											X						6	
	485 °C 3900h	X											X						6	

Table C-26**Fundamental Fatigue Test Matrix for BWR Conditions (SFVQ2A Thermal Aged)**

		Strain Rate (%/s)					DO (ppm)						Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.01	0.001	Extra Low	0.01	0.03	0.05	0.2	1	8	R.T.	150	200	250	289		Total	
SFVQ2A Base Metal S=0.008%	400 °C 2050h	X								X							X	0.3, 0.6	2	12
				X						X							X		2	
					X					X							X		2	
	400 °C 3700h	X								X							X	0.3, 0.6	2	
				X						X							X		2	
					X					X							X		2	
	400 °C 2050h	X					[In-air]						X					0.1-0.6	6	12
	400 °C 3700h	X											X						6	

Table C-27
Fundamental Fatigue Test Matrix for BWR Conditions (SQV2B)

		Strain Rate (%/s)				DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.004	0.0004	0.01	0.05	0.2	1	8	R.T.	150	200	250	289			Total
SQV2B	Base Metal, S<0.001%	X							X						X	0.6	1	4
			X						X						X		1	
				X					X						X		1	
					X				X						X		1	

Table C-28
Fundamental Fatigue Test Matrix for BWR Conditions (304L)

		Strain Rate (%/s)				DO (ppm)					Temperature (°C)					Strain Amplitude ϵ_a (%)	Number of Data	
		0.4	0.04	0.001	Extra Low	0.01	0.05	0.2	1	8	R.T.	150	200	250	289			Total
304L	Base Metal	X				X									X	0.6	1	6
				X		X									X		1	
		X					X								X		1	
				X			X								X		1	
		X						X							X	0.2	1	
				X				X							X		1	
	Base Metal	X				[In-air]					X					0.1-0.6	6	6

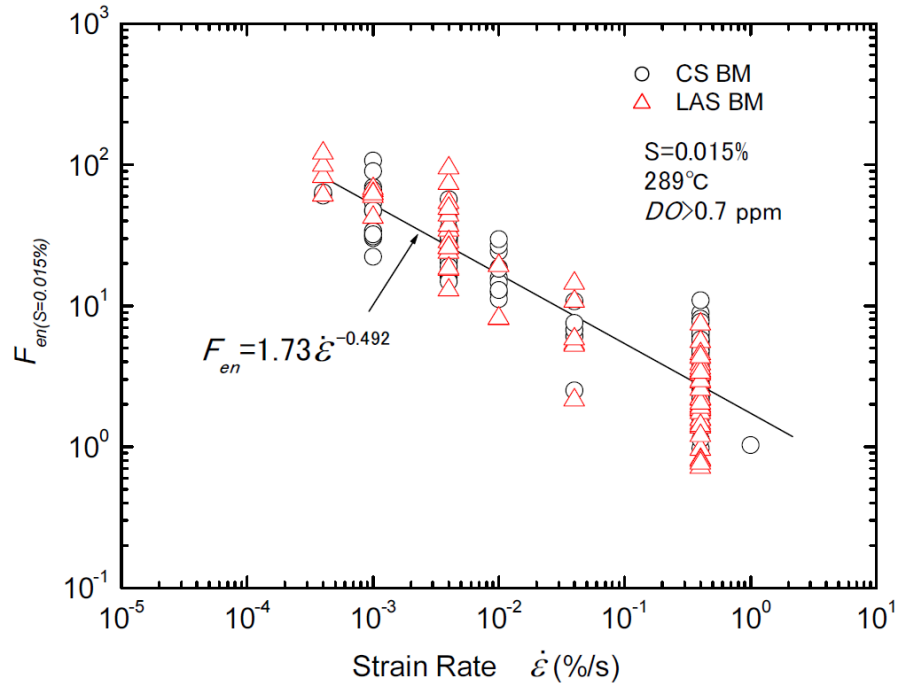


Figure C-9
Relation Between F_{en} and Strain Rate for Carbon and Low Alloy Steels with F_{en} Expressions

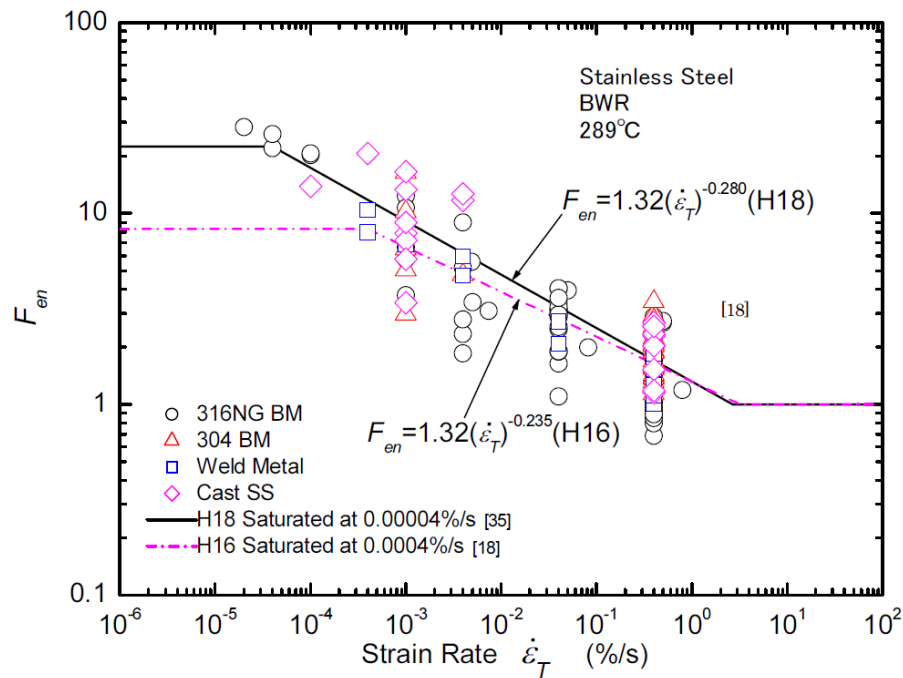
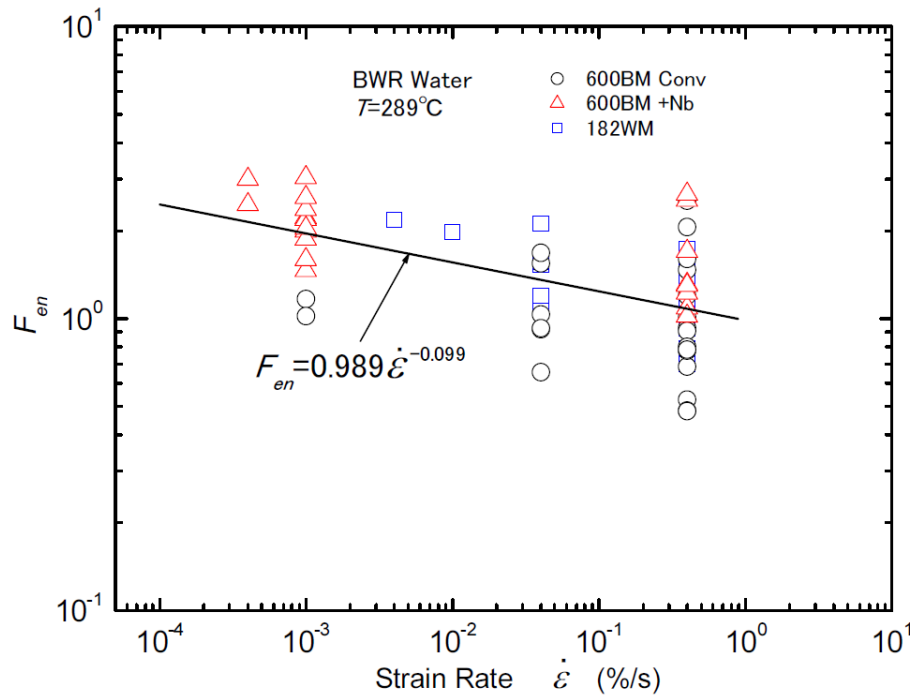


Figure C-10
Relation Between F_{en} and Strain Rate for Austenitic Stainless Steels with F_{en} Expressions (BWR)

**Figure C-11**

Relation Between F_{en} and Strain Rate for High Nickel Alloys with F_{en} Expressions (BWR)

(Figure C-7 through Figure C-11 reprinted from [40] by permission of the Japan Nuclear Regulatory Authority. All rights reserved.)

C.4 JSME Environmental Fatigue Evaluation Method

The JSME published JSME S NF1 “Codes for Nuclear Power Generation Facilities – Environmental Fatigue Evaluation Method for Nuclear Power Plants–” (hereinafter, JSME Environmental Fatigue Evaluation Method) in the 2006 and 2009 Editions of the JSME Code.

The first edition of JSME S NF1 that was published in the 2006 Edition was derived from the TENPES Guideline, and the 2009 Edition was revised from the 2006 Edition. Also, the 2022 Edition is under development and some technical items will be revised.

The outline of each edition is provided below.

C.4.1 2006 Edition (First Edition of JSME S NF1)

The EFT Project proposed a preliminary version of the environmental fatigue evaluation method in 2003 and the revision of the F_{en} expressions in 2004. They were summarized, and the JNES technical report, JNES-SS-0503, was issued. The JNES provided the JSME with those results, and the JSME issued the JSME Environmental Fatigue Evaluation Method in the 2006 Edition (First Edition of JSME S NF1), which was based on incorporating JNES SS-0503.

JNES-SS-0503 was updated from the TENPES Guideline, and the main technical items that were updated are as follows:

F_{en} expressions

- Seismic loads for which strain rates are sufficiently high were added to the exemption from EAF evaluation.
- The F_{en} expressions for carbon and low alloy steels were updated.
- The F_{en} expressions for austenitic stainless steels were updated.
- The F_{en} expressions for high nickel alloys were added.

EAF evaluation method

- The F_{en} expressions for the Factor Multiplication Method were updated based on the newly updated F_{en} expressions.
- The Simplified Method was updated so that each F_{en} value for Transient A and Transient B was calculated and the total F_{en} value was calculated using Equation C-29.
- The Detailed Method was also updated so that each F_{en} value for Transient A and Transient B was calculated by the MRA and the total F_{en} value was calculated using the same equation from the Simplified Method in Equation C-29, which is also expressed in Equation C-32.

The F_{en} expressions proposed in JNES-SS-0503 are as follows:

Threshold for Environmental Effects

The threshold strain amplitudes are as follows:

- 0.042 % or less for carbon and low alloy steels.
- 0.11 % or less for austenitic stainless steels and high nickel alloys.

Seismic loads are exempted from environmental fatigue evaluation because strain rates during seismic loads are sufficiently high that EAF effects are negligible.

For carbon and low alloy steels and their associated welds

$$\ln(F_{en}) = 0.00822(0.722 - \dot{\epsilon}^*) \times S^* \times T^* \times O^* \quad \text{Eq. C-34}$$

where,

$$\dot{\epsilon}^* = \ln(2.16) \quad (\dot{\epsilon} > 2.16 \text{ \%/s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 2.16 \text{ \%/s})$$

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

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

$$T^* = 0.0358 \times T \quad (T < 50 \text{ }^\circ\text{C})$$

$$T^* = \ln(6) \quad (50 \leq T \leq 160 \text{ }^\circ\text{C})$$

$$T^* = \ln(0.3977) + 0.01696 \times T \quad (T > 160 \text{ }^\circ\text{C})$$

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

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

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

For austenitic stainless steels and their associated welds

(1) BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-35}$$

where,

$$C = 1.182$$

$$\dot{\epsilon}^* = \ln(3.26) \quad (\dot{\epsilon} > 3.26 \text{ \%/s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 3.26 \text{ \%/s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 3.26 \text{ \%/s for Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.0004) \quad (\dot{\epsilon} < 0.0004 \text{ \%/s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.00004) \quad (\dot{\epsilon} < 0.00004 \text{ \%/s for Cast SS})$$

$$T^* = 0.000813 \times T$$

(2) PWR environments and PWR plant secondary system environment

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-36}$$

where,

$$C = 3.910$$

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

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 49.9 \text{ \%}/\text{s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.00004 \leq \dot{\epsilon} \leq 49.9 \text{ \%}/\text{s for Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.0004) \quad (\dot{\epsilon} < 0.0004 \text{ \%}/\text{s for except Cast SS})$$

$$\dot{\epsilon}^* = \ln(0.00004) \quad (\dot{\epsilon} < 0.00004 \text{ \%}/\text{s for Cast SS})$$

$$T^* = 0.000782 \times T \quad (T \leq 325 \text{ }^\circ\text{C})$$

$$T^* = 0.254 \quad (T > 325 \text{ }^\circ\text{C})$$

Nickel-Chromium-Iron Alloys and their associated welds

(1) BWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-37}$$

where,

$$C = 0.5878$$

$$\dot{\epsilon}^* = \ln(1.80) \quad (\dot{\epsilon} > 1.80 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 1.80 \text{ \%}/\text{s})$$

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

$$T^* = 0.000339 \times T$$

(2) PWR environments

$$\ln(F_{en}) = (C - \dot{\epsilon}^*) \times T^* \quad \text{Eq. C-38}$$

where,

$$C = 3.262$$

$$\dot{\epsilon}^* = \ln(26.1) \quad (\dot{\epsilon} > 26.1 \text{ \%}/\text{s})$$

$$\dot{\epsilon}^* = \ln(\dot{\epsilon}) \quad (0.0004 \leq \dot{\epsilon} \leq 26.1 \text{ \%}/\text{s})$$

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

$$T^* = 0.0004028 \times T$$

C.4.2 2009 Edition

JNES issued the final report of the EFT Project [40] and the JNES technical report, JNES-SS-0701, as the summary of the EFT Project. Recall that JNES-SS-1005 is the English translation of JNES-SS-0701.

In the 2009 Edition, JSME S NF1 was revised based on JNES-SS-0701, and the main technical items that were revised are as follows:

Best-fit fatigue curves in air

- The best-fit curves in air for carbon, low alloy, and austenitic stainless steels, and high nickel alloys were developed by updating the latest fatigue data.

F_{en} expressions

- The evaluation equations for $DO > 0.7$ ppm were added to the F_{en} expressions for carbon and low alloy steels.
- The transients for BWR conditions were added to the applicable conditions for the F_{en} expressions for carbon and low alloy steels.
- The F_{en} expressions for austenitic stainless steels for BWR conditions were revised.
- The F_{en} expressions for high nickel alloys were revised.

The technical contents of the 2009 Edition are identical to JNES-SS-0701/JNES-SS-1005. The F_{en} expressions are found in Section 4.2.

C.4.3 Future Edition

The JSME is preparing a future Edition with three planned technical revisions:

- New design fatigue curves using tensile strength as a variable.
- New F_{en} expression for austenitic stainless steels for PWR environments.
- Flaw tolerance approach.

The proposals for these three revisions have been approved by the JSME Main Committee. The outlines of each are provided below.

New design fatigue curves using tensile strength as a variable [45]

The DFC Subcommittee was established by the Atomic Energy Research Committee in the JWES from August 2011 to March 2013 (Phase 1) and the DFC Subcommittee Phase 2 followed from April 2013 to March 2016. The purpose of these committees was to propose reasonable design fatigue curves for austenitic stainless, carbon, and low alloy steels that have a clear technical basis. To verify the developed design fatigue curves, a fatigue test program that

consisted of large-scale fatigue tests and small specimen tests was carried out as a Japanese utility collaborative project and the test results were provided to the DFC2 subcommittee to support the development of the fatigue analysis method.

In the JSME Environmental Fatigue Evaluation Method, CUF in air is an input for the calculation of CUF_{en} , but the CUF in air is basically calculated in accordance with the JSME Design and Construction Code. If the design fatigue curves developed in the DFC1/DFC2 subcommittees are incorporated into the JSME Environmental Fatigue Evaluation Method, the environmental fatigue analysis can be optimized. Hence, the Subgroup on Fatigue Evaluation in the JSME Code Committee reviewed the developed fatigue analysis method to incorporate into the JSME Environmental Fatigue Evaluation Method and proposed the revision of the JSME Environmental Fatigue Evaluation Method to incorporate the developed fatigue analysis method with some modifications. The JSME Main Committee approved this proposal during their 98th meeting held on June 23, 2021.

This new fatigue analysis method is also proposed and under discussion as a Code Case (Record Number 19-2068) of the ASME B&PV Section III.

The new fatigue analysis method consists of the best-fit curves, factors for data scatter, correction for mean stress effects, effects of surface finish and fatigue endurance limits as shown in Figure C-12, Figure C-13 and Figure C-14.

The correction for mean stress effects is introduced into the best-fit curve. The factors of data scatter on stress and cycles (α_{stress} and α_{cycle}) are applied to the curve. The effect on the surface finish is applied to the peak stress intensity as a fatigue strength reduction factor for surface finish effect (K_{sf}). The size effect can be ignored. The applicable number of cycles is up to 10^8 cycles and the effect of variable loading amplitude needs to be considered.

One typical feature of this method is to develop the best-fit curves using tensile strength as a variable as follows:

(U.S. Customary Units)

[Carbon and Low Alloy Steels, High Nickel Alloys]

$$S_a = (1.74 \times 10^4 - 28S_u)N_f^{-0.58} + 0.45S_u + 5.2 \quad \text{Eq. C-39}$$

[Austenitic Stainless Steels]

$$S_a = 7.38 \times 10^3 N_f^{-0.485} + 0.488S_u \quad \text{Eq. C-40}$$

(SI Units)

[Carbon and Low Alloy Steels, High Nickel Alloys]

$$S_a = (1.2 \times 10^5 - 28S_u)N_f^{-0.58} + 0.45S_u + 36 \quad \text{Eq. C-41}$$

[Austenitic Stainless Steels]

$$S_a = 5.09 \times 10^4 N_f^{-0.485} + 0.488S_u \quad \text{Eq. C-42}$$

The above best-fit curves were developed by statistical analyses based on large databases. The factors for data scatter are tabulated in Table C-29. The standard deviations and the mean values were obtained for strain ratio (γ_ε) and life ratio (γ_N), and the factors on stress and number of cycles were calculated from γ_ε and γ_N , respectively, as 95% confidence bounds.

For correction of mean stress effects, the Smith-Watson-Topper (SWT) Approach [77] is employed (which is different from current design codes that employ the Modified Goodman Approach):

$$S_{eq} = \sqrt{S_{alt} \cdot (S_{alt} + S_{mean})} \quad \text{Eq. C-43}$$

When $(S_{alt} + S_{mean})$ is greater than the cyclic yield strength (S'_y), S_{mean} is set to $S'_y - S_{alt}$ to accommodate shakedown. The cyclic yield strength (CYS) equations were developed as the following upper-bound relations for CYS:

Carbon and Low Alloy Steels, High Nickel Alloys

$$CYS = 0.726S_u \quad \text{Eq. C-44}$$

Austenitic Stainless Steels

$$CYS = 0.252S_u + 20.5 \text{ (U.S. Customary),}$$

$$CYS = 0.252S_u + 141 \text{ (SI Unit)} \quad \text{Eq. C-45}$$

Variable amplitude effects are explicitly addressed by the following equation:

$$N_3 = [(S_V \cdot N_V^{0.1}) / S_{\ell 2}]^{1/0.1} \quad (N_V = 2 \times 10^6) \quad \text{Eq. C-46}$$

The above equation indicates that the design fatigue curve for variable loading amplitude starts from $N_V = 2 \times 10^6$ with the slope of 1/10, which comes from EN13445-3 [78].

Typical examples of design fatigue curves are shown in Figure C-15 for low alloy steel and in Figure C-16 for 316SS. Both figures identify that the new design fatigue curves predict longer fatigue lives compared to NUREG/CR-6909, Revision 1.

New F_{en} expression for austenitic stainless steels for PWR environments [45]

The F_{en} expression for austenitic stainless steels in the JSME Environmental Fatigue Evaluation Method was developed based on the EFT Project. The experimental F_{en} factor was defined as the ratio of the experimental fatigue life in the environment to the predicted fatigue life by the following best-fit curve in air:

$$\varepsilon_a = 23.0N_f^{-0.457} + 0.11 \quad \text{Eq. C-47}$$

The above best-fit curve was developed based on the Japanese and U.S. fatigue test data in air (20 – 350 °C) for 304, 316, 310 and 347 austenitic stainless steels.

To improve the experimental F_{en} factor for austenitic stainless steels, the best-fit curve in air was developed considering only the materials for which the environmental fatigue tests in the EFT project were performed. For base metal, the following best-fit curve was established based on the

fatigue test data in air for 316SS base metal used in the EFT project in PWR environments as shown in Figure C-17.

$$\epsilon_a = 32.6 N_f^{-0.511} + 0.11 \quad \text{Eq. C-48}$$

The experimental F_{en} factors for the base metal were revised using Equation C-48 and the following improved F_{en} expression for SS base metal was developed as shown in Figure C-18:

$$F_{en} = 1.38(\dot{\epsilon})^{-0.346} \quad [\text{for SS Base Metal}] \quad \text{Eq. C-49}$$

In the same way, the F_{en} expressions were obtained as follows:

$$F_{en} = 0.62(\dot{\epsilon})^{-0.342} \quad [\text{for Cast Stainless Steel}] \quad \text{Eq. C-50}$$

$$F_{en} = 1.11(\dot{\epsilon})^{-0.224} \quad [\text{for SS Weld Metal}] \quad \text{Eq. C-51}$$

The comparison of the F_{en} expressions for the current JSME Environmental Fatigue Evaluation Method, NUREG/CR-6909, Revision 1, and the above F_{en} expressions is shown in Figure C-19. The developed F_{en} expressions for base metal are the most conservative of all developed F_{en} expressions and close to those developed in NUREG/CR-6909, Revision 1. Hence, the developed F_{en} expression for base metal was conservatively selected for use.

To verify the proposed F_{en} expression of Equation C-49, fatigue lives were estimated for the environmental fatigue test data in PWR environments that were obtained from the EFT project shown in Figure C-7. The proposed F_{en} expression of Equation C-49, the developed best-fit curve in air of Equation C-42 using the tensile strength of the experimental data, and the factors of data scatter on stress and cycles (α_{stress} and α_{cycle}) in Table C-29 without the mean stress correction were applied to estimate the environmental fatigue test data. The comparison between the experimental fatigue lives and the estimated fatigue lives is shown in Figure C-20. Figure C-20 shows that all estimated fatigue lives of the experimental data are equivalent or shorter than the experimental fatigue lives, so the applicability of the proposed F_{en} expression of Equation C-49 with the proposed best-fit curve and the factors was confirmed.

Flaw tolerance approach [45]

The original proposal for flaw tolerance in ASME Section III assumed an initial flaw at the start of operation. The premise of this action was challenged by the U.S. NRC so the action was abandoned.

The JSME Task Group on Fatigue Evaluation performed a parameter investigation of initial crack depths and calculated crack growth as shown in Figure C-21. This figure indicates that the flaw tolerance approach that assumes an initial flaw at the start of operation may be too conservative. Therefore, the JSME Task Group proposed a flaw tolerance approach that assumes an initial flaw at the time when $CUF_{en} = 1.0$.

Equivalent single crack aspect ratios were developed by ASME for Section XI Nonmandatory Appendix L using probabilistic fracture mechanics; the background documents for that work are NUREG/CR-6934 [79] and MRP-82 [80].

The JSME Task Group reviewed NUREG/CR-6934 and developed aspect ratios for an initial flaw based on the experience of fatigue cracks in Japanese nuclear power plants, a probabilistic

fracture mechanics code (PEPPER) developed by Tepco Systems Corporation (TEPSYS), and so on.

These results were succeeded by the JSME Subgroup on Fatigue Evaluation and the Subgroup proposed to incorporate the developed flaw tolerance approach into the JSME Fatigue Evaluation Method.

This approach can also be referred to as the total fatigue life approach. Adoption of this approach is under discussion in the ASME Section III Working Group on Environmental Fatigue Evaluation Methods.

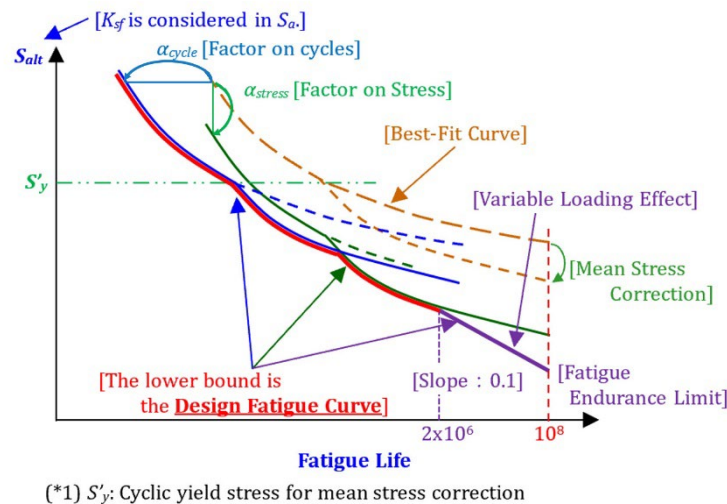


Figure C-12
Concept of the New Design Fatigue Curve

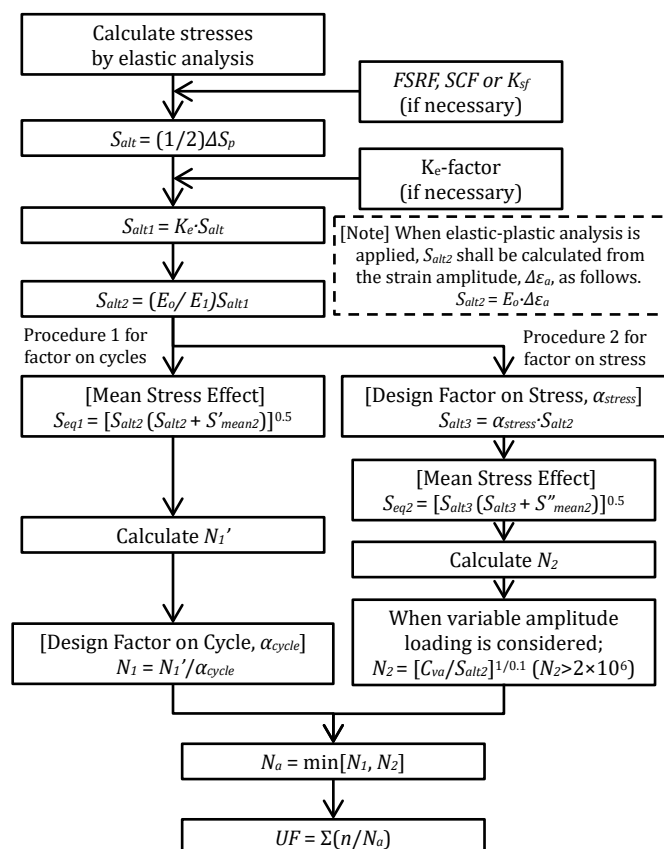


Figure C-13
Flowchart of the New Fatigue Analysis Method

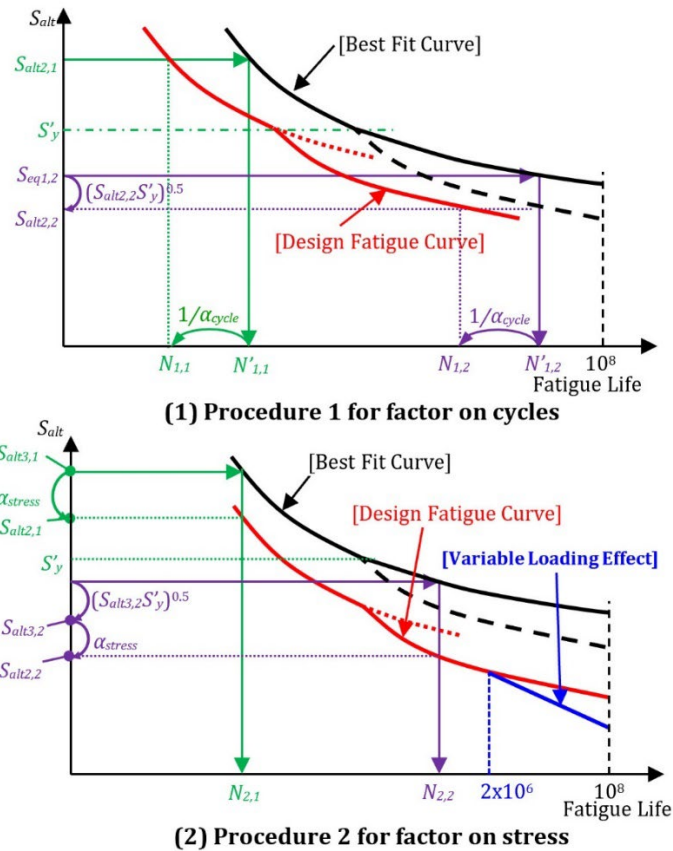


Figure C-14
Scheme of Relation between DFC and BFC Considering Design Factors

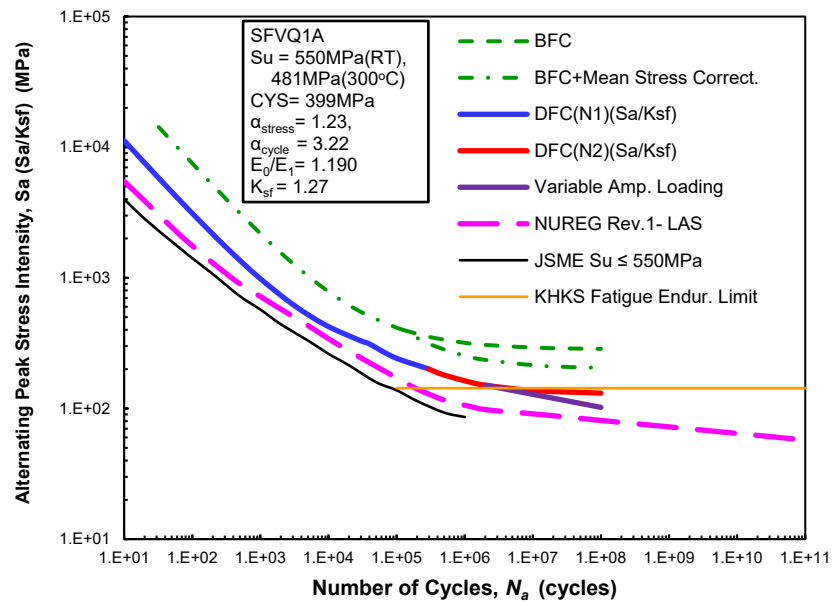


Figure C-15
Design Fatigue Curve for SFVQ1A (equivalent to SA-508 Gr. 3 Cl. 1)

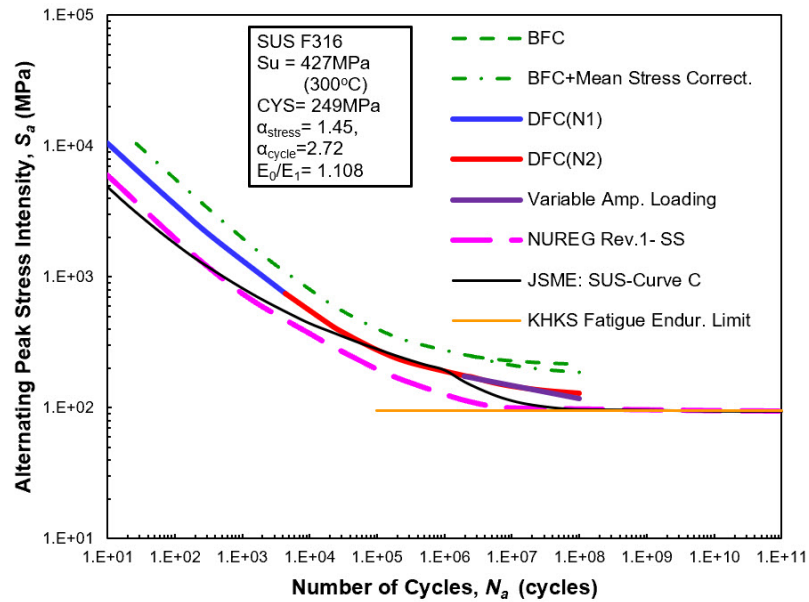


Figure C-16
 Design Fatigue Curve for SUS F316 (equivalent to SA-182 F316)

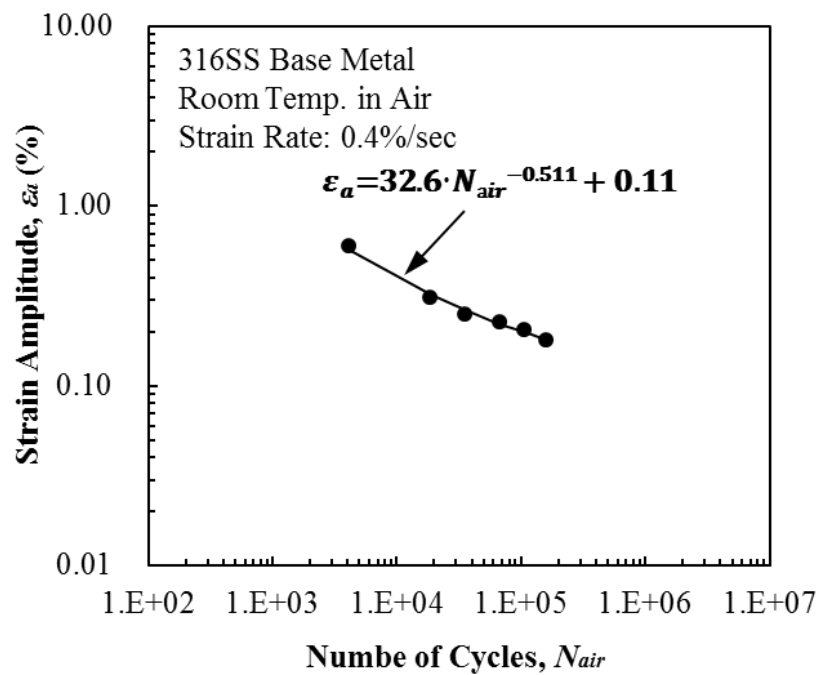


Figure C-17
 The Best-Fit Curve for Base Metal 316SS from the EFT Project

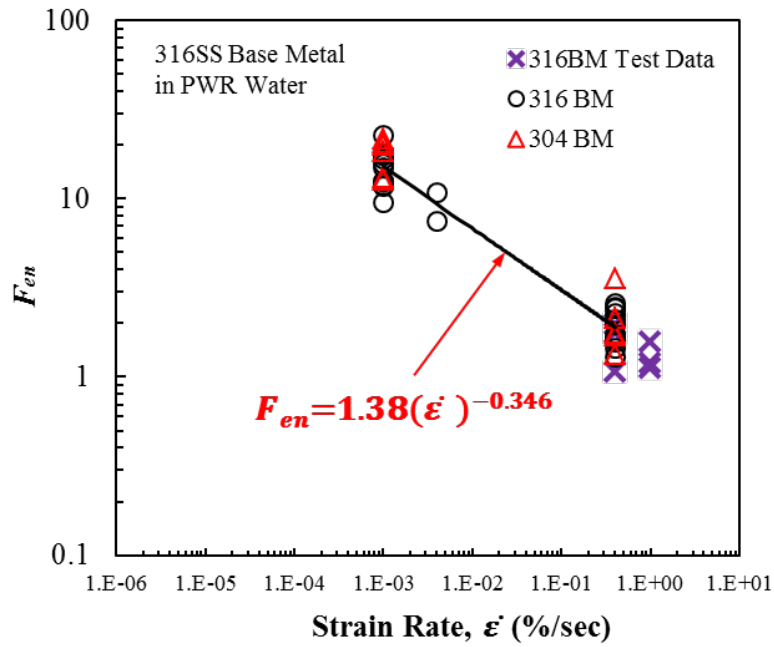


Figure C-18
Developed F_{en} Expressions for SS Base Metal

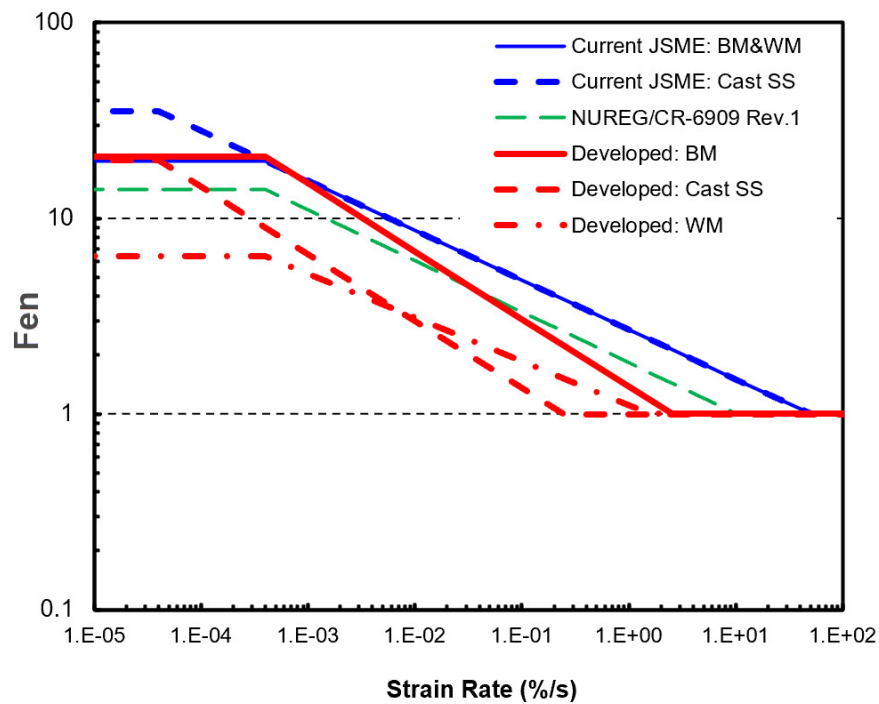


Figure C-19
Comparison of F_{en} Expressions

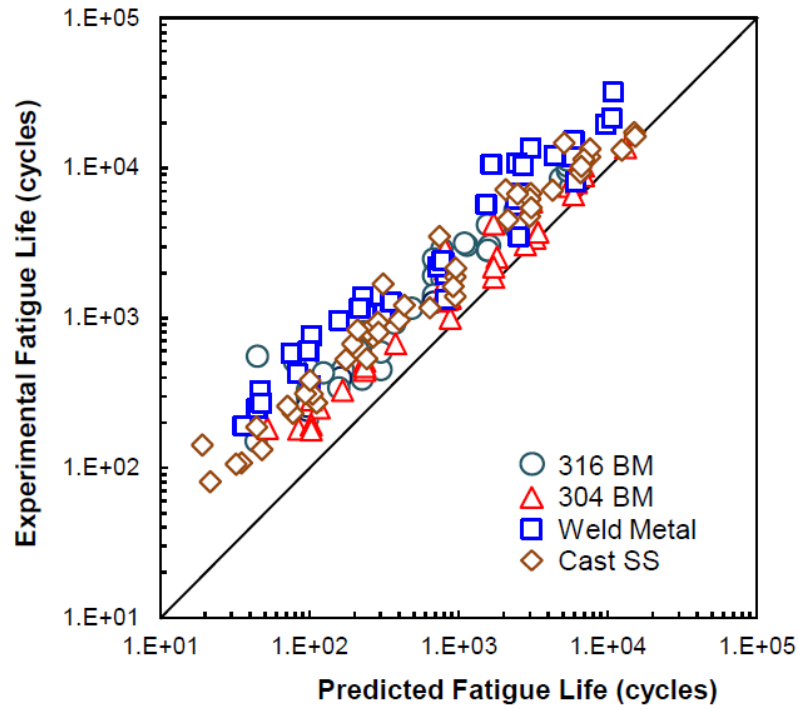


Figure C-20
Comparison of Experimental Fatigue Lives vs. Estimated Fatigue Lives

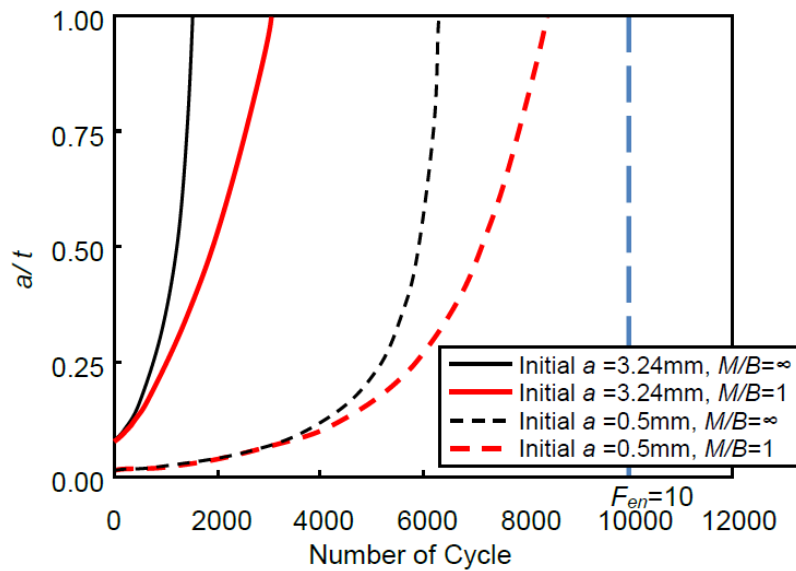


Figure C-21
Parameter Survey of Initial Flaw Depth for Crack Growth

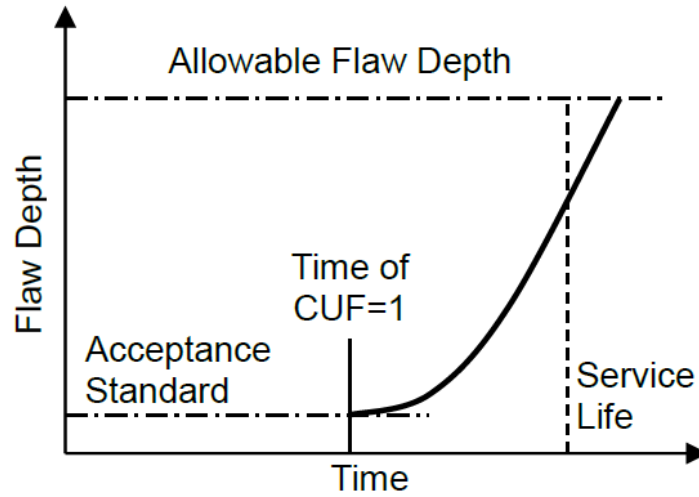


Figure C-22
Proposed Flaw Tolerance Approach

Table C-29
Factors of Data Scatter

		Carbon & Low Alloy Steels	Austenitic Stainless Steels
$\sigma_e^{(*1)}$	Stress (Strain)	0.0458	0.0764
	Number of Cycles	0.169	0.212
$\mu_e^{(*1)}$	Stress (Strain)	3.37×10^{-3}	-6.27×10^{-3}
	Number of Cycles	-2.67×10^{-2}	-9.81×10^{-3}
$\alpha_{stress}^{(*2)}$ (Factor on Stress)		1.23	1.45
$\alpha_{cycle}^{(*2)}$ (Factor on Cycles)		2.32	2.72

(*1) Strain ratio: $\gamma_e = \varepsilon_{DATA} / \varepsilon_{BFC}$, Life ratio: $\gamma_N = N_{DATA} / N_{BFC}$

(*2) $Factor_{95\% \text{ confidence bound}} = 1/10^{\mu_e - 2\sigma_e}$

D

EPRI BWRVIA WATER CHEMISTRY DISCUSSION AND EXAMPLE

For BWRs the dissolved oxygen (*DO*) values for input to environmental fatigue calculations are typically obtained from running an individual plant's chemistry data through EPRI's BWRVIA model [52], except when plant measurements are available for specific locations (i.e., feedwater *DO*). These *DO* values vary from one region of the plant to another, and also over time, based on the plant's water chemistry practices and its intergranular stress corrosion cracking (IGSCC) mitigation history.

Table D-1. IGSCC Mitigation Types [81]

BWR Water Chemistry	Impact on Dissolved Oxygen
Normal Water Chemistry	High levels of <i>DO</i>
Moderate Hydrogen Water Chemistry	<i>DO</i> concentrations are lower for bulk water and metal surface locations
Electrocatalysis + Hydrogen Water Chemistry ¹	Surface <i>DO</i> concentrations are low; bulk water <i>DO</i> concentrations remain elevated

1. Includes classic and on-line Noble Metal Chemical Addition (NobleChem™)

Prior to the existence of IGSCC mitigation programs, Normal Water Chemistry (NWC) conditions were present. NWC is typically associated with relatively high levels of *DO* in the various regions of the plant. This has a particularly significant impact on EAF calculations, since numerous ferritic components are limiting in BWRs, and combined with the fact that transient accumulation rates are often much higher early in plant life than later. Additionally, the current practice to determine CUF_{en} uses bulk *DO* values from BWRVIA that do not consider the effect of electrocatalysis to reduce surface *DO* values for BWR components.

The component locations, or zones, are represented in Figure D-1 and are correlated to the reactor pressure vessel regions defined in the BWRVIA model [52] shown in Figure D-2. The correlation of zones to specific lines of BWRVIA outputs are used to identify *DO* values for each zone from the BWRVIA results.

Additional information can be found in two EPRI document collections: BWRVIP-62, Revision 2 [81, 82] and BWRVIP-190, Revision 1 [83, 84].

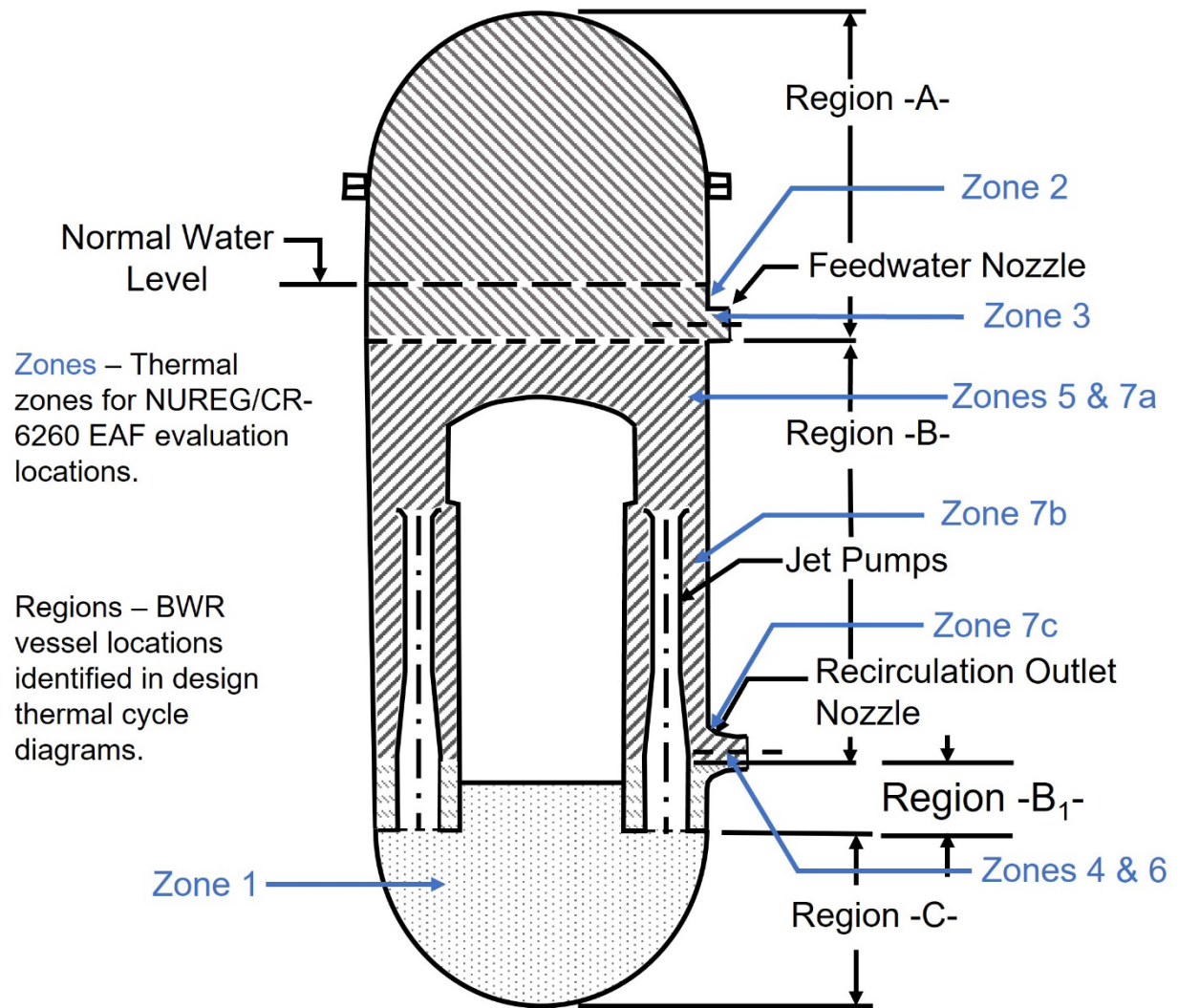


Figure D-1
Reactor Pressure Vessel Thermal Regions and Zone Identification

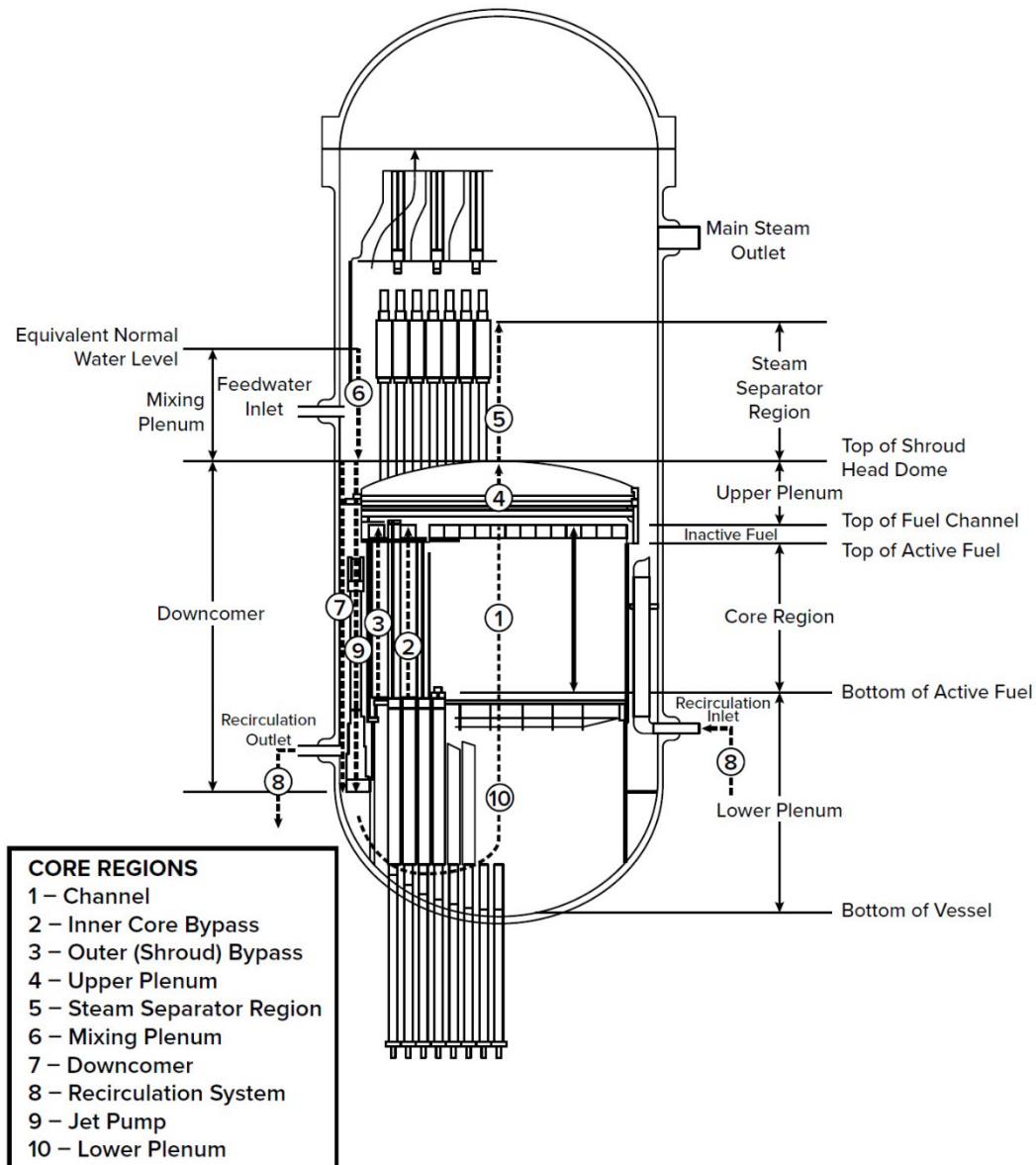


Figure D-2
Radiolysis Model Region and Circuit Identification [52]

E

HISTORICAL EPRI REFERENCE LIST

This appendix documents a review of all available EPRI Reports as of the publishing of this report. For the review, the key references and subreferences were identified. Key references were either directly applicable, providing key design input to the Handbook, or applicable because they provide supporting information such as historical information or sample problems. The rest of the reports were considered subreferences to the EAF Handbook project because they have been superseded, are unrelated to the project, or do not contain useful information except to the extent that the results are reflected in current codes, standards, or regulations. The results of this review are summarized in the lists and table below.

Key References for EAF Handbook

- 18 – 1002814 – Operating Plant Fatigue Assessment
- 24 – 1012017 – EAF in License Renewal
- 25 – 1012896 – Re-evaluation of EAF in SS
- 27 – 1015014 – Evaluation of Ramp Times
- 28 – 1026823 – Guidelines for EAF Calculations
- 30 – 1022876 – Stress-Based Fatigue Monitoring
- 33 – 1025159 – Fatigue Management
- 36 – 3002000684 – Fatigue Monitoring
- 49 – 3002014121 – Life and Gradient Factors
- 50 – 3002014122 – Alternative Simplified EP
- 53 – 3002018260 – EAF Database
- 54 – 3002018262 – EAF Screening Methods
- 58 – 3002023882 – Thermal Fatigue Handbook
- 59 – 3002026454 – Low Cycle Fatigue Handbook
- 60 – 3002026455 – Vibration Fatigue Handbook

References with Supporting Information

- 4 – TR-104691 – Nuclear Plant Fatigue Assessment
- 6 – TR-109051 – EAF in Low Alloy Steel
- 9 – TR-110356 – EAF in a BWR
- 10 – TR-110043 – EAF in a Westinghouse PWR
- 11 – TR-107943 – EAF Evaluation of BWR
- 39 – 3002008119 – EAF during Load Following

NOTE: The first number in the references listed above correspond to the numbering in Table E-1

Table E-1: List of EAF-Related Reports Published by EPRI

(NOTE: Reports in grey have been superseded and are no longer available from EPRI Publications.)

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
1	NP-5775	Y	Environmental Effects on Components: Commentary for ASME Section III	Apr-1988	N
2	TR-100252	N	Metal Fatigue in Operating Nuclear Power Plants	Apr-1992	N
3	TR-102765	Y	Environmentally Assisted Fatigue Crack Initiation in Low-Alloy Steels: A Review of the Literature and the ASME Code Design Requirements	Aug-1993	N
4	TR-104691	Y	Operating Nuclear Power Plant Fatigue Assessments	May-1995	N
5	TR-105759	Y	An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations	Aug-1996	N/A
6	TR-109051	Y	Environmentally-Assisted Fatigue Crack Initiation in Low Alloy Steels	Nov-1997	N
7	TR-107515	Y	Evaluation of Thermal Fatigue Effects on Systems Requiring Aging Management Review for License Renewal for the Calvert Cliffs Nuclear Power Plant	Feb-1998	N
8	TR-110250	Y	Measuring Fatigue Damage in Materials -- Phase 2	Mar-1998	N
9	TR-110356	Y	Evaluation of Environmental Thermal Fatigue Effects on Selected Components in a BWR Plant	May-1998	N
10	TR-110043	Y	Evaluation of Environmental Fatigue Effects for a Westinghouse Nuclear Power Plant	Jun-1998	N

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
11	TR-107943	Y	Environmental Fatigue Evaluations of Representative BWR Components	Aug-1998	N
12	TR-110251	Y	Measuring Fatigue Damage in Materials -- Phase 2	Jun-1999	N
13	TR-110120	Y	Effect of Environment on Fatigue Usage for Piping and Nozzles at Oconee Units 1, 2, and 3	Dec-1999	N/A
14	1000866	Y	Summary of Generic License Renewal Technical Issues Revision 1	Jun-2001	N
15	1006070	Y	Proceedings of the 2000 International Conference on Fatigue of Reactor Components (MRP-46): PWR Materials Reliability Program (PWRMRP)	Jun-2001	N
16	1003079	Y	Materials Reliability Program: Evaluation of Fatigue Data Including Reactor Water Environmental Effects (MRP-49)	Dec-2001	N
17	1003667	Y	Materials Reliability Program: Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low-Alloy Steel Components (MRP-74)	Nov-2002	N/A
18	1002814	Y	Recommended Improvements to ASME Section XI Appendix L (MRP-82)	Dec-2002	Y
19	1003536	Y	Materials Reliability Program: Second International Conference on Fatigue of Reactor Components (MRP-84): July 29-August 1, 2002; Snowbird Ski and Conference Center, Snowbird, Utah	Mar-2003	N

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
20	1007853	Y	Materials Reliability Program: Environmental Fatigue Testing of Type 304L Stainless Steel U-Bends in Simulated PWR Primary Water (MRP-100): Phase A (Optimization of Test Procedures and Baseline Testing)	Dec-2003	N
21	1008207	Y	Materials Reliability Program: Environmental Fatigue Testing of Type 304L Stainless Steel U-Bends in Simulated PWR Primary Water (MRP-137)	Dec-2004	N
22	1011412	Y	Materials Reliability Program, Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low Alloy Steel Components (MRP-74, Revision 1)	Feb-2005	N
23	1011958	Y	Materials Reliability Program: Third International Conference on Fatigue of Reactor Components (MRP-151)	Sep-2005	N
24	1012017	Y	Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47, Revision 1)	Sep-2005	Y
25	1012896	Y	Materials Reliability Program: Reevaluation of Stainless Steel Components in NUREG/CR-6674 (MRP-172)	Nov-2005	Y
26	1013028	Y	Materials Reliability Program, Environmental Fatigue Testing of Type 304L Stainless Steel U-Bends in Simulated PWR Primary Water (MRP-188)	Feb-2006	N

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
27	1015014	Y	Materials Reliability Program: Evaluation of Controlling Transient Ramp Times Using Piping Methodologies When Considering Environmental Fatigue (F_{en}) Effects (MRP-218)	Sep-2007	Y
28	1025823	Y	Guidelines for Addressing Environmental Effects in Fatigue Usage Calculations	Dec-2007	Y
29	1022873	Y	Improved Basis and Requirements for Break Location Postulation	Oct-2011	N
30	1022876	Y	Stress-Based Fatigue Monitoring (MRP-330)	Dec-2011	Y
31	1023012	Y	Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research: Gap Analysis Report	Dec-2011	N/A
32	1024995	Y	Environmentally Assisted Fatigue (EAF) Screening: Process and Technical Basis for Identifying EAF Limiting Locations	Sep-2012	N/A
33	1025159	N	Materials Reliability Program: Integrated Fatigue Management Guideline (MRP-148, Revision 1)	Nov-2012	Y
34	1026724	Y	Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research: Roadmap	Dec-2012	N/A
35	3002000115	Y	Nuclear Plant Fatigue Applications and Environmentally Assisted Fatigue Workshop	Jan-2013	N
36	3002000684	N	Materials Reliability Program (MRP-149, Revision 1) Fatigue Licensing Basis Monitoring Guideline	Dec-2013	Y
37	3002003922	N	Generic Evaluation of Environmentally Assisted Fatigue in BWR and PWR Reactors: A Feasibility Study	Apr-2014	Y

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
38	3002005476	N	Program on Technology Innovation: Crack Tip Strain Rate Models for Environmentally-Assisted Fatigue Crack Growth in BWR and PWR Environments	Nov-2015	N
39	3002008119	Y	Westinghouse and Combustion Engineering Fleet Nuclear Power Plant Operational Variables During Load-Following Operations	Jul-2016	Y
40	3002007850	N	Materials Reliability Program: Environmentally Assisted Fatigue Testing for Application to BWRs, PWRs, and Advanced Plants (MRP-407)	Sep-2016	N
41	3002007969	N	Environmentally-Assisted Fatigue Crack Growth in Irradiated Stainless Steels in LWR Environments	Dec-2016	N
42	3002007973	N	Mechanistic Understanding of Environmentally Assisted Fatigue Crack Growth of Austenitic Stainless Steels in PWR Environments	Dec-2016	N
43	3002009472	Y	Materials Reliability Program: Environmentally Assisted Fatigue of Austenitic Stainless Steel Under Plant-Like Conditions (MRP-415)	Dec-2016	N
44	3002010268	N	Materials Reliability Program: PWR Internals Material Aging Degradation Mechanism Screening and Threshold Values (MRP-175, Revision 1)	Oct- 2017	Y
45	3002010554	Y	Update on the Development of Fatigue Usage Life and Gradient Factors	Nov-2017	N/A
46	3002010555	Y	Update on the Development of an Alternative Approach to ASME Code Simplified Elastic-Plastic Analysis	Nov-2017	N/A

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
47	3002012326	Y	Basis and Method for Assessing Adequacy and Margins for Fatigue Under the Effects of Water Environment and Sources of Uncertainty	May-2018	N
48	3002013213	N	Environmentally Assisted Fatigue Testing for Application to BWRs, PWRs, and Advanced Plants	Sep-2018	N
49	3002013214	Y	EAF Knowledge Gap Analysis: Update and Revision of the EAF Knowledge Gaps	Sep-2018	Y
50	3002014121	Y	Development of Fatigue Usage Life and Gradient Factors	Dec-2018	Y
51	3002014122	Y	Development of an Alternative Approach to ASME Code Simplified Elastic-Plastic Analysis	Dec-2018	Y
52	3002014859	Y	BWRVIP-322: BWR Vessel and Internals Project, Revised Allowable High-Cycle Fatigue Curves for Austenitic and Ferritic Steels	June 2019	Y
53	3002017194	N	Water Chemistry Effects on Environmentally Assisted Fatigue of Stainless Steels Under PWR Conditions	Mar-2020	N
54	3002017811	Y	Small-Scale Multi-Axial Fatigue Testing: Recommended Methodologies for Fatigue Initiation and Crack Growth Testing	May-2020	Y
55	3002018260	N	Pressurized Water Reactor Subsequent License Renewal Environmentally Assisted Fatigue Database	Sep-2020	Y
56	3002018262	Y	Environmentally Assisted Fatigue Screening Methods (Revision 1)	Nov-2020	Y

Historical EPRI Reference List

No.	EPRI Product ID	Publicly Available?	Title	Publication Date	Key Reference?
57	3002021227	N	BWRVIP-343: BWR Subsequent License Renewal Environmentally Assisted Fatigue Database Boiling Water Reactor Vessel and Internals Program	Jan-2022	Y
58	3002023882	N	MRP-478: Management of Thermal Fatigue Outside of Plant Design Specifications	Nov-2022	Y
59	3002026454	N	MRP-481: Low Cycle Fatigue Handbook	July-2023	Y
60	3002026455	N	MRP-482: Vibration Handbook	Sep-2023	Y

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STRATEGIES WHEN FATIGUE ANALYSIS IS NOT AVAILABLE

In the existing operating fleet, there is a mix of construction codes such that a fatigue evaluation may not exist. For example, a detailed fatigue analysis may not be available for primary coolant piping designed to ASME B31.1 (likely designed prior to publication of ASME B31.7 and/or NB-3600) or reactor internals and core supports designed to alternative to Section III, Subsection NG. In these cases, EAF assessments, either through detailed evaluations or through monitoring, are still appropriate. This appendix addresses the guidance for handling these cases where an explicit fatigue evaluation is not performed but is required to complete the CUF_{en} calculations.

F.1 B31.1 Piping Analyses

Piping components designed in accordance with the ASME B31.1 design rules do not have an explicit CUF calculation; rather, cyclic loading is considered in an implicit, simplified manner in the design process using a stress range reduction factor based on the number of thermal cycles expected during the component operating lifetime. If the total number of fatigue cycles is expected to be 7,000 or less, the stress range reduction factor is 1.0. For higher numbers of fatigue cycles, a stress range reduction factor of less than 1.0 is used in the assessment for the piping component, which reduces the allowable stress range. As a result, there is no CUF available for ASME B31.1 piping locations for which to apply F_{en} multipliers and address EAF.

Despite this design methodology difference, system functions, flow paths, and typical components in Class 1 piping systems designed to ASME B31.1 are essentially the same as Class 1 piping designed to ASME Code, Section III, or other standards that require explicit fatigue usage calculation (e.g., ASME B31.7). Therefore, it is valid to generally conclude that a piping system designed to the ASME B31.1 rules would meet the fundamental intent of the ASME Code, Section III rules if reanalyzed. This rationale is discussed in detail in Section 2.8 of EPRI Report 3002018262, Revision 1 “Environmentally Assisted Fatigue Screening Methods” [26]. Rather than the significant effort of reanalyzing ASME B31.1 piping system components to a standard such as ASME Code, Section III to obtain fatigue usage values, it is valid for screening purposes for ASME B31.1 locations that require EAF assessment to demonstrate similarity to a piping system with existing usage factors and to use the applicable values from that “reference” piping system to perform EAF screening.

Once the ASME B31.1 piping locations have been screened, the limiting locations will require a more detailed fatigue analysis to address EAF similar to a Section III evaluation.

F.2 Reactor Internals

In general, for reactor internals and core supports, a fatigue evaluation is required for new construction and may have been conducted for existing construction depending on the applicable code edition. The U.S. NRC has asked licensees to address EAF for reactor internals if CUF

values were computed for components in the design basis (See [54] as an example). MRP-175, Revision 1 [55] contains guidance related to fatigue of internals with consideration for several material degradation mechanisms, including fatigue and EAF. However, there are approaches to credit current inspection programs when an explicit fatigue evaluation is not available. The current inspection program may be sufficient for addressing the fatigue management needs. For example, BWRVIP-315 [85] provides an aging management program-based approach for disposition of cracking due to low-cycle EAF that may fulfill the guidance currently defined in the GALL-SLR Report for managing EAF for internals. PWR plants inspecting reactor internals in accordance with MRP-227 [86] are addressed because that report includes EAF screening for generic applicability. Therefore, the need to address EAF for reactor internals is covered for most operating plants under their internals inspection programs. For new plants, an explicit EAF evaluation can be performed.

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Program:

Pressurized Water Reactor Materials Reliability Program (MRP)

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3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com