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Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47, Revision 1)

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Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47 Revision 1)

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REPORT SUMMARY

For about the last 15 years, the effects of light water reactor environment on fatigue have been the subject of research in both the United States and abroad. Based on a risk study reported in NUREG/CR-6674, the NRC concluded that reactor water environmental effects were not a safety issue for a 60-year operating life, but that some limited assessment of its effect would be required for a license renewal extended operating period beyond 40 years. This guideline offers methods for addressing environmental fatigue in a license renewal submittal.

Background
Many utilities are currently embarking upon efforts to renew their operating licenses. One of the key areas of uncertainty in this process relates to fatigue of pressure boundary components. Although the NRC has determined that fatigue is not a significant contributor to core damage frequency, they believe that the frequency of pipe leakage may increase significantly with operating time and have requested that license renewal applicants perform an assessment to determine the effects of reactor water coolant environment on fatigue, and, where appropriate, manage this effect during the license renewal period. As the license renewal application process progressed starting in 1998, several utilities addressed this request using different approaches. In more recent years, a unified approach has emerged that has obtained regulator approval and allowed utilities to satisfactorily address this issue and obtain a renewed operating license for 60 years of plant operation.

Objectives
- To provide guidance for assessment and management of reactor coolant environmental effects
- To minimize the amount of plant-specific work necessary to comply with NRC requirements for addressing this issue in a license renewal application
- To provide "details of execution" for applying the environmental fatigue approach currently accepted by the NRC in the license renewal application process.

Approach
The project team reviewed previous work by EPRI and utilities related to fatigue environmental effects and license renewal including reports on this subject created by EPRI, NRC, and NRC contractors. Recent license renewal applications, NRC Requests for Additional Information, and the commitments made by the past license renewal applicants provided insight into NRC expectations. After evaluation of all this information, the project team developed alternatives for addressing fatigue environmental effects. This revision provides guidelines based on industry experience, consensus, and insight gained from more than six years of experience with this issue and the license renewal approval process.

Results

The report describes a fatigue environmental effect license renewal approach that can be applied by any license renewal applicant. It provides guidelines for performing environmental fatigue assessments using fatigue environmental factors from currently accepted F_{en} methodology.

EPRI Perspective

Utilities have committed significant resources to license renewal activities related to fatigue. Based on input from applicants to-date, NRC requirements for addressing fatigue environmental effects continued to change for the first few applicants, but more recently have become more unified. These guidelines were developed to provide stability, refined guidance, and assurance of NRC acceptance and include an approach that may be taken to address fatigue environmental effects in a license renewal application. Use of the approach provided in this document should limit the amount of effort necessary by individual license renewal applicants in addressing this requirement and putting activities in place for the extended operating period to manage reactor water environmental effects on fatigue.

Keywords

Fatigue
License Renewal
Reactor Water Environmental Fatigue Effects

ABSTRACT

For about the last 15 years, the effects of light water reactor environment on fatigue have been the subject of research in both the United States and abroad. The conclusions from this research are that the reactor water temperature and chemical composition (particularly oxygen content or ECP) can have a significant effect on the fatigue life of carbon, low alloy, and austenitic stainless steels. The degree of fatigue life reduction is a function of the tensile strain rate during a transient, the specific material, the temperature, and the water chemistry. The effects of other than moderate environment were not considered in the original development of the ASME Code Section III fatigue curves.

This issue has been studied by the Nuclear Regulatory Commission (NRC) for many years. One of the major efforts was a program to evaluate the effects of reactor water environment for both early and late vintage plants designed by all U.S. vendors. The results of that study, published in NUREG/CR-6260, showed that there were a few high usage factor locations in all reactor types, and that the effects of reactor water environment could cause fatigue usage factors to exceed the ASME Code-required fatigue usage limit of 1.0. On the other hand, it was demonstrated that usage factors at many locations could be shown acceptable by refined analysis and/or fatigue monitoring of actual plant transients.

Based on a risk study reported in NUREG/CR-6674, the NRC concluded that reactor water environmental effects were not a safety issue for a 60-year operating life, but that some limited assessment of its effect would be required for a license renewal extended operating period beyond 40 years. Thus, for all license renewal submittals to-date, there have been formal questions raised on the topic of environmental fatigue and, in all cases, utility commitments to address the environmental effects on fatigue in the extended operating period. Many plants have already performed these commitments.

This guideline offers methods for addressing environmental fatigue in a license renewal submittal. It requires that a sampling of the most affected fatigue sensitive locations be identified for evaluation and tracking in the extended operating period. NUREG/CR-6260 locations are considered an appropriate sample for F_{en} evaluation as long as none exceed the acceptance criteria with environmental effects considered. If this occurs, the sampling is to be extended to other locations. For these locations, evaluations similar to those conducted in NUREG/CR-6260 are required. In the extended operating period, fatigue monitoring is used for the sample of locations to show that ASME Code limits are not exceeded. If these limits are exceeded, corrective actions are identified for demonstrating acceptability for continued operation.

Using the guidance provided herein, the amount of effort needed to justify individual license renewal submittals and respond to NRC questions should be minimized, and a more unified, consistent approach should be achieved throughout the industry. More importantly, this revision provides "details of execution" for applying the environmental fatigue approach currently accepted by the NRC in the license renewal application process.

CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Objectives

The nuclear industry has discussed the issue of reactor water environmental fatigue effects with the U. S. Nuclear Regulatory Commission (NRC) staff for several years. All of the license renewal applicants to-date have been required to commit to an approach to evaluate the effects of reactor water environment on specific Class 1 reactor coolant system components for the license renewal term in order to obtain approval for a renewed license.

This report provides discussion of an approach that may be used for addressing reactor water environmental effects on fatigue of reactor coolant system components in the extended operating period (after 40 years). Specific guidance for calculating environmental fatigue usage factors for NUREG/CR-6260 [2] locations is provided using the methodology documented in NUREG/CR-6583 [3] and NUREG/CR-5704 [4]. This report does not provide guidance on addressing fatigue as a Time Limiting Aging Analysis (TLAA) per 10CFR54. The details of monitoring thermal fatigue for acceptance are contained in Reference [23].

Thus, the objectives of this report are as follows:

1. To provide guidance for evaluating the effects of reactor water environmental effects on fatigue for license renewal applicants,
2. To provide specific guidance on the use of NUREG/CR-6583 for carbon and low alloy steels [3] and in NUREG/CR-5704 for austenitic stainless steels [4] in plant specific evaluations of the effects of reactor water environmental effects on fatigue,
3. To provide separate guidance for pressurized water reactors (PWRs) and boiling water reactors (BWRs) to assist in the development of reasonable estimates for the significant parameters (e.g., oxygen, temperature, and strain rate) required by the environmental fatigue assessment methodology at evaluated locations,
4. To provide approaches for removing excess conservatism in existing fatigue analyses to offset the impact of environmental effects,
5. To provide alternatives for managing environmental effects using flaw tolerance evaluation and inspection,
6. To provide guidance that minimizes the amount of effort needed to justify individual license renewal submittals and respond to NRC questions, and promote a more unified, consistent approach throughout the industry, and
7. Incorporate "Lessons Learned" from ASME Code activities supported by the MRP associated with this topic.

This guideline document includes appropriate logic to allow users to efficiently perform environmental fatigue calculations for a plant pursuing license renewal activities. The logic is provided such that some components can be evaluated using simplified methods, whereas others can be evaluated using more complex methods.

Finally, this document also summarizes the approaches for addressing fatigue environmental effects in the extended operating period used by those applicants that have already submitted the license renewal applications.

1.2 Compliance Responsibilities

The Industry Guidelines contained in this report are considered to be "Good Practice".

2 BACKGROUND

2.1 Research Results

NRC research in the area of reactor water environmental effects on fatigue began in the early 1990s. Based on testing both in Japan and in the U.S., fatigue life in a light water reactor (LWR) environment was determined to be adversely affected by certain water chemistries, strain amplitude, strain rate, temperature and material sulfur content (for ferritic steels). Whereas LWR pressure boundary components are in contact with the reactor water at elevated temperatures, the fatigue curves in Section III of the ASME Boiler and Pressure Vessel Code were based on testing in air, primarily at room temperature, adjusted by a structural factor in-part to compensate for temperature and "industrial" environments. In 1993, a set of "interim" fatigue curves for carbon, low alloy, and stainless steels were published in NUREG/CR-5999 [1] based on the results of research testing at that point in time.

To determine the effects of the environment in operating nuclear plants during the current 40-year licensing term and for an assumed 60-year extended period, Idaho National Engineering Laboratories (INEL) evaluated fatigue-sensitive component locations, and documented their results in NUREG/CR-6260 [2]. Using information from existing reactor component stress reports, supplemented by additional evaluations, cumulative fatigue usage factors (CUFs) were calculated for plants designed by all four nuclear steam supply system (NSSS) vendors utilizing the interim fatigue curves provided in NUREG/CR-5999 [1]. The results showed that CUFs would exceed 1.0 at several locations, although the CUFs at many of these were shown to be less than 1.0 if excessive conservatisms were removed from the evaluations.

Continued research led to changes to the fatigue curves utilized in deriving the results presented in NUREG/CR-6260 [2]. The latest proposed environmental fatigue correlations are presented in NUREG/CR-6583 [3] for carbon and low alloy steels and in NUREG/CR-5704 [4] for austenitic stainless steels. These approaches do not use the revised fatigue curve approach originally defined in NUREG/CR-5999, but instead employ a selective environmental fatigue multiplier, or F_{en}, approach that is defined as follows:

$$F_{en} = \frac{N_{air}}{N_{water}}$$

where:

F_{en} = environmental fatigue multiplier

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

N_{water} = fatigue life (number of cycles) in water (environment), at temperature

The fatigue usage derived from air curves is multiplied by F_{en} to obtain the fatigue usage in the associated environment.

More recently, an evaluation was conducted to assess the implications of LWR environments on reducing component fatigue for a 60-year plant life. This study, based on the information in NUREG/CR-6260 [2] and documented in NUREG/CR-6674 [5], concluded that the environmental effects of reactor water on fatigue curves had an insignificant contribution to core damage frequency. However, the frequency of pipe leakage was shown to increase in some cases.

2.2 License Renewal Environmental Fatigue Issue

The environmental fatigue issue for license renewal reached the current disposition via the closeout of Generic Safety Issue 190 (GSI-190) [6] in December 1999. In a memorandum from NRC-RES to NRC-NRR [7], it was concluded that environmental effects would have a negligible impact on core damage frequency, and as such, no generic regulatory action was required. However, since NUREG/CR-6674 [5] indicated that reactor coolant environmental fatigue effects would result in an increased frequency of pipe leakage, the NRC required that utilities applying for license renewal must address the effects of reactor water environments on fatigue usage in selected examples of affected components on a plant specific basis.

2.3 Industry/EPRI Programs

Following the issuance of NUREG/CR-6260 [2], EPRI performed several studies to quantitatively address the issue of environmental fatigue during the license renewal period.

The initial efforts were focused on developing a simplified method for addressing environmental fatigue effects and evaluating more recent research results. The calculations reported in NUREG/CR-6260 [2] were based on the interim fatigue design curves given in NUREG/CR-5999 [1]. The conservative approach in NUREG/CR-6260 [2] and NUREG/CR-5999 [1] over-penalized the component fatigue analysis, since later research identified that a combination of environmental conditions is required before reactor water environmental effects become pronounced. The strain rate must be sufficiently low and the strain range must be sufficiently high to cause repeated rupture of the protective oxide layers that protect the exposed surfaces of reactor components. Temperature, dissolved oxygen content, metal sulfur content, and water flow rate are examples of additional variables to be considered.

In order to take these parameters into consideration, EPRI and GE jointly developed a method, commonly called the F_{en} approach [8], which permits reactor water environmental effects to be applied selectively, as justified by evaluating the combination of effects that contribute to increased fatigue susceptibility.

The F_{en} approach was used in several EPRI projects to evaluate fatigue-sensitive component locations in four types of nuclear power plants: an early-vintage Combustion Engineering (CE) PWR [9], an early-vintage Westinghouse PWR [10], and both late-vintage [11] and early-vintage [12] General Electric (GE) BWRs. Component locations similar to those evaluated in NUREG/CR-6260 [2] were examined in these generic studies.

The NRC staff has not accepted the studies performed by EPRI [13], primarily because the environmental fatigue effects were based on data that was developed prior to the issuance of later reports by Argonne National Laboratory (ANL) [3, 4]. The following issues were raised in a letter from NRC to the Nuclear Energy Institute [13]:

- The environmental fatigue correction factors developed in the EPRI studies were not based on the latest ANL test report.
- The environmental factors developed in the EPRI studies were not based on a comparison of environmental data at temperature to air data at room temperature.
- The NRC did not agree with the use of the reduction factors (Z-factors) of four (for carbon steel) and two (for stainless steel) to account for moderate environmental effects (i.e., $F_{en,\,effective} = F_{en}$/Z-factor). Instead, the NRC staff believed that the maximum factors that could be used were three (for carbon steel) and 1.5 (for stainless steel).
- There was disagreement on the strain thresholds that were used.
- The NRC staff did not agree that credit could be taken for the cladding in omitting consideration of environmental effects for the underlying carbon steel/low alloy steel materials, unless fatigue in the cladding was specifically addressed.
- The staff agreed with the use of a weighted average strain rate for computing environmental effects only if the maximum temperature of the transient was used.

Based on NRC review of more recent Japanese and ANL data, NRC believes that no credit should be given for inherent margins with regard to moderate environmental effects [14], i.e., the above factor of 4 (EPRI)/3 (NRC) for carbon and low alloy steels, and 2/1.5 for stainless steels should not exceed 1.0.

The Pressure Vessel Research Council (PVRC) Steering Committee on Cyclic Life and Environmental Effects (CLEE) has reviewed published environmental fatigue test data and the F_{en} methodology. Based on this review, the most recent findings by ANL have been incorporated into the equations for the environmental factors. More importantly, it was concluded that the environmental factors could be reduced, by factors of 3.0 for carbon/low-alloy steel and 1.5 for stainless steel, to credit moderate environmental effects included in the current ASME Code fatigue design curves. The PVRC recommendations have been forwarded to the Board of Nuclear Codes and Standards (BNCS) [15]. The recommended evaluation procedure is published in Welding Research Council (WRC) Bulletin No. 487 [18]. WRC-487 includes evaluations based on recent data that would support reduction factors of 3.0 for carbon/low-alloy steel and 1.5 for stainless steel.

In conjunction with the PVRC efforts, the MRP reviewed all published industry fatigue data and documented their review of the data and recommended assessment methodologies [19]. Based on those findings, in 2003, the industry pursued a formal response to the NRC regarding the above areas of disagreement for carbon and low alloy steels [20]. The NRC staff ruled against this response in January 2004 [21] citing that an adequate technical basis was not provided to support several of the assumptions used in the industry's proposal. As a result, EPRI has chosen to work with the license renewal applicants on an industry guideline that defines evaluation techniques that plants can use to satisfactorily achieve resolutions to the issues. These prototype resolutions are formulated for use with F_{en} expressions whether from NRC, NUREG, PVRC or other sources, with discussion provided for the NUREG methodology since that methodology is currently accepted for use by license renewal applicants. The industry is pursuing longer-term application of the PVRC rules through ASME Code changes.

3 LICENSE RENEWAL APPROACH

3.1 Overview

This document describes how the technical issues associated with reactor water fatigue environmental effects evaluation may be addressed, and guidelines are provided on how to perform environmental fatigue evaluations using the methodologies documented in NUREG/CR-6583 [3] and NUREG/CR-5704 [4]. To assess the effects of reactor water environment on fatigue life, a limited number of components (including those in NUREG/CR-6260 [2] for the appropriate vintage/vendor plant) are to be assessed considering the effects of recent environmental fatigue data. As explained below, NUREG/CR-6260 locations are considered an appropriate sample for F_{en} evaluation as long as none exceed the acceptance criteria with environmental effects considered. If this occurs, the sampling is to be extended to other locations. These component locations serve as the leading indicators to assess the significance of environmental effects. For this limited number of components, the effects of the environment on fatigue life must be addressed and adequately managed in the extended operating period.

The process chosen to address environmental effects by the first few applicants for license renewal varied. After a series of requests for additional information, the process that the NRC accepted for Calvert Cliffs and Oconee involved an analytical approach coupled with future planned refinements in their plant fatigue monitoring. Since that time, there has been acceptance of the approaches used by other applicants, and some applicants have committed to perform evaluation only just before entering into the license renewal period (i.e., prior to the end of 40 years). Appendix A provides the results of an industry survey of license renewal applicants to-date describing the varied approaches that have been used.

In many cases, the commitment to perform evaluation later by some of the license renewal applicants has been based on uncertainty and lack of consensus on this topic throughout the industry, and reflects a "wait-and-see" attitude and an avoidance of expending resources now on an issue that may change later. Therefore, it is the intent of this report to develop guidelines for aging management of reactor water fatigue effects for license renewal, so that an acceptable and more unified approach for addressing this issue will be clearly documented for future license renewal applicants.

These guidelines provide a process to address environmental effects in the License Renewal Application, and provide specific guidance on the use of currently accepted environmental fatigue evaluation methodologies. Where necessary, these guidelines are consistent with the Thermal Fatigue Licensing Basis Monitoring Guidelines [23], based on today's knowledge and industry experience. The elements of this approach may change in the future as more information becomes available. Attributes of the fatigue management activity are as follows:

1. SCOPE

   The scope is discussed in detail in Section 2.5.2 of Reference [23]. NUREG/CR-6260 locations will be captured and thus automatically included by the activity steps discussed therein.

2. PREVENTIVE ACTIONS

   Cracking due to thermal fatigue of locations specifically designed to preclude such cracking is prevented by assuring that the thermal fatigue licensing basis remains valid for the period of extended operation. The actions taken in Thermal Fatigue Licensing Basis Monitoring are based on reliance on the standards established in ASME Section III and ASME Section XI.

3. PARAMETERS MONITORED OR INSPECTED

   Monitored parameters are defined and discussed in detail in Sections 2.5.2 and 2.6 of Reference [23].

4. DETECTION OF AGING EFFECTS

   The only detectable aging effects of fatigue are the presence of cracks. These cracks may initiate earlier in life and grow to a detectable size sometime after the CUF exceeds 1.0. The Inservice Inspection Plan as governed by ASME Section XI administers a set of actions relative to the inspection for, detection of, and disposition of crack like indications. This guideline is a sister guideline to the Thermal Fatigue Licensing Basis Monitoring Guideline but is not a part of it.

   The Thermal Fatigue Licensing Basis Monitoring Guideline tracks the margin allotted to the point of CUF = 1 (or to a lesser threshold point) as a way of tracking the life expended prior to the onset of structurally relevant fatigue cracking. Refer to Sections 2.5.2 and 2.6 of Reference [23] for a discussion of the parameters monitored for this purpose.

5. MONITORING & TRENDING

   Sections 2.5.2 and 2.6 of Reference [23] provide a discussion of the parameters monitored and the trending of those parameters as the component fatigue life is expended.

6. ACCEPTANCE CRITERIA

   Sections 2.5.2 and 2.6 of Reference [23] provide a discussion of the parameters monitored, the establishment of acceptance criteria for those parameters, and the trending of those parameters as the component fatigue life is expended.

7. CORRECTIVE ACTION

   Section 2.6.3 of Reference [23] provides a detailed discussion of the application of the corrective action requirements.

8. CONFIRMATION PROCESS

   The confirmation process is part of the corrective action program.

9. ADMINISTRATIVE CONTROLS

   The Thermal Fatigue Licensing Basis Monitoring Guideline actions are implemented by plant work processes.

10. OPERATING EXPERIENCE

    Refer to Sections 1.1 and 2.5.2.3 of Reference [23] for a discussion of how operating experience becomes part of the Thermal Fatigue Licensing Basis Monitoring Guideline implementation.

3.2 Method for Evaluation of Environmental Effects

There are several methods that have been published to assess the effects of reactor water environment on fatigue for each specific location to be considered. In this document, guidance is provided for performing evaluations in accordance with NUREG/CR-6583 [3] for carbon and low alloy steels and NUREG/CR-5704 [4] for austenitic stainless steels, since these are the currently accepted methodologies for evaluating environmental fatigue effects. Other methods that have been published, including those currently being used in Japan, are documented in References [18] and [22].

Figure 3-1 is a flowchart that shows an overview of the assessment approach.

- The first step is to identify the locations to be used in the assessment. This step is discussed in Section 3.2.1
- The second step is to perform an assessment of the effects of environmental fatigue on the locations identified in Step 1. This includes an assessment of the actual expected fatigue usage factor including the influence of environmental effects. Inherent conservatisms in design transients may be removed to arrive at realistic CUFs that include environmental effects. This approach is most applicable to locations where the design transients significantly envelope actual operating conditions in the plant. Further discussion is provided in Section 3.2.2. Specific guidance on performing such evaluation is provided in Section 4.0.
- The bottom of Figure 3-1 indicates that fatigue management occurs after the evaluation from Step 2 is performed for each location. This may be as simple as counting the accumulated cycles and showing that they remain less than or equal to the number of cycles utilized in the assessment performed in Step 2. On the other hand, it may not be possible to show continued acceptance throughout the extended operating period such that additional actions are required. Such options are discussed in Section 3.3. Refer also to Reference [23] for a discussion of cycle counting.

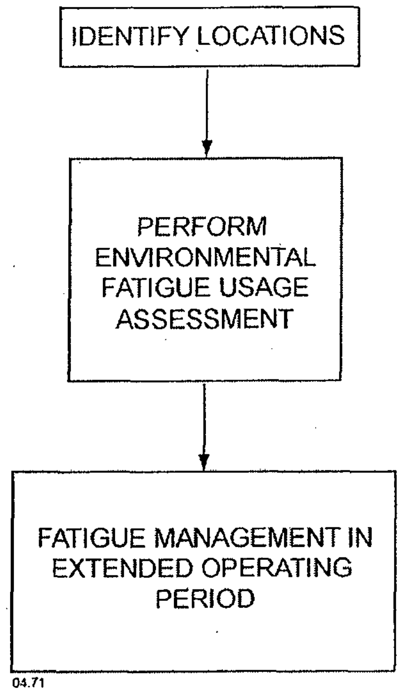


Figure 3-1
Overview of Fatigue Environmental Effects Assessment and Management

3.2.1 Identification of Locations for Assessment of Environmental Effects

A sampling of locations is chosen for the assessment of environmental effects. The purpose of identifying this set of locations is to focus the environmental assessment on just a few components that will serve as leading indicators of fatigue reactor water environmental effects. Figure 3-2 shows an overview of the approach identified for selecting and evaluating locations.

For both PWR and BWR plants, the locations chosen in NUREG/CR-6260 [2] were deemed to be representative of locations with relatively high usage factors for all plants. Although the locations may not have been those with the highest values of fatigue usage reported for the plants evaluated, they were considered representative enough that the effects of LWR environment on fatigue could be assessed.

The locations evaluated in NUREG/CR-6260 [2] for the appropriate vendor/vintage plant should be evaluated on a plant-unique basis. For cases where acceptable fatigue results are demonstrated for these locations for 60 years of plant operation including environmental effects, additional evaluations or locations need not be considered. However, plant-unique evaluations may show that some of the NUREG/CR-6260 [2] locations do not remain within allowable limits for 60 years of plant operation when environmental effects are considered. In this situation, plant specific evaluations should expand the sampling of locations accordingly to include other locations where high usage factors might be a concern.

In original stress reports, usage factors may have been reported in many cases that are unrealistically high, but met the ASME Code requirement for allowable CUF. In these cases, revised analysis may be conducted to derive a more realistic usage factor or to show that the revised usage factor is significantly less than reported.

If necessary, in identifying the set of locations for the expanded environmental assessment, it is important that a diverse set of locations be chosen with respect to component loading (including thermal transients), geometry, materials, and reactor water environment. If high usage factors are presented for a number of locations that are similar in geometry, material, loading conditions, and environment, the location with the highest expected CUF, considering typical environmental fatigue multipliers, should be chosen as the bounding location to use in the environmental fatigue assessment. Similar to the approach taken in NUREG/CR-6260 [2], the final set of locations chosen for expanded environmental assessment should include several different types of locations that are expected to have the highest CUFs and should be those most adversely affected by environmental effects. The basis of location choice should be described in the individual plant license renewal application.

In conclusion, the following steps should be taken to identify the specific locations that are to be considered in the environmental assessment:

- Identify the locations evaluated in NUREG/CR-6260 [2] for the appropriate vintage/vendor plant.
- Perform a plant-unique environmental fatigue assessment for the NUREG/CR-6260 locations.
- If the CUF results for all locations above are less than or equal to the allowable (typically 1.0) for the 60-year operating life, the environmental assessment may be considered complete; additional evaluations or locations need not be considered.
- If the CUF results for any locations above are greater than the allowable for the 60-year operating life, expand the locations evaluated, considering the following:
    - Identify all Class 1 piping systems and major components. For the reactor pressure vessel, there may be multiple locations to consider.
    - For each system or component, identify the highest usage factor locations. By reasons of geometric discontinuities or local transient severity, there will generally be a few locations that have the highest usage factors when considering environmental effects.
    - From the list of locations that results from the above steps, choose a set of locations that are a representative sampling of locations with the highest expected usage factors when considering environmental effects. Considerations for excluding locations can include: (1) identification of excess conservatism in the transient grouping or other aspects of the design fatigue analysis, or (2) locations that have similar loading conditions, geometry, material, and reactor water environment compared to another selected location.

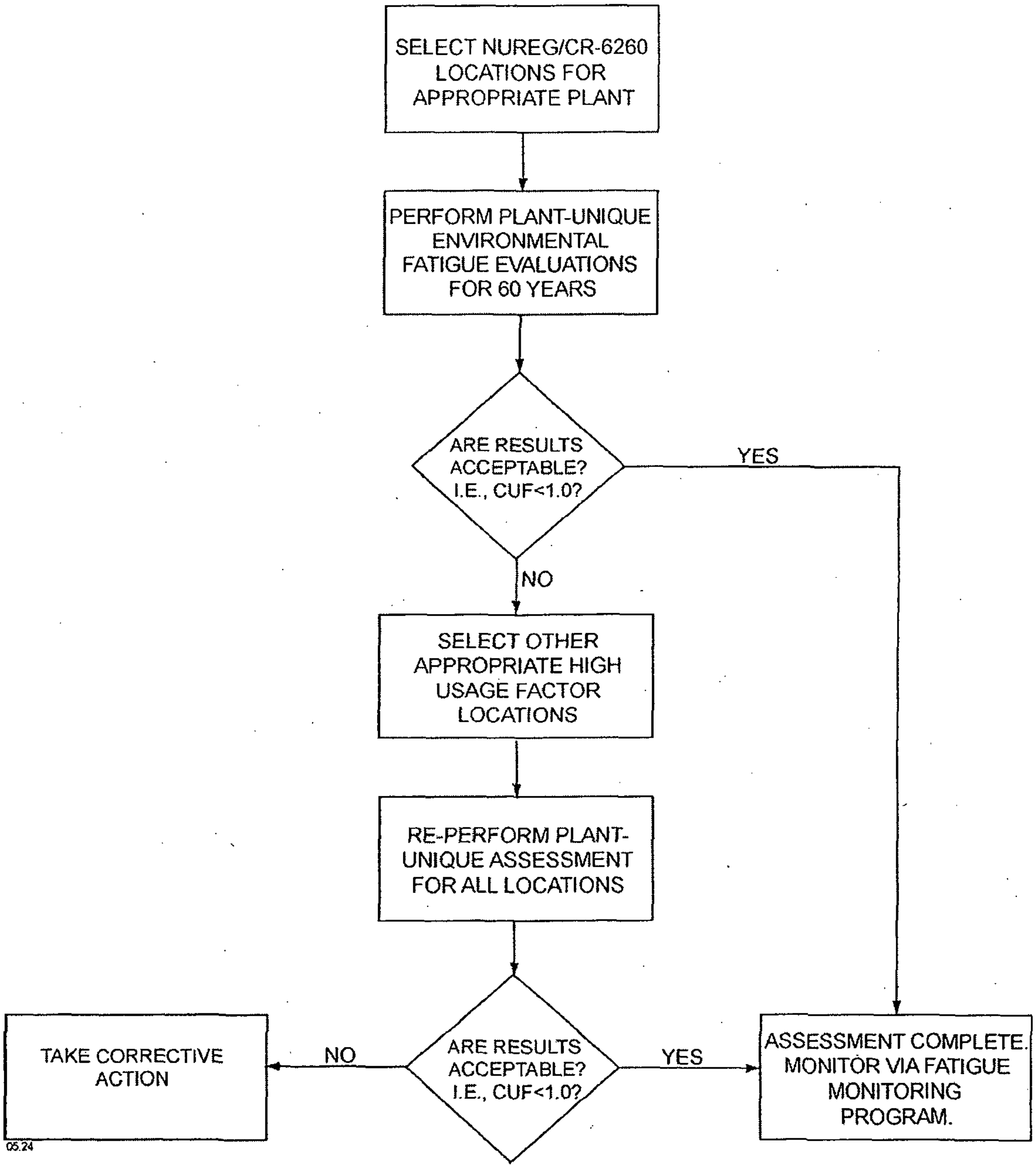


Figure 3-2
Identification of Component Locations and Fatigue Environmental Effects Assessment

3.2.2 Fatigue Assessment Using Environmental Factors

In performing an assessment of environmental fatigue effects, factors to account for environmental effects are incorporated into an updated fatigue evaluation for each selected location using the F_{en} approach documented in NUREG/CR-6583 [3] for carbon and low alloy steels and NUREG/CR-5704 [4] for austenitic stainless steels. Excess conservatism in the loading definitions, number of cycles, and the fatigue analyses may be considered. Figure 3-3 shows the approach for performing the assessment and managing fatigue in the extended operating period.

Determination of Existing Licensing Basis

Existing plant records must be reviewed to determine the cyclic loading specification (transient definition and number of cycles) and stress analysis for the location in question. Review of the analysis may or may not show that excess conservatism exists. Reference [23] provides guidance on reviewing the original design basis, the operating basis, and additions imposed by the regulatory oversight process, to determine the fatigue licensing basis events for which the component is required to be evaluated.

Consideration of Increased Cycles for Extended Period

As a part of the license renewal application process, the applicant must update the projected cycles to account for 60 years of plant operation. The first possible outcome is that the number of expected cycles in the extended operating period will remain at or below those projected for the initial 40-year plant life. In this case, the governing fatigue analyses will not require modification to account for the extended period of operation.

The second possibility is that more cycles are projected to occur for 60 years of plant operation than were postulated for the first 40 years. In this case, an applicant must address the increased cycle counts. One possible solution is to perform a revised fatigue analysis to confirm that the increased number of cycles will still result in a CUF less than or equal to the allowable. A second possibility is to determine the number of cycles at which the CUF would be expected to reach the allowable. This cycle quantity then becomes the allowable against which the actual operation is tracked. Section 3.3 discusses options to be employed if this lower allowable is projected to be exceeded.

Fatigue Assessment

Fatigue assessment includes the determination of CUF considering environmental effects. This may be accomplished conservatively using information from design documentation and bounding F_{en} factors from NUREG/CR-6583 [3] and NUREG/CR-5704 [4], or it may require a more extensive approach (as discussed in Section 4.0).

A revised fatigue analysis may or may not be required. Possible reasons for updating the fatigue analysis could include:

- Excess conservatism in original fatigue analysis with respect to modeling, transient definition, transient grouping and/or use of an early edition of the ASME Code.

- For piping, use of an ASME Code Edition prior to 1979 Summer Addenda, which included the ΔT_1 term in Equation (10) of NB-3650. Use of a later code reduces the need to apply conservative elastic-plastic penalty factors.
- Re-analysis may be needed to determine strain rate time histories possibly not reported in existing component analyses, such that bounding environmental multipliers (i.e., very low or "saturated" strain rates) would not have to be used.

A simplified revised fatigue analysis may be performed using results from the existing fatigue analysis, if sufficient detail is available. Alternatively, a new complete analysis could be conducted to remove additional conservatisms. Such an evaluation would not necessarily need the full pedigree of a certified ASME Code Section III analysis (i.e., Certified Design Specification, etc.), but it should utilize all of the characteristic methods from Section III for computing CUF. In the environmental fatigue assessment, the environmental fatigue usage may be calculated using the following steps:

- For each load set pair in the fatigue analysis, determine an environmental factor F_{en}. This factor should be developed using the equations in NUREG/CR-6583 [3] or NUREG/CR-5704 [4]. (Section 4.0 provides specific guidance on performing an F_{en} evaluation)
- The environmental partial fatigue usage for each load set pair is then determined by multiplying the original partial usage factor by F_{en}. In no case shall the F_{en} be less than 1.0.
- The usage factor is the sum of the partial usage factors calculated with consideration of environmental effects.

<u>Fatigue Management Approach</u>

As shown in Figure 3-3, the primary fatigue management approaches for the extended operating period consist of tracking either the CUF or number of accumulated cycles.

- For cycle counting, an updated allowable number of cycles may be needed if the fatigue assessment determined the CUF to be larger than allowable. One approach is to derive a reduced number of cycles that would limit the CUF to less than or equal to the allowable value (typically 1.0). On the other hand, if the assessed CUF was shown to be less than or equal to the allowable, the allowable number of cycles may remain as assumed in the evaluation, or increased appropriately. As long as the number of cycles in the extended operating period remains within this allowed number of cycles, no further action is required.
- For CUF tracking, one approach would be to utilize fatigue monitoring that accounts for the actual cyclic operating conditions for each location. This approach would track the CUF due to the actual cycle accumulation, and would take credit for the combined effects of all transients. Environmental factors would have to be factored into the monitoring approach or applied to the CUF results of such monitoring. No further action is required as long as the computed usage factor remains less than or equal to the allowable value.

Prior to such time that the CUF is projected to exceed the allowable value, or the number of actual cycles is projected to exceed the allowable number of cycles, action must be taken such that the allowable limits will not be exceeded. If the cyclic or fatigue limits are expected to be exceeded during the license renewal period, further approaches to fatigue management would be required prior to reaching the limit, as described in Section 3.3. Further details on guidelines for thermal fatigue monitoring and compliance/mitigation options are provided in Reference [23].

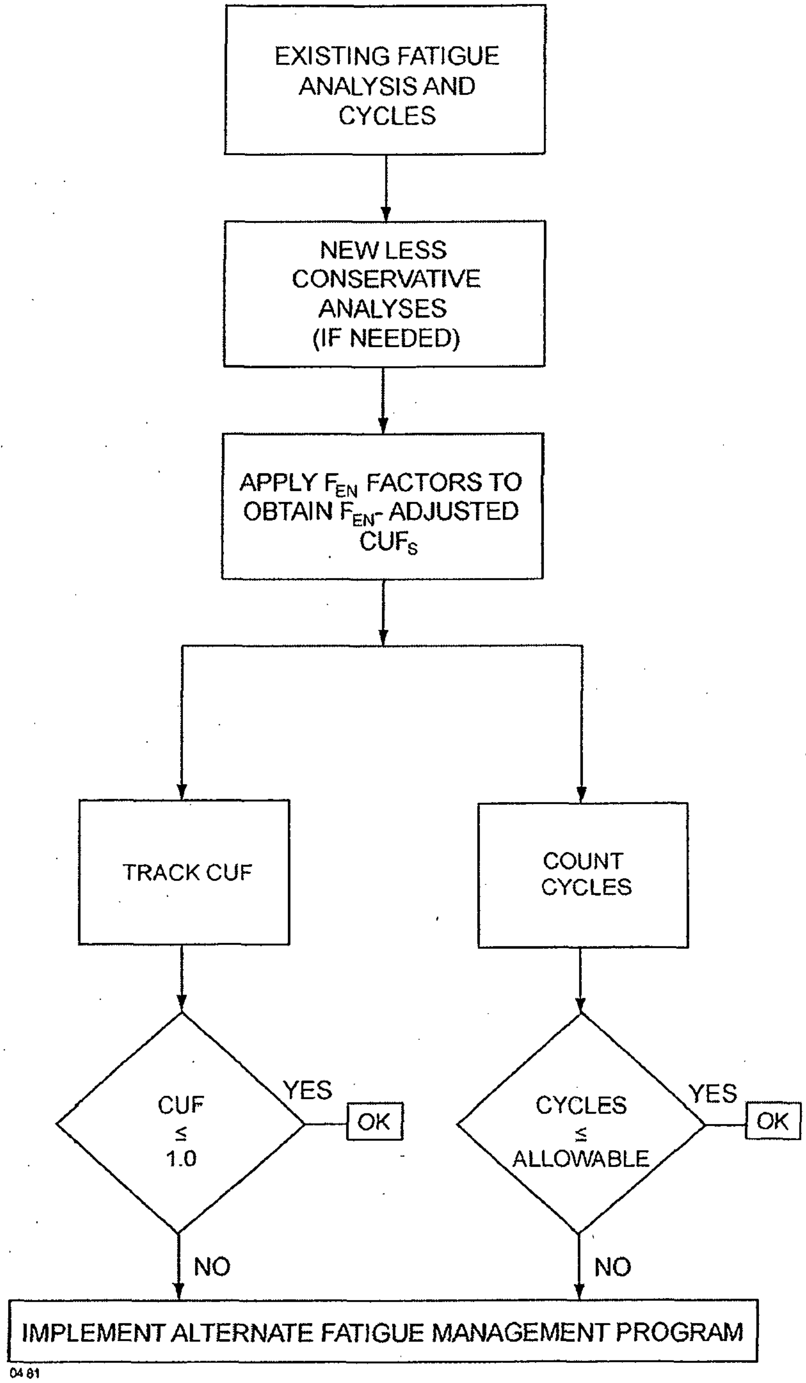


Figure 3-3
Fatigue Management if Environmental Assessment Conducted

3.3 Alternate Fatigue Management in the License Renewal Period

As identified in Section 3.2, and discussed in detail in Reference [23], results from cycle counting or fatigue monitoring may predict that established limits are exceeded during the extended operating period. If this occurs, there are several alternative approaches which may be used to justify continued operation with the affected component in service without having to perform repair or replacement, as follows:

- Reanalysis
- Partial Cycle Counting
- Fatigue Monitoring
- Flaw Tolerance Evaluation and Inspection
- Modified Plant Operations
- Evaluation of Similar Components

In addition, the fatigue management program may need to be expanded if plant-unique or industry experience shows that fatigue limits are exceeded or if cracking is discovered, due to either anticipated or unanticipated transients. Refer to Reference [23] for a comprehensive discussion of these items.

3.4 Guidance for Plants with B31.1 Piping Systems

Many plants that were designed in the 1960s had piping systems that were designed in accordance with the rules of the ANSI B31.1 Power Piping Code. This Code did not require an explicit fatigue analysis. However, the effects of thermal expansion cycles were included. If the number of equivalent full range thermal expansion cycles was greater than 7,000, the allowable range of thermal expansion stress was reduced. There was no consideration of stresses due to through-wall thermal gradients, axial temperature gradients, or bi-metallic welds.

Although ANSI B31.1 and ASME Code, Section III, Class 1 piping rules are fundamentally different, experience in operating plants has shown that piping systems designed to B31.1 are adequate. An evaluation of fatigue-sensitive B31.1 piping systems by EPRI [17] showed that there were only very limited locations in piping systems that exhibited high usage factors. In each case, these locations could be easily identified. It was concluded that high usage factors occurred only at locations that experienced significant thermal transients such as step temperature changes. In addition, the locations with high usage factors were always at a structural or material discontinuity, such as pipe-to-valve or pipe-to-nozzle transition welds. The report also noted that the design features of B31.1 plants are essentially no different than those in more modern plants designed to ASME Code, Section III, Class 1.

The high usage factor locations evaluated in NUREG/CR-6260 [2] were primarily associated with piping system discontinuities and occurred due to severe transients, except for PWR surge lines where a high number of stratification transients contributed to high usage factors.

The operation of B31.1 plants is also not different from that of plants designed to ASME Code, Section III, Class 1. All have limitations on heatup/cooldown rates as required by ASME Code, Sections III and XI, and 10CFR50 Appendix G. The NSSS vendors have also provided continued feedback to plant operators to reduce the thermal fatigue challenges to components based on industry experience. Thus, the approach taken by an applicant with ANSI B31.1 piping systems need not be significantly different than that taken for a more modern plant:

- The locations of NUREG/CR-6260 [2] for the appropriate vintage/vendor plant are selected. For systems without specified design transients, a set of transients for tracking in the extended operating period must be established.
- Evaluations shall be undertaken to establish the usage factors at each of the selected locations. This may be based on similarities in geometry, materials, and transient cycles relative to other similarly designed plants. In addition, the information provided in NUREG/CR-6260 [2] may be used. Alternately, an ASME Code, Section III, Class 1 analysis can be conducted. Such an evaluation would not necessarily need the full pedigree of a certified ASME Code, Section III analysis (i.e., Certified Design Specification, etc.), but it should utilize all of the characteristic methods from Section III for computing CUF. Such an analysis would be used to establish the baseline fatigue usage without environmental effects for the plant.
- Using this information, the approach previously described for the ASME Code, Section III, Class 1 plants can be used to evaluate and manage fatigue environmental effects.

3.5 Consideration of Industry Operating Experience

Consistent with current practice, industry experience with fatigue cracking will continue to be reviewed. The assessment of any fatigue cracking in the extended operating period will consider the effects of environment as a potential contributor. Monitoring of industry experience must consider fatigue cracking for both anticipated and unanticipated transients. An MRP integrated fatigue management guideline is currently under preparation that will consider all aspects of fatigue management, including consideration of industry experience. See Reference [24].

4 GUIDANCE FOR PERFORMING ENVIRONMENTAL FATIGUE EVALUATIONS

This section provides guidance for performing plant specific environmental fatigue evaluations for selected locations. The intent is to unify the process used by applicants to address environmental effects in the License Renewal Application, and provide specific guidance on the use of currently accepted environmental fatigue evaluation methodologies.

There are several methods that have been published to assess the effects of reactor water environment on fatigue for each specific location to be considered. The currently accepted methodologies for evaluating environmental fatigue effects are documented in NUREG/CR-6583 [3] for carbon and low alloy steels and NUREG/CR-5704 [4] for austenitic stainless steels. Although other methods have been developed and published, guidance is only provided for using NUREG/CR-6583 [3] and NUREG/CR-5704 [4]. However, all methods currently published are similar in terms of variables and applicability (i.e., they all use an F_{en} factor approach), so the guidance that follows has general applicability to all methods. For reference, the other published methods, including those currently being used in Japan, are documented in References [18] and [22].

4.1 Environmental Fatigue Factor (F_{en}) Relationships

An environmental correction factor (F_{en}) is defined as the ratio of fatigue usage with environmental effects divided by fatigue usage in air, or allowable cycles to fatigue crack initiation in air divided by allowable cycles with water reactor environmental effects[1]. F_{en} equations are provided in the latest ANL reports for carbon and low alloy steel [3] and stainless steel [4].

From NUREG/CR-5704 [4], the F_{en} relative to room-temperature air for Types 304 and 316 stainless steel is given by the following expression:

$$F_{en} = \exp(0.935 - T^{*}\ \dot{\varepsilon}^{*}\ O^{*})$$

The constants for transformed temperature (T^{*}), transformed strain rate ($\dot{\varepsilon}^{*}$), and transformed dissolved oxygen (O^{*}) in the above expression are defined as follows:

[1] "Fatigue crack initiation" is an investigator determined quantity, often related to a 25% load drop in a load-controlled laboratory fatigue test. This usually corresponds to significant crack depths, typically of the order of 25% of the specimen thickness for the deepest crack.

$T^* = 0$	$(T < 200°C)$
$T^* = 1$	$(T \geq 200°C)$
	T = metal service temperature, °C
$\dot{\varepsilon}^* = 0$	$(\dot{\varepsilon} > 0.4\% /sec)$
$\dot{\varepsilon}^* = \ell n(\dot{\varepsilon}/0.4)$	$(0.0004 \leq \dot{\varepsilon} \leq 0.4\% /sec)$
$\dot{\varepsilon}^* = \ell n(0.0004/0.4)$	$(\dot{\varepsilon} < 0.0004\% /sec)$
	$\dot{\varepsilon}$ = strain rate, %/sec
$O^* = 0.260$	(DO < 0.05 ppm)
$O^* = 0.172$	(DO ≥ 0.05 ppm)
	DO = dissolved oxygen

From NUREG/CR-6583 [3], the environmental correction factors relative to room-temperature air for carbon steel and alloy steel are given by the following expressions[2]:

For carbon steel: $F_{en} = \exp(0.585 - 0.00124\,T - 0.101 S^* T^* O^* \dot{\varepsilon}^*)$

Substituting T = 25°C to yield an F_{en} relative to room temperature air, the above equation becomes:

$$F_{en} = \exp(0.554 - 0.101 S^* T^* O^* \dot{\varepsilon}^*)$$

For low alloy steel: $F_{en} = \exp(0.929 - 0.00124\,T - 0.101 S^* T^* O^* \dot{\varepsilon}^*)$

Substituting T = 25°C to yield an F_{en} relative to room temperature air, the above equation becomes:

$$F_{en} = \exp(0.898 - 0.101 S^* T^* O^* \dot{\varepsilon}^*)$$

The transformed sulfur content (S^*), transformed temperature (T^*), transformed dissolved oxygen (O^*), and transformed strain rate ($\dot{\varepsilon}$*) in the above expressions are defined as follows:

[2] It has been noted that several past license renewal applicants have substituted the maximum operating temperature for T in the second term of the F_{en} expressions (i.e., the " 0.00124 T" term) to represent the metal temperature. Since all ASME Code fatigue applications throughout the industry are based on relating room temperature air data to service temperature data in water, T = 25°C should be used in the F_{en} expressions for the "- 0.00124 T" term, rather than service temperature, as shown above.

$S^* = S$	$(0 < S \leq 0.015$ wt. %)
$S^* = 0.015$	$(S > 0.015$ wt. %)
	S = weight percent sulfur
$T^* = 0$	$(T < 150°C)$
$T^* = T - 150$	$(150 \leq T \leq 350°C)$
	T = metal service temperature, °C
$O^* = 0$	(DO < 0.05 ppm)
$O^* = \ell n\,(DO/0.04)$	(0.05 ppm $\leq$ DO $\leq$ 0.5 ppm)
$O^* = \ell n\,(12.5)$	(DO > 0.5 ppm)
	DO = dissolved oxygen
$\dot{\varepsilon}^* = 0$	$(\dot{\varepsilon} > 1\%/s)$
$\dot{\varepsilon}^* = \ell n\,(\dot{\varepsilon})$	$(0.001 \leq \dot{\varepsilon} \leq 1\%/s)$
$\dot{\varepsilon}^* = \ell n\,(0.001)$	$(\dot{\varepsilon} < 0.001\ \%/s)$
	$\dot{\varepsilon}$ = strain rate, %/sec

4.2 Guidelines for Application of the F_{en} Methodology

This section provides guidelines for performing environmental fatigue evaluations.

As introduced in Section 2.1, F_{en}s are determined and used to adjust the CUF previously determined using the ASME Code air curves. Bounding F_{en} values may be determined or, where necessary, individual F_{en} values are computed for each load pair in a detailed fatigue calculation. The environmental fatigue is then determined as $U_{env} = (U)\times(F_{en})$, where U is the original incremental fatigue usage for each load pair, and U_{env} is the environmentally assisted incremental fatigue usage factor. The total environmental CUF is computed as the sum of all U_{env} values for all load pairs.

Based on industry practice and recommendations available from some of the published F_{en} methods, there are three increasingly refined approaches used to compute the F_{en}s:

- Average strain rate
- Detailed strain rate
- Integrated strain rate

Common to each of these approaches is that the F_{en} is computed for the load pair over the increasing (tensile) portion of the paired stress range only. In other words, the relevant stress range is determined first by assuming that the transient with the maximum compressive stress (or minimum tensile stress) occurs first in time, followed by the transient with the maximum tensile stress. The relevant stress range for F_{en} computation is then from the maximum compressive stress (or minimum tensile stress) to the maximum tensile stress. Further details are given in the discussions that follow.

A separate section follows for each parameter utilized in the F_{en} expressions, that is transformed sulfur content (S^*), transformed temperature (T^*), transformed dissolved oxygen (O^*), and transformed strain rate ($\dot{\varepsilon}^*$). For the transformed strain rate, temperature, and oxygen parameters, the three approaches are discussed. Transformed sulfur does not vary over the three approaches. A single approach should be utilized for all of the transformed parameters in a single load-pair F_{en} determination, although different approaches may be utilized for different load-pair F_{en}s.

First, the typical content of a fatigue calculation is presented.

4.2.1 Contents of a Typical Fatigue Evaluation

This section provides the content of a typical fatigue calculation. Whereas fatigue calculations have varied over the years, their basic content is the same. With the advent of computer technology, the calculations have basically maintained the same content, but computations have become more refined and exhaustive. For example, 30 years ago it was computationally difficult for a stress analyst to evaluate 100 different transients in a fatigue calculation. Therefore, the analyst would have grouped the transients into as few as one transient grouping and performed as few incremental fatigue calculations as possible. With today's computer technology and desire to show more margin, it is relatively easy for the modern-day analyst to evaluate all 100 incremental fatigue calculations for this same problem. Also, older technology would have likely utilized conservative shell interaction hand solutions for computing stress, whereas today finite element techniques are commonly deployed. This improvement in technology would not have changed the basic inputs to the fatigue calculation (i.e., stress), but it would have typically yielded significantly more representative input values.

The discussion here is limited to the general content of most typical fatigue calculations. Discussions of removing excess conservatisms from the input (stress) values of these calculations are not included, as it is assumed that those techniques are generally well understood by engineers performing these assessments throughout the industry.

Two typical fatigue calculations are shown in Figures 4-1 through 4-4. Figure 4-1 reflects an "old" calculation, i.e., one that is typical from a stress report from a plant designed in the 1960s. Figures 4-2 through 4-4 reflect a "new" calculation, i.e., one that is typical from a 1990s vintage stress report. A description of the content of these two calculations is provided below.

The same basic content is readily apparent in both CUF calculations shown in Figures 4-1 through 4-4. However, it is also apparent that much more detail is present in Figures 4-2 through 4-4 for the "new" calculation compared to Figure 4-1 for the "old" calculation. Therefore, with respect to applying F_{en} methodology to a CUF calculation, the guidance provided in the following sections equally applies to both vintages of calculations. The main difference is in assumptions that need to be made for the F_{en} transformed variables due to a lack of detail backing up the calculations in the stress report. Guidance for these assumptions is described in Sections 4.2.2 through 4.2.5, with appropriate reference to the calculations shown in Figures 4-1 through 4-4.

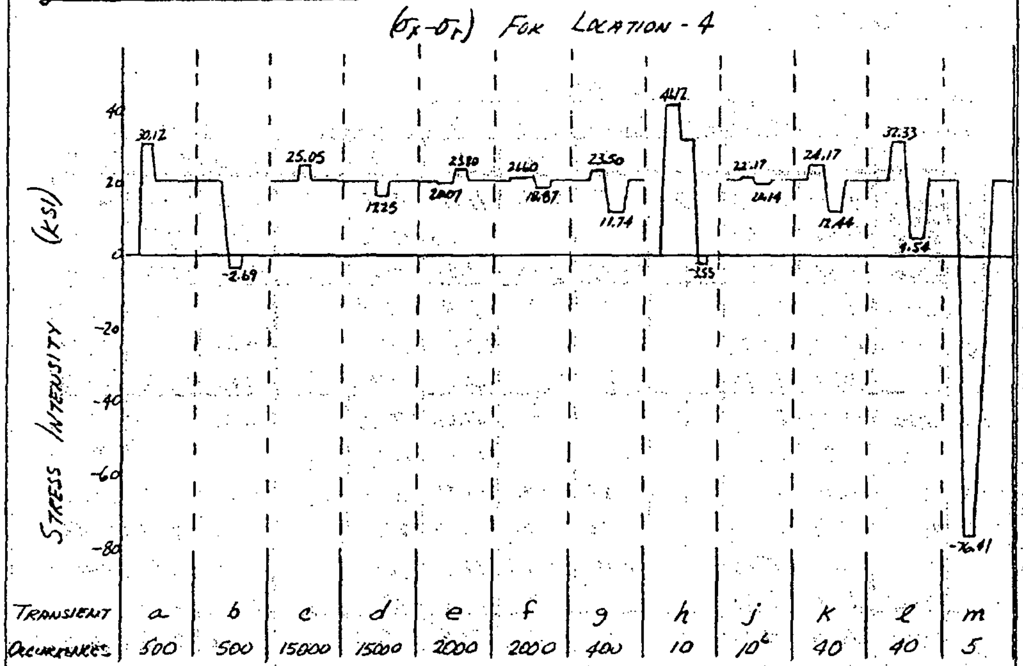
4.2.1.1 "Old" Calculation (Figure 4-1)

The following describes the basic contents of the CUF calculation shown in Figure 4-1. Note that this calculation is an NB-3200-style (vessel) CUF calculation. Reference is made to the heading and the first line in the table shown at the bottom of Figure 4-1.

S_{MAX}	=	maximum stress intensity for transient pair (ksi). For this example, it is seen that it represents the tensile stress for Transient "h" in the stress histogram above the CUF calculation table.
S_{MIN}	=	minimum stress intensity for transient pair (ksi). For this example, it is seen that it represents the compressive stress for Transient "m" in the stress histogram above the CUF calculation table.
S_{ALT}	=	alternating stress intensity (ksi). This is computed as $0.5(S_{MAX} - S_{MIN})$. It is noteworthy that K_e and Young's Modulus corrections are not included in this calculation due to the early ASME Code edition used for the evaluation.
n	=	number of applied cycles for transient pair. For this example, it is seen that this value represents the limiting number of occurrences for the paired transients (i.e., Transients "h" and "m"), which is 5 cycles from the stress histogram above the CUF calculation table. The occurrences of Transient "m" are now exhausted, and 5 cycles of Transient "h" remain for use in the remaining CUF calculation.
N	=	allowable number of cycles from the applicable ASME Code fatigue curve for the material under consideration for S_{ALT}. From the "*" note, ASME Code Figure N-415(a) applies (1960s ASME Code edition).
u	=	incremental CUF for the load pair, computed as n/N.
$U_{OVERALL}$	=	total CUF for this location for the design life of the component, computed as Σu.

5- DETAILED ANALYSIS:

9- FATIGUE EVALUATION:



S_{MAX}	S_{MIN}	S_{ALT}	n	N^*	u
41.12	-76.41	58.76	5	1860	0.00269
41.12	-3.55	22.34	5	40020	0.00013
32.33	-2.69	17.51	40	95650	0.00042
30.12	-2.69	16.41	460	133000	0.00346
25.05	11.74	6.65	400	∞	0

*FROM FIG. N-415(A) OF REFERENCE -1

$U_{OVERALL}$ = 0.0067 ←

Figure 4-1
Example of "Old" Fatigue Calculation

4.2.1.2 "New" Calculation (Figures 4-2 through 4-4)

The following describes the basic contents of the CUF calculation shown in Figure 4-2. Note that this calculation is an NB-3600-style (piping) CUF calculation. References are also made to Figures 4-3 and 4-4 where necessary.

(Note: Near the top of the table shown in Figure 4-2, the maximum load case information is reported, i.e., the two lines beginning with "GELBOW" and "0.512" – the descriptions that follow apply to the information below these lines.)

Load Range	=	paired load cases, as defined in Load Case definitions (see Figure 4-3).
Equation 10 Moment	=	moment (ft-lbf), computed in accordance with Equation (10) of ASME Code, Section III, NB-3600.
Equation 10 Stress	=	stress intensity (psi), computed in accordance with Equation (10) of ASME Code, Section III, NB-3600.
Equation 11 Moment	=	moment (ft-lbf), computed in accordance with Equation (11) of ASME Code, Section III, NB-3600.
Equation 11 Stress	=	stress intensity (psi), computed in accordance with Equation (11) of ASME Code, Section III, NB-3600.
Equation 12 Moment	=	moment (ft-lbf), computed in accordance with Equation (12) of ASME Code, Section III, NB-3600.
Equation 12 Stress	=	stress intensity (psi), computed in accordance with Equation (12) of ASME Code, Section III, NB-3600.
Equation 13 Moment	=	moment (ft-lbf), computed in accordance with Equation (13) of ASME Code, Section III, NB-3600.
Equation 13 Stress	=	stress intensity (psi), computed in accordance with Equation (13) of ASME Code, Section III, NB-3600.
Equation 14 KE	=	elastic-plastic strain concentration factor, K_e, computed in accordance with ASME Code, Section III, NB-3600.
Equation 14 Stress	=	alternating stress intensity (psi), computed in accordance with Equation (14) of ASME Code, Section III, NB-3600.
Cycles Actual	=	number of applied cycles for the transient pair. For this example, the first load pair represents thermal Load Cases 24 and 36, coupled with dynamic Load Case 56 and (E)arthquake. From Figure 4-3, Load Case 24 represents Daily Power Reduction, Load Case 36 represents Vessel Flooding, and Load Case 56 represents OBE/SRV

dynamic loading. From the transient definitions (similar to those shown in Figure 4-4), the number of applied cycles for each load case is obtained. The fatigue analysis uses the limiting number of cycles for all of these loads, which is 10 cycles.

Cycles Allow = allowable number of cycles from the applicable ASME Code fatigue curve for the material under consideration for "Equation 14 Stress".

Usage Factor = incremental CUF for the load pair, computed as "Cycles Actual"/"Cycles Allow".

The total CUF for this location for the design life of the component, computed as Σu, is shown at the top of the table in the summary portion (i.e., 0.6512).

ASME SECTION III CLASS 1 (W78) MEMBER STRESS SUMMARY

UNITS - MIN WALL(IN), MOMENTS(FT-LBF), AND STRESS (PSI)

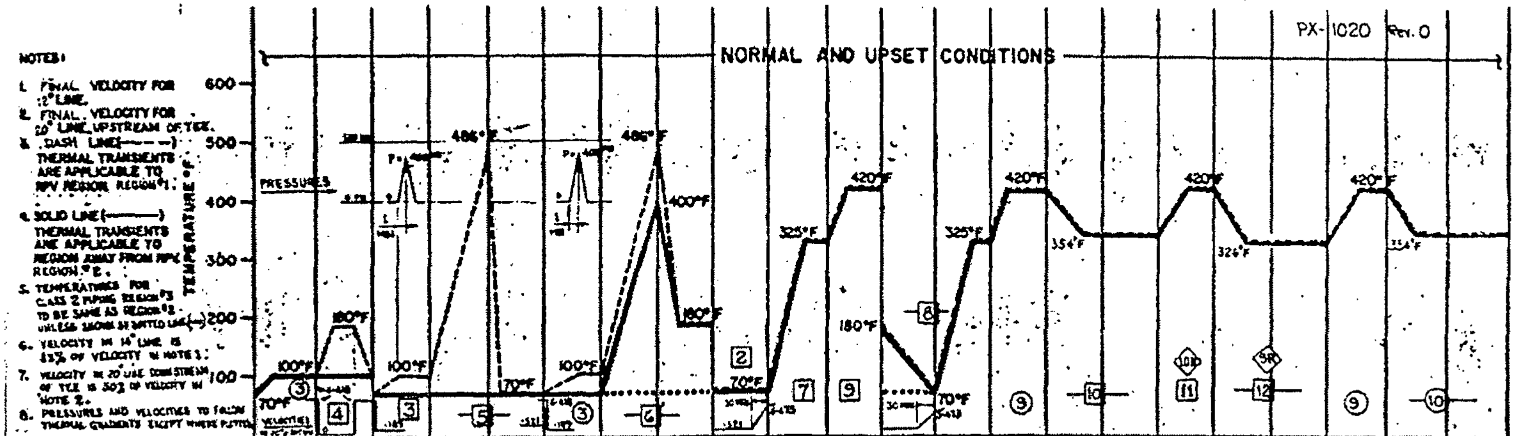
MEMBER/ MIN WALL	END/ EQ.9	LOAD RANGE	EQUATION 10 MOMENT	EQUATION 10 STRESS	EQUATION 11 MOMENT	EQUATION 11 STRESS	EQUATION 12 MOMENT	EQUATION 12 STRESS	EQUATION 13 MOMENT	EQUATION 13 STRESS	EQUATION 14 KE	EQUATION 14 STRESS	CYCLES ACTUAL	CYCLES ALLOW	USAGE FACTOR
GELBOW 0.512	85 18056 (56)	MAXIMUM	143173	77836*	143173	132028	114270	45162	16721	24073	1.62	107166			0.6512
			(E,56,24-36)		(E,56,24-36)			(24-36)	(E,56,35-43)		(E,56,24-36)				
		(E,56,24-36)	143173	77836	143173	132028	114270	45162	16721	21777	1.62	107166	10	494	0.0202
		(E,56,24-27)	142334	75954	142334	130901	113390	45806	16721	18521	1.58	103510	30	542	0.0553
		(E,56,23-24)	137776	74542	137776	127991	108817	43958	16721	19093	1.51	96785	60	650	0.0923
		(56,23-24)	137776	74542	120986	115782	108817	43958	16721	19093	1.28	74319	10	1351	0.0074
		(56,20-24)	137776	72778	120986	112284	108817	43958	16721	19093	1.22	68736	90	1689	0.0533
		(56,30-43)	133983	70332	117164	110055	104930	42389	16721	16077	1.12	61516	1	2335	0.0004
		(56,20-42)	137567	68279	120789	103190	108643	43888	16721	19321	1.07	55353	632	3200	0.1975
		(56,30-44)	133983	66436	117164	105380	104930	42389	16721	12181	1.00	52690	14	3716	0.0038
		(56,15-44)	134892	65752	118061	103094	105894	42778	16721	13323	1.00	51547	15	3974	0.0038
		(56,20-44)	137776	61297	120986	98507	108817	43958	16721	7611	1.00	49254	151	4672	0.0352
		(56,20-41)	122192	62268	105571	93599	93733	37865	16721	17950	1.00	46799	10	5361	0.0019
		(56,20-37)	100145	60316	84455	91572	73932	29866	16721	19093	1.00	45786	1	5743	0.0002
		(56,20-26)	137499	57445	120722	91111	108578	43862	16721	7326	1.00	45555	111	5835	0.0190
		(56,11-20)	137567	55712	120789	88110	108643	43888	16721	6758	1.00	44055	370	6488	0.0570
		(55,11-20)	136226	55171	117210	85508	108643	43888	16721	6755	1.00	42754	72	7139	0.0101
		(55,20-38)	136226	55171	117210	85508	108643	43888	16721	6755	1.00	42754	105	7139	0.0148
		(55,20-40)	107472	57662	88478	84563	79998	32317	16721	17036	1.00	42282	15	7398	0.0020
		(55,20-29)	110898	54134	91830	81742	83254	33632	16721	11324	1.00	40871	15	8254	0.0018
		(55,20-34)	97950	53643	80683	77208	73612	29737	16721	18760	1.00	38604	15	9943	0.0015
		(55,14-20)	112804	51421	93769	75317	85239	34434	16721	12467	1.00	37659	106	10791	0.0098
		(55,33-39)	82511	50218	65317	71849	57520	23236	16721	18750	1.00	35824	15	12743	0.0012
		(55,28-33)	80006	48222	62982	70438	55299	22339	16721	18179	1.00	35219	15	13494	0.0011
		(55,20-32)	82304	47036	66291	68163	60258	24342	16721	18750	1.00	33082	126	16692	0.0075
		(55,25-33)	83526	47061	68483	65820	58760	23737	16721	18179	1.00	32910	111	16992	0.0065
		(55,20-35)	84439	46865	68288	65110	62130	25098	16721	19321	1.00	32665	249	17637	0.0141
		(55,10-31)	73389	44115	57180	60909	51152	20664	16721	18750	1.00	30456	111	22238	0.0050
		(55,12-20)	83180	41690	66876	57581	58845	23771	16721	14751	1.00	28840	486	26985	0.0180
		(55,10-33)	72338	42870	54844	57581	47811	19314	16721	18750	1.00	28780	66	27156	0.0024
		(55,13-20)	79803	34091	63810	48735	57832	23362	16721	8468	1.00	24367	40	50001	0.0008
		(55,10-18)	58920	27787	39612	36710	30996	12521	16721	6755	1.00	18355	307	153886	0.0020
		(55,10-17)	58920	27769	39612	36676	30996	12521	16721	6755	1.00	18338	15	154462	0.0001
		(55,20-22)	59302	27302	40000	34705	31396	12683	16721	8057	1.00	17353	70	195284	0.0004
		(55,20-21)	58022	24124	38710	29175	30104	12161	16721	7177	1.00	14587	2000	424657	0.0047
		(55,19-20)	57005	23559	29713	22466	21094	8521	16721	7006	1.00	11233	4310	999999	0.0000

Figure 4-2
Example of "New" Fatigue Calculation – CUF Calculation

LOAD CASE NUMBER	DESCRIPTION
	Normal/upset condition (Run 004)
1	FT= FLUID TRANSIENT TIME HISTORY (3-PUMP-TRIP)
2	OBEI= OBE INERTIA.....GROUPING BY STD SRSS
3	SSEI= SSE INERTIA.....GROUPING BY STD SRSS
4	SRV (1V,2V,SRVCO2V)..........GROUPING BY STD SRSS
5	SRV (16V,SRVCO16V)..........GROUPING BY STD SRSS
6	COCH= CONDENS.OSCILL & CHUGGING........GROUPING BY STD SRSS
7	PS= POOL SWELL...............GROUPING BY STD SRSS
8	APMSB= ANNULUS PRESSURIZATION M.S.B... GROUPING BY STD SRSS
9	APRCB= ANNULUS PRESSURIZATION R.C.B....GROUPING BY STD SRSS
10	APFWB= ANNULUS PRESSURIZATION F.W.B....GROUPING BY STD SRSS
11	DL= DEADWEIGHT ANALYSIS: TLOAD=3,(P05H - COLDSET LOAD)
12	X-DIR OBE ANCHOR MVMTS
13	Y-DIR OBE ANCHOR MVMTS
14	Z-DIR OBE ANCHOR MVMTS
15	THERM 1= NORMAL OPERATING: (12) PPG @ 420/420/420 F RPV @ 552/528/528
16	THERM 2= TURB ROLL COLD: (4A-1..) PPG @ 70/70/70 F RPV @ 552/552/450
17	THERM 3= BOLT-UP,LEAK TEST: (3A-1..) 70-100
18	THERM 4= HYDROTEST: (2A) 100-180-100
19	THERM 5= START-UP:{UP} (3A-2..) 100-486
20	THERM 6= START-UP:{UP} (3B-2) 100-486
21	THERM 7= TURB ROLL: (4A-2..) 70-325
22	THERM 8= TURB ROLL: (4B-1+2) 180-70-325
23	THERM 9= TURB ROLL: (4A-3..) 325-420
24	THERM 10= DAILY PWR REDCTN : (5-1+2..) 420-354
25	THERM 11= DAILY PWR INCR : (5-3..) 354-420
26	THERM 12= WEEKLY PWR REDCTN : (6-1+2) 420-326
27	THERM 13= FW HTR LOSS: (9-1+2) 420-352
28	THERM 14= FW HTR RESTORTN: (9-3) 352-420
29	THERM 15= SCRAMS: (22-1+2..) 420-275
30	THERM 16= PWR REDUCTN: (13) 420-190
31	THERM 17= HOT STDBY: (14A) 190-70
32	THERM 18= HOT STDBY: (14B-1..) 190-435
33	THERM 19= HOT STDBY: (14B-2) 435-190
34	THERM 20= SHUT-DOWN INITIATN: (15B-1) 435-156
35	THERM 21= SHUT-DOWN INITITN:{UP} (15B-2) 156-395
36	THERM 22= VESSEL FLOODING: (16A-1) 70-157
37	THERM 23= VESSEL FLOODING: (16A-3..) 167-108
38	THERM 24= VESSEL FLOODING: (16A-4..) 108-167
39	THERM 25= VESSEL FLOODING: (16B-1+2) 149-66-152
40	THERM 26= SHUT-DOWN, UNBOLT: (17A..) 167-100

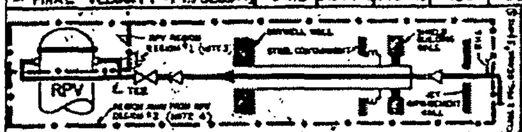
LOAD CASE NUMBER	DESCRIPTION
41	THERM 27= LOSS OF FW PUMP:{UP} (20-1..) 420-573-485
42	THERM 28= PIPE RUPTURE: (27-1+2) 420-259-70
43	THERM 29= START-UP:{DN} (3A-3..) 486-70
44	THERM 30= START-UP:{DN} (3B-3) 486-180
45	THERM 31= SHUT-DOWN INITITN:{DN} (15B-3) 395-149
46	THERM 32= LOSS OF FWP:{DN} (20-13+14) 485-70
47	THERM 33= TMODE 2 WITH P=0 PSI
48	THERM 34= TMODE 15 WITH P=1516 PSI
49	THERM 35= TMODE 15 WITH P=1175 PSI
50	X+Y DIR. OBE ANCHOR MVMTS..........CASES 12+13 BY SRSS
51	OBEA= X+Y+Z EARTHQUAKE ANCHOR MVMTS....CASES 12+13+14 BY SRSS
52	SRV= (SRV MAX).............CASES 4+5 BY MAXIMUM VALUE
53	SRSS(SRV,FT)..............CASES 52+1 BY SRSS
54	SRSS(OBEI,OCCU)= SRSS(OBEI,SRV,FT)...CASES 2+52+1 BY SRSS
55	OBET= ABS(OBEI + OBEA).....CASES 2+51 BY ABS. SUM
56	SRSS(OBET,OCCU)= SRSS(ABS(OBEI+OBEA),SRV,FT)..CASES55+53 BY SRSS
57	SRSS(OBEI,FT)..............CASES 1+2 BY SRSS (FOR 9CN CARD ONLY)
58	FT= FLUID TRANSIENT TIME HISTORY(3 PUMP-TRIP)....(FOR SUMMARY ONLY)
59	OBEI= OBE INERTIA (CASE REPEATED FOR SUMMARY ONLY)
60	SRV(1V,2V,SRVCO2V)..........(CASE REPEATED FOR 9N CARD ONLY)
61	SRV(16V.SRVCO16V).......... (CASE REPEATED FOR 9N CARD ONLY)
	(RUN 007)
1	SETTLE1 = BLDG. SETTLEMENT ... REACTOR BLDG. SETTLES DOWN BY ·66".
2	SETTLE2 = BLDG. SETTLEMENT ... AUX. BLDG. SETTLES DOWN BY ·18".

Figure 4-3
Example of "New" Fatigue Calculation – Load Pair Definitions



EVENT DESCRIPTION	BOLT-UP	DESIGN HYDRO. TEST	START-UP LEAK CHECKS	START-UP RPV HEAT-UP	START-UP RFP FLOW	START-UP [illegible] CHECKS	START-UP RPV-RHCU HEAT-UP	START RFP FLOW
EVENT NUMBER.	1	2A	3A-1	3A-2	3A-3	3B-1	3B-2	3B-3
PRESSURE - PSIG	0	[illegible]	0-400-0	0-600	600-1100	0-400-0	0-600	600-1100
DURATION OF FINAL TEMP. - HR.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	0	INDEF.
NO. OF CYCLES.	123	40	315	105	105	45	15	15
RATE OF TEMP. CHANGE - °F/HR.	≤ 100	≤ 130	≤ 100	≤ 100	-14,560	≤ 100	≤ 100	-16,360 -15,200
TIME - SEC. FOR ΔTEMP.	1080	2880	1080	13,896	60	1080	13,896 [illegible]	60 60
1. FINAL VELOCITY - FT./SEC.	7.38	[illegible]	7.38-.234	.235	.648	7.38-.234	.235	.666
2. FINAL VELOCITY - FT./SEC.	6.418	[illegible]	6.418-.183	.189	.521	6.418-.183	.189	.536

EVENT DESCRIPTION	TURBINE ROLL: INCREASE FWS FLOW	TURBINE ROLL: START-FWS HEATERS	TURBINE ROLL: RAISE FWS FLOW/TEMP	TURBINE ROLL: INCREASE FWS FLOW	TURBINE ROLL: START FWS HTRS	TURBINE ROLL: RAISE FWS FLOW/TEMP	DAILY POWER REDUCTION: DECREASE POWER	DAILY POWER REDUCTION: HOLD PERIOD	DAILY POWER REDUCTION: INCREASE POWER	WEEKLY POWER REDUCTION: DECREASE POWER	WEEKLY POWER REDUCTION: HOLD PERIOD	WEEKLY POWER REDUCTION: INCREASE POWER	ROD PATTERN CHNG.: DECREASE POWER	ROD PATTERN CHNG.: HOLD PERIOD
EVENT NUMBER.	4A-1	4A-2	4A-3	4B-1	4B-2	4B-3	5-1	5-2	5-3	6-1	6-2	6-3	7-1	7-2
PRESSURE - PSIG	1100-1100	1100-1100	1100-1100	1100-1100	1100-1100	1100-1100	1100-1078	1078	1078-1100	1100-1063	1063	1063-1100	1100-1078	1078
DURATION OF FINAL TEMP. - HR.	INDEF.	0.1667	INDEF.	0	0.1667	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.	INDEF.
NO. OF CYCLES.	105	105	105	15	15	15	10,000	10,000	10,000	2000	2000	2000	400	400
RATE OF TEMP. CHANGE - °F/HR.	0	7650	190	-6600	7650	190	-264	0	264	-188	0	188	-264	0
TIME - SEC. FOR ΔTEMP.	—	120	1800	60	120	1800	900	—	900	1800	—	1800	900	—
1. FINAL VELOCITY - FT./SEC.	.666-6.806	7.517	24.342	.666-6.806	7.517	24.342	17.393	17.393	24.342	12.223	12.223	24.342	17.393	17.393
2. FINAL VELOCITY - FT./SEC.	.536-5.473	6.043	19.568	.536-5.473	6.043	19.568	13.362	13.362	19.568	9.143	9.143	19.568	13.362	13.362



REFERENCES:
1. CALCULATION 227.700-001 BY R.J. Mc MORLAND
2. PTP 26-1-15-0 FEED WATER SYSTEM (FSK-6-1/EP17)
TRANSIENT DATA SHEETS ATTACHMENT 'A'.
PICL NO. AP-17 DATED 2-10-84.

☐ Controlling Trans.
◇ Identical cases, temp. comp. reversed.
○ Trans. already considered

PREPARED BY	[illegible]	3-16-84
CHECKED BY	[illegible]	3-4-84
REVIEWED BY	[illegible]	[illegible]
REVIEWED BY	K. B.	[illegible]
APPROVED BY	[illegible]	4-3-84
DATE OF ISSUE		
SHEET 1 OF 5		

THERMAL TRANSIENTS
FEEDWATER SYSTEM (FWS)

STONE & WEBSTER ENGINEERING CORPORATION

12210-SK-TRI7-A-1

Figure 4-4
Example of "New" Fatigue Calculation – Transient Definitions

4.2.2 Transformed Strain Rate, $\dot{\varepsilon}^*$

The transformed strain rate, $\dot{\varepsilon}^*$, is required by both the carbon and low alloy steel F_{en} expressions documented in NUREG/CR-6583 [3], and the stainless steel F_{en} expression documented in NUREG/CR-5704 [4], and is defined as follows:

For carbon/low alloy steels (NUREG/CR-6583 [3]):

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

$$\dot{\varepsilon}^* = \ell n(\dot{\varepsilon}) \qquad (0.001 \le \dot{\varepsilon} \le 1\%/\text{s})$$

$$\dot{\varepsilon}^* = \ell n(0.001) \qquad (\dot{\varepsilon} < 0.001\ \%/\text{s})$$

$\dot{\varepsilon}$ = strain rate, %/sec

For stainless steels (NUREG/CR-5704 [4]):

$$\dot{\varepsilon}^* = 0 \qquad (\dot{\varepsilon} > 0.4\%\ /\text{sec})$$

$$\dot{\varepsilon}^* = \ell n(\dot{\varepsilon}/0.4) \qquad (0.0004 \le \dot{\varepsilon} \le 0.4\%\ /\text{sec})$$

$$\dot{\varepsilon}^* = \ell n(0.0004/0.4) \qquad (\dot{\varepsilon} < 0.0004\%\ /\text{sec})$$

$\dot{\varepsilon}$ = strain rate, %/sec

The above expressions are straightforward to apply if the strain rate, $\dot{\varepsilon}$, is known. This can be relatively straightforward for design transients where definitive ramp rates and temperature differentials are provided. It is much more difficult for actual transients obtained from actual plant data or fatigue monitoring systems. In particular, how two transients that occur separately in time are "linked" together (as shown in Figure 4-9) can have a significant influence on strain rate calculations depending upon the method used.

Section 4.3 discusses other issues associated with calculating the strain rate when applying the F_{en} expressions. Solving those other issues is beyond the scope of this report, so guidance is provided in this section to address only the above three methods of computing strain rate.

Consistent with some of the calculations performed in NUREG/CR-6260 [2], for cases where the magnitudes of the portions of the stress range due to heatup and cooldown are unknown (i.e., only the total stress intensity range is known), or for cases where the stress histories are not available, one-half of the alternating stress intensity may be used to compute strain rate. This is done in the sample problem shown in Section 4.2.7, but it requires that some form of time history information be available for the transient to justify strain rates greater than the slowest saturated strain rate. Parametric studies could also be used to justify time assumptions.

Discussion for each of the three Average, Detailed, and Integrated Strain Rate approaches follows.

Approach #1: Average Strain Rate

The Average Strain Rate approach is simple in that it is based on "connecting the valley with the peak with a straight line and computing the slope." Referring to Figure 4-9, this represents the slope of a line drawn from the lowest stress point of the heatup (maximum compressive) event (i.e., left side of Figure 4-9), to the highest stress point of the cooldown (maximum tensile) event (i.e., right side of Figure 4-9). But, as shown in the area between the two events in Figure 4-9, linking of the two transients is not necessarily straightforward. There are two issues associated with the proper linking of the two events:

- For the maximum compressive stress transient (i.e., left side of Figure 4-9), the return (tensile) side of the transient is important for the strain rate calculation. An estimate of the time until steady state conditions are reached is needed.
- The ending stress for the maximum compressive stress transient (i.e., left side of Figure 4-9) may be different than the beginning stress for the maximum tensile stress transient (i.e., right side of Figure 4-9). This difference causes a discontinuity in the linking process.

The following guidance is provided for each of the above issues:

- For steady state conditions associated with the return (tensile) side of the maximum compressive stress transient, the time for the stress to reach at least 90% of the steady state stress value can be used. This involves a steady state stress solution that includes a time-based solution, which is readily available in most stress analyses, and is readily achievable with the use of all modern-day stress programs.
- For stress discontinuities that exist between the ending stress for the maximum compressive stress transient and the beginning stress for the maximum tensile stress transient, the transients can be linked with a vertical line between the two stress points (i.e., no elapsed time).

Under the above assumptions, the Average Strain Rate is computed as:

$$\dot{\varepsilon} = 100\Delta\sigma/(\Delta t E)$$

where: $\dot{\varepsilon}$ = average strain rate, %/sec

$\Delta\sigma$ = total stress intensity range

= stress difference between the highest stress point of the maximum tensile stress event (i.e., right side of Figure 4-9) and the lowest stress point of the maximum compressive stress event (i.e., left side of Figure 4-9), psi

Δt = time between peak and valley, sec

= time lapse from the event start to the algebraic highest stress point of the maximum tensile stress event (i.e., right side of Figure 4-9) plus the time lapse from the algebraic lowest stress point of the maximum compressive stress event (i.e., left side of Figure 4-9), to the time for the stress to reach at least 90% of the steady state stress value, sec.

E = Young's Modulus, psi, normally taken from the governing fatigue curve used for the fatigue evaluation.

Approach #2: Detailed Strain Rate

The Detailed Strain Rate approach is similar to the average approach discussed above, except that a weighted strain rate is obtained based on strain-based integration over the increasing (tensile) portion of the paired stress range. Referring to Figure 4-9, this represents the integrated slope of strain response from the algebraic lowest stress point of the maximum compressive stress event to the algebraic highest stress point of the maximum tensile stress event, weighted by strain. Similar to the average approach discussed above, linking of the two transients in not necessarily straightforward. However, the two issues associated with the proper linking of the two events that are identified above are less pronounced because of the integration process. Nevertheless, aspects of these issues remain, so the following guidance is provided for each of those issues:

- For steady state conditions associated with the return (tensile) side of the maximum compressive stress transient, the time for the stress to reach at least 90% of the steady state stress value can be used. This involves a steady state stress solution, which is readily available in most stress analyses, and is readily achievable with the use of all modern-day stress programs.
- For stress discontinuities that exist between the ending stress for the maximum compressive stress transient and the beginning stress for the maximum tensile stress transient, the discontinuity can be ignored.

Under the above assumptions and referring to Figure 4-5, the Detailed Strain Rate is computed as:

$$\dot{\varepsilon} = \frac{100 \sum \Delta\varepsilon_i \dfrac{\Delta\varepsilon_i}{\Delta t}}{\sum \Delta\varepsilon_i}$$

where: $\dot{\varepsilon}$ = detailed strain rate, %/sec

$\Delta\varepsilon_i$ = change in strain at Point i, in/in

= $(\sigma_i - \sigma_{i-1})/E$

σ_i = stress intensity at Point i, psi

σ_{i-1} = stress intensity at Point i-1, psi

Δt = change in time at Point i, sec

= $t_i - t_{i-1}$

E = Young's Modulus, psi, normally taken from the governing fatigue curve used for the fatigue evaluation.

The summation is over the range from Point (3) to (4) and the range from Point (1) to (2). In the figure, Points (1) and (4) are assumed coincident. Point (4) is actually taken as the point where the stress returns to at least 90% of the steady state stress value. The strain discontinuity between this point and Point (1) is accounted for by omitting this increment from the total strain range in the denominator.

If two tensile transients are being ranged, the summation ranges from the algebraic minimum of the two Point (1)s to the algebraic maximum of the two Point (2)s. If two compressive transients are being ranged, the summation ranges from the algebraic minimum of the two Point (3)s to the algebraic maximum of the two Point (4)s. If a tensile transient is being ranged with itself (its 'zero' state), the summation ranges from Point (1) to Point (2). If a compressive transient is being ranged with itself (its 'zero' state), the summation ranges from Point (3) to Point (4) with Point (4) again taken where the stress returns to at least 90% of the steady state stress value.

<u>Approach #3: Integrated Strain Rate</u>

The Integrated Strain Rate approach is similar to the detailed approach discussed above, except that an F_{en} factor is computed at multiple points over the increasing (tensile) portion of the paired strain range, and an overall F_{en} is integrated over the entire tensile portion of the strain range (i.e., from the algebraic lowest stress point of the maximum compressive stress event to the algebraic highest stress point of the maximum tensile stress event in Figure 4-9). Thus, this process is more specifically an "integrated F_{en} approach", where strain rate is computed as a part of the process. Similar to the two approaches discussed above, linking of the two transients remains an issue with this method. However, similar to the detailed approach, the two issues associated with the proper linking of the two events are less pronounced because of the integration process. The following guidance is provided for each of those issues:

- For steady state conditions associated with the return (tensile) side of the maximum compressive stress transient, the time for the stress to reach at least 90% of the steady state stress value can be used. This involves a steady state stress solution, which is readily available in most stress analyses, and is readily achievable with the use of all modern-day stress programs.
- For stress discontinuities that exist between the ending stress for the maximum compressive stress transient and the beginning stress for the maximum tensile stress transient, the discontinuity can be ignored.

Under the above assumptions and referring to Figure 4-5, the Integrated Strain Rate F_{en} is computed as:

$$F_{en} = \frac{\sum F_{en,i} \Delta\varepsilon_i}{\sum \Delta\varepsilon_i}$$

where: $F_{en,i}$ = F_{en} computed at Point i, based on $\dot{\varepsilon}_i = 100\Delta\varepsilon_i/\Delta t$ and transformed parameters (T^*) and (O^*) computed using the respective Integrated Strain Rate approaches for each, discussed below.

$\Delta\varepsilon_i$ = change in strain at Point i, in/in

= $(\sigma_i - \sigma_{i-1})/E$

σ_i	=	stress intensity at Point i, psi
σ_{i-1}	=	stress intensity at Point i-1, psi
Δt	=	change in time at Point i, sec
	=	$t_i - t_{i-1}$
E	=	Young's Modulus, psi, normally taken from the governing fatigue curve used for the fatigue evaluation.

The summation is over the range from Point (3) to (4) and the range from Point (1) to (2). In the figure, Points (1) and (4) are assumed coincident. Point (4) is actually taken as the point where the stress returns to at least 90% of the steady state stress value. The strain discontinuity between this point and Point (1) is accounted for by omitting this increment from the total strain range in the denominator.

If two tensile transients are being ranged, the summation ranges from the algebraic minimum of the two Point (1)s to the algebraic maximum of the two Point (2)s. If two compressive transients are being ranged, the summation ranges from the algebraic minimum of the two Point (3)s to the algebraic maximum of the two Point (4)s. If a tensile transient is being ranged with itself (its 'zero' state), the summation ranges from Point (1) to Point (2). If a compressive transient is being ranged with itself (its 'zero' state), the summation ranges from Point (3) to Point (4) with Point (4) again taken where the stress returns to at least 90% of the steady state stress value.

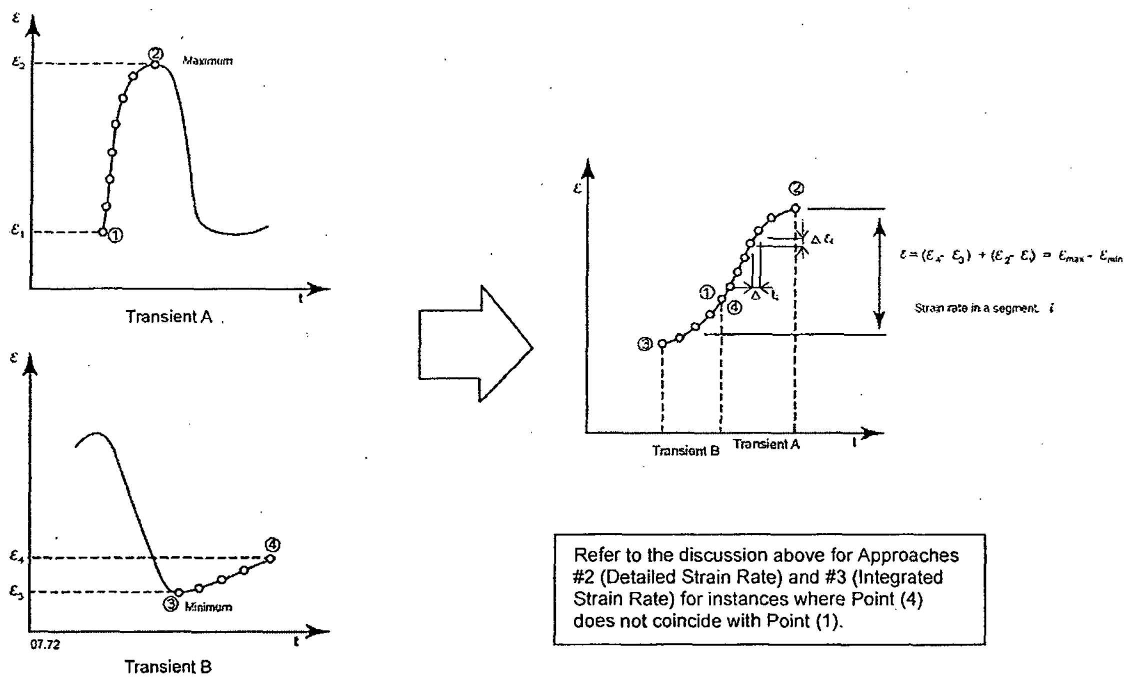


Figure 4-5
Detailed and Integrated Strain Rate Calculation

4.2.3 Transformed Sulfur Content, S*

The transformed sulfur content, S*, is required only by the carbon and low alloy steel F_{en} expressions documented in NUREG/CR-6583 [3], and is defined as follows:

$S^* = S$	$(0 < S \leq 0.015$ wt. %)
$S^* = 0.015$	$(S > 0.015$ wt. %)
	S = weight percent sulfur

There are no ambiguities associated with computing S*, as it is a function of the material sulfur content for the location under consideration. Normally, sulfur content would be obtained from Certified Material Test Reports (CMTRs) that are usually readily available. However, due to the secondary effect of this variable in the F_{en} expressions, most analyses to-date have assumed high sulfur content (i.e., S* = 0.015) for simplicity.

4.2.4 Transformed Temperature, T*

The transformed temperature, T*, is required by both the carbon and low alloy steel F_{en} expressions documented in NUREG/CR-6583 [3], and the stainless steel F_{en} expression documented in NUREG/CR-5704 [4], and is defined as follows:

For carbon/low alloy steels (NUREG/CR-6583 [3]):

$T^* = 0$	$(T < 150°C)$
$T^* = T - 150$	$(150 \leq T \leq 350°C)$
	T = metal service temperature, °C

For stainless steels (NUREG/CR-5704 [4]):

$T^* = 0$	$(T < 200°C)$
$T^* = 1$	$(T \geq. 200°C)$
	T = metal service temperature, °C

The above expressions are straightforward to apply if the metal service temperature, T, is known.

As discussed in Section 4.3, there are other issues associated with temperature when applying the F_{en} expressions. Generally, the issue is, "what temperature should be used for the general transient pairing shown in Figure 4-9?" The answer to this question is dependent upon the refinement on the evaluation used to compute the F_{en} factor. As discussed above at the start of Section 4.2, there are three increasingly refined approaches used to compute the F_{en} factor: Average, Detailed, and Integrated Strain Rate.

The following recommendations are made for determining the temperature, T, for each of the above three approaches:

Approach #1: F_{en} Factor Calculated Based on Average Strain Rate Calculation

For this approach, a constant temperature that is the maximum of the fluid temperatures of both paired transients over the time period of increasing tensile stress should be used. Referring to Figure 4-9, this would include the maximum temperature that occurs during any of the following time periods:

- For the maximum compressive stress transient (i.e., left side of Figure 4-9), beginning at the time of algebraic minimum stress until the end of the transient.
- For the maximum tensile stress transient (i.e., right side of Figure 4-9), beginning at the start of the transient until the time of algebraic maximum stress.

Fluid temperature is an acceptable substitute for the above specified metal temperature in that fluid temperature is more readily available in CUF calculations, as it is a required input with respect to transient definitions. This is true for both older-vintage and modern-day evaluations. Since the maximum fluid temperature envelopes any metal temperature, this is conservative.

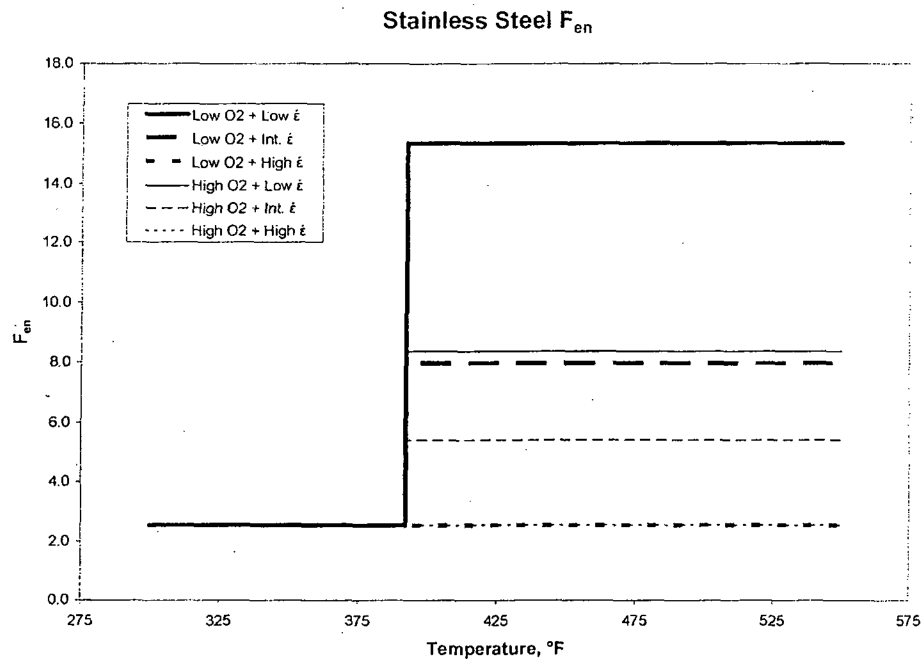
Approach #2: F_{en} Factor Calculated Based on Detailed Strain Rate

For this approach, the maximum fluid temperature of both paired transients over the time period of increasing tensile stress should be used (i.e., same as Approach #1 above).

Approach #3: F_{en} Factor Calculated Based on Integrated Strain Rate

For this approach, F_{en} is computed in an integrated fashion at multiple points between the transient pair stress valley and peak. For this case, the maximum metal temperature of both local time points considered over the period of increasing tensile stress should be used. Referring to Figure 4-5, this represents the maximum of Points i and i-1, or T = MAXIMUM(T_i, T_{i-1}). Metal temperature is more appropriate and avoids potential excess conservatism that would result from using fluid temperature in a heating event and inappropriate omission of effects in a cooling event.

For all three approaches described above, a conservative, simplified, and bounding evaluation would be to use the maximum operating temperature for the component location being evaluated. Note that it is not obvious that the use of maximum temperature in the F_{en} expressions is bounding (due to subtraction of the temperature terms), but routine application of the expressions has demonstrated that the use of the maximum temperature is bounding in all of the F_{en} expressions. This is also shown in Figure 4-6, which shows F_{en} values as a function of temperature.



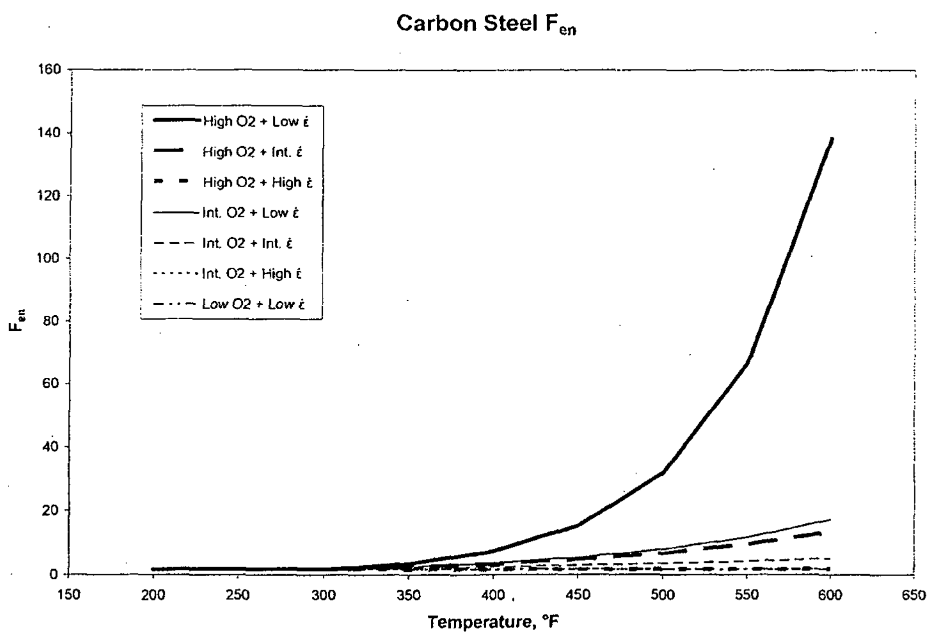


Figure 4-6
F_{en} Values as a Function of Temperature

4.2.5 Transformed Dissolved Oxygen, O*

The transformed oxygen, O*, is required by both the carbon and low alloy steel F_{en} expressions documented in NUREG/CR-6583 [3], and the stainless steel F_{en} expression documented in NUREG/CR-5704 [4], and is defined as follows:

For carbon/low alloy steels (NUREG/CR-6583 [3]):

$O^* = 0$	(DO < 0.05 ppm)
$O^* = \ell n\,(DO/0.04)$	(0.05 ppm $\leq$ DO $\leq$ 0.5 ppm)
$O^* = \ell n\,(12.5)$	(DO > 0.5 ppm)
	DO = dissolved oxygen

For stainless steels (NUREG/CR-5704 [4]):

$O^* = 0.260$	(DO < 0.05 ppm)
$O^* = 0.172$	(DO $\geq$ 0.05 ppm)
	DO = dissolved oxygen

The above expressions are straightforward to apply if the dissolved oxygen level, DO, is known. Although DO measurements are normally available through routine chemistry measurements, they are typically very limited with respect to frequency of collection and locations collected in the reactor coolant system (RCS). Therefore, there are several difficulties associated with determining the DO that is appropriate for use in the F_{en} expressions:

- The DO level is not known at the component location being evaluated. For example, it is the DO directly at the surface of the component that is required, e.g., for a BWR component exposed to saturated steam, the (much lower) DO in the condensate film is really what is applicable to an environmental fatigue analysis, not the much higher DO content of the steam itself.
- The DO level is not known at all times during a transient (i.e., perhaps DO data is only collected once per day as opposed to continuously during a transient).

As discussed in Section 4.3, there are other issues associated with DO when applying the F_{en} expressions. Solving those other issues is beyond the scope of this report, so guidance is provided in this section to address only the above two issues and answering the question, "what DO level should be used for the general transient pairing shown in Figure 4-9?" As with T*, the answer to this question is dependent upon the refinement on the evaluation used to compute the F_{en} factor. Section 4.2 contains the definitions and details for each of these three approaches. The following recommendations are made for determining the dissolved oxygen, DO, for each of the three approaches:

Approach #1: F_{en} Factor Calculated Based on Average Strain Rate Calculation

For this approach, the maximum DO level (for carbon and low alloy steels), or the minimum DO level (for stainless steels) of both paired transients over the time period of increasing tensile stress should be used. Referring to Figure 4-9, this would include the maximum (or minimum) DO level that occurs during any of the following time periods:

- For the maximum compressive stress transient (i.e., left side of Figure 4-9), beginning at the time of algebraic minimum stress until the end of the transient.
- For the maximum tensile stress transient (i.e., right side of Figure 4-9), beginning at the start of the transient until the time of algebraic maximum stress.

Approach #2: F_{en} Factor Calculated Based on Detailed Strain Rate

For this approach, the maximum DO level (for carbon and low alloy steels), or the minimum DO level (for stainless steels) of both paired transients over the time period of increasing tensile stress should be used (i.e., same as Approach #1 above).

Approach #3: F_{en} Factor Calculated Based on Integrated Strain Rate

For this approach, F_{en} is computed in an integrated fashion at multiple points between the transient pair stress valley and peak. For this case, the maximum DO level (for carbon and low alloy steels), or the minimum DO level (for stainless steels) of both local points considered over the time period of increasing tensile stress should be used. Referring to Figure 4-5, this represents the maximum of Points i and i-1 ($DO = MAXIMUM[DO_i, DO_{i-1}]$) for carbon and low alloy steels, or the minimum of Points i and i-1 ($DO = MINIMUM[DO_i, DO_{i-1}]$) for stainless steels.

For all three approaches described above, the following guidance is provided for establishing the DO level:

- In rare cases, DO level measurements are available at or near the component location being evaluated via plant instrumentation. For this case, the plant data is used directly for DO.
- In the majority of cases, DO level measurements are available at periodic intervals during plant operation. These measurements are routinely made remotely from the component location of interest. In some cases, the remote reading may be valid for application at the component location. For these cases, "typical" values can normally be determined based on consultation with the plant chemistry personnel. The typical values should be used with a brief write-up describing the basis for the values. Consideration should be given for variations in the DO level, i.e., consideration of bounding values, as described below, should be factored into the estimates.
- For cases where DO levels have changed over the course of plant operation (i.e., implementation of HWC after plant startup), a time-based average DO level is recommended, based on expected DO levels, as follows:

$$DO = \frac{DO_1\,Time_1 + DO_2\,Time_2 + DO_3\,Time_3 + ...}{Time_1 + Time_2 + Time_3 + ...}$$

where:

	DO	=	time-averaged DO level
	DO_1	=	average DO level for time period $Time_1$
	$Time_1$	=	time period #1 where DO level was relatively constant
	DO_2	=	average DO level for time period $Time_2$
	$Time_2$	=	time period #2 where DO level was relatively constant
	DO_3	=	average DO level for time period $Time_3$
	$Time_3$	=	time period #3 where DO level was relatively constant
	etc.		

Thus, for a case where a BWR operated 20 years under NWC (typical DO = 200 ppb), 10 years with 50% HWC availability (typical DO = 5 ppb), and is projected to complete operation to 60 years with 95% HWC availability, the following DO level is calculated:

$$DO = \frac{(200x20) + (200x0.5x10) + (5x0.5x10) + (5x30)}{(20+10+30)} = 86.25 \text{ ppb}$$

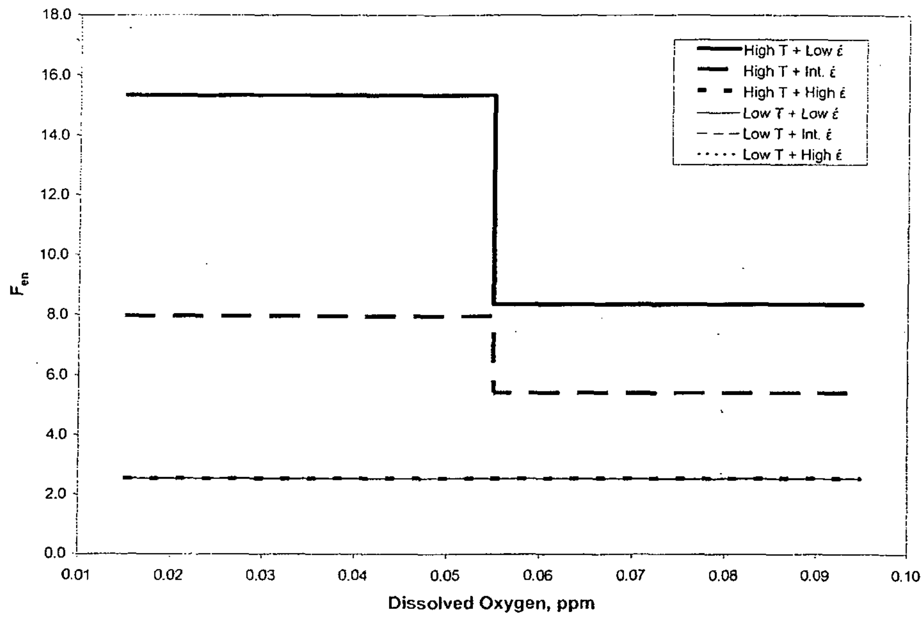
Alternatively, F_{en} factors could be computed for each time period and an overall F_{en} factor calculated based on the weighted average, as follows:

$$F_{en} = \frac{F_{en,200\,ppb} \times 20 + F_{en,200\,ppb} \times 0.5 \times 10 + F_{en,5\,ppb} \times 0.5 \times 10 + F_{en,5\,ppb} \times 30}{(20+10+30)}$$

Another alternative method involves assigning a DO value to each logged transient according to the date it occurred. This is more involved than the above in that the range pair table would need to be apportioned into subsets over the past and future history of the unit and the incremental U-s re-calculated. An approximation of this would be to do a simple apportioning of the range pair U-s according to an assumed linear distribution of the occurrences, n, over the past and future historical DO values.

Similar to that described for T*, a simplified, conservative and bounding evaluation would be to use the maximum DO level (for carbon and low alloy steels), or the minimum DO level (for stainless steels) for the component location being evaluated. Note that it is not obvious that the use of these maximum or minimum DO levels in the F_{en} expressions is bounding (due to subtraction of the oxygen terms), but routine application of the expressions has demonstrated that the use of the maximum DO level is bounding in all of the F_{en} expressions for carbon and low alloy steels, and the minimum DO level is bounding in all of the F_{en} expressions for stainless steels. This is also shown in Figure 4-7 which shows F_{en} values as a function of DO level.

Stainless Steel F_{en}



Carbon Steel F_{en}

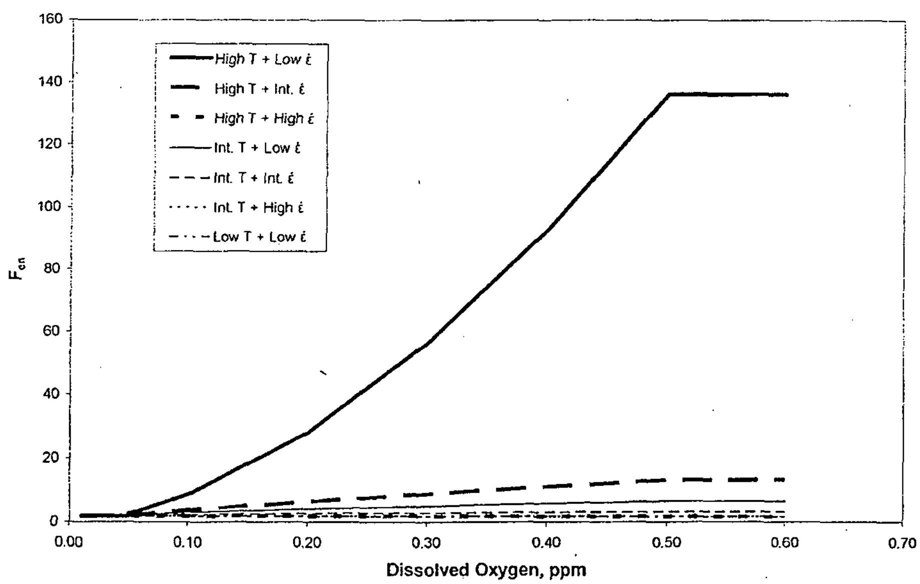


Figure 4-7
F_{en} Values as a Function of DO Level

4.2.6 Additional Considerations

The following additional considerations are provided for the above guidance:

- Dynamic Loading: For load pairs in a CUF calculation that are based on seismic or other dynamic loading, F_{en} = 1.0 for the dynamic portion of the strain for the load pair in question. This is based on the premise that the cycling due to dynamic loading occurs too quickly for environmental effects to be significant. The remaining portion of the strain range should be treated the same as discussed elsewhere in this guideline.
- Thermal Stratification Loading: For load pairs in a CUF calculation that are based solely on thermal stratification loading, the strain rate can generally be taken as the minimum strain rate that produces the maximum environmental effect. Alternatively, the strain rate effects can be determined as for any other cycle pair.
- Pressure and Moment Loading: The stresses for all load pairs in a CUF calculation typically contain stresses due to pressure and moment loading (i.e., non-thermal loads). All of the laboratory testing that forms the basis for the F_{en} expressions was conducted with alternating strain as a result of mechanical loadings, which would be analogous to pressure and moment loadings. Thus, the F_{en}s, as determined herein, should be applied to the strain ranges for cyclic pressure and moment the same as for rapid thermal effects. The effects should be considered appropriately in the Detailed and Integrated Strain Rate approaches if the available stress histories account for different rates of strain for cyclic pressure and moment strains.
- K_e: The stresses for some load pairs in a CUF calculation can contain the effect of K_e. The K_e factor causes a higher strain, thus increasing the strain rate that would be computed for affected load pair, which in turn lowers the F_{en} factor. The strain rate should instead be based on a stress history for the load pair with K_e effects removed.

4.2.7 Sample Calculation

As a demonstration of the guidance provided in Sections 4.2.2 through 4.2.5, a sample problem is provided here based on the "old" fatigue calculation shown in Figure 4-1. The completed environmental fatigue calculation is shown in Figure 4-8.

In the upper portion of Figure 4-8, the original design CUF calculation is reproduced, yielding a total CUF of 0.0067. The only additional information in this step is the total stress intensity range, SR, is computed (= Smax – Smin).

Then, environmental fatigue effects are evaluated using two approaches. Each of these approaches is described below.

Case #1: Bounding F_{en} Multiplier

For this case, since the design CUF is so low, a conservative (but very simple) approach is taken. The maximum possible F_{en} multiplier is determined and applied to the CUF result. Using the rules for low alloy steel documented in Section 4.1, the maximum F_{en} multiplier is computed as 2.45. The environmental fatigue usage factor, U_{env}, is then computed as CUF x F_{en} = 0.0164.

Case #2: Compute F_{en} Multipliers For Each Load Pair

For this case, a more refined approach is taken compared to the first approach. F_{en} multipliers are computed for each load pair. Using the rules for low alloy steel documented in Section 4.1, the overall F_{en} multiplier is also 2.45 for this approach, since the F_{en} does not vary with temperature due to the low DO. The environmental fatigue usage factor, U_{env}, for this case is also computed as 0.0164.

The following descriptions are provided for the calculations for Load Pair #1:

Salt	=	alternating stress intensity from design CUF calculation, psi
t	=	time for tensile portion of stress range in load pair, sec. Obtained from stress report from the tensile portions of both transients = 3 seconds.
Strain Rate	=	computed using the Average Strain Rate approach as 100(Salt/2)/(Et) = 100(58.77/2)/(30,000x3) = 0.03265%/sec
MAX T	=	maximum fluid temperature for tensile portion of stress range, °F. Obtained from stress report from the tensile portions of both transients = 550°F.
T*	=	T-150 since T > 150°C (550°F = 287.8°C) = 287.8 – 150 = 137.8
O*	=	0 since DO < 0.05 ppm (5 ppb = 0.005 ppm)
ε-dot*	=	ln(Strain Rate) since 0.001 ≤ Strain Rate ≤ 1%/sec = ln(0.03265) = -3.422
F_{en}	=	exp(0.898 – 0.101S*T*O*e-dot*
	=	exp(0.898 – 0.101x0.015x137.8x0x-3.422)
	=	exp(0.898)
	=	2.45

Design Basis CUF: 0.0067
Reference: Design Basis CUF Calculation Shown in Figure 4-2
Material: SA-336 (Low alloy steel)
Young's Modulus, E = 3.00E+07 psi
DO Level = 5 ppb (always)
Transformed sulfur content, S* = 0.015 (assume maximum)

Smax	Smin	SR	Salt	n	N	U
41.12	-76.41	117.53	58.77	5	1,860	0.0027
41.12	-3.55	44.67	22.34	5	40,020	0.0001
32.33	-2.69	35.02	17.51	40	95,650	0.0004
30.12	-2.69	32.81	16.41	460	133,000	0.0035
25.05	11.74	13.31	6.66	400	>1e6	0.0000
					Total CUF =	**0.0067**

Note: Above stress are in ksi. (Design CUF is reproduced!)

Approach #1: Use a Bounding F_{en} Multiplier:

Low Alloy Steel: $F_{en} = \exp(0.898 - 0.101S^*T^*O^*\varepsilon^*)$ *Reference: NUREG/CR-6583*

For a DO = 5 ppb = 0.005 ppm, $O^* = 0$.
Therefore, F_{en} is constant vs. T = exp(0.898) = 2.45:

Maximum F_{en} = **2.45**
U_{env} = CUF*F_{en} = **0.0164** (< 1.0 so acceptable!)

Approach #2: Compute F_{en} Multipliers for Each Load Pair:

Salt	t (sec)	Strain Rate (%/sec)	MAX T (°F)	T*	O*	ε-dot*	F_{en}	n	N	U*F_{en}
58.77	3	3.26E-02	550	137.8	0.00	-3.422	2.45	5	1,860	0.0066
22.34	15	2.48E-03	450	82.2	0.00	-5.999	2.45	5	40,020	0.0003
17.51	100	2.92E-04	325	12.8	0.00	-6.908	2.45	40	95,650	0.0010
16.41	1000	2.73E-05	250	0.0	0.00	-6.908	2.45	460	133,000	0.0085
6.66	300	3.70E-05	150	0.0	0.00	-6.908	2.45	400	>1e6	0.0000
									Total = U_{env} =	**0.0164**
									Overall F_{en} = U_{env}/CUF =	**2.45**

Note: Above stress are in ksi. (< 1.0 so acceptable!)

Figure 4-8
Sample Environmental Fatigue Calculation

4.3 Issues Associated With F_{en} Methodology

As a result of industry application of the F_{en} relationships summarized in Section 4.1, there have been several issues identified associated with practical application of the methodology to typical industry fatigue evaluation problems. These issues have led to application of a variety of different solutions applied by analysts depending upon the analyst or the level of detail available in the existing fatigue evaluations. This varied approach has led to non-consistent application of the F_{en} approach between plants, and some amount of confusion amongst the industry.

This guideline document is formulated based on the current "state of the art" with respect to the F_{en} methodology. In many respects, the current state of the technology with respect to the F_{en} methodology is incomplete or lacking in detail and specificity. Recommendations are made in this guideline where needed to fill in these missing details. Further work should focus on the issues associated with areas where the technology is lacking. Some of the issue areas that are associated with the F_{en} methodology are summarized below ("☑" indicates where this guideline provides recommendations):

Issues of Test vs. Application

- There must be more communication between the people performing tests and those who must perform the analysis. This is one driving force behind the biannual series of "Fatigue Reactor Components" conferences that were started by EPRI in 2000. The proceedings of the most recent 2004 meeting (to be published 2005) contain several papers that address this specific issue.
- Testing for environmental effects has resulted in some rules for analysis that are not consistent with real component transient response:
  - Testing involves constant load/unload cycling, while real transients are separated in time, involve various stress magnitudes and non-constant rise times.
  - Hold time at an intermediate stress level or random load magnitude cycling has not been adequately considered in environmental testing, although some work outside the U.S. has addressed these issues.
  - The "real world" is different than laboratory tests, i.e., loading rates are random as opposed to carefully controlled ("ramped" or "saw-toothed") loads applied in the laboratory.
- Strain hardening effects may affect the results of fatigue testing at high cycles.
- May also need more nickel alloy data.

Issues of Analysis and Evaluation

- "Linking" of transients pairs is not straight-forward and can lead to significant differences in results (refer to Figure 4-9):
  - How do you treat cases where the starting and ending stress points are not equal?
  - What rate of change do you assume for the discontinuity between transients?
  - What is strain rate?
    ☑ This guideline makes recommendations in Section 4.2.2 for addressing this issue. Work is also ongoing within the EPRI BWRVIP program to investigate alternative approaches to this issue with regard to ASME Section XI calculations [25].
- Some have questioned the adequacy of Miner's Rule for fatigue analysis and that perhaps design fatigue curves should have a factor to account for this.
  - On the other hand, methods such as Rainflow Cycle Counting will generally show that the use of Miner's Rule with ASME Code analysis is conservative.
- For the purpose of component analysis for environmental effects, perhaps special stress indices and analytical methods need to be developed to distinguish between inside (fluid exposed) surfaces and external (air exposed) surfaces.
- Effect of elastic-plastic correction factor (K_e) on strain rate.
  - To neglect is conservative – how to eliminate conservatism?
    ☑ This guideline makes recommendations in Section 4.2.6 for addressing Ke.

- The F_{en} formulations for stainless steel are based on the NUREG author's own mean stainless steel S-N curve in air, which is different than the ASME mean S-N curve over the high cycle portion of the curve. Therefore, inconsistencies are present in the application of the F_{en} methods since these studies (and most applications of F_{en} being performed throughout the industry) apply F_{en} factors to fatigue results that use the ASME S-N curve.

Analysis Issues: Different Loadings

How are stratification loads addressed?

☑ This guideline makes recommendations in Section 4.2.6 for addressing stratification loads.

How are seismic loads addressed?

☑ This guideline makes recommendations in Section 4.2.6 for addressing seismic and other dynamic loads.

How are pressure and moment loads addressed?

☑ This guideline makes recommendations in Section 4.2.6 for addressing cyclic pressure and moment strains.

Analysis Issues: Oxygen

- Environmental fatigue is typically linked to dissolved oxygen. As previously mentioned, this involves inappropriate over-simplification and ignores the key role of other water chemistry parameters such as conductivity (or more correctly, level of dissolved anionic impurities) and pH. Even with regard just to dissolved oxygen, however:
  - Experts say oxygen is not the correct parameter – should be electrochemical potential (ECP), which is affected by the overall balance of oxidants and reductants in the water, as well as by temperature, flow, surface condition, etc. ECP, rather than dissolved oxygen, is the control parameter used in BWR water chemistry guidelines in the context of stress corrosion cracking mitigation.
  - Hydrogen water chemistry (HWC) may produce much different results, as the oxygen level is significantly lowered for HWC operation (for some locations).
  - What oxygen level to use?
    - Time history during transients not generally available.
    - Value at component location not generally available.
    - What about different periods of operation, i.e., NWC for first 15 years, then intermittent HWC, then reliable HWC?
    - If time history is available:
      - Maximum or minimum of transient?
      - Maximum or minimum local?, i.e., MAX(DO_i, DO_{i-1})
      - Maximum or minimum between peak and valley?

☑ This guideline makes recommendations in Section 4.2.5 for addressing varying historical oxygen levels.

Analysis Issues: Temperature

- Temperature:
  - What temperature to use?
    - Metal? (not generally available)
    - Fluid?
    - Maximum of transient?
    - Maximum local?, i.e., MAX(T_i, T_{i-1})
    - Maximum between peak and valley?

  ☑ This guideline makes recommendations in Section 4.2.4 for addressing temperature.

Analysis Issues: Defining Design Loads

- The strain range (and therefore the CUF) decreases as an imposed temperature change is applied over a longer time period. The longer time period results in a slower strain rate and, all other things being equal, the slower strain rate produces a larger F_{en}. Therefore, a challenge presents itself with respect to defining a set of transients (and their associated temperature ramp rates) that are bounding for design purposes. Component-specific preliminary studies have shown that the F_{en}-adjusted CUF for a variation of temperature ramp rates reaches a maximum when the temperature variation is on the order of 1,000°F/hour or higher [26]. Further investigations are expected to show that it will be possible to define design transients in a manner that will determine the maximum F_{en}-adjusted CUF as the temperature ramp rate (and thus the strain rate) is varied in a narrow range from approximately 1,000°F/hour (or other component-specific rates) to infinite rates. These efforts mirror similar work on crack growth in reactor components through corrosion fatigue [25], and it is expected that such efforts will demonstrate that the issue of defining a transient with a range of ramp rates, extracting the strain rates, performing the design, and monitoring for compliance are all very manageable when utilizing the F_{en} approach for design.

As noted, several of the issues identified above were addressed earlier in this report. Those recommendations are intended to serve as a guide for performing environmental fatigue evaluations. The remaining issues that are not addressed in this report are beyond the scope of the work associated with this report at the current point in time, and some are impossible to resolve with information currently available. An example would be the issue of using ECP/conductivity as a more appropriate parameter for assessing environmental effects. All current F_{en} methodologies are based on measured dissolved oxygen, as that was the only water chemistry parameter recorded during laboratory testing. The remaining non-addressed issues represent the limitations on the current state of the art. As further industry work is completed to address some of the remaining issues summarized above, refinements or additions to these guidelines may be made to further define and enhance plant specific evaluations. Therefore, these guidelines can be thought of as an "instruction manual" for performing plant specific environmental fatigue evaluations based on the current state of technology and information available. Resolution of the remaining non-addressed issues is not needed in order for license renewal applicants to satisfy the current regulatory requirements of addressing reactor water environmental effects.

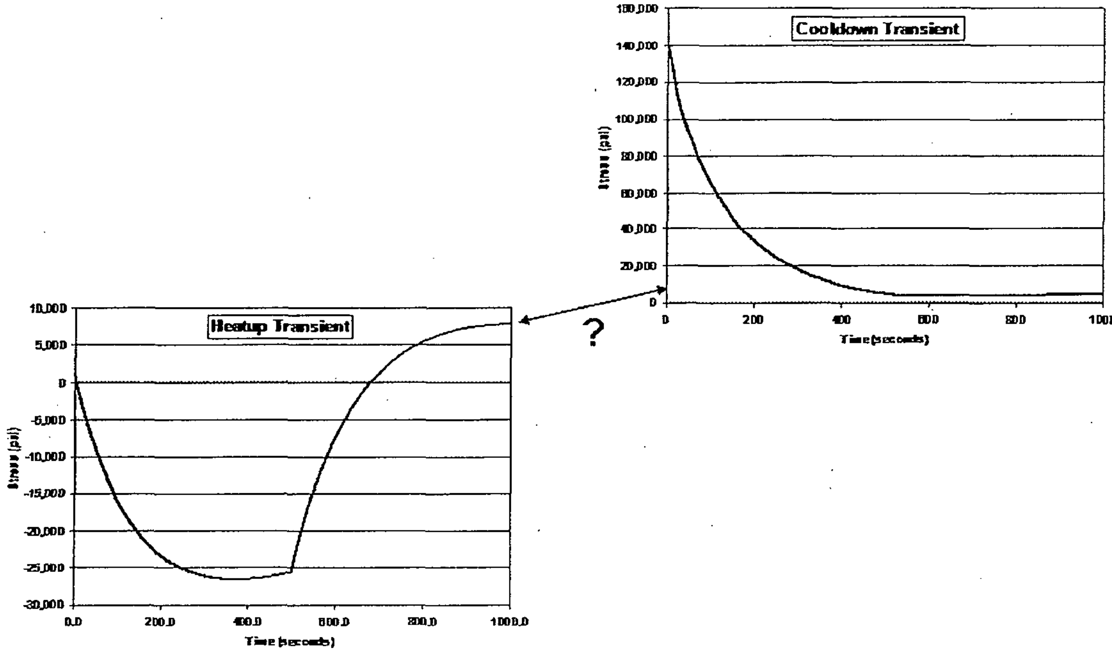


Figure 4-9
Issue of Transient Linking

5 CONCLUSIONS

This report has provided guidance that may be used by individual license renewal applicants to address the environmental effects on fatigue in a license renewal application. The approaches documented in this report are geared to allow individual utilities to determine the optimum approach for their plants, allowing different approaches to be taken for different locations.

The overall approach taken for license renewal is to select a sampling of locations that might be affected by reactor water environmental effects. NUREG/CR-6260 locations are considered an appropriate sample for F_{en} evaluation as long as none exceed the acceptance criteria with environmental effects considered. If this occurs, the sampling is to be extended to other locations. An assessment of the chosen locations is undertaken: (1) to show that there is sufficient conservatism in the design basis transients to cover environmental effects, or (2) or to derive an expected fatigue usage factor including environmental effects. Then, either through tracking of reactor transient cycles or accumulated fatigue usage, utilities can determine if further steps must be taken to adequately manage fatigue environmental effects in the extended operating period.

Different methods are outlined for managing fatigue in the extended license renewal period should fatigue limits be exceeded. These include component re-analysis, fatigue monitoring, partial cycle counting, etc. Flaw tolerance evaluation as outlined in ASME Code, Section XI, Nonmandatory Appendix L, coupled with component inspection verifying the absence of flaws, is also included, although further work is underway by the Code to satisfy past regulatory concerns. Component repair/replacement is also a possibility, but this option is typically reserved to instances where other more economical approaches cannot show acceptable results.

Consistent with current ASME Code, Section XI philosophy for conducting additional examinations when flaws are found in service, the recommendations in this guideline include expansion of the number of locations tracked if fatigue limits are exceeded in the extended operating period. In addition, utilities will continue to monitor operating plant fatigue experience, especially with respect to cracking that might indicate a strong contribution from fatigue environmental effects.

Guidance for performing plant specific environmental fatigue evaluations for selected locations is provided. The intent is to unify the process used by applicants to address environmental effects in the License Renewal Application, and provide specific guidance on the use of currently accepted environmental fatigue evaluation methodologies. The guidance provided by this report is considered to be "Good Practice".

Using the guidance provided in this report, the amount of effort needed to justify individual license renewal submittals and respond to NRC questions should be minimized, and a more unified, consistent approach throughout the industry should be achieved.

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A
SURVEY OF APPROACHES USED TO-DATE FOR ADDRESSING FATIGUE ENVIRONMENTAL EFFECTS IN THE EXTENDED OPERATING PERIOD

This appendix summarizes the approaches for addressing fatigue environmental effects in the extended operating period used by those applicants that have already submitted the license renewal application.

Plant	License Renewal Approach	Extended Operating Period Commitment
Calvert Cliffs	Environmental fatigue calculations will be performed for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Develop Class 1 fatigue analysis for the B31.1 piping locations	Continue to monitor fatigue usage Component with a CUF > 1.0 will be added to the fatigue monitoring system
Oconee	Concluded that the effects of fatigue are adequately managed for the extended period with EAF to be addressed prior to Year 40 Based on 4 EPRI studies and Oconee confirmatory research NUREG/CR-6260 RPV locations accepted via NRC staff SER for BAW-2251A	Update allowable cycles for remaining three locations (all SS) based on EAF adjusted CUF using NUREG/CR-5704 but with a Z-factor of 1.5 Continue to monitor fatigue usage via cycle/severity counting/comparison Participate with EPRI in additional confirmatory research on this issue
ANO-1	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules The EAF for the RPV components specified in NUREG/CR-6260 were determined to be acceptable for the period of extended operation For the piping components, the surge line and HPI nozzles and safe ends had CUF > 1.0. These components are included in the RI-ISI program.	Continue to monitor fatigue usage, and do one of the following for the components where CUF > 1.0: refinement of the fatigue analysis in an attempt to lower the CUF to < 1.0 repair of affected locations replacement of affected components management of the effects of fatigue during the period of extended operation using a program that will be reviewed and approved by the staff through the RI-ISI program

Plant	License Renewal Approach	Extended Operating Period Commitment
Hatch	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Assumed HWC conditions Used 60-year projections of actual cycles and actual fatigue usage to-date (higher than 40-year design basis in some cases) Environmental CUF < 1.0 for 60 years at all locations except reactor recirculation nozzles and feedwater piping	Continue to monitor fatigue usage, perform a refined analysis for feedwater piping and recirculation nozzles before Year 40
Turkey Point	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Revised NUREG/CR-6260 calculations to incorporate power uprate and NUREG/CR-6583 and -5704 methods Used 60-year projections of actual cycles (same as design basis) Environmental CUF < 1.0 for 60 years at all locations except surge line hot leg nozzle	Continue to monitor fatigue usage, aging management for surge line
North Anna/Surry	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Scaled plant-specific results based on results in NUREG/CR-6260 Used 60-year projections of actual cycles (same as design basis) Environmental CUF < 1.0 for 60 years at all locations except surge line elbow	Continue to monitor fatigue usage, aging management for surge line
Peach Bottom	Did not perform environmental fatigue calculations for NUREG/CR-6260 locations Committed to do so before Year 40	Continue to monitor fatigue usage, perform environmental fatigue calculation before Year 40

Plant	License Renewal Approach	Extended Operating Period Commitment
St. Lucie	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Refined several Class 1 fatigue analyses to offset F_{en} impact Used 60-year projections of actual cycles (same as design basis) Environmental CUF < 1.0 for 60 years at all locations except surge line elbow	Continue to monitor fatigue usage, aging management for surge line
Ft. Calhoun	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Revised NUREG/CR-6260 calculations to incorporate NUREG/CR-6583 and -5704 methods Used 60-year projections of actual cycles (same as design basis) Refined surge line Class 1 fatigue analysis to offset F_{en} impact *–Note from OPPD: The refined surge line analysis has already been completed because of pressurizer replacement and power uprate activities, so the surge line had to be reanalyzed for other reasons and wasn't done for License Renewal alone. Otherwise, it probably would still be a pending action.* Environmental CUF < 1.0 for 60 years at all locations	Continue to monitor fatigue usage

Plant	License Renewal Approach	Extended Operating Period Commitment
McGuire/ Catawba	Committed to perform environmental fatigue analysis based on NUREG/CR-6583 for carbon and low-alloy steels and on NUREG/CR-5704 for austenitic stainless steels	Perform environmental fatigue analysis before the end of the 40th year of plant operation Choose sample locations from those in NUREG/CR-6260 and other locations expected to have high EAF adjusted CUF, to ensure that no plant location will have an EAF-adjusted CUF that exceeds 1.0 in actual operation Determine the EAF adjusted CUF using defined transients and/or assumed occurrences which bound or coincide with realistic expectations for an evaluation period Continue to monitor fatigue usage via cycle/severity counting/comparison using EAF adjusted allowable cycles or via tracking EAF adjusted CUF
Robinson	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Revised number of load/unload events to show acceptability Used 60-year projections of actual cycles (same as design basis) Environmental CUF < 1.0 for 60 years at all locations except surge line	Continue to monitor fatigue usage, aging management for surge line
Ginna	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules The EAF for all components specified in NUEG/CR-6260 were determined to be acceptable for the period of extended operation, with the exception of the pressurizer surge line Plant specific F_{en} factors for the piping locations, based on the ASME Class 1 fatigue analysis done in NUREG/CR-6260, were applied to Ginna-specific design basis fatigue usage to determine the environmental fatigue values	Continue to monitor fatigue usage Prior to the end of the current license period, the pressurizer surge nozzle will be inspected

Plant	License Renewal Approach	Extended Operating Period Commitment
Summer	The thermal fatigue management program will be revised by the end of the current licensing term to base future projections on 60 years of operation and to account for EAF	assess EAF before the end of the current licensing period
Dresden/ Quad Cities	Did not perform environmental fatigue calculations for NUREG/CR-6260 locations Committed to do so before Year 40	Continue to monitor fatigue usage, perform environmental fatigue calculation before Year 40
Farley	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 Fen rules Used existing Class 1 fatigue analysis for all NUREG/CR-6260 locations, except surge line and BIT tee to RHR/SI piping Developed Class 1 fatigue analysis for surge line using stress-based fatigue software Used actual fatigue usage to date (based on available stress-based data) and design number of cycles for the surge line Developed Class 1 fatigue analysis for BIT tee to RHR/SI piping using Summer 1979 ASME piping rules The EAF for all components specified in NUREG/CR-6260 were determined to be acceptable for the period of extended operation with the exception of the charging nozzle and RHR locations	Continue to monitor fatigue usage Prior to the end of the current license period, the charging and RHR locations will be addressed further
ANO-2	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 Fen rules Environmental CUF < 1.0 for 60 years for all RPV locations For the pressurizer surge line, charging nozzle and shutdown cooling line CUF > 1.0, safety injection nozzle < 1.0	Continue to monitor fatigue usage, and do one of the following for the components where CUF > 1.0: refinement of the fatigue analysis in an attempt to lower the CUF to < 1.0 repair of affected locations replacement of affected components management of the effects of fatigue during the period of extended operation using a program that will be reviewed and approved by the staff through the RI-ISI program

Plant	License Renewal Approach	Extended Operating Period Commitment
Cook	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Developed Class 1 fatigue analysis for three B31.1 piping locations Used 60-year projections of actual cycles and actual fatigue usage to-date (higher than 40-year design basis in some cases) Environmental CUF < 1.0 for 60 years at 5 of 6 locations. The environmental CUF was greater than 1.0 for the pressurizer surge line.	Continue to monitor fatigue usage
Browns Ferry	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Refined several Class 1 fatigue analyses to offset F_{en} impact Separate oxygen values computed for HWC and NWC conditions, applied based upon historical and projected system availability. Used 60-year projections of actual cycles and actual fatigue usage to-date (higher than 40-year design basis in some cases) Environmental CUF < 1.0 for 60 years for all RPV locations, piping locations > 1.0 TVA is developing Class 1 fatigue analysis for piping locations	Continue to monitor fatigue usage, perform analysis for piping locations

Plant	License Renewal Approach	Extended Operating Period Commitment
Point Beach	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules The EAF for all components specified in NUEG/CR-6260 were determined to be acceptable for the period of extended operation Fatigue monitoring software used to calculate spray line usage Used plant operating data to analyze fatigue for piping locations since design CUF values were not available	Continue to monitor fatigue usage
Brunswick	Performed environmental fatigue calculations for NUREG/CR-6260 locations using NUREG/CR-6583 and NUREG/CR-5704 F_{en} rules Refined several Class 1 fatigue analyses to offset F_{en} impact Developed Class 1 fatigue analysis for two B31.1 piping locations Separate oxygen values computed for HWC and NWC conditions, applied based upon historical and projected system availability. Used 60-year projections of actual cycles and actual fatigue usage to-date (higher than 40-year design basis in some cases) Environmental CUF < 1.0 for 60 years at all locations	Continue to monitor fatigue usage

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