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Washington, DC 20006

**Subject:** Industry Guidance for Addressing Fatigue Environmental Effects in a License Renewal Application

Dear Mr. Imbro:

Enclosed for NRC staff review is Revision G to the EPRI Technical Report entitled "Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application." This revision includes changes to address comments provided by the NRC staff in a January 31, 2001 meeting with NEI and representatives from the EPRI Material Reliability Project. Enclosure 1 is a summary of the changes made and Enclosure 2 is revision G.

This guidance is extremely important to licensees that will submit renewal applications in 2002 and beyond. As we noted in the January meeting, we are looking for appropriate endorsement by the NRC. Once the NRC staff has had an opportunity to read revision G, we would like to have a meeting or conference call to discuss any comments. Please contact Alan Nelson at (202) 739-8110 or by e-mail at [apn@nei.org](mailto:apn@nei.org) to establish a mutually agreeable time.

Submittal of this document is a means of exchanging information with the NRC that is intended to support generic regulatory improvements. Therefore, we believe an exemption from any review fees is warranted based on the criteria in footnote 4 of 10 CFR Part 170.21.

Please contact Alan Nelson or me if you have any questions.

Sincerely,

A handwritten signature in cursive script that reads "Douglas J. Walters".

Douglas J. Walters

*Rec'd 9/4/01  
DCD  
D042*

## Summary of Revisions to MRP-47

### *Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47) Draft Revision G, 06/05/01*

On January 31, 2001, NEI and members of the EPRI Materials Reliability Program (MRP) Fatigue Issue Task Group (ITG) met with the NRC to discuss their comments on Draft Revision F of the *Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application*. Following the meeting, the guidelines document was revised to address comments received. A brief overview of the major changes to the guidelines document is provided below:

#### Changes in Response to NRC Comments

1. ASME XI, Appendix L: NRC raised a concern that ASME Section XI, Appendix L, is not approved. The guidelines document was revised throughout to indicate that flaw tolerance evaluation could be conducted using ASME Section XI, Appendix L, or an NRC-approved document.
2. Reference 12, Page 3-11: The use of Reference 12 was incorrect. The method for determining strain-rate averaging has been explicitly defined.
3. Appendix A: A qualifier was added stating that the conclusions in this appendix would have to be justified for each specific plant. In Table 1, a note was added stating that the table might not be applicable to BWRs that has implemented hydrogen water chemistry.
4. Z-Factor: A significant re-write of Appendix C was provided to justify the Z-factors of 1.5 and 3.0 for austenitic stainless steel and carbon/low alloy steels, respectively.
5. Appendix D and Method 1: The reference to Plant Hatch in Appendix D was removed and a statement was added stating that the assessment was a sample only; plant specific considerations would be needed. General criteria were included on page 3-8 to show how use of other plant data could be justified.

#### Other Changes

1. There were several typographical, formatting and editorial changes in the document that produced no technical change to the document.

**Enclosure 2**

# **EPRI Technical Report**

## **Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47)**

**1003083**

June 5, 2001 Draft Rev. G

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# REPORT SUMMARY

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## **Background**

Many utilities are currently embarking upon efforts to renew their operating licenses. One of the key areas of uncertainty 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. To-date, several utilities have addressed this request using different approaches.

## **Objective**

The objectives of this report are to provide guidance for consideration of reactor coolant environmental effects and to minimize the amount of plant-specific work necessary to comply with NRC requirements for addressing this issue in a license renewal application.

## **Approach**

Previous work by EPRI and utilities related to fatigue environmental effects and license renewal were reviewed. Reports on this subject, created by EPRI, NRC and NRC contractors were compiled. Recent license renewal applications, NRC Requests for Additional Information, and the commitments made by the first two license renewal applicants provided insight into NRC expectations. After evaluation of all this information, alternatives for addressing fatigue environmental effects were developed.

## **Results**

A fatigue environmental effect license renewal approach has been developed that can be applied by any license renewal applicant, using a number of different paths. Based on a sampling approach, an assessment is conducted, using either fatigue environmental factors or demonstrated conservative design transients. Various methods are presented for fatigue management during the extended operating period.

## **EPRI Perspective**

Utilities have committed significant resources to license renewal activities related to fatigue. Based on input from the first few applicants, NRC requirements for addressing fatigue environmental effects are continuing to change. These guidelines were developed to provide stability and assurance of NRC acceptance and include several approaches that may be taken to address fatigue environmental effects in a license renewal application. Use of the approaches 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 fatigue reactor water environmental effects.

## **Keywords**

Fatigue

License Renewal

Fatigue Environmental Effects

# ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY

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For about the last 10 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 is that the reactor water temperature and oxygen content may have a significant effect on the fatigue life of carbon, low alloy and austenitic stainless steels. The degree of fatigue life degradation may be a function of the tensile strain rate during a transient, the specific material, the temperature and the oxygen content. There are certain threshold limits for these variables below which the effects are not significant. The effects of other than moderate environment effects were not considered in development of the ASME Code fatigue curves.

This issue has been evaluated by the Nuclear Regulatory Staff for several 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 US vendors. The results of this 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 water reactor environment could cause fatigue usage factors to exceed the Code-required limit of 1.0. On the other hand, it was demonstrated that usage factors at many locations could be made to be acceptable by re-analysis.

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

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. For some locations, fairly simple assessments may be performed to show that there is adequate conservatism in the design transients to envelop the reactor water environmental effects. For other locations, detailed evaluations, such as conducted in NUREG/CR-6260 may be required. In the extended operating period, cycle counting or fatigue tracking is used for the sample of locations to show that Code limits are not exceeded. If they are, several approaches are identified for demonstrating acceptability for continued operations without repair or replacement of components.

Using the guidance provided herein, the amount of effort needed to justify individual license renewal submittals and respond to NRC questions should be minimized.

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# 1

## INTRODUCTION

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The nuclear industry has discussed the issue of reactor water environment 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.

The purpose of developing this guideline document for addressing reactor water environmental effects in a license renewal application is to define and justify several acceptable approaches that may be used to address this issue.

This report provides a discussion of the approaches 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). This report does not provide guidance on addressing fatigue as a Time Limiting Aging Analysis (TLAA) per 10CFR54.

Thus, the objectives of this report are as follows:

- To provide guidance for consideration of fatigue reactor water environmental effects for license renewal applicants,

- To define various approaches that can be used in the extended operating period to adequately manage the potential effects of reactor water environmental effects on fatigue, and

- To minimize the amount of plant specific work necessary to comply with NRC requirements for considering reactor water environmental effects.

# 2

## BACKGROUND

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### 2.1 Research Results

NRC research in the area of reactor water environmental effects on fatigue began in the early 1990's. 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 oxygen content, strain amplitude, strain rate, temperature and 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. In 1993, a set of "interim" fatigue curves for carbon, low alloy and stainless steel were published in NUREG/CR-5999 [1].

To determine the effects of the environment for operating nuclear plants during the current 40-year licensing term and for an extended 60-year operating period, Idaho National Engineering Laboratories (INEL) evaluated fatigue-sensitive component locations, documenting this study in NUREG/CR-6260 [2]. Using information from existing reactor component stress reports, supplemented by some 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. The results showed that CUFs would exceed 1.0 at many locations, although the CUFs at some of these were shown to be less than 1.0 if excessive conservatism was removed from the evaluations.

Continued research led to changes to the fatigue curves utilized in deriving the results presented in NUREG/CR-6260. The latest proposed environmental fatigue correlations are presented in NUREG/CR-6583 for carbon and low alloy steels [3] and in NUREG/CR-5704 for austenitic stainless steels [4].

More recently, an evaluation was conducted to assess the implications of the LWR environment on component fatigue for a 60-year plant life. This study, based on the information in NUREG/CR-6260 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 was finalized during 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 fatigue reactor coolant environmental effects would result in an increased frequency of pipe leakage, the NRC required that utilities that apply for license renewal address the effects of reactor water environment on fatigue usage in affected components.

## 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 were based on the interim fatigue design curves given in NUREG/CR-5999 [1]. The conservative approach in NUREG/CR-6260 and NUREG/CR-5999 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 continuing rupture of the passivation layer that protects the exposed surface of reactor components. Temperature, dissolved oxygen content, metal sulfur content, and water flow rate are 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], that 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 an EPRI project 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 were examined in these generic studies.

In the early-vintage Westinghouse PWR results [10], actual plant transient data (e.g., hot leg temperature, pressurizer water temperature) over three cycles of operation (1994, 1995, and 1996) were used to derive an effective environmental factor that could be applied to the design-basis CUF. The maximum effective  $F_{en}$  value (ratio of usage factor with reactor water environmental effects to that based on ASME Code fatigue curves) for any of the pressurizer and surge line locations (pressurizer shell, pressurizer surge nozzle, pressurizer spray nozzle, pressurizer water temperature instrument nozzle, RCS hot leg surge nozzle, and charging nozzle)

was 1.91. This value is very low compared to the environmental multiplier  
NUREG/CR-6260.

These findings were confirmed in the other PWR study of an early-vintage CE the pressurizer surge line was studied in detail. This calculation provided another comparison with the same component location evaluated in NUREG/CR-6260. In evaluation, the surge line elbow location, fabricated from austenitic stainless steel basis CUF of 0.705 calculated for 40 years of operation. NUREG/CR-6260 cites a 40-year CUF of 8.07 when reactor water environmental effects are applied. This CUF value is more than ten times the design-basis CUF. The EPRI evaluations [9] the environmental multiplier was actually only about two based on actual plant trans monitoring data.

The NUREG/CR-6260 studies were conservative since they were based on the earlier NUREG/CR-5999 interim fatigue curves and had to be based on extremely conservative rates and other parameters. The use of actual plant data shows that usage factors are much less than the CUFs calculated in the design basis analyses, and that the environmental factors are as extreme as those presented in NUREG/CR-6260.

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 the latest reports by Argonne National Laboratory (ANL) [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 Argonne 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 factors of 4 (for carbon steel) and 2 (for stainless steel) to account for moderate environmental effects. Instead, the NRC staff believed that the maximum factors that could be used were 3 (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 not considering environmental effects for the underlying carbon steel/low alloy steel materials, unless fatigue in the cladding was specifically addressed.
- The staff agreed with use of a weighted average strain rate for computing environmental effects as long as the maximum temperature of the transient was used.

To date, the industry has chosen not to pursue a formal response to the NRC regarding these areas of disagreement. Instead, the industry has worked with the initial license renewal applicants on the prototype resolutions to the issues. These



prototype resolutions are a part of the foundation for this report. For example, Appendix A presents a simplified evaluation showing differences between the fatigue data used in the earlier NUREG/CR-6260 studies and the latest Argonne data.

Based on NRC review of more recent Japanese and ANL data, NRC believes that no credit should be given for moderate environmental effects [14].

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 accommodate 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 included in Appendix B. Appendix C includes evaluations based on recent data that would support factors of 3.0 for carbon/low-alloy steel and 1.5 for stainless steel.

# 3

## LICENSE RENEWAL APPROACH

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### 3.1 Overview

This document describes how the technical issues associated with reactor water fatigue environmental effects evaluation may be addressed. To assess the effects of reactor water environment on fatigue life, a limited number of components will be assessed considering the effects of recent environmental fatigue data. 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 four applicants for license renewal has 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 programs. There has been no acceptance of the approaches used by the other applicants, as these are still in the evaluation process. By developing guidelines for aging management of reactor water fatigue effects for license renewal and obtaining NRC concurrence, an acceptable 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. An aging management program is provided based on today's knowledge. The elements of that program may change in the future as more information becomes available. Attributes of the fatigue management activity are as follows:

**Scope of Program:** The program includes measures to mitigate fatigue cracking of reactor coolant pressure boundary components caused by reactor water environmental effects.

**Preventive Actions:** Tracking of operating transient cycles and/or maintaining usage factors less than 1.0, or assuring that fatigue cracks do not grow to the size allowed by ASME Section XI Appendix L, or an NRC-approval limit, assures that there is adequate margin against component leakage due to fatigue cracking.

**Parameters Monitored/Inspected:** The significant plant transients that cause fatigue damage or crack growth will be monitored. Alternately, more detailed fatigue analysis,

or crack growth analysis combined with component ISI, can be used to show that the effects of transient operating cycles remain within established limits.

**Detection of Aging Effects:** For most locations, plant operating cycles or cumulative usage factors (CUFs) will be tracked against established fatigue limits. Where these limits are exceeded, component in-service inspection (ISI) at an interval sufficient to detect significant cracking may be used.

**Monitoring and Trending:** The program will monitor a sampling of locations expected to be most adversely affected by plant cycles and reactor water environment. Selection of the sample population will consider those locations identified in NUREG/CR-6260 as well as others.

**Acceptance Criteria:** Two alternate acceptance criteria are provided. For most locations, fatigue usage is kept below the ASME Section III Code-allowable limit. If this can not be demonstrated, an alternate approach is to show that any potential cracking is maintained below that allowed by ASME Section XI Appendix L, or an NRC-approved limit.

**Corrective Actions:** The program allows for alternate actions to keep the usage factors from exceeding Code limits, including more rigorous analysis (e.g., partial cycle counting, revised modern analysis, fatigue monitoring), converting to a flaw-tolerance-based approach (ASME Section XI, Appendix L or an NRC-approved methodology), or component repair/replacement.

**Confirmation Process and Administrative Controls:** Consistent with current requirements, site QA procedures, review and approval processes and administrative controls will be implemented in accordance with Appendix B of 10 CFR Part 50.

**Operating Experience:** Consistent with current practice, industry experience will continue to be reviewed. Applicable industry experience will be reviewed for applicability and additional inspections or other analytical programs will be undertaken to assure that unacceptable fatigue cracking does not occur, due to both anticipated and unanticipated transients.

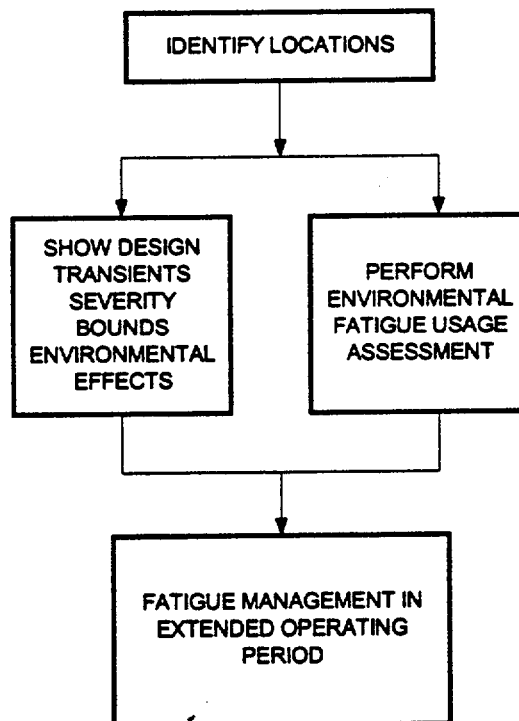
### 3.2 Methods for Evaluation of Environmental Effects

There are several methods that can be used to assess the effects of reactor water environment on fatigue for each specific location to be considered. In this document, two primary methods are provided.

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 select the method that will be used to manage the effects of environmental fatigue.
- Method 1 is based on demonstrating that the fatigue analysis for the design transients, when compared to an evaluation based on actual transients, will bound any environmental effects in the extended operating period. This method will apply to those locations where the design basis fatigue analysis can easily be shown to be very conservative with respect to transient definitions or number of design cycles. Further discussion is provided in Section 3.2.2.
- Method 2 includes an assessment of the actual expected fatigue usage factor including the influence of environmental effects. With this method, 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 reflect actual operating conditions in the plant. Further discussion is provided in Section 3.2.3.
- The bottom of Figure 3-1 indicates that fatigue management occurs after the method is chosen for each location. This may be as simple as counting the accumulated cycles and showing that they remain less than utilized in the assessment. 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.



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**Figure 3-1**

**Overview of Methods for 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 locations.

For both PWR and BWR plants, the locations chosen in NUREG/CR-6260 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. Thus, these locations should be considered in selecting the representative set of locations. Appendix A describes the locations.

The locations evaluated in NUREG/CR-6260 can be evaluated on a plant-unique basis. An evaluation in Appendix A shows that the environmental effects on some of the locations may not be significant. Similar plant unique evaluations may show that the NUREG/CR-6260 locations are also not significantly affected by fatigue, such that they need not be considered. Likewise, plant specific evaluations may identify other locations that are more affected. Thus, plant fatigue analyses should be reviewed to identify the specific locations where high usage factors were identified in the original design.

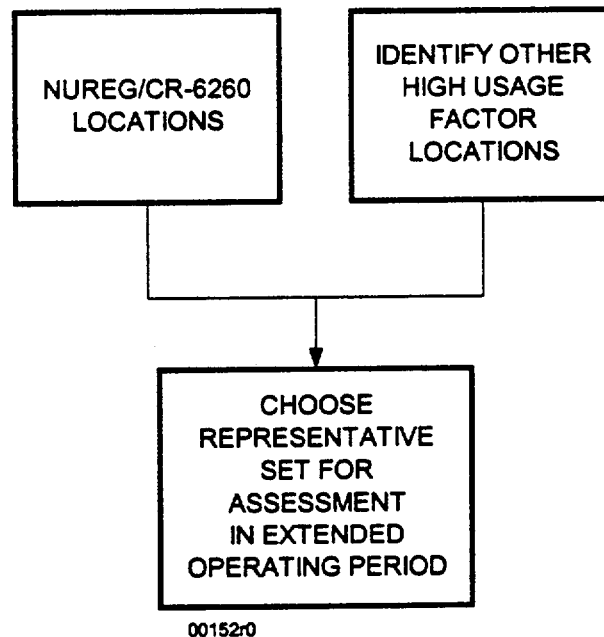
In original stress reports, high usage factors may have been reported in many cases that are unrealistically high, but met the ASME Code requirement of  $CUF < 1.0$ . In these cases, revised analysis may be conducted to derive a more realistic usage factor or to show that the actual usage factor is significantly less than reported.

In identifying the set of locations for the 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 environmental effects, should be chosen as the one to use in the environmental assessment. Similar to the approach taken in NUREG/CR-6260, the final set of locations chosen for the environmental assessment should include several different types of locations that are expected to have the highest CUFs, should be those most adversely affected by environmental effects and should include 6-10 component/system locations. 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 all Class 1 piping systems and major components. For the reactor 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. If the NUREG/CR-6260 locations are not included, add these locations, unless a specific plant evaluation is provided to show that the usage factor with environmental effects is lower than for other similar identified locations.
- From this list of locations, choose a set of 6-10 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, (2) locations that have similar loading conditions, geometry, material and reactor water environment to another selected location, or (3) an assessment of reactor water environmental fatigue effects shows that the expected usage factor with environmental effects is small (such as demonstrated in Appendix A).



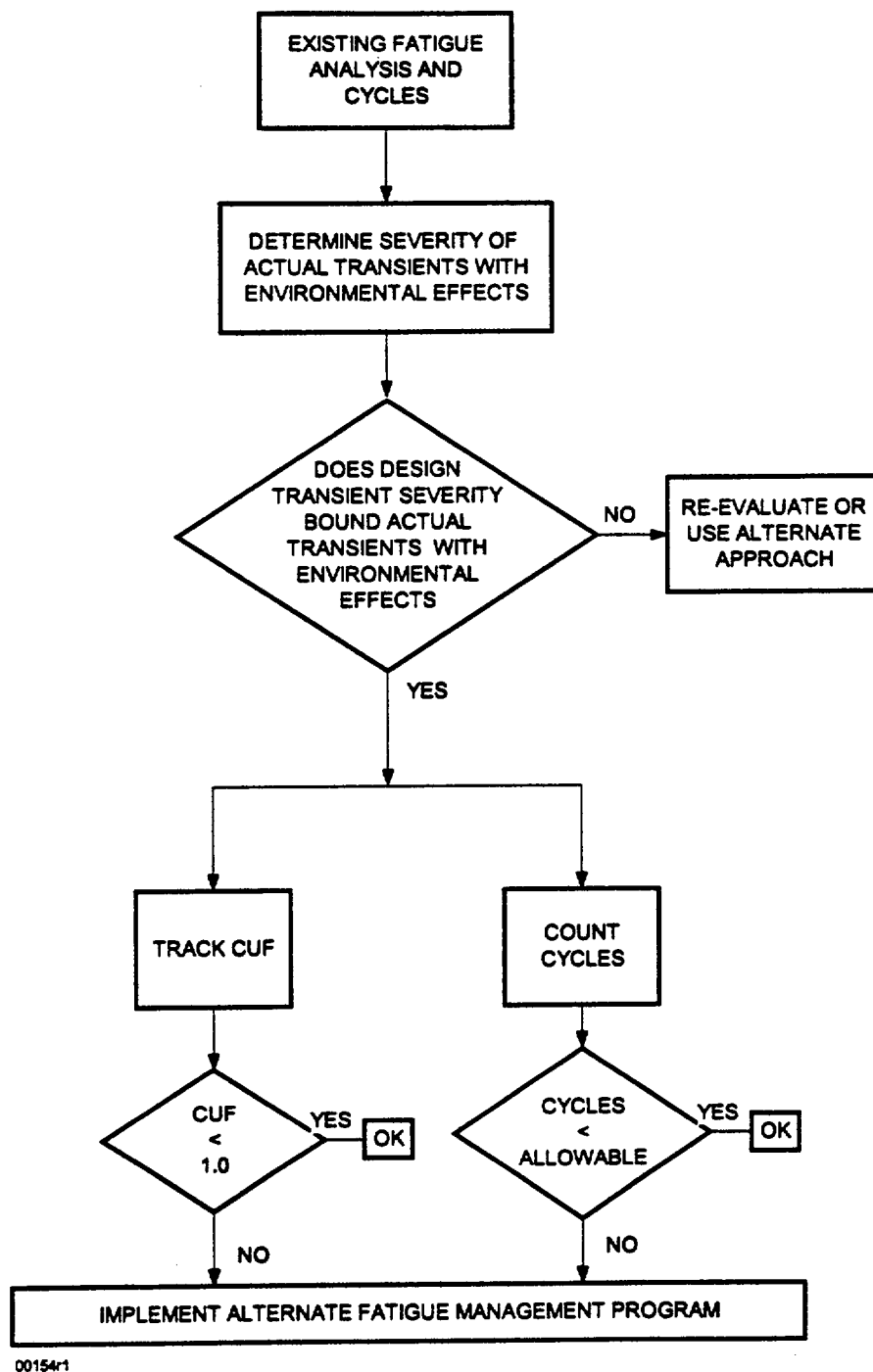
**Figure 3-2**

Identification of Component Locations for Fatigue Environmental Effects Assessment

### 3.2.2 Method 1: Design Basis Loading Assessment

With this assessment approach, the inherent conservatisms in the design basis loadings, considering both severity and number of the transients, are used to bound environmental effects. The influence of environmental effects is shown to be offset by the conservatism in design basis

transients relative to actual plant transients. This assessment can be based on results of industry studies and/or plant fatigue assessments using actual plant data. Figure 3-3 shows the approach for performing the assessment and managing fatigue in the extended operating period.



**Figure 3-3**  
Fatigue Management if Design Transients Bound Fatigue Environmental Effects



### Determination of Existing Design 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. In most cases, the loadings were conservatively defined before there was significant plant operating experience. As a result, the transient load definitions are based on step temperature changes with extremely conservative temperature ranges. When performing the component fatigue analysis, similar transients may have been grouped together to reduce the amount of effort expended in the stress analysis. Further, the number of actual cyclic loadings analyzed may exceed the actual number of expected cycles. This review can arrive at a preliminary assessment as to whether sufficient conservatism exists in the existing fatigue analysis to bound environmental effects.

### Demonstration That Design Transient Conservatisms Bound Actual Transients with Environmental Effects

CUFs with environmental effects include several increasing and decreasing factors relative to a design basis stress analysis to meet ASME Code requirements.

- Increase: There is some increase in fatigue usage due to environmental effects. This is a function of oxygen content, strain rate, strain amplitude, temperature, etc. The actual effect has been demonstrated in industry programs to be less than that derived in NUREG/CR-6260, where worst case parameters were chosen to determine environmental effects.
- Decrease: Actual transients may produce lower stresses than those considered in the design. Temperature and pressure ranges and rates of temperature change are almost always less severe. Because of the shape of fatigue curves, a small reduction in stress can result in a large reduction in CUF.

Plant data from actual operation can be taken for the transients that significantly contribute to usage factors. The actual transients can then be defined and can be compared to design transients. Transient thermal stress analysis can be conducted with both the design transients and actual transients to determine the contributions to usage factor. From this analysis, strain rates can be determined such that actual environmental factors can be determined (as compared to the bounding ones used in NUREG/CR-6260).

A more direct approach is to use results from plant fatigue monitoring based on actual plant transient data. This approach directly determines fatigue usage results based on actual plant data. For some representative operating period, the results from the fatigue monitoring program can be compared to the usage predicted based on design basis transients. Representative strain rates, strain ranges and temperatures during transients can be determined from the data to estimate actual environmental factors for the key transients. This was the approach used in an EPRI project to determine effective environmental factors [9, 10, 11].

Data from similar plants may be used in this evaluation. In the case where data from other plants is used, it shall be justified that the data is representative for the plant under consideration. Considerations shall be given to similarity of design transients, system function and design, system operating procedures and operating history, component size and geometry, operating conditions, etc.

In most plants, the rate of cycle accumulation has decreased significantly since the initial operating period. A comparison of the rate of cycle accumulation versus that considered in the design analysis can be made. Where a significant difference is predicted to the end of the extended operating period, this can be taken into account as one of the conservatisms.

In some cases, especially if the evaluation is based on fatigue monitoring results, some bounding assumptions can be made such that specific environmental factors do not have to be developed for each load set pairing in the fatigue analysis.

Once all this information has been collected, the applicant can perform an evaluation to show that the design transients bound the actual transients with environmental effects considered. A way to accomplish this without resorting to CUF determination is by showing that the severity of the actual transients with environmental effects considered are bounded by the transient severity assumed in the component design. If the results of this effort are satisfactory, an applicant can monitor fatigue. Another option is to count cycles to ensure that the actual count remains less than that assumed in the design. As part of this option, an applicant may determine the number of cycles where  $CUF = 1.0$ . This number becomes the allowable number of cycles. A second option is to count cycles and compute a CUF using the design transient severity to ensure CUF remains below one (1.0). Either method is conservative.

If the above comparison is conducted using CUF values (design CUF and actual with environmental effects included in the CUF), then it is permissible to recalculate the design CUF using higher numbers of transients up to a set that results in design  $CUF = 1.0$ . This set then becomes the new "design" cycle limits. Similarly, it is permissible to use a number of projected actual cycles less than design. One of these variations may permit the comparison to be satisfactory. The allowable number of cycles for cycle counting is the lesser of the two.

Appendix D shows an application of the results from NUREG/CR-6260 and the Industry/EPRI programs to demonstrate that design basis transient definitions are conservative and more than compensate for environmental effects. For the example shown, simple cycle counting and CUF calculation based on design basis transient severity is shown to bound any potential environmental effects.

#### Consideration of Increased Cycles for Extended Period

If a revision to the fatigue analysis is to be performed, the applicant may wish to update the projected cycles. In most cases, it can be demonstrated 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. However, if more cycles are projected, an applicant should consider the significance of this

in respect to the means of fatigue management selected. Before proceeding with the use of cycle counting, an applicant may choose to perform a revised fatigue analysis to confirm that the increased number of cycles will still result in CUF less than 1.0. An applicant may also choose to determine the number of cycles at which CUF would be expected to exceed 1.0. These results can be used to determine the most appropriate method for managing fatigue at a given location.

#### Fatigue Analysis Re-evaluation

An applicant may not be able to show that the design transients bound the actual considering environmental effects. This may be due to the expected number of transients exceeding that assumed in the design, or to the transient severity, when the environment is considered, exceeding that used in the design. In this situation, a fatigue analysis may be revised. In this case, the applicant may update the fatigue analysis to determine the acceptance criteria to be used in the cycle counting approach to fatigue monitoring.

The amount of effort expended in conducting a revised fatigue analysis can vary. A simplified revised fatigue analysis could be performed using results from the existing fatigue analysis if sufficient detail is available. At the other end of the spectrum, a complete new analysis could be conducted. In any revised analysis, the design basis transients shall be utilized in establishing the design transient CUF. Actual transient behavior, combined with environmental effects, shall be considered in evaluating the CUF with environmental effects.

#### Fatigue Management Approach

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 the accumulated cycles. As previously discussed, the CUF is based on the design cycles. At such time that the CUF is projected to exceed 1.0, or the number of actual cycles is projected to exceed the allowable 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.

### **3.2.3 Method 2: Fatigue Assessment Using Environmental Factors**

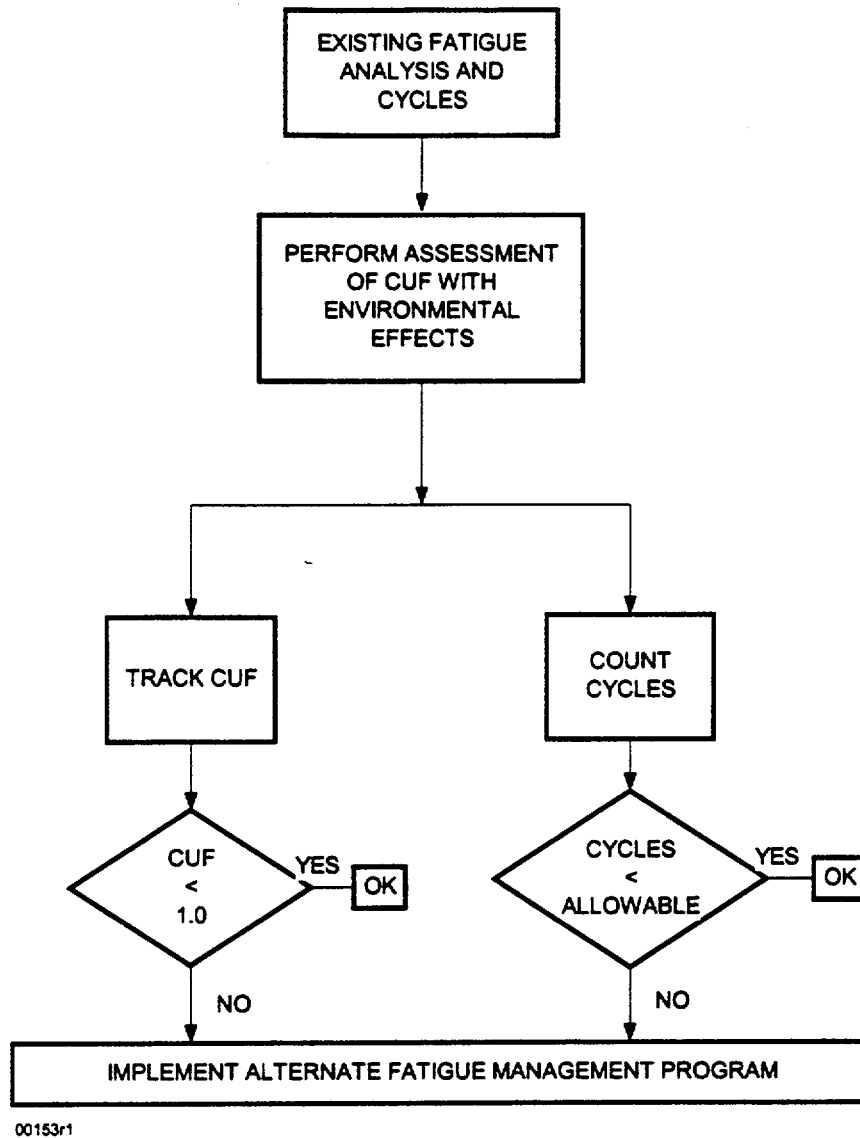
With this assessment method, factors to account for environmental effects are incorporated into an updated fatigue evaluation for the location using the  $F_{en}$  approach outlined in Appendix B. Excess conservatism in both the loading definitions, number of cycles and the fatigue analyses may be considered. Figure 3-4 shows the approach for performing the assessment and managing fatigue in the extended operating period.

#### Determination of Existing Design Basis

Existing plant records must be reviewed to determine the cycling 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.

Consideration of Increased Cycles for Extended Period

If a revision to the fatigue analysis is to be performed, the applicant may wish to update the projected cycles. In most cases, it can be demonstrated 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. However, if more cycles are projected, an applicant should consider the significance of this in respect to the means of fatigue management selected. Before proceeding with the use of cycle counting, an applicant may choose to perform a revised fatigue analysis to confirm that the increased number of cycles will still result in CUF less than 1.0. An applicant may also choose to determine the number of cycles at which CUF would be expected to exceed one (1.0). These results can be used to determine the most appropriate method for managing fatigue at a given location.



**Figure 3-4**  
Fatigue Management if Environmental Assessment Conducted

## Fatigue Assessment

A determination of CUF considering environmental effects is needed. This may be accomplished conservatively using information from design documentation or industry publications and bounding  $F_{en}$  factors, or it may require a more extensive approach.

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, or transient grouping
- For piping, use of an ASME Code Edition prior to 1977, Summer Addenda, which included the  $\Delta T_1$  term in Equation 10.

A simplified revised fatigue analysis may be performed using results from the existing fatigue analysis if sufficient detail is available. Alternately, a new complete analysis could be conducted to remove additional conservatism. In the environment assessment, the environmental fatigue usage may be calculated with 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 (for carbon or low alloy steel components) or NUREG/CR-5704 (for austenitic stainless steel components). Appendix B describes the latest procedure endorsed by the Pressure Vessel Research Council that includes the equations from these documents [15,16].
- The environmental factors may be calculated with consideration of temperature, oxygen and strain range thresholds. The effective  $F_{en,eff}$  may be determined using strain-rate averaging as outlined in Reference 3:

$$F_{en,eff} = 1 + \frac{\int_{\epsilon_{th}}^{\epsilon_{max}} \left( F_{en}(\dot{\epsilon}, S, Do, T) - 1 \right) d\epsilon}{\epsilon_{max} - \epsilon_{th}}$$

where:

$F_{en}$	=	instantaneous value of the environmental factor as a function of the variables in parentheses,
$\dot{\epsilon}$	=	instantaneous strain rate for the tensile portion of the transient,
S	=	sulfur content
Do	=	most conservative dissolved oxygen for the transient pair
T	=	most conservative (maximum) temperature occurring for the transient pair
$\epsilon_{max}$	=	maximum tensile strain for the transient pair
$\epsilon_{th}$	=	threshold value of strain below which no environmental effects are

observed

- Using the  $F_{en,eff}$  from the above step, determine an effective environmental multiplier ( $F'_{en}$ ) by dividing  $F_{en,eff}$  by a Z-factor that accounts for moderate environmental effects. PVRC recommends Z factors of 3.0 for ferritic steel components and 1.5 for austenitic components. (A detailed basis for these Z factors is contained in Appendix C.)
- 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.

In many situations, the original design basis fatigue analysis may have been conducted in a very conservative manner, and may have been based on early versions of the ASME Code. There may be some benefit in conducting a modern fatigue analysis. This revised analysis could take into account actual expected transients, less conservative assumptions or later versions of the ASME Code. For piping components, use of Code versions after the 1979 Edition is especially beneficial since the  $\Delta T_1$  term was removed from Equation 10 of NB-3650, reducing the need to apply conservative elastic plastic penalty factors. The re-analysis could also determine strain rate time histories that are not normally reported in existing component analysis, such that bounding environmental multipliers would not have to be used.

#### Fatigue Management Approach

As shown in Figure 3-4, 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 may be needed if the fatigue assessment determined the CUF to be larger than 1.0. One approach is to derive a reduced number of cycles that would limit the CUF to 1.0. On the other hand, if that CUF was shown to be less than 1.0, the allowable cycles may remain as assumed in the evaluation. So 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 a fatigue monitoring approach that accounts for the actual cyclic operating conditions for the 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. No further action is required as long as the computed usage factor remains less than 1.0.

At such time that the CUF is projected to exceed 1.0, or the number of actual cycles is projected to exceed the allowable 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.

### **3.3 Alternate Fatigue Management in the License Renewal Period**

As identified in Section 3.2, 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 that may be used to justify continued operation with the affected component in service without having to perform repair or replacement. In addition, the fatigue management program may have 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.

#### **3.3.1 Reanalysis**

Each of the methods for fatigue assessment/management described in Section 3.2 are based on fatigue analysis of the affected location. If allowable cycle or CUF limits are predicted to be exceeded during the extended operating period, then a revised analysis may be conducted to remove additional conservatisms. This is applicable to both the Method 1 and Method 2 assessment approaches (3.2.2 and 3.2.3). For Method 1, the re-analysis must be based on design transients, or actual transients with environmental effects, as applicable. For Method 2, excess conservatisms in both the analysis methods and the transient definitions may be considered. This analysis could take advantage of additional on-going industry research to better quantify reactor water environmental effects.

#### **3.3.2 Partial Cycle Counting**

For those locations that are primarily affected by a few significant cycle types, a cycle counting approach may be used to show that the cyclic limits or CUF with environmental effects does not exceed the appropriate limits in the extended operating period. When environmental factors are utilized (as described in 3.2.3), the cycle counting approach may take into account cycle severity and count partial cycles. This is a process where an analytical approach is used to show that cycles less severe than those considered in a design analysis may be counted as fractions of whole cycles. This analysis would not have to be completed until it became apparent that the environmentally affected usage factor limits would be exceeded.

#### **3.3.3 Fatigue Monitoring**

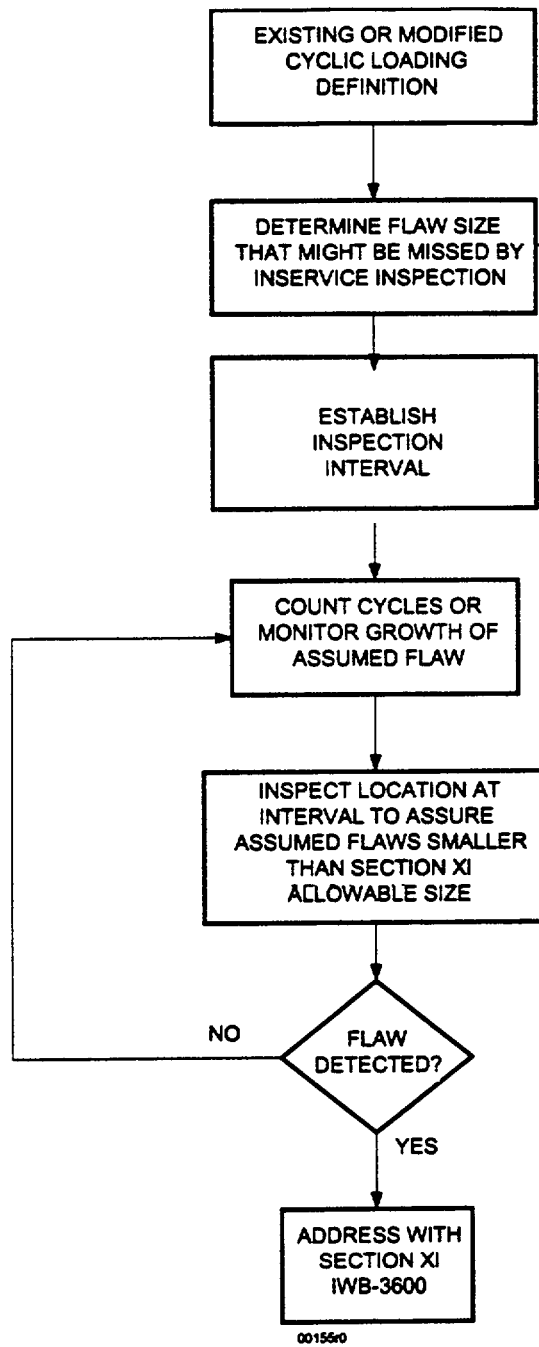
Fatigue monitoring to track CUF may be based on simple algorithms that convert cycles into CUF or may be based on more sophisticated systems that evaluate actual plant transient data. Fatigue monitoring, based on actual plant instrument data, calculates the CUF based on actual plant transient behavior. Its use is thus applicable when the fatigue monitoring assessment



includes environmental effects as described in 3.2.3. It may also be used to form a basis for establishing actual transient severity as described in 3.2.2. The actual predicted CUF is generally much less than that resulting when using design transients. The algorithms in the fatigue monitoring system would have to incorporate environmental factors. This approach is described in more detail in References 9, 10 and 11.

### **3.3.4 *Flaw Tolerance Evaluation and Inspection***

When other methods cannot be used to show that the usage factor is less than 1.0, a flaw tolerance evaluation, coupled with inspection, may be used to justify continued operation. With this approach, it is assumed that a crack exists at the location where the CUF exceeds 1.0. Analysis is conducted to predict expected growth of the crack, including appropriate environmental effects. The crack size is chosen as that which might not be detected during an inspection of the location. An inspection interval is chosen based on the time for the assumed crack to grow to an allowable size. Figure 3-5 shows the approach for performing this assessment and managing fatigue in the extended operating period. An appropriate initial crack size and aspect ratio and an appropriate crack growth law that considers environmental effects must be utilized. This can be accomplished by implementing ASME Section XI, Appendix L or an NRC-approved methodology.



**Figure 3-5**  
Fatigue Management Based on Flaw Tolerance

### Determination of Expected Transient Loadings

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. Alternately, actual plant operating experience may be reviewed to define transients that are conservative but more accurately represent how the plant operates. A conservative definition of the number of plant operating cycles and transients that will occur during the extended operating period must be determined.

### Initial Flaw Size Determination

The initial flaw size (depth and aspect ratio) shall be as defined in ASME Section XI, Appendix L or an NRC-approved methodology. (Work is ongoing to update the initial flaw size definition in Appendix Land to obtain regulatory acceptance.)

### Crack Growth Evaluation

A revised stress analysis for the location may be required to determine the through-wall stress distribution for all significant transient and steady state conditions. Using an appropriate environmentally assisted fatigue crack growth law, fracture mechanics analysis must be conducted to predict the time to grow a crack to the Section XI allowable size. The allowable number of operating cycles and/or transients (or time) between inspections shall be determined per the requirements of ASME Section XI, Appendix L or an NRC-approved methodology.

### Fatigue Management Approach

As shown in Figure 3-5, the fatigue management approach for the extended operating period consists of inspection of the location of the assumed flaw at an interval (or number of cycles) such that the assumed flaw does not exceed to the Section XI, Appendix L allowable flaw size, or such flaw size as allowed by an NRC-approved methodology. So long as no flaw is detected during inspection, the location is accepted for continued operation for another inspection interval. Before this approach can be used for fatigue management, the component must be examined to show that there is no detectable cracking. (If a flaw is ever detected, it must be dispositioned as required by ASME Section XI and related regulatory requirements.)

### **3.3.5 Modified Plant Operations**

In some instances, actions may be taken to revise plant operations to reduce the transient severity or the rate of cycle accumulation. These effects will reduce the rate of usage accumulation (or crack growth rate) and can be taken into account in justifying extended operation.

### **3.3.6 Repair/Replacement**

Although quite extreme, repair or replacement of affected locations may be economical, especially when combined with other component replacements. Prior component repairs or replacements may also be considered in establishing the current CUF at these locations.

### **3.3.7 Evaluation of Similar Components**

If the fatigue management alternates above (e.g., reanalysis, partial cycle counting, fatigue monitoring or modified plant operations) fail to show that limits can be satisfied, such that environmental fatigue usage limits are exceeded and repair/replacement or conversion to a flaw tolerance/inspection approach is required, an assessment of other similar locations shall be undertaken. The next limiting location shall be added to the fatigue management program. The location chosen shall be one with similar loadings, geometry and materials.

## **3.4 Guidance for Plants with B31.1 Piping Systems**

Many plants that were designed in the 1960's 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 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 structural or material discontinuities, 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 Section III, Class 1.

The high usage factor locations evaluated in NUREG/CR-6260 were primarily associated with piping systems 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 than that of plants designed to ASME Section III, Class 1. All have limitations on heatup/cooldown rates as required by ASME Section III/XI, and 10CFR50, Appendix G. The reactor vendors have provided feedback to plant operators to reduce the thermal fatigue challenges to components. 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:

- A sampling of fatigue sensitive locations can be taken, based on NUREG/CR-6260, possibly amplified by evaluations for a similar ASME Section III, Class 1 plant. 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 locations. This may be based on similarity of geometry, materials, and transient cycles relative to other similarly designed plants. Here, the information provided in NUREG/CR-6260 can be used. Alternately, an ASME Section III, Class 1 analysis can be conducted. This establishes the baseline fatigue usage, without environmental effects for the plant.
- Using this information, one of the approaches previously described for the ASME 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.

# 4

## CONCLUSIONS

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This report has developed several approaches that may be used by individual license renewal applicants to address the environmental effects on fatigue in a license renewal application. The approaches 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. 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.

A number of different methods are outlined for managing fatigue in the extended license renewal period should fatigue limits be exceeded. These include component reanalysis, fatigue monitoring, partial cycle counting, etc. Flaw tolerance evaluation as outlined in ASME Section XI, Appendix L, coupled with component inspection, is also included, although further work is underway by the Code to address regulatory concerns. Alternately, an NRC approved methodology could be used. Component repair/ replacement is also a possibility, but is recommended only where other approaches can not show acceptable results.

Consistent with current ASME Section XI philosophy for conducting additional examinations when flaws are found in service, the program includes 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.

Using the guidance provided herein, the amount of effort needed to justify individual submittals and respond to NRC questions should be minimized.

# 5

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# A

## ASSESSMENT OF NUREG/CR-6260 RESULTS

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### 1.0 INTRODUCTION

NUREG/CR-6260 [A1] documents a study by Idaho National Engineering Laboratories (INEL) in 1995 for the Nuclear Regulatory Commission (NRC) to assess the effects of light water reactor environment on fatigue of reactor coolant system components. At the time of the study, the "interim fatigue curves" from NUREG/CR-5999 [A2] were the only ones available; except that some revised interim fatigue curves for stainless steel were provided by Argonne National Laboratories (ANL) in 1994, as documented in NUREG/CR-6260. Following completion of this study, there have been numerous studies by industry, the Japanese, and ANL to improve the data, criteria, and methods for evaluation of fatigue environmental effects. The purpose of this Appendix is to summarize the NUREG/CR-6260 results and to assess the results relative to use as a baseline for evaluating fatigue environmental effects in license renewal. Appendix A, Section 2.0 discusses the "interim fatigue curves" and how they compare to the current data for reactor coolant components. Section 3.0 provides an evaluation of the specific reactor types evaluated in NUREG/CR-6260. The review shows that some of the locations can be excluded from consideration in license renewal evaluations, although plant specific evaluations would be necessary to confirm these conclusions. Section 4.0 provides conclusions reached from this evaluation.

### 2.0 EVALUATION OF NUREG/CR-6260 LOCATIONS USING LATEST ENVIRONMENTAL DATA

In NUREG/CR-6260, the fatigue curves were provided in the form of digitized points of stress amplitude versus number of cycles (S-N curves). The following curves were provided from NUREG/CR-5999:

<b>Stainless Steel:</b>	Single curve for all temperatures and strain rates that was also applicable to Alloy 600. This was updated for stainless steel after the issuance of NUREG/CR-5999 with an equation that also included strain rate dependency.
<b>Carbon/Low Alloy Steel:</b>	Low Oxygen water (single curve) High Oxygen 200°C (various strain rates) High Oxygen 250°C (various strain rates) High Oxygen 288°C (various strain rates)

Since equations were not provided, it is difficult to numerically compare these curves to that which would result using current ANL recommendations for carbon, low alloy and stainless steel. Figures were provided in NUREG/CR-6260 that plotted "Factor of Increase" for each curve relative to the ASME Code Fatigue curves. The "Factor of Increase" is equivalent to the common term  $F_{en}$  that is the ratio of fatigue usage with environmental effects divided by fatigue usage with air, or allowable cycles to fatigue crack initiation in air divided by allowable cycles with water reactor environmental effects.  $F_{en}$  equations are provided in the latest ANL reports for carbon and low alloy steel [A3] and stainless steel [A4]. The environmental correction factor ( $F_{en}$ ) relative to room-temperature air for Types 304 and 316 stainless steel is given by:

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

where the constants for transformed temperature ( $T^*$ ), strain rate ( $\dot{\epsilon}^*$ ), and dissolved oxygen ( $O^*$ ) are defined as follows:

$T^* = 0$	( $T < 200^\circ\text{C}$ )
$T^* = 1$	( $T \geq 200^\circ\text{C}$ )
$\dot{\epsilon}^* = 0$	( $\dot{\epsilon} > 0.4\%/\text{sec}$ )
$\dot{\epsilon}^* = \ln(\dot{\epsilon}/0.4)$	( $0.0004 \leq \dot{\epsilon} \leq 0.4\%/\text{sec}$ )
$\dot{\epsilon}^* = \ln(0.0004/0.4)$	( $\dot{\epsilon} < 0.0004\%/\text{sec}$ )
$O^* = 0.260$	( $\text{DO} < 0.05 \text{ ppm}$ )
$O^* = 0.172$	( $\text{DO} \geq 0.05 \text{ ppm}$ )

In the above,

$T$  = temperature,  $^\circ\text{C}$

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

DO = dissolved oxygen,

The environmental correction factors relative to room-temperature air for carbon steel and alloy steel are given by:

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

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

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

$S^* = S$	$(0 < S \leq 0.015 \text{ wt. \%})$
$S^* = 0.015$	$(S > 0.015 \text{ wt. \%})$
$T^* = 0$	$(T < 150^\circ\text{C})$
$T^* = T - 150$	$(150 \leq T \leq 350^\circ\text{C})$
$O^* = 0$	$(\text{DO} < 0.05 \text{ ppm})$
$O^* = \ln(\text{DO}/0.04)$	$(0.05 \text{ ppm} \leq \text{DO} \leq 0.5 \text{ ppm})$
$O^* = \ln(12.5)$	$(\text{DO} > 0.5 \text{ ppm})$
$\dot{\epsilon}^* = 0$	$(\dot{\epsilon} > 1 \text{ \%}/\text{s})$
$\dot{\epsilon}^* = \ln(\dot{\epsilon})$	$(0.001 \leq \dot{\epsilon} \leq \text{\%/s})$
$\dot{\epsilon}^* = \ln(0.001)$	$(\dot{\epsilon} < 0.001 \text{ \%}/\text{s})$

In the above, the temperature ( $T$ ), dissolved oxygen ( $\text{DO}$ ) and strain rate ( $\dot{\epsilon}$ ) are as previously defined. The weight percent sulfur is  $S$ .

Using these evaluations, the current recommended fatigue life correction factors can be compared to that used in NUREG/CR-6260.

Figure A-1 compares the environmental factors for NUREG/CR-6260 and NUREG/CR-5704 for stainless steel. It is observed that the correction factor in NUREG/CR-6260 was dependent upon the alternating stress amplitude, but was not affected by oxygen content or strain rate.

PWR reactors generally operate at low oxygen. Thus, except in the region near  $S_a = 65\text{ksi}$  or for high strain rate transients, it would be expected that environmental effects would be more severe than reported in NUREG/CR-6260. Since strain rate is generally not available from stress reports utilized in NUREG/CR-6260, the increase is expected to be approximately  $15.4/11 \sim 1.4$  or a 40 percent increase. The factor of 11 is an estimated mean value of the "Factor of Increase".

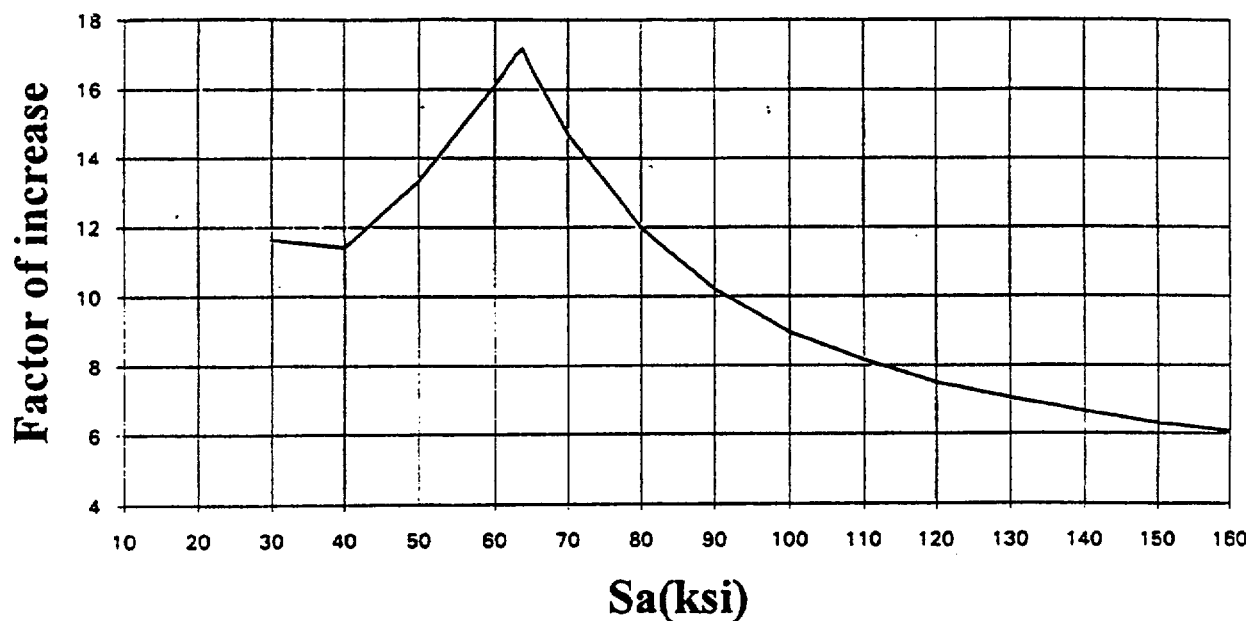
For BWR reactors, the oxygen level is generally much higher. Therefore, the actual environmental factors would be lower than in NUREG/CR-6260 by approximately  $8.4/11 \sim 0.75$  or 25 percent less.

Figure A-2 shows a similar comparison for carbon and low-alloy steels in a low-oxygen environment as might be expected for PWRs. In this case, the environmental factors for low alloy steel are comparable except for high and low stress amplitudes. Thus, the NUREG/CR-6260 values should be about what would be expected with the new environmental data. For carbon steel, the expected environmental factors would be lower by approximately  $1.5/2.1 \approx 0.75$  or 25 percent less.

Figures A-3 to A-5 show comparisons for carbon/low-alloy steels in high oxygen water. In these cases, the current low temperature (200°C) environmental factors appear to be less than that evaluated in NUREG/CR-6260. The high-temperature (288°C) environmental factor in Figure A-5 would be higher by approximately  $58/45 \approx 1.3$  or 30 percent for carbon steel and  $82/45 \approx 1.8$  or 80 percent for low alloy steel. These comparisons would be applicable to BWR components/environments.

In NUREG/CR-6260, revised interim fatigue curves for stainless steel were provided that had a strain rate effect. Comparisons between the NUREG/CR-6260 basic, the revised interim and the NUREG/CR-5704 environmental factors are shown in Figure A-6.

In summary, Table A-1 was generated to summarize the increase or decrease of the environmental factors as compared to those of NUREG/CR-6260. The comparison is approximate, and actual differences would have to be determined based on alternating stresses, strain rates (if available), temperature, dissolved oxygen, etc.



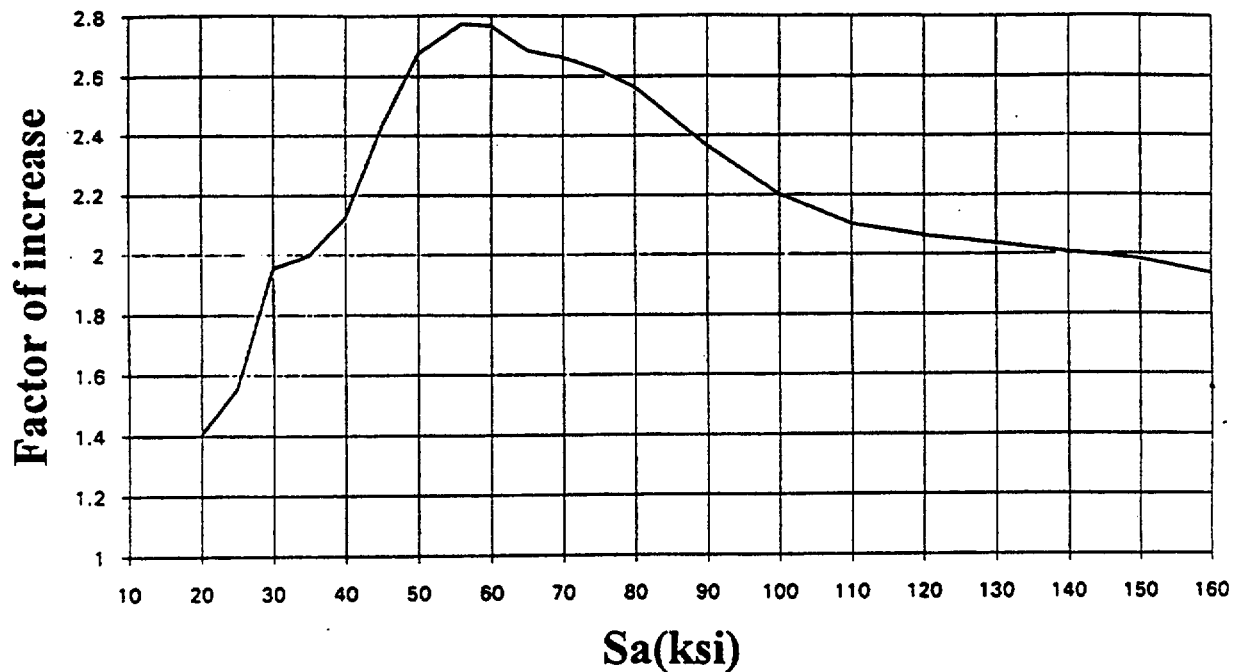
Note: Mean "Factor of Increase" estimated to be  $\approx 11$

NUREG/CR-5704 Eq. 13:

$\dot{\epsilon}$ , %/sec	DO, ppm	$F_{en}$
$\leq 0.0004$	$< 0.05$	15.4
0.004	$< 0.05$	8.4
0.04	$< 0.05$	4.6
0.4	$< 0.05$	2.5
$\leq 0.0004$	$\geq 0.05$	8.4
0.004	$\geq 0.05$	5.6
0.04	$\geq 0.05$	3.8
0.4	$\geq 0.05$	2.5

Figure A-1. Environmental Correction Factor in NUREG/CR-6260 Compared to NUREG/CR-5704 Recommendation for Stainless Steel

NUREG/CR-6260 Figure 3-7 (DO < 0.1 ppm):



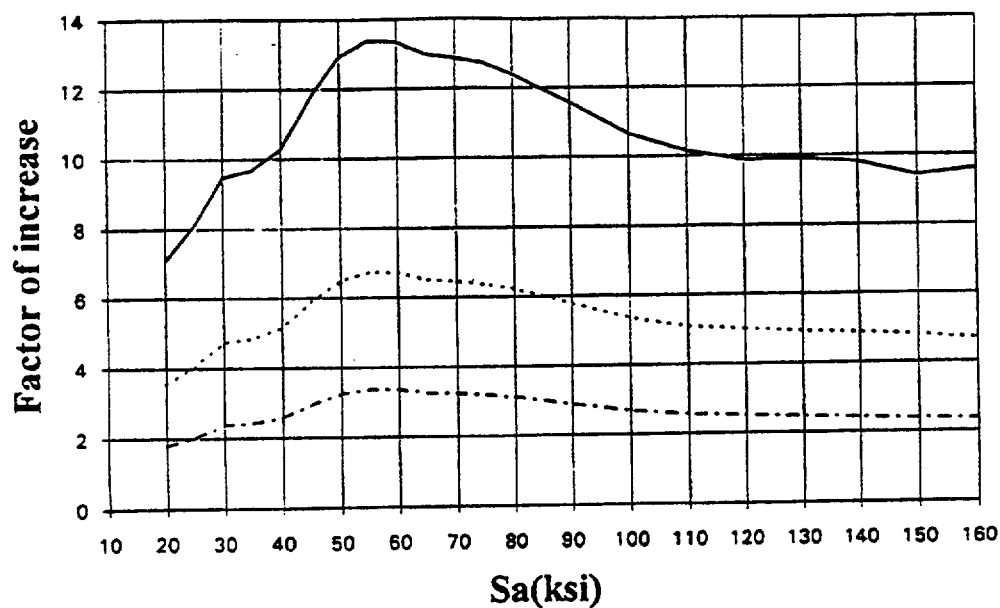
Note: Mean "Factor of Increase" estimated to be  $\approx 2.1$

NUREG/CR-6583 Equation 6.5a/6.5b (DO  $\leq 0.05$  ppm):

Temp., °C	Material	F <sub>en</sub>
200	CS	1.7
250	CS	1.6
288	CS	1.5
200	LAS	2.4
250	LAS	2.3
288	LAS	2.2

Figure A-2. Environmental Correction Factor in NUREG/CR-6260 Compared to NUREG-6583 Recommendation for Carbon/Low-Alloy Steel in Low-Oxygen Environment

NUREG/CR-6260 Figure 3-8 (DO > 0.1 ppm):

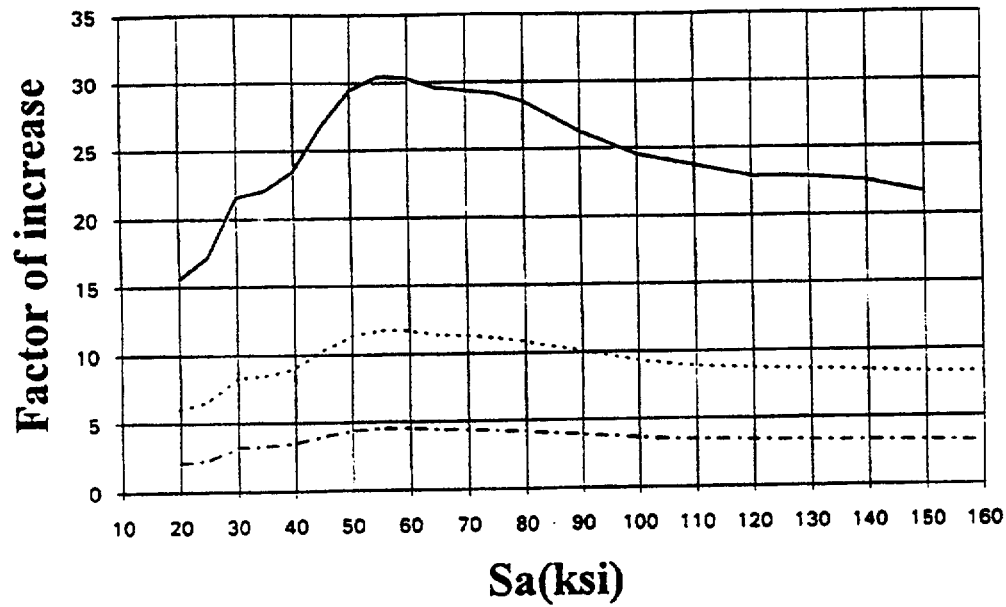


NUREG/CR-6583 Equation 6.5a/6.5b (DO ≥ 0.5 ppm):

$\dot{\epsilon}$ , %/sec	Material	$F_{em}$
≤ 0.001	CS	6.3
0.01	CS	4.1
0.1	CS	2.6
≤ 0.001	LAS	8.9
0.01	LAS	5.7
0.1	LAS	3.7

Figure A-3. Environmental Correction Factor in NUREG/CR-6260 Compared to NUREG/CR-6583 Recommendation for Carbon and Low-Alloy Steel in High Oxygen Environment at 200°C

NUREG/CR-6260 Figure 3-9 (DO > 0.1 ppm):



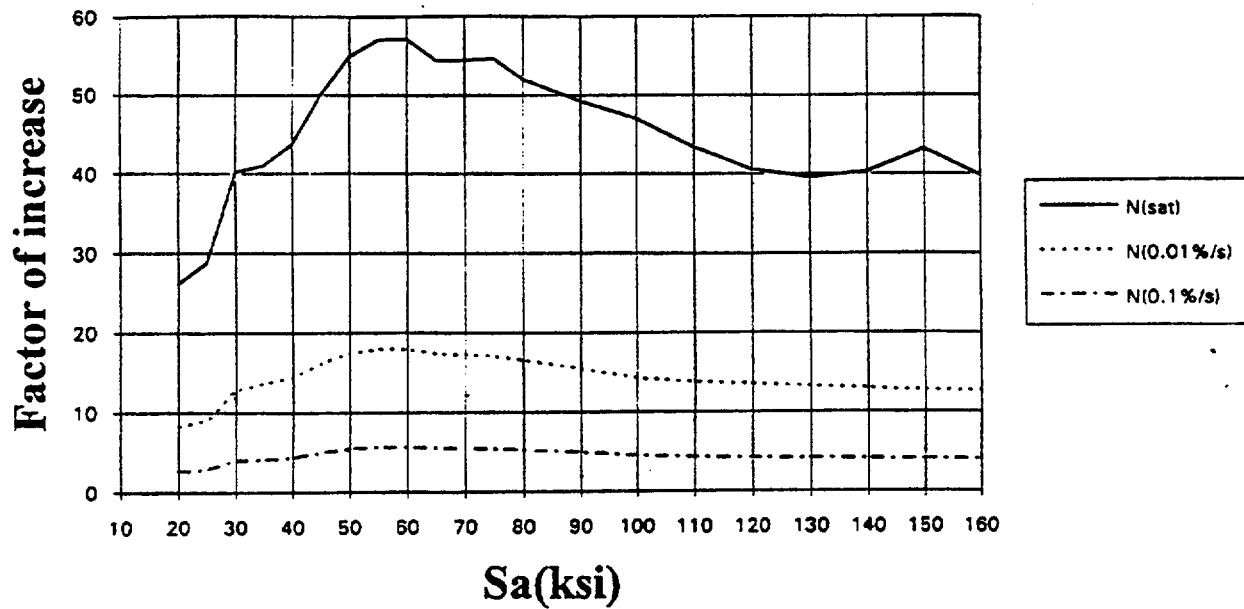
NUREG/CR-6583 Equation 6.5a/6.5b (DO ≥ 0.5 ppm):

$\dot{\epsilon}$ , %/sec	Material	$F_{en}$
≤ 0.001	CS	27.3
0.01	CS	9.23
0.1	CS	3.8
≤ 0.001	LAS	31.4
0.01	LAS	13.0
0.1	LAS	5.4

Figure A-4. Environmental Correction Factor in NUREG/CR-6260 Compared to NUREG/CR-6583 Recommendation for Carbon and Low-Alloy Steel in High Oxygen Environment at 250°C.



NUREG/CR-6260 Figure 3-10 (DO > 0.1 ppm):



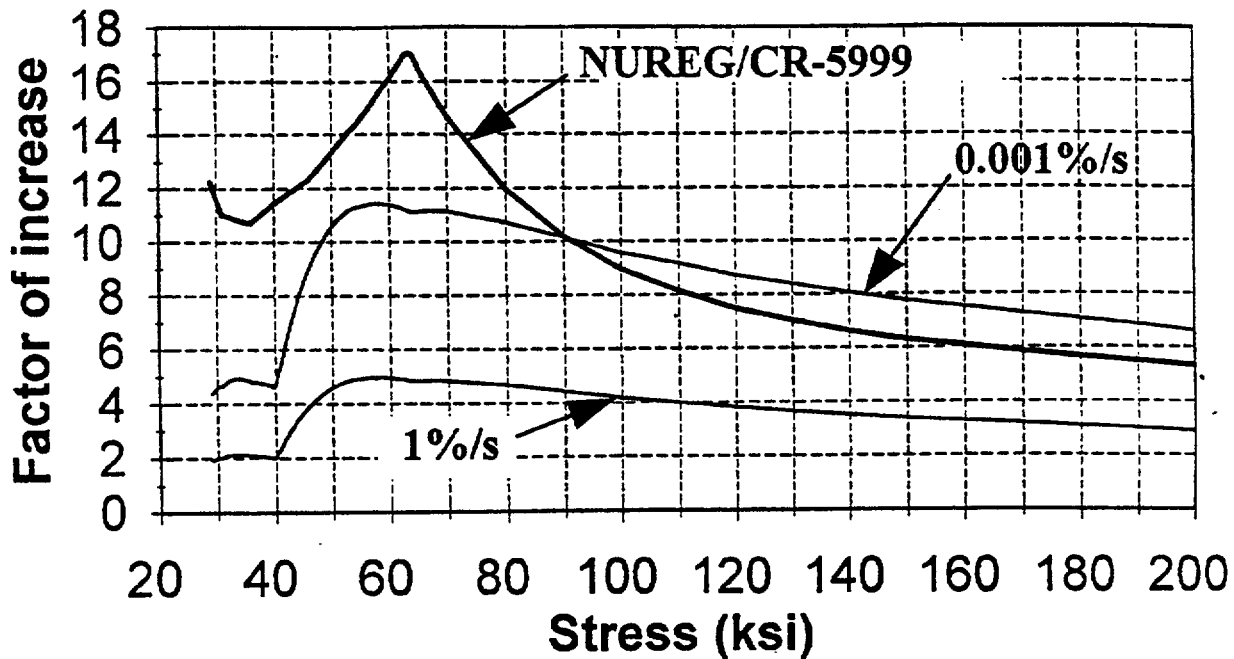
Note: Mean "Factor of Increase" estimated to be  $\approx 45$  for N(Sat)

NUREG/CR-6583 Equation 6.5a/6.5b (DO  $\geq 0.5$  ppm)

$\dot{\epsilon}$ , %/sec	Material	$F_{en}$
$\leq 0.001$	CS	58.1
0.01	CS	17.2
0.1	CS	5.1
$\leq 0.001$	LAS	81.9
0.01	LAS	24.3
0.1	LAS	7.2

Figure A-5. Environmental Correction Factor in NUREG/CR-6260 Compared to NUREG/CR-6583 Recommendation for Carbon and Low-Alloy Steel in High Oxygen Environment at 288°C

NUREG/CR-6260 Figure 3-19:



Note: Curves for 1%/s and 0.001 %/s were revised curves considered in NUREG-6260

NUREG/CR-5704 Eq. 13:

$\dot{\epsilon}, \%/sec$	DO, ppm	$F_{en}$
$\leq 0.0004$	$< 0.05$	15.4
0.001	$< 0.05$	12.1
0.004	$< 0.05$	8.4
0.04	$< 0.05$	4.6
0.4	$< 0.05$	2.5
$\leq 0.0004$	$\geq 0.05$	8.4
0.004	$\geq 0.05$	5.6
0.04	$\geq 0.05$	3.8
0.1	$\geq 0.05$	3.6
0.4	$\geq 0.05$	2.5

Figure A-6. Fatigue Life Correction Factor In NUREG/CR-6260 Compared to NUREG/CR-5704 Recommendation for Stainless Steel Curves

Table A-1

Approximate Increase or Decrease in NUREG/CR-6260 Usage Factors Accounting for  
NUREG/CR-5704 and NUREG/CR-6583 Environmental Factors

Environment	Change, Percent		
	Carbon Steel	Low-Alloy Steel	Stainless Steel
BWR (high O <sub>2</sub> ) <sup>1</sup>	+30	+80	-25
PWR (low O <sub>2</sub> )	-25	0	+40

Note 1: These factors might not be applicable at some locations for BWRs with Hydrogen Water Chemistry.

### 3.0 EVALUATION OF NUREG/CR-6260 CUF SUMMARIES

The following evaluates the usage factor summaries provided in NUREG/CR-6260 for each of the reactor types addressed. The objective is to provide some insight into the relative importance of the locations as candidates for fatigue management in the extended operating period.

In evaluating the NUREG/CR-6260 summary tables, some additional information was found from the text description. This has been reported where significant. The 60-year extrapolations are not shown herein, since in most applications, the 60-year design cycles are the same as those expected for 40 years. On the other hand, if the 40-year CUF predictions in NUREG/CR-6260 were based on expected cycles, it would be appropriate to mentally compare these to a limit of CUF = 0.666 (at 40-years) to compare with a limit of CUF = 1.0 (at 60 years), or alternately multiply the 40-year CUF by a factor of 1.5.

In the previous section, the assessment of the effect of more recent environmental fatigue testing was approximated because the environmental factor was stress dependent. In the following, the NUREG/CR-6260 CUFs are re-evaluated to estimate the effect of later data. In these assessments, the environmental CUFs less than 0.5 (at 60 years) can be assumed to require no additional assessment in a license renewal application. This assumption provides for a factor of two uncertainty in the assessment.

Thus, in calculating an estimated 60-year usage factor accounting for new data, the following formula is used:

$$CUF_{new} = F_{fen} \times F_{60} \times CUF_{old}$$

where:

$CUF_{old}$	=	usage factor from NUREG/CR-6260
$F_{fen}$	=	factor relating new environmental data fatigue curve to that used in NUREG/CR-6260
$F_{60}$	=	factor to extrapolate to 60 years
	=	1.0 if $CUF_{old}$ based on design cycles

$$= 1.5 \text{ CUF}_{\text{old}} \text{ based on expected cycles at 40 years}$$

### 3.1 Newer Vintage Combustion Engineering Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-2. The locations evaluated were either stainless steel or low-alloy steel. Since the plant is a PWR, low oxygen would be expected. From Table A-1, the reported usage factors are assumed to be unchanged for the low-alloy steel locations and increased by about 40 percent for the stainless steel locations.

Table A-3 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-2

Summary of Newer Vintage Combustion Engineering Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Lower head / shell	LAS	0.007	0.014	(1)	(1)	N/A
	Inlet nozzle	LAS	0.182	0.475	(1)	(1)	N/A
	Outlet nozzle	LAS	0.377 (0.334) <sup>2</sup>	0.835	(1)	0.472	N/A
Surge line	Elbow	Stainless steel	0.981	8.684	(1)	3.476	2.597
Charging nozzle	Nozzle	LAS	0.050	0.104	(1)	(1)	N/A
	Safe end	Stainless steel	0.778	4.193	2.556	0.774	0.502
Safety injection nozzle	Nozzle	LAS	0.898	2.101	(1)	0.457	N/A
	Safe end	Stainless steel	0.360	3.215	1.609	0.387	0.286
Shutdown cooling line	Elbow	Stainless steel	0.894	6.100	2.030	0.502	0.487

Note (1): No additional calculations were performed.

(2): Outer surface CUF = 0.377, inner surface CUF = 0.334



Table A-3

Revised Estimate of NUREG/CR-6260 CUFs for New Vintage Combustion Engineering Plant

Location	CUF <sub>new</sub>
Vessel Head/Shell*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.014 = 0.014$
Vessel Inlet Nozzle*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.475 = 0.475$
Vessel Outlet Nozzle	Expected CUF <sub>new</sub> = $1.0 \times 1.5 \times 0.472 = 0.71$
Surge Line Elbow	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 3.476 = 7.30$
Charging Nozzle*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.104 = 0.104$
Charging Safe-End	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.774 = 1.62$
SI Nozzle	Expected CUF <sub>new</sub> = $1.0 \times 1.5 \times 0.475 = 0.72$
SI Safe-end	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.387 = 0.81$
SDC Elbow	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.502 = 1.05$

\* Locations with CUF low enough that further evaluation not required.

### 3.2 Older Vintage Combustion Engineering Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-4. The locations evaluated were either stainless steel or low-alloy steel. Since the plant is a PWR, low oxygen would be expected. From Table A-1, the reported usage factors will remain unchanged for the low-alloy steel locations and increased by about 40 percent for the stainless steel locations.

Table A-5 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-4

Summary of Older Vintage Combustion Engineering Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Lower head to shell juncture	LAS	0.008	0.013	(1)	(1)	N/A
	Inlet nozzle	LAS	0.073	0.172	(1)	(1)	N/A
	Outlet nozzle	LAS	0.284	0.554	(1)	(1)	N/A
Surge line	Elbow	Stainless steel	0.705	8.070	(1)	1.345	0.661
Charging nozzle	Nozzle	Stainless steel	0.266	3.918	(1)	0.666	0.562
Safety injection nozzle	Nozzle	Stainless steel	0.088	1.320	(1)	0.414	0.317
Shutdown cooling line	Inlet transition	Stainless steel	0.014 <sup>(2)</sup>	0.139	(1)	(1)	0.084

Note (1): No additional calculations were performed.

Note (2): Estimated by INEL. CUF calculation not required by licensing basis.



Table A-5

Revised Estimate of NUREG/CR-6260 CUFs for Older Vintage Combustion Engineering Plant

Location	CUF <sub>new</sub>
Vessel lower head/Shell*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.013 = 0.013$
Vessel Inlet Nozzle*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.172 = 0.17$
Vessel Outlet Nozzle	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.554 = 0.55$
Surge Line Elbow	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 1.345 = 2.82$
Charging Nozzle	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.666 = 1.40$
SI Nozzle	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.414 = 0.87$
SDC Inlet*	Design CUF <sub>new</sub> = $1.4 \times 1.0 \times 0.139 = 0.20$

\* Locations with CUF low enough that further evaluation not required.

### 3.3 B&W 177 Fuel Element Assembly Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-6. The locations evaluated were either stainless steel, low-alloy steel, carbon steel or Alloy 600. Since the plant is a PWR, low oxygen would be expected. From Table A-1, the reported usage factors will remain unchanged for the low-alloy steel locations and increased by about 40 percent for the stainless steel locations. The carbon steel location usage factor will be reduced by 25 percent. It will be assumed that the Alloy 600 location remains applicable.

Table A-7 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-6  
Summary of B&W 177 Fuel Assembly Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Near support skirt juncture	LAS	0.120	0.223	(1)	(1)	N/A
	Lower head penetration weld	Ni-Cr-Fe	0.097	1.466	(1)	0.742	0.546
	Outlet nozzle	LAS	0.900	2.148	0.469	(1)	N/A
Surge line	Hot leg nozzle	Carbon steel	0.592	1.092	(1)	0.470	N/A
	Pipe elbow	Stainless steel	0.490	4.656 <sup>(2)</sup>	(1)	2.005	1.338
Makeup/HPI nozzle	Safe end	Stainless steel	0.740	3.977	(1)	1.263	1.051
Core flood nozzle	Nozzle	LAS	0.345	0.632	(1)	(1)	N/A
Decay heat removal line <sup>(3)</sup>	Reducing tee	Stainless Steel	3.310	14.209	1.296	0.610	0.530

Note (1): No additional calculations were performed.

Note (2): Based on multiplier from other four PWR plant surge lines.

Note (3): From alternate B&W 177 fuel assembly plant.

Table A-7

Revised Estimate of NUREG/CR-6260 CUFs for B&amp;W 177 Fuel Element Assembly Plant

Location	CUF <sub>new</sub>
Vessel at Support*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.223 = 0.22$
Lower Head Penetration	Expected CUF <sub>new</sub> = $1.0 \times 1.5 \times 0.742 = 1.11$
Outlet Nozzle*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.469 = 0.47$
Surge Line Nozzle*	Expected CUF <sub>new</sub> = $0.75 \times 1.5 \times 0.47 = 0.50$
Surge Line Elbow	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 2.005 = 4.21$
HPI/Makeup Nozzle	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 1.263 = 2.65$
Core Flood Nozzle	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.632 = 0.63$
Decay Heat Tee	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 0.61 = 1.28$

\* Locations with CUF low enough that further evaluation not required.

### 3.4 Newer Vintage Westinghouse Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-8. The locations evaluated were either stainless steel or low-alloy steel. Since the plant is a PWR, low oxygen would be expected. From Table A-1, the reported usage factors should remain unchanged for the low-alloy steel locations and increased by about 40 percent for the stainless steel locations.

Table A-9 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-8  
Summary of Newer Vintage Westinghouse Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Lower head to shell juncture	LAS	0.012	0.018	(1)	(1)	N/A
	Inlet nozzle	LAS	0.110	0.290	(1)	(1)	N/A
	Outlet nozzle	LAS	0.398	0.658	(1)	(1)	N/A
Surge line	Hot leg nozzle	Stainless steel	0.743	7.562	(1)	2.458	1.734
Charging nozzle	Nozzle	Stainless steel	0.829	5.188	4.859	(1)	3.373
Safety injection nozzle	Nozzle	Stainless steel	0.966	4.874	4.145	1.511	1.460
Residual heat removal line	Inlet transition	Stainless steel	0.896 <sup>(2)</sup>	5.727	(1)	2.371	2.733

Note (1): No additional calculations were performed.

(2): Without stratification, CUF = 0.243



Table A-9

Revised Estimate of NUREG/CR-6260 CUFs for Newer Vintage Westinghouse Plant

Location	CUF <sub>new</sub>
Vessel Head Junction*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.018 = 0.02$
Vessel Inlet Nozzle*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.29 = 0.29$
Vessel Outlet Nozzle	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.658 = 0.68$
Surge Line Nozzle	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 2.458 = 5.16$
Charging Nozzle	Design CUF <sub>new</sub> = $1.4 \times 1.0 \times 4.859 = 6.80$
SI Nozzle	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 1.511 = 3.17$
RHR Inlet	Expected CUF <sub>new</sub> = $1.4 \times 1.5 \times 2.371 = 4.98$

\* Locations with CUF low enough that further evaluation not required.

### 3.5 Older Vintage Westinghouse Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-10. The locations evaluated were either stainless steel or low-alloy steel. Since the plant is a PWR, low oxygen would be expected. From Table A-1, the reported usage factors should remain unchanged for the low-alloy steel locations and increased by about 40 percent for the stainless steel locations.

Table A-11 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-10  
Summary of Older Vintage Westinghouse Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Core support guide weld	LAS	0.290	0.891	(1)	(1)	N/A
	Inlet nozzle	LAS	0.208 <sup>(3)</sup> (0.135)	0.496 <sup>(3)</sup> (0.302)	(1)	(1)	N/A
	Outlet nozzle	LAS	0.431 (0.193)	1.161 (0.499)	(1)	0.347	N/A
Surge line	Hot leg nozzle safe end	Stainless steel	0.900	6.814	(1)	5.860	4.248
Charging nozzle	Nozzle inlet	Stainless steel	0.030 <sup>(2)</sup>	0.349	(1)	(1)	0.319
Safety injection nozzle	Nozzle-to-pipe weld	Stainless steel	0.046 <sup>(2)</sup>	0.416	(1)	0.410	0.327
Residual heat removal line	Tee	Stainless steel	0.022 <sup>(2)</sup>	0.286	(1)	(1)	0.205

Note (1): No additional calculations were performed.

Note (2): Estimated by INEL. CUF calculation not required by licensing basis.

Note (3) Outside surface; numbers in parentheses are inside surface





Table A-11

Revised Estimate of NUREG/CR-6260 CUFs for Older Vintage Westinghouse Plant

Location	CUF <sub>new</sub>
Vessel Support Weld	Design CUF <sub>new</sub> = 1.0 x 1.0 x 0.891 = 0.89
Vessel Inlet Nozzle	Design CUF <sub>new</sub> = 1.0 x 1.0 x 0.496 = 0.50
Vessel Outlet Nozzle	Expected CUF <sub>new</sub> = 1.0 x 1.5 x 0.347 = 0.52
Surge Line Safe-End	Expected CUF <sub>new</sub> = 1.4 x 1.5 x 5.86 = 12.31
Charging Nozzle Inlet*	Design CUF <sub>new</sub> = 1.4 x 1.0 x 0.349 = 0.49
SI Nozzle Weld	Design CUF <sub>new</sub> = 1.4 x 1.0 x 0.416 = 0.58
RHR Tee*	Design CUF <sub>new</sub> = 1.4 x 1.0 x 0.286 = 0.40

\* Locations with CUF low enough that further evaluation not required.

### 3.6 Newer Vintage GE Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-12. The locations evaluated were either Alloy 600, stainless steel, carbon steel or low-alloy steel. Since the plant is a BWR, high oxygen would be expected. From Table A-1, the reported usage factors should be increased by about 80 percent for the low-alloy steel locations, increased by about 30 percent for carbon steel locations and decreased by about 25 percent for the stainless steel locations. It will be assumed that the environmental effects for the Alloy 600 locations remain applicable.

Table A-13 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects:

Table A-12  
Summary of Newer Vintage GE Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Anticipated Cycles	
Reactor vessel	Near CRDM penetration	LAS	0.200	11.702	0.628	(1)	N/A
	CRDM penetration weld	Ni-Cr-Fe	0.407	2.716	0.474	(1)	0.359
Surge line	Thermal sleeve	Ni-Cr-Fe	0.795	5.141	(1)	8.322	6.471
	Safe end	Carbon steel	0.301	1.730	1.085	1.881	N/A
Recirculation system	Tee on suction pipe	Stainless steel	0.298	2.154	0.830	(1)	0.746
Core spray line	Nozzle thermal sleeve	Ni-Cr-Fe	0.165	0.943	(1)	0.517	0.637
	Safe end extension	Carbon steel	0.050	0.675	0.436	(1)	N/A
RHR line	Straight pipe	Carbon steel	0.407	11.260 (2)	(1)	(1)	N/A
Feedwater line	Elbow	Carbon steel	0.435	3.746	3.688	(1)	N/A

Note (1): No additional calculations were performed.

Note (2): Heavily influenced by thermal stratification transient and insufficient information to determine strain rate.

Table A-13

Revised Estimate of NUREG/CR-6260 CUFs for Newer Vintage GE Plant

Location	CUF <sub>new</sub>
Vessel at CRDM Penetration	Design CUF <sub>new</sub> = $1.8 \times 1.0 \times 0.628 = 1.13$
CRDM Weld*	Design CUF <sub>new</sub> = $1.0 \times 1.0 \times 0.474 = 0.47$
FW Thermal Sleeve	Expected CUF <sub>new</sub> = $1.0 \times 1.5 \times 8.322 = 12.48$
FW Safe-End	Design CUF <sub>new</sub> = $1.3 \times 1.0 \times 1.085 = 1.41$
Recirculation Tee	Design CUF <sub>new</sub> = $0.75 \times 1.0 \times 0.83 = 0.62$
CS Thermal Sleeve	Expected CUF <sub>new</sub> = $1.5 \times 1.0 \times 0.517 = 0.77$
CS Safe-End	Design CUF <sub>new</sub> = $1.3 \times 1.0 \times 0.436 = 0.57$
RHR Pipe	Design CUF <sub>new</sub> = $1.3 \times 1.0 \times 11.26 = 14.63$
FW Elbow	Design CUF <sub>new</sub> = $1.3 \times 1.0 \times 3.688 = 4.79$

\* Locations with CUF low enough that further evaluation not required.

### 3.7 Older Vintage GE Plant

The summary of the NUREG/CR-6260 environmental evaluation is shown in Table A-14. The locations evaluated were either Alloy 600, stainless steel, carbon steel or low-alloy steel. Since the plant is a BWR, high oxygen would be expected. From Table A-1, the reported usage factors should be increased by about 80 percent for the low-alloy steel locations, increased by about 30 percent for carbon steel locations and decreased by about 25 percent for the stainless steel locations.

Table A-15 shows either the design usage factors or the 60-year expected usage factors, corrected for environmental effects.

Table A-14  
Summary of Older Vintage GE Plant CUFs (40 Year Life)

Component	Location	Material	Design CUF	NUREG/CR-5999 CUF			Revised SS Curve
				Based on Design Stresses and Cycles	Conservative Assumptions Removed	Based on Expected Cycles	
Reactor vessel	Lower head to shell penetration	LAS	0.032	2.063	0.079	(1)	N/A
Feedwater nozzle	Bore	LAS	0.700	9.859	(1)	3.168	N/A
Recirculation system (3)	RHR return line tee	Stainless steel	0.397 / 0.526 <sup>(2)</sup>	2.901	(1)	3.898	3.256
Core spray line	Nozzle	LAS	0.023	0.441	(1)	0.520	N/A
	Safe end	Stainless steel	0.182	1.778	(1)	2.305	1.772
RHR line (3)	Tapered transition	Stainless steel	0.032 / 0.045 <sup>(2)</sup>	0.366	(1)	0.523	0.478
Feedwater line (3)	RCIC tee	Carbon Steel	0.427 / 0.584 <sup>(2)</sup>	5.016	(1)	6.980	N/A

Note (1): No additional calculations were performed.

Note (2): CUFs based on representative design basis and anticipated number of cycles, respectively.

Note (3): Estimated by INEL using ASME Code NB-3600 techniques. CUF calculation not required by licensing basis.

Table A-15

Revised Estimate of NUREG/CR-6260 CUFs for Older Vintage GE Plant

Location	CUF <sub>new</sub>
Vessel lower Head Penetration	Design CUF <sub>new</sub> = $1.8 \times 0.079 = 0.14$
FW Nozzle Bore	Expected CUF <sub>new</sub> = $1.8 \times 1.5 \times 3.168 = 7.13$
Recirculation/RHR Tee	Expected CUF <sub>new</sub> = $0.75 \times 1.5 \times 3.898 = 4.38$
CS Nozzle	Expected CUF <sub>new</sub> = $1.8 \times 1.5 \times 0.52 = 1.4$
CS Safe-End	Expected CUF <sub>new</sub> = $0.75 \times 1.5 \times 2.305 = 2.59$
RHR Transition	Expected CUF <sub>new</sub> = $0.75 \times 1.5 \times 0.523 = 0.59$
FW RCIC Tee	Expected CUF <sub>new</sub> = $1.3 \times 1.5 \times 6.98 = 13.60$

\* Locations with CUF low enough that further evaluation not required.

## 4.0 CONCLUSIONS

This evaluation of the NUREG/CR-6260 results has provided an update of the expected usage factors at the end of 60 years, this addresses the differences between the environmental correction factors in NUREG/CR-5999 and those available from later fatigue test evaluation. Based on this evaluation, a specific set of locations have been identified for exclusion from further consideration:

Newer Vintage CE	Vessel Head/Shell Vessel Inlet Nozzle
Older Vintage CE:	Vessel Lower Head/Shell Vessel Inlet Nozzle SDC Inlet
B&W:	Vessel at Support Outlet Nozzle Surge Line Nozzle
Newer Vintage Westinghouse	Vessel Head Junction Vessel Inlet Nozzle
Older Vintage Westinghouse	Charging Nozzle Inlet RHR Tee
Newer Vintage GE	CRDM Weld
Older Vintage GE	Vessel Lower Head Penetration

Each applicant should review the plant specific evaluations of these locations to determine if differences in geometry and design/expected loadings would require those locations excluded herein to be considered. In addition, plant specific or other industry evaluations could possibly show that other locations can be excluded from further consideration.

## 5.0 REFERENCES

- A1. NUREG/CR-6260 (INEL-95/0045), "Application of NUREG/CR-5999 Interim Fatigue Curves to Selected Nuclear Power Plant Components," March 1995.
- A2. NUREG/CR-5999 (ANL-93/3), "Interim Fatigue Design Curves for Carbon, Low-Alloy, and Austenitic Stainless Steels in LWR Environments," April 1993.

- A3. NUREG/CR-6583 (ANL-97/18), "Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels," March 1998.
- A4. NUREG/CR-5704 (ANL-98/31), "Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels," April 1999

# **B**

## **PVRC RECOMMENDATIONS FOR EVALUATING REACTOR WATER ENVIRONMENTAL FATIGUE EFFECTS**

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The steering committee on Cyclic Life and Environmental Effects (CLEE) of the Pressure Vessel Research Council (PVRC) has been studying the effects of reactor water environment on fatigue for several years. They have endorsed a revised form of the EPRI/GE methodology for fatigue evaluation methodology [1].

A Non-mandatory Code Appendix has been forwarded to the Board of Nuclear Codes and Standards (BNCS) [2]. The CLEE position and the rationale for the latest methodology are discussed in a recent Pressure Vessel and Piping Conference paper [3]. The proposed Non-Mandatory Code Appendix as recommended by PVRC is reproduced in this Appendix. This approach is recommended for performing assessments of environmental effects on usage factors for reactor components.

### **REFERENCES**

1. "An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations," TR-105759, EPRI, Palo Alto, CA, December 1995.
2. Letter from Greg Hollinger (PVR) to J. H. Ferguson, Chairman Board of Nuclear Codes and Standards, October 31, 1999.
3. Mehta, H. S., "An Update on the Consideration of Reactor Water Effects in Code Fatigue Initiation Evaluations for Pressure Vessels and Piping," PVP-Vol. 410-2, p45-51, American Society of Mechanical Engineers, 2000.



## NONMANDATORY APPENDIX XX

## FATIGUE EVALUATIONS INCLUDING ENVIRONMENTAL EFFECTS

ARTICLE X-1000SCOPE

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

X-1100 ENVIRONMENTAL FATIGUE CORRECTION

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

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

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

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

X-1200 ENVIRONMENTAL FACTOR DEFINITION

X-1210 The nominal values of environmental fatigue correction factors are to be calculated using the expressions below.

## Carbon Steel

$$F_{en,nom} = [\exp (0.559 - 0.101S \cdot T \cdot O \cdot \epsilon' \cdot *)] \quad (1)$$

## Low Alloy Steel

$$F_{en,nom} = [\exp (0.903 - 0.101S \cdot T \cdot O \cdot \epsilon' \cdot *)] \quad (2)$$

## Stainless Steels (wrought and cast)

$$F_{en, nom} = \exp [0.935 - T * O * \varepsilon^{**}] \quad (3)$$

X-1260 The effective environmental fatigue correction factor,  $F_{en}$ , is obtained by dividing the nominal value calculated in X-1210 with a material-specific factor which accounts for moderate environmental fatigue effects already included in the S-N curves of Figures I-9.1 and I-9.2.

$$F_{en} = F_{en, nom} / Z, \text{ but no less than } 1.0$$

Where,  $Z = 3.0$  for carbon and low alloy steels and  $1.5$  for wrought and cast stainless steels.

### X-1300 EVALUATION PROCEDURES

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

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

### X-1400 NOMENCLATURE

The symbols adopted in this Appendix are defined as follows:

E	= Young's Modulus, psi
$F_{en}$	= Effective environmental correction factor applied to fatigue usage calculated using Code fatigue curves
$F_{en}(\tau)$	= Environmental correction factor calculated at a specific instant in time, $\tau$ .
$F_{en, int}$	= Environmental correction factor based on integrated approach.
DO	= Dissolved oxygen content of water (ppm)
O*	= Transformed oxygen content
S	= Sulfur content of carbon and low-alloy steels, weight %
S*	= Transformed sulfur content
$S_{alt}$	= Alternating stress amplitude, psi
$S_{range}$	= Range of stress intensity associated with a transient cycle, psi

$T$	= Temperature ( $^{\circ}\text{C}$ )
$T^*$	= Transformed temperature.
$T_a$	= Average temperature on side 'a' during a temperature transient
$T_b$	= Average temperature on side 'b' during a temperature transient
$T_c$	= Sum of $ T_a - T_b $ , $ \Delta T_1 $ and $ \Delta T_2 $ for temperature transient producing compressive stresses at the component surface in contact with fluid
$T_m$	= Metal temperature during a temperature transient at surface in contact with fluid
$T_t$	= Sum of $ T_a - T_b $ , $ \Delta T_1 $ and $ \Delta T_2 $ for temperature transient producing tensile stresses at the component surface in contact with water
$\Delta T_1$	= Linear temperature gradient through a component wall during a temperature transient
$\Delta T_2$	= Nonlinear temperature gradient through a component wall during a temperature transient
$t_t$	= Elapsed time between the start of temperature transient and the time when $T_t$ is reached, seconds
$t_{T,th}$	= Elapsed time between the start of decreasing temperature transient and the time when metal surface in contact with fluid reaches threshold temperature, seconds
$U_{en}$	= Cumulative fatigue usage factor including the environmental effects
$U_i$	= Cumulative fatigue usage factor for load set pair 'i' obtained by using Code fatigue curves
$\epsilon_i$	= Strain range for load set pair $i$ , %
$\epsilon'$	= Strain rate, %/second
$\epsilon'^*$	= Transformed strain rate
$\epsilon'^*(\tau)$	= Transformed strain rate at elapsed time equal to $\tau$

## ARTICLE X-2000

### ENVIRONMENTAL FATIGUE THRESHOLD CONSIDERATIONS

X-2000 SCOPE

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

X-2100 STRAIN AMPLITUDE THRESHOLDS

X-2110 The strain amplitude threshold for carbon and low alloy steels is 0.07%.  $F_{en}$  values shall be used at strain amplitudes equal to or exceeding 0.08%. A linear interpolation may be used to calculate  $F_{en}$  values for strain amplitudes between 0.07% and 0.08%.

X-2120 The strain amplitude threshold for wrought and cast stainless steels is 0.10%.  $F_{en}$  values shall be used at strain amplitudes equal to or exceeding 0.11%. A linear interpolation may be used to calculate  $F_{en}$  values for strain amplitudes between 0.10% and 0.11%.

X-2130 Calculate the strain amplitude,  $\epsilon_i$  associated with a type of stress cycle or load set pair 'i' by multiplying the alternating stress intensity  $S_{alt,i}$  by 100 and dividing by the modulus of elasticity E. The value of E shall be obtained from the applicable design fatigue curves of Figs. I-9.0.

X-2140 If the value of  $\epsilon_i$  calculated in X-2130 for a load set pair is less than or equal to appropriate value from X-2110 or X-2120, that load set pair satisfies the threshold criterion and the value of  $F_{en,i}$  is 1.0. No further evaluation with respect to other threshold values need be made for this load set pair.

X-2200 STRAIN RATE THRESHOLD

The strain rate threshold is 1.0%/second for carbon and low alloy steels, and 0.4%/second for wrought and cast stainless steels. A load set pair involving only the seismic loading satisfies the strain rate threshold criterion for strain rate and the value of  $F_{en,i}$  is 1.0. No further evaluation with respect to other threshold values need be made for this type of stress cycle or load set pair.

If the strain rate associated with the tensile stress load set for any other load set pair exceeds the threshold value,  $F_{en}$  is 1.0 for that load set pair.

X-2300 TEMPERATURE THRESHOLD

X-2310 The temperature threshold for carbon and low alloy steels is 150°C.

X-2320 The temperature threshold for wrought and cast stainless steels is 180°C.

X-2330 Define the effective temperature,  $T$  associated with a type of stress cycle or load set pair 'i' as equal to the higher of the highest temperatures in the two transients or load sets constituting the type of stress cycle or load set pair.

X-2340 If the temperature calculated in step (b) is less than or equal to the threshold value, the stress cycle or load set pair satisfies the threshold criterion for temperature and the value of  $F_{en i}$  is 1.0.

#### X-2400 DISSOLVED OXYGEN THRESHOLD

This is applicable only to carbon and low alloy steels.

(a) Define the effective dissolved oxygen content, DO associated with a type of stress cycle or load set pair 'i' as equal to the higher of the highest oxygen content in the two transients or load sets constituting the type of stress cycle or load set pair.

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

#### ARTICLE X-3000

#### ENVIRONMENTAL FACTOR EVALUATION

#### X-3100 SCOPE

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

#### X-3200 EVALUATION PROCEDURE FOR DESIGN BY ANALYSIS

#### X-3210 Determination of Transformed Strain Rate

X-3211 The strain rate (%/sec) for a stress cycle is determined as the following:

$$\epsilon' = S_{\text{range } i} \cdot 100 / E \cdot t_{\text{max}}$$

where,  $S_{\text{range } i}$  is the stress difference range for cycle 'i' as determined in NB-3224.4(e)(5) and the  $t_{\text{max}}$  is the time in seconds when the stress difference reaches a maximum from the start of the temperature transient. This calculation is performed only for the step down temperature transient or other tensile stress producing cycle in the stress cycles constituting a pair.

X-3212 The transformed strain rate  $\epsilon'^*$  for carbon and low alloy steels is obtained as the following:

$$\varepsilon'^* = 0 \quad (\varepsilon' > 1\%/sec)$$

$$\varepsilon'^* = \ln(\varepsilon') \quad (0.001 \leq \varepsilon' \leq 1\%/sec)$$

$$\varepsilon'^* = \ln(0.001) \quad (\varepsilon' < 0.001\%/sec)$$

X-3213 The transformed strain rate  $\varepsilon'^*$  for stainless steels is obtained as the following:

$$\varepsilon'^* = 0 \quad (\varepsilon' > 0.4\%/sec)$$

$$\varepsilon'^* = \ln(\varepsilon'/0.4) \quad (0.0004 \leq \varepsilon' \leq 0.4\%/sec)$$

$$\varepsilon'^* = \ln(0.0004/0.4) \quad (\varepsilon' < 0.0004\%/sec)$$

#### X-3220 Determination of Transformed Temperature

X-3221 The temperature, T associated with a stress cycle 'i' is equal to the higher of the highest metal temperatures in the two transients constituting the stress cycle or load set pair.

X-3222 The transformed temperature  $T^*$  for carbon and low alloy steels is obtained as the following:

$$T^* = 0.0 \quad (T < 150^\circ\text{C})$$

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

X-3223 The transformed temperatures  $T^*$  for stainless steels are obtained as the following:

$$T^* = 0.0 \quad (T \leq 180^\circ\text{C})$$

$$T^* = (T - 180)/40 \quad (180^\circ\text{C} < T < 220^\circ\text{C})$$

$$T^* = 1.0 \quad (T > 220^\circ\text{C})$$

#### X-3230 Determination of Transformed DO

X-3231 For carbon and low alloy steels, the effective dissolved oxygen content, DO associated with a load set pair 'i' is equal to the higher of the highest oxygen level in the two transients constituting the load set. The transformed DO,  $O^*$  is obtained as follows:

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

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

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

X-3232 For wrought stainless steels, the effective dissolved oxygen content, DO associated with a load set pair 'i' is equal to the lower of the oxygen level in the two transients constituting the load set. The transformed DO,  $O^*$  is obtained as follows:

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

$$O^* = 0.172 \quad (DO \geq 0.05 \text{ ppm})$$

X-3233 For cast stainless steels,  $O^* = 0.260$

#### X-3240 Determination of Transformed Sulfur for Carbon & Low Alloy Steels

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

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

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

#### X-3250 Determination of $F_{en}$

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

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

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

### **X-3600 EVALUATION PROCEDURE FOR PIPING**

The procedures in this Article use the input information and the partial fatigue usage results from the NB-3650 fatigue evaluation. The example of specific load set information needed is: internal pressure, the three moment components,  $|T_a - T_b|$ ,  $\Delta T1$  and  $\Delta T2$ . When the detailed results of one-dimensional transient heat transfer analyses are available in the form of time history of  $|T_a - T_b|$ ,  $\Delta T1$  and  $\Delta T2$ , such results may be used to reduce conservatisms in the calculated values of environmental correction factor.

#### X-3610 Determination of Strain Rate

The strain rate (%/sec) for a load set pair 'i' is determined as the following:

$$\varepsilon_i' = 200 \bullet S_{alt\ i} \bullet [T_r / (T_i + T_c)] / (E \bullet t_i)$$

where,  $S_{alt\ i}$  is the alternating stress intensity for load set pair 'i' calculated in NB-3653.3. This calculation is performed only for the step down temperature transient in a load set pair.

The transformed strain rate  $\varepsilon_i'^*$  shall be obtained as described in X-3210.

#### X-3620 Determination of Transformed Temperatures

The transformed temperatures shall be obtained as described in X-3220.

#### X-3630 Determination of Transformed DO

The transformed DO shall be obtained as described in X-3230.

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

The transformed sulfur shall be obtained as described in X-3240.

#### X-3650 Determination of $F_{en}$

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

#### X-3660 Determination of $F_{en}$ Based on Integrated Approach

When the results of detailed transient analyses are available to predict strain rate, such results may be used to reduce conservatisms in the calculated values of  $F_{en}$ . The following expression or equivalent shall be used:

$$F_{en,int} = (1/t_{T,th}) \int_0^{t_{T,th}} [F_{en}(\tau)] d\tau$$

The preceding value of  $F_{en}$  may be used in lieu of the  $F_{en}$  value calculated in X-3650.  $F_{en}(\tau)$  is the appropriate environmental factor derived from X-1200, with time dependent properties/factors for the time in the transient where the temperature exceeds the threshold value.



# C

## MODERATE ENVIRONMENTAL EFFECTS

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### C.1 Introduction

One of the critical issues related to evaluation of reactor water environmental effects on component fatigue life is the credit to be taken for “moderate environmental effects.” The original consideration of this sub-issue began with the development of fatigue design by analysis rules in the ASME Code in the 1960s [1]. Reference 1 states that:

*“The design fatigue curves are based on strain-controlled fatigue tests of small polished specimens. A best-fit to the experimental data was obtained by applying the method of least squares to the logarithms of the experimental values. The design stress values were obtained from the best-fit curves by applying a factor of two on stress or a factor of twenty on cycles, whichever was more conservative at each point. These factors were intended to cover such effects as environment, size effect, and scatter of data, and thus it is not to be expected that a vessel will actually operate safely for twenty times its specified life.”*

Cooper [2] has described the partitioning of the factor of twenty for polished specimens tested in air as follows:

- Data scatter is accommodated by a sub-factor of 2.0;
- Size effects are accommodated by a sub-factor of 2.5; and
- The combination of surface finish and environment are accommodated by a sub-factor of 4.0.

Surface finish and environment are combined because of the potential for the surface and its finish to be affected by the testing environment. The product of the sub-factors equals the factor of twenty.

The term “environment” in References 1 and 2 has been interpreted by many, including the Cyclic Life and Environmental Effects (CLEE) Steering Committee of the Pressure Vessel Research Council (PVRC), to mean “moderate environmental effects.” At issue is the portion of the factor of 20 (at the low cycle end of the fatigue design curve) inherent in the ASME Code Section III explicit fatigue design curves that can be attributed to moderate effects of environment when materials are tested in a simulated reactor water environment. The purpose of this appendix is to propose and justify the following distribution of uncertainty sub-factors that, when taken together, account for a factor of 20 margin against cycles to failure for carbon/low alloy steels, and a factor of 10 against cycles to failure for stainless steels:

- Size Effect = 1.4 for both carbon/low alloy and stainless steels;
- Surface Finish = 2.0 for both carbon/low alloy and stainless steels;

- Data Scatter = 2.4 for both carbon/low alloy and stainless steels; and
- Moderate Environmental Effects = 3.0 for carbon/low alloy steels and 1.5 for stainless steels.

The overall margin at the low-cycle end of the fatigue design curve would be the product of the four sub-factors, in this case equal to a factor of 20 for carbon/low alloy steels and a factor of 10 for stainless steels. The first three of these sub-factors can each be shown to be conservative based upon an evaluation of available test data, leaving the remaining sub-factor to account for moderate environmental effects.

The first sub-factor, for size effects, represents margin needed to account for the difference in fatigue life expected in full-scale components as compared to laboratory test specimens. Chopra and Shack [3] have determined the appropriate value for this factor to be 1.4. There is general industry agreement that this value is conservative.

The second sub-factor, for surface finish, represents margin needed to account for the difference in fatigue life expected in full-scale components with industrial-grade surface finishes, as opposed to the smooth, polished surfaces of laboratory test specimens. The data assembled by Juvinal [4], as shown in Figure C-1 (Figure 26 from Reference 4) show that, for materials with a tensile strength of 75 ksi or less:

- A fatigue correction factor of 0.5 applies for an as-forged component;
- A correction factor of 0.67 applies for a hot-rolled component; and
- A factor of 0.78 applies for a machined surface.

The Juvinal factor of 0.5 for roughness of forgings would require that the component allowable life be divided by a factor of 2.0. The most conservative Juvinal factor is equivalent to the sub-factor of 2.0 for surface finish. Therefore, a surface finish uncertainty sub-factor of 2.0 can be used to conservatively account for commercial-grade finishes on actual components in service. This value is also in general agreement with Chopra and Shack [5], who state the following:

“Because carbon and low-alloy steels and austenitic stainless steels develop a corrosion scale in LWR environments, the effect of surface finish may not be significant, i.e., the effects of surface finish are included in the environmentally assisted decrease in fatigue life in LWR coolant environments. In water, the subfactor on life to account for surface finish effects may be as low as 1.5 or may be eliminated completely ....”

To support this point further, fatigue data for components (with commercial-grade finished surfaces) whose internal surfaces were in contact with water have been plotted in Figures C-2(a) and C-2(b) for KWU tests on tubes and in C-3(a) and C-3(b) for GE pipe tests. Also shown in the figures are the mean fit to the ASME mean air curve and the corresponding ASME Code design curve for the material under consideration. The combination of environment, size effect, surface finish effect, etc. is seen to essentially exhaust the factor of 20 on life between the mean air curve and the design curve. When the environmental effect is removed by using the appropriate expression for  $F_{en}$ , the fatigue data are shifted back toward the mean air curve and

beyond, in some cases. This implies that the size and surface finish effects are essentially negligible. At most, the combination of size and surface finish effects is perhaps a factor of 2. This value compares to 2.8 to 4.2 for the combination as estimated in Reference 3.

The third sub-factor, for data scatter, represents an uncertainty factor to account for expected variability in fatigue life among the population of actual components if they were exposed to identical conditions of environment and applied loading. That is, this sub-factor accounts for the variation in performance among a group of identical components under identical conditions. In this case, the performance is defined in terms of the number of cycles of loading to which a component can be subjected before experiencing a fatigue crack. In order to determine an appropriate estimate of the variability to be expected in real components, the variability that was actually found in fatigue test specimens exposed to like conditions should be evaluated on a statistical basis.

Care must be exercised in performing this evaluation to assure that only one variable is being evaluated at a time. If the test samples representing different test conditions are grouped together, the variation due to these test differences would be added to the true data scatter, thus inflating the apparent statistical variation. Therefore, significant test differences must first be determined, and the test data sorted such that each grouping represents similar test conditions. Then the variability of each grouping should be determined, and the results compared. The highest variability found among any group of similar test samples could be considered a reasonably conservative estimate of variability expected among the population of real components exposed to similar conditions, and can be converted to an uncertainty sub-factor representing data scatter.

The most significant test parameter associated with environmental fatigue testing has been determined to be strain rate. The degree of fatigue life reduction has been found to be greater at relatively low strain rates ( $< 0.4$  %/sec) than at relatively high strain rates ( $\geq 0.4$  %/sec). Therefore, in determining the data scatter uncertainty factor, the test results must first be sorted into groups tested with similar strain rates. Otherwise, if these samples were mixed together and analyzed for variability, the strain rate effect variability would be added to the sample variability being sought.

Tables C-1 to C-5 illustrate the approach used to analyze data scatter found in austenitic stainless steel fatigue data obtained in simulated reactor water environments. For example, Table C-1 contains all of the data from the Japanese data set assembled by Tsutsumi et al. [6] for austenitic stainless steels obtained at or near a strain amplitude of 0.6 % with a tensile strain rate of 0.4 %/sec. Table C-2 contains the data from Reference 6 obtained at or near a strain amplitude of 0.6 % with a tensile strain rate less than 0.4 %/sec. Similarly, the data have been grouped in other tables (C-3 to C-9). Only test results representing similar conditions are included within each table. This sorting reduces the sample size of each grouping which adds to the uncertainty of statistical analysis, but this will be accounted for later in the process.

From statistical analysis of the data, presented in Sections C.3 and C.4, the means and standard deviations of each similar grouping were developed. Where indicated, evaluations were also

made with certain data outliers eliminated. We define the data scatter uncertainty sub-factor (or the data scatter factor for brevity) as the ratio of the sum of the mean plus three times the standard deviation, to the mean, i.e., one plus three times the measure of data scatter, taken as  $\sigma/\text{mean}$ . This factor becomes 1.0 with zero scatter. Then, based on the analyses with obvious outliers eliminated, the highest data scatter factor for any grouping was found to be 2.29. This factor is conservatively adjusted to 2.4. Since the overall safety factor on cycles used in developing the ASME fatigue curve for carbon and low alloy steels was 20, and since sub-factors of 1.4 for size effects, 2.0 for surface roughness, and 2.4 for data scatter have been determined to be conservative, the remainder of the original factor of 20 is available to accommodate moderate environmental effects. By dividing the factor of 20 by the product of  $1.4 \times 2.0 \times 2.4$ , a remaining sub-factor of 3.0 for moderate environmental effects can be derived. This shows that the original factor of 20 on cycles for carbon and low alloy steels includes sufficient margin to account for a sub-factor of 3.0 for moderate environmental effects.

The previous evaluations of the sub-factors for size effects, surface finish, and data scatter were not based upon material type. Therefore, the same uncertainty factors apply for stainless steels as well as for carbon and low alloy steels. However, the original factor on cycles used in developing the ASME curve for stainless steels was only 10. Therefore, the remaining sub-factor for moderate environmental effects for stainless steels is obtained by dividing the overall factor of 10 by the product of  $1.4 \times 2.0 \times 2.4$ , resulting in a sub-factor of 1.5. This shows that the original factor of 10 on cycles for stainless steels includes sufficient margin to account for a sub-factor of 1.5 for moderate environmental effects.

These moderate environmental effects sub-factors for low alloy and stainless steels remain valid even after the latest environmental fatigue test data is analyzed for variability, as has been demonstrated. These sub-factors have been referred to as Z factors in industry discussions. The Z factor is considered to be an available margin which can be used in the determination of acceptability of fatigue evaluations which are calculated using environmentally-adjusted fatigue curves or equations appropriate for the material, oxygen concentration, temperature and strain rate for actual plant components.

## C.2 Supporting Technical Information

Van Der Sluys and Yukawa [7] have provided the PVRC technical position on moderate environmental effects for carbon and low-alloy steels. Their analysis of the collected data in air showed a factor of about 4 to account for temperature effects and for data scatter, leaving a factor of 4 on the ASME mean air data as a reasonable "working" definition of moderate environmental effects. The PVRC CLEE also observed that the appropriate moderate environmental effects factor for austenitic stainless steels is about 2, out of the ASME Code factor of 20 at the low-cycle end of the fatigue design curve. This same margin of around 4 was observed as the actual safety margin in the PVRC fatigue tests on large-scale vessels reported in Reference 1.

Another argument in support of a moderate environmental effects factor of 3 to 4 is provided by the characteristics of equations used to fit the laboratory-simulated environmental fatigue data.

These equations do not revert to the equations used to fit laboratory air data; instead, even for testing conditions such that simulated reactor water environmental effects are minimal, the equations contain an "environmental shift" much greater than 1. For example, the equation that fits reactor water environmental fatigue data for austenitic stainless steels predicts an asymptotic environmental shift of 2.55, even for temperatures below the environmental threshold.

The above reasoning supports a moderate environmental effects factor of at least 3 for carbon and low-alloy steels, and a factor of at least 1.5 for austenitic stainless steels. It should be pointed out that, in their most recent publications, the PVRC (see Appendix B) has also recommended moderate environmental effects sub-factors, or Z factors, of 3 for carbon and low-alloy steel, and 1.5 for austenitic stainless steel.

These moderate environmental factors were used in a number of industry generic studies [8, 9, 10, and 11] that were submitted to the NRC staff for review relative to potential closure of Generic Safety Issue 190. When the PVRC recommended values were used as an adjustment to environmental fatigue calculations, the industry studies found that cumulative usage factors (CUFs) could be shown to remain below 1.0 for 60 years of operation. Discussions between the industry and the NRC staff during the review of the generic studies have indicated a disagreement on this critical issue.

At first, the NRC staff agreed with the modified PVRC recommendation [12] for a moderate environmental factor of 3 (instead of 4) for carbon and low-alloy steels, and a factor of 1.5 (instead of 2) for austenitic stainless steels. More recently, however, the NRC staff has stipulated that no moderate environmental effects factor greater than 1.0 can be credited at all, because of the presumably greater data scatter for laboratory-simulated reactor water environmental effects, relative to the scatter in the air data [13]. While the scatter in the fatigue test data in air showed a scatter factor of about  $\pm 2$ , the evaluations of scatter in the fatigue test data in simulated reactor water environments have claimed a scatter factor of about  $\pm 5$ . The NRC staff relied heavily in this judgment on the arguments presented in NUREG/CR-6583 [3]. Reference 3 argued that the size effect portion of the factor of 20 is about 1.4, the surface finish factor is between 2.0 and 3.0, and potential errors in the application of Miner's Rule (loading history) introduces a factor of 1.5 to 2.5. With a data scatter factor of 2.5, the total adjustment ranges between 10.0 and 26.0. Any increase in data scatter beyond a factor of about 2.0 would cause the adjustment to be well above the available factor of 20 on cyclic life at the low-cycle end of the fatigue curves.

Recent evaluations of data from Japanese fatigue testing programs have supported this argument. For example, Tsutsumi et al. [6] have analyzed an extensive set of data on austenitic stainless steels, and have also argued that the data exhibit increased variability. This increased variability, if true, would not permit any allocation of the ASME Code factor of 20 to be assigned to moderate environmental effects, since surface finish, specimen size effects, and other considerations account for the residual factor of 4. A similar argument on data variability has been made by Higuchi [12] for carbon and low-alloy steels. However, the data evaluations seem to be based on a logical inconsistency – the evaluation of data variability also includes varying environmental effects; i.e., the data scatter assessment includes environmental effects variability.

that should be separated statistically from data scatter assessment within a particular water environment data set.

In the following sections, the data for both carbon and low-alloy steels, and for austenitic stainless steels, are reanalyzed with a clear separation between data sets. This is conducted at different environmental conditions, with the intent to separate data scatter within an essentially homogeneous environmental data set from the effects of environmental variability. Section C.3 discusses data scatter evaluations for austenitic stainless steels and Section C.4 discusses data scatter evaluation for carbon and low-alloy steel. Finally, Section C.5 draws conclusions about the portion of the factor of 20 at the low-cycle end of the fatigue design curves that can be attributed to moderate environmental effects.

### C.3 Austenitic Stainless Steel Data Evaluation

In this appendix, the data in Reference 6 have been reanalyzed with a clear separation between data sets at different environmental test conditions. The data set separation begins by dividing the total population of data points at or near a given strain amplitude into a set for which the testing strain rates were relatively high (0.4 %/sec), and a set for which the test strain rate were relatively low (e.g., 0.01 %/sec, 0.04 %/sec, 0.001 %/sec, etc.). Essentially, the first data set contains data points for which the effects of simulated reactor water environments are "moderate," and the second data set contains data points for which the effects of simulated reactor water environments are not moderate. The lack of moderation may vary, but the second data set is analyzed as a single environmental population. Later, the data points in this second data set are shifted, using the  $\ln(N)$  expressions developed by ANL to model the immoderate environmental effects. This permits the data to be compared rationally on an equivalent basis.

For example, at a strain amplitude at or near 0.6 % (say 0.58 % to 0.62 %), the complete data set was, as before, divided into two populations. One population consisted of data points obtained at a relatively high strain rate (0.4 %/sec) and the other population included all of the data points obtained at other (lower) strain rates. Then, the data obtained at strain rates other than 0.4 %/sec were shifted, using the  $\ln(N)$  data fitting formula developed by ANL, as shown below.

For an LWR environment, the data fit is given by

$$\ln(N) = 5.768 - 2.030 \ln(\epsilon_a - 0.126) + T_2^* \eta_1^* O^*,$$

where  $\eta_1^*$ ,  $T_2^*$ , and  $O^*$  are the transformed strain rate, temperature, and dissolved oxygen (DO), respectively, defined as follows:

$$\begin{aligned} \eta_1^* &= 0 & (\eta_1 > 0.4\%/sec) \\ \eta_1^* &= \ln(\eta_1/0.4) & (0.0004 \leq \eta_1 \leq 0.4\%/sec) \\ \eta_1^* &= \ln(0.0004/0.4) & (\eta_1 < 0.0004\%/sec) \end{aligned}$$

$$T_2^* = 0 \quad (T < 200^\circ\text{C})$$

$$T_2^* = 1.0 \quad (T \geq 200^\circ\text{C})$$

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

$$O^* = 0.172 \quad (\text{DO} \geq 0.05 \text{ ppm})$$

It should be noted that  $\eta_1$  is the strain rate and that the normalized strain rate,  $\eta_1^*$ , is 0 for a strain rate of 0.4 %/sec.

The population of data points at or near 0.6 % strain amplitude and a strain rate of 0.4 %/sec consisted of 24 data points (see Table C-1) with strain amplitudes ranging from 0.575 % to 0.61 %. This population had an average value of 1,623 cycles to failure, with a standard deviation of 516 cycles. The ratio of the standard deviation to the mean value was 0.32.

The population of data points at or near 0.6 % strain amplitude and at lower strain rates consisted of 44 data points (see Table C-2) ranging in strain amplitude from 0.58 % to 0.61 %. After the  $\ln(N)$  shift to 0.4 %/sec, the average value was found to be 1,903 cycles to failure, with a standard deviation of 859. However, it was also discovered that the  $\ln(N)$  formula tended to overshift (overcorrect for the environment) for a few data points. In particular, this occurred for cast or welded stainless steels that do not exhibit a substantial decrease in fatigue life in environment. When the first of these (overcorrected) data points was eliminated from the set (now 43 data points), the mean value dropped to 1,837 cycles to failure, with a standard deviation of 747 cycles. Removing the next highest (overcorrected) data point gave a mean value of 1,795 cycles to failure and a standard deviation of 705 cycles. Finally, removing the next highest (overcorrected) data point resulted in a mean value of 1,753 cycles to failure and a standard deviation of 655 cycles. The ratio of the standard deviation to the mean is 0.37. This mean and standard deviation matches very well with the mean and standard deviation for the relatively high strain rate.

In other words, removing three of the 44 data points, representing overcorrected environmental adjustments to fatigue life, allowed the  $\ln(N)$  shift to produce an environmentally-corrected data set that matched the actual data set in statistical properties very closely. Note that if one plus three times the standard deviation divided by the mean is used as the data scatter factor, such factor is approximately  $\pm 2$ , rather than  $\pm 5$ .

The data set at or near 0.6 % strain amplitude is by far the largest and the most reliable data set. However, other data sets were also examined. For example, the data set at or near 0.3 % strain amplitude was also evaluated. There were a total of 43 data points in this data set, 21 data points in the population obtained at a strain rate of 0.4 %/sec (see Table C-3) and 22 data points obtained at lower strain rates (see Table C-4). The same procedure was used as before. For the first population, the mean value of the 21 data points was found to be 9,286 cycles to failure, with a standard deviation of 2,524 cycles. The ratio of the standard deviation to the mean value is 0.27. For the 21 data points obtained at lower strain rates, the mean value of the shifted data was 11,426 cycles, with a standard deviation of 5,614 cycles. Again, it was found that the  $\ln(N)$  formula tended to overcorrect for the environment for some of these specimens. In this case, it

was found that the tendency to overcorrect was more widespread; i.e., many more data points did not reflect very much or any of the presumed environmental effect. When the four most overcorrected data points were removed from the population, the mean value for the remaining 17 data points was 9,172 cycles to failure, with a standard deviation of 2,592 cycles. Again, removing the overcorrected data points results in a mean value and a standard deviation for the shifted data set that matches the statistical properties of the actual 0.4 %/sec data set very closely.

The only other data set of any size is that for a strain amplitude at or near 0.4 % (see Table C-5). The total population consisted of 13 data points, 12 obtained at a strain rate of 0.4 %/sec and only 1 data point obtained at lower strain rates. The mean value for the 12 data points was found to be 4,679 cycles to failure, with a standard deviation of 1,637 cycles. The ratio is 0.35. When the single data point at the lower strain rate is shifted by the  $\ln(N)$  formula, the fatigue life is shifted from 1,561 cycles to 4,073 cycles, reasonably close to the calculated mean value for the actual population.

From the examination of these data, we conclude that the observations of large data scatter for simulated reactor water environmental testing are not warranted. Only by mixing data sets that represent moderate and immoderate environmental effects can large data scatter effects be observed. This data scatter is amplified when environmental-correction formulas are used to shift the data to a common basis, because of the tendency for the environmental shift formulas to overcorrect under some conditions. The overcorrection appears to be more widespread at the lower strain amplitudes. One possible explanation for this tendency to overcorrect at the lower strain amplitudes is the effect of oxidation or passivation layer rupture, or the lack of rupture, during testing at the lower strain amplitudes. The threshold for oxidation/passivation layer rupture has been estimated to be above 0.3 % strain, perhaps with considerable variability. For those specimens that resist oxidation/passivation layer rupture, the overcorrection of the environmental effect obscures the statistical analysis of the data.

The actual data variability for similar materials tested under similar environmental conditions is very small. Similarly, when the data obtained under different environmental conditions is shifted using environmental-correction formulas, the data scatter remains very small, except that the tendency for the environmental-correction formulas to overcorrect under some conditions must be accounted for. In this case, using one plus three times the standard deviation divided by the mean as the data scatter factor, this analysis shows that, for austenitic stainless steels, the actual scatter factor is approximately  $\pm 2$ . This supports the finding by the PVRC that the moderate environmental effect factor is 2 for austenitic stainless steels.

#### **C.4 Carbon and Low-Alloy Steel Data Evaluation**

Laboratory data for carbon and low-alloy steel under simulated reactor water environmental conditions have been collected by PVRC as a part of their studies on cyclic life and environmental effects. These data were provided to EPRI for the data scatter assessment. Again, the data populations were separated into two sets. The first set was those obtained at relatively high strain rate (e.g., 0.4 %/sec), referred to as the moderate environmental effects population. The second set was those obtained at relatively low strain rates, referred to as the immoderate



environmental effects population. Again, this type of separation of data populations permits variability due to data scatter within a population to be isolated from variability caused by stronger reactor water environmental influence.

As with the austenitic stainless steel data, the two populations were further subdivided into subsets with relatively homogeneous testing parameters. For example, data points at reactor operating temperatures (288°C, 300°C, etc.) and at approximately the same strain amplitude (e.g., 0.6 % strain) were grouped together. Much more data was available for low-alloy steels than for carbon steels so that, in some cases, the findings are limited to those applicable to low-alloy steels. The influence of dissolved oxygen (DO) was not found to distort the statistical evaluation, with the exception of the very highest DO levels (8 ppm). The term high DO is used to describe the 8 ppm data, while data at all other DO levels is described as low DO data. Weld data largely fit into the general populations, with the single exception of data from a single Japanese investigator.

As an example, 25 data points were found in the PVRC database for low-alloy (e.g., SA-533B) steel obtained at a relatively high strain rate (0.4 %/sec), at operating temperature (e.g., 288°C), and 0.6 % strain amplitude. Weld data and both high DO and low DO data are included. Of the 25 data points, 11 were included in the high DO subset and 14 were included in the low DO subset. These data are listed in Table C-6. The low DO mean value was found to be 2,378 cycles with an estimated standard deviation of 1,055 cycles. The high DO subset had a mean value of 1,693 cycles with a standard deviation of 419 cycles. The ratio of the standard deviation to the mean value is 0.44 for the low DO population and only 0.25 for the high DO population. The mean value for the combined populations is 2,076 cycles with a standard deviation of 892 cycles. The ratio is 0.43.

The PVRC database contained 8 data points at a strain amplitude of 0.5 %, all from various Japanese investigators with all being low-alloy steels except for one data point. The Japanese data included two high DO data points that fit into the general population. These data points are listed in Table C-7. The mean of the Japanese data was 2,872 cycles with a standard deviation of 850 cycles. The ratio is only 0.30.

The PVRC database contained 16 data points at 0.4 % strain amplitude and moderately high strain rates. All of the data points except one were for low-alloy steel and all came from Japanese investigators. Weld data and high DO data fit into the general population, with the exception of three outliers. These data points were included in the data evaluation. These data points are listed in Table C-8. The data mean for the 16 data points was 6,089 cycles, with a standard deviation of 3,454 cycles. The ratio is 0.57 reflecting the inclusion of three potential outliers and the combined low DO and high DO populations. Excluding the three outliers gives a revised mean of 6,028 cycles with a standard deviation of 2,077 cycles, thereby reducing the ratio to 0.35.

The PVRC database contained 15 data points at 0.3 % strain amplitude and relatively high strain rates. All of the data points came from Japanese investigators. Three data points were for carbon

steel, with 12 data points for low-alloy steel. High DO data, including those for carbon steel piping material, fit into the general population, as did all of the weld data. One data point for low-alloy steel at high DO appeared to be an outlier, but was included in the analysis set. These data points are listed in Table C-9. The data mean was found to be 18,440 cycles with a standard deviation of 9,001 cycles. The ratio for this more inclusive population is 0.49. If the outlier is removed, the mean value 19,600 and standard deviation decreases to 8,094, with a ratio of 0.41.

This evaluation supports the finding by the PVRC that the moderate environmental effect factor is 4 for low alloy and carbon steels. Note that the data scatter in all of these calculations is less than or equal to the data scatter attributed to air environments.

## C.5 Summary

From the examination of these data, it is concluded that the observations of large data scatter for simulated reactor water environmental testing are not warranted. Only by mixing data sets that represent moderate and immoderate environmental effects can large data scatter effects be observed. This relatively low data variability was observed by separating laboratory test data into two populations consisting of a population containing test data obtained at relatively high strain rate (e.g., 0.4 %/sec) and a population containing test data obtained at relatively slow strain rates (e.g., 0.004 %/sec). The implication of this statistical separation is that the relatively high strain rate population exhibits moderate environmental effects, while the relatively slow strain rate population, in general, exhibits a reduction in fatigue life that is greater than moderate.

The statistical analysis of the separated populations shows that:

- Data variability for the relatively high strain rate population is much less than has been reported in the literature when the statistical analyses are based on combined populations. The ratio of the standard deviations to the mean values for both austenitic stainless steels and carbon/low-alloy steels tested at relatively high strain rates is in the range of 0.2 to 0.5, even when the data populations are enlarged to include weld data.
- Very high dissolved oxygen levels do not compromise the relatively high strain rate data variance for austenitic stainless steels and for low-alloy steels. This is true for carbon steels, in general.
- The addition of weld metal fatigue data increased the ratio of standard deviation to mean value in the relatively high strain rate population by about a factor of 2, from a ratio of about 0.25 to about 0.50. In many cases, the most extreme measured values within a strain amplitude population, on both the low side and on the high side, were weld metal data points.
- When the population of data points obtained at relatively low strain rates were shifted, using the  $\ln(N)$  formulas developed by ANL, virtually identical statistical parameters (e.g., mean value, standard deviation) to those for the relatively high strain rate population were

calculated. This was particularly true when a few data points subject to environmental overcorrection were eliminated from the low strain rate population. In other words, one of the items giving rise to estimates of large data scatter is the tendency for a few low strain rate data points that are relatively unaffected by reactor water environments to be overcorrected by the environmental shift formulas, thus skewing the statistical analysis.

The findings from this analysis support the recommendations of PVRC that moderate environmental effects factors of 3 for carbon and low-alloy steel, and 1.5 for austenitic stainless steels, are conservative. Greater moderate environmental effects factors can be justified.

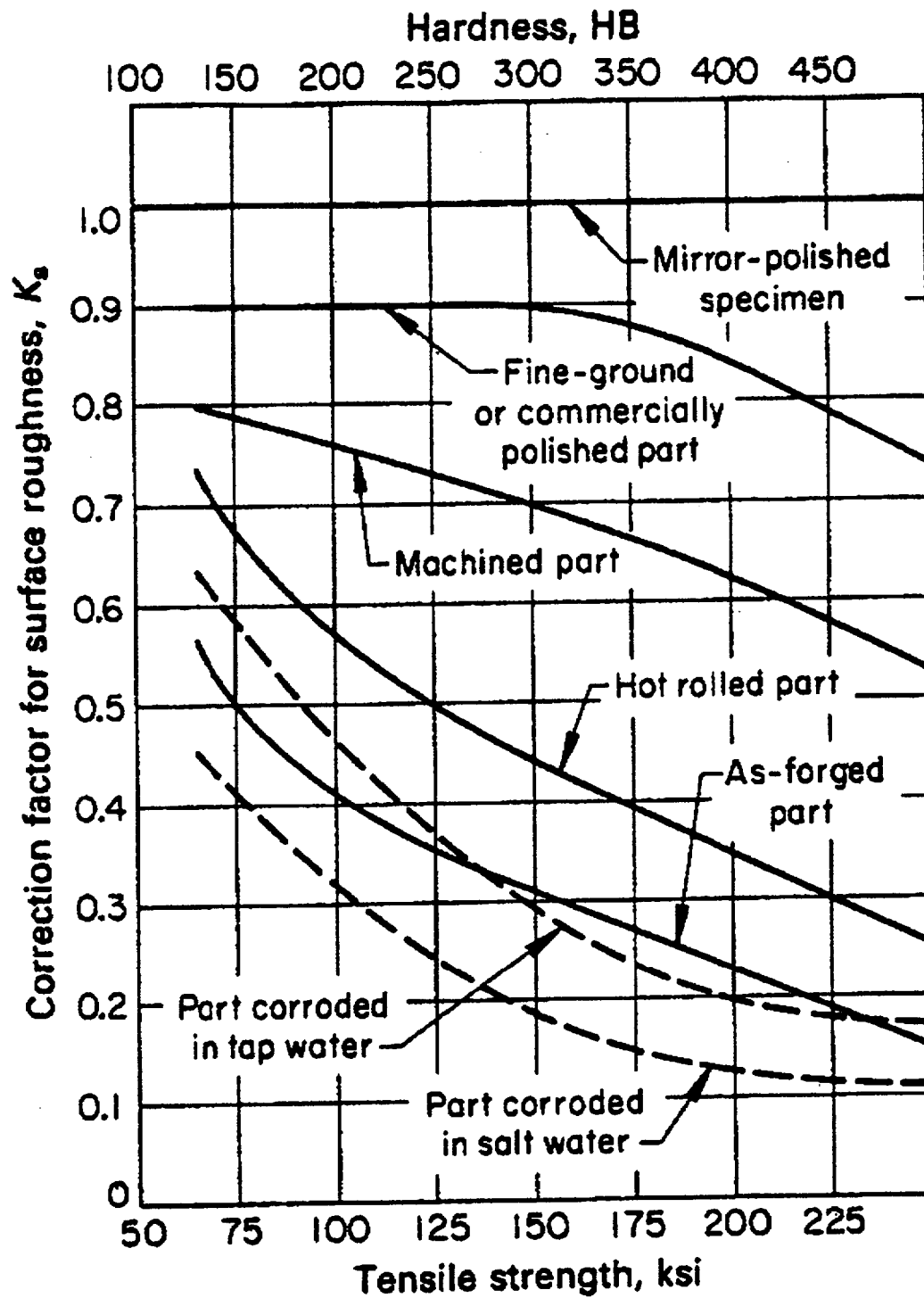
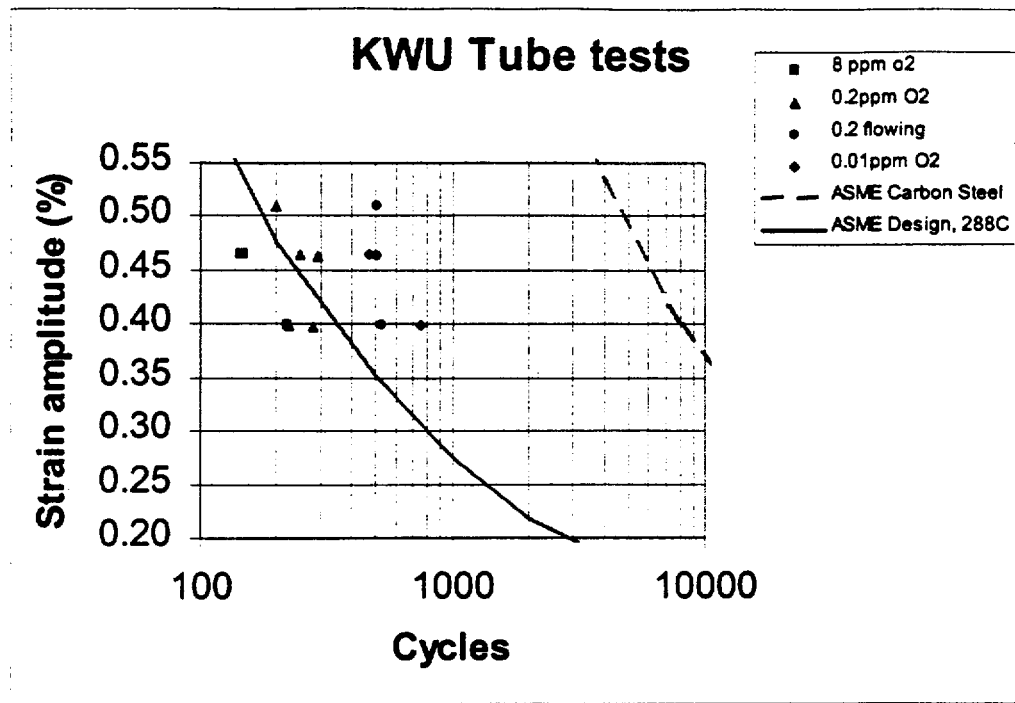


Figure C-1. Effect of Surface Roughness



(a) Raw Data

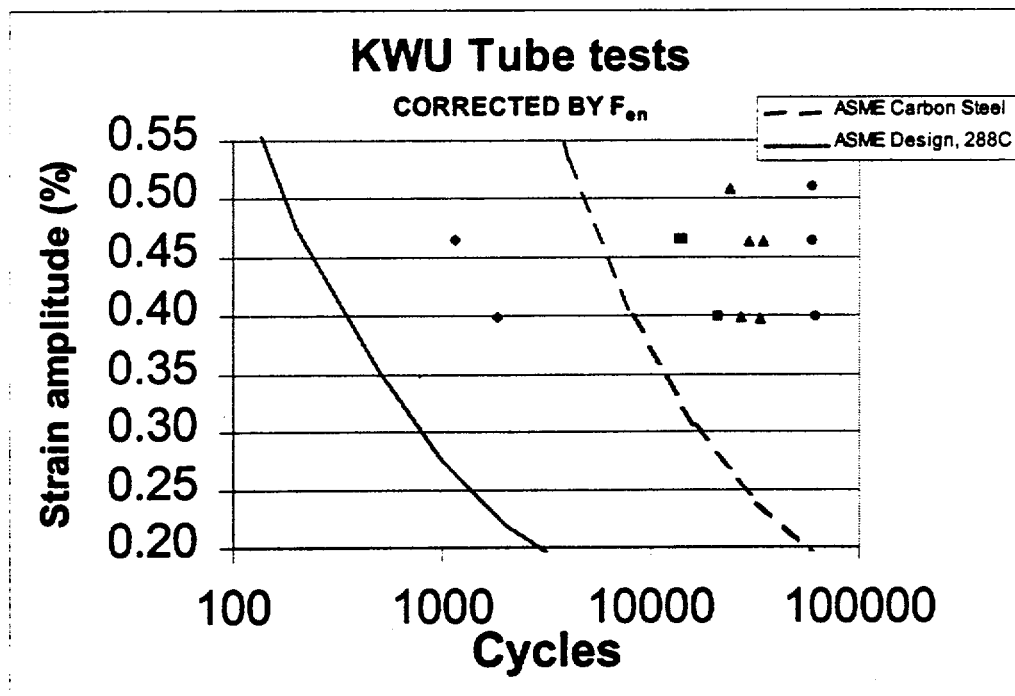
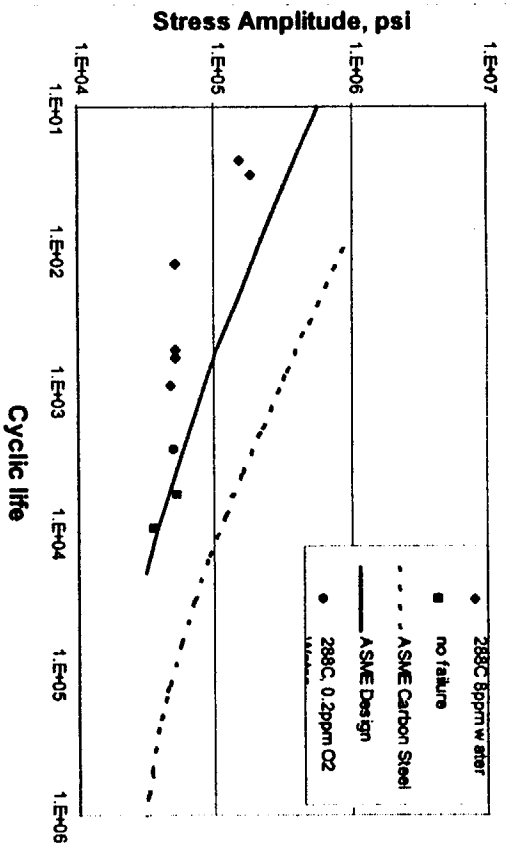
(b) Data Corrected by  $F_{en}$ 

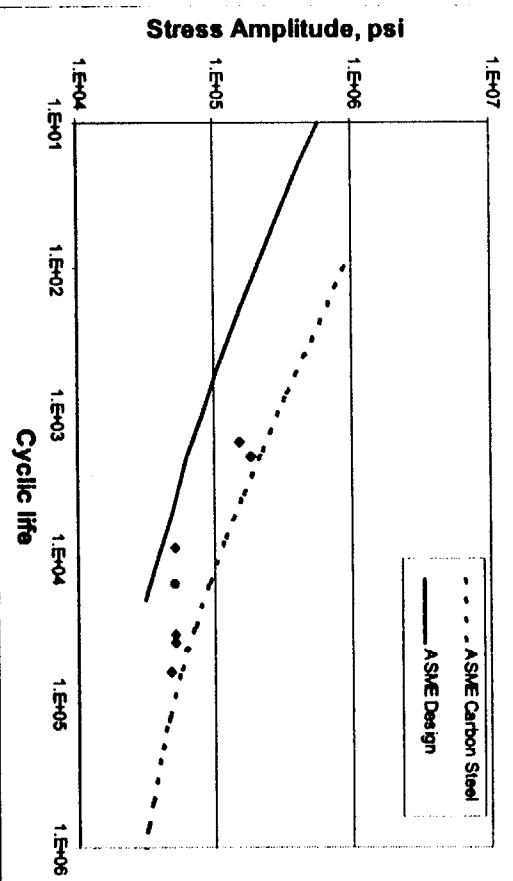
Figure C-2. KWU Tube Test Data

# G.E. Pipe Tests



(a) Test Data

# G.E. Pipe Tests CORRECTED BY $F_{en}$



(b) Test Data Corrected by  $F_{en}$   
Figure C-3. GE Pipe Test Data

<b>TABLE C-1 – Moderate Strain Rate Data for Austenitic Stainless Steel (0.6 % Strain Amplitude)</b>						
<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
304	5	360	0.4	0.58	1172	1172
316 (Sensitized)	5	325	0.4	0.61	2009	2009
316 (Weld)	5	325	0.4	0.61	666	666
316 (Aged)	5	325	0.4	0.61	1075	1075
316	8000	325	0.4	0.6	2027	2027
316 (Forged)	5	325	0.4	0.6	1572	1572
316	5	325	0.4	0.6	2460	2460
316 (Weld)	5	325	0.4	0.6	1922	1922
304	5	325	0.4	0.6	1411	1411
304 (Sensitized)	5	325	0.4	0.6	1318	1318
308 (Weld)	5	325	0.4	0.6	2381	2381
SCS14A (Aged)	5	325	0.4	0.6	1380	1380
CF8M (Aged)	5	325	0.4	0.6	2136	2136
SCS14A (Aged)	5	325	0.4	0.6	663	663
SCS14A	5	325	0.4	0.6	1461	1461
316	5	325	0.4	0.59	2070	2070
316 (Pre-strained)	5	325	0.4	0.59	2238	2238
304	5	325	0.4	0.59	1344	1344
304	8000	325	0.4	0.59	988	988
SCS14A	5	325	0.4	0.59	1606	1606
316	5	325	0.4	0.58	2089	2089
SCS14A	5	325	0.4	0.575	1856	1856

					Moderate Environmental Effects	
316	5	300	0.4	0.605	1916	1916
304	5	300	0.4	0.585	1189	1189
					mean	1,623
					standard deviation ( $\sigma$ )	516
					$\sigma$ /mean	0.32



**TABLE C-2 – Reduced Strain Rate Data for  
Austenitic Stainless Steel (0.6 % Strain Amplitude)**

<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
304	5	360	0.01	0.585	500	1305
SCS14A (Aged)	5	325	0.001	0.63	308	1462
316 (Sensitized)	5	325	0.01	0.61	608	1586
316 (Weld)	5	325	0.0001	0.61	246	2126
304	5	325	0.004	0.605	326	1079
304	5	325	0.04	0.6	668	1216
308 (Weld)	5	325	0.04	0.6	1264	2300
SCS14A (Aged)	5	325	0.04	0.6	1202	2187
316	5	325	0.01	0.6	644	1680
316 (Forged)	5	325	0.01	0.6	388	1012
316 (Weld)	5	325	0.01	0.6	1365	3560*
316 (Weld)	5	325	0.001	0.6	753	3575*
304	5	325	0.01	0.6	512	1336
304	8000	325	0.01	0.6	470	1226
304	5	325	0.01	0.6	443	1156
304 (Sensitized)	5	325	0.01	0.6	474	1237
308 (Weld)	5	325	0.01	0.6	1156	3016
SCS14A (Aged)	5	325	0.01	0.6	741	1934
SCS14A	5	325	0.01	0.6	808	2108
SCS14A	5	325	0.01	0.6	682	1780
316	5	325	0.004	0.6	396	1311
308 (Weld)	5	325	0.004	0.6	955	3162
316	5	325	0.001	0.6	452	2146

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continued on next page  
\* Potential overcorrected shift

Moderate Environmental Effects

**TABLE C-2 – Reduced Strain Rate Data for  
Austenitic Stainless Steel (0.6 % Strain Amplitude) concluded**

<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
308 (Weld)	5	325	0.001	0.6	594	2820
316 (Weld)	5	325	0.0004	0.6	579	3489
SCS14A	5	325	0.0004	0.6	230	1386
316	5	325	0.0001	0.6	550	4752*
316 (Weld)	5	325	0.0001	0.6	325	2808
SCS14A	5	325	0.0001	0.6	131	1132
SCS14A	5	325	0.00004	0.6	107	1173
SCS14A	5	325	0.00001	0.6	80	1258
SCS14A	5	325	0.01	0.595	532	1388
SCS14A	5	325	0.004	0.595	525	1738
316	5	325	0.04	0.59	912	1660
SCS14A	5	325	0.04	0.59	964	1754
316	8000	325	0.01	0.59	803	2095
316	5	325	0.004	0.59	452	1497
SCS14A	5	325	0.001	0.59	269	1277
304	5	325	0.001	0.58	249	1182
316	5	325	0.0004	0.58	507	3055
304	5	325	0.0004	0.58	180	1085
304	5	325	0.0001	0.58	182	1572
316	5	300	0.01	0.6	740	1931
304	5	300	0.01	0.595	457	1192

mean                      1,903 / 1,753\*\*  
standard deviation ( $\sigma$ )      859 / 655\*\*

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$\sigma/\text{mean}$  Moderate Environmental Effects  
0.45 / 0.37\*\*

- \* Potential overcorrected shift
- \*\* Evaluation with outliers removed

**TABLE C-3 – Moderate Strain Rate Data for  
Austenitic Stainless Steel (0.3 % Strain Amplitude)**

<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
316 (Weld)	5	325	0.4	0.31	4125	4125
316	5	325	0.4	0.3	8799	8799
316 (Pre-strained)	5	325	0.4	0.3	8760	8760
316 (Forged)	5	325	0.4	0.3	10754	10754
316 (Sensitized)	5	325	0.4	0.3	7428	7428
316 (Aged)	5	325	0.4	0.3	6184	6184
316 (Weld)	5	325	0.4	0.3	15142	15142
304	5	325	0.4	0.3	7928	7928
304 (Sensitized)	5	325	0.4	0.3	9879	9879
SCS14A (Aged)	5	325	0.4	0.3	11795	11795
CF8M (Aged)	5	325	0.4	0.3	13327	13327
SCS14A	5	325	0.4	0.3	10154	10154
SCS14A	5	325	0.4	0.3	12000	12000
SCS14A	5	325	0.4	0.295	9242	9242
304	5	325	0.4	0.29	8798	8798
308 (Weld)	5	325	0.4	0.29	7954	7954
304	5	360	0.4	0.28	10326	10326
304	5	300	0.4	0.305	7020	7020
316	5	300	0.4	0.285	6391	6391
316	8000	325	0.4	0.29	8761	8761
304	8000	325	0.4	0.29	10242	10242

mean

9,286

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Moderate Environmental Effects
standard deviation ( $\sigma$ ) 2,524
$\sigma$ /mean 0.27

**TABLE C-4 – Data for  
Austenitic Stainless Steel (0.3 % Strain Amplitude)**

<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
SCS14A (Aged)	5	325	0.04	0.31	5376	9783
316	5	325	0.01	0.3	2807	7324
316 (Forged)	5	325	0.01	0.3	3012	7859
316 (Sensitized)	5	325	0.01	0.3	2800	7306
304	5	325	0.01	0.3	1854	4838
304 (Sensitized)	5	325	0.01	0.3	4186	10923
308 (Weld)	5	325	0.01	0.3	5716	14915
SCS14A (Aged)	5	325	0.01	0.3	4480	11690
316 (Weld)	5	325	0.01	0.3	10403	27141*
308 (Weld)	5	325	0.04	0.3	10684	19445*
SCS14A	5	325	0.01	0.29	7116	18566*
SCS14A (Aged)	5	325	.04	0.29	8094	21120*
316	5	325	0.004	0.3	3025	10017
316	5	325	0.001	0.3	2235	10612
304	5	325	0.01	0.295	2522	6581
316	5	325	0.04	0.29	5551	10101
304	5	325	0.04	0.29	5911	10756
304	5	360	0.01	0.3	3970	10359
304	5	300	0.01	0.305	4019	10487
316	5	300	0.01	0.3	3704	9665
316	8000	325	0.01	0.3	4137	7803
304	8000	325	0.01	0.3	2164	4081

mean

11,426 / 9,172\*\*

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	Moderate Environmental Effects
standard deviation ( $\sigma$ )	5,614 / 2,592**
$\sigma$ /mean	0.49 / 0.28**

\* Potential overcorrected shift

\*\* Evaluation with outliers removed



**TABLE C-5 – Data for  
Austenitic Stainless Steel (0.4 % Strain Amplitude)**

<b>Material</b>	<b>DO (ppb)</b>	<b>Temperature (°C)</b>	<b>Tensile Strain Rate (%/sec)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Shifted Cycles to Failure</b>
304	5	360	0.01	0.39	1561	4073
316 (Aged)	5	325	0.4	0.42	2392	2392
316 (Weld)	5	325	0.4	0.4	2521	2521
316 (Weld)	5	325	0.4	0.4	6752	6752
308 (Weld)	5	325	0.4	0.4	6102	6102
SCS14A (Aged)	5	325	0.4	0.4	4705	4705
CF8M (Weld)	5	325	0.4	0.4	6155	6155
316	8000	325	0.4	0.39	5308	5308
304	8000	325	0.4	0.39	3050	3050
SCS14A	5	325	0.4	0.38	6691	6691
304	5	325	0.4	0.37	3387	3387
304	5	300	0.4	0.4	3474	3474
316	5	300	0.4	0.375	5612	5612

mean 4,679\*  
 standard deviation ( $\sigma$ ) 1,637\*  
 $\sigma$ /mean 0.35

\*Based on data for 0.4%/sec only

<b>TABLE C-6</b> <b>Low-Alloy Steel (0.6 % Strain Amplitude)</b>					
<b>Material</b>	<b>DO</b>	<b>Temperature (C)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Investigator</b>
533B LAS	High	290	0.6	1600	Higuchi
533B LAS	High	290	0.6	1690	Higuchi
533B LAS	High	290	0.6	1640	Higuchi
508-3 LAS	Low	250	0.58	3040	Kasai
508-3 LAS	Low	290	0.605	2284	Kasai
508-3 LAS	Low	250	0.58	4210	Kasai
508-3 LAS	Low	290	0.59	2810	Kasai
508-3 LAS	High	290	0.585	2120	Kasai
508-3 LAS	High	290	0.575	2372	Kasai
533B LAS	Low	288	0.6	1728	Nakao
533B LAS	Low	288	0.6	1692	Nakao
533B LAS	Low	288	0.6	1276	Nakao
508-3 LAS	High	290	0.593	783	Endou
508-3 LAS	Low	250	0.584	1695	Endou
508-3 LAS	Low	290	0.587	1899	Endou
508-3 LAS	High	288	0.6	1660	Higuchi
508-3 LAS	High	288	0.6	1920	Higuchi
508-3 LAS	High	288	0.6	1250	Higuchi
508-3 LAS	Low	288	0.6	3540	Higuchi
508-3 LAS	Low	288	0.6	3625	Higuchi
508-3 LAS	Low	288	0.6	3435	Higuchi
533B LAS Weld	High	290	0.6	1810	Higuchi
533B LAS Weld	High	290	0.6	1774	Higuchi

					Moderate Environmental Effects
533B LAS Weld	Low	288	0.6	960	Nakao
533B LAS Weld	Low	288	0.6	1091	Nakao

mean 2,076  
 standard deviation ( $\sigma$ ) 892  
 $\sigma$ /mean 0.43

<b>TABLE C-7</b> <b>Carbon Steel/Low-Alloy Steel (0.5 % Strain Amplitude)</b>					
<b>Material</b>	<b>DO</b>	<b>Temperature (C)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Investigator</b>
533B LAS	High	290	0.5	3348	Higuchi
533B LAS	High	290	0.5	3550	Higuchi
533B LAS	Low	288	0.5	1965	Nakao
508-3 LAS	Low	288	0.498	4022	Nagata
508-2 LAS	Low	288	0.5	2875	Nakao
533B LAS Weld	Low	288	0.5	1888	Nakao
533B LAS Weld	Low	288	0.5	1898	Nakao
333B-3 CS	Low	288	0.5	3426	Higuchi
mean				2,872	
standard deviation ( $\sigma$ )				850	
$\sigma$ /mean				0.30	

TABLE C-8 Carbon Steel/Low-Alloy Steel (0.4 % Strain Amplitude)					
Material	DO	Temperature (C)	Strain Amplitude (%)	Cycles to Failure	Investigator
533B LAS	High	290	0.4	9400	Higuchi
533B LAS	High	290	0.4	6340	Higuchi
508-3 LAS	Low	250	0.395	8573	Kasai
533B LAS	Low	288	0.408	6353	Nagata
533B LAS	Low	288	0.4	8528	Nakao
533B LAS	Low	288	0.4	5700	Nakao
533B LAS	Low	288	0.4	6900	Nakao
533B LAS	Low	288	0.4	4030	Nakao
333B-3 CS	Low	288	0.4	15550*	Higuchi
508-3 LAS	High	290	0.404	1911*	Endou
508-3 LAS	High	288	0.4	5702	Higuchi
533B LAS Weld	High	290	0.4	5610	Higuchi
533B LAS Weld	High	290	0.4	5855	Higuchi
533B LAS Weld	Low	288	0.4	2670	Nakao
533B LAS Weld	Low	288	0.4	2708	Nakao
508-1 LAS	High	300	0.4	1600*	Kitigawa

mean 6,089 / 6,028\*\*  
 standard deviation ( $\sigma$ ) 3,454 / 2,077\*\*  
 $\sigma$ /mean 0.57 / 0.35\*\*

\* Potential outliers

\*\* Evaluation with outliers removed

<b>TABLE C-9</b> <b>Carbon Steel/Low-Alloy Steel (0.3 % Strain Amplitude)</b>					
<b>Material</b>	<b>DO</b>	<b>Temperature (C)</b>	<b>Strain Amplitude (%)</b>	<b>Cycles to Failure</b>	<b>Investigator</b>
533B LAS	High	290	0.3	32080	Higuchi
533B LAS	High	290	0.3	28700	Higuchi
533B LAS	Low	288	0.3	14760	Nakao
508-3 LAS	High	288	0.3	8080	Higuchi
533B LAS Weld	High	290	0.3	18500	Higuchi
533B LAS Weld	High	290	0.3	14800	Higuchi
508-3 LAS	Low	288	0.285	26020	Nakao
533B LAS	Low	288	0.28	26730	Nakao
508-3 LAS	Low	288	0.298	29000	Nagata
533B LAS Weld	Low	288	0.3	13840	Nakao
533B LAS Weld	Low	288	0.3	18730	Nakao
333B-2 CS	High	290	0.3	8460	Higuchi
333B-2 CS	Low	288	0.3	10860	Higuchi
333B-2 CS	Low	288	0.3	23840	Higuchi
508-1 LAS	High	300	0.3	2200*	Kitigawa

mean 18,440 / 19,600\*\*

standard deviation ( $\sigma$ ) 9,001 / 8,094\*\*

$\sigma$ /mean 0.49 / 0.41\*\*

\* Potential outlier

\*\* Evaluation with outlier removed

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# D

## DEMONSTRATING TRANSIENT SEVERITY BOUNDS ENVIRONMENTAL EFFECTS

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This appendix shows an example of the methodology for demonstrating that transient severity bounds any additional effects due to reactor water environmental effects. This example is based on a response to a Request for Additional information (RAI) related to a previously submitted License Renewal Application. It is provided only as an example. There may be additional plant-specific considerations necessary for an individual plant submittal.

### RAI Question:

The License Renewal Application contains a discussion of Generic Safety Issue (GSI) 190, "Fatigue Evaluation of Metal Components for 60-year Plant Life." GSI-190 addresses the effect of the reactor water environment on the fatigue life of metal components. The discussion in the License Renewal Application indicates that EPRI license renewal fatigue studies have demonstrated that sufficient conservatism exists in the design transient definitions to compensate for potential reactor water environmental effects. The staff does not agree with the contention that the EPRI fatigue studies have demonstrated that sufficient conservatism exists in the design transient definitions to compensate for potential reactor water environmental effects. The staff identified several technical concerns regarding the EPRI studies. The staff technical concerns are contained in an August 6, 1999, letter to NEI. Although these concerns involved the EPRI procedure and its application to PWRs, the technical concerns regarding the application of the Argonne National Laboratory (ANL) statistical correlations and strain threshold values are also relevant to BWRs. In addition to the concerns referenced above, the staff has additional concerns regarding the applicability of the EPRI BWR studies to the specific plant. EPRI Report TR-107943, "Environmental Fatigue Evaluations of Representative BWR Components," addressed a BWR-6 plant and EPRI Report TR-110356, "Evaluation of Environmental Thermal Fatigue Effects on Selected Components in a Boiling Water Reactor Plant," used plant transient data from a newer vintage BWR-4 plant. The applicability of the EPRI fatigue studies to the specific plant has not been demonstrated. Provide the following additional information regarding resolution of the environmental fatigue issue:

- a. Indicate whether the staff comments provided in the staff's August 6, 1999, letter to NEI, which are applicable to the specific plant, have been considered in the assessment of the environmental fatigue issue. Discuss how the applicable staff comments were considered in the evaluation of environmental fatigue.

- b. Discuss the applicability of the component fatigue assessments in the EPRI Reports TR-107943 and TR-110356 to components in the specific plant.. The discussion should include a comparison of design transients, operating cycles and fabrication details for each component. Also include a comparison of the hydrogen water chemistry used at the specific plant with the hydrogen water chemistry considered in the EPRI reports.
- c. The staff assessed the impact of reactor water environment on fatigue life at high fatigue usage locations and presented the results in NUREG/CR-6260, "Application of NUREG/CR-5999, 'Interim Fatigue Curves to Selected Nuclear Power Plant Components'," March 1995. Formulas currently acceptable to the staff for calculating the environmental correction factors for carbon and low alloy steels are contained in NUREG/CR-6583, "Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels," and those for austenitic stainless steels are contained in NUREG/CR-5704, "Effects of LWR Coolant Environments on Fatigue Design of Austenitic Stainless Steels." Provide an assessment of the 6 locations identified in NUREG/CR-6260 for an older vintage BWR-4 considering the applicable environmental fatigue correlations provided in NUREG/CR-6583 and NUREG/CR-5704 reports.

RESPONSE TO RAI:

- a. The staff comments provided in the August 6, 1999, NRC letter to NEI have been considered in the assessment of the environmental fatigue issue at the specific plant through the margins present by considering design basis severity of thermal transients.

Primarily, the NRC concerns presented in the August 6, 1999 letter are associated with the more recent laboratory fatigue data in simulated LWR reactor water environments that have been generated by ANL since the time of the EPRI generic studies. These data have resulted in improved environmental correction factor correlations, which are documented in NUREG/CR-6583 (for carbon/low alloy steel) and NUREG/CR-5704 (for stainless steel). The improved correlations were not available at the time the EPRI generic studies were performed.

For carbon and low-alloy steels, the correlations published in NUREG/CR-6583 do not differ substantially from the correlations used in the EPRI generic studies.

However, the change in strain threshold may have a significant effect, and that effect has been evaluated, as follows.

A recalculation was performed based on one of the examples contained in EPRI Report No. TR-105759, "An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessel and Piping Fatigue Evaluations," December 1995, for a BWR carbon steel feedwater piping location with a design-basis fatigue usage factor of 0.1409 for 40 years. An alternating stress threshold of 30 ksi (approximating the alternating strain threshold of 0.10%) was used initially to adjust the incremental fatigue usage for eight out of thirty-one load pairs, giving an additional

(environmental) fatigue usage of 0.0477, for a 40-year adjusted total of 0.1886. The overall environmental multiplier (Fen) in this case was 1.34 (1.68 for the eight affected load pairs).

Reducing the alternating stress threshold to 21 ksi (approximating the revised alternating strain threshold of 0.07%) would require an environmental adjustment for six additional load pairs. Assuming that the Fen multiplier of 1.68 would continue to apply for the fourteen affected load pairs, the estimate for the adjusted fatigue usage factor would be

$$0.1409 - 0.0803 + 1.68 (0.0803) = 0.1955.$$

The overall Fen multiplier increases only to 1.39.

Because the additional load pairs that would have to be included contribute relatively small increments to the total CUF, the change in the strain range threshold does not cause a significant impact on the calculated fatigue usage. Therefore, the results of the EPRI generic studies provide a reasonable estimate of the impact of potential environmental fatigue effects for carbon/low alloy steel components, and are considered to remain valid.

For austenitic stainless steels, the data are more penalizing than the data used in the EPRI generic studies.

For the case of relatively low temperature ( $< 200^{\circ}\text{C}$ ), a low (bounding) strain rate, and either high or low dissolved oxygen, the environmental shift is 2.55. For relatively high temperature ( $> 200^{\circ}\text{C}$ ), low dissolved oxygen, and a low (bounding) strain rate, the environmental shift may be as high as 15.35, although there is a reduction above  $250^{\circ}\text{C}$  where the environmental factor decreases to about 3.20 at  $340^{\circ}\text{C}$ . These factors are higher than those obtained from the relationships used in the EPRI generic studies. As a result, further evaluation was performed as described below.

For most of the component locations evaluated in the EPRI generic studies, these most recent data do not pose a problem for the demonstration that the 60-year CUF is less than 1.0, including reactor water environmental effects. Again, a significant benefit accrues to the Fen approach in this regard, since most of the penalizing thermal transients in the BWR environment lie below the threshold temperature of  $200^{\circ}\text{C}$ . Therefore, the environmental shift is relatively low, provided that separate multipliers are used for the portions of the transient that are above and below  $200^{\circ}\text{C}$ . However, for the most fatigue-sensitive PWR locations, (e.g., surge line elbows), the environmentally-adjusted CUF increases over that calculated in the EPRI generic studies by a factor of about two.

Therefore, a reasonable approach to accounting for the more recent laboratory data for stainless steel material is to conservatively apply a factor of 2.0 to the EPRI generic study results. This is considered to be very conservative for the BWR.

The CUF results from the most applicable EPRI generic study (EPRI TR-110356, see Item (b) below) are shown in Table 1, with modifications to account for the more recent data in NUREG/CR-6583 and NUREG/CR-5704. The design basis fatigue usage for each location is also shown for comparison. The results in Table 1 clearly demonstrate that the conservatism of design basis transient definitions overwhelms all environmental effects. The CUF for all locations, including environmental effects and projected to 60 years, is at least a factor of 12.9 below the original design basis CUF.

These results indicate that tracking CUF based on design basis transient definitions provides conservative estimates of CUF for the license renewal period.

- b. The most applicable evaluation for the specific plant with respect to the EPRI generic studies is EPRI Report No. TR-110356, "Evaluation of Environmental Thermal Fatigue Effects on Selected Components in a Boiling Water Reactor." The other two EPRI reports (EPRI Report Nos. TR-107515 and TR-107943) have limited direct applicability, but were referenced in the specific plant application for completeness, since the EPRI studies built off the results of each other. It was therefore considered necessary to reference the main EPRI study (EPRI Report No. TR-107515), along with both follow-on studies performed for BWRs, to provide a comprehensive reference source.

Nevertheless, focusing on EPRI Report No. TR-110356, those results are considered directly applicable. First, the results documented in that report apply to a BWR-4 that is identical to the specific plant design. Therefore, the Class 1 systems associated with the plants are the same, which defines the characteristics of the thermal transients in these systems. As a result, the design basis transient definitions associated with the plants are very similar. This is demonstrated in Table 2, where the design basis transient definitions for both plants are compared.

The BWR-4 evaluated in EPRI Report No. TR-110356 did not consider hydrogen water chemistry (HWC), as evidenced by the plots of dissolved oxygen in that report. The specific plant has implemented HWC. The maximum effect of the change in dissolved oxygen as a result of HWC implementation is adequately addressed via the conservative factors described under the response to Item (a) above.

There are only two issues relevant to fabrication details and the associated effects of reactor water environment on fatigue. First, the sulfur content, where applicable, was conservatively assumed to be at a maximum level in EPRI TR-110356. Second, the material type (i.e., stainless or carbon/low alloy steel) is similar between the two plants, and was considered appropriately in all fatigue evaluations. In fact, material types between most BWRs are very similar, as evidenced by the comparison shown in Table 3 between the specific plant and the older vintage BWR-4 evaluated in NUREG/CR-6260. Therefore, fabrication details are not considered to have any effect on the application of the results in EPRI Report No. TR-110356.

- c. The locations investigated in NUREG/CR-6260 for the older vintage BWR are listed in Table 3. Also shown in Table 3 are the equivalent locations where CUF is monitored in the specific plant cycle counting program, and the projected 60-year CUF for each location based on plant operation to-date.

Table 3 demonstrates that all BWR locations from NUREG/CR-6260 were evaluated for the specific plant. All of these locations are either bounded by locations monitored via the cycle counting program or the design 40-year CUF is below the 0.10 threshold for monitoring by the program. The projected CUFs for all monitored locations remain within the allowable value of 1.0 for the license renewal period. Furthermore, the specific plant cycle counting program includes several other locations, beyond those evaluated in NUREG/CR-6260, thereby providing a more comprehensive CUF assessment.

As discussed in the response to Item (a) above, the appropriate correlations from NUREG/CR-6583 and NUREG/CR-5704 have been accounted for via the conservatism in design basis transient definitions.

**Table 1**  
**Revised Fatigue Usage Results for BWR (Including Environmental Effects)**

<b>Cas e No.</b>	<b>Location</b>	<b>Projected 60 Year Usage Factor from TR- 110356 (with <math>F_{en}</math>)</b>	<b>Correction Factor to Account for NUREG/CR- 6583 or NUREG/CR- 5704</b>	<b>Revised 60 Year Usage Factor (with <math>F_{en}</math>) <sup>(1)</sup></b>	<b>Design Basis Fatigue Usage <sup>(2)</sup></b>	<b>Margin <sup>(3)</sup></b>
1	1 = CRD Penetration	0.034	2.0	0.068	0.875	12.9
	2 = FW Loop A Safe End	0.009	2.0	0.018	0.471	26.2
	3 = FW Loop A Nozzle Forging	0.001	1.0	0.001	< 0.1	~100
	4 = FW Loop B Safe End	0.009	2.0	0.018	0.471	26.2
	5 = FW Loop B Nozzle Forging	0.001	1.0	0.001	< 0.1	~100
2	1 = CRD Penetration	0.013	2.0	0.026	0.875	33.7
	2 = FW Loop A Safe End	0.009	2.0	0.018	0.471	26.2
	3 = FW Loop A Nozzle Forging	0.001	1.0	0.001	< 0.1	~100
	4 = FW Loop B Safe End	0.009	2.0	0.018	0.471	26.2
	5 = FW Loop B Nozzle Forging	0.001	1.0	0.001	< 0.1	~100
3	1 = CRD Penetration	0.016	2.0	0.032	0.875	27.3
	2 = FW Loop A Safe End	0.009	2.0	0.018	0.471	26.2
	3 = FW Loop A Nozzle Forging	0.001	1.0	0.001	< 0.1	~100
	4 = FW Loop B Safe End	0.009	2.0	0.018	0.471	26.2
	5 = FW Loop B Nozzle Forging	0.001	1.0	0.001	< 0.1	~100

- Notes:
1. The "Revised 60-Year Usage Factor" is equal to the "Projected 60-Year Usage Factor from TR-110356" multiplied by the "Correction Factor to Account for NUREG/CR-6583 or NUREG/CR-5704."
  2. As documented in the governing design basis fatigue analysis report.
  3. The "Margin" is equal to the "Design Basis Fatigue Usage" divided by the "Revised 60-Year Usage Factor."

**Table 2**  
**Design Basis Plant Transient Comparison for the BWR-4**  
**in EPRI Report No. TR-110356 vs. Specific Plant**

<b>Transient</b>	<b>BWR-4 No. of Cycles</b>	<b>Unit 1 No. of Cycles</b>	<b>Unit 2 No. of Cycles</b>
Boltup	123	123	123
Design Hydrostatic Test	130	130	130
Startup	117	120	117
Turbine Roll & Increase to Rated Power	not specified	120	not specified
Daily Reduction to 75% Power	10,000	10,000	10,000
Weekly Reduction to 50% Power	2,000	2,000	2,000
Rod Pattern Change (Rod Worth Test)	400	400	400
Loss of Feedwater Heaters, Turbine Trip with 100% Steam Bypass, Unit 1 = Turbine Trip at 25% Power	10	10	10
Loss of Feedwater Heaters, Partial Feedwater Heater Bypass	70	70	70
SCRAM, Turbine Generator Trip, Feedwater On, Isolation Valves Stay Open	40	40	40
SCRAM, All Other	140	147	140
Rated Power Normal Operation	not specified	not specified	not specified
Reduction to 0% Power	111	118	111
Hot Standby	111	118	111
Shutdown/Vessel Flooding	111	118	111
Unbolt	123	123	123
Refueling	not specified	not specified	not specified
Pre-Operational Blowdown	10	0	10
Loss of Feedwater Pumps, Isolation Valves Close	5	10	5
Reactor Over Pressure with Delayed SCRAM, Feedwater Stays On, Isolation Valves Stay Open	1	1	1
Single Relief or Safety Valve Blowdown	8	2	8

<b>Automatic Blowdown</b>	<b>1</b>	<b>0</b>	<b>1</b>
<b>Improper Start of Cold Recirculation Loop</b>	<b>1</b>	<b>5</b>	<b>1</b>
<b>Sudden Start of Pump in Cold Recirculation Loop</b>	<b>1</b>	<b>5</b>	<b>1</b>
<b>Improper Startup with Recirculation Pumps Off &amp; Drain Shut Off</b>	<b>1</b>	<b>0</b>	<b>1</b>
<b>Pipe Rupture and Blowdown</b>	<b>1</b>	<b>0</b>	<b>not specified</b>
<b>Natural Circulation Startup</b>	<b>3</b>	<b>0</b>	<b>3</b>
<b>Loss of AC Power, Natural Circulation Restart</b>	<b>5</b>	<b>0</b>	<b>5</b>
<b>Code Hydrostatic Test</b>	<b>0</b>	<b>3</b>	<b>3</b>



**Table 3**  
**Locations Evaluated in NUREG/CR-6260 for**  
**Older Vintage General Electric Plant (BWR-4) vs. Specific Plant**

NUREG/CR-6260 Location	NUREG/CR-6260 Material	Addressed by Plant Cycle Counting Program ?	Specific Plant Material	Projected 60-Year CUF for Specific Plant <sup>(1)</sup>
Reactor Vessel (Lower Head to Shell Transition)	SA-302 Low Alloy Steel	YES <sup>(2)</sup>	SA-533 Grade B Class 1 Low Alloy Steel	U1 = 0.0669 U2 = 0.0513
Feedwater Nozzle (Bore)	SA-508 Low Alloy Steel	YES	SA-508 Class 2 Low Alloy Steel	U1 = 0.1663 U2 = 0.3643
Recirculation System (RHR Return Line Tee)	SA-358 Type 304 Stainless Steel	YES <sup>(3)</sup>	SA-358 Type 316NG Class 1 Stainless Steel	U1 < 0.1500 <sup>(7)</sup> U2 < 0.1500 <sup>(7)</sup>
Core Spray System (Nozzle)	SA-302 Grade B Low Alloy Steel	YES <sup>(4)</sup>	SA-508 Class 2 Low Alloy Steel	U1 = 0.4796 U2 = 0.2983
Core Spray System (Safe End)	SA-376 Type 316 Stainless Steel	YES <sup>(5)</sup>	SA-182 Type F304 Stainless Steel	U1 = 0.1605 U2 < 0.1500 <sup>(7)</sup>
Residual Heat Removal Line (Tapered Transition)	SA-358 Type 304 Stainless Steel	YES <sup>(3)</sup>	SA-358 Type 316NG Class 1	U1 < 0.1500 <sup>(7)</sup> U2 < 0.1500 <sup>(7)</sup>
Feedwater Line (RCIC Tee)	SA-106 Grade B Carbon Steel	YES <sup>(6)</sup>	SA-106 Grade B Carbon Steel	U1 = 0.5607 U2 = 0.7435 <sup>(8)</sup>

Notes:

1. Based on actual transient counts through 12/31/1999.
2. The limiting location in the RPV shell is monitored for both units at specific plant, which is considered to adequately represent the NUREG/CR-6260 location.

3. The limiting location in the Unit 2 RHR suction piping, at the elbow near the recirculation suction tee, was previously monitored with cycle counting program, and was considered to adequately represent the NUREG/CR-6260 location. Newer stress analysis shows the 40-year CUF  $< 0.10$ , so this location will no longer be monitored. The 40-year design CUF  $< 0.10$  for the Unit 1 RHR suction piping and was never monitored by the cycle counting program. Therefore, the plant cycle monitoring program addresses this location for both units by determining the CUF is below the threshold for monitoring.
4. The RPV recirculation inlet nozzle, which bounds the core spray nozzle, is monitored for both units in the specific plant cycle monitoring program. This is considered to adequately represent the NUREG/CR-6260 location.
5. The limiting location in the Unit 1 core spray piping system is monitored in the specific plant cycle monitoring program, and is considered to adequately represent the NUREG/CR-6260 location. The 40-year design CUF  $< 0.10$  for the Unit 2 core spray piping system.
6. The limiting location in the feedwater piping system is monitored for both units in the specific plant cycle monitoring program, which is considered to adequately represent the NUREG/CR-6260 location. On Unit 1, the monitored piping includes the HPCI, RCIC, and RWCU Class 1 piping connected to the feedwater line.
7. The 40-year design CUF is less than 0.10 for this location so it is not monitored.
8. The RCIC Tee on Unit 2 is in the Class 2 portion of the system. The CUF given is for the bounding location on the Class 1 portion of the feedwater line.