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NUCLEAR ENERGY INSTITUTE

Alexander Marion
DIRECTOR, ENGINEERING
NUCLEAR GENERATION DIVISION

September 4, 2003

Dr. P.T. Kuo
Program Director
License Renewal and Environmental Impacts
Division of Regulatory Improvement Programs
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: Response to NRC Request for Additional Information on Proposed Interim Staff Guidance (ISG)-11: Environmental Assisted Fatigue for Carbon/Low-Alloy Steel

PROJECT NUMBER: 690

On June 30, 2003, the Nuclear Regulatory Commission (NRC) forwarded to the Nuclear Energy Institute (NEI) a request for additional information (RAI) on proposed ISG-11. The RAI was subsequently discussed during a public meeting held July 24, 2003 and a telecon held August 11, 2003 with members of the Electric Power Research Institute (EPRI) Materials Reliability Program (MRP) Fatigue Issue Task Group (ITG).

The EPRI MRP Fatigue ITG has performed significant additional analyses in response to the RAI. Enclosed is the information requested in the RAI as augmented during the two meetings. As a result of the additional analyses performed in response to the RAI, Attachment 1 (Technical Basis Document) of the proposed ISG will be revised. We anticipate submittal of the revised ISG by September 19, 2003.

The industry believes that the overall conclusion of the ISG remains that current programs used to manage fatigue can be continued from the current term through the license renewal term, with no need for explicit incorporation of reactor water environmental effects, for carbon and low-alloy steel components for either PWR or BWR components.

If you have any questions, please call me at (202) 739-8080 or Fred Emerson at (202) 739-8086.

Sincerely,

Alex Marion

Alexander Marion

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Enclosure

1776 I STREET, NW SUITE 400 WASHINGTON, DC 20006-3708 PHONE 202.739.8080 FAX 202.785.1898 am@nei.org

Rec'd 10/8/03

Response to NRC Request for Additional Information on ISG-11, "Environmental Assisted Fatigue for Carbon/Low-Alloy Steel"

For each response below, the original request for additional information (RAI) is repeated for clarity.

1. *The proposed ISG is based on re-evaluation of the carbon and low alloy steel components originally evaluated by Pacific Northwest National Laboratory (PNNL) and presented in NUREG/CR-6674, "Fatigue Analysis of Components for 60-Year Plant Life." This re-evaluation is presented in EPRI Report, "Materials Reliability Program: Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low-Alloy Steel Components (MRP-74)." EPRI claims that more realistic assumptions were used in the re-evaluation of these components and the use of these more realistic assumptions results in probabilities of crack initiation and leakage that are significantly less than indicated in NUREG/CR-6674. The most significant change made to the original study was in the standard deviation assumed for the endurance limit strain in the PNNL study. EPRI proposed to replace the standard deviation used in the PNNL study with a much smaller standard deviation. EPRI cites a typical value of fatigue data scatter proposed by Wirsching (Probabilistic Structural Mechanics Handbook, edited by C. Sundararajan, Chapman & Hall, New York, NY 1995, Chapter 7) as the basis for the change. This reference is general in nature and not directly applicable to carbon and low alloy steels used in nuclear power plants. The standard deviation for the endurance limit strain used in the PNNL study is based on a statistical evaluation of test data relevant to carbon and low alloy steels described in NUREG/CR-6335, "Fatigue Strain-Life Behavior of Carbon and Low-Alloy Steels, Austenitic Stainless Steels, and Alloy 600 in LWR Environments and NUREG/CR-6717, "Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels." Provide the following additional information regarding the EPRI endurance limit strain and its standard deviation:*

   A. *The revised probabilistic fatigue curves do not appear consistent with the data for carbon and low alloy steels. For example, compare probabilistic curves developed using the EPRI assumption for the standard deviation of the endurance limit with the data presented in Figure 14 of Attachment 1 of the submittal.*

   Response:

   Figure 1 shows the comparison of the ASME low-alloy steel air data from Figure 14 of Attachment 1 of the submittal with Equation 18 of NUREG/CR-6335 and the standard deviation of the endurance limit (10 percent of the endurance threshold) used in MRP-74. Indeed, there are a few points near the endurance limit that are low relative to the EPRI predictions. However, the bulk of the data are above the mean line.

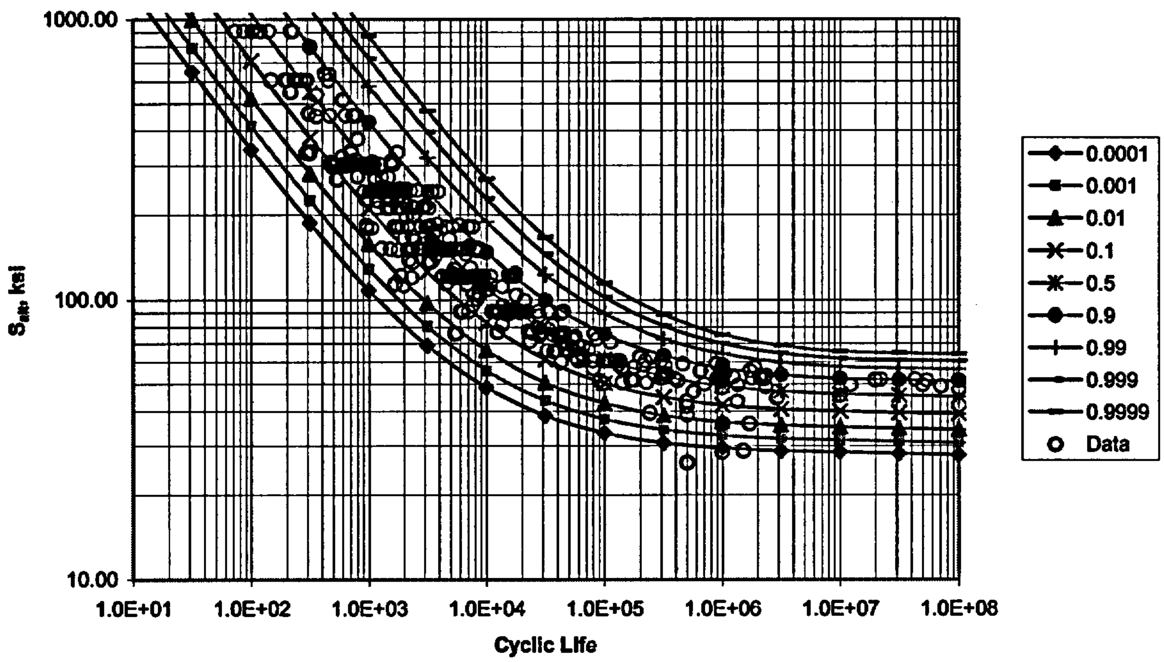

Figure 1. LAS Uncorrected Data Plotted Against NUREG/CR-6335 Equations and 10% Endurance Limit Standard Variation for Various Quantiles

Further study of the data plotted in Figure 1 revealed that the data falling below the curve represented A508 Class 3/Class 4 material with the fatigue testing conducted at an R-ratio (S_{min}/S_{max}) greater than zero, versus the standard test approach using $R = -1$. Since the testing was conducted with a mean stress effect, the apparent stress is higher. Table 1 shows the eight lowest data points as an example.

Table 1
Evaluation of Low-Strain Amplitude LAS Air Data

Data Source	S_{alt}, ksi	Cyclic Life	R-ratio	Effective S_{alt}, ksi
Endou	26.1	500,000	0.14	46.5
Kou	28.5	1,000,000	0.19	48.7
Kou	28.8	1,500,000	0.05	48.0
Kou	36.1	1,010,000	0.19	54.6
Kou	36.1	1,700,000	0.05	54.6
Endou	38.8	500,000	0.14	56.4
Kou	39.4	242,000	0.19	56.8
Endou	41.5	496,900	0.14	58.0

Note: Cyclic Life stated to be 25% area reduction; all material A508 Class 3/Class 4

To determine the effective alternating stress due to the high-mean stress testing approach used, the data were corrected using the modified Goodman approach, which derives an adjusted stress for entering a fatigue curve based on reversing strain (*R=-1*) testing. The rules applied for calculating this adjusted value when the Modified Goodman approach is applied are taken directly from the ASME Code Section III/VIII Div. 2 criteria document and are summarized as follows:

Let S'_{mean} = basic value of mean stress (calculated directly from loading cycle)
S_{mean} = adjusted value of mean stress
S_{alt} = amplitude (half range) of stress fluctuation
S_y = yield strength
S_{eq} = value of stress to be used in entering the fatigue curve to find the allowable number of cycles.

$$\left.\begin{array}{l} \text{If } S_{alt} + S'_{mean} \le S_y,\ S_{mean} = S'_{mean} \\ \text{If } S_{alt} + S'_{mean} > S_y \text{ and } S_{alt} < S_y,\ S_{mean} = S_y - S_{alt} \\ \text{If } S_{alt} + S'_{mean} \ge S_y,\ S_{mean} = 0. \end{array}\right\} \quad (1)$$

$$S_{eq} = \frac{S_{alt}}{1 - \frac{S_{mean}}{S_u}}. \quad (2)$$

The effective alternating stress amplitude for testing conducted with an R-ratio other than *R= -1*, may be determined as follows:

$$\left.\begin{array}{lcl} R & = & S_{min}/S_{max} \\ S'_{mean} & = & (S_{min} + S_{max})/2 \\ & = & S_{max}(1+R)/2 \\ S_{alt} & = & (S_{max} - S_{min})/2 \\ & = & S_{max}(1-R)/2 \end{array}\right\} \quad (3)$$

Combining these equations,

$$S'_{mean} = \frac{S_{alt}(1+R)}{1-R} \quad (4)$$

The effective alternating stress in Table 1 has been determined with the above equations, using the ASME Code criteria basic values of S_y = 70 ksi, and S_u = 100 ksi that are appropriate for this alloy steel. These revised values of S_{alt} were used to replot the ASME air data curve shown in Figure 1. The mean stress corrected data are shown in Figure 2.

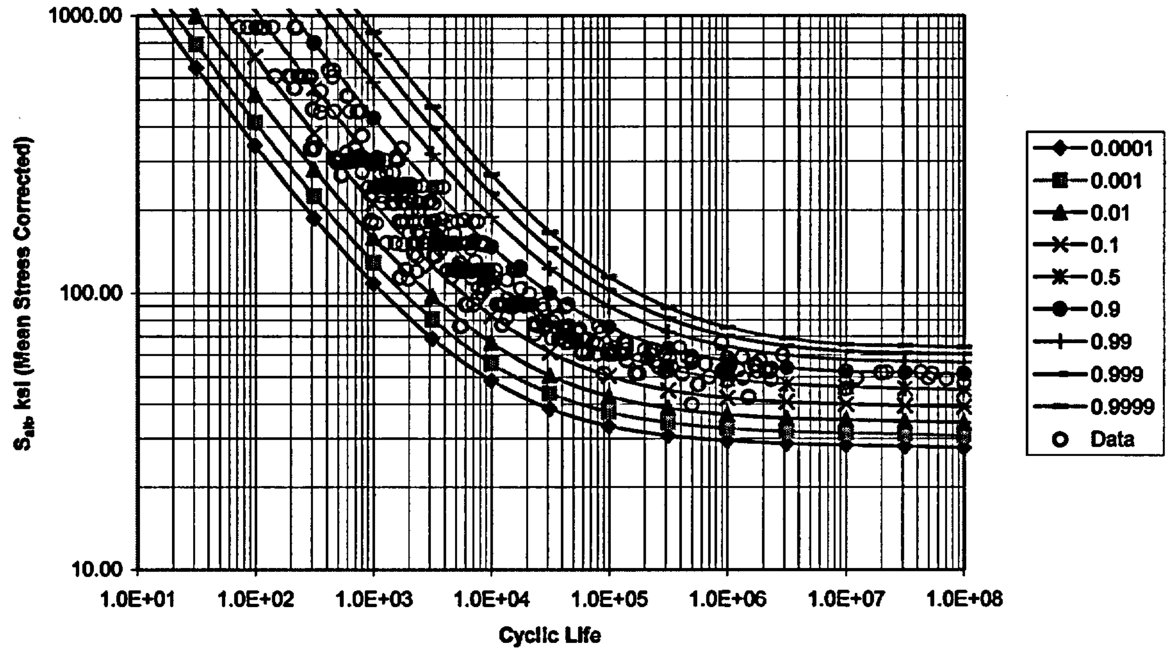

Figure 2. Mean-Stress Corrected LAS Data Plotted Against NUREG/CR-6335 Equations and 10% Endurance Limit Standard Variation for Various Quantiles

In addition, the Argonne National Laboratory (ANL) database for carbon steel (CS) and LAS was obtained[1] to assure that the data being used in the response to this question were consistent with that used in the ANL curve development. In the ANL data, there were only points for $R=-1$ testing so there was no issue relative to mean stress effects within the data. These data have been plotted with both the ANL and the 10-percent (MRP-74) endurance limit variations using Equation 18 of NUREG/CR-6335. For the air data, all data were corrected to 25°F; for water data, the environmental factor was combined with the predicted number of cycles to initiation to determine adjusted initiation cycles using the environmental corrections contained in NUREG/CR-6583:

$$\text{Air:} \quad \ln(N_{25})_{adjusted} = \ln(N_{25})_{test} + 0.00124\,(T_{test}-25)$$

$$\text{Water:} \quad \ln(N_{25})_{adjusted} = \ln(N_{25})_{test} - 0.101\, S^{*}T^{*}O^{*}\dot{\varepsilon}^{*}$$

This allowed all data to be shown on a single plot of alternating stress versus effective life. Figures 3 to 10 show the results. In all cases, there is no indication of any data that fall below the 5-percent quantile in the high-cycle region affected mainly by the endurance limit. There were some data in the ANL database that were less than the 5-

[1] Private communication, Omesh Chopra, Argonne National Laboratory, August 2003.

percent quantile in the low-cycle regime for both the ANL and the MRP-74 endurance limit variances.

It was not practical to perform a regression analysis on the data to show a reduced endurance limit variation since there is insufficient data, as reflected in the ANL reports. However, the figures presented herein all reflect that the endurance limit data are above the 5-percent quantile, indicating that 95 percent of the data would fall above this line. This, in combination with an alternate, more conservative approach for addressing surface finish, size, and geometry effects, as described in the responses to other RAI questions, demonstrates that the alternate endurance limit variation is reasonable for performing probabilistic fracture mechanics evaluations.

In subsequent discussions with the NRC[2], it was noted that there were sources of data that indicated significant data scatter. One specific source was from PVP-Vol. 383, "Evaluation of Stress Intensification Factors for Circumferential Fillet Welded or Socket Welded Joints." 1999. In this document, stress intensification factors based on data from many sources were evaluated. Review of the document indicates that the scatter presented therein represents that due to socket/fillet weld geometry variability (principal source), weld defects (also likely a major source of variability given the lack of effective NDE for fillet welds), weld size, and material variability. There is significant discussion in the paper related to variability of stress intensification factor results due to "large defects", minimum size welds, oversize welds, etc. Thus, use of this data to suggest that the coefficient of variation used in the EPRI study is not conservative is not justified and not appropriate.

[2] NRC public meeting with the Nuclear Energy Institute to discuss staff's RAI on environmental assisted fatigue, July 24, 2003, Washington, DC.

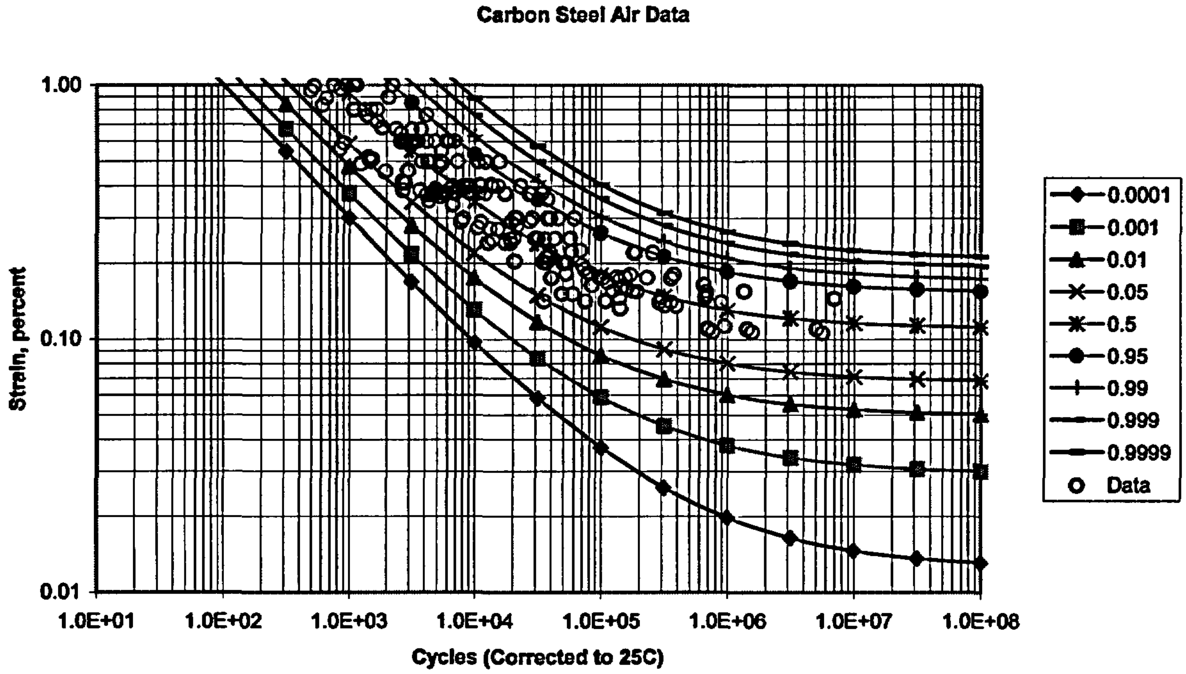

Figure 3. ANL Data for Carbon Steel in Air – ANL Endurance Limit Variation

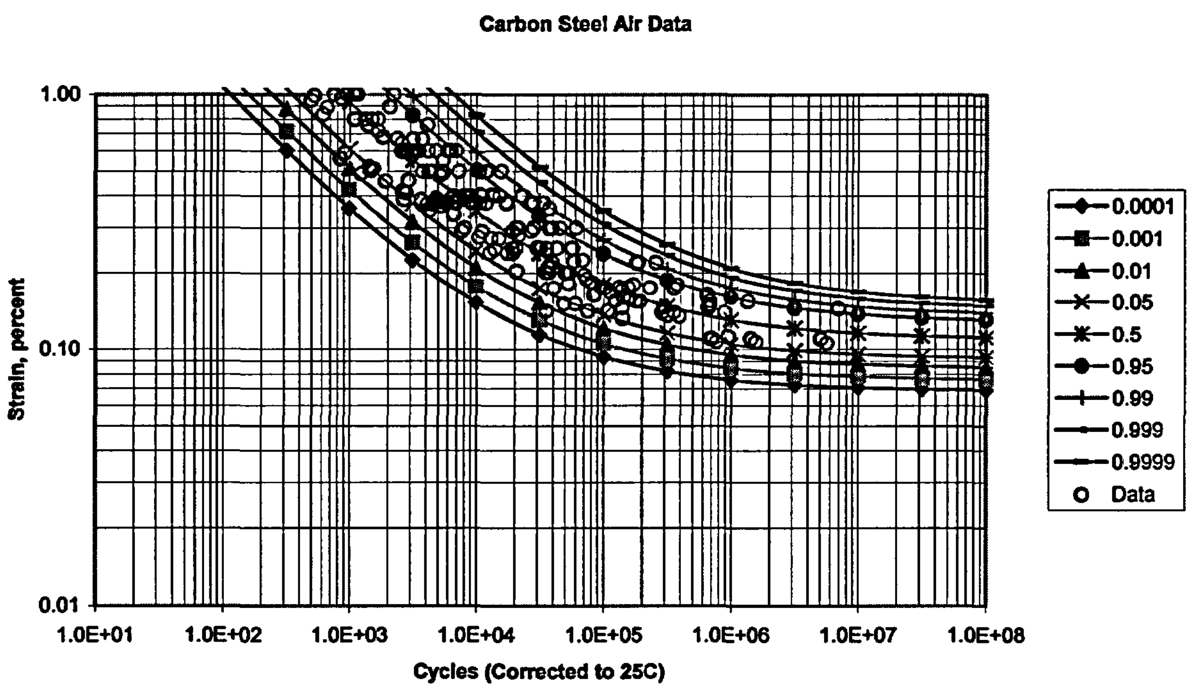

Figure 4. ANL Data for Carbon Steel in Air – 10-Percent Endurance Limit Variation

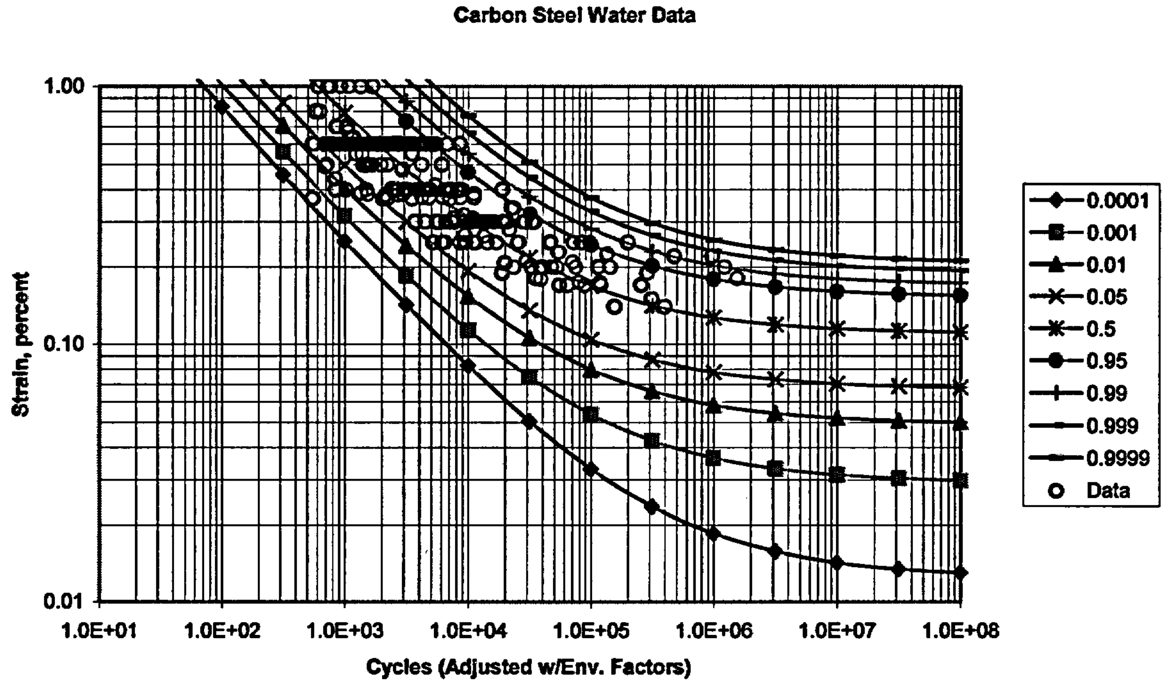

Figure 5. ANL Data for Carbon Steel in Water – ANL Endurance Limit Variation

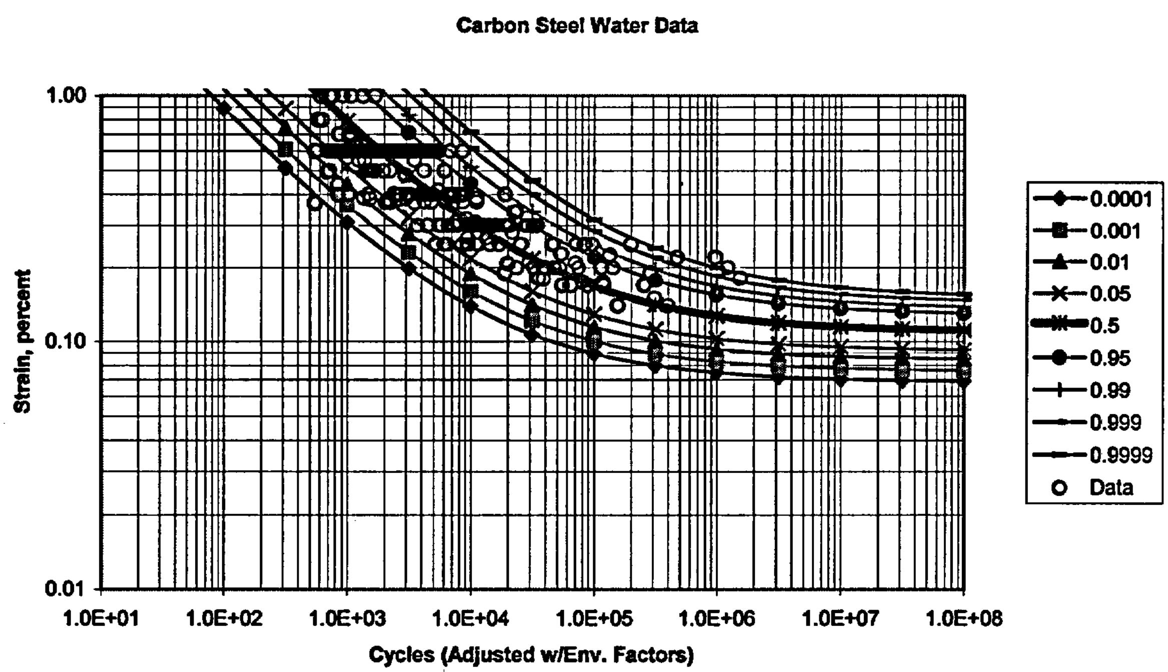

Figure 6. ANL Data for Carbon Steel in Water – 10-Percent Endurance Limit Variation

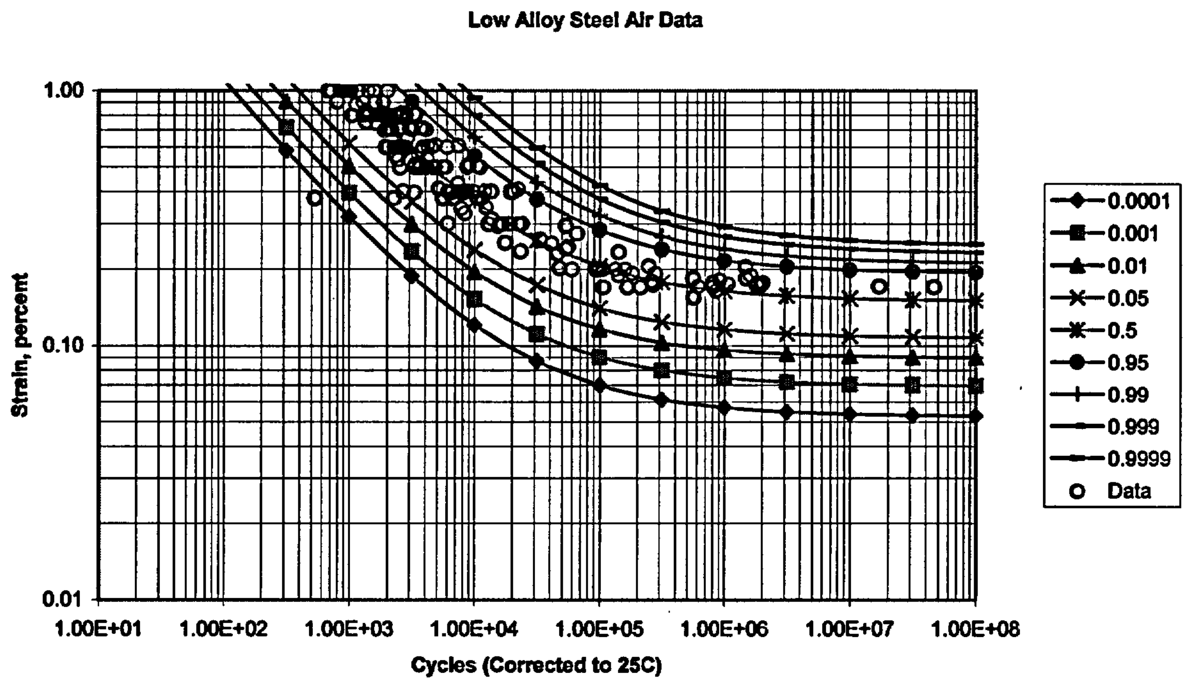

Figure 7. ANL Data for Low Alloy Steel in Air – ANL Endurance Limit Variation

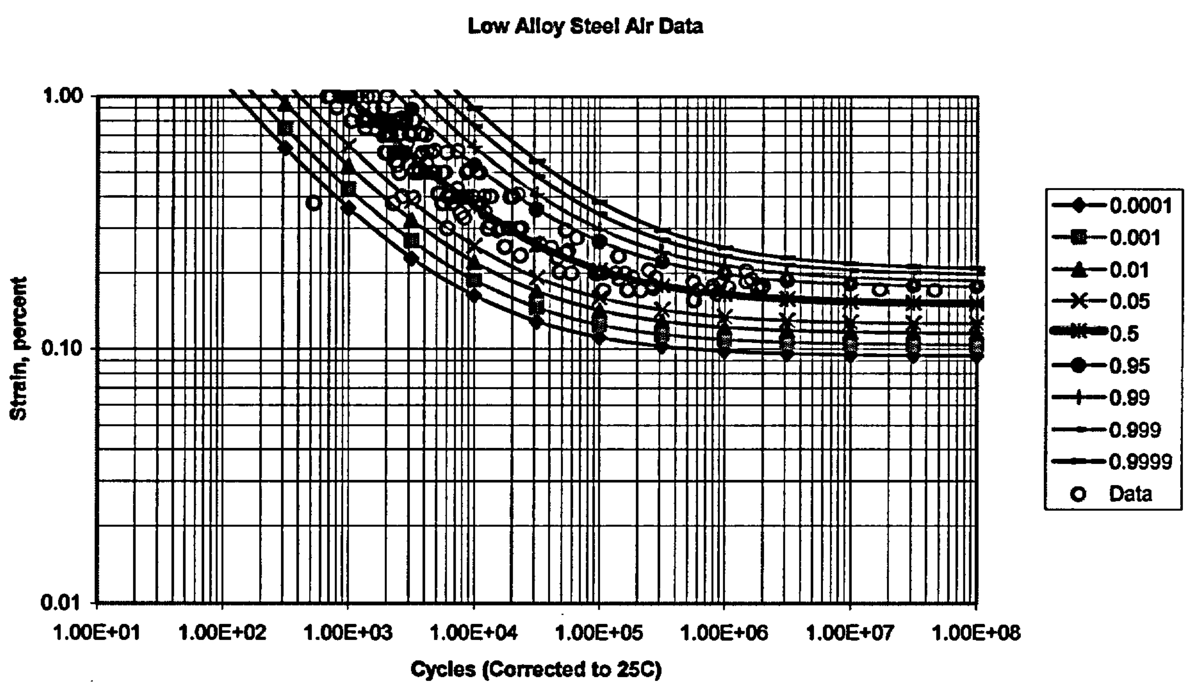

Figure 8. ANL Data for Low Alloy Steel in Air – 10-Percent Endurance Limit Variation

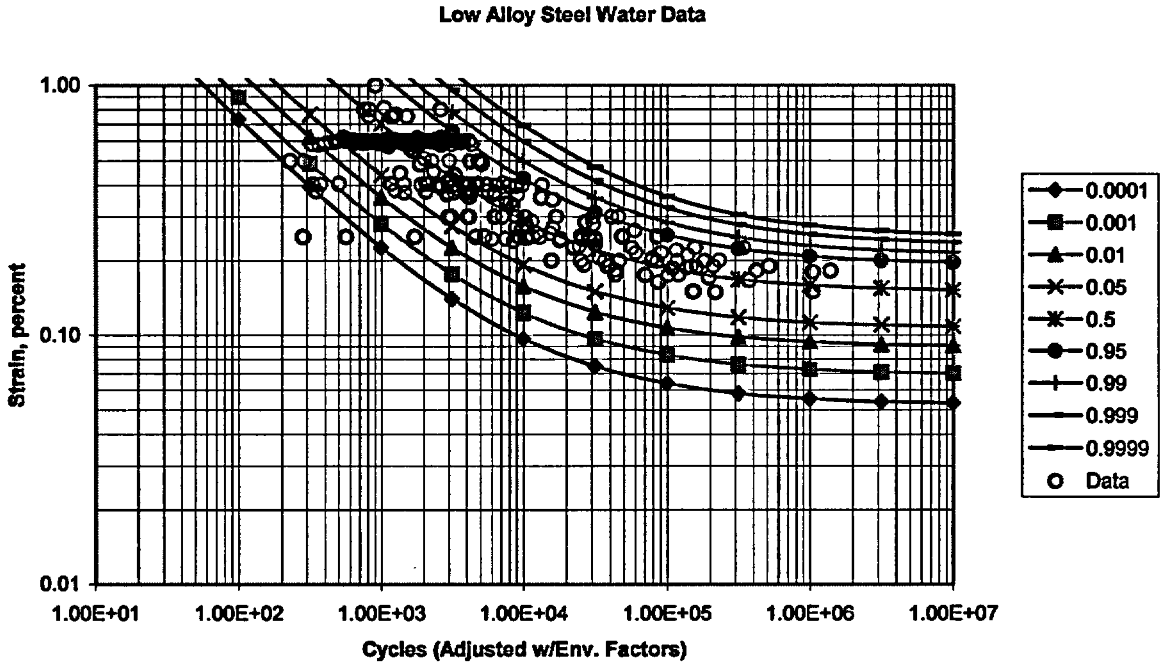

Figure 9. ANL Data for Low Alloy Steel in Water – ANL Endurance Limit Variation

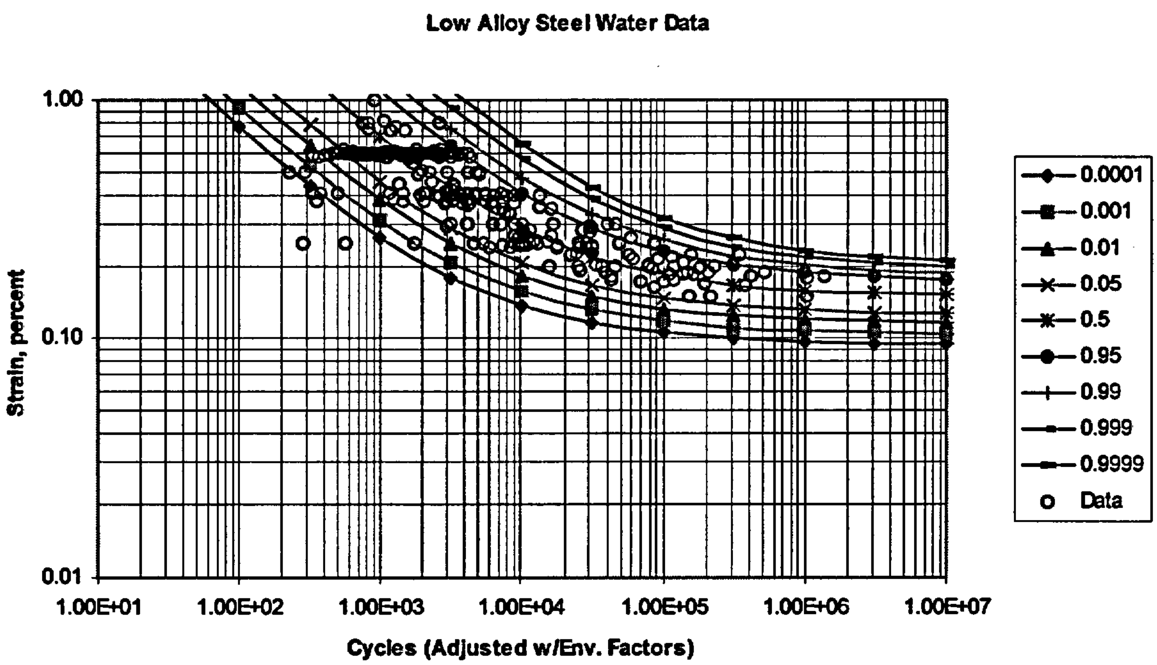

Figure 10. Data for Low Alloy Steel in Water – 10-Percent Endurance Limit Variations

B. *The study does not appear to adjust the endurance limit strain to account for the differences between smooth specimen data and actual components. The ANL correlation used by PNNL was developed to account for this difference. Provide the basis for not adjusting the endurance limit to account for the difference between the specimen data and actual components.*

Response:

The methods for adjustment between best-fit data curves and estimated S-N curves are described in Section 7.3 of NUREG/CR-6335. As described in NUREG/CR-6335, a modification to the data curve was developed to account for the most adverse effects of mean stresses, using the same approach as was used for development of curves for the ASME Code. Then, factors were developed to account for the effects of size/geometry and surface roughness. The following factors were considered:

- The effects of size/geometry could be accounted for by factors of 1.4 on cycles, and 1.25 on strain.
- The effects of surface finish could be accounted for by factors of 3 on cycles and 1.3 on strain.
- It was concluded that the individual factors on cycles could be covered by a total factor of 4 on cycles (approximate product of 1.4 and 3).
- It was concluded that the factors on strain were associated primarily with the endurance limit and that they would not be cumulative. Thus, the factor of 1.3 would be applicable.
- It was concluded that the factors on strain for size/geometry and surface finish were adequately covered by the 5% quantile endurance limit uncertainty that was associated with material variability. Thus, there was no explicit factor included for size/geometry and surface finish when using the ANL equations. Using this approach in a probabilistic evaluation is not correct, since at the mean of the material variability curves, no factor on stress is included. At probabilistic levels above the percent level, the "factor" would have been negative.

In MRP-74, the factor on strain for size/geometry and surface finish was also not explicitly included. However, the endurance limit uncertainty was reduced to better reflect endurance limit test data scatter. There should have been the additional consideration of size/geometry and surface finish at the high-cycle end of the curves. The factor of (4) on cycles, that affects primarily the low end of the fatigue curves, was included.

An alternate approach for consideration of the effects of size/geometry and surface finish that is consistent with the ASME Code approach for inclusion of margins has been developed. This is included in Attachment A, and has been used to re-evaluate the initiation and leakage probabilities for carbon and low-alloy steel components.

C. *The EPRI report indicates that a strain threshold was used in the evaluation but does show how the threshold was applied. The EPRI Report, page 3-11, references NUREG/CR-6717 for the strain threshold values used for the evaluation. As discussed in NUREG/CR-6717, the thresholds are strain levels at which environmental effects are considered moderate. These thresholds were proposed for use in the development of fatigue design curves. NUREG/CR-6717 also indicates that the threshold strain is approximately 20% higher than the fatigue limit (endurance limit) of the steel. Therefore, the threshold strain should be related to the endurance limit. Additionally, the proposed 0.07% threshold strain for the carbon and low alloy steel design curves has not been universally accepted at this time. For example, some fatigue researchers have proposed using the endurance limit strain of 0.042% as the threshold value. As a consequence, the use of a fixed threshold strain in the probabilistic study is questionable. Explain how the strain threshold values were used in the evaluations presented in Chapter 4 of the EPRI report. Provide the results of the EPRI evaluations without using strain threshold values.*

Response:

The strain thresholds in MRP-74 were set at the values provided therein without any consideration of material variability. They were shown to have a negligible effect on the outcome of the results.

The thresholds in NUREG/CR-6717 were used, as described in MRP-74. For a given value of S_{alt}, pcPRAISE was modified to first adjust the stresses with a mean stress correction. Then, if the adjusted stress was above the high threshold, there was no adjustment to the environmental effects (the environmental multiplier factor due to the thresholds was 1.0). If the adjusted stress was below the low threshold, a multiplier of zero was applied to the environmental effects. Between, there was a linear interpolation. Thus, for mean-stress adjusted S_{alt} less than 21 ksi, there would be no environmental effects applied; above 24 ksi environmental effects would be fully applied. Figures 4-5 and 4-6 of MRP-74 show that the combined effects of thresholds, mean stress effects and the high-cycle extension of the fatigue curves have no effect on components that have high initiation and leakage probabilities. This is due to the fact that it is high stress ranges that are the major contributor to fatigue usage and crack growth, not those that are down around the proposed strain thresholds.

For the revised analysis presented in Attachment A, strain thresholds were not considered. This is a conservative assumption.

D. *The strain thresholds are discussed on page 26 of NUREG/CR-6717. NUREG/CR-6717 indicates that, after mean stress effects are taken into account, a threshold strain amplitude of 0.07% provides a 90% confidence level for both carbon and low alloy steels. As discussed previously, the threshold strain is approximately 20% higher than the endurance limit of the steel. Consequently, the 10 percent probabilistic fatigue curve should approach a strain amplitude of approximately 0.06% at 10E6 cycles. The 10 percent probability curve shown in Figure 3-11 of the EPRI report is not consistent with a strain of 0.06%. Discuss this discrepancy* *between Figure 3-11 of the EPRI report and the data assessment contained in NUREG/CR-6717.*

Response:

Since the effects of size/geometry and surface finish were not implicitly included, there is a discrepancy. However, the modified approach described in Attachment A provides a consistent basis with the data assessment presented in NUREG/CR-6717. Table 2 demonstrates that the 90% confidence limit provides a conservative level of strain as compared to the 0.07 percent strain threshold determined in NUREG/CR-6717. This comparison is shown for conditions with high environmental effects using the NUREG/CR-6335 equations (high sulfur, 550°F, high oxygen, and low strain rate).

Table 2
Demonstration of Strain Threshold Equivalence

Mean Data Strain and Adjustments	Carbon Steel	Low Alloy Steel
Mean strain at 10^6 cycles (percent)	0.1121	0.1509
90-percent confidence lower bound strain using 10% variation of endurance threshold strain (percent)	0.0973	0.1314
Above strain adjusted for mean stress effects[1] (percent)	0.0865	0.0748
Above strain adjusted for size/geometry and surface finish with a factor of 1.3 (percent)	0.0666	0.0575

[1] Using S_y/S_{uts} of 40/80 ksi for CS and 70/100 ksi for LAS

Thus, there is no discrepancy between the revised results in Attachment A and the data assessment of strain threshold of NUREG/CR-6717. However, as described in the response to the previous question, strain environmental thresholds were not considered in the revised analysis. This is a conservative assumption.

2. *The EPRI report, page 3-3, indicates that the ANL adjustment of ln(4), used to account for the differences between laboratory specimens and actual components, was included in the study in accordance with the discussion in the PNNL study. Section 4.7 of the PNNL study indicates that the ln(4) value was adjusted to account for the potential for multiple crack initiation sites. The PNNL study further indicates that the adjustment was calibrated against the data from the 9-inch diameter vessel tests described in the ANL report. Describe how this adjustment was applied in the EPRI study.*

Response:

The life adjustment correction between laboratory specimens and multiple initiation sites were applied in exactly the same fashion in the EPRI study (MRP-74) and in the revised analysis of Attachment A as in the PNNL study.

Discussions were held with Dr. Fred Simonen of PNNL[3] to gain additional insight into the basis for the adjustment and for the analysis that had been conducted to derive the factor of 3. Dr. Simonen recollected that the adjustment had originally been determined to be a variable that included consideration of the number of locations where fatigue initiation might occur. The calibration had been developed by analysis of the small-scale vessel testing characterized as a 9-inch diameter vessel in NUREG/CR-6674. The data evaluated are shown in Figure 26 of NUREG/CR-6335. The basic premise in the calibration was that size effects were inherently introduced by the simultaneous evaluation of multiple locations in a component. When the number of locations being evaluated increased, the probability that fatigue cracking would initiate would also increase. Thus, combination of the factor of ln(4) factor and the multiple location simulation would be a double count.

Evaluation of the PNNL data files for the pcPRAISE analysis showed that the reduction had been taken as a factor of 3 and had not been input as a parameter based upon the number of fatigue locations (where the number of locations is taken as the circumference of the component exposed to water divided by two inches per location).

To gain further understanding of this, evaluations were conducted representative of the carbon steel data points in Figure 26 of NUREG/CR-6335. For stress amplitude levels of 45 and 70 ksi, pcPRAISE analyses were run to simulate simultaneous fatigue initiation at 1, 7, 14 and 28 locations. The 14-location run was consistent with the "9-inch" vessel quoted in NUREG/CR-6674. Analysis was conducted for ambient temperature water conditions using the PNNL model used in NUREG/CR-6674 and the model described in Attachment A. In both cases, the model included the factor on the natural logarithm of 4 in the fatigue equations that introduced the factor of 4 for size/geometry and surface finish. Results of this analysis are shown in Figures 11 and 12 for the 45 ksi case and in Figures 13 and 14 for the 70 ksi case.

The results show that the probability of crack initiation increases with the number of loading cycles and with the number of locations around the circumference. The dashed line represents the single location probability with cycles reduced by a factor of three, as was determined to represent a conservative life adjustment factor as described in NUREG/CR-6674.

The first two cases (Figures 11 and 12) represent the lower-strain case in NUREG/CR-6335 Figure 26 for carbon steel. The cycles to the 50 percent probability of crack initiation is about 45,000 for both the PNNL and the Attachment A methodology, consistent with the mean of the two lower data points for the vessel testing. This indicates that the natural logarithm of 4 is an appropriate measure of reduction for size/geometry and surface finish effects for analysis of a single location. For the models with more locations being evaluated simultaneously, the number of cycles to initiation is

[3] Private communication, August 2003

under predicted significantly, demonstrating the "double count." Both figures show that the multi-locations modeling under predicts the probability of initiation except when there is a very low probability of initiation. The 14-location model predicts initiation significantly sooner than the single-model results corrected by the factor of 3 (the dashed line). Since initiation must occur prior to crack growth, the reduction by a factor of three is conservative, especially for components with diameter greater than 9 inches (which represent all of the components in Attachment A).

Results of the second case for higher stress amplitude (Figures 13 and 14) is consistent with the first case and adequately predict the higher stress testing at the 50 percent probability level. Although the method described in Attachment A predicts a slightly higher number of cycles to reach the 50 percent probability level, the reduction factor of three is still conservative. This is especially true since the carbon and low-alloy steel components of the evaluation are all significantly greater than 9-inches diameter.

Thus, the application of the factor of three for life-adjustment in the pcPRAISE analysis is appropriate.

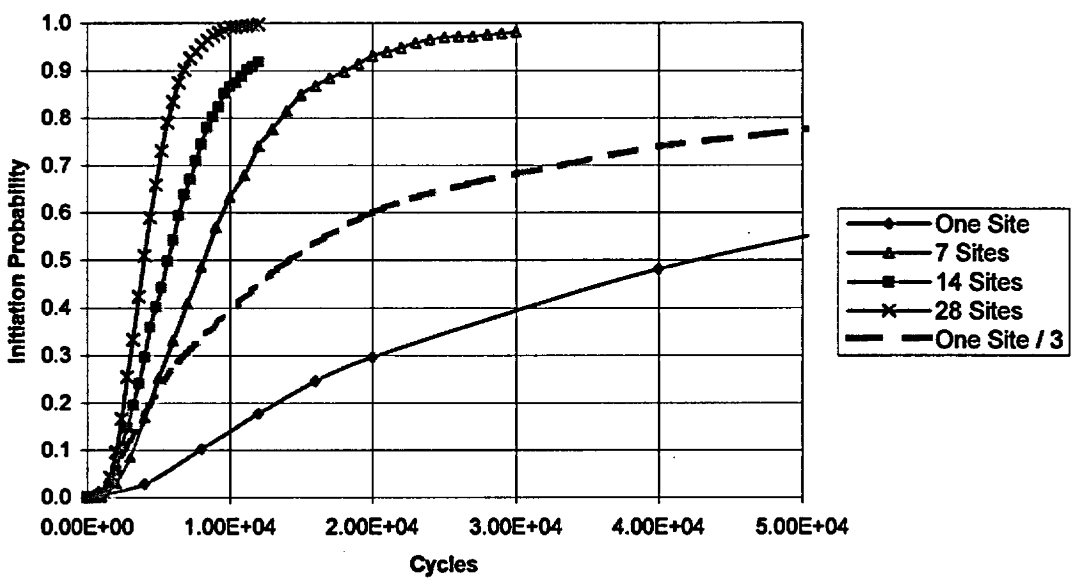

Figure 11. Initiation Probability versus Cycles for 45 ksi Stress Amplitude (PNNL Method)

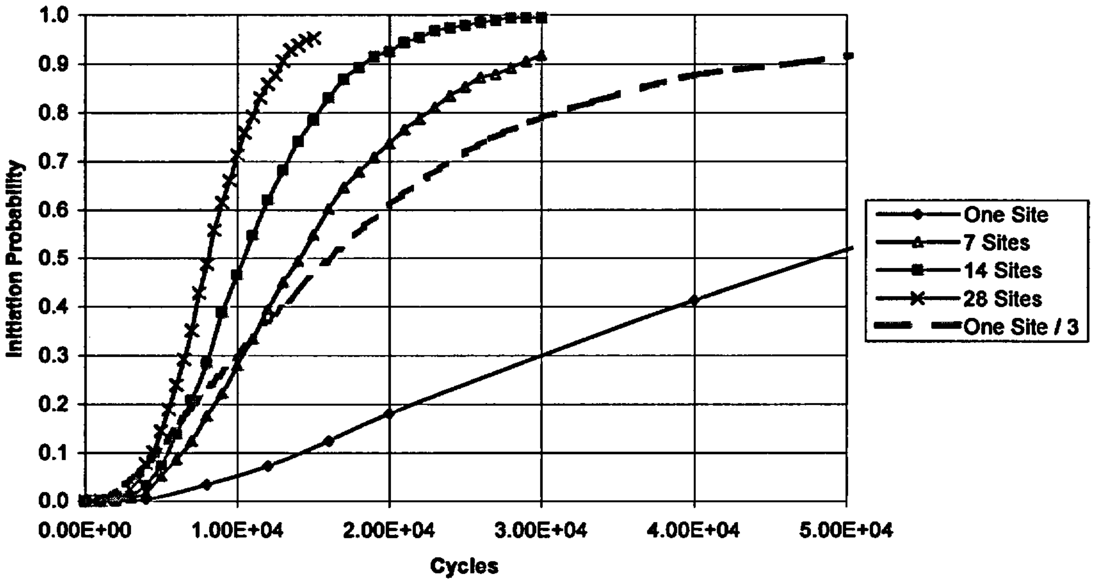

Figure 12. Initiation Probability versus Cycles for 45 ksi Stress Amplitude (Att. A Method)

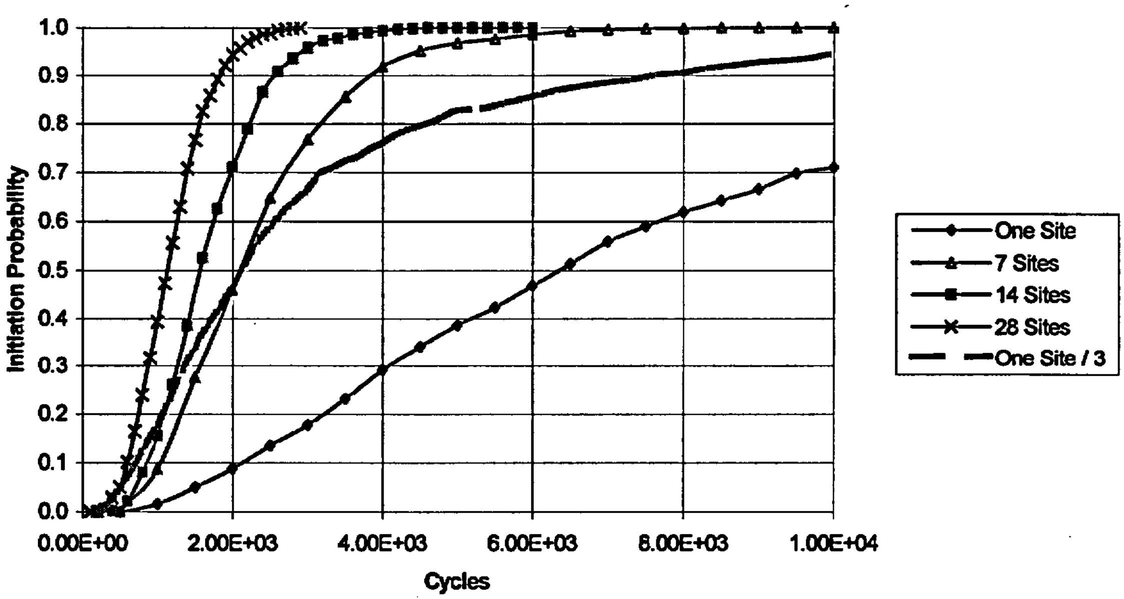

Figure 13. Initiation Probability versus Cycles for 70 ksi Stress Amplitude (PNNL Method)

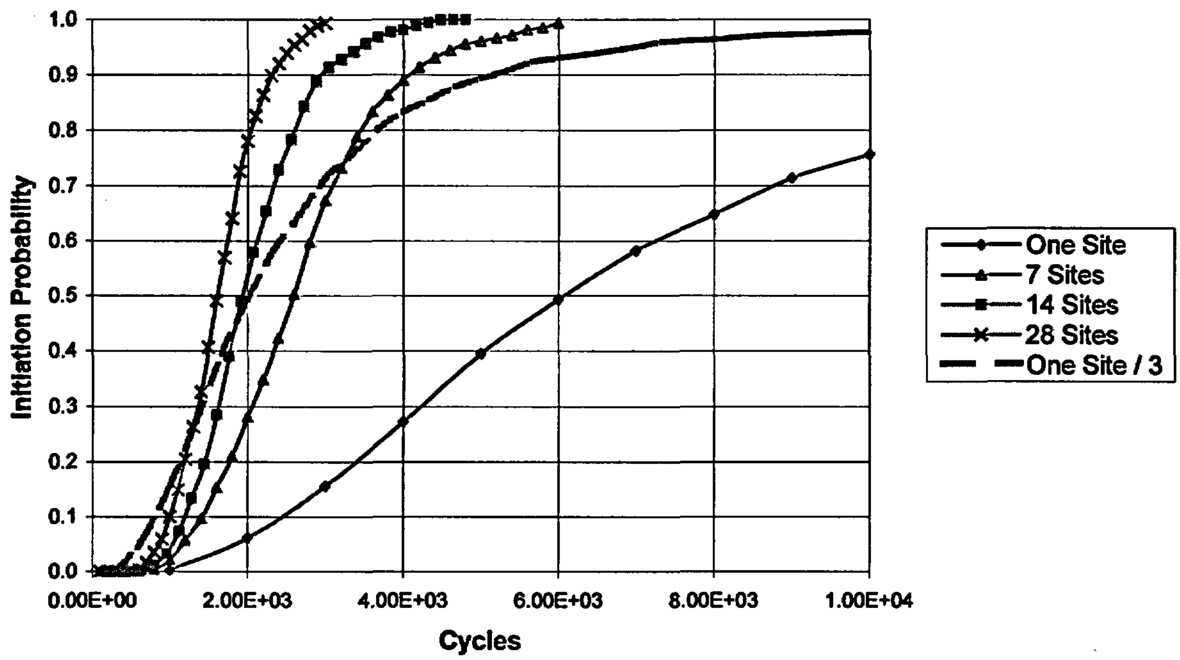

Figure 14. Initiation Probability versus Cycles for 70 ksi Stress Amplitude (Att. A Method)

3. *The EPRI report, page 3-11, provides a procedure to account for mean stress effects. Show how this procedure was implemented in the evaluations presented in Chapter 4 of the report. Discuss the consistency of the mean stress adjustment used in the Chapter 4 evaluations with the mean stress adjustment discussed in NUREG/CR-6717.*

Response:

The mean stress adjustment based on the modified Goodman relationship is reflected in equations (1) and (2) of Section 5 of NUREG/CR-6717. These equations were used in the original versions of ASME Section III to conservatively adjust the fatigue curves for the most adverse potential mean stress effects. The equations were used to reduce the high-cycle end of the mean fatigue data curves that fell below the yield strength of the carbon or low alloy steel material. This is also discussed in NUREG/CR-6335, where this correction was made to the mean data curves (Equation 5, Section 4) to arrive at a set of shifted curves with mean stress incorporated (Equation 18, Section 7.3).

In the EPRI report, a more standard approach for consideration of mean stress effects was utilized. Equation 3-5 of MRP-74 is derived from the same equations described above for the most adverse mean stress conditions:

$$S_{alt} = S_{alt}' \times S_u / (S_u - S_y + S_{alt}) \qquad (5)$$

Thus, for an applied alternating stress, a corrected stress is used when determining the number of allowable cycles from the fatigue curve. Figures 15 and 16 show the difference between using NUREG/CR-6335 Equation 18 for carbon and low-alloy steels, and for using the NUREG/CR-6335 Equation 5 mean data curves, including the NUREG/CR-6335 coefficients for material variability, with mean stress corrections for S_y = 40 ksi and S_{ult}= 80 ksi for carbon steel and S_y = 70 ksi and S_{ult}= 100 ksi for low alloy steel, as were used in deriving the ASME Code curves and Equation 19. There are slight differences since the NUREG/CR-6335 modified fits to include data scatter are not exact fits of the modified Goodman procedure. However, the two are nearly identical, except that the mean stress approach used in MRP-74 is more conservative. Figure 17 shows a similar comparison for low-alloy steel with no environmental effects included.

The one inconsistency in the MRP-74 approach was the assumed value of the yield and ultimate tensile strengths. The values used in NUREG/CR-6335 were the upper bound values derived from the ASME Code basis document (S_y = 70 ksi and S_{ult} = 100 ksi for low-alloy steel and S_y = 40 ksi and S_{ult} = 80 ksi for carbon steel. In MRP-74, the standard values from pcPRAISE for determining critical flaw sizes were S_y = 30.8 ksi and S_{ult} = 70 ksi for low-alloy steel and S_y = 28.3 ksi and S_{ult} = 60 ksi for carbon steel.

Attachment A further describes how this approach is used along with a size/geometry/ surface finish-corrected probabilistic fatigue curve to perform a re-analysis of the initiation and leakage probabilities for the CS and LAS components.

The consistency of this approach is also demonstrated in the response to Question 1.D.

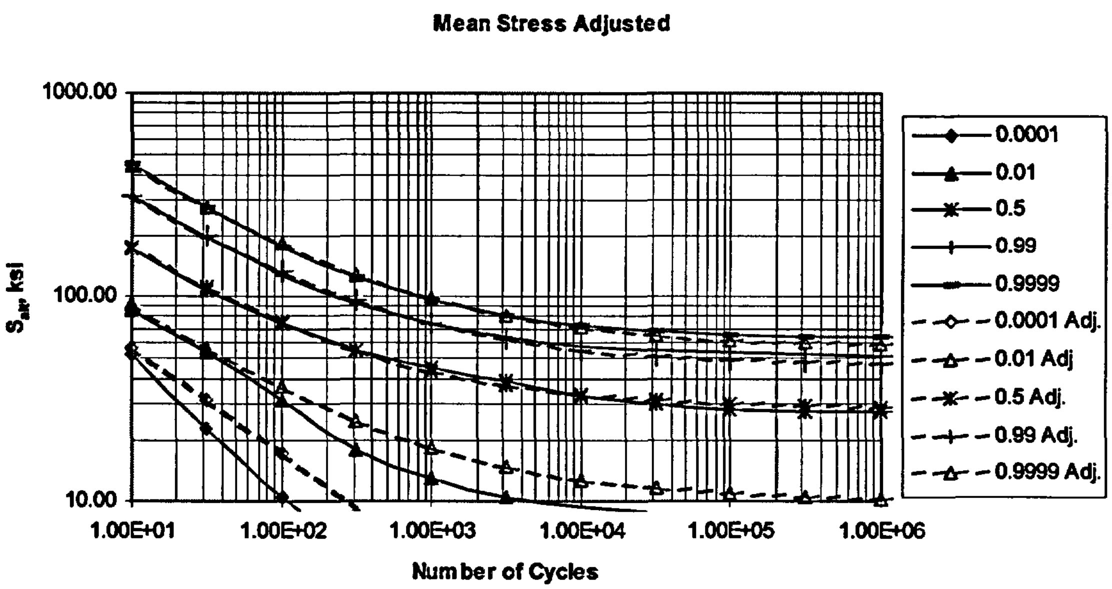

Figure 15. Comparison of Effective Fatigue Curves Using NUREG/CR-6335 Data Fits and Modified Fatigue Curves for Carbon Steel (Note: Maximum Environmental Effects at 550°F. Solid lines are mean-stress corrected data curves and dotted lines are NUREG/CR-6335 Equation 18.)

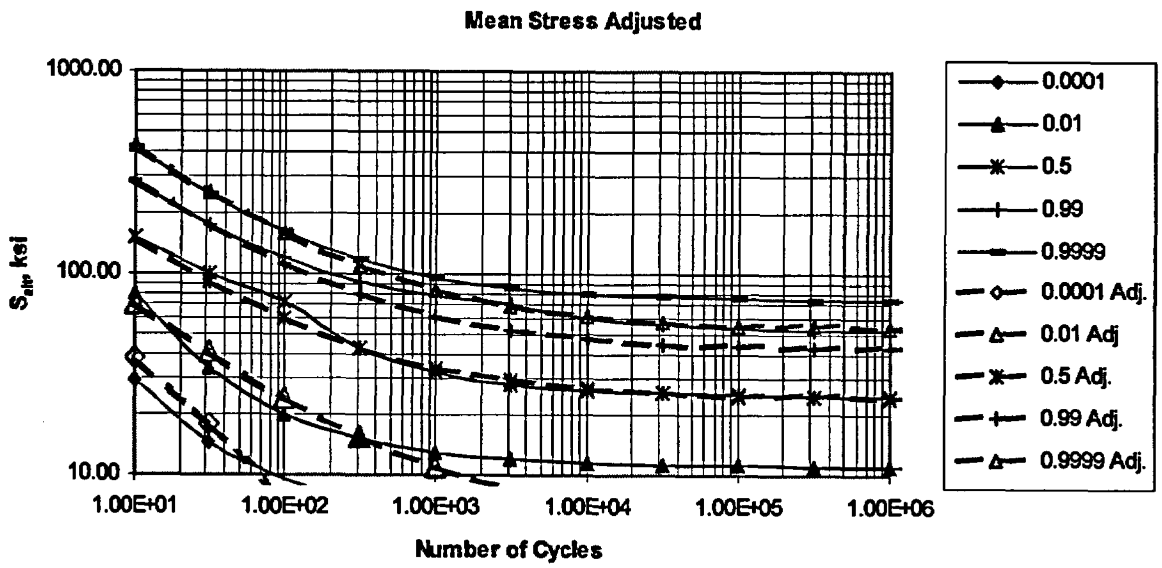

Figure 16. Comparison of Effective Fatigue Curves Using NUREG/CR-6335 Data Fits and Modified Fatigue Curves for Low-Alloy Steel (Note: Maximum Environmental Effects at 550°F. Solid lines are mean-stress corrected data curves and dotted lines are NUREG/CR-6335 Equation 18.)

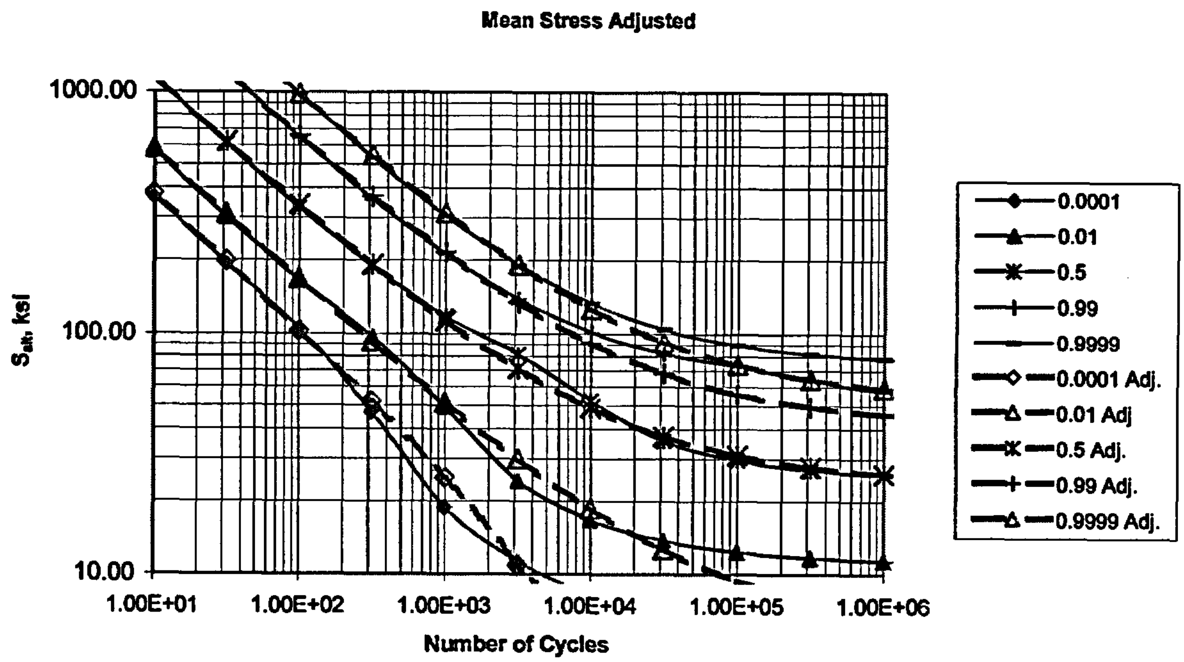

Figure 17. Comparison of Effective Fatigue Curves Using NUREG/CR-6335 Data Fits and Modified Fatigue Curves for Low-Alloy Steel (Note: No environmental effects. Solid lines are mean-stress corrected data curves and dotted lines are NUREG/CR-6335 Equation 18.)

4. *Several of the component evaluations presented in Chapter 4 of the EPRI report use stresses and cycle counts that are different than those used in the PNNL study. The changes affect the calculated environmental fatigue usage factors for these components. Provide the environmental fatigue usage factors based on the revised component stress and cycle assumptions. Discuss the actions that would be required by a license renewal applicant to address components with these usage factors.*

Response:

Seven component locations from NUREG/CR-6260 were re-analyzed using different cycle counts and stresses. Five of those component locations were for PWR reactor vessel outlet nozzles (B&W, new vintage CE, older vintage CE, new vintage Westinghouse, and older vintage Westinghouse) and one other component location was for a PWR reactor vessel inlet nozzle (older vintage Westinghouse). In all six of these PWR nozzle locations, no change was made to the alternating stress amplitude, only to a single load pair representing load-following power changes. The approach taken to reduce the number of cycles for load pairs not relevant to base-load plant operation is consistent with and was suggested in NUREG/CR-6260. The former and the revised CUFs for these six PWR nozzle locations are provided in Attachment A (Tables A-4, A-5, A-6, A-7, A-8, and A-9). Note that the "As-Designed" CUFs are not identical to those calculated in NUREG/CR-6260 because of changes to the environmentally-adjusted fatigue design curves, based on more recent data. Note also that, in some cases, the re-calculated CUF is substantially lower, but not in all cases.

One additional component location – an older vintage BWR feedwater line RCIC tee – was also re-analyzed. In this case, fewer seismic cycles were used and less conservative strain rates were also used. The revised CUF did not change significantly from that reported in NUREG/CR-6260.

For several other BWR component locations, revised initiation and leakage probabilities were calculated using less conservative temperatures than those used in NUREG/CR-6674. However, no changes were made to the alternating stresses and CUFs calculated in NUREG/CR-6260.

The most important finding from these re-calculations is not the revised CUF values. Instead, the major finding is the reduction in 40-year and 60-year through-wall leakage probabilities by several orders of magnitude. Comparing the results in Tables A-1 and A-2 with those obtained by reducing load-following power change cycles shows that the reduction in leakage probability is influenced significantly by the large number of load-following power change cycles.

Another finding from these re-calculations is that, while high environmentally-adjusted CUFs are moderately useful predictors of initiation probability, they are not accurate predictors of leakage probability. In many cases, the leakage probabilities for a number of component locations with relatively high environmentally-adjusted CUFs are much less than those component locations with environmentally-adjusted CUFs well under one. Therefore, as stated in MRP-74, license renewal applicants should not be required to take further action for carbon and low-alloy steel component locations, other than to continue existing programs to manage the effects of fatigue.

5. *The submittal references the evaluation of the component fatigue tests contained in EPRI Report MRP-49. The evaluation of the component fatigue test data is similar to the evaluation contained in EPRI Technical Report, "Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application (MRP-47)," Draft Revision G dated June 5, 2001. This report was submitted to the NRC by NEI letter dated July 31, 2001. The staff transmitted a request for additional information regarding the evaluation of the component fatigue tests by letter dated June 26, 2002. The staff has not received a response to its request for additional information. Indicate how the relevant June 26, 2002, staff comments have been addressed in the test data evaluation contained in EPRI Report MRP-49.*

Response:

The submittal will be modified to remove direct reference to EPRI Report MRP-49, in accordance with the verbal agreement reached in the meeting with the NRC staff on July 24, 2003. The information from EPRI Report MRP-49 was used in the submittal to provide technical support for the ISG recommendations in three areas: (1) interpretation of laboratory environmental fatigue data supporting the NUREG/CR-6674 re-calculations of initiation and leakage probabilities; (2) interpretation of structural component fatigue test data with one surface in contact with oxygenated water, showing consistent agreement with relevant laboratory environmental fatigue data; and (3) industry operating experience in consistent agreement with relevant laboratory environmental fatigue data and with component structural fatigue test data. The primary information supporting the recommendations in the submittal continues to be the MRP-74 re-calculation of initiation and leakage probabilities using more realistic input with full consideration of reactor water environmental effects. Adding the information from EPRI MRP-49, which raises concern regarding the applicability of laboratory environmental fatigue data to operating environments, provides a persuasive body of information in support of those probabilistic re-calculations, but that direct reference will be eliminated.

Response to NRC Request for Additional Information
On ISG-11, "Environmental Assisted Fatigue for Carbon/Low-Alloy Steel"

Attachment A

Re-Evaluation of Fatigue Initiation and Leakage Probabilities For Carbon and Low-Alloy Steel Components

Introduction

Questions raised by the NRC [1] have led to further evaluations on the correct procedures for implementation of a probabilistic fatigue curve into the pcPRAISE program [2] that was used to evaluate fatigue initiation and leakage probabilities in NUREG/CR-6674 [3] and MRP-74 [4]. A question of significance is that the work in MRP-74 did not specifically include consideration of component size/geometry and surface finish effects. In the work supporting the probabilistic fatigue curves used in NUREG/CR-6674, as reported in NUREG/CR-6335 [5], this effect was indirectly included by consideration of a very conservative fatigue curve endurance limit probabilistic variation.

In this attachment, the revised approach is defined. Then, results of the re-analysis of all carbon steel (CS) and low-alloy steel (LAS) components are provided. The conclusions from this re-evaluation are compared to those reached in MRP-74.

Description of Modified Probabilistic Fatigue Curve

In deriving a fatigue curve for the ASME Boiler Code Section III, certain corrections were applied to fatigue data curves to derive curves for use in design [6]:

1. The mean data curve was shifted downward to account for mean stress effects that might be produced by welding and material forming.

2. The design curves were then determined from the mean-stress adjusted curve by either reducing the cycles by a factor of 20 or the alternating stress intensity by a factor of 2, whichever is more conservative. These factors were meant to "cover such effects as environment, size effect, and scatter of data ..."

To perform a probabilistic analysis of fatigue initiation, the same effects should be considered. An approach to incorporate these effects is described in the following.

Figure A-1 is a typical representation of the fatigue data and its variation, as derived in NUREG/CR-6335. The curves represent the data scatter observed in fatigue testing, with variation assigned to both the number of cycles and to the strain amplitude. In a probabilistic fatigue analysis, one of these curves is randomly chosen for each Monte Carlo sampling.

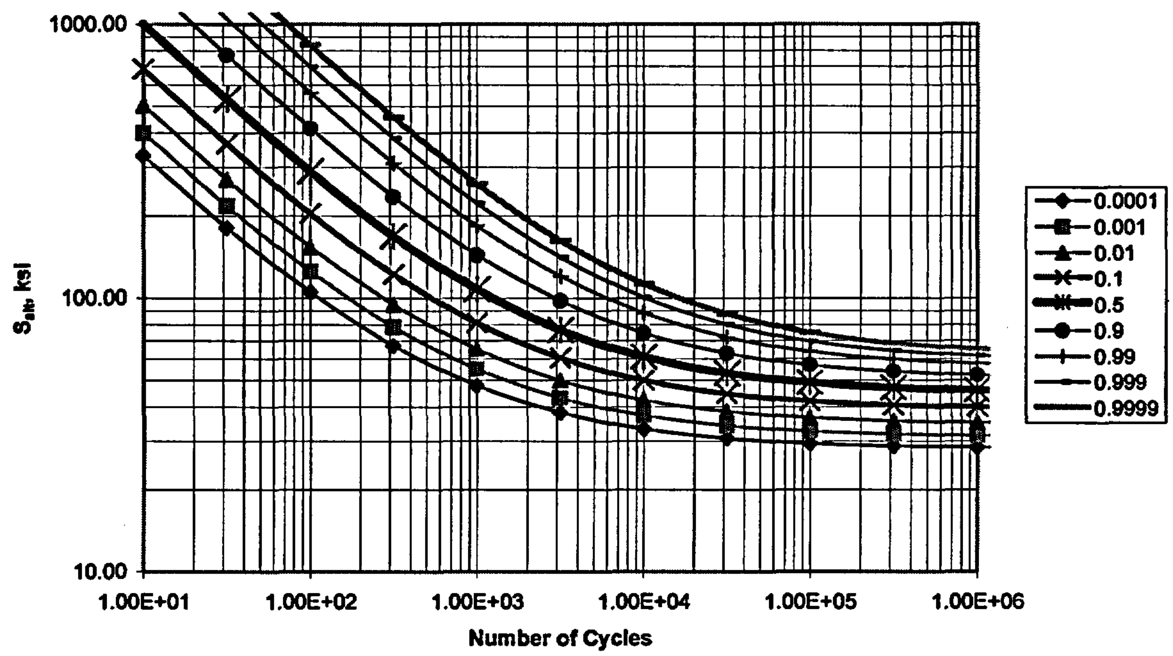

Figure A-1. Typical Fatigue Data Curve Representing Data Scatter during Testing

The rational approach to perform the evaluation is to implement the same approach as included for the ASME Code. Figure A-2 shows how this is done.

1. Define a curve that is shifted to the left that accounts for the effects of size/geometry and surface effects. Per NUREG/CR-6335, the curve is shifted to the left by a factor of four. This factor was judge to cover the cumulative effects of surface finish and size/geometry effects, and governs in the low-cycle range. An equivalent method for determining the number of allowable cycles with consideration of size/geometry and surface finish effects is to determine the number of allowable cycles from the probabilistic data curve and reduce the number of allowable cycles by a factor of four.

2. Define a curve that is shifted downward in stress amplitude by a factor of 1.3. In NUREG/CR-6335, the effects of surface finish and size/geometry were not judged to be cumulative, so that a factor of 1.3 on stress amplitude could be used. An equivalent method for determining the number of cycles from this second shifted curve is to determine the number of cycles from the data curve based on stress amplitude increased by a factor of 1.3.

3. The two curves so determined in steps 1) and 2) represent the material being analyzed, with consideration of surface finish, and size/geometry effects. The minimum of the allowable cycles determined when considering both possible effects is used in the fatigue evaluation.

4. The third consideration is mean stress. The more common approach for evaluating mean stress effects is to modify the stress amplitude under consideration using the Modified

Goodman approach, as described in MRP-74. Whereas the ASME Code approach shifts the fatigue curve downward to make the correction, the more common approach in fatigue analysis is to shift the stress amplitude upward to make the mean stress adjustment. This modified stress is used in entering the fatigue curves as determined above. For stress amplitudes above the yield stress, there is no resulting correction.

5. Based on the modified stresses and determining the allowable number of cycles for the two cases above, the number of allowable cycles is the minimum of the two cases. This is illustrated for a relatively low stress and for a relatively high stress in Figure A-2. In both cases, the "design stress amplitude" would be adjusted for mean stress effects before determining the number of allowable stresses.

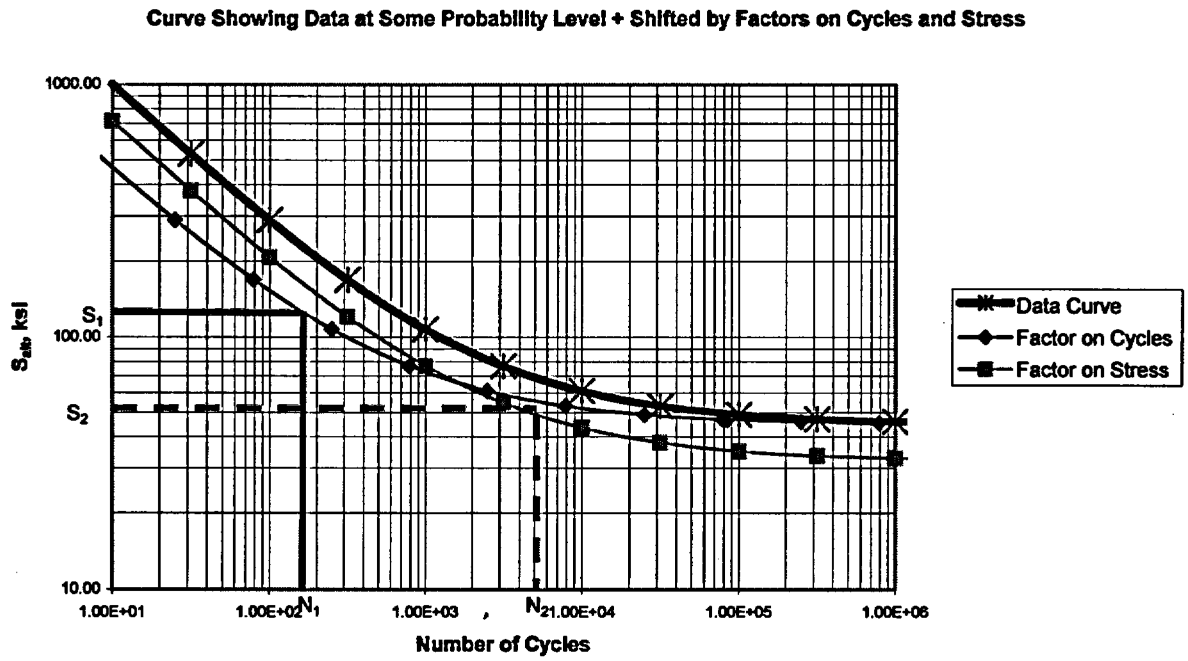

Figure A-2. Definition of Curve Shift due to Factors on Stress and Cycles (shown as an example 50 percent mean probability fatigue curve – but applicable to any probability level)

Since thresholds below which environmental effects are important are very low, there is no consideration given to these thresholds in the modified evaluation herein.

In the analysis presented in MRP-74, typical values of yield stress (S_y) and ultimate tensile strength (S_{uts}) were utilized in performing the mean stress corrections, so minimal changes resulted from mean stress effects. In the revised analysis presented herein, the higher values used in making the ASME Code curve corrections are used:

Material	S_y, ksi	S_{uts}, ksi
CS	40	80
LAS	70	100

In the revised analysis, the environmental fatigue curves defined in NUREG/CR-6335 [Reference 5, Equation 10] are used, except that the endurance limit variance is retained at 10 percent of the endurance limit threshold (0.011 for CS and 0.015 for LAS versus the value of 0.026 presented in NUREG/CR-6335).

Re-Analysis of PNNL Input Files

The original data files from PNNL for the Carbon/Low-Alloy Steel locations were re-run to repeat the analysis presented in NUREG/CR-6674. In performing the review of the differences of the PNNL results to the work in MRP-74, three major inconsistencies were identified in the work by PNNL.

1. First, the version of pcPRAISE developed by PNNL to incorporate the environmental curves converted stresses to strains using the modulus of elasticity at the maximum temperature. Since the stresses from NUREG/CR-6260 have been adjusted to the room temperature modulus of elasticity required by the ASME Code, this error produced strains that were too high. (This was corrected in the revised analysis.)

2. Second, the environmental coefficient of 0.1097 [Reference 3, page 1] should have been retained as 0.554 since the O^* for oxygen was not logarithmic in the PNNL fatigue curves that were otherwise consistent with NUREG/CR-6335. This reduced the probability of initiation results for the PNNL study for components with conditions that produced significant environmental effects.

3. Several of the materials types were incorrectly identified.

Table A-1 shows the PNNL results from NUREG/CR-6674. Table A-2 shows results of the revised analysis using the original PNNL input files. Figures A-3 and A-4 compare the initiation and the leakage results, respectively. The revised analysis methodology results in an overall decrease in initiation and leakage probability compared to the NUREG/CR-6674 results. However, the revised analysis methodology does increase the probabilities as compared to the results originally reported in MPR-74.

Table A-1
PNNL Results for CS/LAS Components From NUREG/CR-6674

Location	Material	Initiation Probability		Leakage Probability	
		40 Years	60 years	40 Years	60 years
B&W RPV OUTLET NOZZLE	LAS	7.74E-01	8.99E-01	1.83E-01	5.44E-01
CE-NEW RPV OUTLET NOZZLE	LAS	4.22E-01	6.89E-01	1.74E-03	2.90E-03
CE-NEW SAFETY INJECTION NOZZLE	LAS	1.01E-03	4.81E-03	1.00E-06	1.90E-05
CE-OLD RPV OUTLET NOZZLE	LAS	5.91E-01	8.46E-01	7.05E-02	3.53E-01
GE-NEW EEDWATER NOZZLE SAFE END	CS	1.04E-01	2.53E-01	1.31E-03	1.47E-02
GE-NEW RHR LINE STRAIGHT PIPE	CS	4.73E-01	6.71E-01	4.10E-01	6.21E-01
GE-NEW FEEDWATER LINE ELBOW	CS	1.59E-01	3.65E-01	1.03E-03	1.46E-02
GE-OLD RPV FEEDWATER NOZZLE BORE	LAS	7.27E-02	2.42E-01	1.00E-05	8.80E-04
GE-OLD FEEDWATER LINE - RCIC TEE	CS	3.76E-01	7.82E-01	2.99E-03	5.92E-02
W-NEW RPV OUTLET NOZZLE	LAS	8.62E-01	9.49E-01	3.65E-01	7.42E-01
W-OLD RPV INLET NOZZLE INNER SURFACE	LAS	3.91E-01	6.44E-01	4.38E-03	5.04E-02
W-OLD RPV OUTLET NOZZLE INNER SURFACE	LAS	4.90E-01	7.53E-01	9.33E-03	9.60E-02

Table A-2
Revised Analysis Using Original PNNL Input Files

Location	Material	Initiation Probability		Leakage Probability	
		40 Years	60 years	40 Years	60 years
B&W RPV OUTLET NOZZLE	LAS	2.63E-01	5.41E-01	1.35E-02	1.16E-01
CE-NEW RPV OUTLETNOZZLE	LAS	3.91E-02	1.53E-01	9.00E-05	1.37E-03
CE-NEW SAFETY INJECTION NOZZLE	LAS	2.00E-05	1.20E-04	<1.00E-05	<1.00E-05
CE-OLD RPV OUTLETNOZZLE	LAS	1.16E-01	3.08E-01	6.79E-03	5.51E-02
GE-NEW FEEDWATER NOZZLE SAFE END	CS	1.80E-04	1.46E-03	<1.00E-05	2.00E-05
GE-NEW RHR LINE STRAIGHT PIPE	CS	3.38E-03	1.49E-02	2.19E-03	1.01E-02
GE-NEW FEEDWATER LINE ELBOW	CS	1.17E-03	8.25E-03	<1.00E-05	9.00E-05
GE-OLD RPV FEEDWATER NOZZLE BORE	LAS	7.07E-02	2.35E-01	2.00E-05	7.90E-04
GE-OLD FEEDWATER LINE - RCIC TEE	CS	1.87E-02	1.06E-01	6.00E-05	1.75E-03
W-NEW RPV OUTLETNOZZLE	LAS	4.15E-01	7.20E-01	5.02E-02	2.79E-01
W-OLD RPV INLET NOZZLE INNER SURFACE	LAS	3.84E-02	1.38E-01	1.60E-04	2.82E-03
W-OLD RPV OUTLETNOZZLE INNER SURFACE	LAS	7.56E-02	2.46E-01	3.50E-04	8.06E-03

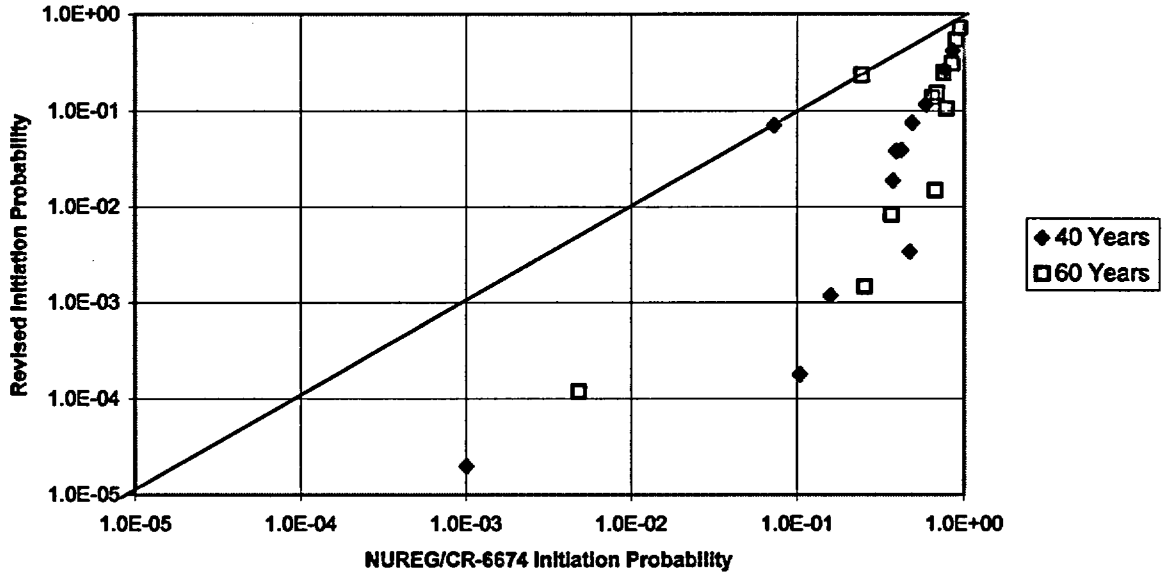

Figure A-3. Comparison of Initiation Probabilities – Re-Run of Original PNNL Input Files versus NUREG/CR-6674 Results

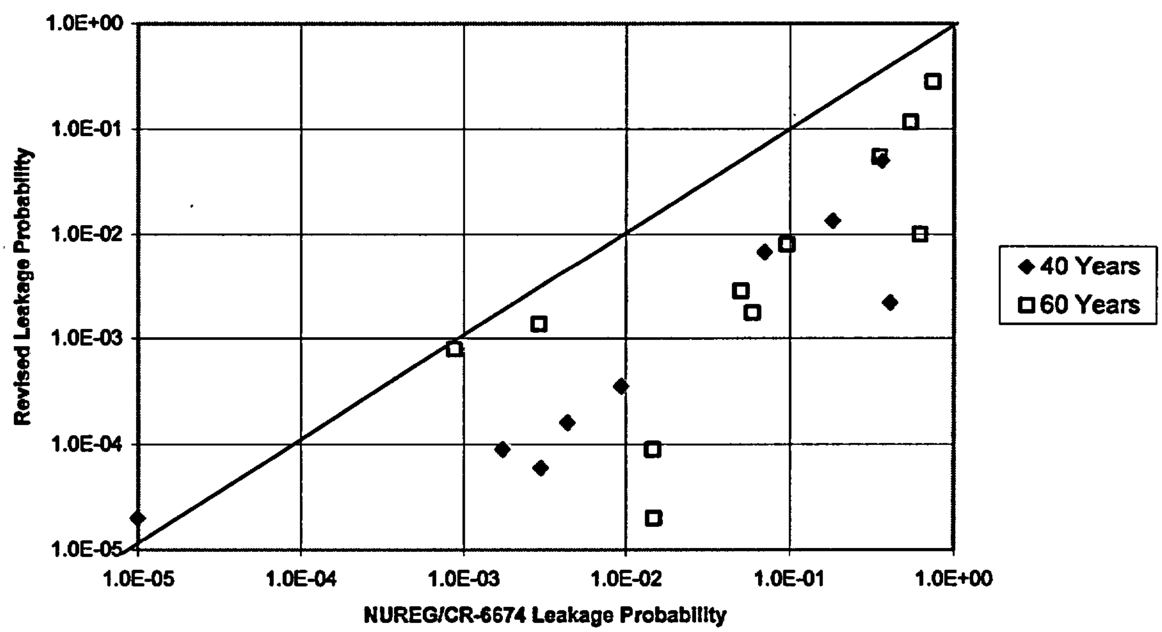

Figure A-4. Comparison of Leakage Probabilities – Re-Run of Original PNNL Input Files versus NUREG/CR-6674 Results

Analysis to Remove Conservatism

In MRP-74, a number of cases were presented to show how conservatisms in the NUREG/CR-6674 analysis could be reduced to show lower, and more realistic, probabilities of initiation and leakage. Some of these cases will be repeated, and others will be added to reduce the probabilities presented in the previous section. The reduced initiation and leakage probabilities are summarized in Table A-3 and are described below.

In cases where there is a reduction of cycles, environmental fatigue usage factors are provided using the CS/LAS fatigue curve from the current ASME Code and the F_{en} correction factors of NUREG/CR-6583 (Equations 6.5a) and 6.5b) with T for the air environment equal to 25°C).

Table A-3
Revised Analysis Results With Conservatisms Reduced

Location		Material	Initiation Probability		Leakage Probability	
			40 Years	60 years	40 Years	60 years
B&W	RPV OUTLET NOZZLE	LAS	2.35E-03	1.07E-02	< 1.00E-05	1.00E-05
CE-NEW	RPV OUTLETNOZZLE	LAS	4.36E-03	2.81E-02	<1.00E-05	4.00E-05
CE-NEW	SAFETY INJ. NOZZLE (unchanged)	LAS	2.00E-05	1.20E-04	<1.00E-05	<1.00E-05
CE-OLD	RPV OUTLETNOZZLE	LAS	4.00E-04	2.50E-03	<1.00E-05	<1.00E-05
GE-NEW	FEEDWATER NOZZLE SAFE END	CS	1.00E-05	1.72E-04	<1.00E-05	<1.00E-05
GE-NEW	RHR LINE STRAIGHT PIPE	CS	2.28E-03	9.35E-03	1.47E-03	6.34E-03
GE-NEW	FEEDWATER LINE ELBOW	CS	9.00E-05	8.90E-04	<1.00E-05	<1.00E-05
GE-OLD	RPV FEEDWATER NOZZLE BORE	LAS	1.21E-02	5.64E-02	<1.00E-05	1.05E-04
GE-OLD	FEEDWATER LINE - RCIC TEE	CS	7.00E-04	5.36E-03	<1.00E-05	2.00E-05
W-NEW	RPV OUTLETNOZZLE	LAS	1.27E-02	4.86E-02	4.00E-05	2.90E-04
W-OLD	RPV INLET NOZZLE INNER SURFACE	LAS	1.77E-03	7.94E-03	<1.00E-05	1.00E-05
W-OLD	RPV OUTLETNOZZLE INNER SURFACE	LAS	8.99E-03	4.38E-02	1.00E-05	9.00E-05

B&W Plant RPV Outlet Nozzle

The fatigue usage of the B&W outlet nozzle is controlled by the 48,000 plant loading/plant unloading cycles, where the plant is assumed to be loaded about three times per day over the 40 year life of the plant. Reducing the plant loading/plant unloading event to once per week, decreases the number of cycles to 2,080 cycles in a 40 year life, which is very conservative since the plants in the US fleet operate as base load and do not load follow. The existing design basis number of cycles are assumed for the remainder of the loading conditions (although the information in NUREG/CR-6260 showed that other cycles would reduce based on actual plant experience and projections), the usage factor is considerably reduced.

The design and the revised environmental usage factors are shown in Table A-4.

Table A-4
Revised Environmental Fatigue Usage Factors for B&W Outlet Nozzle
for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
Heatup/Cooldown	45.05	240	0.098	240	0.098
Step Load/Reactor Trip	29.24	480	0.049	480	0.049
Plant Loading/Unloading	24.33	48000	2.800	2080	0.121
All Others	23.78	9850	0.536	9850	0.536
		CUF	3.483	CUF	0.804

The probabilities of initiation and leakage are reduced as follows:

	Initiation Probability		Leakage Probability	
	40 Years	60 years	40 Years	60 years
B&W Outlet Nozzle	2.35E-03	1.07E-02	< 1.00E-05	1.00E-05

New CE Plant RPV Outlet Nozzle

This plant also was designed for daily plant loading and unloading. Reducing this to 2080 cycles reduces the usage factor considerable as shown in Table A-5.

Table A-5
Revised Environmental Fatigue Usage Factors for the New CE Plant RPV Outlet Nozzle
for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
Cooldown/Plant Load	51.51	500	0.307	500	0.307
Leak Test/Plant Unload	50.85	200	0.118	200	0.118
Heatup/Plant Load	39.24	500	0.135	500	0.135
Plant Load/Unload	20.84	13800	0.415	1880	0.057
Plant Unload/Upset	19.82	480	0.011	480	0.011
Plant Unload/OBE	14.32	200	0.001	200	0.001
Plant Unload/Step Load	12.71	520	0.001	520	0.001
		CUF	0.990	CUF	0.631

The probabilities of initiation and leakage are reduced as follows:

	Initiation Probability		Leakage Probability	
	40 Years	60 years	40 Years	60 years
New CE Outlet Nozzle	4.36E-03	2.81E-02	<1.00E-05	4.00E-05

Old CE Plant RPV Outlet Nozzle

This plant also was designed for daily plant loading and unloading. In addition, information was available from the original stress report, as documented in MRP-74, such that strain rates could be reduced below the conservative values used in NUREG/CR-6674. The revised usage factors are shown in Table A-6.

Table A-6
Revised Environmental Fatigue Usage Factors for the Old CE Plant RPV Outlet Nozzle for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
Loss of secondary pressure/Hydrotest	67.01	5	0.007	5	0.007
Hydrotest A/Hydrotest B	34.61	5	0.001	5	0.001
Heatup/Loss of Load	29.62	40	0.004	40	0.004
Heatup/Loss of Flow	28.56	40	0.004	40	0.004
Heatup/Cooldown	28.38	420	0.039	420	0.039
Cooldown/Plant loading	26.73	80	0.006	80	0.006
Reactor Trip/Plant Loading	23.25	400	0.020	400	0.020
Reactor Trip/Plant Unloading	21.41	14520	0.500	2080	0.072
		CUF	0.581	CUF	0.153

The probabilities of initiation and leakage, based on modified design cycles and revised strain rates, were reduced as follows:

	Initiation Probability		**Leakage Probability**	
	40 Years	60 years	40 Years	60 years
Old CE Outlet Nozzle	4.00E-04	2.50E-03	<1.00E-05	<1.00E-05

New Westinghouse Plant RPV Outlet Nozzle

This plant also was designed for a significant number of cyclic events that normally are not identified in operating reactors. For this case, it was not possible to define specific loading conditions because the cycles were not documented in NUREG/CR-6260 (quoting that the design information was not readable). For this case, any cycling that was greater than 2080 cycles was reduced to 2080 cycles based on the conservative assumption that the plant would go through a transient loading/unloading cycle no more than weekly. Using the remainder of the design cycles reduces the usage factor considerable as shown in Table A-7.

Table A-7
Revised Environmental Fatigue Usage Factors for New Westinghouse Plant RPV Outlet Nozzle for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
(not identified in	48.68	80	0.041	80	0.041
NUREG/CR-6260)	45.4	10	0.004	10	0.004
	44.34	20	0.008	20	0.008
	39.94	20	0.006	20	0.006
	34.39	70	0.012	70	0.012
	29.31	130	0.013	130	0.013
	28.3	150	0.014	150	0.014
	27.09	50	0.004	50	0.004
	26.99	30	0.002	30	0.002
	21.37	40	0.001	40	0.001
	20.2	1930	0.050	1930	0.050
	20.2	2000	0.052	2000	0.052
	20.13	9270	0.235	2080	0.053
	18.85	60	0.001	60	0.001
	18.44	230	0.004	230	0.004
	18.35	10	0.000	10	0.000
	18.05	80	0.001	80	0.001
	17.64	160	0.002	160	0.002
	17.64	26400	0.412	2080	0.032
	17.05	2000	0.028	2000	0.028
	16.39	400	0.005	400	0.005
	15.99	13200	0.140	2080	0.022
	15.37	13200	0.117	2080	0.018
	14.9	80	0.001	80	0.001
	14.84	80	0.001	80	0.001
	14.7	70	0.001	70	0.001
		CUF	1.156	CUF	0.377

The probabilities of initiation and leakage, based on modified design cycles, were reduced as follows:

	Initiation Probability		Leakage Probability	
	40 Years	60 years	40 Years	60 years
New Westinghouse Outlet Nozzle	1.27E-02	4.86E-02	4.00E-05	2.90E-04

Old Westinghouse Plant RPV Outlet Nozzle (Inner Surface)

This plant was designed for daily loading/unloading. Reducing these cycles to 2080 reduced the usage factor by about 40 percent, as shown in Table A-8.

Table A-8
Revised Environmental Fatigue Usage Factors for the Old Westinghouse Plant RPV Outlet Nozzle for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
Heatup/Cooldown	17.22	350	0.005	350	0.005
Plant Loading/Unloading	18.89	14100	0.282	2080	0.042
OBE A/OBE B	20.94	400	0.012	400	0.012
Combination	32.78	2760	0.410	2760	0.410
		CUF	0.709	CUF	0.469

The probabilities of initiation and leakage, based on modified design cycles, were reduced as follows:

	Initiation Probability		Leakage Probability	
	40 Years	60 years	40 Years	60 years
Old Westinghouse Outlet Nozzle (Inside)	8.99E-03	4.38E-02	1.00E-05	9.00E-05

Old Westinghouse Plant RPV Inlet Nozzle (Inner Surface)

This plant was designed for daily loading/unloading. Reducing these cycles to 2080 reduced the usage factor by about 50 percent, as shown in Table A-9.

Table A-9
Revised Environmental Fatigue Usage Factors for the Old Westinghouse Plant RPV Nozzle (Inner Surface) for Design and Revised Cycles

Load Pair	S_{alt} (adjusted)	As-Designed		Design Modified	
		n	u	n	u
Heatup/Cooldown	15.00	350	0.001	350	0.001
Plant Load/Unload	19.44	14500	0.131	2080	0.019
Combination	25.56	2760	0.076	2760	0.076
		CUF	0.208	CUF	0.096

The probabilities of initiation and leakage, based on modified design cycles, were reduced as follows:

	Initiation Probability		**Leakage Probability**	
	40 Years	60 years	40 Years	60 years
Old Westinghouse Inlet Nozzle (Inside)	1.77E-03	7.94E-03	<1.00E-05	1.00E-05

BWR Plant Re-Evaluations

In MRP-74, there were several cases evaluated for minor changes in the pcPRAISE input as compared to what was reported in NUREG/CR-6674. These cases were re-run to account for more realistic, but still conservative temperatures than were used by PNNL. Usage factors did not change as compared to those stated in NUREG/CR-6260, except for the Old GE Feedwater Line RCIC Tee (where reduced strain rates, and less seismic cycles were used). The revised usage factors for this component are shown in Table A-10. The usage factor is not significantly changed from that reported in NUREG/CR-6260.

The results of the BWR plant component locations were as follows:

	Initiation Probability		**Leakage Probability**	
	40 Years	60 years	40 Years	60 years
New GE FW Line Safe-End	1.00E-05	1.72E-04	<1.00E-05	<1.00E-05
New GE FW Line Elbow	9.00E-05	8.90E-04	<1.00E-05	<1.00E-05
Old GE FW Line RCIC Tee	7.00E-04	5.36E-03	<1.00E-05	2.00E-05
New GE RHR Line Straight Pipe	2.28E-03	9.35E-03	1.47E-03	6.34E-03
Old GE FW Nozzle Bore	1.21E-02	5.84E-02	<1.00E-05	1.05E-04

Summary of Re-Evaluations

The results of the revised analysis are summarized in Table A-3 and may be compared with Tables A-1 (original NUREG/CR-6674 analysis) and A-2 (re-run of PNNL files). Figures A-5 and A-6 graphically show the final results of the revised analysis. Figure A-5 compares the revised initiation probability to the NUREG/CR-6674 results. Figure A-6 compares the revised leakage probability to the NUREG/CR-6674 results. As shown in Table A-3, the maximum probability of leakage at 60 years is 0.00634. All remaining components demonstrated a 60-year leakage probability of less than 0.001. This demonstrates that the probability of leakage is not significant when the potential effects of reactor water environment are considered.

Table A-10
Revised Environmental Fatigue Usage Factors for the Old GE Feedwater Line RCIC Tee for Revised Cycles

Load Pair	S_{alt} (adjusted)	Expected Cycles	
		n	u
Low Load set/RCIC Initiation	121.95	10	0.304
Low Load set/RCIC & RWCU initiation	73.1	12	0.083
Low Load set/RCIC & RWCU initiation	70.78	423	2.699
Low Load Set/OBE	54.46	5	0.018
High Load Set/RCIC & RWCU initiation	51.82	65	0.138
Low Load Set/null	51.04	55	0.158
High Load Set/null	46.88	32	0.071
High Load Set/null	46.88	10	0.022
Low Load Set/null	46.56	120	0.260
High Load Set A/High Load Set B	46.12	30	0.063
High Load Set/Low Load Set	45.89	232	0.481
High Load Set/High Load Set	45.31	22	0.044
High Load Set/High Load Set	43.6	68	0.121
High Load Set/RCIC Initiation	42.58	50	0.083
(remaining load pairs not identified)	42.25	284	0.461
	42.05	22	0.035
	41.08	352	0.525
	39.82	22	0.030
	38.53	105	0.130
	38.06	19	0.023
	37.69	22	0.025
	35.19	284	0.259
	32.87	22	0.016
	31.13	3	0.002
	30.99	155	0.092
	24.88	3	0.001
	24.32	22	0.006
		CUF	6.150

Note: Design cycles not shown since stresses/cycle pairing was slightly different in NUREG/CR-6260

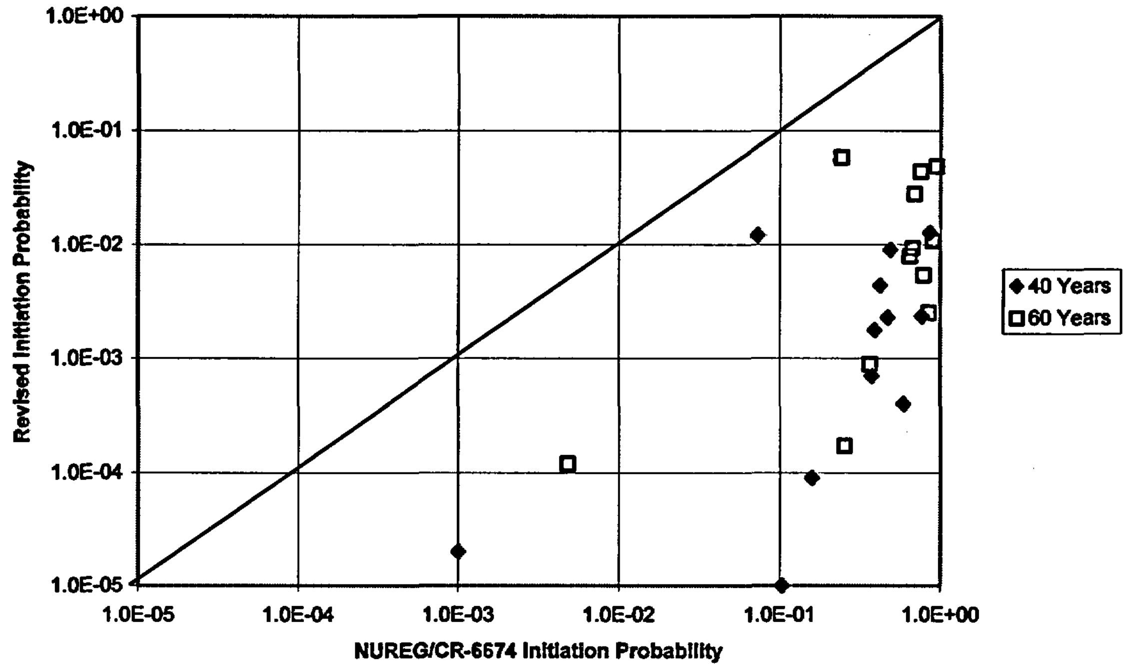

Figure A-5. Comparison of Initiation Probabilities – Revised Analysis versus NUREG/CR-6674

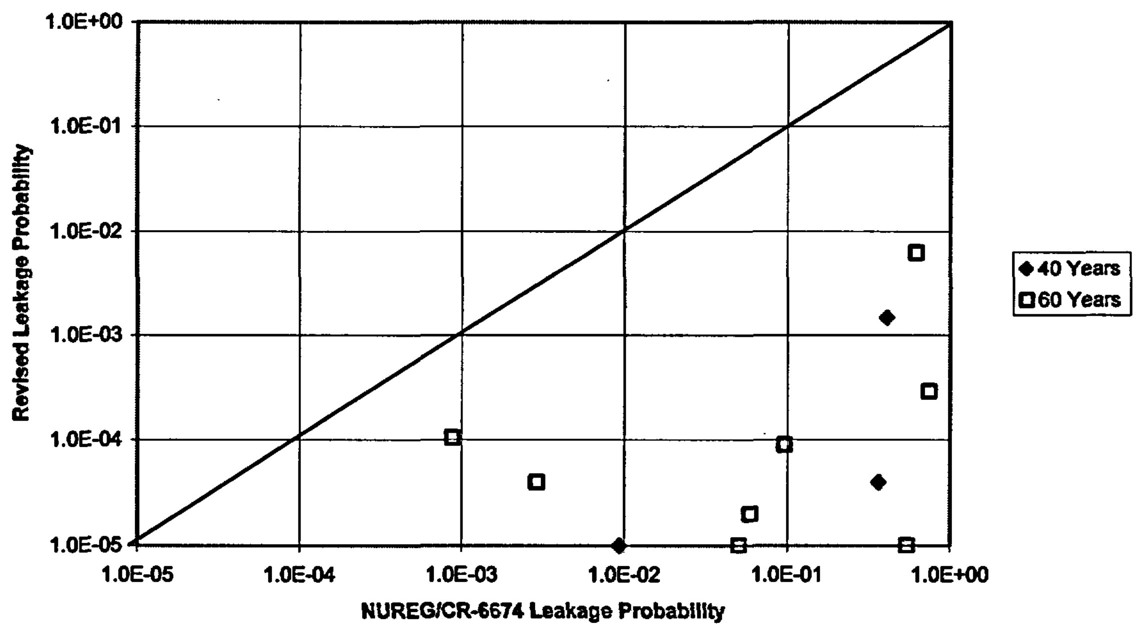

Figure A-6. Comparison of Leakage Probabilities – Revised Analysis versus NUREG/CR-6674

Re-Evaluation of Core Damage Frequency

The core damage frequency (CDF) was also re-evaluated as described in MRP-74. Table A-11 provides the results. The limiting 60-year CDF is for the New Westinghouse RPV outlet nozzle (as it was in NUREG/CR-6674). The re-evaluated CDF is reduced from the NUREG/CR-6674 value of 1.2×10^{-7} per year to 1.1×10^{-10} per year. The CDFs of all other locations are less. In the re-evaluation, the maximum number of Monte Carlo simulations was limited to 10^5, so where no leaks occurred after 10^5 iterations, the CDF is quoted as zero.

Table A-11
Calculation of Core Damage Frequencies

Locations		PL(40)	PL(60)	$F_{twc}(40)$	$F_{twc}(60)$	Method	CDF(40)	CDF(60)
B&W	RPV OUTLET NOZZLE	$<10^{-5}$	10^{-5}	0	0	Note 1	0	0
CE-NEW	RPV OUTLET NOZZLE	$<10^{-5}$	$<10^{-5}$	0	0	Note 1	0	0
CE-NEW	SAFETY INJECTION NOZZLE	$<10^{-5}$	$<10^{-5}$	0	0	Note 1	0	0
CE-OLD	RPV OUTLET NOZZLE	$<10^{-5}$	$<10^{-5}$	0	0	Note 1	0	0
GE-NEW	FEEDWATER NOZZLE SAFE END	$<10^{-5}$	$<10^{-5}$	0	0	Note 1	0	0
GE-NEW	RHR LINE STRAIGHT PIPE	1.47×10^{-3}	6.34×10^{-3}	1.22×10^{-4}	3.98×10^{-4}	LSQ[2]	2.3×10^{-13}	3.6×10^{-12}
GE-NEW	FEEDWATER LINE ELBOW	$<10^{-5}$	$<10^{-5}$	0	0	Note 1	0	0
GE-OLD	RPV FEEDWATER NOZZLE BORE	3×10^{-6}	1.05×10^{-4}	5.5×10^{-7}	1.42×10^{-5}	LSQ	8.2×10^{-15}	2.1×10^{13}
GE-OLD	FEEDWATER LINE - RCIC TEE	$<10^{-5}$	3×10^{-5}	0	2.5×10^{-6}	LSQ	0	3.8×10^{-13}
W-NEW	RPV OUTLET NOZZLE	4×10^{-5}	2.9×10^{-4}	4.0×10^{-6}	4.0×10^{-5}	LSQ	1.1×10^{-11}	1.1×10^{-10}
W-OLD	RPV INLET NOZZLE INNER SURFACE	$<10^{-5}$	10^{-5}	0	0	Note 1	0	0
W-OLD	RPV OUTLET NOZZLE INNER SURFACE	10^{-5}	9×10^{-5}	0	1.2×10^{-5}	Note 1	0	3.2×10^{-11}

1. Insufficient failures in Monte Carlo simulations to estimate CDF
2. See MRP-74 (including Table 4-13) for methodology for calculating CDF and nomenclature

Conclusions

Although the results of the re-evaluation show that leakage probabilities are slightly higher than previously presented in MRP-74, it is still concluded that the probability of leakage is sufficiently low that explicit consideration of environmental effects for carbon and low-alloy steel components in a license renewal extended operating period is not warranted.

References

1. Letter from P. T. Kuo (NRC) to F. A. Emerson (NEI), "Request for Additional Information for Proposed Interim Staff Guidance (ISG)-11 Recommendations for Fatigue Environmental Effects in a License Renewal Application," dated June 30, 2003
2. U. S. Nuclear Regulatory Commission, *Theoretical and User's Manual for pcPRAISE,* D. O. Harris, D. Dedhia, and S. C. Li, NUREG/CR-5864, 1992.

3. U. S. Nuclear Regulatory Commission, *Fatigue Analysis of Components for a 60 Year Plant Life,* M. A. Khaleel, et. al., NUREGE/CR-6674, 2000.
4. *Material Reliability Program: Re-Evaluation of Results in NUREG/CR-6674 for Carbon and Low-Alloy Steel Components (MRP-74),* EPRI, Palo Alto, CA and U. S. Department of Energy, Washington, DC: 20021 1003667
5. U. S. Nuclear Regulatory Commission, *Fatigue Strain-Life Behavior of Carbon and Low-Alloy Steels, Austenitic Stainless Steels, and Alloy 600 in LWR Environments.* J. Keisler, O. K. Chopra, and W. J. Shack, NUREG/CR-6335, 1995.
6. American Society of Mechanical Engineers, *Criteria for the ASME Boiler and Pressure Vessel Code for Design by Analysis in Section III and Section VIII, Division 2,* 1969.
7. U. S. Nuclear Regulatory Commission, *Effects of LWR Coolant Environments on Fatigue Design Curves of Carbon and Low-Alloy Steels.* O. K. Chopra, and W. J. Shack, NUREG/CR-6583, 1997.