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Observations and Recommendations for Further Research Regarding Environmentally Assisted Fatigue Evaluation Methods[1]

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) and Argonne National Laboratory (ANL) have completed research activities on environmentally assisted fatigue (EAF) methods. This work has led to a revision of NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials," in its entirety. This report was issued for public review and comment in April 2014. These revisions addressed the following areas:

- A much larger fatigue (ε–N) database was used to recalculate the air and water fatigue curves. The additional data expanded the ε–N data previously used by the NRC and ANL by as much as 74%. Despite the large increase in data, the NRC's previous best fit air and water curves did not change appreciably.
- The environmental fatigue multiplier (F_{en}) expressions for carbon, low-alloy, stainless, and nickel-alloy steels and comments from interested stakeholders related to:
    - constants in previous F_{en} expressions that results in F_{en} values of approximately 2.0 even when the strain rate is very high or the temperature is very low,
    - temperature dependence of the F_{en} expression for carbon and low-alloy steels, and
    - dependence of F_{en} on water chemistry for austenitic stainless steels.
- Validation of the F_{en} expressions using the results of five different experimental data sets obtained from fatigue tests that simulated actual plant conditions.
- The appropriateness of a strain threshold and the possible effects of hold periods.
- The potential effects of dynamic strain aging (DSA) on cyclic deformation and environmental effects.

In the course of performing the foregoing EAF research activities, the NRC and ANL identified the following areas where further research could yield reduced conservatism in EAF evaluation:

- more refined, material-specific fatigue (S-N) curves,
- S-N curves for ferritic materials based on material tensile strength,
- component testing (rather than small-scale specimen testing),
- ASME Code cumulative usage factor (CUF) calculation methods, and
- the effect of neutron irradiation on fatigue crack initiation in austenitic stainless steels.

This paper describes those observations and provides recommendations for further research efforts.

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INTRODUCTION

In April 2014, the U.S. NRC released a draft of Revision 1 to NUREG/CR-6909 (hereinafter referred to as "Rev. 1") for public review and comment [1]. The report summarizes, reviews, and quantifies the effects of the light-water reactor (LWR) environments on the fatigue lives of reactor materials, including carbon steels, low-alloy steels, nickel-chromium-iron (Ni-Cr-Fe) alloys, and austenitic stainless steels. The primary purpose of this report is to provide the background and technical bases to support a revision to Regulatory Guide (RG) 1.207, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors" [2]. NRC is now working on Revision 1 to RG 1.207, which is planned for release for public review and comment later in 2014.

The original version of NUREG/CR-6909 included a review of the fatigue ε-N data available to the NRC up to about 2005 for carbon steels, low-alloy steels, Ni-Cr-Fe alloys, and austenitic stainless steels. This review evaluated the potential effects of key material, loading, and environmental parameters on the fatigue lives of the steels. The functional form and bounding values of these parameters related to these effects were based on experimental data trends. An approach was developed that incorporated the effects of LWR coolant environments into the ASME Code, Section III [3] fatigue evaluations based on an environmental fatigue multiplication factor, F_{en}. The fatigue usage for a specific stress cycle or load set pair derived using the ASME Code Section III fatigue design air curves was multiplied by F_{en} to account for environmental effects, as follows:

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

Where:
- U_{en} = total environmentally-adjusted cumulative usage factor
- n = number of load set pairs in the cumulative usage factor calculation
- U_i = partial usage factor in air for the i^{th} load set pair
- $F_{en,i}$ = environmental fatigue multiplier for the i^{th} load set pair, defined as the ratio of fatigue life in air at room temperature ($N_{air,RT}$) to that in water at the service temperature (N_{water}), $N_{air,RT}/N_{water}$

For Rev. 1, additional fatigue ε-N data available since the original publication of the report, most particularly from Japan [4], were incorporated into the database and the fatigue life models were updated. In addition, feedback from interested stakeholders obtained since the original publication of the report were evaluated and incorporated, where appropriate.

The previously established methods for establishing reference air fatigue curves were revisited, and updated environmental correction factors were defined for use in evaluating the fatigue lives of reactor components exposed to LWR coolants and operational experience. The updated expressions are as follows:

Carbon and low-alloy steels

$$F_{en} = \exp((0.003 - 0.031^{*})\ S^{*}T^{*}O^{*}) \qquad (1)$$

Where:
- S^{*} = transformed sulfur content
  - = $2.0 + 98\ S$ ($S \le 0.015$ wt. %)
  - = 3.47 ($S > 0.015$ wt. %)
- T^{*} = transformed temperature
  - = 0.395 ($T < 150$ °C)
  - = $(T - 75)/190$ ($150°C \le T \le 325$ °C)

O^*	=	transformed dissolved oxygen (DO) content	
	=	1.49	(DO < 0.04 ppm)
	=	ln(DO/0.009)	(0.04 ppm ≤ DO ≤ 0.5 ppm)
	=	4.02	(DO > 0.5 ppm)
ε^*	=	transformed strain rate	
	=	0	(strain rate, ε' > 2.2%/s)
	=	$\ln(\varepsilon'/2.2)$	(0.0004%/s ≤ ε' ≤ 2.2%/s)
	=	ln(0.0004/2.2)	(ε' < 0.0004%/s)

<u>Wrought and cast austenitic stainless steels</u>

$$F_{en} = \exp(-\,T^*\,O^*\,\varepsilon^*) \qquad (2)$$

Where:

T^*	=	0	(T ≤ 100°C)
	=	(T – 100)/250	(100°C ≤ T < 325°C)
ε^*	=	0	(ε' > 10%/s)
	=	$\ln(\varepsilon'/10)$	(0.0004%/s ≤ ε' ≤ 10%/s)
	=	ln(0.0004/10)	(ε' < 0.0004%/s)

For DO less than 0.1 ppm, i.e., for PWR or BWR HWC water:

O^*	=	0.29	(for all wrought and cast SSs and heat treatments and SS weld metals)

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

O^*	=	0.29	(for sensitized high-carbon wrought and cast SSs)
	=	0.14	(for all wrought SSs except sensitized high-carbon SSs)

<u>Ni-Cr-Fe alloys</u>

$$F_{en} = \exp(-\,T^*\,O^*\,\varepsilon^*) \qquad (3)$$

Where:

T^*	=	0	(T ≤ 50°C)
	=	(T – 50)/275	(50°C ≤ T < 325°C)
ε^*	=	0	(ε' > 5.0%/s)
	=	$\ln(\varepsilon'/5.0)$	(0.0004%/s ≤ ε' ≤ 5.0%/s)
	=	ln(0.0004/5.0)	(ε' < 0.0004%/s)

For DO less than 0.1 ppm, i.e., for PWR or BWR HWC water:

O^* = 0.14

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

O^* = 0.06

The NRC's evaluations conclude that the existing ASME Code Section III fatigue curves are appropriate for use in fatigue calculations for austenitic stainless steels (e.g., Types 304, 316, and 316NG) and Ni-Cr-Fe alloys, and are conservative for use in fatigue calculations for carbon and low-alloy steels.

SUMMARY OF NEW ε-N DATA

The air fatigue data evaluated in the NRC's recent research activities are summarized in Tables 1, 6, and 9 of Rev. 1 for carbon/low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys, respectively. Tables 10, 11, and 12 of Rev. 1 summarize the environmental (water) data for carbon/low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys, respectively. A summary of that data compared to the data evaluated in the original version of NUREG/CR-6909 is provided in Table 1. Table 1 indicates that the fatigue database of available ε-N data increased significantly compared to the data available for the initial publication of NUREG/CR-6909 and RG 1.207 in 2007 (hereinafter referred to as "Rev. 0"). This increase in data was principally due to the inclusion of the Japanese data [4].

Table 1. Summary of ε-N Air Data Used in Rev. 0 and Rev. 1 of NUREG/CR-6909

Material	Data Available for Rev. 0	Data Available for Rev. 1	Increase
Carbon Steels	153 points (8 heats) [Figure 7(a) of Rev. 0]	254 points (19 heats) [Figure 32(b) of Rev. 1]	66 %
Low-Alloy Steels	358 points (19 heats) [Figure 7(b) of Rev. 0]	430 points (22 heats) [Figure 32(d) of Rev. 1]	20 %
Austenitic Stainless Steels	357 points (38 heats) [Figure 35 of Rev. 0]	622 points (40 heats) [Figure 45(b) of Rev. 1]	74 %
Ni-Cr-Fe Alloys	Not reported	559 points (8 heats) [Section 3.3 of Rev. 1]	N/A

Despite the large increase in data (e.g., 66% for carbon steels), the NRC's previous best fit air curves did not change appreciably. For example, Figure 1 shows the best fit air curves for carbon steel developed in Rev. 0 compared to updated air curves developed during the assessment of the Rev. 1 data. The ASME and NRC/ANL design fatigue curves are also included for comparison. These best fit air curves are fit using a Langer relationship of the following form:

$$\ln(N) = A - B\ln(\varepsilon_a - C) \quad (4)$$

where A, B, and C are constants, ε_a is the strain amplitude (%), and N is the number of cycles. Figure 1 indicates no appreciable difference in the Rev. 0 and Rev. 1 air curves; in fact, the Rev. 0 and Rev. 1 air curve fits vary by less than 1% in strain amplitude at any fatigue life. Similar results were obtained for low-alloy steels and austenitic stainless steels/Ni-Cr-Fe alloys (Ni-Cr-Fe and austenitic stainless steel data were evaluated as one data set). As a result, in Rev. 1, the NRC elected to maintain the same air curve best fit expressions that were developed in Rev. 0 for three material groups. Those best fits expressions were defined in Equations (15), (16), and (32) of Rev. 0, and are defined in Rev. 1 by Equations (24), (25), and (29) for carbon steels, low-alloy steels, and austenitic stainless steels/Ni-Cr-Fe alloys.

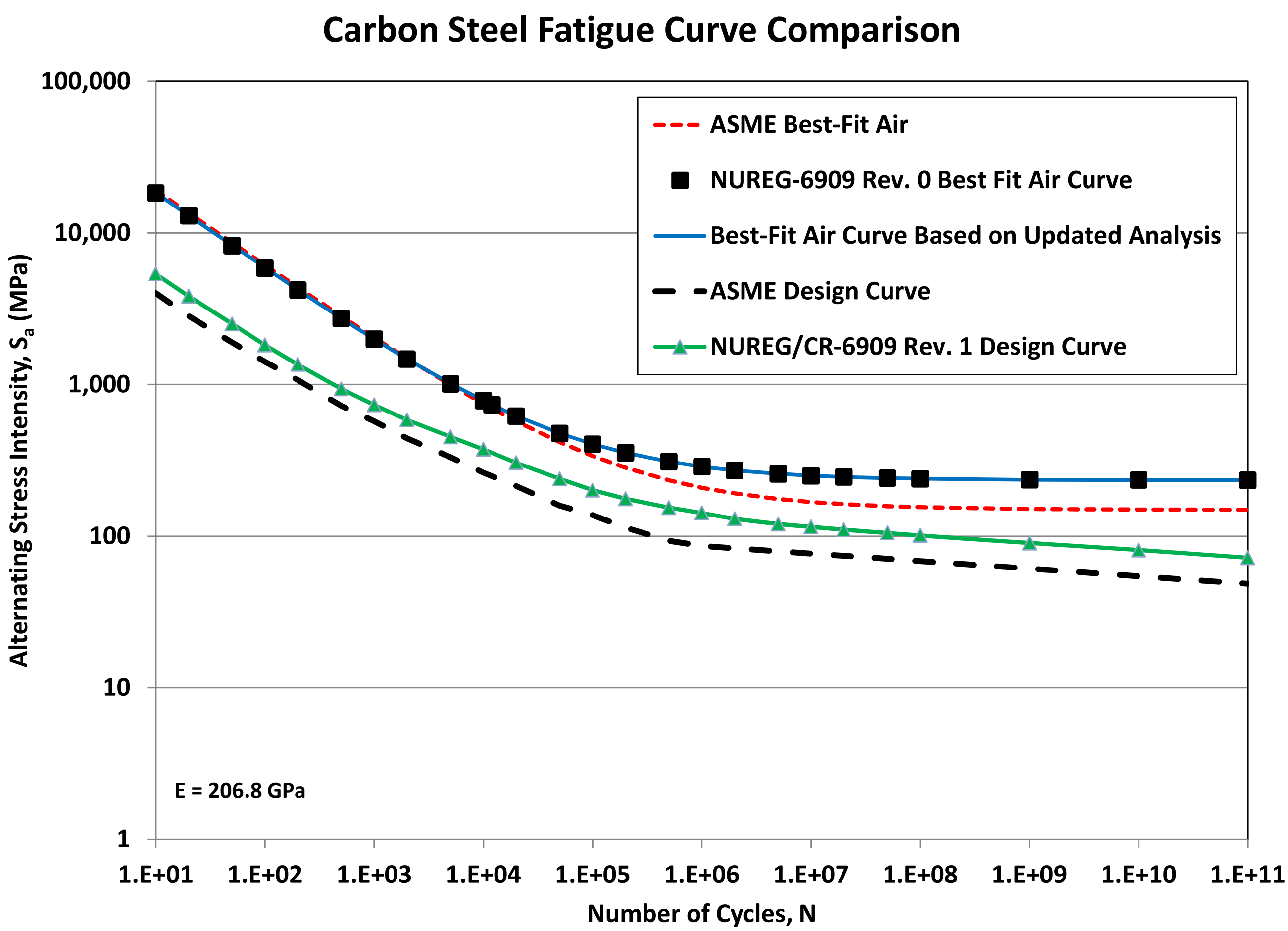

Figure 1. Comparison of Best Fit Air Curves for Carbon Steels

MATERIAL-SPECIFIC ε -N CURVES

With the additional ε-N data now available, more refined observations regarding the effects of different material types on the air ε-N curves are possible. One example is the difference in the fatigue curves for carbon steels vs. low-alloy steels. Section III of the ASME Code combines both material types into one ε-N curve, whereas the NRC/ANL developed separate curves for each material type (i.e., refer to Figures 36 and 37 in Rev. 1).

Another example is illustrated by evaluating available air ε-N data for austenitic stainless steels and Ni-Cr-Fe alloys. The data for these materials was separated into three categories: 304 SS (includes Types 304, 304L, and 304NG stainless steels), 316 SS (includes Types 316, 316L, and 316NG stainless steels), and Ni-Cr-Fe alloys (includes Alloys 600, 690, 800, and 718). The data evaluation was "simplified" in that the only difference is that the fitted curves were developed by minimizing the distance in measured fatigue lives based on a best fit Langer relationship for each of the three categories, compared to the more comprehensive and rigorous distance minimization scheme shown in Figure 30 of Rev. 1. In this simplified assessment, coefficients A and B of the

Langer fit equation were varied in the minimization while coefficient C was maintained at a value of 0.112 for all cases. The Solver routine in Microsoft Excel® was used to quickly perform the minimization evaluation.

The rationale behind using this simplified approach was to perform a preliminary investigation of the effects of separating material types that would indicate whether further pursuit of this idea was warranted. A more appropriate assessment would be to group austenitic materials based on carbon content rather than grade of steel because the higher carbon content steels with higher strength typically have longer fatigue lives. Further investigation may be performed to address these issues.

Figure 2 show the results of the simplified evaluation for the air data. Both the raw data and the Langer best fits are shown for each of the three material categories. The results indicate that ε-N curves based on only the data associated with each material type can lead to fairly significant differences in predicted fatigue lives. Based on this simplified evaluation, further refined evaluation based on material type could lead to improved fatigue life definitions. There is now sufficient test data available to perform such evaluation and develop improved ε-N air curves for many grades of austenitic stainless steels and Ni-Cr-Fe alloys.

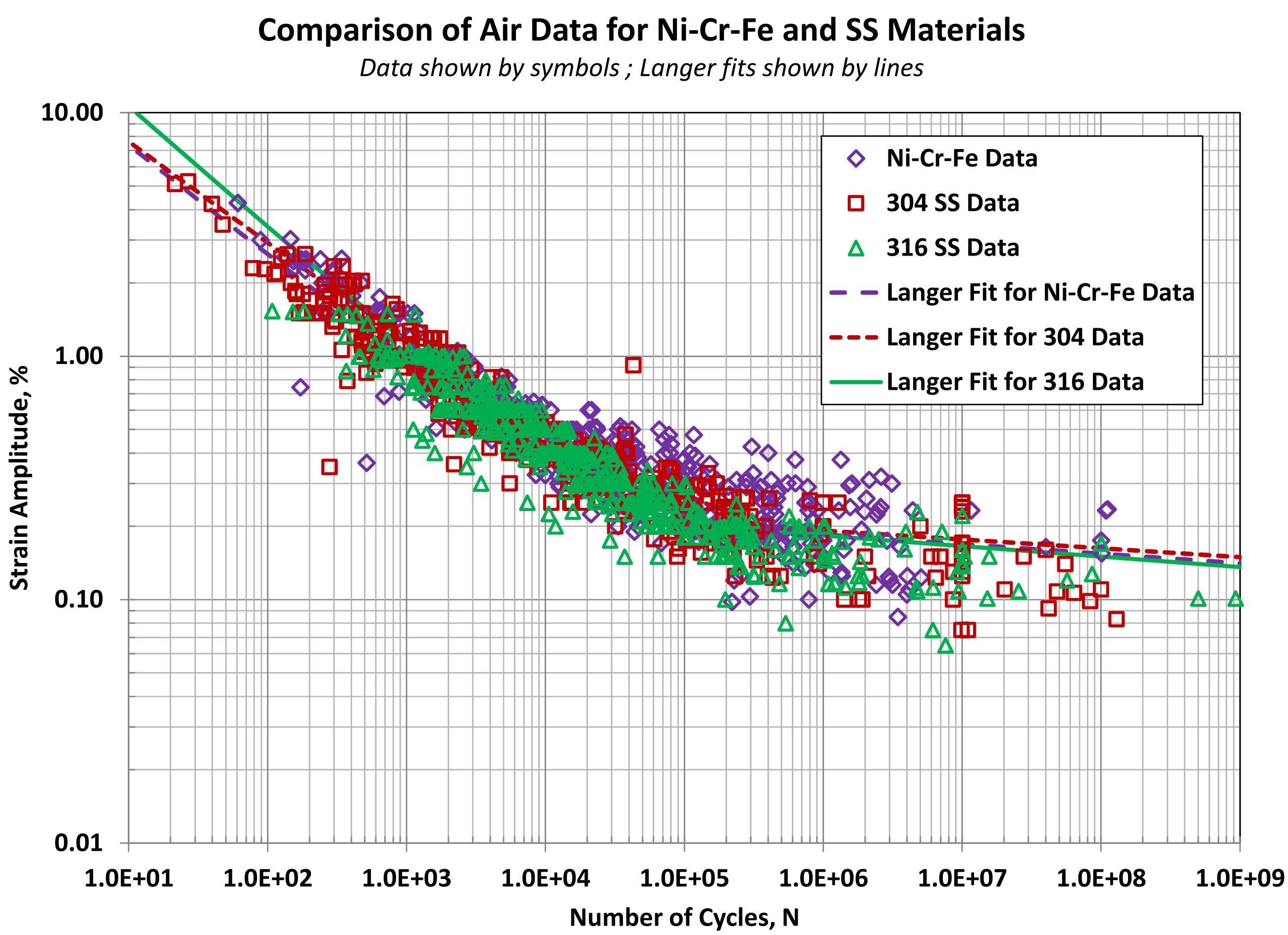

Figure 2. Best Fit Air Curves for Austenitic Stainless Steels and Ni-Cr-Fe Alloys

ε-N CURVES FOR FERRITIC MATERIALS BASED ON MATERIAL TENSILE STRENGTH

Similar to the material type evaluation performed above for austenitic stainless steels and Ni-Cr-Fe alloys, simplified analysis was also performed to determine if fatigue lives for carbon steels can be evaluated as a function of ultimate tensile strength (UTS). The available carbon steel air data was separated into four categories based on UTS: (a) UTS < 500 MPa, (b) 500 < UTS < 550 MPa, (c) 550 < UTS < 600 MPa, and (d) materials where the UTS was not reported. Again, simplified data evaluation was performed that fitted the data by minimizing the difference between the measured fatigue lives and a best fit Langer relationship for the first three categories of data where UTS was available using the Solver routine in Microsoft Excel®. For the purposes of this simplified assessment, coefficients A and B of the Langer fit equation were varied in the minimization while coefficient C was maintained at a value of 0.113 for all cases. While this approach is not rigorous, it was used to determine whether further pursuit of grouping the data by the UTS is worthwhile. Further investigation will be performed to address this issue.

Figure 3 show the results of the simplified evaluation for the carbon steel air data. Both the raw data and the Langer best fits are shown for each of the four UTS categories. The results indicate that ε-N curves based on UTS can lead to fairly significant differences in predicted fatigue lives. Based on this simplified evaluation, the NRC concludes that further refined evaluation based on UTS for ferritic materials would lead to improved fatigue life definitions. There is now sufficient test data available to perform such evaluation and develop improved ε-N air curves for UTS levels for carbon and low alloy steels.

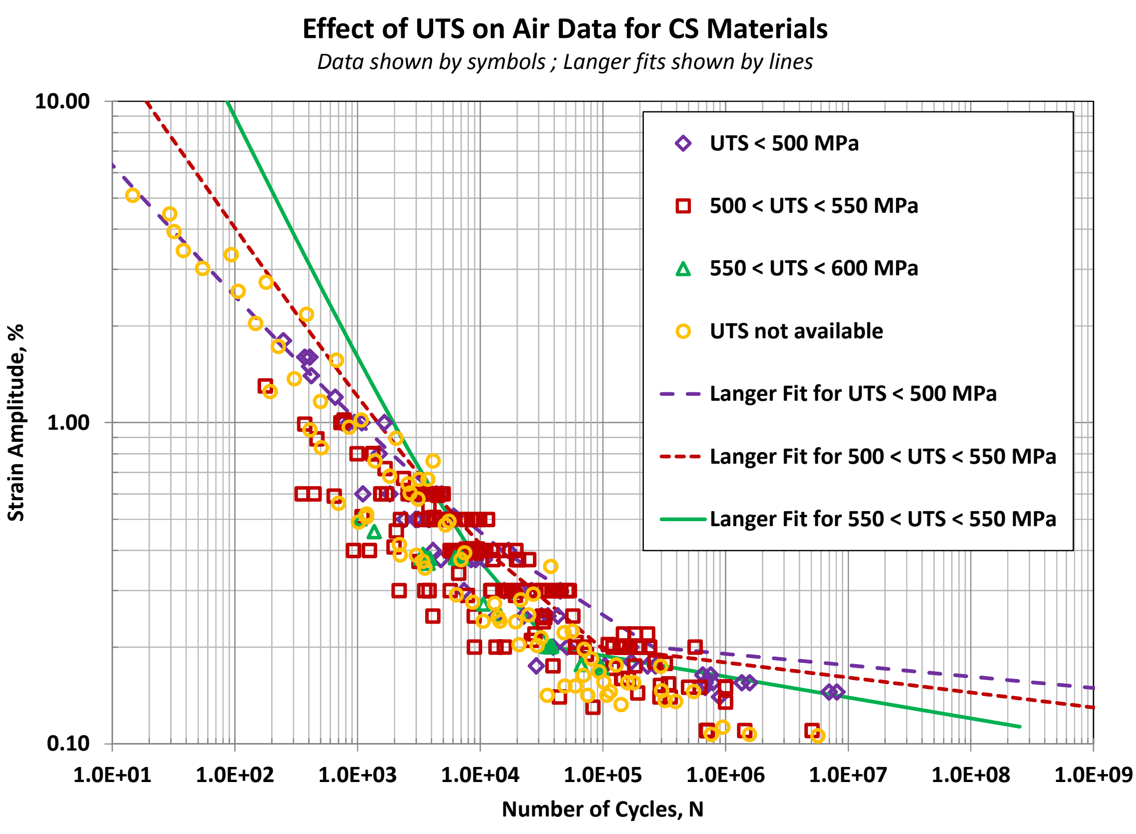

Figure 3. Best Fit Air Curves as a Function of UTS for Carbon Steels

COMPONENT TESTING

There is also a known disparity between laboratory results and operating experience. Whereas fatigue calculations using the F_{en} method often lead to high U_{en} values, to-date there have been very few observed instances of low-cycle fatigue cracking in components throughout the nuclear industry. There have been relatively few experimental studies performed directed at understanding this disparity. Available test data obtained with test specimens having geometric and loading features similar to plant components are very limited because actual component testing is expensive and time consuming. Two examples of actual component testing are the Bettis stepped pipe tests [5] and the EPRI U-bend tests [6-8]. Both of these tests were evaluated against F_{en} calculations in Section 6 of Rev. 1 with very limited success.

Nevertheless, the outcome from these tests, as well as the evaluations of the F_{en} method for those tests, taken together, indicate that a significant benefit would be obtained from further component testing. In particular, studies indicate that the through-wall stress distribution (gradient vs. membrane) is an important contributor to the observed disparity. Gradient loading is more representative of the type of loading in actual components, whereas nearly all of the fatigue test results from small-scale specimens are based on constant through-thickness (membrane) loading. Consideration of gradient loading will generally lead to longer fatigue lives.

The effects of surface finish may also lead to differences in fatigue lives between laboratory specimens and components. Actual components have industrial–grade surface finishes compared to the smooth polished surfaces of test specimens. Fatigue lives are sensitive to surface finish; cracks are more likely to initiate at surface irregularities that act as stress risers. The height, spacing, shape, and distribution of surface irregularities are important for crack initiation. Whereas there is some data that addresses surface finish effects, as discussed in Section 5.3 of Rev. 1, the data are limited. Consideration of actual surface finish effects will generally lead to shorter fatigue lives. This, consideration of surface finish will tend to counteract any benefits gained from consideration of gradient loading.

Therefore, there are several areas where further research may lead to more realistic environmentally assisted fatigue evaluation methods. While surface finish and stress distribution are highlighted here, EPRI's Gap Report [9] also recommends several other areas for further research.

ASME CODE CUF CALCULATION METHODS

Another reason that fatigue life predictions often do not align with field experience is the conservatism in the ASME Code CUF calculation method. These calculations often lead to high computed values of U_{en} while no field failures are observed. Inaccuracy in the F_{en} method is often cited as a principal reason for this discrepancy. However, the ASME Code prediction of fatigue lives is composed of many adjustment factors and analyst assumptions and practices. The F_{en} method only comprises one part of this complex process. However, other parts of the process likely contribute more to the disparity between calculation results and field observations. These include differences between test specimens and actual components as discussed above, but inherent conservatism of ASME Code calculation procedure, and the necessity for significant analyst judgment as part of this procedure are also important considerations.

Section 5 of Rev. 1 describes conservatisms in ASME Code Section III fatigue evaluations. These conservatisms typically arise from (a) the fatigue evaluation procedures and necessary assumptions that must be implemented by the analyst, (b) the fatigue design curves, and/or (c) the adjustment factors included in the fatigue design curves. The overall conservatism in ASME Code Section III fatigue evaluations has also been demonstrated by comparing the predicted with the measured fatigue lives for component testing [10, 11].

Much of the margin in ASME Code Section III fatigue evaluations arises from conservative design requirements (e.g., stress analysis rules and assumptions). Also, since Section III of the ASME Code is not fully prescriptive, there is a wide variation in the specific methods and assumptions that are used in fatigue evaluations by different analysts [12]. Modern computer capabilities, particularly modern finite element methods, fatigue monitoring, and improved K_e factors, may allow for evaluation refinements that significantly decrease the conservatisms traditionally applied in fatigue evaluation procedures performed in the past.

The results of the reanalysis of the fatigue adjustment factors in Rev. 1 indicates that, for all materials, the current ASME Code Section III use of a factor of 20 on cycles to account for the effects of material variability and data scatter, as well as specimen size, surface finish, and loading history, may be conservative by as much as a factor of 2. To reduce this conservatism, fatigue design air curves derived in Rev. 1 were based on reduced factors of 2 on stress and 12 on cycles. The factor that is more conservative for a particular lifetime is used. Chapter 5 (specifically, Table 14) of Rev. 1 describes the basis for the revised adjustment factors, which includes reductions in the factors for size effects and surface finish compared to those used to originally develop the Section III fatigue curves. In the 2009 Addenda, Section III of the ASME Code adopted this same fatigue curve for austenitic stainless steels.

The conservatisms that are present in the ASME Code calculation process have not been typically evaluated through testing. Therefore, future research efforts aimed at providing a basis for refining ASME Code procedures are likely to decrease the significant differences that are currently observed between predicted fatigue lives and field experience.

EFFECTS OF NEUTRON IRRADIATION ON FATIGUE CRACK INITIATION IN AUSTENITIC STAINLESS STEELS

Section 1.3.2 of Rev. 1 discusses the potential effects of neutron irradiation on the fatigue lives of reactor structural materials. Irradiation effects were not included in the ASME Code Section III fatigue curves and, as a result, they are not included in evaluations performed for either reactor core support structures or reactor internal components. As discussed in Rev. 1, the work of several researchers suggest that neutron irradiation does not result in a further reduction in fatigue properties and, in some cases, may result in an improvement of fatigue life [13, 14, 15]. However, limited testing has indicated that the neutron spectrum and testing environment are important considerations. Materials irradiated under LWR conditions and tested at LWR operating temperatures exhibit significant differences in the microstructure and microchemistry compared with materials irradiated in fast neutron test reactors. Specifically, cavities and helium (He) bubbles were observed in austenitic stainless steels irradiated at a temperature of 320°C (608°F) to high neutron fluence levels in pressurized water reactors (PWRs). Such microstructures could lead to embrittlement of the material [16]. Some fatigue test results also indicate significant differences in the cyclic hardening behavior of the irradiated materials relative to unirradiated materials [14].

The effect of these irradiation effects on fatigue lives, however, is currently not well understood. One study illustrated irradiated Type 308 stainless steel weld metals showed moderate decreases in fatigue lives in the low-cycle regime but superior fatigue lives in the high-cycle regime compared to unirradiated material [13]. Similar effects were also observed on the room-temperature fatigue behavior of irradiated Type 347 stainless steels [14]. However, other tests revealed that the fatigue life of irradiated stainless steel was longer than that of unirradiated stainless steel when the strain amplitude was less than 0.6%. This increase in fatigue strength was postulated to be due to the increase of tensile strength after irradiation [15].

It is therefore concluded that the impact of irradiation on the fatigue lives of materials exposed to LWR environments is inconclusive due to the limited available data. Although some small-scale laboratory fatigue test data indicate that neutron irradiation decreases the fatigue lives of austenitic stainless steels, particularly at high strain amplitudes, it is not possible to quantify the impact of irradiation on the prediction of fatigue lives based on the limited data currently available. Additional fatigue data on reactor structural materials irradiated under LWR operating conditions are needed to determine whether there are measurable effects of neutron irradiation on the fatigue lives of these materials and, if so, to better quantify those impacts. In the absence of such data, the F_{en} methods described in Rev. 1 are considered appropriate for application to materials exposed to significant levels of irradiation, such as stainless steel reactor internals components.

CONCLUSIONS

Based on the recent research efforts aimed at updated the F_{en} methods documented in NUREG/CR-6909 and RG 1.207, the following recommendations for further research efforts can be summarized as follows:

- There is sufficient fatigue data based on specimen testing to define best fit air curves for three grouping of materials: carbon steels, low-alloy steels, and austenitic stainless steels/Ni-Cr-Fe alloys. An increase in available data by as much as 74% since the 2007 time frame did not significantly impact the best fit equations. Therefore, additional specimen testing and evaluations which maintain these material groupings will not likely significantly alter the existing curve fit expressions.
- The results of simplified ε-N curve evaluation indicate that ε-N curves based on more refined material groupings can lead to fairly significant differences in predicted fatigue lives. The test data now available supports refined grouping of individual grades of austenitic stainless steels and Ni-Cr-Fe allow which would lead to improved fatigue life predictions.
- The results of simplified ε-N curve evaluation for carbon steels indicate that ε-N curves defined as a function of UTS can also lead to fairly significant differences in predicted fatigue lives. The test data now available supports refined evaluation for carbon steels based on UTS which would lead to improved fatigue life predictions.
- Further research on surface finish and loading type may lead to more realistic environmentally assisted fatigue predictions. These effects are not typically considered in small-scale specimen fatigue testing.
- Field experience does not always align with analyst predictions of fatigue lives. Since the conservatisms that may be present in the ASME Code calculation process are not typically evaluated by testing, future research efforts aimed at evaluating and refining ASME Code procedures are recommended to address the significant differences that are observed between fatigue predictions using the ASME Code and field experience.
- The F_{en} methods described in Rev. 1 are considered sufficiently conservative for application to materials exposed to significant levels of irradiation, such as stainless steel reactor internals components. However, fatigue data on LWR irradiated materials should be developed to further quantify the effects of neutron irradiation on fatigue lives of materials exposed to LWR environments. This additional understanding could allow for a more realistic assessment of irradiation effects.

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