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Fatigue Management Considering LWR Coolant Environments

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Abstract

Design fatigue curve for structural materials in the ASME Boiler and Pressure Vessel Code do not explicitly address the effects of reactor coolant environments on fatigue life. Environmentally assisted cracking(EAC) of low-alloy steels in light water reactor(LWR) coolant environments has been a concern since the early 1970's. And, recent fatigue test data indicate a significant decrease in fatigue lives of carbon steels, low-alloy steels and austenitic stainless steels in LWR coolant environments. For these reasons, fatigue of major components has been identified as a technical issue remaining to be resolved for life management and license renewal of nuclear power plants. In the present paper, results of recent investigations by many organizations are reviewed to provide technical justification to support the development of utility approach regarding the management of fatigue considering LWR coolant environments for the purpose of life management and license renewal of nuclear power plants.

1. Introduction

Fatigue of metal components has been identified as a high-impact issue remaining to be resolved for life management and license renewal of nuclear power plants. The fatigue issue, especially, environmental fatigue considering light water reactor(LWR) coolant environments, has been a concern since the pioneering work by Kondo et al.[1] who demonstrate the environmentally assisted cracking(EAC).

From then a lot of environmental fatigue tests have been performed to identify the mechanism of EAC, and to confirm the validity of ASME Boiler and Pressure Vessel Code, Section III, design fatigue curve and Section XI, fatigue crack growth rate curve. From the early 1970's to 1980's, fatigue tests have been performed mostly about the fatigue crack growth rate, and test specimens were mainly carbon and low-alloy steels. And, from the late 1980's, fatigue tests have been performed mainly to generate strain-life(S-N) data, and test specimens are extended to austenitic stainless steels and Inconel alloys.

Design fatigue curve for structural materials in the ASME Boiler and Pressure Vessel Code do not explicitly address the effects of reactor coolant environments on fatigue life as described in Section III, Subsection NB-3121. And, recent fatigue test data indicate a significant decrease in fatigue lives of carbon steels, low-alloy steels and austenitic stainless steels in LWR coolant environments.

Recently, a program was initiated at Argonne National Laboratory(ANL) to provide data under conditions that are not addressed in the existing data base and to develop models for estimating the fatigue life of primary pressure boundary materials in LWR coolant environments. Majumdar et al.[2] developed interim design fatigue curves to address environmental effects on fatigue life of carbon steels, low-alloy steels and austenitic stainless steels. Keisler et al.[3-5] developed statistical model to estimate the effects of various materials and loading conditions on fatigue life of these materials. And, Pleune and Chopra[6] applied artificial neural networks to predicting EAC.

In regarding to regulatory concerns, EPRI has performed a lot of efforts to help utilities identify locations susceptible to various fatigue mechanisms and implement cost-effective monitoring and corrective actions to prevent fatigue-related failures.

In the present paper, results of recent investigations by many organizations are reviewed to provide technical justification to support the development of utility approach regarding the management of fatigue considering LWR coolant environments for the purpose of life management and license renewal of nuclear power plants.

2. ASME Code Approach to Fatigue

2.1 History of Code Development

2.1.1 Code for Design of Piping

The first piping design standard was issued as the USAS B31.1 "Power Piping" Standard in 1951. In 1955, the B31.1 Standard was reissued with additional design considerations such as, prevention of fatigue failure due to thermal expansion stresses, the concept of stress ranges and maximum shear stress, and the evaluation of local stresses using stress intensification factors for piping. That is, the effect of peak stress on fatigue usage was first addressed in the 1955 Pressure Piping Code B31.1. In 1962, the applicability of B31.1 was extended to include nuclear power plant piping.

In 1967, the Standard was revised, dividing the existing sections into their own separate documents. This 1967 edition of B31.1 is the most commonly referenced piping code for early nuclear power plants.

The B31.7 "Nuclear Power Piping" Standard issued in 1969 was the first piping standard developed specifically for nuclear piping systems. This standard included the use of stress indices, established fatigue usage concepts, and presented a simplified elastic-plastic evaluation method.

2.1.2 Code for Design of Components

In 1963, the ASME Boiler & Pressure Vessel Committee first issued Section III, Nuclear Vessels, as a separate code. In this edition, a formal fatigue analysis procedure for nuclear components was provided. Two design fatigue curves were enclosed in this edition of the Section III Code, one for carbon and low-alloy steels, and the other for 18-8 stainless and Ni-Cr-Fe alloy materials. The design curves include factors of 2 on stress or 20 on cycles relative to the mean of test data to account for differences between specimen test conditions and real vessels.

In 1971, the scope of the ASME Section III Code was significantly altered. The Code was changed from a "Nuclear Vessel" Code to a "Nuclear Power Plant Components" Code. In this Code, the effect of plastic strain is compensated by material factors n and m.

In the 1980 revision to Section III, code rule for piping components for thermal stress due to linear portion of temperature gradient through the wall was relaxed by classifying this thermal stress as a peak stress instead of a secondary stress.

The 1983 revision to Section III extended the design fatigue curves for austenitic steels from 10^6 to 10^{11} cycles. The 1983 revisions also included separate design fatigue curves for base metal and weld zone. In fig. 1, the design fatigue curves for carbon steels, low-alloy steels and austenitic stainless steels are represented.

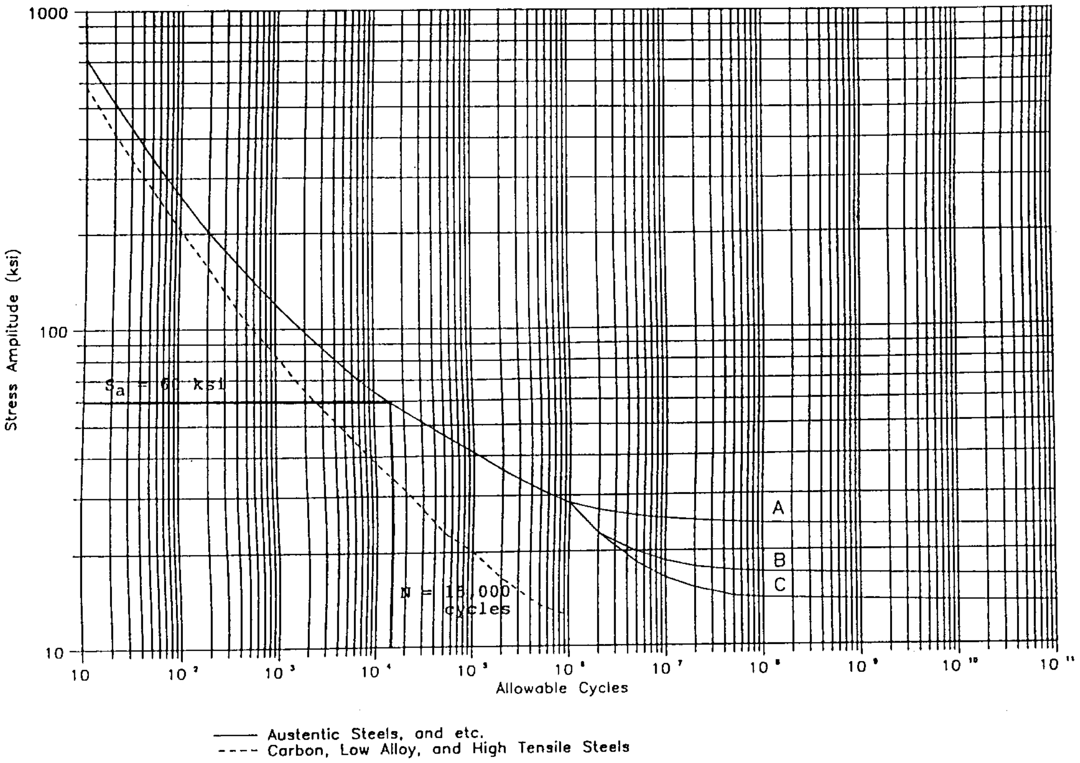

Fig. 1. ASME Section III design fatigue curves.

2.1.3 Code for Operating Nuclear Power Plants

In contrast to the ASME Section III, the ASME Section XI Code imposes inservice inspection requirement, which is intended to detect significant flaw growth as well as the development of new flaws in service.

The first reference fatigue crack growth curves was included in the 1972 addenda to Section XI. After the curves were agreed, a concern that the reference fatigue crack growth curves were not an upper bound to crack growth in a reactor water environment began to come out. In the long run, the reference fatigue crack growth curves for carbon and low-alloy steels were corrected to account for the reactor water environment in the 1980 addenda to Section XI as represented in fig. 2. Ford[7] proposed that 1980 edition of ASME XI is generally conservative, especially for more modern low-sulfur steels in deaerated environments.

The 1989 edition of Section XI includes crack growth curves for stainless steels in air environment. Crack growth curves for stainless steels in LWR coolant environment are planned.

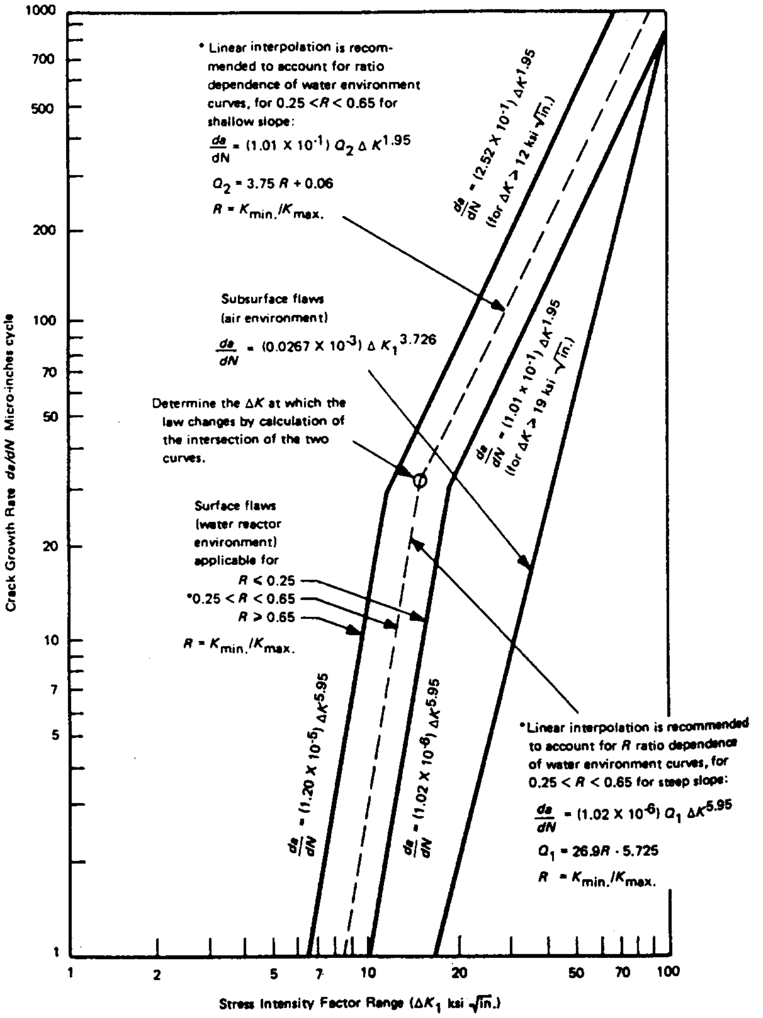

Fig. 2. Reference fatigue crack growth curves for carbon and low-alloy ferritic steels.

2.2 Fatigue Assessment in Operating Nuclear Power Plants

Once a nuclear power plant begins commercial operation, the focus of concern shifts from design qualification to component fitness for service. To assess the fitness for service ASME Section XI was developed. Fitness-for-service evaluations are designed to answer two basic questions - "Is the component safe?" and "How long will the component remain safe?" The answer to these questions should not rely solely on design analyses but should incorporate data and information obtained from inspections, monitoring programs and industry experience.

The fatigue crack growth reference curves in the 1972 Section XI were not an upper bound to crack growth in a reactor water environment. The curves had been based on a straight factoring of the air data curve by 10 times to accommodate the minimal amount of data generated with great experimental difficulty in simulated reactor water environments. Kondo had shown that the environmental effect could not be represented by a simple factoring of air fatigue data, which was relatively independent of stress ratio and frequency[8].

Industry experience demonstrated that most service-induced fatigue failures resulted from load conditions not considered in the original design process(i.e., unanticipated loads such as bypass leakage, thermal mixing, thermal stripping and stratified flow). Cumulative usage factor(CUF) as calculated in accordance with ASME Section III Class 1 design rule, was determined to be a design threshold, not a measure of component fatigue life. These facts demonstrate that the ASME Section III approach to fatigue design has proven to be an effective method to qualify a design for initial construction; however, it was recommended that the ASME Section III approach should not be the only basis for determining serviceability in operating plants. The inherent conservatisms in this design basis approach and the absence of any alternative operating basis criteria could force utilities to implement unnecessary repairs or replacements.

3. Test data

3.1 Carbon and Low-alloy Steels

The reduction of fatigue strength was observed in general to be accentuated with increasing applied strain amplitude and a reduction in strain rate. Higuchi and Iida[9] introduced correction factor, K_{en} to account for this reduction in the case of high-temperature water environments. The value of K_{en} is dependent on type of steel, rate of strain applied, environmental temperature and content of oxygen dissolved in the water.

Chopra and Shack[10] investigated that water environments can have a significant effect on fatigue life only when all of the following four conditions are satisfied; sulfur content of the steel was >0.003wt.%, temperature of the water was >150°C, concentration of dissolved oxygen(DO) in the water was ≥0.05ppm, and applied strain rate was ≤1%/s.

However, Nakao et al.[11] reported that if the water temperature is under 200°C, there is little or no effect of water on fatigue life. And, Katada and Sato[12] investigated that low cycle fatigue lives of a low-alloy pressure vessel steels showed discontinuous temperature dependence; fatigue life showed no conspicuous dependence at lower temperature than 150°C, while fatigue life was the longest at 200°C, and rapidly decreased with increasing temperature at higher temperature than 250°C.

On the other hand, Tice et al.[13] reported that only minor environmental enhancement of fatigue crack growth was observed for any of the materials tested at 290°C or below 150°C. However, at intermediate temperatures, between 190°C and 270°C, significant time dependent crack growth was observed for thick section steam generator upstand forgings, but not for the ring forgings as used for reactor pressure vessel fabrication. Tice et al. concluded that the differences in behavior appear to be due to some differences in the sulfide inclusion composition or morphology, probably related to difference in the fabrication routes for the thick section and ring forgings[12].

Chopra and Shack[10, 14] also investigated the effect of strain on EAC. The fatigue life of carbon and low-alloy steels decreases rapidly with decreasing strain rate. A minimum strain is required for decrease in fatigue life. This threshold strain range appears to be 0.36%.

In regard to dissolved oxygen level, Chopra and Shack[10] and Nakao et al.[11] reported that environmental effects of fatigue life are significant at high dissolved oxygen levels, e.g., 0.5-0.8ppm dissolved oxygen at particular high temperature above 250°C. However, Katada and Sato[12] reported that the discontinuous temperature dependence of fatigue life could be occurred without any contribution of dissolved oxygen concentration.

Wire and Kandra[15] reported that EAC in low-alloy steel is generally believed to be activated by dissolution of MnS inclusions at the crack tip in high temperature LWR coolant environments. EAC is the increase of fatigue crack growth rate of up to 40 to 100 times the rate in air that occurs in high temperature LWR coolant environments. EAC will initiate only above a critical crack velocity and cease below this same velocity. Localized EAC starting at large sulfide clusters reduces the calculated threshold velocity from the value predicted for a uniform distribution of sulfides. When account is taken of sulfide segregation and localized EAC, quantitative values for the lower bound values of EAC initiation velocity are consistent with basic theory in stagnant, low oxygen water where diffusion is the main means of mass transport.

The effect of the dissolved oxygen increases rapidly with increasing concentration up to ≒ 0.2ppm, but above this level there is relatively little effect on fatigue life from further increases up to 8ppm. For the same environment and the same strain range, lives can vary by a factor of ≒50, depending on the strain rate. At a given strain rate, fatigue life increases by a factor of ≒5 or more as the temperature is decreased from 288°C to 200°C. The critical conclusions from the fracture mechanics modeling studies is that there exists a saturation strain below which fatigue life does not decrease with decreasing strain rate. The estimated maximum reduction in life for a high-sulfur carbon or low-alloy steel in water with 0.2ppm dissolved oxygen at 288°C is ≒46. This occurs at strain rates of $\leq 10^{-5}s^{-1}$. At higher strain rates, the reduction in life is smaller. Chopra et al.[16] investigated the effect of strain rate on fatigue life. And, they suggested that the actual value of saturation strain rate might vary with dissolved oxygen and sulfur content of the steel.

Based on a review of the available data on high cycle fatigue life, the design stress at 10^6 cycles would appear to be a somewhat nonconservative estimate of the allowable design stress, and it is proposed that the design stress for 10^8 cycles in carbon steels be taken as 7.9ksi(compared to a design stress of 12.5ksi for 10^6 cycles). For low-alloy steels, the design stress for 10^8 cycles is taken as 9.7ksi[2].

3.2 Stainless Steels

Recently, a lot of fatigue tests were performed on stainless steels including Type 316NG. According to the test results of Chopra and Gavenda[17], the fatigue lives of Type 304 and 316 stainless steels are comparable and those of Type 316NG are superior. Similar results were also obtained by Higuchi and Iida[18]. Chopra and Gavenda[17] reported that fatigue life might decrease up to 30% with decreasing strain rate. These results indicate that the current ASME Code mean curve is not consistent with the existing fatigue S-N data for austenitic stainless steels. The fatigue lives at 288°C and ≒0.25% strain range fall very close to the ASME Code design curve. Unlike carbon and low-alloy steels, environmental effects are more pronounced in low-dissolved oxygen than in high-dissolved oxygen water. At ≒0.004%/s strain rate, reduction in fatigue life in water containing <10ppb dissolved oxygen is greater by a factor of ≒2 than in water containing >200ppb dissolved oxygen. In a simulated PWR environment, a decrease in strain rate from 0.4 to 0.004%/s decreases fatigue life by a factor of ≒8[17].

Like carbon steels, the fatigue life of stainless steels of Type 316NG decreased with the decrease of strain rate. There was a linear relation between the fatigue life and strain life in a double-logarithmic scale. For a piping material of Type 316NG, the fatigue life in water at 288°C was 30% to 40% shorter at a strain rate of 0.4%/s, and 50% to 60% shorter at a strain rate of 0.04%/s, than that in air at 288°C. For a weld metal of Type 316NG, there was no difference in fatigue life between dissolved oxygen contents of 8ppm and 0.01ppm or less. For a base metal of Type 316NG, the fatigue life lowered more significantly at 0.01ppm or less of oxygen than at 8ppm. This tendency was quite different from the tendency observed with carbon steels[18]. And, test results similar to this tendency were also obtained by Chopra and Smith[19, 20].

3.3 PVRC Data

The extent of fatigue life reduction depends on the values of the influencing variables which include the dissolved oxygen content, temperature, amplitude, rate of cyclic hardening. and possibly the flow velocity of the coolant water. In addition, for ferritic steels, the sulfur content of the material may be another factor.

Sluys and Yukawa[21] reported the summaries of the database collected by pressure vessel research council(PVRC). They categorized the database by materials, test environment and test parameters for carbon steels, low-alloy steels, austenitic stainless steels and nickel alloys as shown in table 1[21]. Based on examination of the database, it was determined that values of independent parameters as listed in table 2 should result in only moderate detrimental effect on cyclic life.

Table 1. Summary of PVRC S-N Database

Materials	Environment	Number of data points	Temperature (°C)	Strain amplitude(%)	Strain rate (%/sec)	Oxygen content
Carbon Steel	Air	191	25 - 288	0.11 - 1.78	9.8 - 0.004	
	PWR	45	300	0.11 - 1.27	5.1 - 0.4	
Low Alloy Steel	Air	425	25 - 350	0.09 - 6.6		
	PWR	28	288	0.17 - 0.4	0.4 - 0.004	0.003-0.009
Weld Metal	Air	20	25	0.14 - 1.5	1 Hz	
Inconel 600	Air	100	25 - 288			
Inconel Weld	Air	13	25 - 260	0.175 - 0.8	0.4	
304 SS	Air	234	25 - 300	0.11 - 2.62		
316 SS	Air	395	21 - 650	0.13 - 1.5	0.04 - 4.0	
Alloy 800	Air	24	20 - 427	0.2 - 3.0		
310 SS	Air	8	26	0.3 - 4.0		
348 SS	Air	15	427	0.7 - 1.67		
347 SS	Air	116	20 - 350	0.2 - 1.3		
Inconel 718	Air	205	20 - 427	0.15 - 4.2		

Table 2. Values of independent parameters for acceptable or moderate environmental effects on the S-N fatigue life of carbon and low-alloy steels

Parameters	Values
Strain Amplitude	≤0.1%
Strain Rate	≥0.1%/sec
Dissolved Oxygen Content	≤0.1ppm
Temperature	≤150°C
Sulfur in Steel	≤0.003%
Water Flow Velocity	>3m/s

4. Recent Approach to Operating Nuclear Power Plants

The CUFs from the design stress reports show that the actual fatigue usage factors are plant specific. A sample of the maximum reported usage factor according to current ASME Section III in fatigue sensitive locations are shown in table 3[22].

Table 3. Maximum Reported Fatigue Usage Factor in a Typical PWR

Component	Subcomponent	Fatigue Usage Factor
RCPB Piping	Surge Nozzle	0.203
	Safety Injection Nozzle	0.316
	Charging Inlet Nozzle	0.778
	Cold Leg Spray Nozzle	0.492
Pressurizer	Surge Nozzle	0.411
Steam Generator	Feedwater Nozzle	0.652
	Tubesheet	0.434
Reactor Vessel	Inlet Nozzle	0.182
Reactor Internal	Lower Core Plate	0.8
	Lower Support Column	0.44
	Core Barrel Nozzle	0.71
	Upper Core Plate Alignment	0.52
	Baffle Former Assembly Bolts	~1.0

There are basically three distinct approaches to calculate the environmental fatigue correction factor, F_{en}. The first one is that proposed by Highuchi-Iida approach(K_{en})[9], and the second one is the NUREG/CR-5999 approach. The last one is proposed by Mehta-Gosselin [23, 24] which utilize the statistical characterization in NUREG/CR-6335. According to the results of Mehta-Gosselin[23, 24], there is a modest increase in calculated fatigue usage, which is considerably less than the results obtained when the NUREG/CR-5999 curves are applied directly.

Keisler et al.[3-5] developed statistical models to estimate the effects of the various service conditions on the fatigue life of materials. In this approach, fatigue S-N curves for components have been determined by adjusting the best-fit experimental curves for the effect of mean stress and then setting margins for size, geometry, and surface finish to the probability distribution curves for test specimens. The results indicate that in air at stress levels <60ksi, the ASME Code mean curve for carbon steels is conservative with respect to the data. Furthermore, the ASME Code design fatigue curve for carbon and low-alloy steels does not adequately address the effect of environment on fatigue life in high-dissolved oxygen water. At stress level <150ksi, the current ASME Code design curve for austenitic stainless steels is nonconservative with respect to the data. For a specific service condition, the interim design curves represent a lower probability of cracking in carbon steel components than low-alloy steel components.

For carbon and low-alloy steel components, the NUREG/CR-5999 interim fatigue curves increased the CUF by an average factor of 2.2 times the design basis. For stainless steel and Alloy 600, the average multiplication factor is 9.2. The 40-years CUFs calculated using the NUREG/CR-5999 interim fatigue curves are summarized in table 4.

Representative CUFs for components on older vintage plants designed to the B31.1 Code, for which no fatigue analyses were required, were determined to be less than 1.0 using the current ASME Code. Two major steps to reduce the CUF were (1) more detailed finite element analyses or (2) fatigue monitoring of the transients. A plastic analysis in which the strain are computed, rather than using the K_e(elastic-plastic multiplier) factor to adjust the elastic stresses, will lower the CUF. The best method to lower the CUF for the few worst locations appears to be fatigue monitoring. However, where thermal stratification exists, a combination of fatigue monitoring and more analyses may be needed[25]. Calvert Cliffs Nuclear Power Plants[26] and Oconee Nuclear stations[27], that acquired the license renewal from NRC in March and May 2000 respectively, stated that the effect of environment would be assessed using statistical correlation developed by ANL and published in NUREG/CR-5704.

Table 4. Component CUFs for 40-Years Life Using NUREG/CR-5999 Interim Fatigue Curves

Component	CE		B&W	Westinghouse	
	New	Old		New	Old
RV Shell/Head	0.014	0.013	0.742	0.018	0.891
RV Nozzle	0.475	0.554	0.469	0.658	0.496
Surge Line	3.476[a]	1.345[a]	2.005[a,b]	2.458[a]	5.860[a]
Charging Nozzle	0.774	0.666	1.263[c]	4.859[d]	0.349
SI Nozzle	0.457	0.414	0.632[e]	1.511[f]	0.410
RHR Line	0.502	0.139[g]	0.610[h]	2.371[a,i]	0.286

a. Includes thermal stratification transients.
b. Detailed analysis unavailable. Estimated based on B&W design basis CUF for this plant and change in other four PWR surge line CUFs.
c. High pressure injection/makeup nozzle.
d. NB-3600 analysis. Other PWR plants used NB-3200 analysis for charging nozzle.
e. Core flood nozzle.
f. Boron injection tank nozzle. No thermal sleeve. NB-3600 analysis.
g. Shutdown cooling line.
h. Decay heat removal line.
i. Only PWR plant to include postulated thermal stratification transients for RHR line.

Fig. 3 shows a comparison of the predicted F_{en} values for carbon steels using the three approaches.

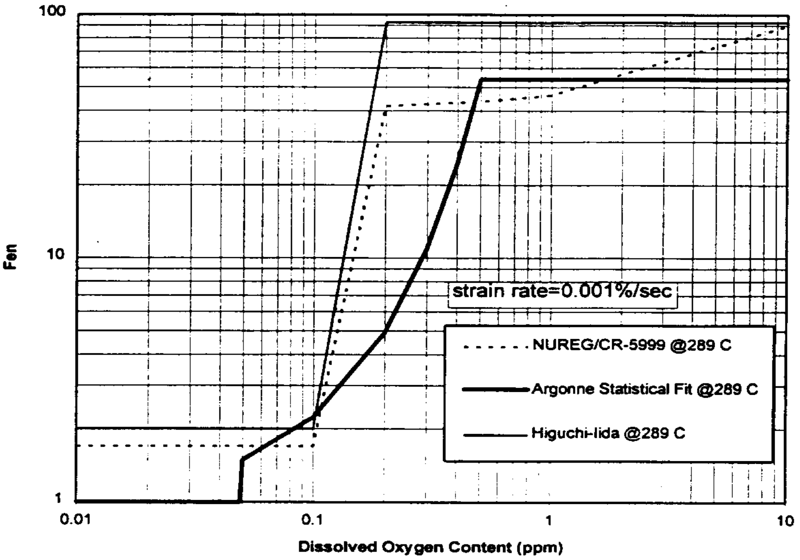

Fig. 3. Comparison of predicted F_{en} values.

5. Conservatisms in ASME Section III

The current ASME Code Section III design fatigue curves were based primarily on strain-controlled fatigue tests of small polished specimens at room temperature in air. Best-fit curves to the experimental test were lowered by a factor of 2 on stress or a factor of 20 on cycles, whichever was more conservative, to obtain the design fatigue curves. The factors were intended to account for differences and uncertainties in relating the fatigue lives of laboratory test specimens to those of actual reactor components. The factor of 20 on cycle is the product of three subfactors: 2 for scatter of data, 2.5 for size effects, and 4 for surface finish, atmosphere(atmosphere was intended to reflect the effect of an industrial environment rather than the controlled environment of a laboratory), etc. However, environmental effects on fatigue resistance of materials were not explicitly addressed in these design fatigue curves.

Keisler et al. reviewed data available in the literature to evaluate the effects of size, geometry, and surface finish of a component on its fatigue life[3]. The results suggest that a factor of 20 on cycles can be used to obtain a design curve for components from the best-fit curve of the experimental data. However, in the analysis of NUREG/CR-6237, the factor of 20 is a product of three subfactors: 3.5 for surface finish, 2 for size and geometry, and 3 for material variability and data scatter. The effect of steel type on fatigue life under all service condition is minimal. The effect of temperature in air environment is a factor of < 2 when temperature is increased from room temperature to 300°C.

Under service conditions that yield a maximum effect of environment on fatigue life, i.e. ≥ 0.5ppm dissolved oxygen(DO) in water, ≥0.015wt.% S, ≤0.001%/S strain rate, and 250-290°C, the interim design curves represent a 5% probability of crack initiation at strain amplitude ≥ 0.1% and 1% or lower probability of crack initiation at strain amplitude <0.1%. The current ASME Code design fatigue curve for carbon and low-alloy steel does not adequately address the effect of environment on fatigue life at strain amplitudes >0.1%. On the basis of present data, the ASME Code design fatigue curve appears to be adequate at strain amplitude ≤0.1%.

Under certain conditions of loading and environment, i.e., temperature >250°C, dissolved oxygen >0.1ppm, strain rate ≤0.01%/S, and sulfur content in the steel >0.006wt.%, fatigue lives in the test environments can be more than a factor of 100 shorter than those for the tests in air. This implies that the factors of 2 and 20 applied to the mean-data curve may not be adequate[3].

By examining actual design records, the margins that exist in between Code minimum requirements and those that exist in the field have been assessed. The conservatism in the design transient definitions are shown by comparing fatigue usage results from actual monitored plant data to that computed based on design transients. The effects of the environment on the fatigue evaluation are also evaluated using the actual monitored data. The current licensing basis for fatigue is adequate including both the current design basis and an extension beyond the current operating basis. The only potential exceptions are components with geometric discontinuities(socket welds), and components with severe step change thermal transient loadings.

According to the analysis of Smith et al.[28], conservatisms in fatigue evaluation of ASME Class 1 pressure vessels and piping are identified due to the following sources:

- Grouping of design transients.
- Simplified bounding stress analysis: The thermal stress analysis was performed by use of simple bounding formulas which were based on closed-form solutions from the theory of elasticity. These formulas assume complete restraint of thermal expansion, and

depending upon the geometry of the component, they can be very conservative. The use of the results from the plastic analysis allowed a reduction in the fatigue usage from 2.27 to 0.28.

- Bounding heat transfer analysis: There was 82% reduction of the usage factor when a varying, instead of a constant, heat transfer coefficient was used.
- Conservative selection of material properties and allowable stresses.
- Conservatisms within Code/Code edition.
- Conservative design transients : It is worthwhile to note that there was no fatigue usage attributable to events not associated with startup and shutdown transients.

Shack and Chopra[29] reported that at high crack growth rates the observed enhancement in LWR coolant environments is relatively small. And, Ware et al.[25] reported the conservatism of interim design fatigue curves by stating that the CUFs using the revised curves were reduced by an average of about 20% from the CUF computed using the NUREG/CR-5999.

6. Considerations in Improving Fatigue Curves

Although many strides have been made in recent years in development of fatigue criteria for nuclear power plant component materials, much is still not understood well and room for improvement exists. In reviewing the numerous factors affecting fatigue life, some of the following factors should be considered in improving fatigue curves:

- Time base description of fatigue crack growth curves: Tomkins[8] proposed that fatigue crack growth curves in water environment should be expressed on a time rather than cycles base.
- Stress ratio: Limited data indicate that the stress ratio effect diminishes somewhat for stress ratio exceeding about 0.75[30].
- Key factors of loading sequence, size and surface finish.
- Effect of short crack on initiation model: The initiation and growth of small cracks is important because these defects have been shown to propagate more rapidly and at lower ΔK level than LEFM would predict. In regard to this matter, Park and Chopra[31, 32] developed a fracture mechanics model to predict fatigue initiation and growth of small cracks in air and LWR coolant environments.
- Better quantification of fatigue threshold limits.
- Extension of fatigue curves to very high cycles: The time spent during crack initiation accounts for a majority of life in the high cycles regime, so more accurate crack growth predicts become critical. High cycle fatigue can be induced by flow mechanisms, such as thermal striping, and by mechanical loads such as vibration[30].
- Crack closure effect: Crack closure effect produce a crack driving force which is less than $\Delta K=K_{max}-K_{min}$. Thus, life predictions, which do not account for crack closure effect, give inaccurate life estimation, especially for fully reversed loadings[33].
- Constraint effects: A more recent application of crack growth rate data involves correcting existing S-N failure data obtained in air to account for environmental effects such as reactor water, using crack growth rate data obtained in a reactor water environment. Constraint effects should be considered in evaluating crack closure effects on S-N fatigue data[34].
- Describing parameter: Recent changes in the ASME Code Section XI, Appendix A had

recognized work relating to crack effects on tests of four-point bend specimens. These tests demonstrated that fatigue crack growth rates can be empirically correlated using K_{max} in place of ΔK where the compressive portion of fatigue cycle contribution of K is ignored[35]. On the other hand, Shoji et al.[36] proposed that crack growth rates can not be uniquely interpreted as a function of K, and they suggested the use of displacement rate at loading point.

- Environmental effects: Moderate to large reduction in S-N life relative to life in air environment tests can occur for some combinations of water chemistry, mechanical test parameters, and material characteristics; however, the range of combination are generally not typical of operating LWR plants. So, more data are needed in the following items[21].
  - Effect of flow velocity
  - S-N properties of ASS
  - S-N properties of all weld metal
  - Effect of sulfur content for carbon and low-alloy steels
  - Effect of high mean stress

7. Fatigue in License Renewal

The USNRC staff believes that no immediate staff or license action is necessary to deal with the fatigue issues addressed by the Fatigue Action Plan[37]. SECY-95-245 found that fatigue failure of piping is not a significant contributor to core-melt frequency, and the USNRC staff does not believe it can justify requiring a backfit of the environmental fatigue data to operating plants. However, SECY-95-245 found that Fatigue Action Plan issues should be evaluated for any proposed extended period of operation for license renewal. The concerns of the NRC staff regarding fatigue for license renewal fall into five categories:

- Adequacy of the fatigue design basis when environmental effects are considered.
- Adequacy of both the number and severity of design-basis transients.
- Adequacy of inservice inspection requirements and procedures to detect fatigue indications.
- Adequacy of the fatigue design basis for class 1 piping components designed in accordance with ANSI B31.1[38].
- Adequacy of actions to be taken when the fatigue deign basis is potentially compromised.

In regarding to these concerns, EPRI has performed a lot of efforts to help utilities identify locations susceptible to various fatigue mechanisms and implement cost-effective monitoring and corrective actions to prevent fatigue-related failures as follows:

- Selective application of environmental correction factor.
- Revised stress intensification factors.
- Fatigue management handbook[39].

If the license renewal applicant is unable to demonstrate that the current fatigue design basis envelops the projected cyclic duty through the license renewal term, augmented programs are required to manage the effects of fatigue for the license renewal term, with alternatives ranging from repair/replacement of the component to assurance that the component location is included in the plant service examination program, to some form of fatigue reanalysis incorporating appropriate environmental effects[40].

8. Conclusions

As a result of reviewing the fatigue data considering LWR coolant environments, it is considered that the current ASME Code design fatigue curves and reference crack growth curves do not adequately address the effect of environments on fatigue life of reactor pressure boundary materials.

Evaluation of environmental effects of LWR coolant on fatigue life of reactor coolant pressure boundary materials will require additional studies and testing to take account of water chemistry, mechanical test parameters and material characteristics.

It is considered that there is the need to evaluate a sample of components with high fatigue usage using the latest available environmental fatigue data in the preparation of life management of nuclear power plants.

Since there are a lot of conservatisms in current ASME Code, no immediate action is necessary to deal with the fatigue issues in life management of nuclear power plants in the aspect of fatigue considering LWR coolant environments.

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