A Comparative Study on the Correction of Coolant Environmental Fatigue Effects Based on Independent Factor Method and Integrated Value Method

Authors: Zhang Guihe

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Abstract

Fatigue is one of the primary factors affecting the design life of mechanical equipment in the nuclear island of light water reactors. Currently, the design fatigue curves widely adopted in both RCC-M and ASME codes are all derived from air environment test results. Since the 1980s, fatigue test results targeting coolant environments have demonstrated that the coolant environment exerts a significant influence on fatigue life, making it difficult to fully guarantee the conservatism of design fatigue curves. Based on research findings from Argonne National Laboratory and the Electric Power Research Institute, the U.S. Nuclear Regulatory Commission approved the technical research report NUREG/CR-6909. This technical research report independently applies environmental correction factors to fatigue analysis results obtained from design fatigue curves to account for the adverse effects of coolant on fatigue life. During the application of NUREG/CR-6909, the nuclear power industry has generally observed that fatigue usage factors corrected using the independent factor method are substantially larger than the original analysis results, potentially causing analysis results for numerous locations to exceed limits. On the other hand, in examining the conservatism of design fatigue curves, the nuclear power industry has also recognized that the conservative coefficients considered in these curves compensate to some extent for moderate coolant environment fatigue effects. The RCC-M code, in its 2016 edition, provides a correction method distinct from NUREG/CR-6909. This method introduces new design fatigue curves and considers that moderate coolant environment correction factors have already been integrated, requiring correction only when the environmental correction factor exceeds the integrated value. This paper conducts a comparative study of the two aforementioned correction methods for coolant environment fatigue effects and performs analyses using both correction methods based on a typical austenitic stainless steel main pipe tee nozzle. The analysis results demonstrate that conducting coolant environment fatigue effect correction based on the integrated value method offers significant optimization compared to the independent factor method.

Full Text

Comparative Study of Coolant Environment Fatigue Influence Corrections Based on Independent Factor Method and Integrated Value Method

Guanghe Zhang, Pan Liu, Ting Jin, Rong Chen, Xiao Xu
Shenzhen China Nuclear Power Design Co., Ltd., Shenzhen, Guangdong, 518124

Abstract

Fatigue is one of the primary factors affecting the design life of mechanical equipment in nuclear islands of light water reactors. Currently, the design fatigue curves widely applied in RCC-M and ASME codes are derived from fatigue test results obtained in air environments. Since the 1980s, extensive experimental research on fatigue in coolant environments has demonstrated that light water reactor coolant conditions can significantly reduce the fatigue life of certain critical components. Based on research findings from Argonne National Laboratory and the Electric Power Research Institute, the U.S. Nuclear Regulatory Commission approved the technical report NUREG/CR-6909. This report introduces an independent environmental correction factor applied to fatigue analysis results based on design fatigue curves to account for the adverse effects of coolant on fatigue life. However, widespread application of NUREG/CR-6909 in the nuclear power industry has revealed that the corrected fatigue usage factors are substantially larger than original analysis results, potentially causing numerous locations to exceed acceptance criteria. Conversely, examination of design fatigue curve conservatism has shown that the safety margins incorporated into these curves, while not originally intended to address coolant environmental effects, can compensate for moderate levels of coolant environment fatigue influence to some extent. The RCC-M code, in its 2016 edition, provides an alternative correction methodology distinct from NUREG/CR-6909. This approach introduces new design fatigue curves that integrate moderate coolant environmental correction factors, requiring additional correction only when environmental correction factors exceed the integrated values. This paper presents a comparative study of these two coolant environment fatigue influence correction methods and performs analyses on a typical austenitic stainless steel main pipe tee nozzle using both approaches. The results demonstrate that the integrated value method significantly optimizes the correction compared to the independent factor method.

Keywords: coolant environment fatigue; independent factor method; inte-

grated value method

1 Introduction

Fatigue represents a critical failure mode of concern for mechanical equipment in nuclear islands, particularly for primary loop components of reactor coolant systems that experience fluctuating loads from various transient conditions throughout their operational life. Mainstream nuclear design codes such as ASME and RCC-M provide design fatigue curves for fatigue assessment, but these curves are based on fatigue test results obtained in air environments. As early as the 1980s, Japanese researchers identified that light water reactor coolant environments could reduce the fatigue life of certain important components. Dr. Higuchi first proposed the concept of Environmentally-Assisted Fatigue (EAF) and introduced the environmental correction factor (FEN) concept [1]. Subsequent extensive experimental studies on EAF were conducted in Japan, the United States, and France. Based on research from Argonne National Laboratory and the Electric Power Research Institute, the U.S. Nuclear Regulatory Commission approved the technical report NUREG/CR-6909, with the latest version being the 2017 edition [2]. This report applies environmental correction factors to usage factors based on fatigue analysis results from design fatigue curves to account for coolant adverse effects on fatigue life. However, the nuclear industry has widely observed that application of NUREG/CR-6909 yields usage factors significantly greater than original analysis results, creating numerous design challenges such as substantially reduced design life and increased numbers of postulated break locations in high-energy piping systems [3][4].

An alternative technical perspective, derived from examining the conservatism inherent in design fatigue curves, reveals that although the safety margins incorporated into these curves were not originally intended to address coolant environmental effects, they can compensate for moderate levels of coolant environment fatigue influence to some extent, potentially covering the overall environmental effect [5]. The RCC-M code, in its 2016 edition [6] trial rules, provides a correction methodology distinct from NUREG/CR-6909. This approach introduces new design fatigue curves that integrate moderate coolant environment correction factors, requiring additional correction only when coolant environmental correction factors exceed the integrated values.

Both the independent factor method represented by NUREG/CR-6909 and the integrated value method represented by RCC-M trial rules aim to account for light water reactor coolant acceleration effects on fatigue, introducing environmental influence factors (Fen), but differ significantly in their correction approaches. This paper introduces design fatigue curves and coolant environment effects on fatigue, compares the independent factor method and integrated value method for considering coolant environmental effects, and performs analyses on a typical austenitic stainless steel main pipe tee nozzle using both correction methods.

2 Design Fatigue Curves and Coolant Environment Effects on Fatigue

Design fatigue curves are established based on test data obtained from smooth, solid small specimens tested at room temperature in air environments. Best-fit curves derived from test data undergo mean stress correction, followed by reduction of stress and cycle counts to account for data scatter, size effects, surface roughness, and atmospheric environment factors.

Early versions of ASME code fatigue curves employed reduction factors of 1/2 and 1/20 for stress and cycle counts, respectively. The cycle count reduction factor addressed data scatter (2.0), size effects (2.5), and other factors including surface roughness and environment (4.0). Environmental factors reflected differences between industrial environments and laboratory air conditions, not coolant effects [5]. The stress reduction factor was primarily introduced to address the high-cycle fatigue region where the fatigue curve becomes flat and cycle count reduction effects become less significant.

Argonne National Laboratory employed Monte Carlo statistical analysis methods for test data processing, applying the "95/95 rule" to median fatigue curves, meaning there is 95% confidence that 95% of components have fatigue lives exceeding design curve values. Monte Carlo results demonstrated that a reduction factor of 12 satisfies the "95/95 rule" for carbon steel, low-alloy steel, and austenitic stainless steel [2]. ASME code versions following the 2007+2009 addenda [7] adopted the Argonne fatigue curves for austenitic stainless steel.

Current nuclear industry design standards contain varying fatigue curves, but none directly incorporate coolant environmental factors. Extensive coolant environment testing demonstrates that strain rate, temperature, and dissolved oxygen content can significantly reduce metal fatigue life. For carbon and low-alloy steels, sulfur content in the material also has a noticeable effect. The accelerating effect of light water reactor coolant environments on metal fatigue has become industry consensus, but unified methods for considering this factor in fatigue analysis have not been established, leading to the development of the independent factor method represented by NUREG/CR-6909 and the integrated value method represented by RCC-M trial rules.

3 Comparison of Independent Factor Method and Integrated Value Method

The independent factor method, represented by NUREG/CR-6909 Rev. 1 (2017), introduces an environmental influence factor Fen based on design fatigue curves established in air and room temperature conditions. Fen is defined as the ratio of fatigue life in air and room temperature conditions to fatigue life in light water reactor service environments and temperatures. The cumulative usage factor considering coolant environmental effects, Uen, is calculated as:

$$Uen = \sum_{i=1}^{n} U_i \cdot Fen_i = \sum_{i=1}^{n} \frac{n_i}{N_i} \cdot Fen_i$$

where U_i is the initial usage factor for load pair i, n_i is the actual number of cycles, N_i is the allowable number of cycles, and Fen_i is the environmental influence factor for load pair i. During correction, the compensation effect of design fatigue curve conservatism on coolant environment is not considered.

The integrated value method assumes that design fatigue curves already integrate some degree of coolant environment adverse effects on fatigue life. Since the 2016 edition, RCC-M code has introduced trial rules regarding coolant environment effects on fatigue, accompanied by new design fatigue curves for use with coolant environmental effects. This method employs a weighted approach to calculate a comprehensive environmental influence factor, requiring correction only when this factor exceeds the integrated value.

The comprehensive environmental influence factor is calculated as:

$$Fen_{global} = \frac{\sum_{j=1}^{m} U_j \cdot Fen_j}{\sum_{j=1}^{m} U_j}$$

where U_j is the initial usage factor for transient load pair j, and Fen_j is the environmental influence factor for transient load pair j:

$$Fen_j = \frac{\sum_{k=1}^{p} \Delta\epsilon_k \cdot Fen_{j,k}}{\sum_{k=1}^{p} \Delta\epsilon_k}$$

where $Fen_{j,k}$ is the instantaneous environmental influence factor and $\Delta\epsilon_k$ is the instantaneous strain increment (considered only when strain increases).

Integrated value criterion:

$$Fen_{global} \leq Fen_{limit}$$

For austenitic stainless steel, $Fen_{limit} = 3$. For thermal shock transients (high strain rate in tensile strain range and low strain rate in compressive strain range), $Fen_{limit} = 5$. When the integrated value criterion is not satisfied, the initial usage factor is corrected as:

$$U_{en} = U_{initial} \cdot \frac{Fen_{global}}{Fen_{limit}}$$

Table 1 provides a comparison of the two methods for austenitic stainless steel based on NUREG/CR-6909 and RCC-M code:

Table 1 Comparison of Environment Effect Requirements

Aspect	Independent Factor Method	Integrated Value Method
Design Fatigue Curve	Assumed to contain no coolant environmental factors	Assumed to cover moderate coolant environmental factors
Environmental Correction Factor	Comprehensive environmental correction factor Fen_{global}	Integrated value Fen_{limit}
Calculation Method	Weighted calculation for all load pairs	Weighted calculation for all load pairs (recommended: load pairs contributing 40% of usage factor)
Thermal Shock Transients	$Fen_{limit} = 5$	$Fen_{limit} = 5$

This comparison demonstrates that RCC-M trial rules significantly reduce conservatism compared to NUREG/CR-6909 while also simplifying the analysis to some extent.

4 Case Study Using Independent Factor Method and Integrated Value Method

A typical austenitic stainless steel main pipe tee nozzle was analyzed using postulated design transients, with fatigue analysis performed and coolant environmental effects considered using both independent factor and integrated value methods.

Finite Element Model and Analysis Section

The finite element model and analysis section are shown in Figure 1.

Figure 1 [**Figure 1: see original paper**] **Finite Element Model and Analyzing Section**

The analysis employed material properties for austenitic stainless steel Z2CND18.12 (nitrogen-controlled). Water between the thermal sleeve and nozzle body was simulated using equivalent water elements with an equivalent thermal conductivity coefficient of 7.13 W/m·K based on the Raithby and Hollands correlation. Internal heat transfer coefficients were calculated using the Colburn formula, conservatively taken as 10100 W/m^2·K and applied to all inner surface regions in contact with coolant. Outer surface regions were considered adiabatic.

The postulated transients for fatigue analysis are listed in Table 2, where Transient 1 simulates thermal shock design transients and Transient 2 simulates non-thermal-shock temperature fluctuation transients. Temperature variation curves are shown in Figure 2.

Table 2 Assumed Transient

Transient	Temperature Change Rate ($W/(m^2 \cdot K)$)
Transient 1	[Data]
Transient 2	[Data]

Figure 2 [Figure 2: see original paper] Variation of Temperature

Design fatigue curves used in the analysis are shown below, employing NUREG/CR-6909 Rev. 1 (2017) (adopted in ASME Code after 2009 edition) and RCC-M 2016 trial rule fatigue curves. Specific values are provided in Table 3.

Table 3 Fatigue Curve Used

Alternating Stress (MPa)	Allowable Cycles (NUREG/CR-6909)	Alternating Stress (MPa) (RCC-M Trial Rule)
[Data]	[Data]	[Data]

Fatigue analysis results are presented in Table 4. Due to similar design fatigue curves, cumulative usage factors without coolant environmental factor correction are essentially comparable.

Table 4 Fatigue Analysis Result

Method	Cumulative Usage Factor (without environmental correction)
NUREG/CR-6909 2017	[Data]
RCC-M 2016	[Data]

Section 3 yielded the most critical results, with detailed transient load pair results shown in Table 5.

Table 5 Fatigue Analysis Load Pair Result of Section 3

Based on NUREG/CR-6909 Fatigue Curve: CUFinitial = 0.15211

Transient and Time	Membrane+Bending Range	Elastic-Plastic Correction	KE(SALT)	Allowable Cycles	Usage Factor
1-13.33s	[Data]	[Data]	[Data]	[Data]	[Data]
1-3613.33s	[Data]	[Data]	[Data]	[Data]	[Data]
2-250s	[Data]	[Data]	[Data]	[Data]	[Data]
2-3850s	[Data]	[Data]	[Data]	[Data]	[Data]

Based on RCC-M Trial Rule Fatigue Curve: CUFinitial = 0.15287

[Similar table structure with RCC-M data]

Environmental influence factor calculation formulas differ slightly between NUREG/CR-6909 Rev. 1 (2017) (adopted in ASME Code after 2009 edition) and RCC-M 2016 trial rules.

NUREG/CR-6909 Rev. 1 (2017):

$$Fen = \exp(-\mathcal{E})$$

where $\mathcal{E}$ is calculated based on temperature, strain rate, and dissolved oxygen content.

RCC-M 2016 Trial Rule:

$$Fen = \exp(-\mathcal{E}_{RCCM})$$

The primary task in environmental influence factor calculation is determining strain rate. NUREG/CR-6909 provides two methods: average strain rate method and modified strain rate method. RCC-M trial rules provide simplified and detailed calculation methods, where the detailed method is essentially consistent with the modified strain rate method. Fen calculation and fatigue correction for Section 3 were performed using NUREG/CR-6909 modified strain rate method and RCC-M trial rule detailed calculation method, with results shown in Table 6.

Table 6 Fen Calculation Result and CUF Correction

Method	Comprehensive Environmental Influence Factor	Initial Usage Factor	Usage Factor Correction	Cumulative Usage Factor Correction
NUREG/CR-6909, Fen,global = 4.433	[Data]	[Data]	[Data]	[Data]
RCC-M Trial Rule, Fen,global = 1.012	[Data]	[Data]	[Data]	[Data]

The comparison demonstrates that for this structure, material, and transient combination, the independent factor method yields a comprehensive environmental influence factor of 4.433, with environmental factor correction increasing cumulative usage factor by more than 4 times, significantly impacting fatigue design life. While individual transient load pair environmental influence factors differ minimally between methods, the integrated value method assumes design fatigue curves already incorporate moderate environmental influence factors, requiring no correction when calculated environmental influence factors are below integrated values. In this example, Transient 1 (thermal shock) has Fen = 4.672 with an integrated value of 5; Transient 2 (non-thermal shock) has Fen = 7.066 with an integrated value of 3, yielding a comprehensive environmental influence factor of 1.012. Environmental influence factors no longer significantly affect cumulative usage factors and cease to be a dominant factor affecting fatigue design life.

5 Conclusions

This paper conducted a comparative study of two correction methods for considering coolant environment effects on fatigue—independent factor method and integrated value method—and performed analyses on a typical austenitic stainless steel main pipe tee nozzle using both approaches.

The analysis results demonstrate that the independent factor method shows coolant environmental factors significantly influencing usage factors, becoming a dominant factor affecting fatigue design life. The integrated value method assumes design fatigue curves already incorporate moderate environmental influence factors, yielding significantly optimized comprehensive environmental influence factors that have minimal impact on cumulative usage factors, no longer representing a dominant factor affecting fatigue life.

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Note: Figure translations are in progress. See original paper for figures.