# A Study on the Application of Dissolved Oxygen for Environmental Fatigue Evaluation

Yang Ho Cheon [*], Byeong Ho Park, Seong Chan Park and Eun Kee Kim
*KEPCO Engineering & Construction Company, Inc.,*
*989-113, Daedeokdaero Yuseong-gu, Daejeon, 305-353, KOREA*
[*]*Corresponding author: yhcheon@kepco-enc.com*

## 1. Introduction

Most of the operating nuclear power plants have a design life of 40 years. As material properties are continuously improved, a number of studies and research have been done on plant life extension from 40 to 60 years, domestically and internationally. To increase the design life of a specific plant from 40 to 60 years, it is necessary to evaluate its impact on the pressure boundary integrity, which may cause aging the materials, such as corrosion, fatigue and irradiation. Fatigue has been considered as the important failure mechanism to assess integrity and design life of nuclear power plant in the design for class 1 components and water chemistry control plays an important role in the degradation of materials, fuels integrity, and radiation control [1, 2].

Regulatory Guide 1.207 [3] requires that environmental fatigue analysis of pressure boundary components should be performed in addition to the fatigue evaluation based on ASME Code Section III. The key parameters that influence fatigue life in Pressurized Water Reactor (PWR) environments are temperature; dissolved oxygen (DO) level in Reactor Coolant (RC); strain rate; strain (or stress) amplitude; and, for carbon and low-alloy steel, sulfur content in the steel. One of the major influences is DO. The condition of materials is deteriorated because of DO in the RC. The strict management of DO in the RC is necessary. Especially, as to environmental fatigue analysis about the carbon and low-alloy steels, it is considered that the environmental effect of the DO is most serious.

This paper discusses a methodological approach as well as the selection and application guidelines of DO concentration limits in the RC to be applied for environmental fatigue evaluation.

## 2. Results and Discussion

### *2.1 Methodology to Evaluate Environmental Effects*

Regulatory Guide 1.207 provides guidance for use in determining the acceptable fatigue life of ASME Class 1 components, with consideration of the light-water reactor environment. The methods to evaluate environmental fatigue life of structures and components that are exposed to the RC are indicated. The environmental fatigue life correction factor ($F_{en}$) shall be used to evaluate the effect of the environmental fatigue. The $F_{en}$ is the factor of the reduction effect of fatigue life in high temperature water and is defined as the value obtained by dividing the fatigue life in air with the particular strain amplitude by the fatigue life in the reactor coolant per equation (1).

$$F_{en} = \frac{N_A}{N_W} = \frac{\text{Fatigue life in air at room temperature (cycles)}}{\text{Fatigue life in water (cycles)}} \quad (1)$$

The detailed evaluation methods for each material are shown in Table I. The cumulative fatigue usage factor with the environmental effects, $CUF_{en}$ can be expressed by using $F_{en}$ in the following equation (2).

$$CUF_{en} = CUF \times F_{en}(1) = CUF(1) \times F_{en}(1) + \ .... \ + CUF(n) \times F_{en}(n) \quad (2)$$

where, $F_{en}$ (n) is the nominal environmental fatigue correction factor for the $n^{th}$ stress cycle. Practical procedure to evaluate $CUF_{en}$ is in accordance with Reference [4].

### *2.2 Effect of DO in the RC*

#### *2.2.1 Carbon and Low-alloy Steels*

The dependence of fatigue life of carbon steel on DO content in the RC is shown in Fig. 1. The results indicate a minimum DO level of 0.04 ppm above which environment decreases the fatigue life of the steel. The effect of DO content on fatigue life saturates at 0.5 ppm, i.e., DO levels above 0.5 ppm do not cause further decreases in life. For DO levels between 0.04 and 0.5 ppm, fatigue life appears to decrease logarithmically with DO. In PWR environments, the effect of DO level on the fatigue life of carbon and low-alloy steels is explicitly considered in $F_{en}$ value defined in Equations in Table I.

#### *2.2.2 Austenitic Stainless Steels and Ni-Cr-Fe Alloys*

The dependence of fatigue life of austenitic stainless steels and Ni-Cr-Fe alloys on DO content in the RC is described in the Reference [4]. In contrast to the behavior of carbon and low-alloy steels, the fatigue life of austenitic stainless steels and Ni-Cr-Fe alloys decreases significantly in low-DO (i.e., <0.05 ppm DO) water. Also, environmental effects may be lower in high-DO than in low-DO water. In PWR environments, the effect of DO level on the fatigue life of austenitic stainless steels and Ni-Cr-Fe alloys is explicitly considered in $F_{en}$ value defined in Equations in Table I.

The effect of DO for carbon and low-alloy steels associated with a stress cycle is higher than austenitic stainless steels and Ni-Cr-Fe alloys in the transients.

### *2.3 Method to Calculate $F_{en}$ for the Transients*

Method to calculate $F_{en}$ for the transients is used as the following equation [5].

$$F_{en} = \frac{CUF(1) \times F_{en}(1) + \ \ldots. \ + CUF(n) \times F_{en}(n)}{CUF(1) + \ \ldots. \ + CUF(n)} \quad (3)$$

The DO content is obtained from each transient constituting the stress cycle alike as the following equation (4).

$$DO = \frac{DO(1) \times Time(1) + DO(2) \times Time(2) + DO(3) \times Time(3) + \ \ldots.}{Time(1) + Time(2) + Time(3) + \ \ldots.} \quad (4)$$

The DO concentration in the RC in contact with the material during the time segment being evaluated in accordance with thermal hydraulic (T/H) transients is used. Fig. 2 shows DO behavior related to temperature per operating mode. T/H transients have a minimal impact on DO behavior in the RC. The T/H transients inject only relatively small volumes of water into the RC at temperatures greater than 121 ℃, so that the dissolved hydrogen residual in the RC is fully capable of rapidly neutralizing the oxygen and reducing the oxygen concentration to acceptable levels.

### *2.4 DO Application Guidelines for Environmental Fatigue Evaluation*

For evaluation of fatigue design criteria for class 1 components, reactor coolant T/H design transient conditions (design transients) are classified to take into account the criteria and conditions for normal, heatup, cooldown and test operations. DO concentrations with regard to the normal operation, test conditions, and T/H transient conditions (heatup and cooldown) for environmental fatigue evaluation are provided for materials in Table II.

In particular, DO values applied to carbon and low-alloy steels for environmental fatigue evaluation are shown in Table II with detailed classification according to the transient conditions. DO values applied to austenitic stainless steels and Ni-Cr-Fe alloys components considering environmental fatigue evaluation are in compliance with regulatory guidelines and technical standards at all conditions of T/H transients.

## REFERENCES

[1] ASME Code Case N-792, “Fatigue Evaluations Including Environmental Effects, Section III, Division 1,” September 20, 2010.

[2] Electric Power Research Institute, “PWR Primary Water Chemistry Guidelines,” EPRI Report 1014986-Rev.06, December 2007.

[3] US NRC, “Guidelines for Evaluating Fatigue Analyses Incorporating Life Reduction of Material Components Due to the Effects of the Light Water Reactor Environment for New Reactors,” Regulatory Guide 1.207, 2007.

[4] US NRC, “Effects of LWR Coolant Environments on the Fatigue Life of Reactor Materials,” NUREG/CR-6909, 2007.

[5] Electric Power Research Institute, “Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a Licensing Renewal Application (MRP-47 Revision 1),” EPRI Report 1012017-Rev.01, September 2005.

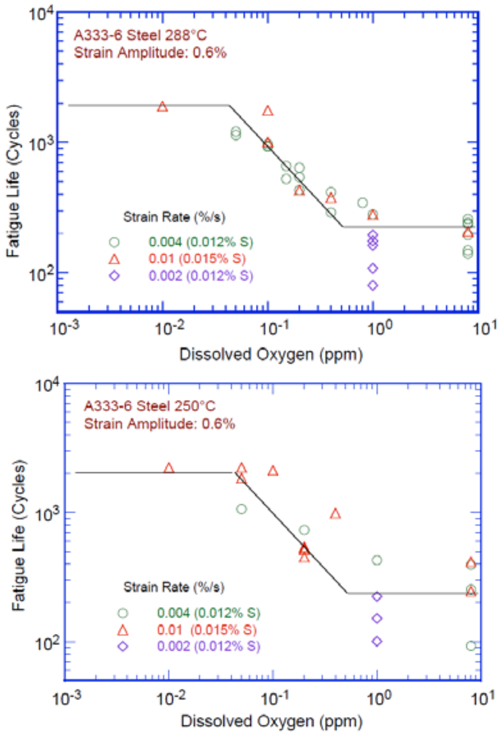


Fig. 1. Dependence on DO of fatigue life of carbon steel in high-purity RC [4].

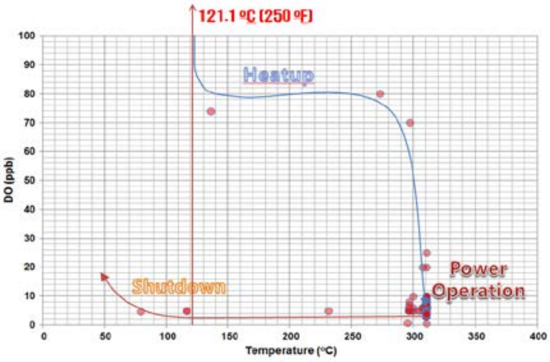
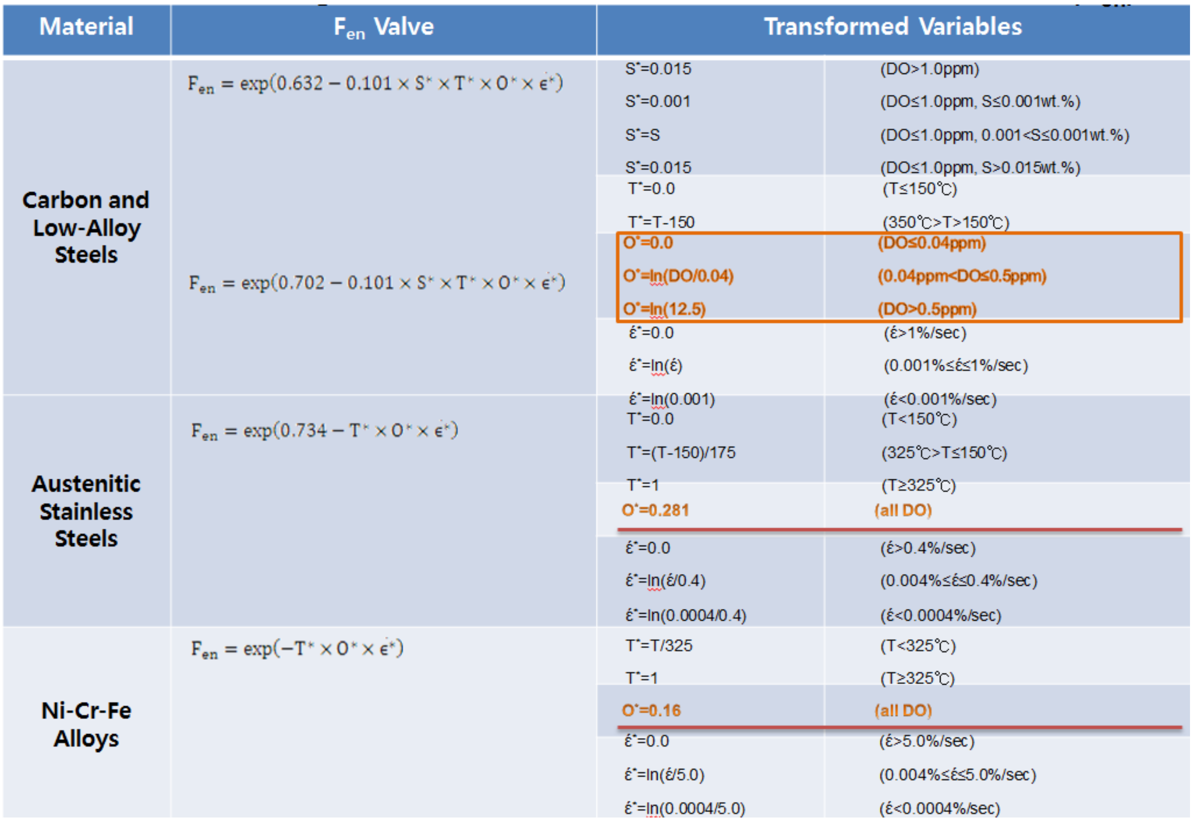


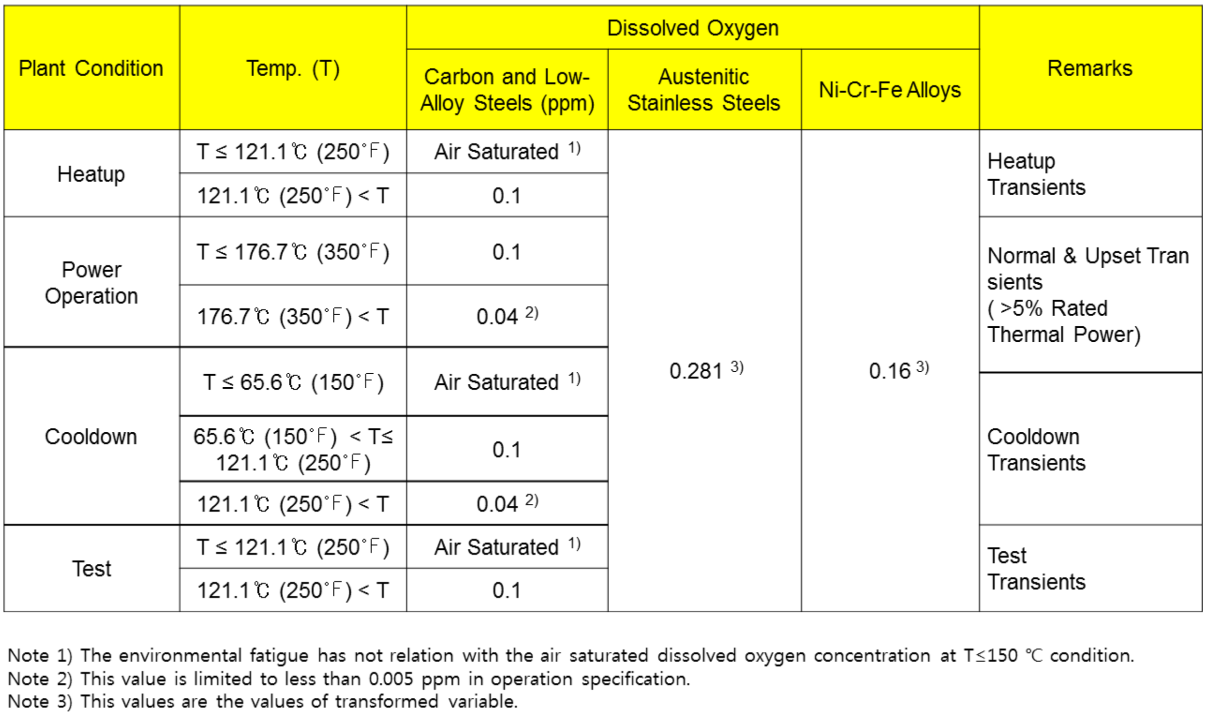
Fig. 2. DO behavior related to temperature per operating mode.

Table I. Environmental fatigue evaluation – Environmental correction factor ($F_{en}$) [4]



| Material | $F_{en}$ Valve | Transformed Variables | |
|---|---|---|---|
| **Carbon and Low-Alloy Steels** | $F_{en} = \exp(0.632 - 0.101 \times S^* \times T^* \times O^* \times \dot{\epsilon}^*)$<br>$F_{en} = \exp(0.702 - 0.101 \times S^* \times T^* \times O^* \times \dot{\epsilon}^*)$ | $S^*=0.015$ | (DO>1.0ppm) |
| | | $S^*=0.001$ | (DO≤1.0ppm, S≤0.001wt.%) |
| | | $S^*=S$ | (DO≤1.0ppm, 0.001<S≤0.001wt.%) |
| | | $S^*=0.015$ | (DO≤1.0ppm, S>0.015wt.%) |
| | | $T^*=0.0$ | (T≤150℃) |
| | | $T^*=T-150$ | (350℃>T>150℃) |
| | | $O^*=0.0$ | (DO≤0.04ppm) |
| | | $O^*=\ln(DO/0.04)$ | (0.04ppm<DO≤0.5ppm) |
| | | $O^*=\ln(12.5)$ | (DO>0.5ppm) |
| | | $\dot{\varepsilon}^*=0.0$ | ($\dot{\varepsilon}$>1%/sec) |
| | | $\dot{\varepsilon}^*=\ln(\dot{\varepsilon})$ | (0.001%≤$\dot{\varepsilon}$≤1%/sec) |
| | | $\dot{\varepsilon}^*=\ln(0.001)$ | ($\dot{\varepsilon}$<0.001%/sec) |
| **Austenitic Stainless Steels** | $F_{en} = \exp(0.734 - T^* \times O^* \times \dot{\epsilon}^*)$ | $T^*=0.0$ | (T<150℃) |
| | | $T^*=(T-150)/175$ | (325℃>T≤150℃) |
| | | $T^*=1$ | (T≥325℃) |
| | | $O^*=0.281$ | (all DO) |
| | | $\dot{\varepsilon}^*=0.0$ | ($\dot{\varepsilon}$>0.4%/sec) |
| | | $\dot{\varepsilon}^*=\ln(\dot{\varepsilon}/0.4)$ | (0.004%≤$\dot{\varepsilon}$≤0.4%/sec) |
| | | $\dot{\varepsilon}^*=\ln(0.0004/0.4)$ | ($\dot{\varepsilon}$<0.0004%/sec) |
| **Ni-Cr-Fe Alloys** | $F_{en} = \exp(-T^* \times O^* \times \dot{\epsilon}^*)$ | $T^*=T/325$ | (T<325℃) |
| | | $T^*=1$ | (T≥325℃) |
| | | $O^*=0.16$ | (all DO) |
| | | $\dot{\varepsilon}^*=0.0$ | ($\dot{\varepsilon}$>5.0%/sec) |
| | | $\dot{\varepsilon}^*=\ln(\dot{\varepsilon}/5.0)$ | (0.004%≤$\dot{\varepsilon}$≤5.0%/sec) |
| | | $\dot{\varepsilon}^*=\ln(0.0004/5.0)$ | ($\dot{\varepsilon}$<0.0004%/sec) |

Table II. Dissolved oxygen concentration in the RC to be applied for environmental fatigue evaluation



| Plant Condition | Temp. (T) | Dissolved Oxygen | | | Remarks |
|---|---|---|---|---|---|
| | | Carbon and Low-Alloy Steels (ppm) | Austenitic Stainless Steels | Ni-Cr-Fe Alloys | |
| Heatup | T ≤ 121.1℃ (250°F) | Air Saturated $^{1)}$ | 0.281 $^{3)}$ | 0.16 $^{3)}$ | Heatup Transients |
| | 121.1℃ (250°F) < T | 0.1 | | | |
| Power Operation | T ≤ 176.7℃ (350°F) | 0.1 | | | Normal & Upset Transients ( >5% Rated Thermal Power) |
| | 176.7℃ (350°F) < T | 0.04 $^{2)}$ | | | |
| Cooldown | T ≤ 65.6℃ (150°F) | Air Saturated $^{1)}$ | | | Cooldown Transients |
| | 65.6℃ (150°F) < T≤ 121.1℃ (250°F) | 0.1 | | | |
| | 121.1℃ (250°F) < T | 0.04 $^{2)}$ | | | |
| Test | T ≤ 121.1℃ (250°F) | Air Saturated $^{1)}$ | | | Test Transients |
| | 121.1℃ (250°F) < T | 0.1 | | | |

Note 1) The environmental fatigue has not relation with the air saturated dissolved oxygen concentration at T≤150 ℃ condition.
Note 2) This value is limited to less than 0.005 ppm in operation specification.
Note 3) This values are the values of transformed variable.