PROBABILISTIC ASSESSMENT OF NUCLEAR PIPING INTEGRITY BY USING RECENT ENVIRONMENTAL FATIGUE EQUATIONS

Md Nasimul Goni[1], Seung Hyun Kim[1], Yoon-Suk Chang[1,*]

*[1, *] Department of Nuclear Engineering, Kyung Hee University*
1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea
[*]Corresponding author: yschang@khu.ac.kr

One of the main concerns of the nuclear industry is to safely operate power plants beyond their original design lives. In this context, understanding of aging mechanisms and accurate integrity assessment by taking into account relevant uncertainties become important. The objective of this research is to examine effects of environmentally assisted fatigue on nuclear piping integrity. Firstly, a part of probabilistic assessment code of PINTIN was modified based on recent studies by U.S.NRC and JSME. Subsequently, sensitivity analyses for typical nuclear piping were carried out in use of different governing equations. Finally, resulting probabilities of crack initiation, small leak, big leak and loss of coolant accident were compared, and key findings were discussed.

I. INTRODUCTION

Most of operating nuclear power plants (NPPs) were designed with original permission period of 40 years but extension of their lives has been considered world widely. To achieve this goal, structural integrity against aging mechanisms such as fatigue, thermal aging, primary water stress corrosion cracking and boric acid corrosion etc. should be assured. Among them, the fatigue has been known as important aging mechanisms defining component lives and, particularly, environmental effects were controversy since 1990's. On the other hand, several probabilistic assessment codes have been developed for determining failure probabilities of structural components. For example, PINTIN (Piping INTegrity INner flaws) (Ref. 1) was made due to limitations of other codes. It can be executed for circumferential or axial welds and base metal crack failure probabilities of austenitic stainless steel and carbon or low alloy steel materials, which are commonly used for PWR (Pressurized Water Reactor). To perform the probabilistic assessment of nuclear piping integrity, equations and parameters described in NUREG/CR-6909Rev.1 (Ref. 2), JSME S NF1-2009 (Ref. 3), ASME Code Case N-792-1 (Ref. 4) are employed for the revised PINTIN. At this moment, different approaches for incorporating the effect of coolant water environment exist while the general trend towards to a more uniform approach worldwide. The most common approach is the incorporation of an environmental fatigue correction factor (F_{en}) in the fatigue evaluation based on the *CUF* (Cumulative Usage Factor). The F_{en} formulas and the S-N fatigue curves differ but the general Eq. (1) are:

$$F_{en} = \frac{N_{air}}{N_{water}}, CUF = U_{partial} \times F_{en\ partial} \tag{1}$$

The objective of this research is to examine effects of environmentally assisted fatigue on nuclear piping integrity. Firstly, a part of probabilistic assessment code of PINTIN was modified based on recent studies by U.S.NRC and JSME. Subsequently, sensitivity analyses for typical nuclear piping were carried in use of different fatigue evaluation equations. Finally, resulting probabilities of initiation, small leak, big leak and loss of coolant accident (LOCA) were compared.

II. EVALUATION METHODS

PINTIN includes various probabilistic assessment modules for the evaluation of piping integrity. In this study, two of them such as crack initiation and growth were investigated in relation to the environmental fatigue.

II.A. Previous Fatigue Crack Initiation and Growth Modules

Crack initiation can be evaluated based on revised ANL2006 (Fatigue crack initiation model, termed as ANL2006 in the code) model for LAS (Low Alloy Steel) and SS (Austenitic Stainless Steel) from ANL2000 (Fatigue crack initiation model, termed as ANL2000 in the code) model. Here, they got ANL2006 model from NUREG/CR-6909 and ANL2000 model from NUREG/CR-6674 (Ref. 5), "Fatigue analysis of components for 60-year plant life" for LAS and NUREG/CR-6934 (Ref. 6), "Fatigue crack flaw tolerance in nuclear power plant piping; a basis for improvements to ASME Code Section XI Appendix L" for SS. Relevant equations of ANL2006 fatigue life model for low-alloy steels (A533-Grade B, A302-Grade B, A508-Class 2, and A508-Class 3) are as follows:

$$\ln[N_i(x)] = 5.747 - 1.808\ln(\varepsilon_a - 0.151) + 0.101S^*T^*\dot{\varepsilon}^* \tag{2}$$

where S*, T*, O*, and $\dot{\varepsilon}$ * are the sulfur content, temperature, DO (Dissolved Oxygen) level and strain rate, respectively, defined as

$$
\begin{array}{ll}
S^* = 0.015 & (DO \le 1.0 \text{ ppm}) \\
S^* = 0.001 & (DO \le 1.0 \text{ ppm and } S \le 0.001\text{wt.\%}) \\
S^* = S & (DO \le 1.0 \text{ ppm and } 0.001 < S \le 0.015\text{wt.\%}) \\
S^* = 0.015 & (DO \le 1.0 \text{ ppm and } S > 0.015\text{wt.\%}) \\
T^* = 0 & (T \le 150℃) \\
T^* = T - 150 & (150 < T \le 350℃) \\
O^* = 0 & (DO \le 0.04 \text{ ppm}) \\
O^* = \ln(DO/0.04) & (0.04\text{ppm} < DO \le 0.5 \text{ ppm}) \\
O^* = \ln(12.5) & (DO > 0.5 \text{ ppm}) \\
\dot{\varepsilon}^* = 0 & (\dot{\varepsilon} > 1\%/s) \\
\dot{\varepsilon}^* = \ln(\dot{\varepsilon}) & (0.001 \le \dot{\varepsilon} \le 1\%/s) \\
\dot{\varepsilon}^* = \ln(0.001) & (\dot{\varepsilon} < 0.001\%/s)
\end{array}
$$

Moreover, relevant equations for austenitic stainless steels (Types 304, 304L, 316, 316L, 316NG, CF-3, CF-8, and CF-8M) are as follow:

$$\ln[N_i(x)] = 6.157 - 1.920\ln(\varepsilon_a - 0.112) + T^*O^*\dot{\varepsilon}^* \tag{3}$$

where T*, O* and $\dot{\varepsilon}$ * are defined as

$$
\begin{array}{ll}
T^* = 0 & (T \le 150℃) \\
T^* = T - 150 & (150 < T \le 350℃) \\
\dot{\varepsilon}^* = 0 & (\dot{\varepsilon} > 0.4\%/s) \\
\dot{\varepsilon}^* = \ln(\dot{\varepsilon}) & (0.0004 \le \dot{\varepsilon} \le 0.4\%/s) \\
\dot{\varepsilon}^* = \ln(0.0004/0.4) & (\dot{\varepsilon} < 0.0004\%/s) \\
O^* = 0.281 & (\text{all } DO \text{ levels})
\end{array}
$$

The PINTIN code was also constructed to analyze fatigue crack growth of primary piping in PWRs. This module encompass influence of temperature, environment, and mean load affect. Within a scatter band of about one order of magnitude on crack growth rate, it was found that the data could be represented by the following relation.

$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{1/2}}\right]^4 \tag{4}$$

The scatter in the data is represented by a lognormal value of C with a median of 9.14×10^{-12} and standard deviation of 2.0×10^{-11}. This relation is applicable to weld metal, base metal, and heat-affected zone as well as suitable air and water. A threshold value for fatigue crack growth is also considered, which means no crack growth if $\Delta\overline{K}_{\iota}$ is less than ΔK_{th}, where ΔK_{th} is given by

$$\Delta K_{th} = \left\{\begin{array}{cc} 4.6(1-R)^{\frac{1}{2}} & R < R^* \\ 4.6(1-R^*) & R > R^* \\ \multicolumn{2}{c}{R^* = 0.9} \end{array}\right\} \tag{5}$$

II.B. Revised Fatigue Crack Initiation Module

Several equations were used for constructing crack initiation module of the revised PINITN. For instance, *S-N* curves developed by ANL were incorporated as best-fit data as well as equations in NUREG/CR-6909 Rev.1 (Ref. 2) were adopted to estimate fatigue lives. The values of F_{en} can be obtained from the aforementioned Eq. (1), which is the ratio between N_{air} is defined in air and N_{water} is defined in water. In particular, the fatigue life, N, of low alloy steels can be calculated by Eq. (6).

$$\ln[N_i(x)] = 6.449 - 1.808\ln(\varepsilon_a - 0.151) \tag{6}$$

Subsequently, the environmental fatigue correction factor of low alloy steel is determined by substituting Eq. (6) for Eq. (2). In addition, there are further changes relating to environmental fatigue correction factor in the NUREG/CR-6909 Rev.1; transformed sulfur content, temperature, *DO* level and strain rate.

$$F_{en} = \exp(0.702 - 0.101S^*T^*O^*\dot{\varepsilon}^*) \tag{7}$$

By taking the environmental fatigue correction factors in Eq. (7), we can get revised fatigue lives of components made of carbon and low alloy steel in LWR coolant at operating temperature. Similarly, the fatigue live can be determined by other equations for different materials as well as proposed by several institutes. The revised environmental fatigue life estimation equations are summarized as bellows for Carbon and Low Alloy Steel (C/LAS), Stainless Steel (SS) and Ni-Cr-Fe Alloy with the guidelines of United States Nuclear Regulatory Commission (U.S.NRC) (NUREG/CR-6909 Rev.1), The Japan Society of Mechanical Engineers (JSME) (JSME S NF1-2009) (Ref. 3) and code case (N-792-1) (Ref. 4) of The American Society of Mechanical Engineers (ASME);

U.S.NRC (NUREG/CR-6909 Rev.1)
$\ln[N] = 6.449 - 1.808\ln(\varepsilon_a - 0.151) - (0.003 - 0.31\dot{\varepsilon}^*)\,S^*T^*O^*$ [C/LAS]
$\ln[N] = 6.891 - 1.920\ln(\varepsilon_a - 0.112) + T^*O^*\dot{\varepsilon}^*$ [SS]
$\ln[N] = 6.891 - 1.920\ln(\varepsilon_a - 0.112) + T^*O^*\dot{\varepsilon}^*$ [Ni-Cr-Fe Alloy]

JSME (JSME NF1-2009)
$\ln[N] = 6.449 - 1.808\ln(\varepsilon_a - 0.151) - 0.00822(0.772 - \dot{\varepsilon}^*)\,S^*T^*O^*$ [C/LAS]
$\ln[N] = 6.891 - 1.920\ln(\varepsilon_a - 0.112) - (3.910 - \dot{\varepsilon}^*)T^*$ [SS]
$\ln[N] = 6.891 - 1.920\ln(\varepsilon_a - 0.112) - (2.94 - \dot{\varepsilon}^*)T^*$ [Ni-Cr-Fe Alloy]

ASME (Code Case N-792-1)
$\ln[N] = 6.328 - 1.808\ln(\varepsilon_a - 0.151) - 0.101\dot{\varepsilon}^*\,S^*T^*O^*$ [C/LAS]
$\ln[N] = 6.157 - 1.920\ln(\varepsilon_a - 0.112) + O^*\dot{\varepsilon}^*T^*$ [SS]
$\ln[N] = 6.157 - 1.920\ln(\varepsilon_a - 0.112) + O^*\dot{\varepsilon}^*T^*$ [Ni-Cr-Fe Alloy]

II.C. Revised Fatigue Crack Growth Module

In general, the water environment reduces the fatigue life due to increased fatigue growth rate. As the fatigue crack growth module of the revised PINTIN, ASME code case N-809 model was employed for better investigation of growth rate (Ref. 7). The fatigue crack growth rate, *da/dN*, of the SS material is characterized in terms of the range of the applied stress intensity factor, ΔK. This characterization is generally in the form of Eq. (8),

$$\frac{da}{dN} = C_0 \Delta K^n \tag{8}$$

where n and C_0 are parameters dependent on the material and environmental conditions. n of SS is 2.25 and represents the slope of log *(da/dN)* versus log (ΔK) curve. C_0 is the scaling parameter which accounts for the effect of a number of variables on crack growth rate. The fatigue crack growth rate of nuclear materials is affected by R ratio (K_{min}/K_{max}), loading rate and environmental conditions. These variables are accounted for determining C_0 in Eq. (9);

$$C_0 = C S_T S_R S_{ENV} \tag{9}$$

where C is the material crack growth rate constant in units of mm/cycle, and S_T, S_R and S_{ENV} are the parameters defining effects of temperature, R ratio and environment on the crack growth rate, respectively as bellows;

$C = 9.10 \times 10^{-6}$ for Type 304/316
$C = 1.39 \times 10^{-5}$ for Type 304L/316L

$$S_T = e^{-2516/T_K} \qquad (150°C < T < 343°C)$$
$$S_T = 3.39 \times 10^5 e^{\left(-\frac{2516}{T_K} - 0.0301\, T_K\right)} \qquad (20°C < T < 150°C)$$

$$S_R = 1 + e^{8.02(R-0.748)} \qquad (0 \le R < 1.0, \text{type 304 and 316})$$
$$S_R = 1.0 \qquad (0 \le R \le 0.7, \text{type 304L and 316L})$$
$$S_R = 1 + 1.5(R - 0.7) \qquad (0.7 < R < 1.0, \text{type 304L and 316L})$$
$$S_R = 1.0 \qquad (\text{R} \le 0.0, \text{all material})$$

$$S_{ENV} = 0.3 T_R$$

where ΔK_{th} defined as 1.10 MPa-m$^{0.5}$ is the threshold of ΔK such that $C = 0$ for $\Delta K < \Delta K_{th}$. T_R is the load rise time in seconds.

III. ANALYSIS OF PIPING INTEGRITY

III.A. Analysis Conditions

Evaluation of fatigue crack initiation and growth was carried out by using the revised PINTIN to predict small leak, big leak and LOCA probabilities. According to IWB-3641-1 and IWB-3641-2 of the ASME B&PV code Section XI, leakage (through-wall cracks) occurs when the depth of the crack is greater or equal to 75% of wall thickness and break (or LOCA) occurs when the applied stress exceeds the material's flow strength based on net-section failure criterion. The small and big leaks were classified when the leak rate is equal or greater than 30 and 500 gpm (gallons per minute), respectively.

Hot leg of reactor coolant system in a typical nuclear power plant was selected for this benchmarking analyses. Its diameter and thickness were 878.84 mm and 71.12 mm under operating coolant temperature of 319.39°C (Ref. 8). The input conditions for calculation of crack initiation and growth probabilities as a part of pipe structural integrity assessment were summarized in Table 1. Fig. 1 shows the user friendly input screen of the revised PINTIN. Sensitivity analyses for this typical nuclear piping were carried in the use of different fatigue evaluation equations, and the resulting probabilities of small leak, big leak and LOCA were compared for each pipe material (C/LAS, SS, Alloy steels).

Table I. Input conditions of pipe structural integrity assessment (Ref. 8)

Operating conditions	
Deadweight	14.34 MPa
Deadweight + Thermal expansion	59.16 MPa
Operation pressure	15.51 MPa
Plant life time	40 years
Fatigue crack growth properties for 304 SS	
Fatigue constant, *C*	9.14×10^{-12}
Fatigue exponent, *n*	4.0
Water chemistry and conditions	
Oxygen at plant start-up	0.01 ppm
Sulfur content	0.015 wt.%
Duration of plant heat-up	5 hours

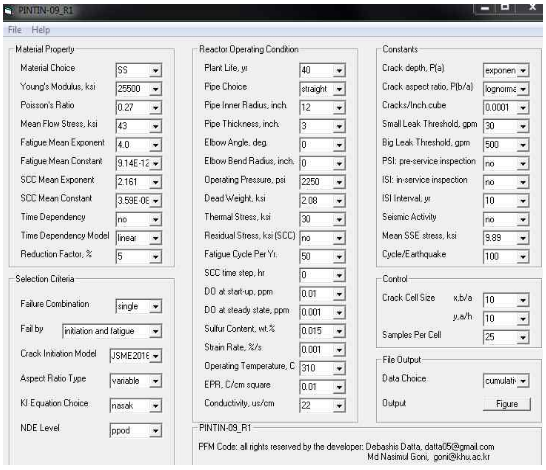

Fig. 1. Input screen of the revised PINTIN

III.B. Results of Probability

While both crack initiation and growth probabilities were evaluated by the aforementioned models incorporated in the revised PINTIN, mainly, the former results were indicated in this manuscript. In case of C/LAS material, the crack initiation probability was estimated high by the revised JSME model as shown Fig. 2. The difference comparing to the original model was 10% approximately, however, the effect of the revised model was not significant. Fig. 3 compares crack initiation probabilities of SS material according to the revised and original models. The probability estimated by JSME model was higher than those of the U.S.NRC and ASME models. Also, the magnitude of the probability by JSME model was 10% higher, approximately, than that of the original PINTIN model (ANL 2006). Fig. 4 compares crack initiation probabilities of Ni-Cr-Fe Alloy material, which shows the original PINTIN model provides higher crack initiation probability.

Fig. 5 compares crack growth probabilities of SS material with regard to small leak, big leak and LOCA under 40 years of plant operating time. As shown in the figure, significantly different results were obtained according to different crack growth equations dealing with the environmental effect. For example, in relation to the LOCA probability, the values by the original PINTIN increased from $7.14\text{x}10^{-15}$ to $3.55\text{x}10^{-13}$ whereas those by the revised PINTIN increased from $2.72\text{x}10^{-11}$ to $8.28\text{x}10^{-10}$ because the environmental fatigue crack growth rate was higher than that of the original PINTIN.

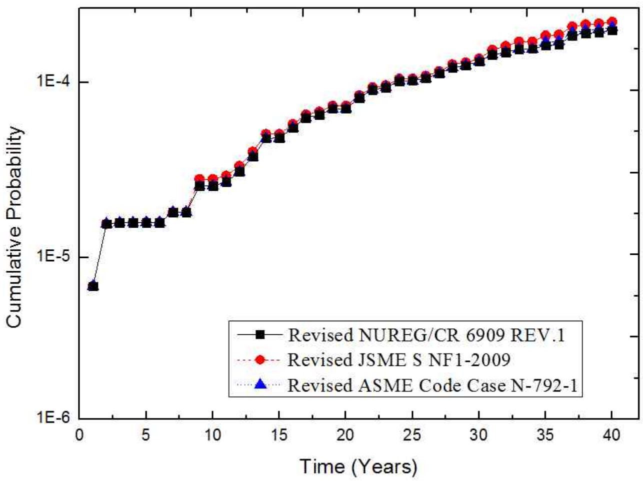

Fig. 2. Crack initiation probabilities (C/LAS)

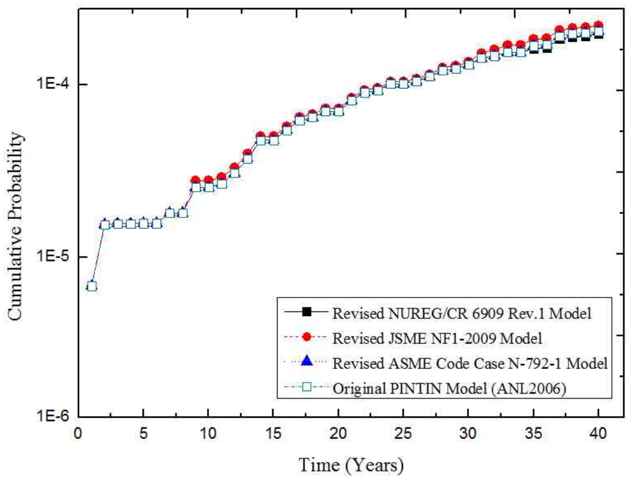

Fig. 3. Crack initiation probabilities (SS)

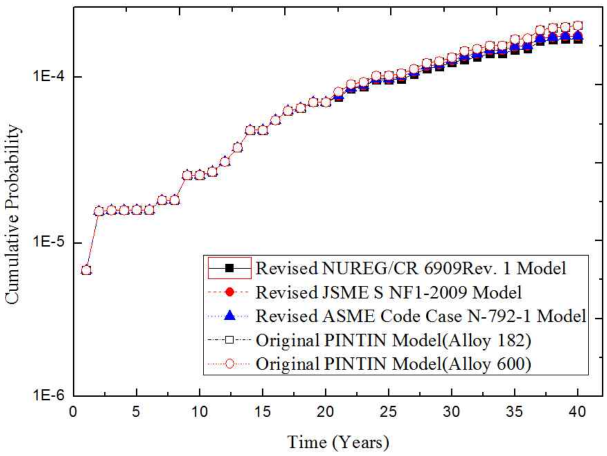

Fig. 4. Crack initiation probabilities (Ni-Cr-Fe Alloy)

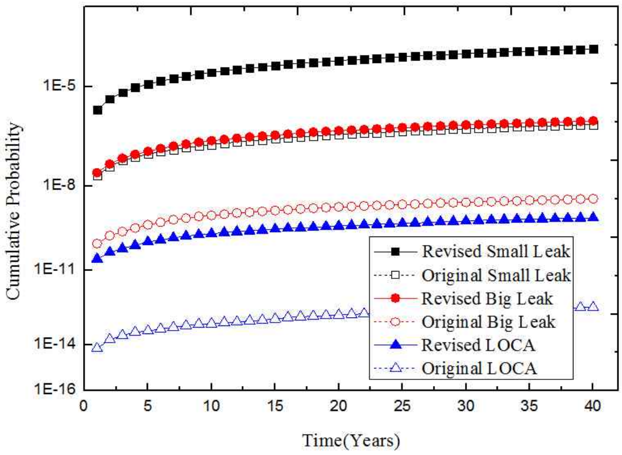

Fig. 5. Leakage and LOCA probabilities (SS)

IV. CONCLUSIONS

In this study, environmentally assisted fatigue crack initiation and growth evaluation equations were examined and applied to nuclear piping integrity assessment of a typical nuclear power plant condition and the following conclusions were derived.

(1) In the revised PINTIN, for the better performance of probabilistic assessment, the fatigue crack initiation and growth modules were incorporated based on recent U.S.NRC, JSME and ASME guidelines.
(2) In terms of crack initiation probability, differences according to three materials and revised equations of U.S.NRC, JSME and ASME were not significant within 10% approximately.
(3) With regard to crack growth probability of SS material, the revised PINTIN provided higher value than the original one. The difference of leakage and LOCA probabilities were 10^3 times approximately.

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