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PFM APPLICATION FOR THE PWSCC INTEGRITY OF Ni-BASE ALLOY WELDS – DEVELOPMENT AND APPLICATION OF PINEP-PWSCC

JONG-DAE HONG[1], CHANGHEUI JANG[1,2*], and TAE SOON KIM[3]
[1]Dept. of Nuclear and Quantum Engineering, KAIST, Daejeon, Republic of Korea
[2]Dept. of Nuclear Engineering, Khalifa University, Abu Dhabi, U.A.E.
[3]Central Research Institute, KHNP, Daejeon, Republic of Korea
[*]Corresponding author. E-mail : chjang@kaist.ac.kr

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Often, probabilistic fracture mechanics (PFM) approaches have been adopted to quantify the failure probabilities of Ni-base alloy components, especially due to primary water stress corrosion cracking (PWSCC), in a primary piping system of pressurized water reactors. In this paper, the key features of an advanced PFM code, PINEP-PWSCC (Probabilistic INtegrity Evaluation for nuclear Piping-PWSCC) for such purpose, are described. In developing the code, we adopted most recent research results and advanced models in calculation modules such as PWSCC crack initiation and growth models, a performance-based probability of detection (POD) model for Ni-base alloy welds, and so on. To verify the code, the failure probabilities for various Alloy 182 welds locations were evaluated and compared with field experience and other PFM codes. Finally, the effects of pre-existing crack, weld repair, and POD models on failure probability were evaluated to demonstrate the applicability of PINEP-PWSCC.

KEYWORDS : PFM (Probabilistic Fracture Mechanics), PWSCC (Primary Water Stress Corrosion Cracking), Ni-base alloys, Alloy 182, PINEP-PWSCC

1. INTRODUCTION

Over the years, incidents of cracking, known as primary water stress corrosion cracking (PWSCC), have been reported for many components made of Alloy 600 and Alloy 82/182 dissimilar metal welds (DMW) in pressurized water reactors (PWR), such as pressurizer heater sleeves, reactor pressure vessel head penetrations, and bottom-mounted instrumentation nozzles. In particular, incidents of PWSCC in Ni-base alloy butt welds raised a serious concern for structural integrity of primary piping systems in operating PWRs, especially when high residual stresses are suspected. Naturally, it has been one of the key areas of active research in many countries [1-10].

Despite a great deal of effort to understand the mechanism of PWSCC, the proposed mechanisms are not sufficient to explain the complex phenomena observed in the field and in test laboratories. In addition, the uncertainties in test results, variation in materials heat, and operating conditions, further complicate the quantitative evaluation of the risk associated with PWSCC. Therefore, the risk evaluation by probabilistic approaches is considered a viable alternative which can provide quantitative risk values for such complex phenomena. The probabilistic approaches using PFM codes have been widely used to evaluate the risk, or failure probability of reactor pressure vessel and piping components at operating nuclear power plants. For many years, researchers have made extensive efforts to accurately evaluate the PWSCC failure probability and developed various PFM codes such as PRO-LOCA [11], xLPR [12] and PASCAL-NP. Also, one of the authors developed PFM codes, PINTIN, for piping integrity analysis, in which PWSCC was considered as one of failure mechanisms for Ni-base alloy components in piping systems [13-15]. However, the majority of such PFM analysis codes were developed for their specific purposes and based on limited information and research results, thus their applicability and accuracy are limited. For example, the main objective of PRO-LOCA and xLPR, whose development was funded by NRC, was to use them in the regulatory licensing and review processes of operating plants. For this reason, somewhat conservative models and assumptions are used in the calculation modules, and the analysis results are more or less conservative. So it is not appropriate to use them in realistic evaluation of the risk of specific components and locations associated with PWSCC for the purpose of quantifying the risk. Meanwhile, other existing PFM codes are somewhat outdated as they did not include the latest test and research results in the relevant models.

To evaluate the integrity of Ni-base alloy welds in a PWR primary piping system, an advanced PFM code, PINEP-PWSCC (Probabilistic INtegrity Evaluation for nuclear Piping-PWSCC), has been developed with the aim of less conservative and more realistic PFM analysis by adopting recent research results and advanced models in calculation modules. Previously, a trial version of the PINEP-PWSCC was developed and introduced by authors with a few example application results [16,17]. For more realistic analysis, improvements were made on the trial version, such as PWSCC crack initiation and growth models, a performance-based probability of detection (POD) model for Ni-base alloy dissimilar metal welds, and so on. In this paper, the details of the PINEP-PWSCC code are described. To verify the code, the failure probabilities for various Alloy 182 butt welds locations were evaluated and compared with field experience and other PFM codes. Finally, the effects of pre-existing crack, weld repair, and POD model on failure probability were evaluated to demonstrate the applicability of PINEP-PWSCC.

2. DEVELOPMENT OF PINEP-PWSCC

The PINEP-PWSCC has been developed using PFM approaches for the realistic evaluation of the failure probabilities of Ni-base alloy components by PWSCC in a primary coolant piping system. Basically, the random number sampling methods are used on some parameters considering scatters and uncertainties. The trial version was developed and applied to evaluate the failure probabilities of Alloy 600 control rod drive mechanism (CRDM) nozzles and various Alloy 182 butt welds locations [16,17]. In the trial version, the POD model for austenitic stainless steel was used and a crack initiation model based on the failure experience of steam generator tubes was adopted as such models for Ni-base alloy butt welds were not available. Therefore, the evaluation results using the trial version of the code may not be appropriate for assessing the risk associated with the PWSCC of Ni-base alloys welds locations in a primary coolant piping system.

To overcome such limitations, PINEP-PWSCC has been continuously modified since its first introduction. As a result, advanced features were included in the current version such as PWSCC crack initiation and growth models, a performance-based POD model for Ni-base alloy dissimilar metal welds, etc. A new PWSCC initiation model was developed by correlating the laboratory test data with field failure data of Alloy 182 butt welds. In the model, several parameters were incorporated, such as the effect of material variability and water chemistry as well as stress and temperature at the locations. In the crack growth module, the effects of dissolved hydrogen and crack orientation were considered. In a non-destructive evaluation (NDE) module, the most recent performance-based POD models for Ni-base alloy DMW were adopted. Also, a programming error in application of a stratified sampling method for handling the PWSCC initiated crack was identified and corrected in the current version. The details of the key PFM analysis modules in PINEP-PWSCC are described below.

2.1 General Characteristics

The overall flow of PINEP-PWSCC code is shown in Fig. 1. PINEP-PWSCC code consists of several modules to calculate or simulate each parameter. First, the size of a pre-existing crack is randomly extracted from initial crack size distribution. The sampled crack size is then subjected to pre-service inspection (PSI), such that, if detected using a POD curve, it is removed from the population of pre-existing cracks entering the service. The initiation of PWSCC cracks is dependent on temperature, stress, material characteristics, and water-chemistry of the component location to be analyzed. In case the applied stress intensify factor (SIF) is larger than the threshold value, pre-existing cracks and PWSCC initiated cracks grow separately at the rates calculated in the crack growth module. In the meantime, such propagating cracks are also subject to in-service inspection (ISI). Again, if detected using a POD curve for the specific non-destructive evaluation (NDE) technique, that crack is repaired and considered being removed from the population of cracks. For the cracks not detected by NDE, failure criteria were applied to determine whether the component location failed or not. All of these processes are iterated for a sufficient number of times to provide statistically meaningful failure probability.

Both pre-existing cracks and PWSCC initiated cracks are assumed to be a semi-elliptical shape at the inner surface of pipes. For simplicity of calculation, it is also assumed that the aspect ratio is maintained during crack

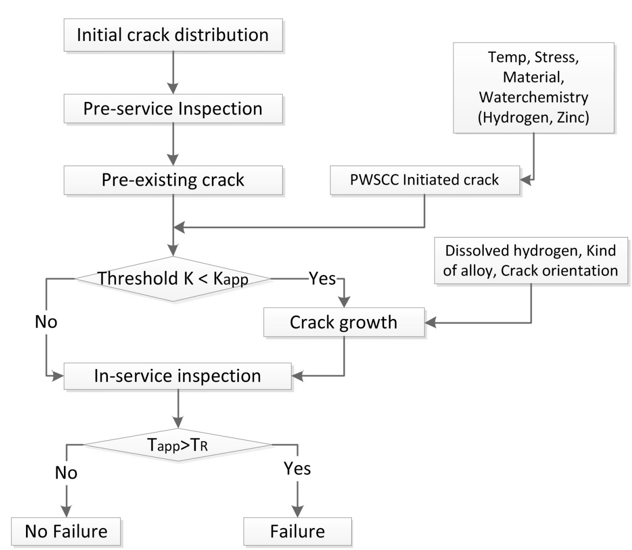

Fig. 1. Flow Chart of PINEP-PWSCC Code

growth. In the analysis, only axially oriented cracks were simulated, considering that the applied stresses on Ni-base alloy welds are predominant hoop-direction. In practice, only one or two flaws were circumferentially oriented among over 100 cracks observed.

2.2 Simulation of Pre-existing Crack

The probability of having at least one pre-existing defect in a weld volume was the same as the value used in PINTIN [13]. Previously, crack density of 0.0001/in^3 (or 6.1/m^3) and Marshall distribution, which were based on the database of ferritic steels, were used in the trial version [16,17]. However, in the current version of PINEP-PWSCC, the number density of pre-existing cracks and their size distribution were updated with those of austenitic stainless steels which was used as a reference for sensitivity analysis of various welding procedures [18]. The number density of pre-existing crack is assumed to be 0.0128/in^3 (or 781/m^3) and the crack size distribution is expressed by the lognormal distribution. The aspect ratio distribution is expressed by the lognormal distribution. Using these distribution functions, the size and aspect ratio of the pre-existing cracks is randomly extracted. Then, as mentioned in the previous section, the sampled crack is subject to pre-service inspection (PSI), and if detected, it is removed from the crack population entering the service.

2.3 Simulation of PWSCC Crack Initiation

It is assumed that crack initiation in the Ni-base alloy components occurs only by PWSCC and the contribution of low cycle fatigue is neglected. Such assumption is based on the previous analysis result which showed that the majority of Ni-base alloy component failures are caused by PWSCC [14]. PWSCC initiated cracks are also assumed as axially oriented semi-elliptical at the inner surface. In the current analysis, the size of PWSCC initiated flaw is assumed as 0.003 inches deep [15], while the depth was assumed to be 0.001 inch, the value suggested based on the boiling water reactor experience, in the trial version. The aspect ratio of PWSCC initiated crack is assumed to be 1.5.

The PWSCC initiation model of Ni-base alloy components was developed by applying two-parameter Weibull analysis on laboratory test data and field data of Alloy 182 welds. First, among the laboratory test results of Dozaki using three-point bend (TPB) specimens of Alloy 182 welds [2], those tested in simulated PWR condition (320 ºC, 25 cc/kg of dissolved hydrogen) were selected and analyzed. As shown in Fig. 2, the Weibull fitting of the data showed that characteristic life is 2.734 years and Weibull slope is 4.35. The short characteristic life in test data could have been caused by very high stress, 570 MPa, applied on the TPB specimens during the tests. Second, as field data, the failure analysis results of U.S pressurizer dissimilar welds summarized in EPRI report were used [1]. To fit the field data, the Weibull slope derived from the laboratory test data was applied. As shown in Fig. 2, the fitting is excellent with new characteristic life of 43 years, which suggests that the fixed Weibull slope can be used to describe the PWSCC initiation of Alloy 182 welds in PWR water chemistry conditions. As a result, the following equation is derived for PWSCC crack initiation model of Alloy 182 welds.

$$P_{ini} = 1 - \exp[-(\frac{t}{\eta_{mod}})^{4.35}] \quad (1)$$

where, P_{ini} (t): probability of crack initiation,
t : time (in effective full power years)
η_{mod} : modified characteristic life by equation (2)

It should be noted that equation (1) is only applicable to the conditions where the field data were obtained, or the representative operating conditions of pressurizer dissimilar welds such that hoop stress is 175.82 MPa[19] and temperature is 345ºC. When water chemistry and operating conditions for specific Ni-base alloy components locations differ from those used to derive equation (1), the characteristic life, η_{mod} should be properly modified by equation (2).

$$\eta_{mod} = \eta_{ref}(\frac{I_{m,ref}}{I_m})(\frac{\sigma_{ref}}{\sigma})^4 \exp[(\frac{Q}{R})(\frac{1}{T}-\frac{1}{T_{ref}})]\exp[(0.0013(DH-29.2)^2] \quad (2)$$

where, I_m : material index (see Table. 1)
σ : applied stress
Q : thermal activation energy for crack initiation= 51 kcal/mole [20]
R : universal gas constant
T : operating temperature (ºK)
DH: concentration of dissolved hydrogen (cc/kg-H_2O)
Subscript ref : Reference value where η_{ref} is obtained
(η_{ref} = 43 years; $I_{m,ref}$ = 8.4; σ_{ref} = 175.82 MPa; T_{ref} = 618 ºK)

The effects of applied stress, material variability and

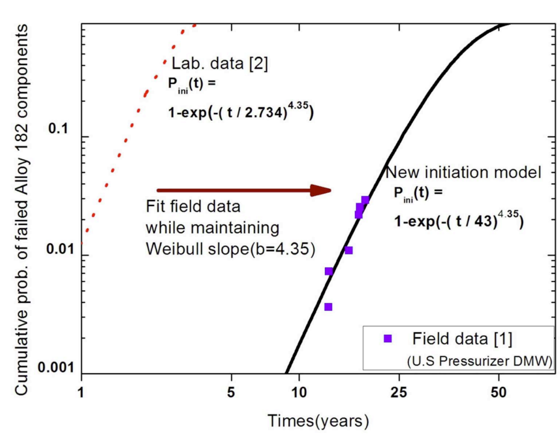

Fig. 2. Weibull Fitting of New PWSCC Initiation Model Correlated with Laboratory Data and Field Data [1,2]

Table 1. Material Index for Calculating Time to Initiation

	Microstructure*	A	B	C	D
Cold Worked	Low T Anneal	8.4			
	High T Anneal		1	0.288	0.051
Hot Worked	Low T Anneal	8.4			
	High T Anneal		0.222	0.064	0.011
Welds	Low C (<0.03%)	8.4			
	High C (>0.03%)	0.288			
Other	Stress Relived	0.133			

*Key to Microstructure Types
A=Fine grain size with few or no grain boundary carbides
B=Some grain boundary carbide decoration (<75%)
C=Substantial grain boundary carbide decoration (75-90%)
D=Almost complete grain boundary carbide decoration (>90%)

operating temperature reflected in equation (2) are based on the previously proposed empirical model [3]. The stresses used in the evaluation include residual stresses as well as the normal sustained operating stresses (pressure, deadweight, and thermal). The material index, listed in Table 1, is used to reflect effects of material variability such as various processing (cold work, annealing, weld, stress relieved) and grain boundary carbide coverage [4]. The final term in equation (2) is included to consider the effects of dissolved hydrogen (DH) on PWSCC crack initiation as suggested in EPRI report [5]. According to recent research results, PWSCC resistance of Ni-base alloys increase as DH moves away from the current nominal content of about 25 cc/kg-H_2O, which is clear in equation (2).

Unlike the above mentioned parameters which change the characteristic life, the remedial effects of zinc addition is reflected as the decrease of Weibull slope. The decrease of Weibull slope was calculated using the observed beneficial effects of zinc addition on steam generator tubes in Sequoyah Unit 2 (31% decrease in Weibull slope with 5ppb Zn) and Beaver Valley-1 (79% decrease in Weibull slope with 35ppb Zn).

2.3 PWSCC Crack Growth

In PINEP-PWSCC code, it is assumed that the pre-existing cracks and PWSCC initiated cracks can grow by PWSCC. While only stress and temperature are considered for crack growth by SCC mechanisms in many existing PFM codes, the effect of crack direction in welds and dissolved hydrogen content are also considered in PINEP-PWSCC. For the crack growth analysis, applied stress intensity factor at the crack tip is calculated using equations in the EPRI Ductile Fracture Handbook [21]. When applied stress intensity factor is greater than the threshold value, it is considered that cracks grow at the rate expressed as the following equation [6-8].

$$\frac{da}{dt} = \alpha f_{alloy} f_{ori} (K - K_{th})^{\beta} \exp[-\frac{Q_g}{R}(\frac{1}{T} - \frac{1}{T_{ref}})] \text{ [in/yr]} \quad (3)$$

where, α : crack growth amplitude
K : Applied stress intensity factor
K_{th} : threshold stress intensity factor (Alloy 600 =8.1ksi√in, Alloy 82/182=0)
Q_g : thermal activation energy for crack growth =31kcal/mole
R : universal gas constant
T : operating temperature (°K)
T_{ref} : reference temperature used to normalize data = 598 °K
β : power-law exponent = 1.16 for Alloy 600, 1.6 for Alloy 82/182
f_{alloy} : 0.385 for Alloy 82, 1 for Alloy 182
f_{ori} : 0.5 for crack growth perpendicular to the direction of the dendrites
1.0 for crack growth parallel to the direction of the dendrites

Among the parameters in equation (3), heat-to-heat variation is reflected to the crack growth amplitude, α, which is randomly extracted from log-normal distributions for Alloy 600 [6] and Alloy 82/182 welds [7]. Then the effect of dissolved hydrogen concentration is estimated according to the modified Morton's model [8] and multiplied to the crack growth amplitude extracted for specific materials. As mentioned before, it is assumed that the aspect ratio is maintained during crack growth.

2.4 Non-destructive Examination (NDE)

In the NDE module, when a randomly selected number, between 0 and 1, is less than the value on POD curve at crack size of interest, that crack is considered detected. Further, once cracks are detected, they are considered to be eliminated by repair and maintenance and no longer considered in the subsequent analysis. Generally, most PFM codes adopt theoretical POD models, such as advanced performance (APOD), very good performance (VGPOD), and marginal performance (MPOD). Previously, authors have used the performance based POD (PPOD) model for austenitic stainless steels in piping PFM analysis [13-15] because proper POD model for Ni-base alloys welds were not available.

In PINEP-PWSCC, the recent results of Program for the Inspection of Nickel Alloy Components (PINC) round-robin exercises, are fitted and adopted [9]. The adopted performance-based POD curves for axial cracks in Ni-base alloy dissimilar welds are plotted in comparison with POD model for austenitic stainless steel [22] in Fig. 3. Of the 3 POD models shown in the figure, eddy current is the most effective in detecting cracks in Ni-base alloy welds, while potential drop is the least effective. Also, it is clear from the figure that cracks in Ni-base alloy welds are more difficult to detect compared with austenitic stainless steels.

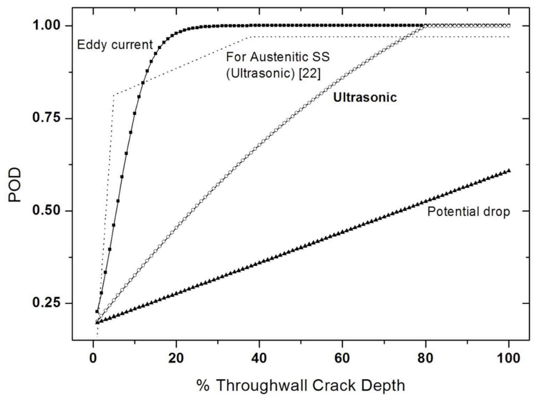

Fig. 3. Performance-based POD Models for Ni-base Alloys Welds and Austenitic Stainless Steel [22]

2.5 Failure Criteria

In determining whether a specific component location fails by PWSCC propagated crack or not, crack stability analysis using J integral/Tearing modulus method was used. For the failure analysis, J-R curves measured in PWR operating conditions [23] are used. The cracks are judged to be a failure when applied J-integral is greater than the materials fracture toughness, J_{IC}, and the following unstable crack growth condition is met.

$$T_{app} > T_R(unstable) \text{ where } T = \frac{E}{\sigma_0^2}\left(\frac{dJ}{da}\right) \quad (4)$$

where E is Young's modulus, T_{app} and T_R are applied tearing modulus and material's tearing modulus, respectively. Flow stress, σ_0 is calculated as the average of yield stress and ultimate tensile strength.

2.6 Calculation of Failure Probability

For pre-existing cracks, the stratified sampling method [24] is used for the computational efficiency as in the previous research [13-15]. In the stratified sampling method, the sample space is divided into a set of mutually exclusive cells representing a certain crack depth and aspect ratio. Then the probability that the weld has failed at or before time t, $P(t_f \leq t)$ can be determined by equation (5) [24].

$$P(t_f \leq t) = \sum_{m=1}^{M'} \frac{N_{F,m}(t)}{N_m} p_m \quad (5)$$

where M' is the total number of cells, N_m is the number of samples from the m-th cell, $N_{F,m}(t)$ is the number of samples taken from the m-th cell which have failed at or before time t, p_m is the probability of an initial crack having dimensions within the region of the m-th cell. The details of the stratified sampling method are described in the reference [24]. In the case of PWSCC initiated cracks, the stratified sampling scheme is not implemented as the PWSCC initiated cracks are assumed to have a fixed depth and aspect ratio as mentioned in section 2.3. Unlike the pre-existing cracks, PWSCC cracks can be initiated in the Ni-base alloy welds during operation, and thus more than one crack may be initiated in the weld as the operating year increases.

3. VERIFICATION OF PINEP-PWSCC

3.1 Failure Probabilities of Various Alloy 182 Butt Welds

Sample analyses were conducted to verify PINEP-PWSCC by comparing the results with other PFM codes. Alloy 182 components known to be susceptible to PWSCC, such as RPV outlet nozzles, pressurizer surge line nozzles, and pressurizer safety relief nozzles, were selected for sample analysis. The typical geometry of the selected components is quoted from EPRI report [10] and summarized in Table 2. To describe the residual stress distribution at selected components, the 3rd order polynomial fitting was applied to the data presented in the same report, and the results are plotted in Fig. 4. Basic input values for the sample analysis are shown in Table 3. The interval of ISI is every 10 years in accordance with the present ASME code requirement.

The calculated cumulative failure probabilities vs. effective full power year (EFPY) of the selected components are shown in Fig. 5. The figure shows the distinctive trend for three Ni-base alloy nozzles as EFPY increases.

Table 2. Geometry of Alloy 182 Welds Components [10]

Locations	Inner radius (inch)	Pipe thickness (inch)
RPV outlet nozzle	15	2.3
Pressurizer Surge Nozzle	5	1.66
Pressurizer Safety Relief Nozzle	2.5	1.59

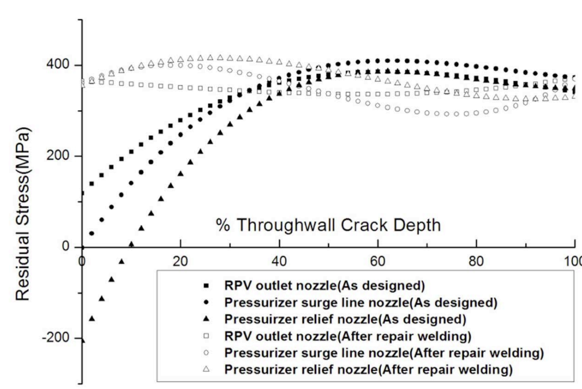

Fig. 4. Residual Hoop Stress Distribution Model for Alloy 182 Welds (Fitted the Data from Reference [10])

Table 3. Reference Analysis Inputs for PINEP-PWSCC

Materials properties • YS = 372.37 MPa • UTS = 583.30 MPa • Poisson's Ratio = 0.32 • Young's modulus = 197.2 GPa • Tearing modulus = 373 • Strain hardening exponent(n) = 4.18 • Dimensionless const(α)=9.49 • Material Index=8.4
Operating conditions • Pressure : 15.5 MPa • Temperature : 323.89ºC (RPV outlet nozzle), 343.33ºC (Pressurizer) • Plant life : 80 years (64 EFPY at 80% capacity factor) • Concentration of dissolved hydrogen = 30 cc/kg • Concentration of zinc addition = 0 ppb • Thermal stress [25] = 41.71 MPa (RPV outlet nozzle) = 102.6 MPa (Pressurizer) • Pre-service inspection : YES • In-service inspection : YES, intervals = 10 years • NDE level = PPOD with ultrasonic technique
Crack grows by PWSCC only (parallel to dendrite) Cell size : 25 X 25 Crack density of pre-existing crack : 0.0128/in^3 Sample space : 100 samples/cell Iteration for SCC initiated crack : 100,000

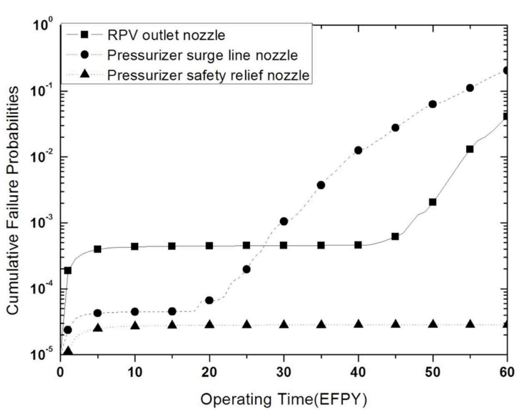

Fig. 5. Cumulative Failure Probabilities of Various Alloy 182 Welds in As-designed Condition

In the case of pressurizer safety relief nozzles, where the operating stress is lower because of small size and more importantly, the residual stress is compressive at the inner surface in the as-designed condition. Thus, the cumulative failure probability barely changes with EFPY, indicating the contribution of PWSCC is minimal. On the other hand, pressurizer surge line nozzles show lower failure probability than RPV outlet nozzles because of lower operating stress and residual stress up to about 25 EFPY. However, after 25 EFPY, the failure probability of pressurizer surge line nozzles becomes greater than that of RPV outlet nozzles as the contribution of PWSCC becomes significant because of high operating temperature at the pressurizer. The high failure probability of RPV nozzle during the early years is due to the contribution of pre-existing cracks to overall failure probability. The more detailed discussion on the contribution of pre-existing cracks is provided in section 4.1. Overall, the PINEP-PWSCC calculated results of failure probability of Ni-base alloy welds components in typical PWR verifies the accepted effects of operating and residual stress on the risk of PWSCC.

3.2 Comparison with Field Experience

The calculated failure probability by PINEP-PWSCC was compared with the available field experience data. The statistical failure database of RPV outlet nozzles, PIPExp was analyzed and summarized in a report by Pacific Northwest National Laboratory (PNNL) for PFM evaluation [11]. PNNL estimated the average frequency of through-wall crack as 9.1 x 10^{-5} per weld-year after about 20 years of operation based on the number of relevant welds per plant and the number of reactor years of operation. From the cumulative failure probability shown in Fig. 5, PINEP-PWSCC estimated the failure frequency of 2.25 x 10^{-5} per weld-year during the first 20 EFPY. The discrepancy can be explained with two factors. First, the PNNL's estimation is based on a single PWSCC failure event, probably the V.C. Summer event in which the repair welding was identified as the key contributing factor. Thus, PNNL's estimation indicates that failure probability of RPV outlet nozzles of typical PWR plants without excessive repair welding is practically zero. Second, the detailed review of the failure probability results of PINEP-PWSCC analysis revealed that all failures are from crack growth of pre-existing cracks and none from PWSCC initiated cracks during the first 20 EFPY. Therefore, at 20 EFPY, failure probability of RPV outlet nozzles due to PWSCC initiation and growth is practically zero, which is in agreement with the PNNL's estimation. As shown in Fig. 5, the sudden increase in failure probability after 40+ EFPY is related to the PWSCC initiation and growth. The effects of pre-existing cracks on the overall failure probability are discussed in detail later in section 4.1.

3.3 Comparison with Trial Version

To compare the effects of recent improvements to PINEP-PWSCC on the failure probability estimation, failure probabilities of various Alloy 182 nozzles are estimated using both current and trial versions. As an example, the calculated failure probabilities of RPV outlet nozzles are shown in Fig. 6. It is clear from the figure that the trial version shows fairly uniformly increasing cumulative

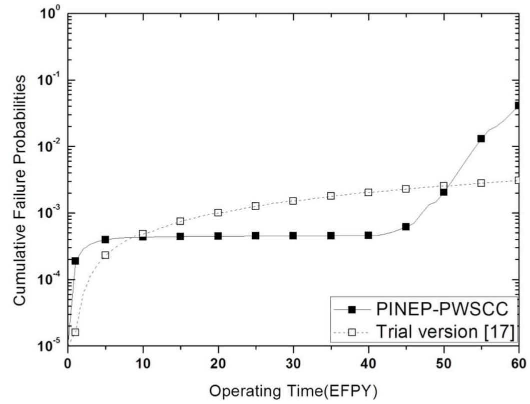

Fig. 6. Cumulative Failure probabilities of RPV Outlet Nozzle by PINEP-PWSCC (Latest Version) and Trial Version [17]

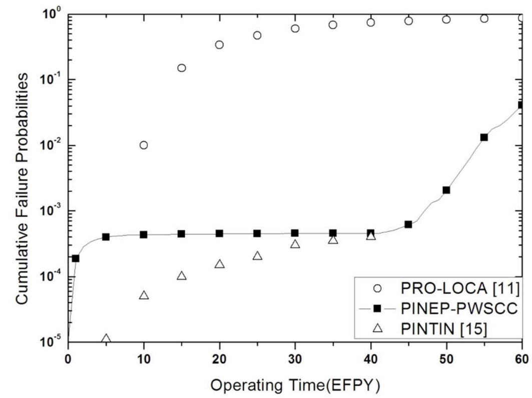

Fig. 7. Failure Probabilities of RPV Outlet Nozzle Calculated by Various PFM Codes [11,15]

failure probability, or more or less the same failure probability per EFPY, which is rather unlikely considering the exponential dependency on time for PWSCC cracking expressed in equation (1). On the other hand, the current version of PINEP-PWSCC shows that the calculated failure probability is low in early years but becomes much larger in later years because of the contribution of PWSCC initiated cracks, which is in agreement with the general understanding of the PWSCC phenomena.

One of the reasons for the errors in the trial version could be caused by the inadvertent application of the stratified sampling scheme to PWSCC initiated cracks, which should have not been treated in that way. To correct the problem, PWSCC initiated cracks are not included in the stratified sampling scheme in the current version of PINEP-PWSCC. The minor errors in handling the density of pre-existing cracks and PWSCC initiated cracks in the trial version resulted in somewhat greater failure probability except at very larger EFPY. Except these errors, other sources of difference could be the modifications in individual analysis modules. Among them, the most important modification was made to the PWSCC crack initiation module as described in section 2.2. Meanwhile, the effects of new NDE performance models are rather small because there is relatively little effect of NDE performance on the failure probability as described later in section 4.3. With corrections and modifications mentioned above, the current version of PINEP-PWSCC simulates the failure probability, or the risk associated with the Ni-base alloys welds in PWR environments.

3.4 Comparison with other PFM Codes

In Fig. 7, the analysis results of PINEP-PWSCC are compared with those of PRO-LOCA [11] and PINTIN [15] for RPV outlet nozzles. As shown in the figures, PRO-LOCA over-predicts the failure probabilities by several orders of magnitude when compared with PINEP-PWSCC. One of the reasons that PRO-LOCA predicts very high-failure probability is that it is developed for regulatory purpose and, therefore tends to use relatively conservative models and inputs. One such example is the use of conservative residual stress taken from the field data of cracked components for crack initiation analysis, as explained in the PNNL report [11]. For this reason, the calculated crack initiation time is quite short and the crack initiation probability reaches 50% after only 10 years of operation. Available PINTIN analysis for axial cracks in RPV outlet nozzles are taken from reference [15] and shown in Fig. 7. It should be noted that, in PINTIN analysis for Alloy 182 section, only pre-existing cracks grown by PWSCC were considered. Though the density of pre-existing cracks in PINTIN analysis (= 0.0001/in^3) was quite a bit lower than that used in PINEP-PWSCC analysis (= 0.0128/in^3), the large tensile residual stress of 200 MPa was assumed in PINTIN analysis. The overall result is that the cumulative failure probability of both analyses becomes comparable at 40 EFPY.

In summary, PINEP-PWSCC analysis results are consistent with the predicted effects of operating stress, operating temperature, and contribution of pre-existing cracks on the failure probability of Ni-base alloy weld components in PWR environments. Also, by comparing the trial version and other PFM codes, the effects of improvements of models and inputs in PINEP-PWSCC were well understood. Therefore, we consider that PINEP-PWSCC is sufficiently verified and can be used for realistic estimation of failure probability of Alloy 182 components by PWSCC during operation. A few example application of PINEP-PWSCC are described below.

4. APPLICATION OF PINEP-PWSCC

4.1 Effect of Pre-existing Crack

To evaluate the contribution of pre-existing cracks (number density = 0.0128/in^3, as described in section 2.2)

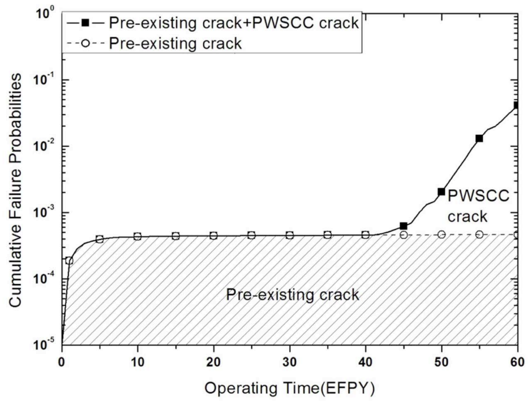

Fig. 8. Failure Probabilities of RPV Outlet Nozzle with Pre-existing Crack Only and with Pre-existing Crack and PWSCC Initiated Crack

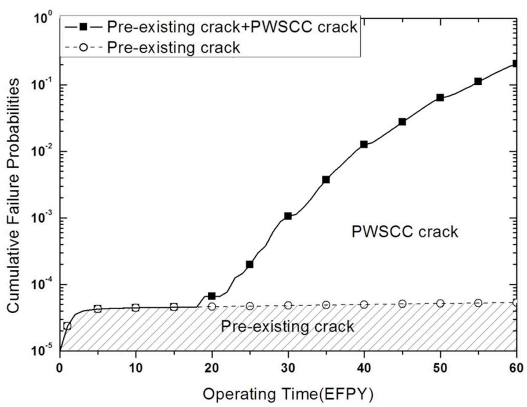

Fig. 9. Failure Probabilities of Pressurizer Surge Line Nozzle with Pre-existing Crack Only and with Pre-existing Crack and PWSCC Initiated Crack

on the total PWSCC failure probability, sample calculations were performed for a RPV outlet nozzle and pressurizer surge line nozzle. In the analysis, failure probabilities were estimated assuming with pre-existing cracks only and with pre-existing cracks and PWSCC initiated cracks. The results are shown in Fig. 8 and 9. For the RPV outlet nozzle, the failures from the PWSCC initiated crack shows up after 40 EFPY, because the stress level at Alloy 182 welds is not high enough. After that, the majority of failure probability is from PWSCC initiated cracks. A similar trend was observed for the pressurizer surge line nozzle. As shown in Fig. 9, the failure probability of Alloy 182 welds caused from pre-existing cracks is lower in that nozzle because of the smaller volume of welds compared to the RPV outlet nozzle. However, the failure from PWSCC initiated cracks become dominant after about 20 EFPY, which is earlier than the RPV outlet nozzle. This is primarily due to the higher operating temperature at the pressurizer surge line nozzle (343.33 ºC) than at the RPV outlet nozzle (323.89 ºC). In both cases, the contribution of pre-existing cracks to overall failure probability of Alloy 182 welds is quite small except in the early years of operation.

In our analysis, we assumed that pre-existing weld cracks can be grown by PWSCC mechanisms. However the recent mechanistic research by EPRI indicated that there are fundamental differences between SCC and hot or ductility-dip cracking which are the common causes of weld cracks of Alloy 182 welds [7]. In addition, microscopic characterization using cracked samples from the Ringhals Unit 4 and the experimental program show that there is no significant interaction between weld defects and PWSCC cracks. Thus it was suggested that there is no significant effect of weld defects on the PWSCC of Alloy 182 welds. Considering this, our analysis further proved that even if the pre-existing cracks are assumed to grow by PWSCC for the sake of conservatism, still their contribution is small and the failures of PWSCC initiated cracks are governing the overall risk of Alloy 182 welds in PWR.

4.2 Effect of Weld Repair

Weld repairs are often the most important root causes in triggering PWSCC in Alloy 182 welds. The repair welding creates high tensile residual hoop stresses at the inner surface of welds, which increases the susceptibility to PWSCC for Alloy 182 welds. To assess the effect of weld repairs, failure probabilities of Alloy 182 welds were evaluated in the as-designed condition (without weld repair) and in repair-welded condition (with inner-diameter repairs over 360°). Again, the RPV outlet nozzle is considered. The residual stress distributions in as-designed and repair-welded conditions are shown in Fig. 4 and used in the analysis. It is shown that repair welding produced fairly high and uniform tensile residual stresses through the thickness. Thus, the inner diameter regions of Alloy 182 welds are under high tensile residual stress because of repair welding. The calculated failure probabilities are shown in Fig. 10. With the repair welding condition, the huge increase in failure probability is observed after 15 EFPY, considerably shorter than the case for as-designed condition. The failure probability for repair-welded Alloy 182 welds is up to 3-orders of magnitudes larger than that for as-designed welds. Such a huge increase in failure probability is caused by the failure of PWSCC initiated cracks, which initiate earlier and grow faster under high tensile residual stress in the inner diameter region. In practice, all the critical PWSCC cracking incidents, such as V.C. Summer, Tsuruga 2, and TMI-1 proved to be associated with extensive weld repair regions. PINEP-PWSCC analysis also confirmed that the repair-welded locations are highly susceptible to PWSCC cracking, and therefore should be carefully inspected to prevent unexpected failure during operation.

4.3 Effect of NDE

The PWSCC cracks could be detected with proper NDE methods, but timely detection of these cracks in the

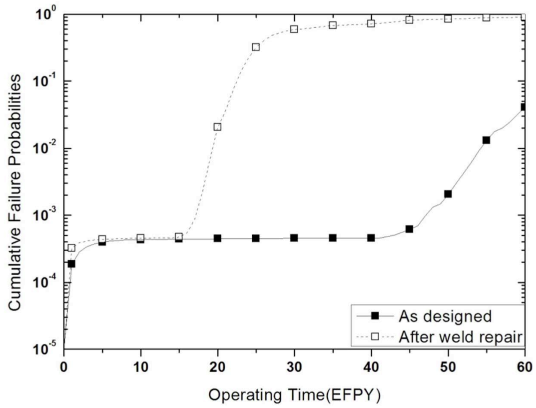

Fig. 10. Failure Probabilities of RPV Outlet Nozzle in As-designed and Repair-welded Conditions

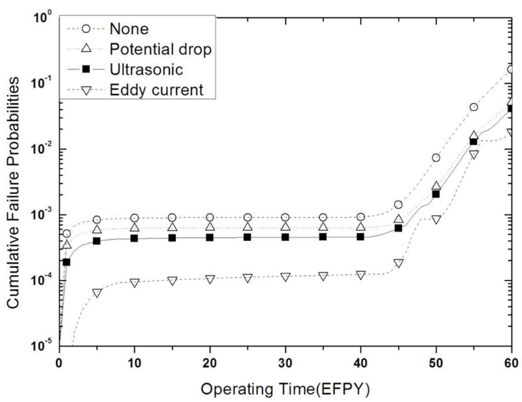

Fig. 11. Failure Probabilities of RPV Outlet Nozzle with Various NDE Techniques

field is difficult because of long incubation time and fast crack growth. In section 2.4, POD models of several NDE techniques are described. In this section, failure probabilities for RPV outlet nozzles are evaluated to quantitatively assess the effectiveness of various NDE techniques. Analysis conditions are the same as those used in the previous section, and the only variable is the choice of NDE techniques. In Fig. 11, failure probabilities of RPV outlet nozzles are shown for various NDE options, such as without inspection, and inspections with ultrasonic, eddy current, and potential drop techniques. From the analysis results, it is shown that in-service inspection is useful in reducing the failure probability by PWSCC mechanism, reducing the risk by up to an order of magnitude. Among the NDE techniques, eddy current is the most effective in reducing the failure probability, which can be explained by the high POD shown in Fig. 3. For other techniques, the reduction in failure probability is relatively small. Similar results were reported previously that, by using PRO-LOCA, failure frequency of pressurizer spray line nozzle-to-safe-end welds decreased by half while POD was improved from 50% to 90% [11]. Therefore, it can be said that in-service inspection alone could not reduce the failure probability of Alloy 182 welds sufficiently, and other PWSCC mitigation methods should be used to further lower the risk of PWSCC failure. Another implication is that, at present, ultrasonic testing is the most widely used technique for PWSCC crack detection and characterization, but the analysis results demonstrate it is less effective than the eddy current technique. In practice, the high sensitivity of the eddy current technique was proved in the inspection of CRDM nozzle of North Anna-2 [26]. Thus, development and application of the eddy current technique for PWSCC crack inspection in Alloy 182 welds should be considered as an option to reduce the PWSCC risk of Alloy 182 welds.

5. SUMMARY

This paper described the development of a PFM code, “PINEP-PWSCC (Probabilistic INtegrity Evaluation for nuclear Piping-PWSCC)”, for more realistically evaluation associated with failure of Ni-base alloy welds in PWR by PWSCC during operation. In developing the code, we adopted the most recent research results and advanced models in calculation modules such as PWSCC crack initiation and growth models, a performance-based probability of detection (POD) model for Ni-base alloy welds, and so on. The development of PWSCC initiation model is based on the correlation with laboratory test data and field data of Alloy 182 butt welds failure in PWR. In the model, effects of material variability and water chemistry were incorporated. In PWSCC crack growth model, the effects of dissolved hydrogen and crack orientation as well as temperature were considered.

To verify the code, the failure probabilities for various Alloy 182 welds locations were evaluated and compared with field experience and other PFM codes. It was found that PINEP-PWSCC analysis results were consistent with the predicted effects of operating stress, operating temperature, and contribution of pre-existing cracks on the failure probability of Ni-base alloy weld components in PWR environments.

Then, the effects of pre-existing cracks, weld repairs, and POD models on failure probability were evaluated to demonstrate the applicability of PINEP-PWSCC. Through the analyses, it was found that the contribution of pre-existing cracks was small and the failures of PWSCC initiated cracks were dominant to the failure probability of Alloy 182 welds in PWR. Also PINEP-PWSCC analysis showed that the failure probability of repair-welded Alloy 182 welds was up to 3-orders of magnitudes larger than that for as-designed welds, indicating that such locations should be carefully inspected to prevent unexpected failure during operation. Finally, it was shown that in-service inspection was useful in reducing the failure probability by PWSCC, but not significantly.

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REFERENCES

[1] Materials Reliability Program: Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service (MRP-220). EPRI, Palo Alto, CA: 2007. 1015427.

[2] K. Dozaki et al, "Effects of Dissolved Hydrogen Content in PWR Primary Water on PWSCC Initiation Property," *E-Journal of Advanced Maintenance*, vol.2, pp. 65-76 (2010).

[3] E. S. Hunt and D. J. Gross, "PWSCC of Alloy 600 Materials in PWR Primary System Penetrations," EPRI TR-103696, EPRI (1994).

[4] D. J. Seman, G. L. Webb and R. J. Parrington, "Primary Water Stress Corrosion Cracking of Alloy 600 – Effects of Processing Parameters," *Proceedings: 1991 EPRI Workshop on PWSCC of Alloy 600 in PWRs*, EPRI TR-100852, EPRI (1992).

[5] Materials Reliability Program: Effects of Hydrogen, pH, Lithium and Boron on Primary Water Stress Corrosion Crack Initiation in Alloy 600 for Temperatures in the Range 320 – 330°C (MRP-147). EPRI, Palo Alto, CA: 2005. 1012145.

[6] Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials (MRP-55) Revision 1, EPRI, Palo Alto, CA: 2002. 1006695.

[7] Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115), EPRI, Palo Alto, CA: 2004. 1006696.

[8] S.A. Attanasio and D.S. Morton, "Measurement of the Ni/NiO Transition in Ni-Cr-Fe Alloys and Updated Data and Correlations to Quantify the Effect of Aqueous Hydrogen and Primary Water SCC," *Proc. 11th Int. Conf. on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors*, Stevenson, USA, August 11-14, 2003.

[9] S.E. Cumblidge, S.R. Doctor, P.G. Heasler, and T.T. Taylor, "Results of the Program for the Inspection of Nickel Alloy Components," NUREG/CR-7019, U.S. Nuclear Regulatory Committee (2010).

[10] Materials Reliability Program: Welding Residual and Operating Stresses in PWR Alloy 182 Butt Welds (MRP-106), EPRI, Palo Alto, CA: 2004. 1009378.

[11] F. A. Simonen et al, "Probabilistic Fracture Mechanics Evaluation of Selected Passive Components — Technical Letter Report," PNNL-16625, Pacific Northwest Laboratory (2007).

[12] D. Rudland et al, "Development of Computational Framework and Architecture for Extremely Low Probability of Rupture(xLPR) Code," *Proceedings of the ASME Pressure Vessels & Piping Division / K-PVP Conference*, Bellevue, USA, July 18-20, 2010.

[13] D. Datta and C. Jang, "Development of an advanced PFM code for integrity evaluation of nuclear piping system", submitted to *International Journal of Pressure Vessels and Piping* (2010).

[14] D. Datta and C. Jang, "Integrity Evaluation of Nuclear Piping System under Combined Aging Mechanisms – Development of PINTIN-CAM Code," submitted to *Journal of Pressure Vessel Technology* (2011).

[15] D. Datta, "Development of an advanced PFM code for the integrity evaluation of nuclear piping system under combined aging mechanisms," Ph.D. Thesis, Department of Nuclear and Quantum Engineering (KAIST), 2010.

[16] J. D. Hong and C. Jang, "Probabilistic Fracture Mechanics Application for Alloy 600 components in PWRs," *Proc. of 2010 International Congress on Advanced in Nuclear Power Plants (ICAPP'10)*, San Diego, USA , June 13-17, 2010.

[17] J. D. Hong and C. Jang, "Probabilistic Fracture Mechanics Application for Alloy 82/182 Welds in PWRs," *Proc. of the ASME 2010 Pressure Vessels & Piping Division / K-PVP Conference*, Bellevue, USA, July 18-20, 2010.

[18] M. A. Khaleel and F. A. Simonen, "Evaluations of Structural Failure Probabilities and Candidate Inservice Inspection Programs," NUREG/CR-6986, U.S. Nuclear Regulatory Committee (2009).

[19] L. J. Bond, T. T. Taylor, S. R. Doctor, A. B. Hull and S. N. Malik, "Expert Panel Report on Proactive Materials Degradation Assessment," NUREG/CR-6923, U.S. Nuclear Regulatory Committee (2007).

[20] B. Grimmel, "U. S. Plant Experience with Alloy 600 Cracking and Boric Acid Corrosion of Light-Water Reactor Pressure Vessel Materials," NUREG-1823, U.S. Nuclear Regulatory Committee (2005).

[21] A. Zahoor, "Ductile Fracture Handbook", EPRI NP-6301-D, EPRI (1989).

[22] S. R. Gosselin, F. A. Simonen, P. G. Heasler, S. R. Doctor, D. A. Jackson and W. E. Norris, "Fatigue Crack Flaw Tolerance in Nuclear Power Plant Piping," NUREG/CR-6934, U.S. Nuclear Regulatory Committee (2007).

[23] W. J. Mills and C. M. Brown, "Fracture Toughness of Alloy 600 and EN82H Weld in Air and Water," Bettis Atomic Power Laboratory Report No.B-T-3264, Bettis Atomic Power Laboratory (2001).

[24] D. O. Harris, D. D. Dedhia and S. C. Lu, "Theoretical and User's Manual for pc-PRAISE, A Probabilistic Fracture Mechanics Computer Code for Piping Reliability Analysis," NUREG/CR-5864, U.S. Nuclear Regulatory Committee (1992).

[25] R. Tregoning, L. Abramson and P. Scott, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process," NUREG-1829, U.S. Nuclear Regulatory Committee (2005).

[26] S. E. Cumblidge et al, "Nondestructive and Destructive Examination Studies on Removed from-Service Control Rod Drive Mechanism Penetrations," PNNL-16628, Pacific Northwest Laboratory (2007).