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Wall Thinning Trend Analyses for Secondary Side Piping of Korean NPPs

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ABSTRACT

Since the mid-1990s, nuclear power plants in Korea have experienced wall thinning, leaks, and ruptures of secondary side piping caused by flow-accelerated corrosion (FAC). The pipe failures have increased as operating time progresses. In order to prevent the FAC-induced pipe failures and to develop an effective FAC management strategy, KEPRI and KOPEC have conducted a study for developing systematic FAC management technology for secondary side piping of all Korean nuclear power plants. As a part of the study, FAC analyses were performed using the CHECWORKS code. The analysis results were used to select components for inspection and to determine inspection intervals on each nuclear power plant. This paper describes the introduction of the FAC analysis method and the wall thinning trend analysis results by reactor type, system, and water treatment amine. This paper also represents the site application feasibility for secondary side piping management. The site application feasibility of the analysis results was proven by comparisons of predicted and measured wear rates.

KEY WORDS: wall thinning, flow-accelerated corrosion, wear rate analysis

INTRODUCTION

Flow-accelerated corrosion (FAC) has continued to cause problems in nuclear power plants. Wall thinning caused by FAC has lead to many leaks and complete ruptures. FAC damage to plant piping can result in costly outages and repairs and can affect plant reliability and safety. The pipe failures caused by FAC have increased as operating time progresses. Nuclear power plants in Korea have experienced wall thinning, leaks, and ruptures of secondary side piping caused by FAC since the mid-1990s. Although there were limited FAC management programs for secondary side piping on Korean nuclear power plants, they were not systematic in terms of FAC analyses, selection of inspection locations, inspection intervals, etc. To prevent FAC-induced pipe failures and to develop an effective FAC management strategy, KEPRI and KOPEC have performed a study for developing a systematic FAC management technology for all domestic nuclear power plants. In the study conducted by KEPRI and KOPEC, FAC analyses for predicting wear rates and selecting intervals for regular inspections were included. FAC analyses were performed using the CHECWORKS code that has been applied worldwide to wall thinning analyses for secondary side piping and has proven its reliability. The analysis results were used to select components for inspection and to determine inspection intervals for each nuclear power plant. This paper describes the function of the CHECWORKS code and the FAC analysis results for secondary side piping of four representative plant types among the fourteen Korean nuclear power plants. The plants are the Kori Unit 2 (Westinghouse NSSS) and Ulchin Unit 1 (Framatome NSSS) Pressurized Water Reactor (PWR) types, Wolsung Unit 1 (AECL NSSS) Pressurized Heavy Water Reactor (PHWR) type, and Ulchin Unit 3 Korea Standard Nuclear Power plant (KSNP). Kori Unit 1 was used to identify wall thinning trends by water treatment amine. This paper also compares wall thinning trends by reactor type and system. The site application feasibility of the analysis results was proven by comparisons of predicted and measured wear rates.

FUNCTIONAL DESCRIPTION OF CHECWORKS

CHECWORKS can be utilized to predict the rate of wall thinning on a component-by-component basis, evaluate the wall thickness data taken during inspections, predict the remaining service life for each component, prioritize the inspections, etc. CHECWORKS is composed of analyses and support tasks. The analysis tasks are composed of water chemistry analysis, network flow analysis, wear rate analysis, and UT data analysis. The support tasks are composed of plant data management, isometric viewer, heat balance editor, FACTRAK, and import utility [1]. FAC analysis using CHECWORKS is performed in three stages, such as systematic pipe classification, database creation, and wear rate analysis. In the first stage, piping lines and components of secondary systems are classified to facilitate database creation and site application. Line and component names should not be duplicated because several thousand piping components in a typical nuclear power plant are stored in the FAC database. Heat balance diagram is also built to perform water chemistry analysis and to serve as a gateway into the database. In the second stage, design and operating data such as temperature, pressure, enthalpy, power level, water chemistry data, component geometry data, etc., are inputted into the FAC database. Finally, the wall thinning analysis based on a created database is performed to obtain wear rate and residual service life. The FAC analysis is performed according to the procedures of water chemistry analysis, network flow analysis, and wear rate analysis.

To predict the FAC wear rate accurately, it is essential that the pH and dissolved oxygen be precisely determined at the desired location for all plants. This is the purpose of the water chemistry analysis. The various elements involved in the water chemistry analysis are the heat balance diagram, steam cycle data, power level data, and water treatment data. The network flow analysis is performed to predict the flow constriction in piping system or at a piping exit if it occurs. The flow calculations for the piping runs include pressure drop due to friction, acceleration due to both density and area change, and pressure changes due to variation in elevation. The network flow analysis is mainly performed in the condensate return lines with initially subcooled liquid which flashes and becomes a two-phase mixture on the way back to the condenser or to storage. The wear rate analysis is performed to calculate the wear rates in cases related to single phase water and two-phase steam piping systems. The wear rate analysis is component based. A component is a specific element within a piping system like an elbow, tee or a reducer. Given the time of operation, the total lifetime wear is calculated and the thickness is predicted to determine the component life.

DB CREATION

Objects for FAC Analysis

To identify wall thinning trends and compare wear rates by reactor type, four types of nuclear power plants were selected for this paper. Kori Unit 2 is a Pressurized Water Reactor type designed by Westinghouse. Wolsung Unit 1 is a Pressurized Heavy Water Reactor type designed by AECL. Ulchin Unit 1 is a Pressurized Water Reactor type designed by Framatome. Ulchin Unit 3 is a Korea Standard Nuclear Power plant (KSNP) type designed by KOPEC. In addition to the plant type, these plants are different in terms of BOP designer, power rating, design approach, water treatment method, etc. Table 1 shows the differences among the plants.

Table 1. Comparisons by reactor type

	Kori-2	Wolsung-1	Ulchin-1	Ulchin-3
Core Type	PWR	CANDU	PWR	PWR (KSNP)
Service Years	20	20	15	4
NSSS Supplier/ BOP Designer	Westinghouse/GEC	AECL/Canatom	Framatome/S&L	KHNP/KOPEC
Power Rate, Mwe	650	679	986	1,051
Number of SGs	2	4	3	2
SG Outlet Temp., F	522	500	518	549
Water Treatment Amine	Ammonia	Morpholine	Ammonia	Ammonia

Global Database Creation

The global plant data are applied to all components stored in the FAC database. The global plant data contains the heat balance diagram, power level, plant period, steam cycle data, and water treatment data. The heat balance diagram enables the simulation and analysis of the secondary water treatment for subsequent FAC analyses. The power level was defined as the 100% normal operation because most nuclear power plants in Korea are base loaded. The plant periods are used to specify the plant's operating history. The duration of the time when the plant was operating was classified as an operating period. The duration of time when the plant was not operating due to refueling was classified as a maintenance period. The steam cycle data are used to view and edit the thermodynamic data associated with a plant's heat balance diagram. The operating thermodynamic data based on the final safety analysis report for each plant were inputted as steam cycle data. The corrosiveness of water used in power plants depends on the pH and the concentration of dissolved oxygen. The water chemistry data was inputted with average values sampled at the locations of the final feedwater, steam generator blowdown, and condensate line in the FAC database. In Kori Unit 2, Ulchin Unit 1, and Ulchin Unit 3, ammonia has been used as the pH control amine. Morpholine has been used as the pH control amine in Wolsung Unit 1.

Component DB Creation

The component data stored in the FAC database contains pipeline information, such as line identification, class, phase, etc.; design information, such as geometry, size, material, design temperature and pressure, etc; and operating information, such as operating pressure, temperature, enthalpy, steam quality, etc. The component data is used as the basic information of the water chemistry, network flow, and wear rate analysis. To facilitate the site application, the pipelines of each system were classified systematically based on isometric drawings and P&IDs. Component names were also determined in accordance with isometric drawings and installed locations in the plants. Table 2 presents the situation of the FAC database created for Kori Unit 2, Wolsung Unit 1, Ulchin Unit 1, and Ulchin Unit 3. The differences of the number of components and lines are due to power rate and plant scale.

FAC ANALYSES AND DISCUSSIONS

To reflect the water chemistry and steam cycle conditions of individual components, the water chemistry and network flow analyses were performed prior to performing the wear rate analyses. The water chemistry analyses were

performed once for Kori Unit 2, Wolsung Unit 1, Ulchin Unit 1, and Ulchin Unit 3 because the water treatment methods have not been changed during the operating duration. The network flow analyses for Kori Unit 2, Wolsung Unit 1, Ulchin Unit 1, and Ulchin Unit 3 were performed for 54, 65, 61, and 147 pipelines, respectively, such as condensate return lines with initially subcooled liquid which flashes and becomes a two-phase mixture on the way back to the condenser or to storage. The wear rate analyses were performed for 217, 235, 297, and 326 pipelines, respectively. The wear rate analyses for several pipelines could not be performed because of the unavailability of operating data. The reason that the number of the network flow and wear rate analyses varies, is due to the differences in reactor type, power rate, design type, etc.

Table 2. Situation of DB creation

	Kori-2	Wolsung-1	Ulchin-1	Ulchin-3
Pipeline Groups	44	35	48	43
Pipelines	251	336	300	326
Components	5,429	5,076	5,598	6,485

Wall Thinning Trend by Reactor Type and System

Figures 1 to 4 show the comparisons of average wear rates based on the analyses of CHECWORKS for Kori uint 2, Wolsung Unit 1, Ulchin Unit 1, and Ulchin Unit 3. The systems involved in these comparisons are the condensate (CD), main feedwater (MFW), main steam (MS), extraction steam (EXT), and heater drain (HD) systems. To identify the wall thinning trends by reactor type, the average wear rates were re-arranged according to the level of wear rate, and 200 components (by system) were listed in decreasing order by wear rate for comparison. Plants susceptible to FAC damage can be identified by comparising the figures. As shown in the figures, the secondary side piping of Kori Unit 2 as the whole are more susceptible to FAC damage than those of the other plants. On the other hand, the piping of Wolsung Unit 1 are less susceptible to FAC damage compared with the other plants. Although several components of some systems have high wear rates, the systems most susceptible to FAC damage by reactor type are the main feedwater system for Kori Unit 2, Wolsung Unit 1, and Ulchin Unit 1 and the condensate system for Ulchin Unit 3.

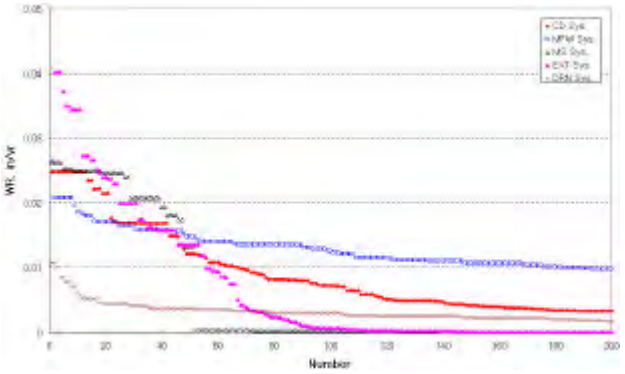

Fig. 1 Comparisons of wear rate for Kori-2

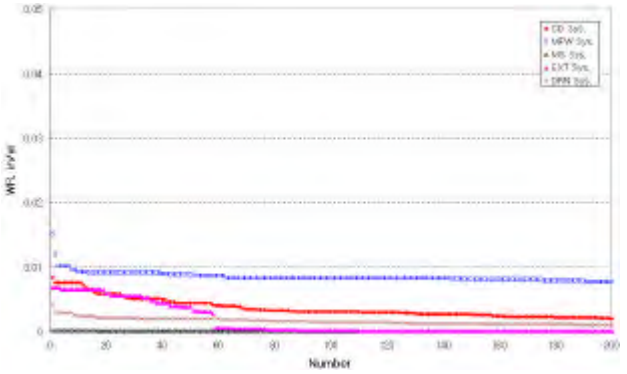

Fig. 2 Comparisons of wear rate for Wolsung-1

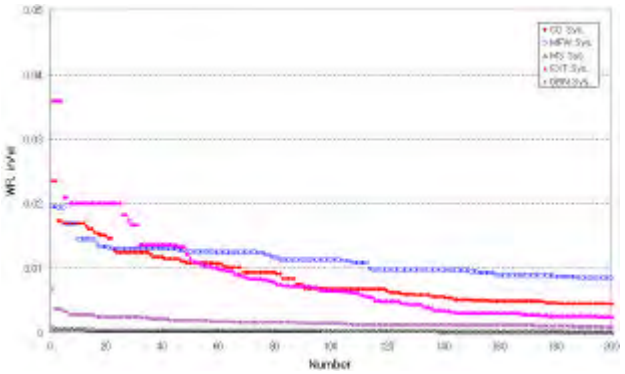

Fig. 3 Comparisons of wear rate for Ulchin-1

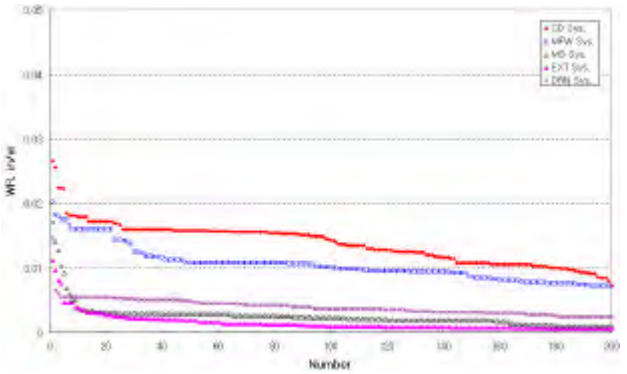

Fig. 4 Comparisons of wear rate for Ulchin-3

Figures 5 to 9 show the comparisons of average wear rates by system for the five systems. The comparison method is similar to the comparisons by reactor type. The purpose of the comparisons by system is to identify the most FAC susceptible plant among the same systems of four reactor types. As shown in Figures 5, 7, and 9, the piping of Ulchin Unit 3 for the CD, MS, and HD systems are more susceptible to FAC damage than the other plants. As shown in Figures 6 and 8, the MFW system piping for Kori Unit 2 and the EXT system piping for Ulchin Unit 1 are more susceptible to FAC damage than the other plants. The susceptible systems to FAC damage are different on each plant.

These results were utilized to select the locations for inspection based on the EPRI guideline [2]. Among these four plants, it was determined that the wear rates for the secondary side piping of Wolsung Unit 1 is lower than those of the other plants. It seems this is due to the water treatment method using morpholine and the low flow rates in pipelines.

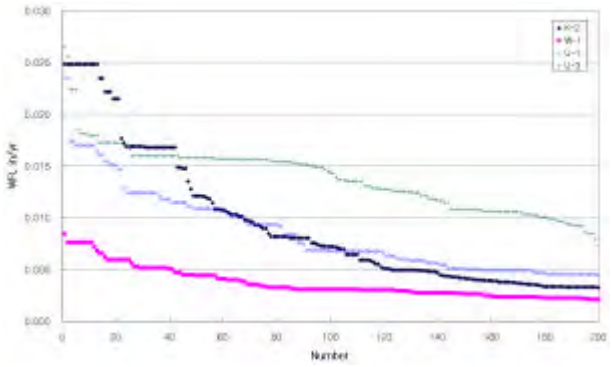

Fig. 5 Wear rate comparisons for CD systems

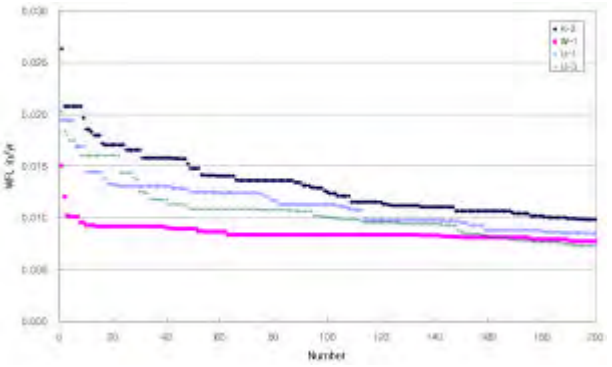

Fig. 6 Wear rate comparisons for MFW systems

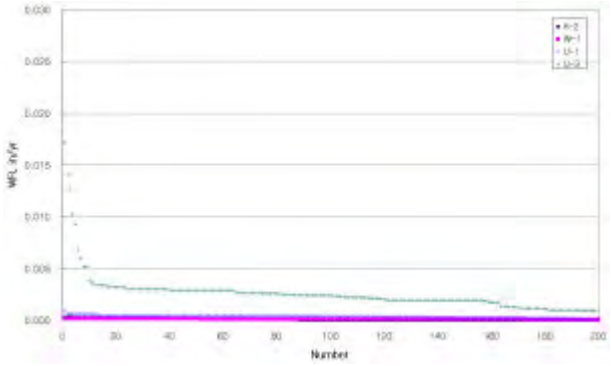

Fig. 7 Wear rate comparisons for MS systems

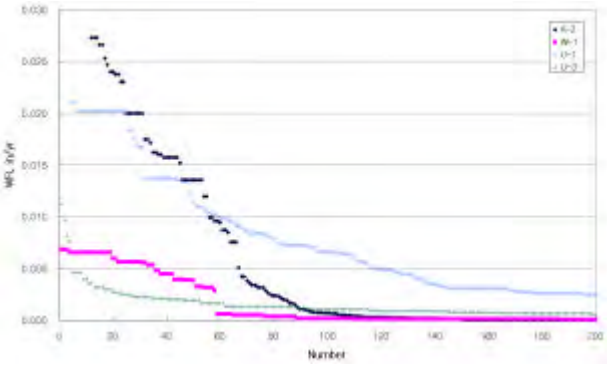

Fig. 8 Wear rate comparisons for EXT systems

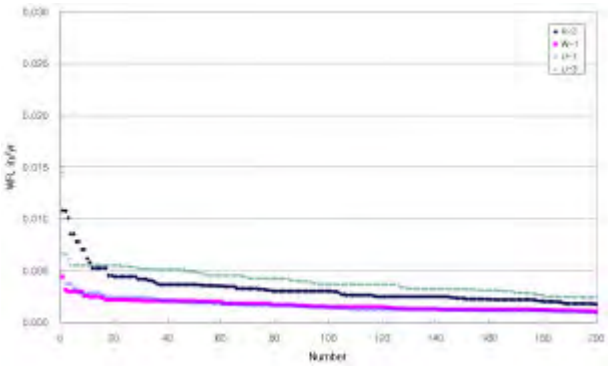

Fig. 9 Wear rate comparisons for HD systems

Wall Thinning Trend by Water Treatment Amine

In order to identify the wall thinning trends by water treatment amine, the wear rate analysis results of Kori Unit 1 and Wolsung Unit 1 were utilized. Ethanolamine (ETA) has been used in Kori Unit 1 as the pH control amine after the 17th refueling outage whereas ammonia was used prior to ETA. On the other hand, ammonia has been continuously used in Wolsung Unit 1 to date. The water chemistry analyses were performed twice for Kori Unit 1 because of a change in the water treatment method after the 17th refueling outage and once for Wolsung Unit 1. For Kori Unit 1, parameters except for the pH control amine were taken to be constant.

To identify the wall thinning trends by water treatment amine, the average wear rates were re-arranged according to the level of wear rate, and 200 components (by system) were selected in order of high wear rate for comparison. The comparison method is similar to the comparisons by reactor type. Figures from 10 to 14 show the comparisons of average wear rates by water treatment amine for the CD, MFW, MS, EXT, and HD systems. As shown in Figures 10 and 11, the wear rates calculated using ETA for single phase piping of the CD and MFW systems were higher than those calculated using ammonia. On the other hand, the wear rates calculated using ammonia for two phase piping of the MS, EXT, and HD systems were higher than those calculated using ETA as shown in Figures 12 to 14. The wear rates calculated using morpholine for all system piping of Wolsung Unit 1 were lower than those calculated using both ammonia and ETA. From these facts, it was determined that the wear rates by water treatment amine are sensitive to the

pH variation. Also, it was identified that the primary factors responsible for the variation in pH are the additives used for pH control, the operating temperature, and the volatility of the additives where steam and water separate.

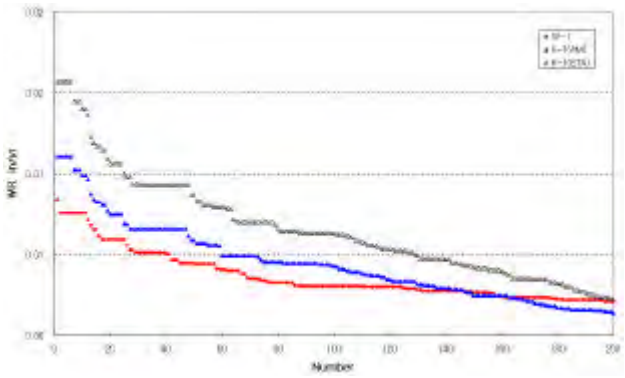

Fig. 10 Wear rate comparisons by water treatment amine for CD systems

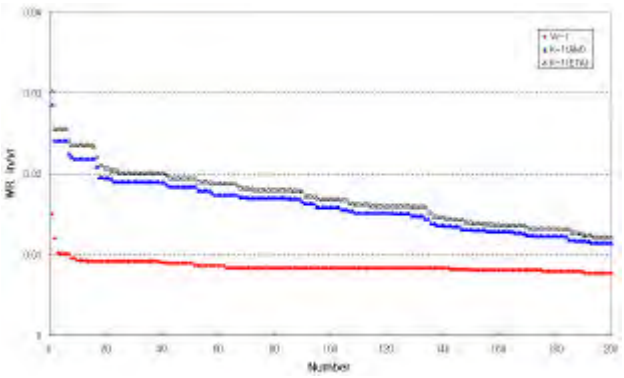

Fig. 11 Wear rate comparisons by water treatment amine for MFW systems

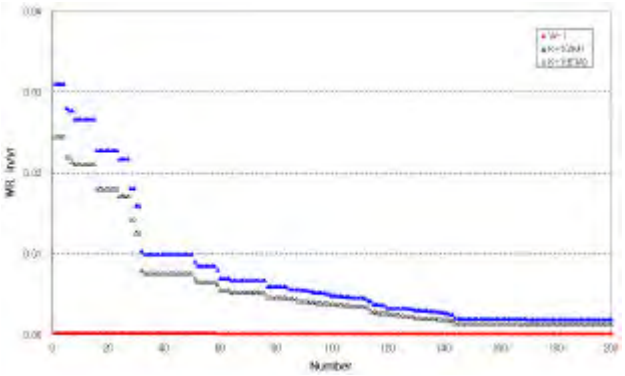

Fig. 12 Wear rate comparisons by water treatment amine for MS systems

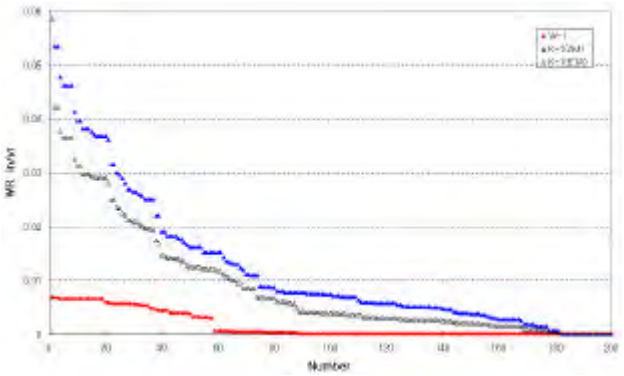

Fig. 13 Wear rate comparisons by water treatment amine for EXT systems

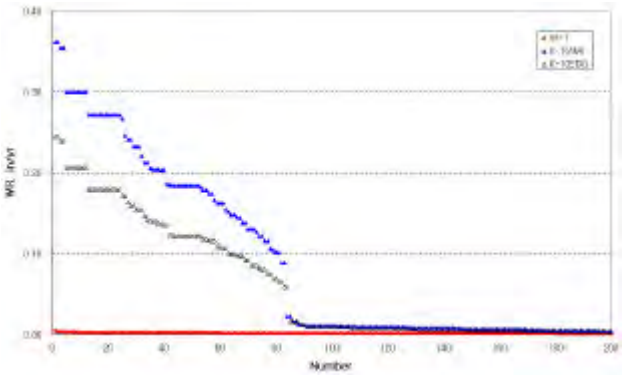

Fig. 14 Wear rate comparisons by water treatment amine for MS systems

VALIDATION AND APPLICATION OF FAC ANALYSIS RESULTS

To validate the site application of FAC analysis results, the predicted wear rates by CHECWORKS were compared with measured wear rates. The measured wear rates were calculated based on the ultrasonic test (UT) data which were measured at the same locations over a long time period. The measured pipe thickness data of Kori Unit 1 and Ulchin Unit 1, PWR types, and Wolsung Unit 1, a PHWR type, were used to compare the predicted and measured wear rates.

The measured pipe thickness data were obtained from five main systems: condensate, main feedwater, main steam, extraction steam, and heater drain systems. The number of components used in comparing the predicted and measured wear rate was 189 for PWR and 86 for PHWR. The curve fitting method was used in calculating the measured wear rate based on the measured data for a long period of time. Figures 15 and 16 show the comparisons of the predicted and measured wear rates for PWR and PHWR, respectively. The data points deviating from the two diagonal lines represent over and under predicted results in the two figures. Although several data points deviate from the validated range, as shown in Figures 15 and 16, it was identified that the majority of the points are within the range.

Figures 17 and 18 show the comparisons of the predicted and measured wear rates for PWR and PHWR, which are re-arranged according to the level of the predicted wear rates, to identify the prediction trends of CHECWORKS. From the fact that the measured wear rates for both PWR and PHWR overall are lower than the predicted wear rates (as shown in Figures 17 and 18), it is considered that the analysis results by CHECWOKS are basically conservative in the two types of reactors. Although several predicted wear rates differ greatly from the measured wear rates, it is considered that the predicted results can be applied to the FAC management of secondary side piping. The FAC analysis results and database were used for the following tasks:

- Selecting and scheduling components for inspection.
- Evaluating inspection data.
- Repairing and replacing components as required.
- Selecting cost effective ways of controlling FAC.
- Providing a useful tool to manage FAC inspection activities during refueling outages.

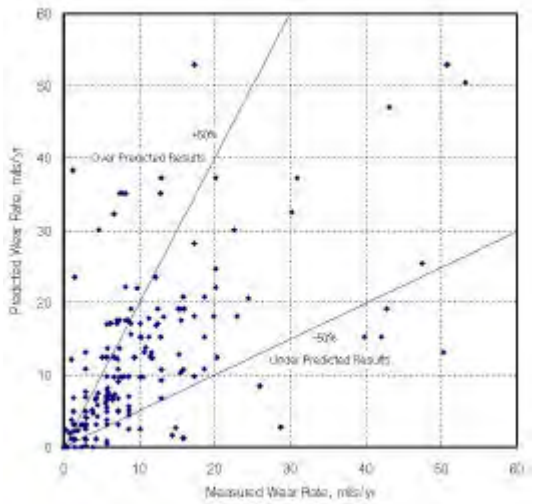

Fig. 15 Comparisons of predicted and measured wear rate for PWR

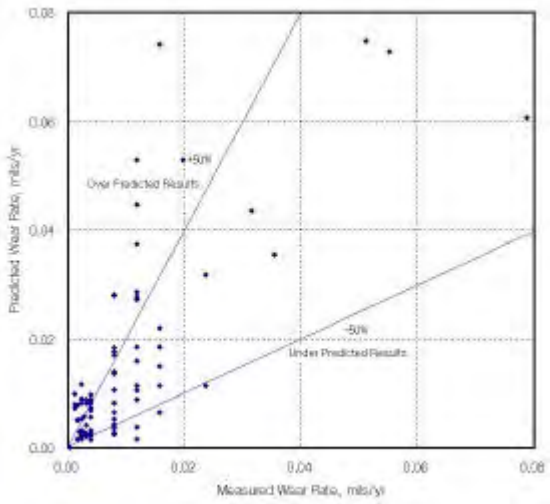

Fig. 16 Comparisons of predicted and measured wear rate for PHWR

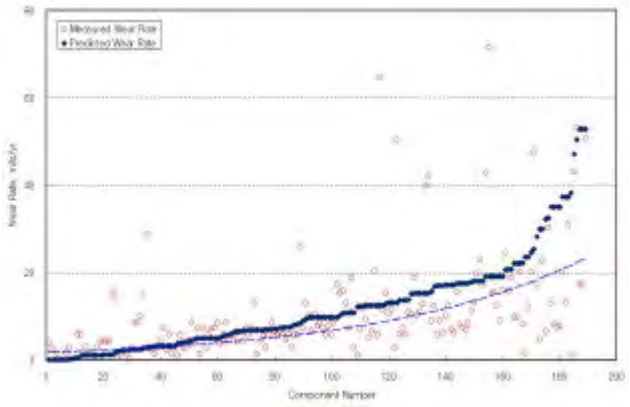

Fig. 17 Comparisons of predicted and measured wear rate by ranking of wear rate for PWR

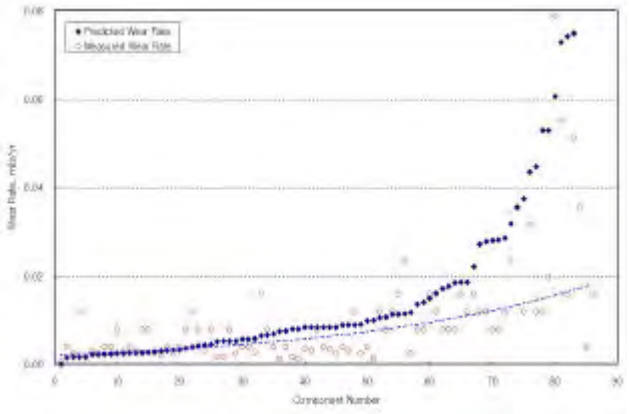

Fig. 18 Comparisons of predicted and measured wear rate by ranking of wear rate for PHWR

CONCLUSION

The functional description of CHECWORKS, the database creation, the FAC analyses and discussions, and the validation and application of FAC analysis results are described in this paper. The FAC analyses were performed using the CHECWORKS code for secondary side piping of all Korean nuclear power plants. To analyze the wall thinning trends by reactor type, system, and water treatment amine, the wear rate analysis results for secondary side piping of four types of plants were compared. The results based on the FAC analyses and the wall thinning trends analyses are as follows:

- Systems susceptible to FAC damage are the main feedwater system for Kori Unit 2, Wolsung Unit 1, and Ulchin Unit 1 and the condensate system for Ulchin Unit 3

- Wear rates for secondary side piping of Wolsung Unit 1 are lower than those of the other plants due to the water treatment method and the low flow rates
- Wear rates calculated using ETA for single phase piping are higher than those calculated using ammonia
- Wear rates calculated using ammonia for two phase piping are higher than those calculated using ETA
- Wear rates calculated using morpholine are lower than those calculated using both ammonia and ETA

To validate the site application of FAC analysis results, the predicted wear rates by CHECWORKS were compared with measured wear rates for two types of reactors. Based on the fact that the measured wear rates for two types of reactors are lower than the predicted wear rates as a whole, it is concluded that the analysis results by the CHECWORKS code are basically conservative in the two types of reactors and the predicted results can be applied in the FAC management for secondary side piping.

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