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Demonstration of EPRI CHECWORKS Code to Predict FAC Wear of Secondary System Pipings of a Nuclear Power Plant

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Abstract

The credibility of CHECWORKS FAC model analysis was evaluated for plant application in a model plant chosen for demonstration. The operation condition at each pipe component was defined before the wear rate analysis by plant data base, water chemistry analysis, and network flow analysis. The predicted wear was compared with the measured wear for 57 sample components selected from 43 susceptible line groups analysed. The inspected 57 locations represent components of highest predicted wear in each line group. Both absolute value and relative ranking comparisons indicated reasonable correlations between the predicted and the measured values. Four components showed much higher measured wear rates than the predicted ones in the feed water train from main feed water pump discharge to steam generator, probably due to high hydrazine concentration operation the effect of which had not been incorporated into the CHECWORKS model. The measured wear was higher than the predicted one consistently for components with least susceptibility to FAC. It is believed that the conservatism maintained during UT data analysis dominated the measurement accuracy. A great deal of enhancement is anticipated over the current plant pipe management program when a comprehensive plant pipe management program is implemented based on the model analysis.

Key Words : FAC(flow accelerated corrosion), EPRI CHECWORKS code, FAC model analysis, wear prediction, grid, UT inspection, UT data analysis

1. Introduction

FAC(Flow Accelerated Corrosion) is a damaging mechanism to carbon steel pipings of nuclear power plants by metal dissolution accelerated by fluid flow.[1,2,3] FAC is distinguished from erosion because it is basically an electrochemical dissolution of metal, while mechanical damage by moving fluid is the basic aspect of erosion. FAC is a practical threat to carbon steel pipings of nuclear Power plants. Without a systematic pipe management program, rupture or leakage of carbon steel pipings due to wall thickness reduction by FAC is inevitable for any nuclear power plants. Besides, a single event of a high energy pipe rupture can be a very serious accident from the point of view of both safety and economy.

A comprehensive program includes measurement of wall thickness reduction and repair and/or replacement of damaged piping components. A damaged component is defined as the one the thickness of which is reduced below the critical thickness required to sustain the design pressure or is expected to be reduced below the critical thickness in the near future. The removal of possibility of pipe rupture due to FAC damage by a comprehensive management program is a challenging task. It is challenging because there are so many pipe components, more than a few thousands, to be managed for each plant. The simple strategy of repair or replacement based on inspection has limitation in the effectiveness. Even though hundreds of piping components are inspected each outage, those inspected are less than one tenth of total components to be managed. Furthermore, some components are hardly inspectable because they are masked by support structures, or located in such positions that the probe is hardly accessible. So that a systematic management based on FAC model analysis is necessary. In this respect, in 1989, U.S. NRC Generic Letter 89-08[4] was issued. This required all U.S. nuclear plants to institute long-term, comprehensive programs based on FAC model analysis to avoid pipe rupture caused by FAC.

EPRI developed a CHECWORKS computer code as a tool for supporting utility' s comprehensive program.[5,6] The code includes FAC analysis model and other useful functions such as UT(Ultrasonic Test) data analysis, critical thickness calculation, data base management, and isometric viewer. Most U.S. utilities use CHECWORKS for their pipe management program currently. EPRI issued NSAC-202L guidelines in 1993, and its first revision in 1996, which cover all programmatic elements required to implement a comprehensive program.[7] It is believed that combination of CHECWORKS and NSAC- 202L constitutes the most updated pipe management program.

The basics of CHECWORKS FAC model are expressed as the following equation.

$$WR = f\{T, AC, MT, O_2, pH, G, \alpha\} \quad (1)$$

where WR is FAC wear rate, T temperature, AC alloy content including chromium, molybdenum, and copper, MT mass transfer, O_2 dissolved oxygen content, pH of liquid at the operating condition, G geometry of component, α void fraction of liquid-steam two phase fluid. These factors are interrelated, and the model is not linear. The model has been developed based on both mechanistic understanding of FAC and empirical wear rate data base derived from both laboratory test and plant wear measurement. All these variables should be defined for each component before performing the analysis using equation (1). The accuracy of the model is an important element of the plant pipe management program. The more credible the model analysis, the more effective the pipe management program.

The credibility of CHECWORKS FAC model analysis will be discussed for plant application by the following procedure.

- performing model analysis for a model plant (denoted as plant R hereafter) chosen for demonstration
- plant wear rate measurement by UT

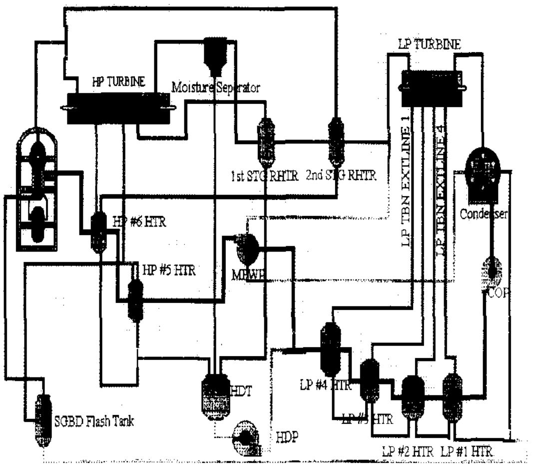


Fig. 1. Heat Balance Diagram for CHECWORKS FAC Model Analysis of the Secondary System Pipings of Plant R(Kori #3)

- comparison between the predicted and the measured wear rate

2. Description of CHECWORKS FAC Model Analysis

2.1. Exclusion from Wear Rate Analysis

It is not an efficient way to analyse all the lines in the secondary system since a significant portion of them are not susceptible to FAC. The following lines are considered to be non-susceptible to FAC, since it is well known from the mechanistic understanding that those lines are not susceptible.[7]

- lines made of non-susceptible materials, such as stainless steel or carbon steel having more than 1.25% chromium content
- lines of superheated steam
- lines of fluid with high dissolved oxygen content
- lines of single water phase fluid the temperature of which is below 93℃
- lines without fluid flow or with flow during less than 2% of normal operation period

2.2. Plant Data Base

The plant data base is composed of global and component data base. Global data base is composed of steam cycle data, operation history, and water chemistry data. The steam cycle data includes flow rate, enthalpy, pressure, and temperature. Operation history means duration of operation each cycle with water chemistry and % power identified. Water chemistry data means pH values at sampling locations and type of amine used for pH control. The global data is established through the heat balance diagram as shown in figure 1.

Components are individual elements which compose a line. Nozzle, straight pipe, valve, tee, elbow, reducer, expander, and orifice are examples of each component. The line is defined as a chain of components which links two equipments, such as tank, heat exchanger, pump, turbine, and condenser. If there are more than one parallel lines between two equipments, the group of trains is called a line group. The component data base is composed of data of each component which include the name of line to which it belongs, its name, geometry, size and thickness, materials, type of insulation and its thickness, operating pressure and temperature, etc.

2.3. Water Chemistry Analysis and Network Flow Analysis

Water chemistry analysis is performed through the heat balance diagram shown as figure 1. Amine distribution is calculated throughout the overall system. The steam quality is calculated for each two phase line. pH value is calculated from the amine distribution as both hot pH and cold pH. Hot pH is the pH of water at the operation condition for the two phase lines.

When pressure and enthalpy are different significantly between inlet and outlet of a line, the variation of these parameters throughout the course of the line can be simulated by network flow analysis. Network flow analysis was performed mostly for steam extraction lines from turbine, moisture separator drain and vent lines, first stage and second stage reheater drain and vent lines.

2.4. Wear Rate Analysis

After every variable affecting FAC wear rate, as represented in equation (1), is defined for each component, wear rate of each component is calculated through wear rate analysis module. The output of the analysis is wear rate, current wall thickness, critical thickness, and remaining life for each component. The current wall thickness is the one projected from wear rate and initial nominal thickness. The critical thickness is calculated according to ASME Code Case N-480.[8] The remaining life is the difference between the current and the critical thicknesses divided by wear rate.

3. Plant Wear Rate Measurement

3.1. Sampling for Inspection

The total of 43 line groups, including 135 lines and 2801 components, were analysed for FAC wear rate. This includes most of important FAC susceptible lines in the secondary system of the chosen plant, Kori Unit 3. A few susceptible lines are not included since detailed component data are missed, operation condition is not defined with precision, or the configuration is so complicated that detailed modeling requires unreasonably many man-hours. FAC susceptible but non-analysed line groups are gland steam lines, cold reheat drain line, main feedwater pump turbine out to condenser line, main steam drain line, main steam header, 2nd stage reheater heating steam, 2nd stage reheater drain tank vent to reheater, 1st stage reheater tank vent to reheater, casing drain of main feed water pump turbine, moisture separator drain tank vent to moisture separator, and heater drain pump suction from low pressure discharge header. Those lines should be managed separately based upon experiences and engineering judgement.

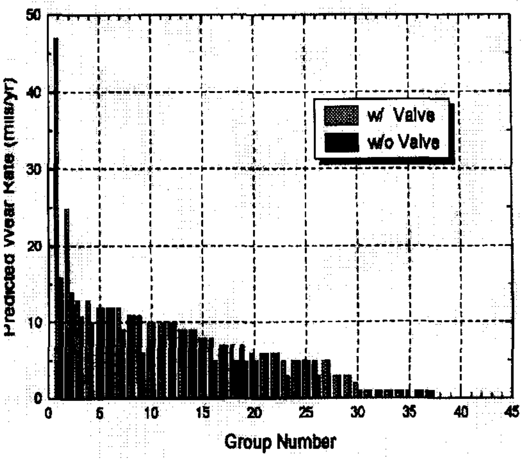
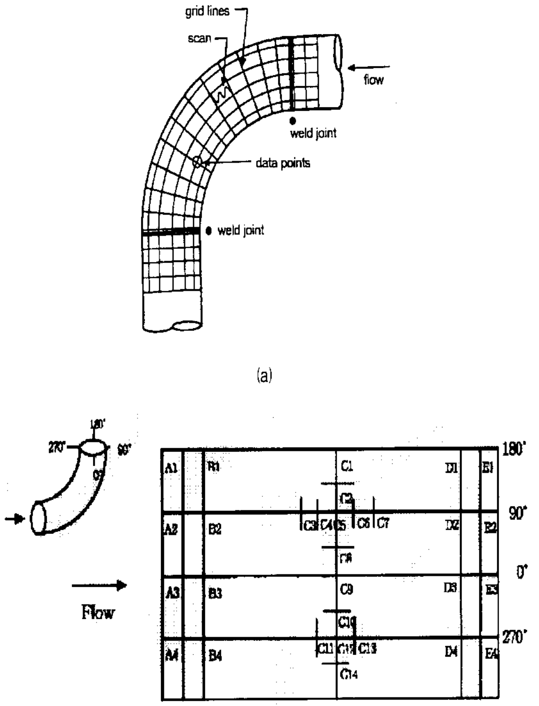


Fig. 2. The Highest Predicted Wear Rate versus the Rank Assigned to Each Line Group

Before sampling for inspection, the 43 line groups analysed were ranked from 1 to 43, where 1 denoted the most susceptible and 43 the least. The susceptibility of a line group was defined as wear rate of a component with the highest wear rate among all the components in the line group. The predicted wear rate for each rank of line group is shown as figure 2. Two predicted wear rates are defined for each line



(a)

(b)

Fig. 3. (a) Full Grid, and (b) Partial Grid

group, with valve and without valve involved. Valves are included in the ranking as defined in figure 2. Valves showed very high predicted wear rate for a few line groups. But valves are not inspected by UT. They are separately managed by visual inspection.

The sampling strategy was simple, more inspection locations for highly susceptible lines and less locations for less susceptible lines. As many as four locations were selected each group for the most susceptible lines and only one location for least susceptible lines. Among 75 locations sampled for inspection, the actual plant measurement data were taken from 57 locations. Measurement data could not be taken from 18 locations because of limitations of plant schedule and inaccessibility of UT probe.

3.2. Grid for UT Inspection

There are two ways of defining grid for UT inspection, partial grid and full grid. Examples of both grids are shown in figure 3. The partial grid is based on an assumption that the location of maximum wear is predictable in a given component inspected. For an elbow, as an example, the maximum wear is assumed to be located near either extrados or intrados, so that the inspection is focused in those areas. The full grid is recommended by EPRI NSAC-202L guidelines,[7] based on the recent experiences that the location of highest wear is not predictable. Another advantage of full grid is that the wear measurement data, thickness and location of each grid point, are handled easily as electronic data base.

The partial grid is adapted for the current plant pipe management program. The grids are drawn in many inspection locations already. New grid lines should be drawn again in order to replace full grid for the existing partial grid.

3.3. UT Data Analysis

UT inspection data for 24 locations were taken from full grids, and the other 33 were from partial grids. The UT inspection data base were provided as raw data of thickness measured at each grid point for each component. The raw data were processed to give wear rate and remaining life of each component. The wear rate is defined as the difference between the initial thickness and the minimum thickness measured divided by operation period. The remaining life is defined as the difference between the minimum thickness measured and the critical thickness divided by the measured wear rate. The difficulty in UT data analysis comes from uncertainties in defining the initial thickness. The nominal thickness is given for each component by as-built isometric drawings. In many instances, however, real components are thicker than the nominal value specified in the design drawings. Even if the nominal thickness is identical to the one specified in the drawing, ±5% error is tolerable for the true thickness. Moreover, the thickness is not uniform for each component, especially for complex geometries such as tee, nozzle, reducer/expander.

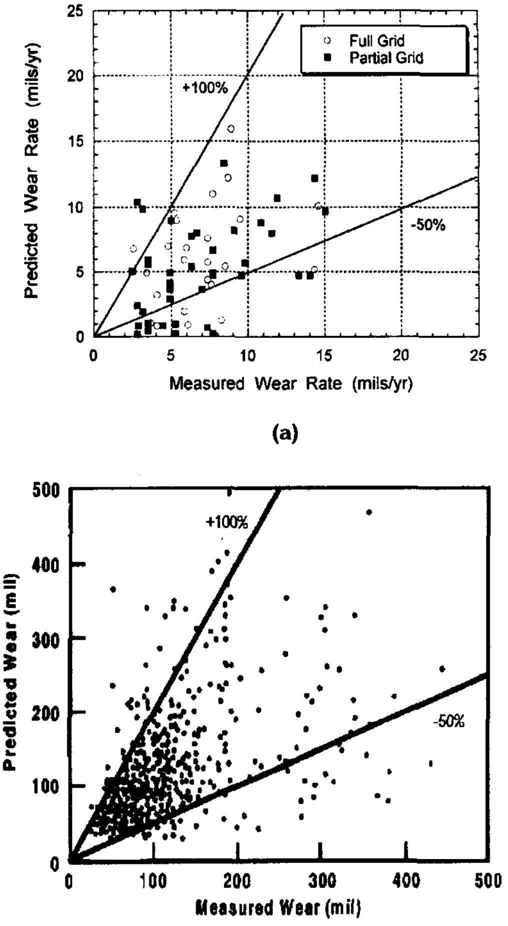
Unless the initial thickness was defined by measurement before operation, which is a very unlikely case, the initial thickness should be determined from the wear measurement data. The initial thickness was determined by a moving blanket method as developed by EPRI. The details of this method is available elsewhere.[7] If the initial thickness determined by the moving blanket method is thinner than the nominal thickness, then the nominal thickness was chosen as the initial thickness in order to guarantee conservatism necessary to prevent pipe rupture event.

4. Results and Discussion

4.1. Comparison Between the Predicted and the Measured Wear

The credibility of the FAC model analysis can be evaluated from both absolute value and ranking point of view. It is the best if the model analysis provides quantitative wear rate values with high precision. It is still valuable, however, from the management point of view if the ranking of wear rate among various components can be predicted consistently even though the absolute wear rate values are far from precise.

Figure 4 shows a correlation between the predicted and the measured wear rate for 57 sample components. The accompanied figure is the identical one from EPRI plant data base. +100/-50% lines were drawn to compare both figures with clarity. Most of the data points are bounded by the two lines with some exceptions. It is believed that the results of the present FAC model analysis shows the same extent of credibility with those of United States industry data base. The source of error is composed of two parts. The first is the intrinsic error included in the model represented as equation (1). Even



(a)

(b)

Fig. 4. Comparison Between the Predicted Wear and the Measured Wear
(a) Plant R (b) EPRI plant data base [3]

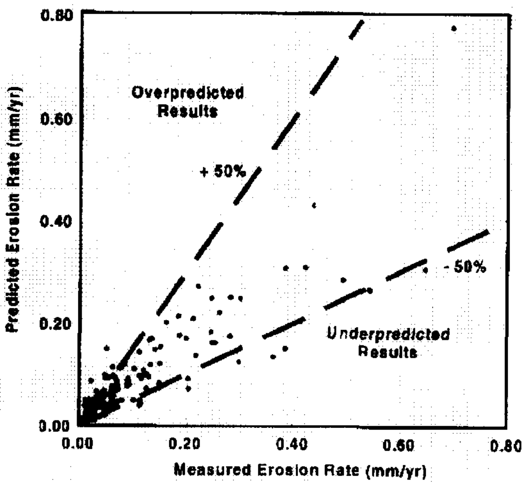


Fig. 5. Comparison Between the Predicted Wear and the Measured Wear for Laboratory Test Database [3]

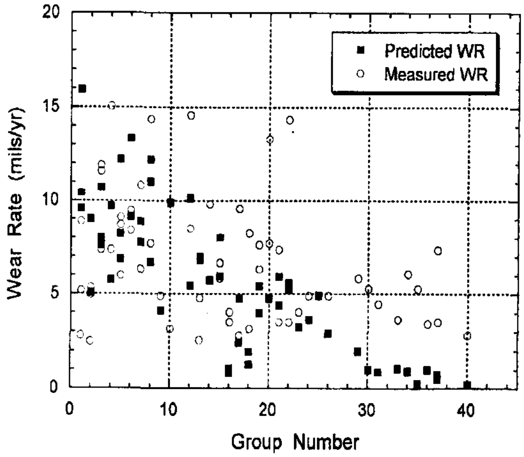


Fig. 6. The Predicted Wear and the Measured Wear versus the Rank Assigned to Each Line Group

though all the variables in equation (1) are defined with high precision, certain amount of error is inevitable for this multi variable non-linear correlation. The other part of the error comes from inaccuracies of defining the variables of equation (1). Determination of operating condition for each component with high precision is hardly achievable. Figure 5 shows EPRI data base for comparison between the predicted wear and laboratory test data. It is apparent that the correlation is far better than for the plant data base.[3]

Figure 6 shows the predicted and the measured wear rates in the order of line group ranking number. It is apparent that the overall trend of the predicted relative ranking and the measured ranking is consistent with each other. One thing to be noted in Figure 6 is that the measured wear rates are higher than the predicted ones for low ranked line groups, line group number above 25, consistently. It is believed that the current thickness measurement technique is not good enough to measure the low wear rate with precision, and that the conservatism involved in the initial thickness determination as described already is the cause of the consistent discrepancies. The other one to be noted is regarding the five data points which show highest measured wear rates, around 15 mils/year. Those components show higher wear rates than the predicted ones. They are from high pressure heater #5 inlet from header, high pressure heater #5 to #6, heater drain pump discharge to main feed water pump suction header, HP heater #6 out to header, and S/G feedwater inlet from header. All the lines are for single phase fluid, and four of the five components are located from high pressure heater inlet to steam generator inlet lines. The model plant has been operating in the high hydrazine mode, as high as 130 ppbs at the condensate compared to conventional 20 to 30 ppbs. Recent test data indicated that high hydrazine content in the single phase fluid accelerated FAC of carbon steel.[9] A test program using 60 m/sec jet of water to carbon steel at an angle of incidence of 45° indicated that

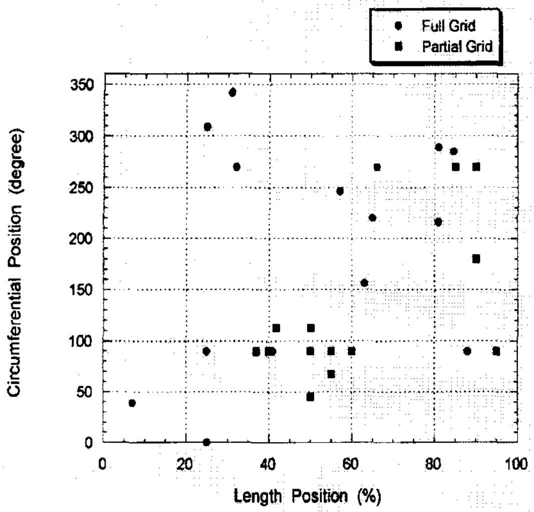


Fig. 7. Measured Minimum Thickness Locations for Elbow

the wear can be more than doubled by raising the hydrazine content from 20~30 ppb to above 100 ppbs. High hydrazine mode operation is a general trend currently since it is believed that high concentration of hydrazine is beneficial to prevent corrosion of steam generator tubes by guaranteeing reducing environment in the tube bundle.[10] The effect of hydrazine concentration on FAC wear is not incorporated into the CHECWORKS model used for this study. It is understood that the high measured wear rate of components located in the high pressure feed water train is caused by the effect of high hydrazine operation.

4.2. Locations of Maximum Wear

The locations of minimum wall thickness for elbows where the thickness measurements were taken are shown in figure 7. For data taken from partial grids, the tendency of locations of minimum thickness cannot be evaluated since the measurements were focused near extrados and intrados. For data from full grid, even though the number of data points are limited as only 15 data points, it is clearly seen that the maximum wear is concentrated near neither extrados nor intrados. The maximum wear locations are rather widespread. It is believed that the geometry of lines are such complex chains that definition of distribution of fluid dynamics in a given simple component is far from predictable in the actual plant pipe lines. The necessity of using full grid rather than partial grid is undoubted.

4.3. Extent of Wear in the Model Plant

For most components which showed very short predicted remaining life, less than one year for a few, it was found that the measured remaining life was rather longer not because the measured wear rate was significantly less than the predicted one, but because the initial thickness of actual components was far thicker than specified as nominal value in isometric drawings. So that the structural integrity of those components are being maintained by the discrepancies between design data and actual plant components. The inspection should be strengthened for those components in order to guarantee there are enough wall thickness margins left. For five components among the 57 components where wear measurements were taken, the measured remaining lifes are estimated below 10 years. The sampling for inspection should be expanded to cover neighborhoods of those components and those at other parallel trains.

4.4. Plant Application

It is believed that the credibility of the CHECWORKS FAC model analysis has been verified for plant application through the demonstration test in a model plant. Discrepancies between the predicted and the measured wear rate can be reduced by line calibration. By defining a calibration coefficient for each line to compensate for the discrepancies, systematic errors caused by uncertainties of defining operation variables affecting FAC wear can be reduced. More data from plant wear measurement are required to cover the whole secondary system pipings susceptible to FAC before performing the line calibration.

Piping management based on FAC model analysis will provide a great deal of advantages over the current program depending mostly on inspection. The efficiency of inspection is improved by strengthened inspection for highly susceptible lines and by inspection schedule based upon wear rate and remaining life. The wear of components hardly accessible for inspection, which is one of concerns regarding the current program, can be evaluated by combination of analysis and measurement of nearby components. It is believed that the risk of pipe rupture can be reduced significantly even with the reduced number of locations to be inspected each outage.

Considering that the wear rate prediction by the model analysis is not of quantitatively high precision and that the actual thickness of many components are different from design drawings, the plant pipe management program should not depend solely on the analysis. Plant experiences and engineering judgement should be incorporated into the program to some extent depending on plant specific features.

5. Conclusions

The credibility of CHECWORKS FAC model analysis was verified for plant application in a model plant chosen for demonstration. A great deal of advantage is anticipated when the current plant pipe management program is replaced by the one based on the model analysis.

Acknowledgement

It is acknowledged that the plant wear measurement data were taken by plant personnels.

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