Advanced management of pipe wall thinning based on prediction-monitor fusion

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Abstract: This article is concerned with pipe wall thinning management system by means of hybrid use of simulation and monitoring. First, the computer-aided simulation for predicting wear rate of piping system is developed based on elucidation of thinning mechanism such as flow-accelerated corrosion (FAC). The accurate prediction of wear rate allows us the useful information on region of interest of inspection. Secondly, several monitoring methods are considered in accordance with interest of inspection. Thirdly, probability of detection (POD) is considered for the reliability of inspection data. The final part of this article is devoted to how to improve safety performance under the hybrid use of predicting and monitoring on the proposed pipe wall management.

Keyword: nuclear safety; simulation; inspection; flow-accelerated corrosion; probability of detection

1 Introduction

There have been rupture troubles caused by piping wastage since 1970s. In order to prevent any rupture accident, pipe wall thinning management (PWTM) in nuclear power plants (NPP) has been aimed at providing a plant life management (PLIM) ensuring replacement or repair prior to in-service failure. After Fukushima's accident, there is much attention for advanced management system of piping system connected with risk analysis. In this paper, a NISA-supported project on prediction-monitor fusion for aged nuclear plants is presented. The main objective of the project is to establish a new management system by means of the hybrid use of simulation and monitoring for pipe wall thinning. The computer-aided simulation for predicting wear rate of piping system is developed based on elucidation of thinning mechanism such as flow-accelerated corrosion (FAC). The high-risk components of piping system can be obtained by predicting wear rate. In order to evaluate the safety margin of the high-risk component, the latest technologies for inspection methods are summarized. The reliability of those inspection methods can be evaluated from the so-called probability of detection (POD). The final part of this presentation is devoted to how to improve safety performance under the hybrid use of predicting and monitoring on the proposed pipe wall thinning management.

2 Pipe wall thinning management

Pipe wall thinning management is to implement inspection programs in order to prevent catastrophic events due to leaks, raptures and severe thinning. In the past decade, there has been much progress in the investigation of pipe wall thinning mechanism. FAC and liquid droplet impingement erosion (LDI) are well-known wall thinning mechanisms that commonly affect carbon steel piping. These occur on a piping internal wide range at an orifice, an elbow, and a reducer down stream. Although it is very important to predict the wear rate of piping system, there are several thousand piping components in NPPs that are potentially susceptible to FAC damages. Thus PWTM has been critical issues for keeping the safety of NPPs. Major tasks in PWTM include the selecting and scheduling components for inspection and the decision making for repair or replacement of the specific components of the piping system based on the wear rate.

3 Prediction by FAC analyses

FAC is determined by six parameters, a flow parameter (mass transfer coefficient, MTC), a

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material parameter (chromium content in materials), and 4 environmental parameters (temperature, pH, and O_2 and Fe^{2+} concentrations in the water) [1].

Six calculation steps were prepared for predicting FAC occurrence and wear rate (Fig.1)[2]. Flow pattern and temperature along the flow path were obtained with a 1D CFD code (Step 1) and then O_2 concentration was calculated with the O_2-N_2H_4 reaction code (Step 2) [3, 4]. FAC occurrence was evaluated based on 1D FAC code (Step 3). Precise flow patterns around the structure surface are calculated with a 3D CFD code and then distributions of mass transfer coefficients at the surface are obtained (Step 4) [5]. Then, wear rates are calculated with the coupled model of static electrochemical analysis and dynamic double oxide layer analysis (Step 5). As a final evaluation, residual lifetime of the pipes and applicability of countermeasures against FAC are evaluated in Step 6. From V&V procedures, it was confirmed that the prescribed wear rates agreed with the measured ones within a factor of 2[6]. The disadvantage of the 3D FAC code based on Steps 1 through 6 was in 3D CFD analysis, which required a lot of computational time and memory. The purpose for developing the code reassembling Steps 1 through 3 was to prepare a speedy and easy-to-handle FAC code based on 1D CFD analysis and to apply it to the whole plant system in a restricted computer time to point out the locations where future problems might occur, where inspections should be required, and where early implementation countermeasures should be taken [7]. For this purpose, not only the probability of serious wall thinning occurrence in the future but also a hazard scale of pipe rupture due to the serious wall thinning should be analyzed. To do this, FAC risk has been defined as the mathematical product of the possibility of seriously large wall thinning occurrence and its hazard scale. The maximum values of wear rate around the pipe with complex geometries were calculated with the 1D FAC code by applying the approximate MYC, which were obtained by multiplying 1D MTC by the geometrical factors [8]. The calculated results with the 1D FAC code were compared with the maximum values obtained from the 3D FAC code (Fig. 2). For the orifice, experiments were carried out under neutral condition (pH: around 7). Thinning rate for the neutral condition was larger than that for PWR conditions with high pH value. Calculated results for both conditions were scattered in the region of factor of 2.

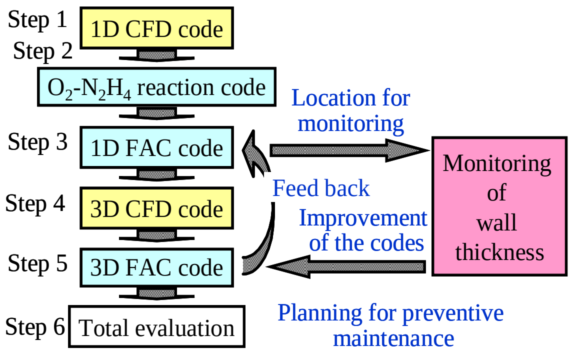


Fig.1 Prediction steps for wall thinning due to FAC.

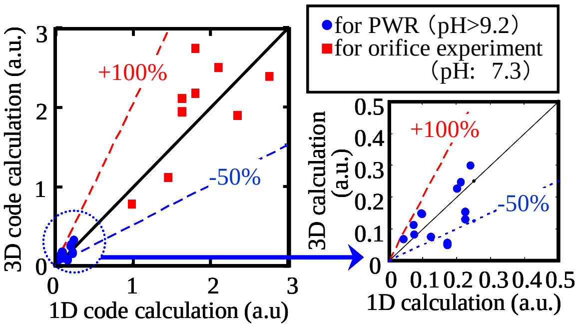


Fig.2 Comparision of wall thinning rates calculated with 1D and 3D FAC codes.

Time to reach the minimum permissible thickness that is designated as time margin can be determined by Eq. (1) for constant thickness value and wear rate.

$$t_m=(T_{Wo}-T_{Wmin})/(da/dt) \qquad (1)$$

where t_m: time margin (y);
T_{Wo}: original wall thickness (m);
T_{Wmin}: minimum permissible thickness (m);
da/dt:wear rate (m/y).

By applying uncertainties in da/dt, T_{Wo} and T_{Wmin}, the probability of the time to reach T_{Wmin}: was calculated and then the time margin for pipe rupture could be designated as the time to reach 5 % of the peak value (Fig. 3) [7].

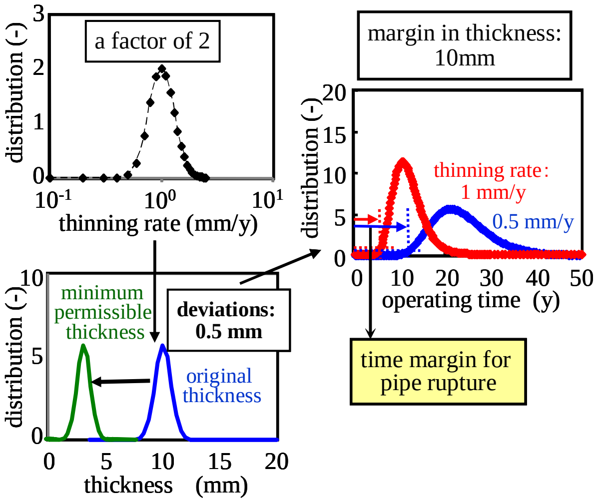
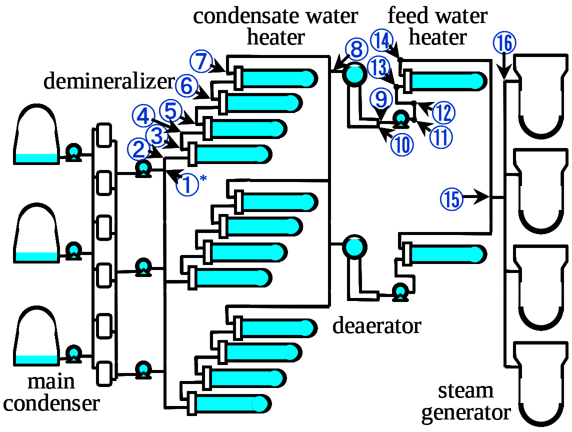


Fig.3 Probablicstic evaluation of thinning rate, margin in thickness and rupture time.

The time margin for time rupture and hazard scale are calculated for the secondary cooling system of a PWR (Fig. 4).



*The numbers correspond to the location in Fig.5

Fig.4 PWR secondary cooling system.

Calculated time margin for time rupture and hazard scale, defined as enthalpy of water in the pipe multiplied by the square of the pipe inner diameter are shown in Fig. 5. By considering the time margin and hazard scale, the number of inspection zones can be narrowed down and continuous wall thick monitoring can be applied at high priority locations. At the same time precise data from continuous measurement of wall thickness can be applied for tuning the prediction tool and improving prediction accuracy.

4 Condition monitoring

Current inspection rules for PWTM in Japanese NPPs are based on ultrasonic testing (UT) and radiography testing (RT). Recommended inspection procedures in Japanese utilities have been prescribed by JISZ2355 for UT and JEAG4224-2009 for RT. Figure 6 illustrates JSME codes for nuclear power generation facilities [9]. Recommended rules on PWTM is composed of two steps using UT. Those consist of making a grid patterns on the components and of taking wall thickness measurement at the grid points in order to find the minimum thickness at the specific components. In the normal process, measurements should be made on coarse mesh gridding. Then, in case where the minimum thickness is less than the specific standard, the further detailed survey should be performed on the fine mesh in order to the minimum thickness. The use of conventional UT includes several crucial issues. For instance, PWTM needs a cursory inspection of a large number of inspections, while a few components involve the target of required managements. Recently, JSME sub-committee summarized critical issues on pipe wall inspection used in the conventional inspection methods [10]. Under those reviews, the sub-committee investigated the latest NDE techniques for PWTM. There are two categories of new NDT techniques. One is a screening technique that employs long-range inspection. Guided wave ultrasonic inspection (GWUT) is one of the latest techniques in this category (Fig. 7). Nondestructive method using microwave is also a promising future technique. However the method is still under study. The other category of latest technologies is a continuous surveillance technique that allows remote inspection based on fixed sensors allocation. Nondestructive method using electromagnetic acoustic transducer (EMAT) is one of the promising techniques in the latter category [11]. Figure 8 depicts a pipe wall thickness measurement using vertical type of EMAT sensor. Potential difference method (PDM) is also used in pipe wall thinning inspection in practice. Pulsed eddy current method (PECT) and Ultrasonic time of flight diffraction method (TOFD) are the other promising future techniques. Especially, it has been recently verified that those techniques are effectively tested in pipe wall thinning with support plate. Table 1 summarizes the feature of the latest technologies in both categories.

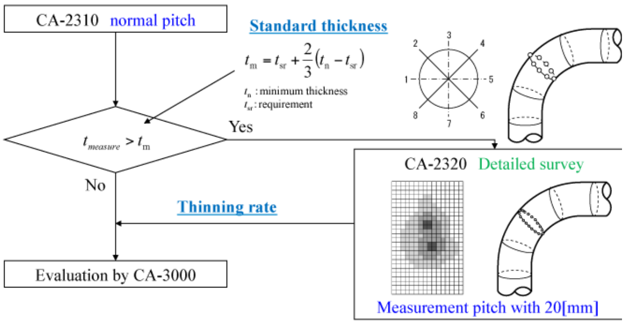


Fig. 6 JSME codes for nuclear power generation facilities.

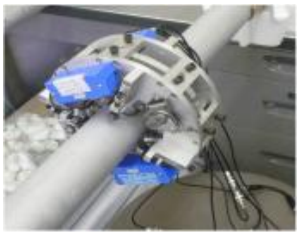


Fig. 7 Guided wave sensor.

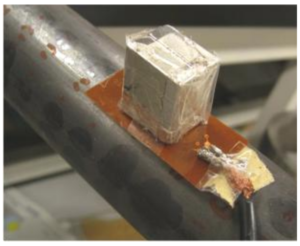


Fig. 8 Vertical type of EMAT sensor.

Table 1 Summary of latest technology in pipe wall inspection

Method	Type	Status
GWUT	Screening	Applicable
Microwave	Screening	Under study
EMAT	Monitoring	Applicable
PDM	Monitoring	Applicable
PECT	For support plate	Under study
TOFD	For support plate	Applicable

5 Reliability assessment

Probability of detection means a probability that acceptable wall thickness from the population would be detected given a defined inspection system and also given a population of experienced wall thinning. His/Miss method and $\hat{a}$ versus a method are typical performance indices for POD analyses. Also confidence bound on the POD function can provide the quantitative measures for reliability assessment. POD provides the capability to develop a feasible inspection model used for quantifying inspection reliability for PWTM [12]. As illustrated in Fig. 9, POD in PWTM so far reveals the hardware variability of the inspection techniques and does not yet take into account the application factors (damage factors like FAC) as well as human factors. Signal response analysis for a specific inspection plays a key role in POD evaluation. The following formula is commonly used to describe the relation between the quantity of wall thickness (a) and the corresponding signal $(\hat{a})$:

$$\ln\hat{a} = \beta_0 + \beta_1 \ln a + \delta \qquad (2)$$

where β_0 and β_1 denote the interception and the slope for the linear logarithmic regression between a and $\hat{a}$. The third term of Eq. (2) describes the model uncertainties for variety of random effects, such as complex geometries of wall thinning, operational conditions, and probe limitations, *etc*. In general, statistical property of δ is characterized by the normal distribution:

$$\delta \sim N(0, \sigma_\delta).$$

Once the prescribed inspection technique is specified, signal response data are collected corresponding to many different inspections for piping system with variety of wall thinning. Using the collected data, the regression parameters $(\beta_0, \beta_1, \sigma_\delta)$ can be estimated. Those estimate values can be evaluated from the maximum likelihood approach. Figure 10 depicts the signal response analysis based on EMAT NDE system. After completing the signal response analysis, the POD function can be evaluated from the following formula:

$$POD(a) = Prob\{\ln\hat{a} > \ln\hat{a}_{dec}\} = \Phi\left(\frac{\ln a - \mu}{\sigma}\right)$$

(3)

Where

$$\mu = \frac{\ln\hat{a}_{dec} - \beta_0}{\beta_1}, \qquad \sigma = \frac{\sigma_\delta}{\beta_1}.$$

The reliably quantitative value for the applied inspection system can be detected by the inverse of the POD(a) function:

$$a_{NDE} = POD^{-1}(\alpha) \qquad (4)$$

where α denotes the preassigned probability. Traditionally, those have been designated as

$$a_{90}, a_{90/95} \ .$$

The first quantitative value means $\alpha = 0.9$ in Eq. (4) and the second one can be derived from the confidence bound of the POD(a) function, *i.e.*,

$$POD_\gamma(a) \ .$$

The asymptotic statistical properties of the maximum likelihood estimates can be used to calculate the confidence bound. The lower confidence bound $POD_\gamma(a)$ can be represented by

$$POD_\gamma(a; \hat{a}_{dec}) = \Phi(\hat{z} - h) \qquad (5)$$

where

$$\hat{z} = \frac{\ln a - \hat{\mu}}{\hat{\sigma}}, \qquad h = \sqrt{\frac{\gamma}{nk_0}\left\{1 + \frac{(k_0\hat{z} + k_1)^2}{(k_0k_2 - k_1^2)}\right\}}$$

and where the parameters $k_i\,(i = 0,1,2)$ denote the components of the information matrix[13]. Figure 11 demonstrates the POD(a) function and its 95% confidence bound for the signal response analysis in Fig. 10. Figure 12 shows the dimensions of the reducer used in one reliable analysis. Figure 13 and Table 2 summarize the results of the reliable qualification using the associated confidence bound.

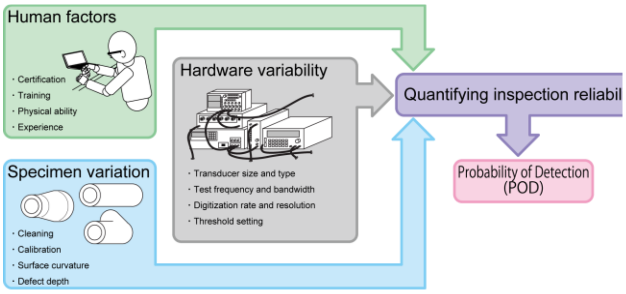


Fig. 9 Illustration of POD.

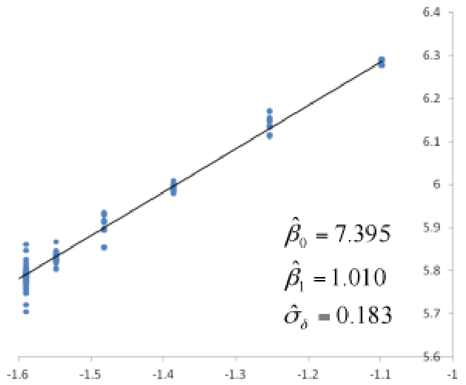


Fig. 10 Linear regression of logarithmic model.

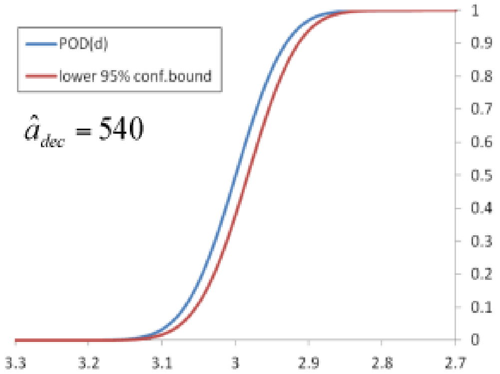


Fig. 11 POD function and its confidence bound.

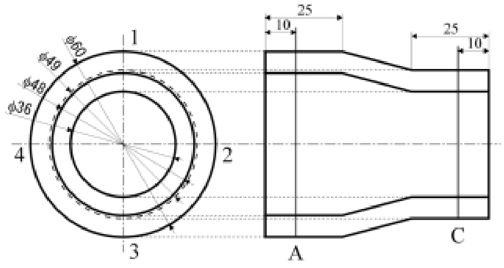


Fig. 12 Dimension of test pipe (reducer).

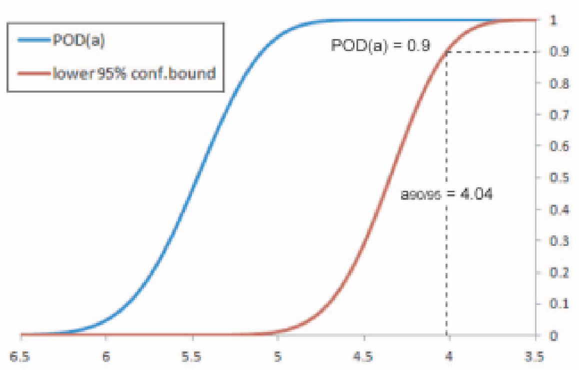


Fig. 13 Reliable parameter value at A1.

Table 2 Summary Experimental results (Reducer)

		1	2	3	4
A	a_{true}	5.50	5.29	5.46	5.5
	$a_{90/95}$	4.04	3.86	4.00	4.04
C	a_{true}	6.38	6.15	6.34	6.40
	$a_{90/95}$	4.97	4.79	4.94	4.98

6 New strategy of PWTM

Probability of detection plays an essential role in the management. Current and future works on the advanced management are discussed. The structural integrity and safety margins are maintained for the piping systems by providing the acceptance criteria for wall thinning. The current safety measure of piping system is based on the acceptable thickness of pipe wall. Figure 14 depicts a safety measure by the usable duration of the target piping components. More specifically, the analyses of wall thinning could provide the user with the wear rates of components. Then the inspection data could provide the time remaining before a specified minimum wall thickness is reached. The acceptable margin can be determined by the allowable thickness of pipe wall. Probabilistic risk analysis can be also implemented by using probabilistic evaluation proposed in Section 3 and by merging it into the reliability quantification of the applied inspection method in Section 5. Those investigations play key roles in the project and are currently under study. On the other hand, the new strategy of PWTM must involve the capability of updating parameters and/or reconstructing predictive models for their improvement. Innovative inspection methods could provide the capability to use measured data to improve the accuracy of the wall thinning managements. Thus, as illustrated in Fig. 15, the predictive plant model for piping system could utilize the results of wall thickness inspections to enhance the wall thinning predictions. The practical implementation Future works in this issue include how to increase and sustain the safety connecting with PLIM by the positive spiral structure through the interactions between simulation and monitoring methods.

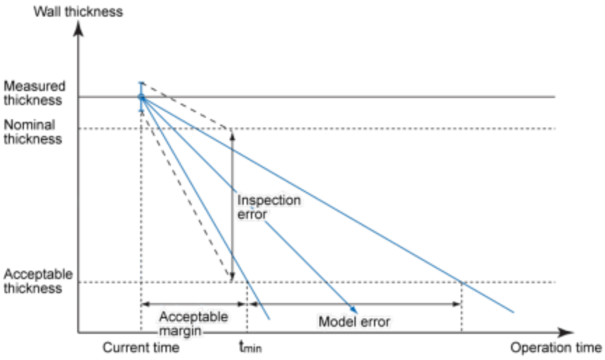


Fig. 14 Link to safety measure.

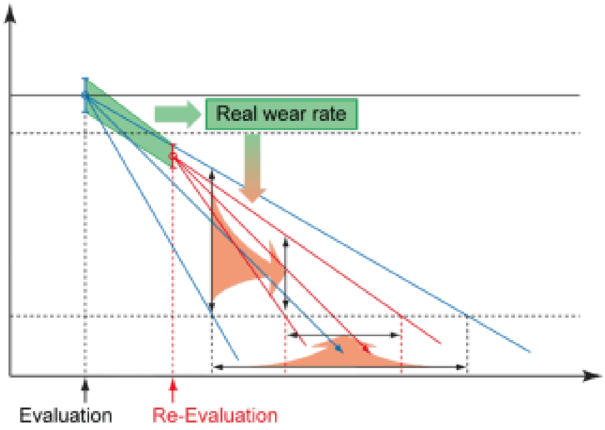


Fig. 15 Prediction and monitor fusion.

7 Concluding remarks

Current investigation on pipe wall thinning management was summarized. The method for determining region of interest of inspection was shown based on the predictive model. Under the use of latest inspection methods, it was shown that the probability of detection plays an essential role in the management. Finally, current and future works on the advanced management were considered.

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