Nuclear Engineering and Design 337 (2018) 84–95

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Improvement of plant reliability based on combination of prediction and inspection of wall thinning due to FAC

Shunsuke Uchida[a,*], Hidetoshi Okada[a], Masanori Naitoh[a], Masayoshi Kojima[b], Hiroshige Kikura[b], Derek H. Liste[c]

[a] Institute of Applied Energy, Tokyo, Japan
[b] Tokyo Institute of Technology, Tokyo, Japan
[c] University of New Brunswick, Fredericton, Canada

ARTICLE INFO

Keywords:
Plant reliability
Risk evaluation
FAC
Prediction
Inspection
Uncertainty analysis

ABSTRACT

Improvement of plant reliability based on reliability-centered-maintenance (RCM) is going to be undertaken in nuclear power plants (NPPs). RCM is supported by three types of maintenances: risk-based maintenance (RBM); time-based maintenance (TBM); and condition-based maintenance (CBM). RBM is supported by suitable combinations of prediction, inspection and maintenance of elemental defects in stages of their propagations. Especially the combination of prediction and inspection is one of the key issues to promote RBM. As an example of RBM, the fusion of the prediction and inspection related to wall thinning due to flow-accelerated corrosion (FAC) has been introduced. Early prediction of FAC occurrence and its propagation should be confirmed throughout the entire plant systems which should be accomplished by inspections at the target locations followed by timely application of suitable countermeasures such as water chemistry improvements. At the same time, transparency and traceability as well as accuracy are strongly required for the prediction. A one dimensional FAC code based on analysis of materials and water interaction was applied for evaluation of FAC risk as well as FAC occurrence and propagation. The details of FAC mechanism have been reported along with the expected accuracy of prediction to prepare for ensuring their transparency and traceability. Based on prediction results, primary points for inspections will be determined. Unfortunately, it is still difficult to evaluate some key parameters in the plants, e.g., local flow turbulence. From the inspections, accumulated data will be applied to confirm the accuracy of the code, to tune some uncertainties of the key data for prediction, and then, to increase their accuracy. The synergetic effects of prediction and inspection on application of effective and suitable countermeasures are expected. In the paper, the procedures for the combination of prediction and inspection are introduced.

1. Introduction

In order to maintain sufficient reliability of nuclear power plants (NPPs), especially aged NPPs, periodic, systematic and precise inspections are required throughout the entire plant systems. Major targets for the inspection to maintain the plant reliability are divided into three categories: (1) dynamic equipment; (2) control equipment; and (3) static equipment. The reliability of the plants can be established by maintaining reliability of each piece of elemental equipment. The reliability of dynamic and control equipment can be maintained by monitoring their performance during plant operation, testing such as operational tests, leakage tests and overhauling them during plant shutdown periods and exchanging their component parts periodically. However, it is rather difficult to confirm the reliability of static

Abbreviations: 1-3D, one- to three-dimensional; AC, alternating current; AESJ, Atomic Energy Society of Japan; AT, acoustic emission testing; BWR, boiling water reactor; CBM, condition-based maintenance; CFD, computational fluid dynamics; CF, corrosion fatigue; CS, carbon steel; DC, direct current; DREAM-FAC, a name of 1D FAC code; ECP, electrochemical corrosion potential; FAC, flow-accelerated corrosion; FIAs, failures, incidents and accidents; FMEA, failure mode and effect analysis; FPP, fossil fuel power plant; HCF, high cycle fatigue; IGSCC, intergranular stress corrosion cracking; JSME, Japan Society of Mechnaicl Engineers; MTC, mass transfer coefficient; NPP, nuclear power plant; PT, penetration testing; PWR, pressurized water reactor; PWSCC, primary water stress corrosion cracking; RBI, risk-based inspection; RBM, risk-based maintenance; RCM, reliability-centered maintenance; RPN, risk priority number; SN, "stree" – "number of cycles to failure" curve; SS, stainless steel; SCC, stress corrosion cracking; SSC, system, structures and components; TBM, time-based maintenance; UT, ultrasonic testing; V&V, verification and validation

* Corresponding author.
E-mail addresses: suchida@iae.or.jp (S. Uchida), hokada@iae.or.jp (H. Okada), mnaito@iae.or.jp (M. Naitoh), kojima.m.al@m.titech.ac.jp (M. Kojima), kikura@lane.iir.titech.ac.jp (H. Kikura), dlister@unb.ca (D.H. Liste).

https://doi.org/10.1016/j.nucengdes.2018.06.007
Received 10 November 2017; Received in revised form 25 May 2018; Accepted 1 June 2018

Nomenclature

$[O_2]$, [Fe]	concentration in water (mol/L)
[Cr]	chromium content in steel (wt%)
C_s	solubility of ferrous ion (mol/L)
D	diffusion coefficient (m^2/s)
F	factors determined wall thinning rate (-) [subscript: χ, Cr; h*, mass transfer]
K_c	geometry factor
P	pipe inner pressure (Pa)
Re	Reynolds number (–)
Sc	Schmidt number (–)
S_u	permissible tensile stress (Pa)
T	temperature (°C)
a	wall thickness (m)
d_{out}	outer diameter of pipe (m)
h	mass transfer coefficient (m/s) [superscript: *, multiplied by geometry factor]
k	constant (–) [k = 2]
t	time (s)
t_m	time to reach the minimum permissible thickness (s)
$\sigma_{\tau Wo}$	deviation of measured wall thickness (m)
$\sigma_{\tau Wmin}$	deviation of evaluated value for the minimum permissible thickness (m)
σ	deviation of thinning rate [subscript: T, temperature; η, pH; Re, Reynolds number]
η	pH (–)
τ_{Wmin}	minimum permissible thickness (m) [superscript: *, mean value]
τ_{Wo}	original wall thickness (m) [superscript: *, mean value]

equipment which often includes a pressure boundary and consists of structural materials that may often degrade with operation time without any change in their apparent performance. In order to maintain the reliability of the static equipment, its systematic and periodic non-destructive testing is required based on its degradation mechanism-oriented scenario.

Periodical inspections of structural materials are essential for maintaining reliability of the static equipment and, subsequently the plant reliability. The reliability-based inspection results in increasing inspection points, and therefore also inspection times, inspection worker-hour and inspection costs with a reduction in plant operation duty factor.

The optimal combination of plant reliability and plant duty factor can contribute to reliable, economical and safe plant operation. For this, primary static components with potentially higher risks are inspected based on precise understanding of the degradation mechanism and predicting degradation risks (risk-based-inspection (RBI)), which contributes to the concentration of inspection resources and rationalism of inspection while at the same time improving inspection quality. The secondary effects of RBI are acquisition of qualified data on important equipment and important materials, which can contribute to improving the degradation models and the major parameters applied for the models. The fusion of prediction based on degradation models and inspection can contribute to synergetic effects for inspection rationalism and degradation prediction improvement (Kojima and Uchida, 2012).

The fusion of prediction and inspection should be supported by a well-arranged computer simulation model for prediction and a data acquisition system for comparison of the predicted and measured results. The computer model should be expressed by a formula with sufficient information on input data, which can prepare for transparency and traceability of prediction for back-checking by third parties, if necessary (Suzuki et al., 2013). The prediction results may at any time involve certain uncertainties caused by the model itself and major input data.

In the author's previous paper, the effects of uncertainty of predicted wall thinning rate on pipe lifetime were evaluated (Uchida et al., 2016). The uncertainty of wall thinning rate was one of the consequences of propagation of uncertainties of elemental parameters. In order to improve wall thinning prediction based on the result of fusion of prediction and inspection, uncertainty of each parameter and its propagation to that of wall thinning rate should be evaluated and the major parameters should be tuned based on the comparison. Suitable countermeasures can be applied to keep plant reliability by following these procedures. In the paper, procedures for the fusion of prediction and inspection are demonstrated for flow-accelerated corrosion (FAC) based on uncertainty propagation evaluation.

2. Plant reliability based on reliability-centered maintenance

2.1. Approaches for establishing plant reliability

Plant reliability could be established by a trio of procedures (Fig. 1), i.e., prediction, detection (inspection) and maintenance when problems were indicated to be developing on structural materials. There were several approaches toward establishing plant reliabilities, e.g. time-based maintenance (TBM), condition-based maintenance (CBM) and risk-based maintenance (RBM), and the final approach was reliability-centered maintenance (RCM), where indications of the problems, which might result in decreased plant reliabilities, were predicted, they were detected and confirmed at their early stages and then they were removed by early maintenance to prevent the future risks (Ling et al., 2007), (Yssaad and Abene, 2015). Inspection targets were often selected based on inspection schedule charts (time-based maintenance (TBM)), while the targets were selected based on experienced anomaly performance or experiences with other plants (condition-based maintenance (CBM)). The candidates for inspection targets which were selected based on risk prediction were confirmed as the maintenance targets where the maintenance was carried out (RBM).

For RBM, failure mode and effect analysis (FMEA) were often applied to predict inspection targets, determine maintenance targets and then select suitable maintenance tasks for the targets (Kojima et al., 2017; Kojima et al., 2018). For FMEA, failure modes of systems, structures and components were extracted based on the experiences with past failures and information on failures, incidents and accidents (FIAs) (Nuclear Standard Committee of JEA, 2007). Major components for FMEA were divided into three categories (Table 1): (1) dynamic equipment including power supply systems; (2) control equipment including DC power systems; and (3) static equipment. For dynamic equipment and control equipment on-line evaluation of FIAs can be applied, while for static equipment off-line evaluation of FIAs can be applied.

Risk priority number (RPN) for off-line evaluation of FIAs was defined as a function of three indexes, predicting index (Capability-A), inspecting index (Capability-B) and maintaining index (Capability-C) (Kojima et al., 2018).

2.2. Risk-Based inspection (RBI)

RBM was also supported by risk-based inspection (RBI), where prediction of FIAs and their inspection were tightly combined as a fusion of prediction and inspection. In the paper covered mainly RBI shown in blue in Fig. 1. Relationships among prediction, inspection and maintenance are shown in Fig. 2.

Based on analysis of occurrences of component failures due to FAC and other problems and their propagations to incidents and accidents,