Framework for Probabilistic EAC Management of Ni-base alloy in PWR

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1. Introduction

As nuclear power plants get older, corrosion-induced aging becomes an issue, because the mode of degradation can affect the structural integrity of systems and components. With the advent of risk-informed regulation, the assessment of risk by aging becomes an important issue as extended operation is accepted worldwide as an economical and technically viable approach. The License Renewal (LR) of nuclear reactors has been recognized as a key solution to the societal resistance to new plant constructions. in U.S., as such applications, if approved, will extend nuclear plant operation for an additional 20 years beyond the current 40-year limit.[1] The Periodic Safety Review (PSR) has been accepted by many countries to seek extended operations based on IAEA guidelines. To ensure the safety in extended operations, it is essential to assess the effects of age-related degradation through time-limited aging analyses (TLAA) [1,2,3].

In this paper we propose a framework for probabilistic assessment of primary pressure-boundary components, with particular attention to Environmentally Assisted Cracking (EAC) of piping and nozzles on Nuclear Power Plants (NPP). The framework for EAC management is targeted for the degradation prediction using mechanism and probabilistic treatment and probabilistic assessment of defect detection and sizing.

EAC of piping and nozzles have occurs mainly in weld regions including heat affected zones when material, environment, and stress factors are superimposed in unfavourable manners. In the aging-related assessment, it is necessary to select components that have non-negligible potential for EAC occurrence and to perform an integrity assessment taking into account of three factors mentioned above.

The PWSCC of Alloy 600 components is directly related to plant safety as root causes of potential rupture of SG tubes or nozzles despite the fact that they have relatively large safety margins. With increasing number of plants approaching to or operating beyond their design lives, rapidly growing numbers of PWSCC are observed in Ni-base components. Therefore it is desired to establish a risk assessment of plant safety impact due to PWSCC in the primary pressure-boundary. In order to cope with increasing plant risk associated with EAC, a traditional reactive approach has been widely exercised by involving detection and sizing of a crack by inspection and implementation of countermeasures based on Section XI of ASME Boiler Pressure Vessel Code. In case of PWSCC, however, non-destructive examinations often underestimate crack size due to their tightly closed nature. It is a new challenge to develop a model for Probability of Detection (POD) for PWSCC. Growth behavior of a detected PWSCC has been modeled as function of stress intensity factor and temperature, derived from laboratory data and field experiences. Recently PWSCC growth rate has been shown to depend significantly on electrochemical corrosion potential. Prediction models therefore should incorporate the behaviors and allow for probabilistic treatment. Final rupture probability may also be predicted using elastic-plastic fracture mechanics methodology. In this paper, we suggest an integrated approach for assessing risk contribution of PWSCC by addressing probabilistic treatments of detectability, crack growth rates, and final rupture behaviors.

2. Methodologies

2.1 Models on Alloy 600 PWSCC

Earlier studies have shown that dissolved hydrogen concentration in high temperature water affects the PWSCC susceptibility of nickel base alloys. [4,5,6] It has highlighted that the crack growth rate under a given stress intensity factor and temperature displays a bell-shape peak in the vicinity of dissolved hydrogen concentration that corresponds to thermodynamic equilibrium between nickel metal (Ni) and nickel oxide (NiO). It has been shown that both PWSCC initiation time and crack growth rate were systematically varied as a function of hydrogen partial pressure in high temperature water. These observations are believed to provide strong evidences that the PWSCC mechanism is highly activated in the vicinity of electrochemical corrosion potential (ECP) corresponding to Ni/NiO equilibrium.

2.2 Bayesian updating with Uncertainties in Inspection

NDE techniques for flaw detection are subject to considerable noise contamination leading to uncertainty in inspection performance. Their quality is therefore expressed in probabilistic terms. The most commonly used inspection quality characteristics is the Probability of Detection, POD. Inspection quality models depending on defect size can therefore directly be used for Bayesian updating of probabilistic models. Although

POD models are normally dependent on one defect size dimension only, more accurate models can be derived based on defect depth and length. A limit state function for the event of detection is needed for the updating of defect models based on inspection results. This Bayesian failure probability analysis can be incorporated with information from nondestructive inspections performed on the structure to derive more realistic reliability estimates. But, the variability is also captured by assuming the crack growth model parameters to be random variables and using the corresponding distributions to quantify the uncertainty of inspection data. A further complication is that data sets are often sparse, usually obtained through component inspections. When there are less observations of a crack than assumed sources of variability, the problem becomes ill-posed since the crack growth model cannot be inverted to obtain unique values for the unknown parameters. This consideration makes Bayesian inference an appropriate choice for these inferences.

2.3 Fracture Mechanics Analysis on Stress Intensity Factor

Accurate stress analyses of surface EAC are needed for reliable prediction of their fracture strength as well as crack growth rates. However, because of the variable parameter including crack shape and position, exact solution are not available. In this study, stress intensity factor which is one of most important variable for fracture strength and crack growth behaviors calculated with a three dimensional Finite element analysis for shallow and deep semielliptical surface cracks. Only loads which cause mode I deformation were considered.
To investigate the effect of configuration parameters on stress intensity factor, the boundary correction factor along the crack front position was calculated as a function of the ratio of crack depth to plate thickness, and compared with the detailed solutions of Newman and Raju [6] in Figure 1

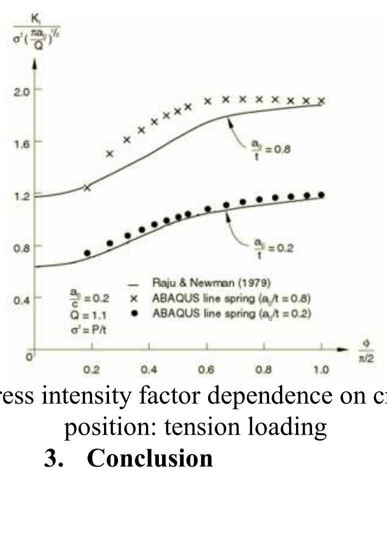

Fig. 1 Stress intensity factor dependence on crack front position: tension loading

3. Conclusion

This paper summarized the effects of some important factors on concepts of EAC growth rate, fracture mechanics and inspection. This framework has been prepared for Environmentally Assisted Cracking (EAC) growth and failure in primary piping and nozzles in PWR's. The framework for EAC aging management requires the statistical EAC growth rate model based on established database.
It has been emphasized that uncertainty in crack size detected by non-destructive examination must be concepted to assess potential failure probability. An integrated probabilistic treatment of EAC phenomena is the future goal of this study.

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