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Reliability based inspection of nickel-based alloy welds in boiling water reactor environment

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ABSTRACT

Stress corrosion cracking (SCC) problems are routinely observed in boiling water reactor (BWR) units. Nickel-based alloy welds are commonly used in BWR units; the nickel content of the material improves resistance to stress corrosion cracking. However, stress corrosion cracking is still a problem for these welds. When a crack is detected, a decision whether an immediate repair in needed has to be made. A model for estimating reliability of BWR nickel-based alloys welds subjected to SCC using non-destructive inspection techniques is introduced. The proposed methodology and model has been illustrated through a numerical example to estimate the required re-inspection interval in order to keep the target reliability level.

1. Introduction

Nickel-based alloys are commonly used in the manufacture of boiling water reactors (BWR). Examples of nickel-based alloys components are as follows: steam generator tubes, instrumentation nozzles and penetrations of the control rod drive mechanisms in reactor pressure vessels heads. Nickel-based Alloy 182 (Inconel 182) and 82 (Inconel 82) weld metals are often used in dissimilar welding applications such as joining Alloy 600 (Inconel 600) to stainless steel, joining low alloy steel reactor vessel nozzles to stainless steel pipes, and joining stainless steel cladding to reactor pressure vessel fabricated of low alloy steel. Fig. 1 shows applications of Alloy 600, 182 and 82 in BWR.

Various papers in the literature addressed the probabilistic failure analysis of components subjected to stress corrosion cracking (SCC). Probabilistic failure analysis of nuclear piping of BWR plant was carried out by You and Wu [11]. Ting [9] analyzed the crack growth due to intergranular SCC in stainless steel piping of BWR plants. Zhang et al. [12] carried out experimental investigations to determine the time to crack initiation and crack propagation velocity for intergranular stress corrosion cracks in sensitized type 304 stainless steel in dilute sulphate solutions. From the statistical analysis results obtained by Zhang et al. [12], it was seen that the time of crack initiation follows an exponential distribution, whereas the crack growth rate follows a Weibull distribution. Harris and Dedhia [3] developed a computer code named PRAISE (piping reliability analysis including seismic events) for estimating the probability of pipe leakage under SCC. Rahman [8] has developed another computer code named PSQUIRT (probabilistic seepage quantification of upsets in reactor tubes) to determine the probability of leakage of piping made of stainless steel and carbon steel subjected to intergranular stress corrosion cracking (IGSCC) and corrosion fatigue. Failure probabilities of a piping component subjected to SCC was computed by Priya et al. [6] using a Monte Carlo simulation (MCS) technique.

In the present paper, a probabilistic failure analysis is carried out in order to estimate the reliability of nickel-based Alloys 600, 182 and 82 welds subjected to SCC in a BWR environment taking into account the different values of the probability of detection of the inspection technique. The results are then, used to determine the required inspection interval in order to maintain the acceptable (target) reliability level.

The reliability of the component is a function of two probabilities. The probability of detection (POD) which is a measure of the ability of a specific non-destructive testing technique to predict correctly the presence of an existing crack, and the probability that a crack grows in size to reach a critical size before the next inspection. We will call the latter probability the probability of critical crack occurrence. The critical size of a crack is the crack size which causes the component to fail. In the following sections, we will present a method for estimating these two probabilities as a function of the time interval between two successive inspections. We will then use this information to determine the time interval between two successive inspections which guarantee a specified level for the reliability of the component.

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Nomenclature

BWR	boiling water reactors
SCC	stress corrosion cracking
IGSCC	intergranular stress corrosion cracking
MCS	Monte Carlo simulation
POD	probability of detection
NDI	non-destructive inspection
da/dt	crack growth rate (m/s)
PWSCC	primary water stress corrosion cracking
Q_g	thermal activation energy for crack growth (kJ/mol)
R	universal gas constant (kJ/mol K)
T	absolute operating temperature (K)
T_{ref}	absolute reference temperature (K)
K_{I}	crack tip stress intensity factor (MPa m$^{1/2}$)
α	crack growth rate coefficient (MPa m$^{1/2}$)
K_{th}	crack tip stress intensity factor threshold (MPa m$^{1/2}$)
β	crack growth rate exponent
C	material constant for crack growth rate (MPa m$^{1/2}$)
σ	applied stress (MPa)
F	geometry function
a_0	initial crack size (mm)
a_t	crack size at time t (year)
P_{f}	probability of failure
$P_{\mathrm{nd}}(a)$	probability of non-detection of a crack size “a”
$P(a>a_{\mathrm{cr}})$	probability of critical crack occurrence
$E[\mathrm{POD}]$	expected probability of detection
t_{cr}	critical time to failure (mm)
a_{cr}	critical crack size to failure (mm)
t_{insp}	inspection interval between the two inspections (year)
N_1	number of simulations at which the initial crack size, “a_0” grows to the critical size before the next inspection
N_2	number of simulations at which the initial crack size “a_0” does not grow to the critical size before the next inspection

2. Probability of detection (POD) function

The POD function is a measure of the ability of the NDI technique to correctly detect an existing flaw in a component. The ability of the NDI technique to detect a flaw in a component depends on many factors. These include the degradation mechanism; the location of the flaw, the shape and orientation of the flaw; the shape of the component, and the material; the experience of the inspector, and the inspection procedure.

For a specific NDI technique used for detecting flaws in a component subjected to certain degradation mechanism, POD can be expressed as a function of the flaw size, a. This probability is equal to the ratio of the number of the detected flaws having a size a, to the total number of the flaws actually existing. Berens and Hovey [2] suggested using the log-odds or log-logistic model for expressing the POD function as follows:

$$\mathrm{POD}(a)=\frac{\exp(A+B\ln a)}{1+\exp(A+B\ln a)} \tag{1}$$

where a is the crack size in mm, and A and B are experimentally determined parameters.

The POD functions for the three NDI techniques (ultrasound, magnetic and penetrant) based on data obtained from test results of a flat plate collected by Berens and Hovey [2] are shown in Fig. 2 and Table 1.

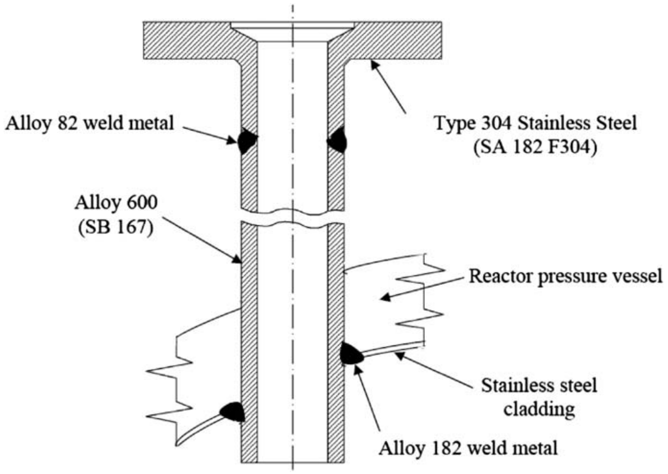

Fig. 1. Schematic drawing showing applications of Alloys 600, 182 and 82 in BWR.

3. Probability of critical crack occurrence

Probability of critical crack occurrence can be defined as the probability that a crack grows in size to reach the critical size.

This probability depends on the growth rate of the crack.

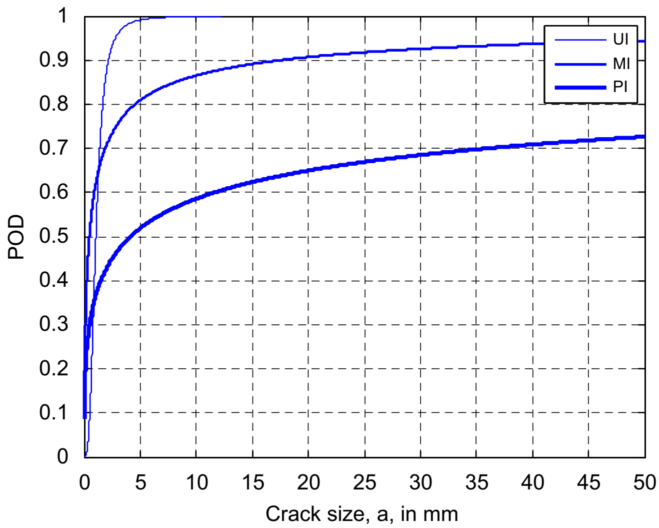

Fig. 2. POD curves for ultrasonic, UI, magnetic, MI and penetrant, PI, inspections (redrawn after Berens and Hovey [2]).

Table 1
Probability of detection obtained by Berens and Hovey [2].

$\mathrm{POD}(a)=\frac{\exp(A+B\ln a)}{1+\exp(A+B\ln a)}$		
NDI technique	A	B
UI	−0.119	2.986
MI	0.466	0.604
PI	−0.561	0.393