Reliability analysis of stainless steel piping using a single stress corrosion cracking damage parameter

A. Guedri*

Infra-Res Laboratory, University of Souk Ahras, P.O. Box 1553, Souk Ahras 41000, Algeria

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A B S T R A C T

This article presents the results of an investigation that combines standard methods of fracture mechanics, empirical correlations of stress-corrosion cracking, and probabilistic methods to provide an assessment of Intergranular Stress Corrosion Cracking (IGSCC) of stainless steel piping. This is done by simulating the cracking of stainless steel piping under IGSCC conditions using the general methodology recommended in the modified computer program Piping Reliability Analysis Including Seismic Events, and by characterizing IGSCC using a single damage parameter. Good correlation between the pipe end-life probability of leak and the damage values were found. These correlations were later used to generalize this probabilistic fracture model. Also, the probability of detection curves and the benefits of in-service inspection in order to reduce the probability of leak for nuclear piping systems subjected to IGSCC were discussed for several pipe sizes. It was found that greater benefits could be gained from inspections for the large pipe as compared to the small pipe sizes. Also, the results indicate that the use of a better inspection procedure can be more effective than a tenfold increase in the number of inspections of inferior quality.

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1. Introduction

In Boiler Water Reactor (BWR) piping, the susceptible material to Stress Corrosion Cracking (SCC) is usually AISI304 stainless steel in a sensitized condition next to weldments. The susceptibility of this material to Intergranular SCC (IGSCC) is due to chromium carbide precipitation in the grain boundaries, which leaves the regions immediately adjacent to these grain boundaries low in corrosion-resistant chromium [1,2]. The precipitation occurs most commonly under the thermal conditions encountered during welding. The stress is primarily due to weld shrinkage during fabrication, and the corrosive environment results from coolant oxygen and low impurity levels according to the operating specifications [1,2].

Zhang et al. [2] carried out experimental investigations to determine the time to crack initiation and crack propagation velocity for intergranular stress corrosion cracks in sensitized type AISI304 stainless steel in dilute sulfate solutions. Their work is considered instrumental in this area of research, which lacks field data and served as a base for several work. Several researchers [3–11] addressed the probabilistic failure analysis of components subjected to stress corrosion cracking (SCC) based on fracture mechanics. Failure probabilities of a piping component subjected to IGSCC, including the effects of residual stresses, was computed by Guedri et al. [12,13] using Monte Carlo Simulation (MCS) techniques. Trends of data from these studies were used in the work described below to develop input data for the probabilistic failure analysis. The purpose of this paper is to apply probabilistic fracture mechanics to analyze the influence of ultrasonic (UT) inspections on austenitic stainless steels piping structural reliability under the effect of IGSCC. IGSCC in the heat-affected zones of stainless steel welds is much more difficult to detect by UT inspection techniques and in-service inspection (ISI), conducted in accordance with the minimum requirements of Section XI of the ASME boiler and Pressure Vessel Code, which tends to be of little value for this problem [14,15].

In this study, the simulation of stainless steel piping cracking under IGSCC conditions is based on the general methodology recommended in the Piping Reliability Analysis Including Seismic Events (PRAISE) computer program [16], which is explained briefly in the next section. The proposed procedure to characterize IGSCC by a single damage parameter which depends on residual stresses, BWR environment conditions, and degree of sensitization is outlined in Section 3. Details of the simulation and numerical examples including the benefit of in-service inspections considered to evaluate the structural reliability and to identify most effective
6. Conclusions

This paper presents the results of an investigation that combines standard methods of fracture mechanics, empirical correlations of stress-corrosion cracking, and probabilistic methods to provide an assessment of IGSCC of stainless steel piping using the modified PRAISE code. The modifications in the PRAISE code included the adjustment of residual stress factors to better fit experimental data and the change of the stress intensity factors expressions to ameliorate the previous more conservative ones. This model was used to predict the probability of failure of different level of pipe damages. Good correlation between the pipe end plant-life probability of leak and the damage values were found. These correlations were used to generalize this probabilistic fracture model. In BWRs, the failure rate from IGSCC is lower for small piping than for large piping. Moreover, for small piping costs are considerably lower and leakage has much less impact. Finally, the probability of detection curves and the benefits of in-service inspection in order to reduce the probability of leak for nuclear piping systems subjected to IGSCC were discussed.

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References


Notation

- A_crack: crack depth
- A_0: area of crack
- A_cross-section: area of cross-section of pipe
- A_cross-section: area of cross-section of pipe
- A_length: length of crack
C1–C9: material dependent constants
C12, C13, C15: material dependent constants
C14: material dependent random variable
d: spacing between two cracks
Dn: damage parameter
E: modulus of elasticity
f1: sensitization term
f2: environmental term
f3: loading term
G: material dependent constant
h: pipe wall thickness
J: material dependent random variable
K: stress intensity factor
Kd: stress intensity factor in the depth direction of crack
Kap: stress intensity factor for applied stress
Kb: stress intensity factor in the length direction of crack
Kres: stress intensity factor for residual stress
l, l1, l2: crack length
n: number of possible initiation sites in the pipe
N: number of simulations
Nf: number of failure cases
O2: oxygen concentration
Pf: probability of failure
Q: leak rate
Ri: internal radius of pipe
tc: time to initiation of stress corrosion cracking
T: temperature
v1: initiation crack growth velocity
v2: fracture mechanics based crack growth velocity
γ: water conductivity
δ: crack opening displacement
ε: smallest possible PND for very large cracks
σ: applied stress
σf: flow stress
σLC: load-controlled component of stress
σnet: net-section stress
ν: Poisson’s ratio

Units
1 inch (in): 25.4 mm
1 gallon (gal.): 3.8 L
1 mil: 0.0254 mm

Abbreviations and acronyms
ASM: American Society of Materials
IGSCC: Intergranular Stress-Corrosion Cracking
ISI: In-Service Inspection
MCS: Monte Carlo simulation
M-PRAISE: Modified PRAISE
NDE: Non-Destructive Examination
PRAISE: Piping Reliability Analysis Including Seismic Events
PND: Probability of Non-Detection
PNNL: Pacific Northwest National Laboratory
SCC: Stress Corrosion Cracking