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

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ABSTRACT

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.

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

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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

[1] Andresen PL, Ford FP. Fundamental modeling of environment cracking for improved design and lifetime evaluation in BWRs. International Journal of Pressure Vessels and Piping 1994;59(1–3):61–70.
[2] Zhang S, Shibata T, Haruna T. Initiation and propagation of IGSCC for sensitized type 304 stainless steel in dilute sulfate solutions. Corrosion Science 1997;39(9):1725–39.
[3] Harris DO, Lim EY, Dedhia DD. Load Combination Program Project 1 Final Report. NUREG/CR-2189. Probability of pipe fracture in the primary coolant loop of a PWR plant volume 5: probabilistic fracture mechanics analysis, vol. 5. Washington, D.C: U.S. Nuclear Regulatory Commission; 1981.
[4] Harris DO, Dedhia DD, Eason ED. Probabilistic analysis of initiation and growth of stress corrosion cracks in BWR piping. New York: American Society of Mechanical Engineers; 1986a. ASME Paper 86-PVP-11.
[5] Harris DO, Dedhia DD, Eason ED, Patterson SD. NUREG/CR-4792. Probability of failure in BWR reactor coolant piping: probabilistic treatment of stress corrosion cracking in 304 and 316NG BWR piping weldments, vol. 3. Washington, D.C: U.S. Nuclear Regulatory Commission; 1986b.
[6] Guedri A, Djebbar Y, Khaleel MA, Zeghloul A. Structural reliability improvement using in-service inspection for intergranular stress corrosion of large stainless steel piping. In: Belov Alexander, editor. Applied fracture mechanics. InTech, ISBN 978-953-51-0897-9; 2012. http://dx.doi.org/10.5772/48521.
[7] Ting K. The evaluation of intergranular stress corrosion cracking problems of stainless steel piping in Taiwan BWR-6 nuclear power plant. Nuclear Engineering and Design 1999;191(2):245–54.
[8] Rahman S. A computer model for probabilistic leak-rate analysis of nuclear piping and piping welds. Int. J. Pres. Ves. Pip. 1997;70:209–21.
[9] Helie M, Peyrat C, Raquet G, Santarini G., Sornay Ph. Phenomenological modelling of stress corrosion cracking. First Global Internet Corrosion Conferences. 1996.
[10] Lu BT, Chen ZT, Luo JL, Patchett BM, Xu ZH. Pitting and stress corrosion cracking behaviour in welded austenitic stainless steel. Electrochimica Acta 2005;50(6):1391–403.
[11] Anoop MB, Balaji Rao K, Lakshmanan N. Safety assessment of austenitic steel nuclear power plant pipelines against stress corrosion cracking in the presence of hybrid uncertainties. International Journal of Pressure Vessels and Piping 2008;85(4):238–47.
[12] Guedri A, Zeghloul A, Merzoug B. Reliability analysis of BWR piping including the effect of residual Stresses. International Review of Mechanical Engineering (IREME) 2009;3(5):640–5.
[13] Guedri A, Merzoug B, Khaleel MA, Zeghloul A. Reliability analysis of low alloy ferritic piping materials. In: Damage and fracture mechanics. Failure analysis of engineering materials and structures. Netherlands: Springer; 2009. p. 33–42.
[14] Kupperman DS, Reimann KJ, Ellingson WA. Evaluation of ultrasonic techniques for detection of stress-corrosion cracks in stainless steel piping. Report EPRI NP-761. Palo Alto, California: Electric Power Research Institute; June 1978.
[15] Guedri A. Effects of remedial actions on small piping reliability. Journal of Risk and Reliability, Proceedings of the IMechE 2013;227(2):144–61. 227(Part O).
[16] Harris DO, Dedhia DD. Theoretical and user's manual for PC-PRAISE. A probabilistic fracture mechanics computer code for piping reliability analysis. Washington, DC: US Nuclear Regulatory Commission; July 1992. NUREG/CR-5864, UCRL-ID-109798.
[17] Chapuliot S, Lacire MH, Le Delliou P. Stress intensity factors for internal circumferential cracks in tubes over a wide range of radius over thickness ratios. In: Fatigue, fracture, and high temperature design methods in pressure vessels and piping365. ASME PVP; 1898. p. 95–106.
[18] Anderson TL, Thornwald G, Revelle DA, Lanaud C. Stress intensity solutions for surface cracks and buried cracks in cylinders, spheres, and flat plates. Structural Reliability Technology final report to The Materials Property Council, Inc.; March 14, 2000.
[19] Anderson TL. Stress intensity and crack opening area solutions for through-wall cracks in cylinders, and spheres. Structural Reliability Technology Final Report to The Materials Property Council, Inc.; January 29, 2003.
[20] Jang-Shyong You, Wen-Fang Wu. Probabilistic failure analysis of nuclear piping with empirical study of Taiwan's BWR plants. International Journal of Pressure Vessels and Piping 2002;79:483–92.
[21] American Society of Materials. ASM handbook: fatigue and fracture. USA: Materials Information Society International; 1996.
[22] Priya C, Rao KB, Anoop MB, Lakshmanan N, Gopika V, Kushwaha HS, et al. Probabilistic failure analysis of austenitic nuclear pipelines against stress corrosion cracking. (Part C). Journal of Mechanical Engineering Science – Proceedings of the IMechE 2005;219(7):607–26.
[23] BS 7910. Guidance on methods of assessing the acceptability of flaws in metallic structures. London, UK: British Standard Institution; 1999 [chapter 7].
[24] R6. Assessment, of the integrity of structures containing defects. Gloucester: British Energy Generation Ltd; 2001. [Revision 4, chapter I and II.3].
[25] ASME. Boiler and pressure vessel design code, section XI. Philadelphia: American Society of Mechanical Engineers; 1992.
[26] Leek TH, Howard IC. An examination of methods of assessing interacting surface cracks by comparison with experimental data. International Journal of Pressure Vessels and Piping 1996;68:181–201.
[27] Leek TH, Howard IC. Rules for the assessment of interacting surface cracks under mode I load. International Journal of Pressure Vessels and Piping 1994;60:323–39.
[28] Howard IC, Leek TH. Estimating the elastic interaction factors of two coplanar surface cracks under mode I load. International Journal of Pressure Vessels and Piping 1994;60:307–21.
[29] Shi P, Mahadevan S. Corrosion fatigue and multiple site damage reliability analysis. International Journal of Fatigue 2003;25:457–69.
[30] Pitt S, Jones R. Multiple-site and widespread fatigue damage in aging aircrafts. Engineering Failure Analysis 1997;4:237–57.
[31] Harris DO, Dedhia DD, Eason ED, Patterson SD. Probabilistic treatment of stress corrosion cracking in sensitized 304 stainless steel weldments in BWR piping. Livermore, California: Failure Analysis Associates Report to Lawrence Livermore National Laboratory; 1985.
[32] Khaleel MA, Simonen FA, Harris DO, Dedhia D. The impact of inspection on intergranular stress corrosion cracking for stainless steel piping. Risk and safety assessment: where is the balance, vol. 266. ASME PVP; 1995411–22. SERA-vol. 3.
[33] Khaleel MA, Simonen FA. Evaluations of structural failure probabilities and candidate in-service inspection programs. NUREG/CR-6986; PNNL-13810. Richland, WA: Pacific Northwest National Laboratory; 2009.
[34] Lim EY. 2189. Probability of pipe fracture in the primary coolant loop of BWR plant, vol. 9. NUREG/CR; 1981.
[35] Lee NY, Hwang IS, Yoo H. New leak detection technique using ceramic humidity sensor for water reactors. Nuclear Engineering and Design 2001;205(1–2):23–33.
[36] Harris DO, Lim EY. Application of fracture mechanics model of structural reliability to the effects of seismic events on reactor piping. Progress in Nuclear Energy 1982;10:125–59.
[37] Doctor SR, Becker FL, Heasler PG, Selby GP. Effectiveness of U.S. in-service inspection technologies: a round Robin test. In: . Proceedings of a specialist meeting on defect detection and sizing 1983;vol. 2. p. 669–78. (CSNI Report No. 75 and EUR 9066 II EN).
[38] Taylor TT, Spanner JC, Heasler PG, Doctor SR, Deffenbaugh JD. An evaluation of human reliability in ultrasonic in-service inspection for intergranular stress corrosion cracking through round robin testing. Materials Evaluation 1989;47:338.
[39] Heasler PG, Doctor SR. Piping inspection round Robin. NUREG/CR-5068, PNNL-10475. Washington, D.C: U.S., Nuclear Regulatory Commission; 1996.
[40] Khaleel MA, Simonen FA. Effects of alternative inspection strategies on piping reliability. Nuclear Engineering and Design 2000;197:115–40.

Notation

a: crack depth
A_{cr}: area of crack
A_p: area of cross-section of pipe
b: one-half of crack length

C_1–C_9: material dependent constants
C_{12}, C_{13}, C_{15}: material dependent constants
C_{14}: material dependent random variable
d: spacing between two cracks
$D\sigma$: damage parameter
E: modulus of elasticity
f_1: sensitization term
f_2: environmental term
f_3: loading term
G: material dependent constant
h: pipe wall thickness
J: material dependent random variable
K: stress intensity factor
K_a: stress intensity factor in the depth direction of crack
K_{ap}: stress intensity factor for applied stress
K_b: stress intensity factor in the length direction of crack
K_{res}: stress intensity factor for residual stress
l, l_1, l_2: crack length
n: number of possible initiation sites in the pipe
N: number of simulations
N_f: number of failure cases
O_2: oxygen concentration
Pa: degree of sensitization
P_f: probability of failure
Q: leak rate
Ri: internal radius of pipe
t_I: time to initiation of stress corrosion cracking
T: temperature
v_1: initiation crack growth velocity
v_2: fracture mechanics based crack growth velocity
γ: water conductivity
δ: crack opening displacement
ε: smallest possible PND for very large cracks
σ: applied stress
σ_f: flow stress
σ_{LC}: load-controlled component of stress
σ_{net}: net-section stress
υ: 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