Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Engineering and Design 235 (2005) 1909–1918

Nuclear Engineering and Design

www.elsevier.com/locate/nucengdes

Sensitivity analysis of input parameters for pressure tube integrity evaluation

Sang-Log Kwak [a,*], Joon-Seong Lee [b], Young-Jin Kim [c], Youn-Won Park [d]

[a] *Safety Research Team, Korea Railroad Research Institute, Uiwang-city, Kyonggi-do 437-050, Republic of Korea*
[b] *Division of Mechanical System Design Engineering, Kyonggi University, Suwon, Republic of Korea*
[c] *Division of Mechanical Engineering, Sungkyunkwan University, Suwon, Republic of Korea*
[d] *Korea Institute of Nuclear Safety, Daejeon, Republic of Korea*

Received 18 November 2004; received in revised form 26 May 2005; accepted 30 May 2005

Abstract

Pressure tubes in CANDU reactor are the most important components that contain fuel. The operating experiences show leaks and burst in pressure tubes over the past two decades. The integrity of pressure tubes is, therefore, key concern in CANDU reactor. Once a CANDU reactor put into operation, their integrity could be checked by in-service-inspection. However, comparing to the total number of pressure tubes in a CANDU reactor, only a small number of pressure tubes are selected for inspection, since there is no weld. The inspection scope and results have been treated so far using a deterministic approach. Taking into account the difficulty in inspection sampling and in extrapolating the results to the entire core, a probabilistic approach is necessary. In this study, probabilistic integrity assessments are carried out considering key factors, such as initial hydrogen concentration, defect shape, delayed hydride cracking (DHC) velocity and fracture toughness. The leak and failure probabilities are calculated as a function of time by applying Monte Carlo simulation.

1. Introduction

Since several incidents of leaking in the pressure tube have been experienced, significant efforts have been made to improve the pressure tube integrity design, material and fabrication upgrades during the last decade. As a result of the research, the fitness for service guideline (Hopkins et al., 1998) provides the flaw acceptance criteria for pressure tubes. FFSG is developed under the basis of ASME Code Sec. XI Code (1996), where FFSG uses conventional deterministic fracture mechanics approaches are used.

Due to the uncertainty in examination, conservative data are used for the integrity evaluation. For example, lower bound in fracture toughness and upper bound in stress data, crack growth rate are used. It results in, therefore, difficulty in estimating lifetime. The 53 tubes at Wolsong unit 1 are inspected, the number is

* Corresponding author. Tel.: +82 31 460 5544; fax: +82 31 460 5509.
E-mail address: slkwak@korea.com (S.-L. Kwak).

0029-5493/$ – see front matter
doi:10.1016/j.nucengdes.2005.05.008

Nomenclature

a	crack depth
c	crack length
COV	coefficient of variance
DHC	delayed hydride cracking
DHCV	delayed hydride cracking velocity
FAD	failure assessment diagram
FAL	failure assessment line
K_I	stress intensity factor
K_{IC} or K_C	fracture toughness
N_{fail}	number of failure
R	inner radius
t	pipe thickness
TSS	terminal solid solubility
TSSD	terminal solid solubility for hydride in dissolving
TSSP	terminal solid solubility for hydride precipitation
σ	standard deviation of probabilistic variable
σ_a	applied stress
σ_c	plastic collapse stress
μ	mean values of probabilistic variable

far beyond the code requirement (CSA, 1994). Statistical analysis of inspection results by Park et al. (2002) shows that about 45% of pressure tube has defects regardless of their significance. Considering the inspection coverage is limited to 15% of pressure tubes, it is necessary to develop a tool for evaluating pressure tube integrity accounting for un-inspected portion. The probabilistic approach would be a suitable way for the evaluation in taking into account the uncertainties associated with important integrity parameters, such as in-service-inspection sampling sizes, flaws distribution, initial hydrogen concentration and material properties (Bloom, 1984). Many outstanding probabilistic research works have been conducted, especially for reactor pressure vessel in the event of pressurized thermal shock (Jhung et al., 2003; OECD/NEA, 1999; Shibata, 1999; USNRC, 1896) and also for nuclear piping (Dillstrom, 2000; Harris, 1992). However, since the probabilistic integrity assessment of pressure tubes requires more complicated input data, only limited studies were so far performed.

In this paper, the evaluation of failure probabilities of pressure tubes considering delayed hydride cracking (DHC) mechanism was investigated using Monte Carlo simulation (Rubinstein, 1981). PROBie-PT (probabilistic integrity evaluation code for CANDU pressure tube) was developed. Sensitivity analysis for each input variables were conducted using PROBie-PT.

2. Flaw initiation and growth

Since Monte Carlo simulation is an iterative technique repeating deterministic analysis, deterministic integrity assessment is the basis of probabilistic analysis. Many references (Douglas and Edwin, 1999; Moan et al., 1990; Pan et al., 1996) are available for details of deterministic analysis on CANDU pressure tubes. The characteristic of pressure tubes integrity assessment is cracking mechanism. Pressure tube cracking mechanism is governed by delayed hydride cracking, whereas the cracking mechanisms of other structures are governed by fatigue or corrosion. While the fatigue crack growth is in the order of 10^{-8} m/cycle, the crack growth by DHC is in the order of 10^{-6} m/cycle (Moan et al., 1990) in pressure tube. Therefore, the integrity evaluation is focused on the contribution of DHC in this study.

According to the inspection results analysis by Park et al. (2002), axial crack is dominant in pressure tubes because the metallurgical structure of pressure tubes is favorable for axial cracking rather than circumferential direction and hoop stress is higher than axial stress by two times. In general, the axial defects found in pressure tubes are associated with debris or scratch that make easier to produce defect in axial direction. Once a sharp notch is made, the stress concentrates at the tip. The hydride formation and its associated crack are very susceptible to high stress location. When a hydrogen concentration is higher than terminal solid solubility and a stress intensity factor is above a threshold value, hydrides are predicated and crack growth by DHC occurred (Moan et al., 1990). The DHC velocity is independent of the stress intensity factor once the threshold was exceeded. Since the velocity is a function of temperature, the cumulative crack growth is determined by numerically integrating the velocity (m/s) over the cool-down time (s). The probabilistic distribution of DHC velocity is used for probabilis-