Transactions of the Korean Nuclear Society Autumn Meeting
Jeju, Korea, October 21-22, 2010

Development of an Integrity Assessment Procedure for CANDU Pressure Tubes

Hansub Chung
Nuclear Power Generation Lab, KEPRI, 65 Munji-Ro Yuseong-Gu, Daejeon 305-380, Korea
hschung@kepri.re.kr

1. Introduction

The pressure tubes used in a CANDU reactor are made from Zr-2.5Nb. During service the pressure tubes operate at temperatures between about 150 and 310℃, and with variable coolant pressures up to 11MPa corresponding to hoop stress of up to 130MPa. The maximum flux of fast neutrons (E>1MeV) from the fuel is about $4 \times 10^{17} nm^{-2}s^{-1}$. The pressure tubes are exposed to very severe degradation environment. The aging degradation of the pressure tubes are summarized as below.

- Geometric deformation; axial elongation, diametric creep, and wall thinning.
- Deuterium uptake; some fraction of the deuterium generated by the corrosion of pressure tubes is absorbed into the pressure tubes. Total equivalent hydrogen content in the pressure tube is the sum of the initial hydrogen content before operation and the deuterium uptake during operation. High concentration of hydrogen inside the pressure tubes makes the metal susceptible to Delayed Hydride Cracking. The DHC is a degradation mechanism of prime importance for CANDU pressure tubes. Mechanical properties, in particular fracture toughness, are deteriorated by high concentration of dissolved hydrogen.
- Flaws; volumetric flaws are generated during operation. Wear scars by debris fretting, and bearing pad fretting are common. These volumetric flaws can be a site of crack initiation by fatigue or DHC. Cracks can propagate by DHC or fatigue crack propagation if conditions are met.
- Material properties degradation; mechanical properties are affected by neutron irradiation. Yield strength and tensile strength are increased, and fracture toughness is deteriorated. The susceptibility to DHC is also affected.

The integrity assessment of the pressure tube is a procedure to determine if the risk of pressure tube failure is controlled to maintain acceptably low.

CSA N285.4 and 285.8 are two important guidelines regarding the integrity of pressure tubes. N285.4 is to guide in-service inspection, and N285.8 integrity assessment. A terminology, core assessment, is used to denote the procedure to assess the overall integrity of each reactor. The core assessment is to determine that the risk of failure of the pressure tubes is maintained acceptably low.

2. Pressure Tubes Failure Scenarios

DHC is the degradation mechanism of prime importance for the pressure tubes. DHC is a failure mechanism that hydride is precipitated near tip of flaws under tensile stress and then the hydride is broken. The crack grows by repetitive precipitation and growth and breakage of hydrides. As the equivalent concentration of hydrogen is increased, the pressure tube is getting more susceptible to DHC. The hydrogen concentration is increased with operation years by deuterium uptake. If the equivalent hydrogen content exceeds the terminal solid solubility of the pressure tube, then the material is susceptible to DHC. The terminal solid solubility is 34ppm at 260℃, and 66ppm at 310℃. If the equivalent hydrogen content exceeds the terminal solid solubility under normal operation temperature, then the pressure tubes are susceptible to DHC during normal operation. Otherwise, the pressure tubes are susceptible to DHC only during heat-up and cool-down. Inappropriate combination of low temperature and high pressure during heat-up and cool-down may make the pressure tube susceptible to DHC.

There are flaws in the pressure tubes. Some of them may be originated from manufacturing stages, while most flaws are generated during operation. Bearing pad fretting flaws, debris fretting flaws, scratches are typical examples. These flaws are important because they can be the sites for crack initiation. DHC may be initiated near the tip of flaws. Fatigue may be another mechanism of initiating cracks. The crack, once initiated, can grow by DHC mechanism if the criteria of hydrogen concentration and loading are met.

The DHC crack grows in the radial and axial direction. The transverse texture makes the pressure tube more susceptible to DHC in the axial direction than in the circumferential direction, and the hoop stress is double the tensile stress. Once a crack penetrates the wall of pressure tube, then the crack grows only in the axial directions. The integrity of pressure tubes against rupture is supported by the leak before break. Once a through-wall crack penetrates the pressure tube, the Annulus Gas System detects the leakage and a safe shutdown procedure is initiated. This response of a station should be fast enough to cool down the reactor before the length of the crack reaches the critical length for rupture.

Roll joint region is a location of particular concern since high residual stress is formed by the rolling process, and the deuterium uptake rate is higher in the roll joint zone.

3. Integrity Assessment

The CSA code N285.8 provides a detailed guidance for the integrity assessment of pressure tubes. The core assessment denotes a procedure to determine if the probability of failure for the entire pressure tubes of a reactor is controlled acceptably low. Both deterministic and probabilistic assessment can be used. Detail of the procedure is described elsewhere[1,2].

There are a lot of variables involved in the integrity assessment of the pressure tubes, as below.

- Geometric deformation of pressure tubes
- Deuterium uptake and equivalent hydrogen concentration
- Flaws
- Material properties including DHC susceptibility
- Residual stress distribution in the roll joint
- Cool-down and heat-up curves
- DHC initiation criteria
- Plant's leak detection system and emergency shut-down procedure

An extensive calculation program is going on in order to assess the sensitivities of each variable affecting the integrity of pressure tubes. The assessment is based on the calculated probability of DHC initiation and failures of pressure tubes. The failure denotes fracture initiation and plastic collapse. Leak before break capability is also assessed by both deterministic and probabilistic methods.

It is verified through the current calculation that Wolsong pressure tubes have excellent LBB capability. The rupture of the pressure tube may not become a concern until the end of the designed life.

The results of the calculation program will be presented by probability of failures of pressure tubes against operation year. The sensitivity of each variable is assessed by the change of probability of failure led by change of each variable.

The plant in-service inspection program monitors the geometric deformation, deuterium uptake, flaws, and possibly the material properties. Most of them are monitored in a small number of sampled pressure tubes. Probabilistic distribution of those variables should be considered in order to assess the risk of failure for an entire reactor. There are uncertainties of the residual stress and deuterium uptakes distribution in the roll joint region. Cool-down and heat-up procedure may have a significant influence on the integrity of the pressure tubes. DHC initiation criteria are also very influential variables. A simple peak stress criterion may lead to very conservative calculations. Consideration of the hydride non-ratcheting heat-up/cool-down cycles, which is believed to be prevalent for Wolsong pressure tubes, may reduce the conservatism significantly.

From the preliminary assessment, it appears that the material properties, cool-down and heat-up curves, and DHC initiation criteria are the most influential variables. The pressure tubes are exposed to very severe degradation environment, and the long term operation may lead to severe degradation of materials properties. There are not good enough databases such that represent material properties of pressure tubes which operated very long approaching the end of design life. The uncertainty of the degraded material properties by long term operation is an important subject when the life of the pressure tube is assessed. This sensitivity assessment provides a valuable insight into the integrity of the pressure tube affected by degradation of material properties after long-term operation.

4. Conclusions

The integrity of the CANDU pressure tubes are assessed in accordance with the guidance provided in CSA code N.285.8. An extensive calculation program has been implemented in order to assess sensitivity of many variables affecting the integrity of the pressure tube. Material properties, DHC initiation criteria, and heat-up/cool-down curves were found the dominant variables affecting the calculation. Profound interest should be focused on the long-term degradation of the material properties for the fuel channel life cycle management plan.

REFERENCES

[1] CSA Standard N285.4-05, Periodic inspection of CANDU nuclear power plant components (2005)

[2] CSA Standard N285.8-05, Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors (2005)