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Effect of the Updated DHC and Fracture Toughness Models on the CANDU Pressure Tube Leak-Before-Break Evaluation

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1. Introduction

Pressure tubes serve as the coolant pressure boundary of the primary heat transport system of the CANDU reactor. However, they have degraded not only their material properties such as fracture toughness, hardness and other mechanical properties but also deformation, wear, crack and fracture under the severe operating conditions of a high neutron flux, high temperature and pressure. Thus, pressure tubes in the operating CANDU reactors should be checked periodically their integrity whether they maintain their function appropriately in spite of the degradation. CSA N285.8 code [1] provides the technical requirements and evaluation procedure for the integrity assessment of the operating pressure tube.

Many researches [2–4] have been done regarding the pressure tube integrity assessment such as the evaluation of the flaw assessment, delayed hydride crack (DHC) initiation and growth, leak-before-break (LBB) assessment by applying the deterministic and probabilistic methodology based on the CSA code issued in 2005.

However, CSA N285.8 code has updated its models for pressure tube integrity assessment and the latest version has been issued in 2015 [5]. The latest CSA N285.8 suggested new models for the fracture toughness and delayed hydride cracking rate which are used in the LBB assessment of the pressure tube.

KAERI has been developing the integrity assessment program for aged pressure tubes in CANDU reactors in order to secure the safe operation of domestic CANDU reactors at least until the design life span and has been issuing research results [6-9] regarding the flaw evaluation and failure assessment of the pressure tubes.

In this paper, we have focused on the LBB assessment and the newly suggested DHC and fracture toughness models from 2015 version of CSA N285.8 were verified and the effect of the models on the LBB assessment were compared with the former models described in 2005 version of CSA code. Since DHC and fracture toughness are key parameters in LBB assessment, we can get insights from the results how to overcome the safety issues occurred from the aged pressure tubes.

2. LBB Evaluation of CANDU Pressure Tubes

Although the term "leak-before-break" has been used in reference of pressure retaining components, in this paper, the term is used in the context of pressure tubes of CANDU reactor.

The premise of LBB evaluation is that the materials used are sufficiently tough (ductile) that small through-wall cracks resulting in coolant leak rates well in excess of those detectable by installed leak detection system would remain stable and not result in a guillotine break or equivalent rupture. The elements of LBB are as follows:

- Exclusion of active failure mechanism,
- Adequate ductility in the material
- Leakage detection capability
- Adequate time for safe shutdown
- Stability of large through-wall cracks

LBB assessment is a mechanistic application of fracture mechanics which considers all of the potential failure mechanisms, design loads, installed leak detection capabilities, the geometry of the postulated crack, and the material properties. The objective of the assessment is to quantify the margins that are available between detectable through-wall cracks and idealized cracks that are at the point of instability [10].

Fig. 1 shows the rough procedure of LBB assessment described in CSA N285.8 code. In order to accomplish LBB assessment we should calculate the delayed hydride cracking growth rate, fracture toughness of the material and critical crack length at which the unstable failure occurs.

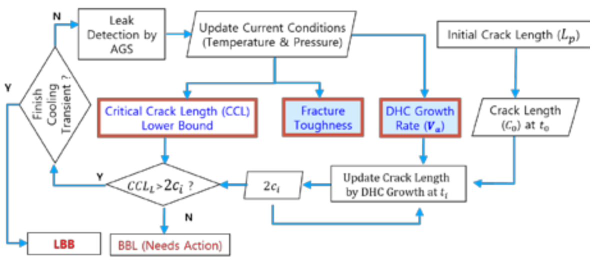

Fig. 1. LBB assessment procedure of pressure tube

To assure LBB in CANDU pressure tubes it is required that:

- The crack length at wall penetration be less than the critical crack length (CCL) for unstable propagation

- The leak be detected and the reactor put into a cold, depressurized condition before the crack length exceeds the CCL

Therefore, we should determine that how much time is available to detect the leak and to take action and how much time is required to detect the leak.

3. Effect of Updated Models of DHC rate and Fracture Toughness

3.1 Effect of DHC Growth Rate

Equations (1) and (2) show the DHC growth rate issued in 2005 and 2015, respectively [1, 5]. 2005 model considers the operating temperature only, but 2015 model includes the fluence which is dependent on the axial position of the pressure tube and it means that that the DHC growth may be different at the inlet and outlet locations.

$$V_a^U = 5.2\times10^{-3}\,exp\left(\frac{-Q_a}{R(T+273)}\right) \quad (1)$$

$$V_a^U = 6.989\,exp\left(-\frac{5951.4}{T+273} - 0.01834T_i + 0.01511\varphi - \frac{2.324}{\sqrt{t}}\right) \quad (2)$$

Fig. 2 shows the results of the calculated DHC grow rate from 2005 and 2015 models according to the temperature. As shown in the figure, DHC growth rates at the inlet and middle part of the pressure tube from 2015 model show more risky situation than 2005 model because of the fluence effect. However, DHC growth rate at the outlet shows more stable in the case of 2015 model than 2005 model. From the results, it was proven that the pressure tube at the inlet region is more susceptible to DHC crack so that the more focus has to be given at the inlet region of pressure tube.

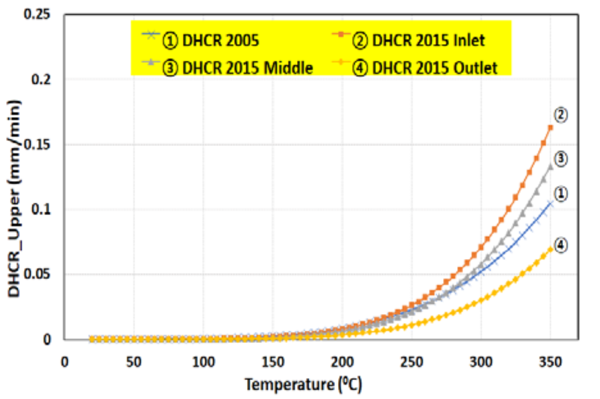

Fig. 2. Results comparison of DHC growth rate.

3.2 Effect of Fracture Toughness

Deterministic fracture toughness model K_C for both 2005 and 2015 model considers only temperature as show in equation (3).

$K_C = 27 + 0.3T$ MPa(m)$^{1/2}$ (T<150^{0}C), or

$K_C = 72$ MPa(m)$^{1/2}$ (T>150^{0}C) (3)

Fig. 3 shows the lower-bound fracture toughness and lower 90th percentile of fracture toughness distribution for 30 ppm or less hydrogen concentration from CSA N285.8.

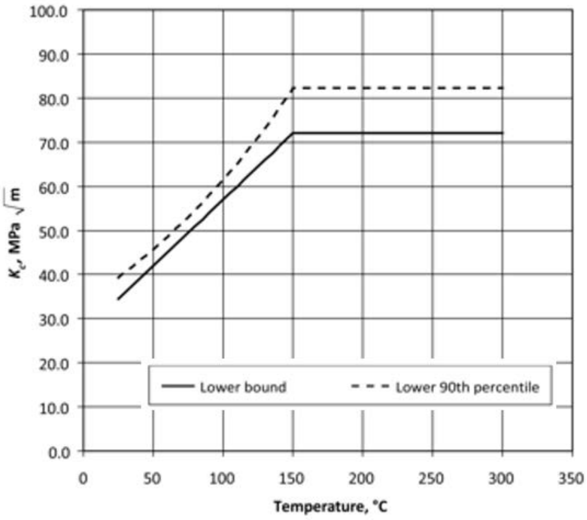

Fig. 3. Deterministic fracture toughness model [5].

However, in the case of probabilistic assessment, while 2005 fracture toughness model does not consider the hydrogen concentration variation, 2015 fracture toughness model is segmented its calculation region according to the hydrogen content and temperature range. Fig. 4 shows the calculated fracture toughness results from 2005 and 2015 models. As shown in the results, all calculated fracture toughness values from 2015 model are bounded for 2005 model and it means that the former model is more conservative.

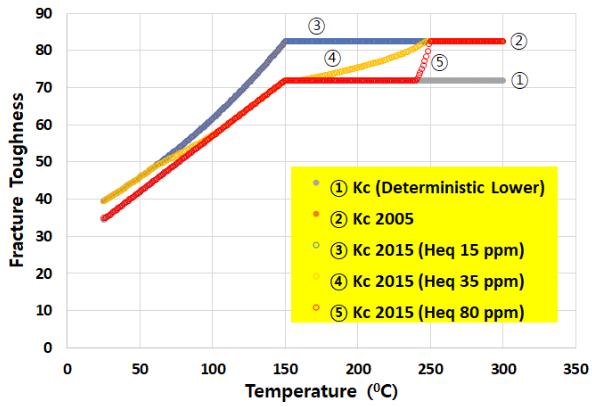

Fig. 4. Results comparison of fracture toughness.

4. Conclusions

In this study, the updated models for DHC growth rate and fracture toughness were verified from the CSA N285.8 code. Since DHC and fracture toughness are key parameters in LBB assessment, we can get insights from the results how to overcome the safety issues occurred from the aged pressure tubes. From the comparison results, it was found that the DHC growth rate was more susceptible at the inlet and middle region because of the temperature and fluence effect and the fracture toughness became non conservative than former criterion.

ACKNOWLEDGEMENTS

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