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Flaw Assessment Method of Pressure Tube in CANDU Reactor

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ABSTRACT

In CANDU reactor, each pressure tubes contain twelve fuel bundles and provide the inlet and outlet for the primary coolant. If a leak develops in the pressure tube, it is detected by Annulus Gas System which contains circulating dry CO_2 gas. Since the leaks caused by the flaws are resulted in pressure tube break, establishment of flaw assessment method is very significant in view of the fracture mechanics. In this paper, various criteria for assessing the flaws are presented to prevent the tube rupture and ensure the integrity of reactor operating.

1. Introduction

Pressure tube is a key component of the Primary Heat Transport System in CANDU reactor because they locate/support the fuel bundles in the reactor core, with the heat that is generated by the fuel being carried away by the pressurized heavy water primary coolant. Therefore pressure tubes experience high temperature, high internal pressure and high neutron flux. They also undergo corrosion by the slightly alkaline heavy water primary coolant that flows through them, with some of the deuterium resulting from this corrosion process being absorbed by the tubes.

Initially a pressure tube has less than 5 ppm of hydrogen. But deuterium is slowly absorbed by pressure tubes from the primary coolant (Figure 1). Eventually brittle hydrides will form in the pressure tubes that will break when they experience a high stress. In some early CANDU reactors, a few pressure tubes leaked becaues of Delayed Hydride Cracks (DHC). The cracks were easily detected by their leakage into Annulus Gas System (AGS), and then leaked tubes were identified and replaced.

Leak-Before-Break (LBB) of pressure tubes has already been demonstrated by the few in-reactor incidences of DHC that have occured. Confidence in LBB is created by the very sensitive leak detection system that exists for pressure tubes. AGS, which contains circulating dry CO_2 in annular space between pressure tube and calandria tube, can accurately detect a small water leak less than an hour after it starts (Figure 2).

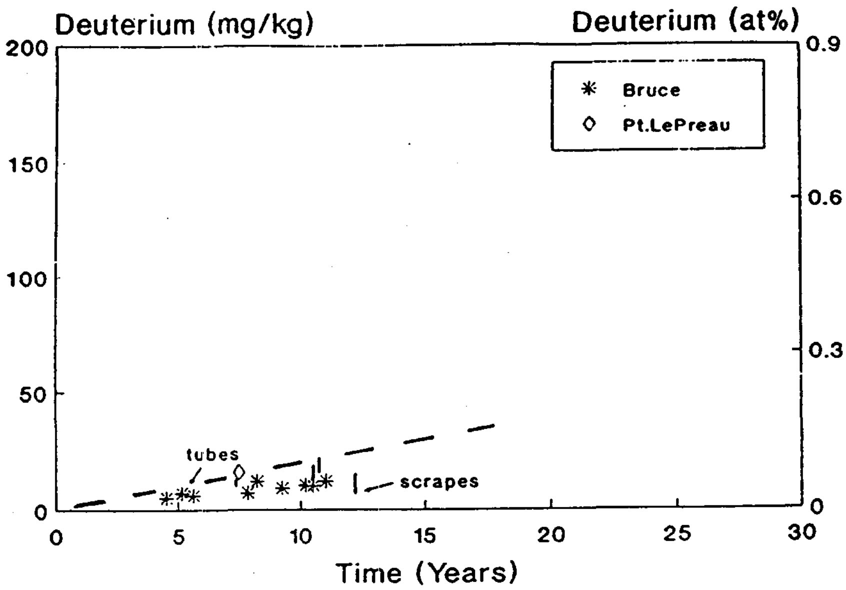

Figure 1. Increase of Deuterium Concentration in CANDU Reactor Pressure Tubes during Service

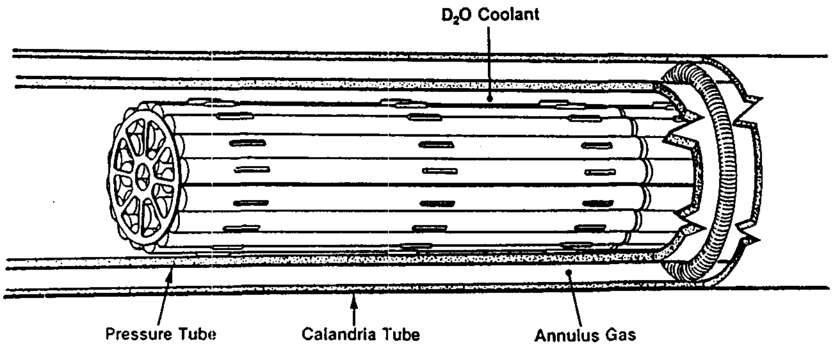

Figure 2. Annulus Gas System surrounding Pressure Tube

Applying LBB concept to the pressure tube, G.D.Moan and C.E.Colman discussed a methodology based on crack growth behaviour and leak detection capability available to operators [1]. Fitness for Service Guidelines was developed to provide acceptance criteria for flaws found in pressure tubes, as well as a standardized approach for the procedures used to assess the integrity of operating Zr-2.5% Nb pressure tubes [2]. For the evaluation of pressure tubes found to contain crack-like flaws, analytical procedures are defined for calculating the sub-critical fatigue and DHC flaw growth that could occur during the evaluation period [3]. In this paper, various criteria for flaw assessment are discussed to ensure margins against unstable fracture continue to be adequate.

2. Flaw Assessment

A pressure tube containing a flaw is assessed as being acceptable for continued operation if the following criteria are satisfied.

2.1 Demonstrate that fracture will not occur

$$K_I < K_i / \sqrt{10} \quad \textit{for Level A and B conditions}$$
$$K_I < K_i / \sqrt{2} \quad \textit{for Level C and D conditions} \qquad (1)$$

where

K_I = the maximum applied stress intensity factor for the loading condition being evaluated and the caculated flaw size a_f.

a_f = the maximum depth to which a detected flaw is calculated to grow during the evaluation period.

K_i = the critical stress intensity factor for fracture initiation based on temperature, neutron fluence and predicted hydrogen concentration.

2.2 Demonstrate that failure by plastic collapse will not occur

Circumferential flaws

$$\sigma_a < \sigma_m / 3.0 \quad \textit{for Level A and B conditions}$$
$$\sigma_a < \sigma_m / 1.5 \quad \textit{for Level C and D conditions} \qquad (2a)$$

where

σ_a = the maximum applied primary axial stress for the loading condition being evaluated.

σ_m = membrane stress corresponding to plastic collapse for the crack depth and angle being evaluated.

Longitudinal flaws

$$\sigma_h < \sigma^l_h / 3.0 \quad \textit{for Level A and B conditions}$$
$$\sigma_h < \sigma^l_h / 1.5 \quad \textit{for Level C and D conditions} \qquad (2b)$$

where

σ_h = the maximum applied primary hoop stress for the loading condition being evaluated.

σ^l_h = the hoop stress at plastic collapse for the crack depth and length being evaluated.

2.3 Demonstrate that DHC will not occur

$$K_I < K_{IH} \qquad (3)$$

where

K_I = the applied stress intensity factor for normal full power conditions and the final flaw size, a_f.

K_{IH} = the threshold stress intensity factor for DHC.

2.4 Demonstrate that crack initiation due to cyclic loading will not occur for service level A and B conditions

$$S_{max} < S_{th}, \qquad \sum_i n_i / N_i < 1.0 \tag{4}$$

where

S_{max} = the maximum alternating peak stress at the flaw tip (one-half of the stress range) for all Service Level A and B loading conditions.

S_{th} = the threshold alternating stress for fatigue crack initiation as determined from the fatigue crack initiation curve, which utilizes a factor of 2.0 on stress or 20 on cycles, whichever gives the more conservative result.

n_i = the number of load cycles up to the end of the evaluation period for each transient, i, being evaluated.

N_i = the allowable number of load cycles for the peak alternating stress at the flaw tip, associated with transient, I. N is to determined from the fatigue crack initiation curve, which utilizes a factor of 2.0 on stress or 20 on cycles which ever gives the more conservative result.

2.5 Demonstrate that even if the flaw could propagate by DHC through-wall, Leak Before Break (LBB) is assured

To assure LBB in 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.

LBB is demonstrated if $t > T$

where

t = the calculated time for an assumed through-wall crack to grow from its length at penetration to the critical crack length.

T = the response time of the leak detection system which includes the time required to confirm the presence of a leak at normal operating conditions and the time required to reach a cold depressurized condition.

The methodology for calculating the time t is described in Reference 3 and summarized below :

$$t = \frac{CCL - L_P}{2V} > T \qquad (5)$$

where

L_P = the initial length of crack at leakage.

CCL = the critical crack length which is defined as the minimum length of an axial through-wall crack that would be unstable at the temperature and pressure being evaluated.

V = the delayed hydride crack growth rate in the axial direction at the temperature being evaluated.

3. Conclusion

A flaw assessment method is available for pressure tubes in CANDU reactor. For flaws detected during in-service inspections, presented criteria in this paper will be used as a defense-in-depth for preventing pressure tube rupture. If the flaws penetrate into the tube wall and the leaks develope in pressure tube, the time available for the station operators to take a action is assured.

4. References

[1] G.D.Moan, C.E.Colman, E.G.Price, D.K.Rodgers and S.Sagat, "Leak-Before-Break in the Pressure Tubes of CANDU Reactors", *Int. J. Pres. Ves. & Piping 43 (1990) 1-21.*

[2] H.Wong, G.Moan, P.Richinson and D.Scarth, "Pressure Tube Fitness for Service in CANDU Reactors", *3rd IAEA Technical Committee Meeting, Bombay, India, Feb.1994.*

[3] E.G.Price, G.D.Moan and C.E.Coleman, "Leak-Before-Break Experience in CANDU Reactors", *ANS-ASME Topical Meeting, Myrtle Beach, Apr. 1988.*