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Effect of Transient Loads on Crack Growth in PHWR Pressure Tubes

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1. Introduction

A few hundreds of pressure tubes are the primary pressure boundary structure and are a key component in securing the safety of pressurized heavy water reactor. Pressure tubes are designed to maintain integrity during reactor operation. However, damage can occur as the operating time elapses due to high pressure, temperature and neutron flux [1].

Pressure tubes are evaluated on detected or postulated flaws based on CSA (Canada Standard Association) N285.8 [2]. Pressure tubes rupture assessment includes DHC (Delayed Hydride Cracking) initiation, fatigue crack initiation, DHC growth, fatigue crack growth, fracture initiation, plastic collapse. If crack initiation occurs due to fatigue crack or DHC, fatigue crack and DHC growth evaluation are performed from that time.

Fatigue crack growth is calculated for each transient state for the operating conditions. DHC growth occurs when stress intensity factor is higher than the threshold value (K_{IH}) and temperature is lower than temperature of hydrogen equivalent concentration (T_{TSSD}). And crack growth is terminated when fracture initiation or plastic collapse occurs.

As the operation time elapses, cracks may increase with the initiation and growth, which may lead to the fracture initiation or plastic collapse. Therefore, it is necessary to examine the effects of grown cracks on the integrity of the pressure tubes. In this study, the difference of crack growth was derived through parametric study as a deterministic evaluation method, and transient conditions variation.

2. Pressure Tubes Evaluation

2.1. Procedure of Integrity Assessment

During normal operation, when the operating load and time history load act on pressure tubes with the volumetric flaws, it develops fatigue crack or delayed hydride crack. In the case of fatigue initiation, the initiation time is calculated based on the S-N curve. In the case of DHC, the initiation time is calculated using hydride overload evaluation procedure. Fatigue and DHC growth are cumulatively calculated for each transient state, and rupture time of the pressure tubes is recorded by performing the fracture initiation and plastic collapse evaluation based on grown crack size.

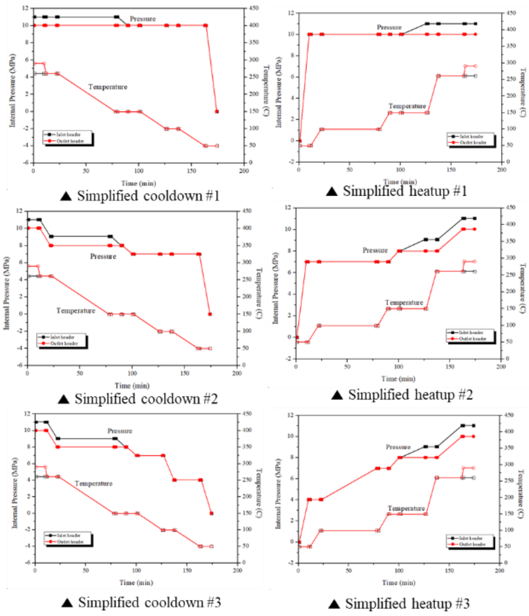


Fig. 1 Simplified transient conditions

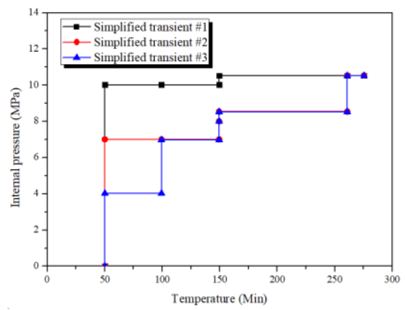


Fig. 2. Pressure-temperature relationship of transient conditions

2.2. Transient Conditions

Transient curves presented in Fig. 1 were used to analyze the difference in crack growth by combining three simplified CD (cooldown), HU (heatup) curves. Fig. 2 shows the temperature and pressure relationships for each transient. In transient #1 pressure considerably increase at low temperatures, and #2 and #3 increase the pressure step by step.

2.3. Crack Growth Condition

DHC growth occurs when the applied stress intensity factor is greater than a threshold value (K_{IH}) and the temperature is lower than a specific value (T^{c}_{DHC}). The K_{IH} and T^{c}_{DHC} are presented in CSA N285.8 as follows:

$$K_{IH} = 4MPa\sqrt{m}$$
$$T^{c}_{DHC} = T_{TSSD} - \Delta T^{c}_{DHC} \quad (1)$$
$$T_{TSSD} = \frac{-Q_D}{R\ln(H_{eq}/C_D)} - 273$$

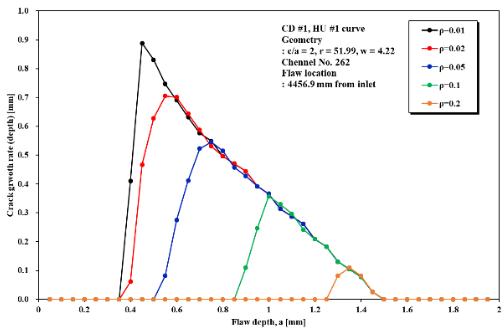
where, K_{IH}, T^{c}_{DHC}, ΔT^{c}_{DHC}, Q_D and C_D are threshold stress intensity factors for DHC, maximum temperature for DHC growth during continuous cooling, amount of undercooling below the T_{TSSD} required to initiation DHC growth during continuous cooling, activation energy for terminal solid solubility for hydrogen dissolution and terminal solid solubility for hydrogen dissolution constant, respectively.

3. Applicability

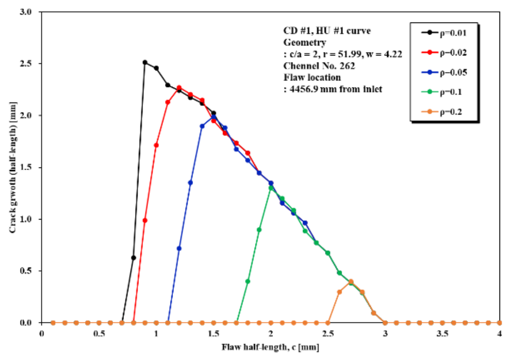
It is assumed that pressure tubes feature with an inner diameter of 51.99mm and a thickness of 4.22 mm and have no deformation over time. When the ratio of flaw half-length (c) and flaw depth (a) was c/a=2, flaw half-length and depth growth were analyzed.

As shown in Fig. 3, when CD #1 and HU #1 were applied, the smaller the root radius (ρ), the smaller the size at which crack growth occurs. Also, maximum crack growth decreases with increasing root radius.

The difference in crack growth with the change of transient condition is shown in Fig.4. When CD #1 is applied, it grows at a small flaw size than CD #2 and CD #3. Similarly, the difference according to the change in HU curves was examined but the change in three HU curves did not occur.

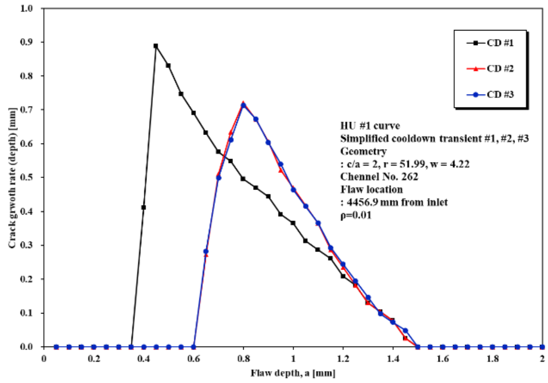


(a) Variation of flaw depth

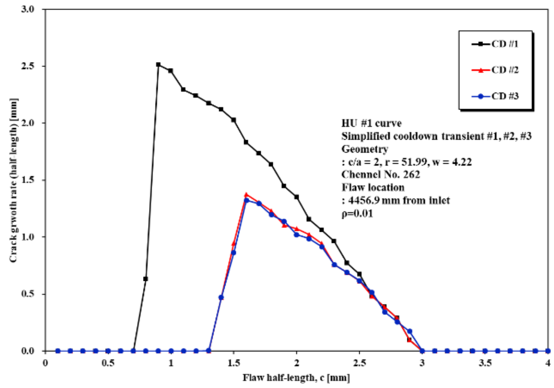


(b) Variation of flaw half-length

Fig. 3. Effect of crack-tip root radius



(a) Variation of flaw depth



(b) Variation of flaw half-length

Fig.4. Effect of cooldown transients

4. Conclusions

In this study, the difference of crack growth according to root radius and transient conditions was analyzed by the deterministic method.

(1) While the amount of crack growth depended on root radius and CD transient, changes in HU transients did not affect the crack growth.

(2) The flaw size at which crack growth occurred dependent on the root radius, and the sharper the crack, the smaller the size at which crack growth occurs.

(3) Maximum crack growth rate reduced when applying the step by step cooldown scenario, and change the size at which crack growth begins from 0.35 mm to 0.6 mm at flaw depth and 0.7 mm to 1.3 mm at flaw half-length.

REFERENCES

[1] Oh, Y.J. and Chang, Y.S., “Deterministic evaluation of delayed hydride cracking behaviors in PHWR pressure tubes”, Nuclear Engineering and Technology, Vol. 45, No. 2, pp. 265~276, 2012.

[2] CSA group, “Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors”, CSA N285.8-15, 2015.