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Sensitivity Analysis of Integrity Parameters in CANDU Pressure Tube using Probabilistic Fracture Mechanics

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ABSTRACT

Pressure tubes in CANDU reactor are the most important components that contain fuels. 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 inservice inspection. However, comparing to the total number of pressure tubes in a CANDU reactor, only small portion of pressure tubes is selected for inspection since there is no weld. The inspection scope and results have been treated so far using deterministic approach. Taking into account the difficulty in inspection sampling and in extrapolating the results to the entire core, the probabilistic approach is necessary. In this study, probabilistic integrity assessments are carried out considering key factors such as initial hydrogen concentration, defect shape, DHC velocity, and fracture toughness. The leak and failure probabilities are calculated as a function of time by applying Monte Carlo (MC) simulation.

KEY WORDS: delayed hydride cracking, failure assessment diagram, failure probability, integrity evaluation, Monte Carlo simulation, probability density function, probabilistic fracture mechanics

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 research, the fitness for service guideline (FFSG [1]) provides the flaw acceptance criteria for pressure tubes. FFSG is developed under the basis of ASEM Sec. XI Code[2], FFSG uses conventional deterministic fracture mechanics approaches.

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, which is far beyond the code requirement [1a]. Statistical analysis of inspection results by Park[3] shows that about 45% of pressure tube have defects whatever the 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 uninspected 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 ISI sampling sizes, flaws distribution, initial hydrogen concentration, and material properties[4]. Many outstanding probabilistic research works have been conducted especially for reactor pressure vessel in the event of pressurized thermal shock[5~8] and also for nuclear piping[9,10]. 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 in pressure tubes considering delayed hydride cracking (DHC) mechanism was investigated using Monte Carlo simulation[11]. PROBie-PT (Probabilistic Integrity Evaluation code for CANDU Pressure Tube) was developed. Sensitivity study for each input variables were conducted using PROBie-PT.

DETERMINISTIC INTEGRITY ASSESSMENT

Since Monte Carlo simulation is iterative technique repeating deterministic analysis, deterministic integrity assessment is the basis of probabilistic analysis. Many references[12] 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 (DHC) whereas 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[12] in pressure tube. Therefore, the integrity evaluation is focused on the contribution of DHC in this study.

Flaw initiation and growth

According to inspection results analysis by Park[3], axial crack is dominant in pressure tube because the metallurgical structure of pressure tube 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 easy produce defect in axial direction. Once a sharp notch is made, the stress concentrates at the tip. The hydride formation and its associated crack is very susceptible to high stress location. When a hydrogen concentration is higher than terminal solid solubility (TSS) and a stress intensity factor is above a threshold value, hydrides are predicated and crack growth by DHC occurred[13]. The delayed hydride cracking velocity (DHCV) was independent of the stress intensity factor once the threshold was exceeded. Since the velocity is a function of temperature, the cumulative crack growth was determined by numerically integrating the velocity over the cooldown cycle. The probabilistic distribution of DHCV was used for probabilistic analysis whereas upper bound is used for the deterministic analysis. Axial crack velocity is used to estimate flaw growth along the tube length. DHC propagation is possible if the hydrogen concentration at the flaw equals or exceeds the terminal solid solubility for hydride in dissolving (TSSD). However, in the present probabilistic analysis, hydrogen concentrations with terminal solid solubility for hydride precipitation (TSSP) temperature is used for conservatism. Relationship for the TSSD and TSSP as a function of temperature are shown in Fig. 1. Cooldown transient curve used in this study is shown in Fig. 2.

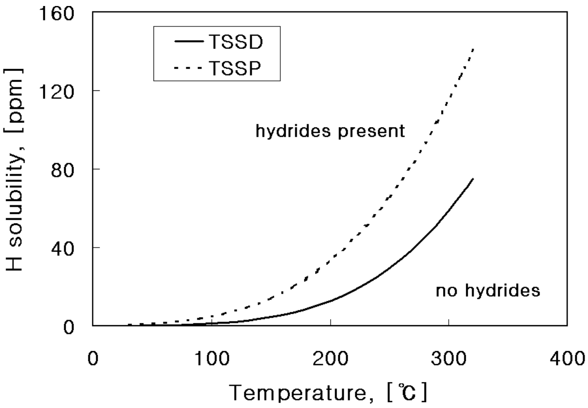

Fig. 1. Relationship of terminal solid solubility for dissolving and precipitation

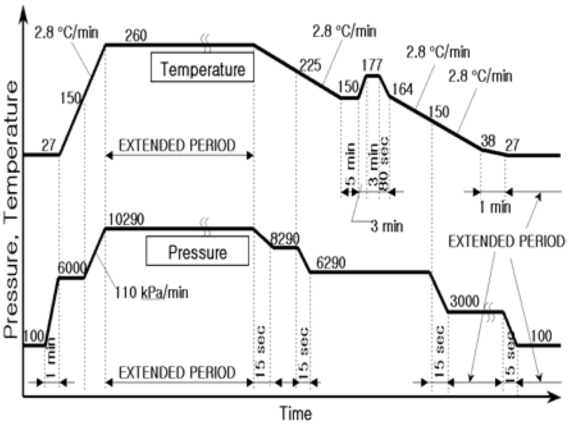

Fig. 2. Temperature pressure change during cooldown

Failure criteria

Pressure tube material is enough ductile at installation. However, as operating time elapsed, it loses ductility due to hydride precipitation and irradiation embrittlement. Current failure criteria used for pressure tubes are unstable fracture and plastic collapse. For the consideration of material behavior change the failure assessment diagram (FAD)[14] is used. For the application of FAD, failure parameters such as stress intensity factor (K_I), fracture toughness (K_{IC}), plastic collapse stress(σ_c) and applied stress(σ_a) should be available. Failure assessment line(FAL) used in FAD is shown in Eq. (1)~(3).

$$K_{r,\,FAL} = \left[1 + \frac{L_r^2}{2}\right]^{-1/2} \times \left[0.3 + 0.7\exp(-0.6L_r^6)\right] \tag{1}$$

$$K_r = K_I / K_{IC} \tag{2}$$

$$L_r = \sigma_a / \sigma_c \tag{3}$$

In general the stress intensity factor can be calculated using Raju-Newman equation[15]. In that Raju-Newman equation is applicable to radius/thickness ratio(R/t) equal 10 and the pressure tube has R/t ratio between 12 and 14, the stress intensity factor data were, therefore, derived by performing 3D finite element models for various surface crack shapes considering R/t ratio. A total of 40 analyses were performed for the ratio of crack depth to length from 0.2 to 1.0 and crack depth to wall thickness from 0.2 to 0.8. The loading condition was set to 10.4MPa of internal pressure considering normal operating condition. In this study fracture toughness is assumed to be log-normally distributed probabilistic variable. Mean value is expressed as function of absolute temperature (T) by Eq. (4), and the coefficient of variance is assumed to be 0.2.

$$K_{IC} = 61.3 + 0.22T \quad [MPa\sqrt{m}] \tag{4}$$

The global plastic collapse stress is determined using Zahoor's solution[16] whereas local collapse is determined using Kiefner solution[17]. Failure is assume to occur when crack depth to thickness ratio is greater than 0.8. LBB (Leak-Before-Break) condition cannot be applied simultaneously in the deterministic analysis. The LBB analysis means that when an unlikely leak through-wall DHC crack occurs, throughout the period of time needed for leak detection, confirmation, location and finally placing the reactor in a cold depressurized state, the growing crack length is always less than the critical crack length (CCL) in order to assure that the probability of an unstable pressure tube rupture is extremely low. Even with through-wall crack that produces leak, the failure of pressure tube does not occur immediately. Under the local collapse condition, plastic collapse is assumed to occur when crack depth is greater than 80% of wall thickness. Therefore, the LBB can be considered at global collapse condition. As shown in Fig. 3 that is FAD, straight line (box) is current failure criteria, whereas FAL is failure criteria used in this study. FAL is determined by recent SINTAP[10] results. Current criteria cannot explain region "B" in Fig. 3. In the FAD, two data set are displayed: one is derived from actual tensile strength and fracture toughness, and the other from mean value of tensile strength and fracture toughness.

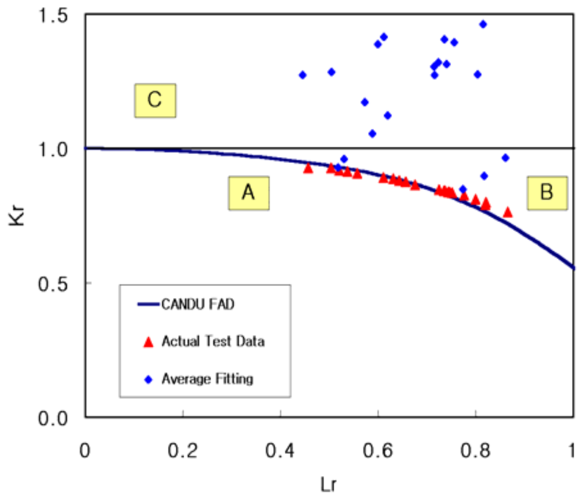

Fig. 3. Failure assessment line versus burst test data

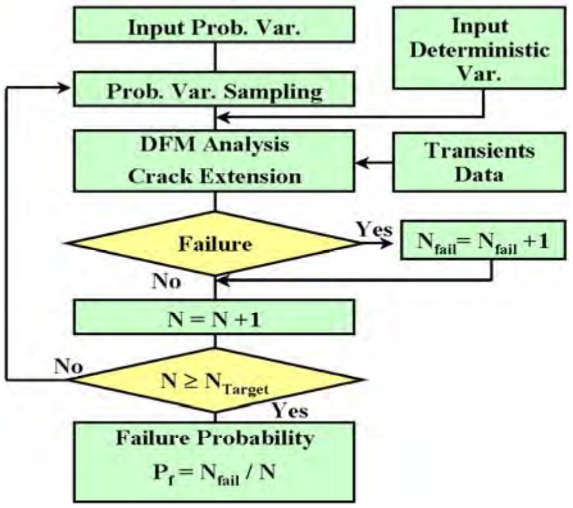

Fig. 4 Flow of PFM analysis

PROBABILISTIC INTEGRITY ASSESSMENT

Among various probabilistic approach Monte Carlo(MC) method is used in this study to evaluate failure probabilities as a function of operation time. Figure 4 illustrates the flow chart of PROBie-PT developed by KINS. Some probabilistic variables are selected according to an employed analysis model. Probabilistic variables include initial crack size, material properties and so on. Crack growth simulations by DHC are performed by deterministic fracture mechanics considering ISI and transients data. Finally, failure probabilities are calculated as a function of operation time. In MC simulation the convergence was obtained when number of iterations equal to 10^6. In order to decrease the random number effect, five independent simulations are carried and an average value is used as a result.

SENSITIVITY ANALYSIS FOR MAJOR INPUT PARAMETERS

The sensitivity analyses were carried out for the major input parameters that have large variation. Probabilistic density function (PDF) for each probabilistic variable assumed in this study was derived from ISI and testing data. Only axial surface crack grown by DHC is considered in this study because the fatigue crack growth is negligible comparing with that of DHC. Five cooldown cycles per year were assumed and a simplified analysis model is shown in Fig. 5. Details of probabilistic variables are shown in Table 1 and sensitivity analyses are explained in the following.

Table 1 Details of probabilistic variables

Probabilistic variables	PDF type	Mean	S.T.D.	Min. value	Max. value
Aspect ratio (*a/c*)	Exponential	0.12	N.A.	0.1	1.0
Depth ratio (*a/t*)	Log-normal	0.10	0.08	0.01	0.5
Fracture toughness (K_{IC}) [$MPa\sqrt{m}$]	Log-normal	67.0	12.0	20.0	120.0
Coeff. of radial crack extension($\times 10^{-2}$) [m/s]	Log-normal	5.30	0.58	2.0	14.0
Coeff. of transverse crack extension($\times 10^{-2}$) [m/s]	Log-normal	2.40	0.48	1.0	5.5
Initial hydrogen [ppm]	Normal	8.30	2.65	5.0	15.5
Flow stress [MPa]	Normal	1063.3	55.4	600	1400

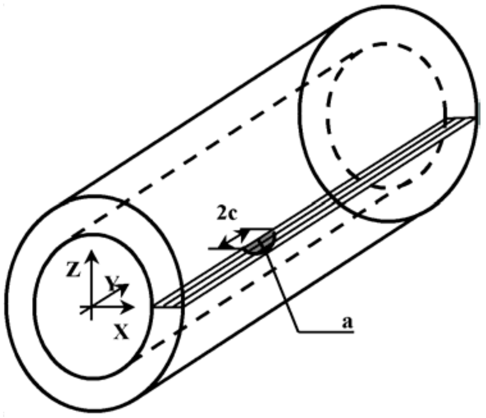

Fig. 5 Tube geometry with axial surface crack

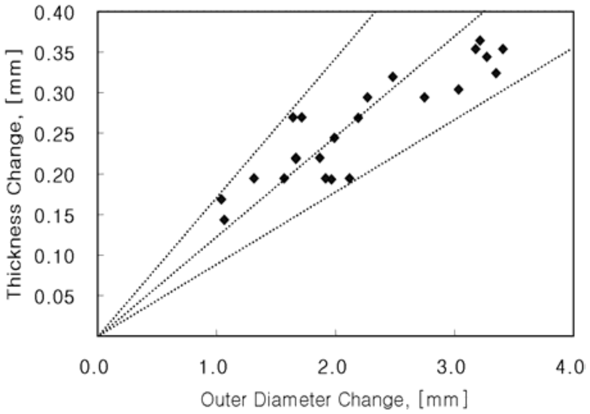

Fig. 6 Correlation between diameteral expansion and thickness decrease

<u>Dimensional change</u>

Physical deformations of pressure tubes, such as diametral increase, elongation, wall thickness decrease and so on, are produced as operation time elapses due to thermal creep, irradiation creep and irradiation growth. The design allowance for the diametral expansion of pressure tubes is conservatively limited to 5% of the initial value. The analysis of inspection data [3] shows that the dimensional changes in diameter and wall thickness are linearly dependent with operation time. The maximum change rates are obtained from ISI data with 0.03mm/year in thickness reduction and 0.11mm/year in radius increase. ISI data shows that there is strong correlation between thickness decrease and diametral increase as shown in Fig. 6. Dimensions used in these analyses are shown in Table 2. As shown in this table, three different cases were considered in dimensional change: no change, average change, and maximum change from the operation experience.

<u>Initial hydrogen concentration</u>

Initial hydrogen concentration is very important for DHC initiation and growth, however, it has such a large variation by up to four times. All ISI results show it has normal distribution with different mean values. The effects of initial hydrogen concentration was investigated using four different values as shown in Table 3.

<u>Fracture toughness and Flow stress</u>

Material properties on irradiated pressure tube material are dependent on temperature and even at the same temperature some variation exist. Therefore, sensitivity analysis was conducted for five cases of tensile properties and seven casees of fracture toughness. Tensile properties were considered to have normal distribution and fracture toughness to have log-normal distribution. Details of analysis case are shown in Table 4 & 5.

Table 2 Analysis case for dimensional change

	Initial dim. [*mm*]		End of life dim. [*mm*]		Dim. change rate [*mm/year*]	
	D_i	t	D_i	t	D	t
No dim. change	104.0	4.30	104.0	4.30	N.A.	N.A.
Ave. dim. change	104.0	4.30	110.4	3.10	0.16	0.02
Max. dim. change	104.0	4.30	112.8	3.10	0.22	0.03

Table 3 Parameter for hydrogen concentration sensitivity analysis

	Mean (μ)	S.T.D. (σ)	Min. value	Max. value	S.T.D. /Mean
Case 1	5.0	1.5	3.0	20.0	0.30
Case 2	7.0	2.1			
Case 3	8.3	2.7			
Case 4	10.0	3.0			

Table 4 Parameter for fracture toughness sensitivity analysis

Table 5 Parameter for flow stress sensitivity analysis

	Mean (μ)	S.T.D. (σ)	Min. value	Max. value	S.T.D. /Mean
Case 1	30.0	6.0	20	120.0	0.20
Case 2	40.0	8.0			0.20
Case 3	50.0	10.0			0.20
Case 4	60.0	12.0			0.20
Case 5	67.0	12.0			0.18
Case 6	67.0	20.0			0.30
Case 7	67.0	26.8			0.40

	Mean (μ)	S.T.D. (σ)	Min. value	Max. value	S.T.D. /Mean
Case 1	850.0	42.5	600	1400	0.05
Case 2	900.0	45.0			0.05
Case 3	950.0	47.5			0.05
Case 4	1000.0	50.0			0.05
Case 5	1063.0	55.4			0.52

Number of cooldown

At normal operation the hydride precipitation does not occur because the temperature is higher than TSSP. However, the hydride begin to precipitate as the reactor cooldown progresses if the solved concentration is above the TSSP. Therefore, it is assumed that DHC growth mainly occurs at cooldown process. Nine-cooldown cycles per year were assumed in design manual of pressure tube. However, in reality, the cooldown number is limited to one or two cooldowns per years. In this analysis, the number of cooldowns was accounted from one per year to five per year.

Flaw shape

Five analyses have been done for flaw shape distribution. ISI data of Wolsong unit 1 show that the crack aspect ratios are exponentially distributed. The exponential distributions with mean value of 0.12, 0.20, 0.30, 0.40 and logistic distribution with mean value of 0.61 and S.T.D. of 0.063 were used respectively. Since the flaw distributions observed in abroad were in logistic shape that is different from Korean one, not only the exponential distribution but also logistic distribution were considered.

Flaw initiation time

Since pressure tubes are subjected to sampling inspection, it is not easy to define when a crack is initiated. Operational experience shows a bathtub shape distribution that the probability of flaw initiation is higher at beginning and end of life rather than mid-span of life. This flaw initiation characteristic can be represented by beta distribution. Five analyses have been performed to investigate the effect of flaw initiation time as follows:

Case 1: Flaws are present from the start
Case 2: Flaws are uniformly generated during operation
Case 3: Flaws are generated to Beta(0.8, 0.6)
Case 4: Flaws are generated to Beta(0.8, 0.4)
Case 5: Flaws are generated to Beta(0.6, 0.2)

Effect of probabilistic variable selection

Among the seven probabilistic variables mentioned above, the effects of the probabilistic variable selection on failure probability were investigated considering the following 5 cases.

Case 1: All the seven probabilistic variables(aspect ratio, depth ratio, fracture toughness, two values of DHC velocity, initial hydrogen and flow stress) are considered.
Case 2: Six variables are accounted except initial hydrogen concentration that is assumed to be constant value of 8.3ppm.
Case 3: Six variables are accounted except fracture toughness assumed to be 67 $MPa\sqrt{m}$ at 27°C
Case 4: Six variables are accounted except flow stress assumed to be 1063MPa at 27°C
Case 5: Six variables are accounted except flaw aspect ratio assumed to be 0.12

Analysis Results

The results are represented by failure or leak probabilities of pressure tube as a function of time, which are shown in Figs.7~14. In general, a maximum allowable failure probability is provided for reactor pressure vessel and nuclear piping. But it is not for CANDU pressure tube. It is assumed to be 10^{-5} for the comparison of analyses results. Under these assumption dimensional change has the highest effect on failure probability as shown in Fig. 7. It changes 20 year for the analysis conditions. It means that pressure tubes which have high dimensional change must be inspected in detail during ISI.

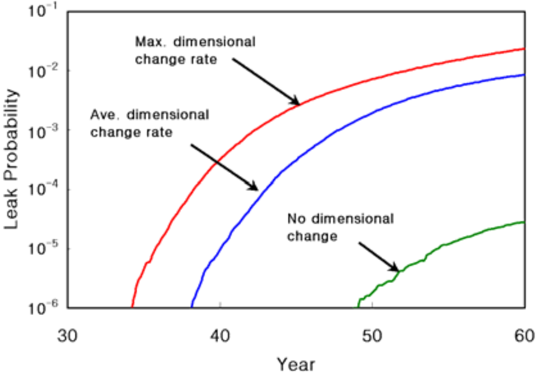

Fig. 7 Comparison of leak probability change as dimensional change

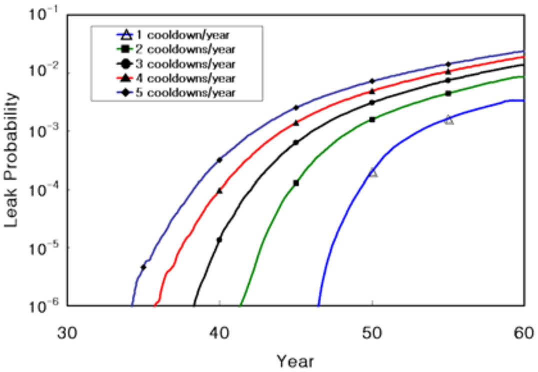

Fig. 8 Leak probability change as cooldown transient occurrence changes

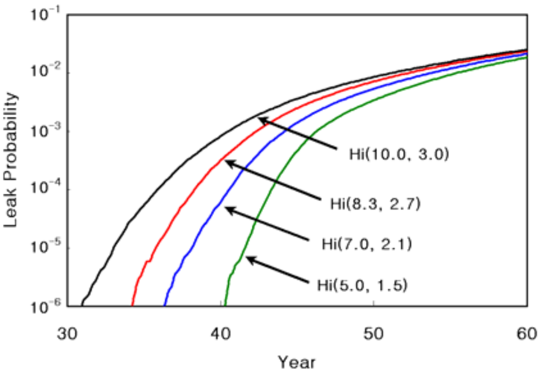

Fig. 9 Leak probability change as initial hydrogen concentration changes

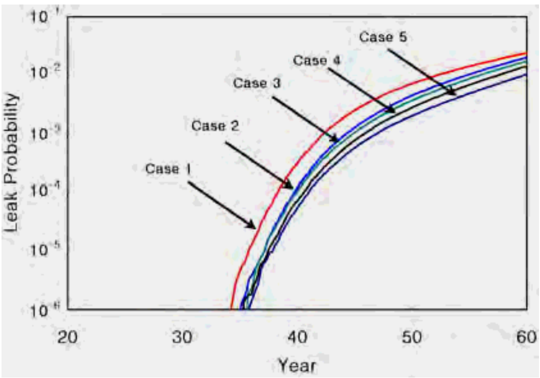

Fig. 10 Leak probability change for various flaw initiation models

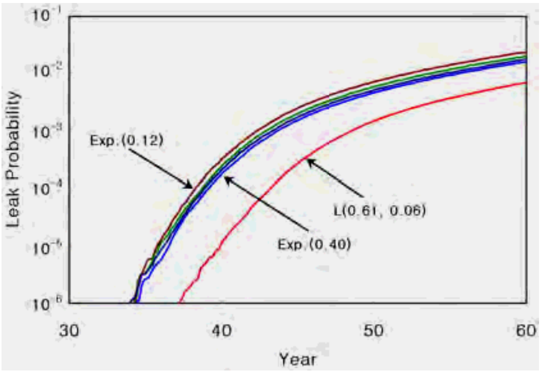

Fig. 11 Leak probability change for various flaw shapes

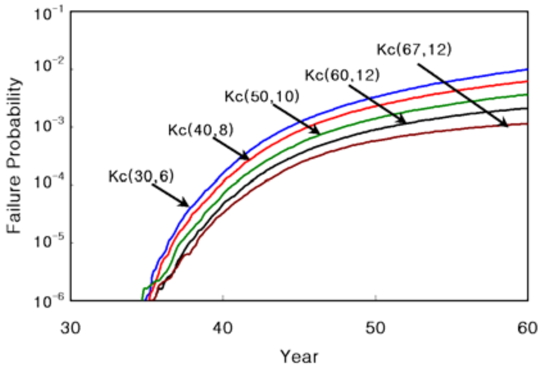

Fig. 12 Failure probability change for fracture toughness change

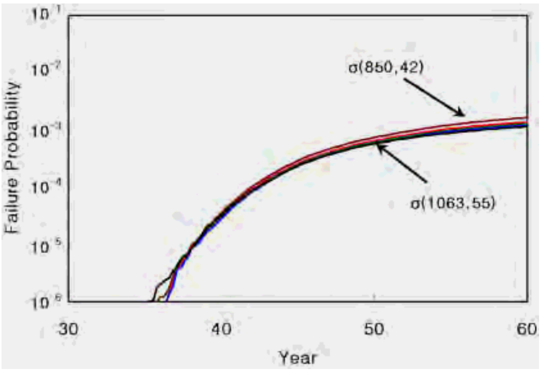

Fig. 13 Leak probability change for various flow stress distribution

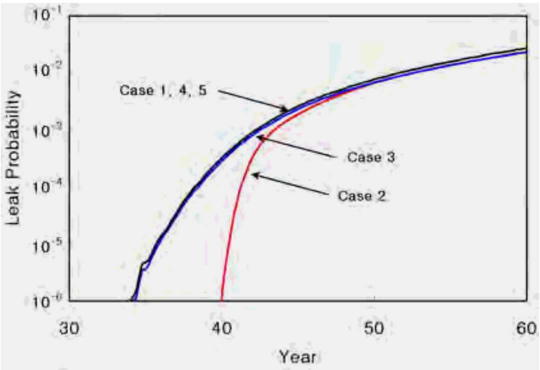

Fig. 14 Leak probability change for probabilistic variable selection

Number of cooldown and initial hydrogen concentration have high effects as well on failure probability as shown in Fig. 8 and 9 respectively. They change about 10 year for the analysis conditions. Fig. 10 shows about two-year difference in the flaw initiation model. This is because the growth by DHC is not expected at the low hydrogen concentration during the former part of operation time. Aspect ratio, fracture toughness and flow stress have low effects on failure probability. Results are shown in Figs 10~13. Fracture toughness has less effect on the failure probability than leak probability. The results of sensitivity analysis on the fracture toughness are shown in Fig. 12. Only two-year difference is observed as fracture toughness distribution changes. It means that pressure tube material is high enough in fracture toughness so that no safety margin can be applied on fracture toughness. In the deterministic analysis maximum value of applied stress intensity factor does not exceed the minimum value of fracture toughness. So failure is not expected until crack depth is increase as to 80% of pressure tube. In Fig. 11, small effect is observed for aspect ratio with exponential distribution, but some difference were observed in case of logistic and exponential distribution.

Figure 14 shows an effect of probabilistic variable selection. For example, when initial hydrogen concentration is assumed to be deterministic variable allowable life can be extended by 6 year. It means actual failure could be expected only when probabilistic variables are properly selected.

CONCLUSION

Sensitivity analyses were conducted for evaluating CANDU pressure tube integrity using probabilistic fracture mechanics. For more realistic failure estimation FAD are applied instead of current failure criteria that explains test data more exactly.

Among the parameters selected for the probabilistic failure analysis, the dimensional change and number of cooldown cycle have high sensitivity for failure probability whereas fracture toughness, flow stress, flaw generation time have low sensitivity.

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