Journal of the Korean Nuclear Society
Volume 27, Number 5, October 1995

《Technical Report》

Safety Margin Improvement Against Failure of Zr-2.5Nb Pressure Tube

Yong Hwan Jeong and Young Suk Kim
Korea Atomic Energy Research Institute
(Received January 11, 1995)

Zr-2.5Nb압력관 파손에 대한 안전여유도 개선

정용환 · 김영석
한국원자력연구소
(1995. 1. 11 접수)

Abstract

This study is to assess the effects of increasing wall thickness on the safety margin of pressure tube in operating and of lowering initial hydrogen concentration on the DHC growth in respect to the improvement of the reliability of pressure tube in CANDU reactors.

The pressure tube with thicker wall of 5.2 mm shows much higher safety margin for flaw tolerance by 25% than the current 4.2 mm tube. The thicker pressure tubes have a great benefit in LBB assessment including the initial crack depth at which DHC occurs, the crack length at onset of leaking and the available time for action. The resistance for the pressure tube ballooning at LOCA accident is also increased with the thicker tube. The calculations for Heq concentration after 20 years of operation as a function of wall thickness and initial hydrogen concentration show that the 5.2 mm wall thickness tube with 5 ppm initial hydrogen concentration is the most resistant to DHC. With the lower initial hydrogen concentration, TSS temperature for the precipitation of hydride decreases and the crack growth during cooldown reduces.

요 약

CANDU 원자로에서 압력관의 건전성을 향상시키기 위한 방안으로 압력관의 두께를 증가시키는 방법과 압력관 제조공정에서 초기수소농도를 줄이는 방법이 연구중에 있다. 본연구에서는 압력관 두께증가가 가동중 압력관의 안전여유도에 미치는 영향과 새로운 압력관의 낮은 수소농도가 파손의 주원인인 DHC에 미치는 영향에 대해 연구하였다.

가동중 압력관에 날카로운 결함이 발생할 경우 5.2mm 두꺼운 압력관은 안전여유도 관점에서 현행 2mm 압력관에 비해 25% 증가효과를 보이는 것으로 나타났다. LBB평가에서도 두꺼운 압력관은 DHC

발생에 필요한 초기균열 길이(a), 중수누설 감지 시점에서의 균열길이(Lp), 중수누설후 압력관 파단까지의 허용시간(t)등에서 많은 이점이 있는 것으로 평가되었으며, 또한 LOCA시 압력관 파단관점에서도 유익한 것으로 나타났다. 여러가지 다른두께 및 다른 초기수소농도를 갖는 압력관을 대상으로 20년 가동후의 총 누적 수소량을 계산한 결과, 5ppm의 초기 수소량을 갖고 두께가 5.2 mm인 압력관이 가장 우수한 저항성을 보였다. 결함 성장평가에 있어서 초기에 낮은 수소량을 갖는 압력관은 20년 가동후에도 수소화물의 석출이 일어나는 TSS 도달 온도가 낮게 유지되며 냉각시 균열성장량도 매우 적은 것으로 나타났다.

1. Introduction

A fuel channel in CANDU reactors is consisted of zirconium alloy pressure tubes, sealed at each end with the end fitting that has side port connected to the heat transport system(HTS). Pressure tubes are in the most severe environment of CANDU reactor, i.e, high neutron flux, relatively high temperature, stress due to fluid pressure and corrosion from the heavy water of HTS. Pickering Units 2 [1], 3 and 4 [2] and Bruce Unit 2 [3] have experienced pressure tube failure caused by delayed hydride cracking (DHC), hydride blister and manufacturing defects. In Wolsong unit 1 three pressure tubes have also been replaced due to possible DHC at the surface flaws seemingly caused by debris fretting wear.

The problems in the pressure tube result in the reduction of the lifetime of CANDU reactor and can affect the assurance of its safety. Therefore the reliability of pressure tube is significant. There are two ways to improve the reliability of pressure tube; one is the improvement of material properties of Zr-2.5Nb by changing manufacturing process [4, 5] and the other by changing wall thickness. Thicker pressure tubes have disadvantage with respect to the neutron economy, but it can be compensated by the use of slightly enriched uranium(SEU) which is now under feasibility study to be used in Large CANDU.

The initial hydrogen concentration is another major item to assure the reliability of pressure tube because DHC depends on the hydrogen concentration and stress in a tube during service. The initial hydrogen concentration in a new tube is mostly uniform along the length, around the circumference and through the thickness. The currently optimized process has been successful in keeping the concentration less than 5 ppm in new tubes made since 1992 [4] and with the use of an increased wall thickness this value is considered not to be changed.

This study is to assess the effect of using thicker wall thickness on a flaw tolerance and a leak before break(LBB) and the effect of reducing initial hydrogen concentration on DHC during cooldown. Since the optimum wall thickness for the pressure tube has still to be determined, it is simply called "w" in this study, and the Tables contain the results of the calculations for different values of w between 4.2mm and 5.2mm which are the wall thickness of current pressure tube and the available maximum thickness for fuel burnup penalty assessed by AECL[6], respectively.

2. Safety Margin Assessment in Thicker Pressure Tube

2.1. Flaw Tolerance Assessment

The major flaws in pressure tubes arise from DHC and result in pressure tube fracture. Sharp flaws are acceptable if the following criteria are satisfied [7]; $K_I < K_{IH}$, where K_I is the stress intensity factor and K_{IH} is the threshold stress intensity factor to initiate delayed hydride cracking, hydrides are not present, the safety margin against fracture initiation is greater than or equal to $\sqrt{10}$ for service level A(nomal) and B(upset) conditions and $\sqrt{2}$ for service level C(emergency) and D(faulted) conditions, and the safety margin against plastic collapse is greater than or equal to

Table 1. Safety Margin Against Fracture Initation in a Flaw Tolerance Assessment

Wall Thickness (mm)		4.2 (std.)	4.4	4.6	4.8	5.0	5.2
Hoop Stress at Crack Tip, σ_H (MPa)	Inlet	169	163	155	149	144	139
	Outlet	147	140	135	130	125	120
Stress Intensity Factor, K_I (MPa$\sqrt{m}$)	Inlet	9.29	8.86	8.45	8.10	7.81	7.52
	Outlet	8.07	7.66	7.36	6.95	6.67	6.39
Safety Margin, (K_{IC}/K_I)	Inlet	3.49	3.66	3.83	4.00	4.15	4.31
	Outlet	4.12	4.34	4.52	4.79	4.99	5.21
Safety Margin Increase (%)	Aver.	0	5.1	9.7	15.4	20.0	25.0

3.0 for service level A and B conditions and 1.5 for service level C and D conditions. The safety margin for fracture initiation is indicated as K_{IC}/K_I, where K_{IC} is the fracture toughness of Zr-2. 5Nb alloy. This ratio is the safety margin and it is increased by increasing the wall thickness of the tube.

Table 1 shows the variation of hoop stress, stress intensity factor and safety margin for tubes with different wall thickness from 4.2mm to 5.2mm. The pressure at inlet and outlet ends used in calculation are 12.7 and 12.03 MPa, respectively. The lower bound fracture toughness of Zr-2.5Nb is given by[7]: $K_{IC} = 26.3 + 0.022T$, where T is the temperature in °C. This relation is based on lower bound K_{IC} values measured from pressure tube removed from reactors. The fracture toughness of Zr-2.5Nb alloy used in calculation of safety margin are 32.43 MPa$\sqrt{m}$ at inlet(278°C) and 33.29MPa$\sqrt{m}$ at outlet(318°C).

Using the pressure tube with the increased wall thickness leads to decrease in the hoop stress as shown in Table 1. As the wall thickness changes from 4.2mm to 5.2mm, the stress intensity factors, K_I, reduce from 9.29 to 7.52MPa$\sqrt{m}$ at inlet and from 8.07 to 6.39MPa$\sqrt{m}$ at outlet due to reduction of the hoop stress. Therefore, the safety margin is increased by 25% for the 5.2mm wall thickness tube with sharp flaw. The stress intensity factors associated with the flaw size were calculated to compare the safety margin against fracture initiation with different wall thickness [7]. This calculation is based on the flaw dimension(length 2c = 4.2mm, depth a = 1.2mm) found on the pressure tube O-08 in Wolsong Unit 1 in 1992 [8]. From reference 7, the stress intensity fac tor for a semi-elliptical surface crack is given by:

$$K_I = \sigma\sqrt{\pi a/QF}$$

where σ = applied hoop stress, Q = flaw shape parameter $[1.0 + 1.46(a/c)^{1.65}]$, a = flaw depth, c = half flaw length, F = geometry correction factor which is a function of a/c and a/w, $[M_1 + M_2(a/w)^2 + M_3(a/w)^4 f_1 f_2]$, $M_1 = 1.13 - 0.09(a/c)$, $M_2 = -0.54 + 0.89/[0.2 + (a/c)]$, $M_3 = 0.5 - 1.0/[0.65 + (a/c)] + 14[1.0 - (a/c)]^{24}$, $f_1 = [(a/c)^2(\cos\phi)^2 + (\sin\phi)^2]^{1/4}$, $f_2 = 1 + (1.0 - \sin\phi)^2[0.1 + 0.35(a/w)^2]$, ϕ = angle around the flaw front and $\phi = 90°$ corresponds to the deepest point of the flaw.

The effect of wall thickness on the safety margin at the inlet and outlet ends and the increase is shown in Fig. 1. This result means that the service life of pressure tube increases by 25% with using the thicker wall thickness.

2.2. LBB Assessment for Thicker Pressure Tube

LBB is based on the concept that fluid leaking from a crack can be detected and action taken before the flaw reaches a critical size. LBB is used in CANDU reactors as one item in the defence in dep-

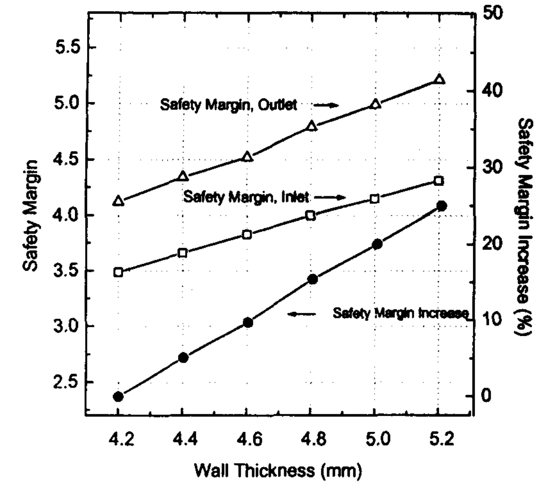

Fig. 1. The Varation of Safety Margin Increase in a Flaw Tolerence Assessment

th to avoid the pressure tube rupture. DHC may initiate on the inside surface of the tube if both of the following conditions are satisfied simultaneously; hydride present at the temperature and K_I exceeds K_{IH}. When the reactor is at power, there are no hydrides present because hydrogen concentration at operating temperature does not exceed terminal solid solubility (TSS). Therefore the flaws do not grow at high temperature. During cooldown, the hydrogen concentration exceeds TSS at certain temperature, and DHC continues during the cooldown. The crack growth occurs in the radial and axial directions during cooldown, at rates that depend on the local temperature. The radial growth eventually leads to wall penetration and leakage. After wall penetration, additional crack growth occurs by DHC in the axial direction (if the H concentration is high enough) and the crack length increases by the growth in the inboard and outboard directions. The operators receive warning about the leakage from the dewpoint and beetle alarms, and have to take action before the crack reaches axially to the critical length at which the crack becomes unstable and the tube ruptures.

To assure LBB, it is required that the crack length at wall penetration is less than the critical crack length(CCL) for unstable propagation, that the leak is detected, and that the action is taken before the crack length exceeds the CCL. The time available for action, (t), is given as follows [9]:

t = (CCL-Lp)/2V (at the body of tube)

t = (2CCL-Lp-CR)/2V (at the rolled joint)

where CCL is the critical crack length, V is the growth rate of axial crack tip, CR is the crack length when the outboard growth stops at the rolled joint, and Lp is the crack length at onset of leaking and the upper bound of 4W(4 times wall thickness) which is based on two hundred measurement of crack shapes in pressure tubes from reactors, with average crack length of 3. 6W[10].

Increasing the wall thickness has the following effects in LBB calculations; Lp (=4W) increases and hoop stress decreases, so that CCL is increased and delayed hydride cracking velocity(DHCV) no effect. Table 2 shows the values of CCL, Lp and available time for action with increasing wall thickness of pressure tube. The initial crack depth for DHC is calculated from the equation of $K_{IH}=\sqrt{(2\pi a)}=4.5\text{MPa}\sqrt{\text{m}}$, where a is crack depth and $4.5\text{MPa}\sqrt{\text{m}}$ is the lower bound value in irradiated pressure tube[9, 10]. The lower bound CCL values are based on the data in reference 9, Lp is given as 4 times of the wall thickness at the body of tube and 7 times at the rolled joint, and CR is measured to be 22mm in the tubes removed from Pickering NGS A in 1973–74 [10]. The crack velocities are calculated from the equations of $\log10V=-2.61-(2244/T)+(102400/T^2)$ for the body of tube and $V=2.24\times10^{-3}\exp(-5204/T)$ for the rolled joint [9]. However the crack growth rate can be increased due to hydrostatic stress in the thicker wall thickness tube. To investigate the effect of wall thickness on DHC, experimental work is being performed for unirradiated Zr-2. 5Nb alloy with different wall thickness.

As shown in Table 2, the size of a sharp flaw needed for DHC increases with increasing the wall thickness. Therefore, the resistance to crack initiation

Table 2. LBB Assessment Data in an Increased Wall Thickness Tube

Wall Thickness (mm)		4.2 (std.)	4.4	4.6	4.8	5.0	5.2
Initial Crack Depth for DHC (mm)		0.11	0.12	0.13	0.14	0.15	0.16
CCL (mm)		60	63	66	69	73	77
Lp (mm)		16.8	17.6	18.4	19.2	20.0	20.8
Available Time (h)	at Tube	11.7	12.3	12.9	13.5	14.6	15.3
	at R/J	62	66	71	75	80	86

increases for the thicker wall thickness pressure tube. The available time for action at the body of a pressure tube is increased from 11.7h for 4.2mm wall thickness to 15.3h for 5.2mm wall thickness. Therefore, the benefit for LBB increases with the thicker wall thickness pressure tube. The effect of wall thickness on the initial crack depth to initiate DHC, on Lp and on CCL are shown in Fig. 2. It is seen that Lp increases with increasing wall thickness, but its effect on the available time from the equation of $t = (CCL\text{-}Lp)/2V$ is compensated for by the increase in CCL. Also, Fig. 3 shows the effect of wall thickness on the time available for action in the thicker pressure tube. The available time at rolled joint is increased from 62h to 86h in thicker pressure tube and much longer than that at the body of tube.

In this study CCL values for the quadruple melted(QM) new pressure tubes are considered to be the same as those for double melted(DM) old pressure tubes because tests have not yet been completed on the quadruple melted material. It is expected, however, that the measured increase in fracture toughness in the QM material[11] will be reflected in an increase in the CCL values, that will lead to a larger

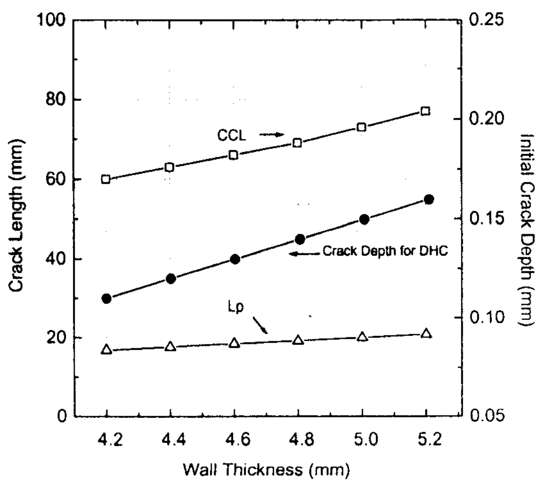

Fig. 2. Effect of Wall Thickness on Critical Length and Initial Crack Length and Initial Crack Depth for DHC

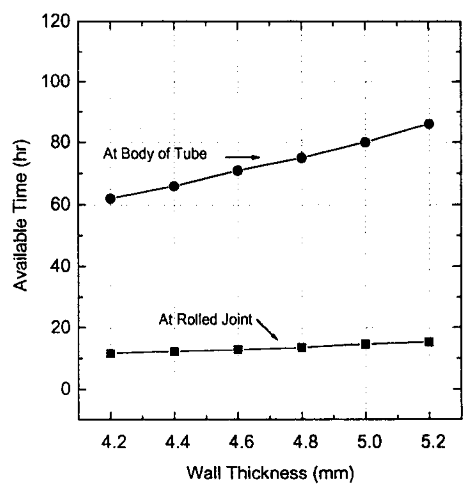

Fig. 3. Variation of Time Available for Action in LBB Assessment

margin in the LBB calculations.

The effect of a thicker pressure tube on an accident analysis indicates that the total pressure tube strain of the thicker tube is reduced during a large LOCA because of lower hoop stress. Therefore, pressure tube with an increased wall thickness is beneficial for pressure tube ballooning. If the thicker pressure tube contacts the calandria tube, it will contain more heat at the time of contact than the standard tube. This effect will tend to increase the heat flux from the outside of the calandria tube to the moderator just after contact and lead to a reduction margin to dryout. During LOCA/LOECC, if ECC is unavailable, additional pressure tube/calandria tube contact due to pressure tube ballooning or sag will occur. Sag contacts are not likely to be a problem because the heat transfer between the pressure and calandria tube is relatively low. An increase of pressure tube thickness might prevent the pressure tube from breaking during ballooning and might also delay the channel failure due to other mechanisms such as contact of molten materials with the pressure tube.

3. Effect of Lower Hydrogen Concentration on DHC During Cooldown

3.1. Equivalent Hydrogen Concentration (Heq)

The predicted total hydrogen concentration, Heq, is made up from the initial hydrogen concentration ($H_{initial}$) plus deuterium pickup (D_{pickup}) during operation. Since it is not expected that Heq exceeds TSS in the body of tube at operation, DHC may not occur at operation. However TSS can be exceeded during cooldown and DHC may initiate at sharp flaws during cooldown when TSS is exceeded.

The crack growth from a sharp flaw during one cycle of cooldown and the benefit arising from using tubes with lower initial hydrogen concentrations were assessed in this study.

The H equivalent concentration is given by: $Heq = H_{initial} + 0.5\ D_{pickup}$. The D pickup rate was discussed for 4.2 and 5.2mm tubes in reference 12. The use of a 5.2mm thick tube leads to 19% reduction in the D pickup rate. The initial hydrogen concentrations used for calculation are 15, 10, and 5 ppmH which represent the hydrogen concentration in some old tubes, in most old tubes, and in new tubes made since 1992, respectively.

Table 3 shows the predicted hydrogen equivalent concentration in tubes with different wall thicknesses and with different initial hydrogen concentrations. Hydrogen concentration is calculated by the use of 95% upper confidence level(UCL) deuterium pickup rate at 290°C in CANDU 6 pressure tube based on 1992 scrape data. Fig. 4 shows the variation of total hydrogen concentrations of a current 4.2mm tube and a thicker pressure tube with different initial hydrogen concentration during 30 years operation. As operation year increases, the gap of hydrogen concentration between 4.2mm and 5.2mm wall thickness tube increases at the same initial hydrogen concentration. Among the various tubes with different wall thicknesses and initial hydrogen concentrations assessed in this study, the 5.2mm wall thickness tube with

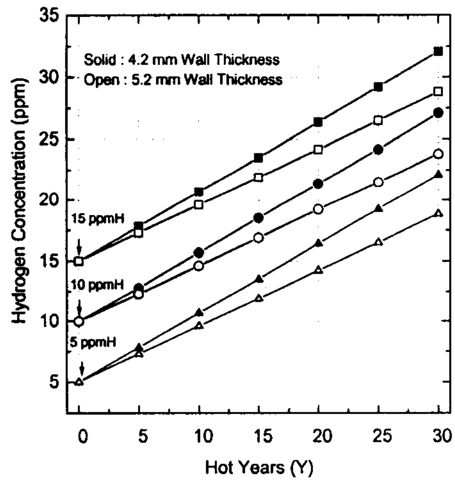

Fig. 4. Hydrogen Equivalent Concentration of Thicker Wall Thickness Tube with Different Initial Hydrogen Concentration

Table 3. Predicted Equivalent Hydrogen Concentration of Increased Wall Thickness Tube with Different Hydrogen Concentration.

Initial Hydrogen Concentration(ppm)	Wall Thick. (mm)	D-pickup* (ppmH/EFPY)	Hydrogen Concentration** (ppm) Years 0	5	10	15	20	25	30
	4.2	0.57	15	17.8	20.7	23.5	26.4	29.2	32.1
	4.4	0.54	15	17.7	20.4	23.1	25.8	28.5	31.2
15 ppm	4.6	0.52	15	17.6	20.2	22.8	25.4	28.0	30.6
TSS = 56ppm	4.8	0.50	15	17.5	20.0	22.5	25.0	27.5	30.0
at 290°C	5.0	0.48	15	17.4	19.8	22.2	24.6	27.0	29.4
	5.2	0.46	15	17.3	19.6	21.9	24.2	26.5	28.8
	4.2	0.57	10	12.8	15.7	18.5	21.4	24.2	27.1
	4.4	0.54	10	12.7	15.4	18.1	20.8	23.5	26.2
10ppm	4.6	0.52	10	12.6	15.2	17.8	20.4	23.0	25.6
TSS = 56ppm	4.8	0.50	10	12.5	15.0	17.5	20.0	22.5	25.0
at 290°C	5.0	0.48	10	12.4	14.8	17.2	19.6	22.0	24.4
	5.2	0.46	10	12.3	14.6	16.9	19.2	22.5	23.8
	4.2	0.57	5	7.8	10.7	13.5	16.4	19.2	22.1
5ppm	4.4	0.54	5	7.7	10.4	13.1	15.8	18.5	21.2
(new tube)	4.6	0.52	5	7.6	10.2	12.8	15.4	18.0	20.6
TSS = 56ppm	4.8	0.50	5	7.5	10.0	12.5	15.0	17.5	20.0
at 290°C	5.0	0.48	5	7.4	9.8	12.2	14.6	17.0	19.4
	5.2	0.46	5	7.3	9.6	11.9	14.2	16.5	18.8

* Calculated 95% Upper Confidence Level(UCL) D-pickup rate at 290°C by CANDU 6 pressure tubes based on 1992 scrape data and constant values with time

** $H_{eq} = H_{Initial} + D_{pickup}$

5ppm initial hydrogen concentration showed the lowest value of Heq in the body of tube.

3.2. DHC Growth Calculation

For simplicity of the calculation, it is assumed that the flaw is sharp and that K_I exceeds K_{IH}. To calculate the crack growth that occurs during a cooldown, it is also assumed that DHC starts immediately when TSS is exceeded. This assumption is very conservative because hydrides take time to form during cooldown and are not formed immediately when TSS is exceeded; also DHC needs an initiation time. For the calculation of the DHC crack growth during cooldown the followings are used.

1. The flaw is sharp, depth 1.0mm.
2. The flaw is located in the tube where operation temperature is 290°C.
3. The Heq concentrations for the different cases examined are listed in Table 3.
4. As the temperature is reduced during cooldown, the TSS is reduced and approaches the Heq concentration.
5. When Heq exceeds TSS, it is assumed that hydrides are formed and that DHC starts immediately. The crack growth rate, DHCV, depends on temperature.

6. With further cooling additional crack growth occurs by DHC at a rate that depends on the temperature.
7. The cooldown rates used were those applicable to Wolsong Unit 1, ie. 2.7°C/minute from 290 to 149°C then 1.8°C/minute from 148 to 100°C.

To calculate the amount of crack growth during cooldown, two different methods were applied; temperature interval method(5°C) and time interval method(5 minutes). Table 4 shows the effect of one cooling cycle on the culmulative depth of an initial flaw 1.0mm in a pressure tube with different initial hydrogen concentrations after 20 EFPY. It shows that lower initial hydrogen concentration decreases the Heq concentration and TSS temperature, and that the total crack growth during a cooldown cycle is smaller in a tube with low initial hydrogen concentration. The result also shows the effect of wall thickness on crack growth during a cooldown cycle; the 2mm wall thickness tube has a smaller crack growth than the 4.2mm tube with same H-initial concentration. Therefore, a 5.2mm wall thickness tube with 5ppm initial hydrogen concentration represents the least crack growth during cooldown.

In comparison of calculation for crack growth between 5°C interval method and 5 minute time interval method, it is shown that the crack sizes calculated using the temperature interval method are slightly higher than those from the 5 minute time interval method. It is noted that both methods are conservative since DHC is assumed in calculation to start immediately when TSS is exceeded.

4. Conclusions

The effects of an increased wall thickness on the safety margin of pressure tube and an initial hydrogen concentration on DHC crack growth during cooldown are studied. The results are as follows;

1. As the wall thickness is changed from 4.2mm to 5.2mm in pressure tube, the stress intensity factor, K_I, reduces from 9.27 to 7.52MPa$\sqrt{m}$ at inlet. Thus the safety margin for flaw tolerance increases by 25% for the 5.2mm wall thickness tube with a same flaw.
2. The available time for action in LBB assessment in the thicker pressure tube increases from 11.7h for 4.2mm to 15.3h for 5.2mm wall thickness. This means that the safety margin for LBB increases in the thicker wall thickness tube.
3. The effect on accident analysis indicates that the thicker pressure tube is benefical for pressure tube ballooning during large LOCA.
4. Among the various tubes with different wall thickness and different initial hydrogen concentration assessed in this study, the 5.2mm wall thickness

Table 4. DHC Flaw Growth Data in Pressure Tubes with 1.0mm Initial Flaw Depth and Different Initial Hydrogen Concentration

Initial H-concentration (ppm)	Wall Thickness (mm)	Predicted Heq. in 20 EFPY (ppmH)	TSS Temperature (°C)	Culmul. Flaw Depth (mm)	
				by Temp. Interval(5°C)	by Time Interval(5min.)
15	4.2	26.4	239.71	1.2937	1.2870
	5.2	24.2	234.46	1.2654	1.2626
10	4.2	21.4	227.24	1.2303	1.2235
	5.2	19.2	221.03	1.2034	1.2007
5	4.2	16.4	212.27	1.1700	1.1635
	5.2	14.2	204.54	1.1446	1.1420

tube with 5ppm initial hydrogen concentration is the best resistant with respect to Heq during service and DHC crack growth during cooldown.

References

1. G.J. Field, J.T. Dunn and B. A. Chedle; Can. Met. Quartely, 24, No. 3, 181 (1984)
2. P.A. Ross-Ross, J.T. Dunn, A.B. Mitchell, G.R. Towgood and T.A. Hunter; AECL report 5261 (1976)
3. C.E. Coleman, S. Saget, G.K. Shek, D.B. Graham and M.A. Durand; Int. J. Pres. Ves. & Piping, 43 187 (1990)
4. G.D. Moan, J.R. Theaker, P.H. Davies, I. Aitchison and C.E. Coleman; INS Conference Proceedings, C18-1, Toronto (1993)
5. J.R. Theaker, R. Choubey, G.D. Moan, S.A. Aldridge and C.E. Coleman; 10th int. Symposium on Zr in the Nuclear Industry, Baltimore (1993)
6. B.G. Kim and A. Gray; AECL Memo, 69 −03310−000 (1994)
7. Fitness for Service Guidelines for Zirconium Alloy Pressure Tube in Operating CANDU Reactors, COG 91−96 (1991)
8. Summary of 1992 CIGAR Inspection of Wolsong Unit 1 (1992)
9. G.D. Moan, S. Sagat, P.J. Ellis, J.K. Mistry and E. Coleman; PVP-Vol. 266, Creep, Fatigue Evaluation, and Leak-Before-Break Assessment, ASME (1993) 205
10. G.D. Moan, C.E: Coleman, E.G. Price and S. Sagat; Int. J. Pres. Ves & Piping, 43, 1 (1990)
11. J.R. Theaker, R. Choubey, G.D. Moan, S.A. Aldridge, L. Davis, R.A. Graham, and C.E. Coleman; ASTM STP 1245, 221 (1994)
12. Y.H. Jeong and Y.S. Kim; J. Korean Nuclear Society, 27, No. 2, 226 (1995)