Journal of the Korean Nuclear Society
Volume 27, Number 2, April 1995

《Technical Report》

Effect of an Increased Wall Thickness on Delayed Hydride Cracking in Zr-2.5Nb Pressure Tube

Yong Hwan Jeong and Young Suk Kim
Korea Atomic Energy Research Institute
(Received August 6, 1994)

Zr-2.5Nb 중수로 압력관의 수소지연파괴에 미치는 압력관 두께의 영향

정용환 · 김영석
한국원자력연구소
(1994. 8. 6 접수)

Abstract

The wall thickness of a pressure tube is increased in order to reduce the probability of failure in a pressure tube of CANDU type reactor. It is presented here that the variation of wall thickness changes stress, hydrogen concentration and delayed hydride cracking in Zr-2.5Nb pressure tube. When the wall thickness is increased from 4.2 mm to 5.2 mm, the stress exerted on the tube and the deuterium taken up during operation are reduced by 19%. Further, the calculated allowable depth of the surface flaw over which delayed hydride cracking(DHC) is susceptible increases by 50%. DHC initiation is controlled by the stress and by the hydrogen concentration in the pressure tube. The res ults are therefore very significant in such a respect that increased wall thickness may reduce DHC initiation. As the wall thickness increases the hydrostatic tension will increase. Its impact on the acceleration of the crack growth rate of DHC deserves further studies.

요 약

CANDU 원자로에서 심각하게 대두되는 압력관 파손을 방지하기 위해 압력관의 두께를 증가시키는 방안이 연구되었다. 본 연구에서는 압력관 두께변화가 Zr-2.5Nb 압력관의 응력, 수소농도 및 수소지연파괴에 미치는 영향에 대해 연구를 수행하였다.

압력관 두께가 현재의 4.2 mm에서 5.2 mm로 증가할 경우에 압력관이 받는 응력과 발전소 가동중에 누적되는 중수소 흡수량은 19% 줄어드는 것으로 나타났으며, 압력관에 균열이 발생할 경우 발전소 냉각동안에 일어나는 균열 성장은 상당히 감소한다. 수소지연파괴는 압력관이 받는 응력과 누적되는 수소량에 의해 지배되는데 이와같은 결과로부터 두꺼운 압력관은 수소지연파괴 관점에서 상당한 이점이 있는 것으로 평가되었다. 그러나 압력관 두께 증가는 수소지연파괴의 성장속도를 가속할수도 있으므로 앞으로 연구할 사항이다.

1. Introduction

The fuel channel in CANDU reactor consists of a zirconium alloy pressure tube, sealed at each end with end fitting that has side port connections to the heat transport system as shown in Fig. 1. The gap, or annulus, between the pressure tube and the surrounding Zircaloy-2 calandria tube is filled with an insulating gas and contains four close-coiled helical spring spacers that provide physical separation between the two tubes and partial support for the pressure tube [1]. The pressure tube is the most important component in the fuel channel and is designed to be replaceable. Pickering Units 1 and 2, which are the early units had the pressure tubes made of Zircaloy-2. The remainder of CANDU units use an alloy of Zr-2.5Nb on which AECL has devoted an intensive research effort.

Pressure tubes are in the most severe environment of CANDU reactor, embracing conditions of high neutron, relatively high temperature, fluid pressure stress, and corrosion from the heat transport system heavy water. Pickering Units 2 [2], 3 and 4 [3] and Bruce Unit 2 [4] had experienced the failure of pressure tubes caused by DHC(delayed hydride cracking), hydride blister and manufacturing defects. In Wolsong Unit 1 the three pressure tube has also been replaced due to possible DHC at the surface flaws seemingly caused by debris fretting wear.

The problems with the pressure tube result in the reduction of the life time of CANDU reactor and can affect the assurance of its safety. Therefore, the reliability of pressure tubes should be assured. There are two ways to improve the reliability of pressure tube; one is the improvement of material properties of Zr-2. 5Nb by the change of manufacturing process [5, 6] and the other the design change of pressure tube wall thickness. Thicker pressure tubes have disadvantage over the neutron economy, but it can be compensated by the use of SEU(Slightly Enriched Uranium) which is now under feasibility study for Large CANDU.

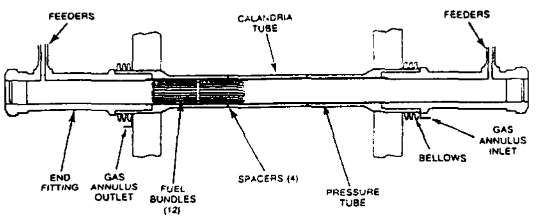

Fig. 1. Simplified Description of a Fuel Channel.

This study is to assess the effect of an increased wall thickness of pressure tube on stresses, deuterium pickup and delayed hydride cracking in the body as well as the rolled joint of pressure tube. Since the optimum wall thickness for the pressure tube has still to be determined, it is simply called "w" in this study, and Tables contain the results of the calculations for different values of w from 4.2 mm up to 5.2 mm.

2. Effect of an Increased Wall Thickness on Stress and Deuterium Pickup

2.1. Stress of Pressure Tube

The major stress in the pressure tube during operation is the hoop or circumferential stress arising from the internal pressure. The use of an increased wall thickness leads to a decrease in the hoop stress in the body of the tube as indicated in Table 1. The values in Table 1 show the variation of the inlet and outlet hoop stresses for different wall thicknesses from 4.2 mm up to 5.2 mm, and the percentage reduction over the values for a 4.2 mm tube. There is a 19% reduction in the hoop stress if the pressure tube thickness is increased to 5.2 mm. The stresses in the rolled joint are made up from the pressure stress plus the residual stresses from the rolling operation. The pressure stresses will be reduced slightly from those in current rolled joints because the thickness of the effect is considered minor. The more important stress is the residual stress. A review of stresses measured in the pressure tube in zero clearance rolled

Table 1. The Variation of Hoop Stress with Increased Wall Thickness

Wall Thickness (mm)		4.2 (Std.)	4.4	4.6	4.8	5.0	5.2
Hoop Stress (MPa)	Inlet*	156	149	142	136	131	126
	Outlet*	136	129	124	119	114	109
Hoop Stress Change(%)		0	−4.5	−8.9	−12.8	−16.0	−19.2

* The pressure at inlet and outlet ends are 12.7 MPa and 11.03 MPa, respectively.

joints [7] indicates that rolled joints made with pressure tubes having a wall thickness up to 5.5 mm provide acceptable residual stress. The residual hoop stresses on the inside surface of 5.5 mm thick pressure tube are generally below 70 MPa which compares well with the standard zero clearence joint in which the residual hoop stresses are between 35 and 70 MPa. The residual axial stresses at the inside surface were up to 480 MPa, compared with 300 MPa for current wall thickness. The residual stresses in the outside surface are slightly higher in tubes with thicker walls.

Fig. 2 shows the variation of stress intensity factor with increasing the wall thickness. The stress intensity factors associated with the flaw size were calculated

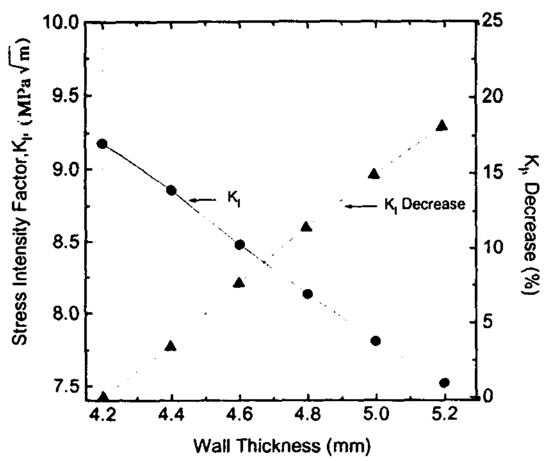

Fig. 2. Stress Intensity Factor in the Body of Tube with Thicker Wall Thickness

to compare the safety margin against fracture initiation with different wall thickness [8]. This calculation is based on the flaw dimension(length 2c = 4.2 mm, depth a = 1.2 mm) found on the pressure tube O-08 in Wolsong Unit 1 in 1992 [9]. From reference 8, the stress intensity factor for a semi-elliptical surface crack is given by:

$$K_I = \sigma\sqrt{\pi a/Q}F$$

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 = 90° corresponds to the deepest point of the flaw. If the wall thickness increase from 4.2 mm to 5.2 mm, the stress intensity factor, K_I, for 5.2 mm tube is reduced by about 18%. This means that the resistance to fracture is increased by 18% at the same flaw.

2.2. Deuterium Pickup in the Body of Tube

In CANDU fuel channnels that use CO_2 as the annulus gas it is considered that very little deuterium is picked up via the outside surface, and in the body of the tube it can be assumed that all of the deuterium is picked up from the inside surface as a result of the corrosion reaction at the inside surface :

$$Zr + 2D_2O \rightarrow ZrO_2 + 4D.$$

Most of the deuterium released by this reaction dissolves in the D_2O coolant, but about 5% of it is absorbed by the pressure tube [10]. At the oxide thicknesses found in CANDU pressure tubes the corrosion rate and total deuterium(D) pickup at the inside surface are independent of the wall thickness of the tube. Thus the total deuterium pickup in the body of the tube is not affected by the wall thickness ; the deuterium concentration is, however, affected by the wall thickness, as the deuterium concentration is calculated from the amount of D picked up divided by the material that absorbed it.

For tubes with deuterium pickup only at the inside surface the deuterium concentration in a thicker tube be smaller than that in a current tube, and depends on the inverse of the wall thickness, ie :

$$D_{thick} = D_{4.2}(4.2/w)$$

where D_{thick} is the deuterium concentration in a tube with wall thickness w compared with the D concentrarion in a 4.2 mm thick tube($D_{4.2}$). D pickup rates were calculated by the 95% upper confidence level in CANDU 6 pressure tube based on 1992 scrape data. Table 2 shows how the 95% D pickup rate (in ppmH per 8760 EFPH) at 310°C changes as the

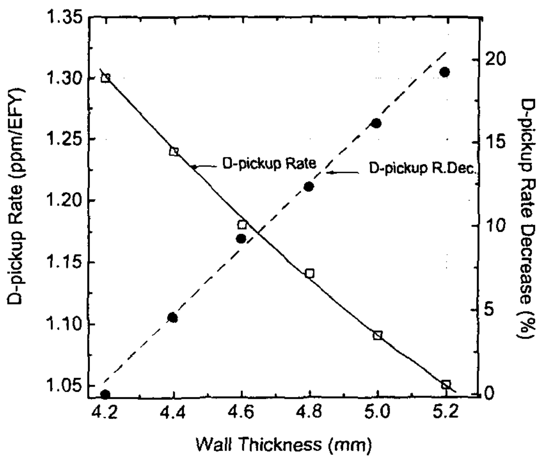

Fig. 3. Effect of Increased Wall Thickness on Deuterium Pickup

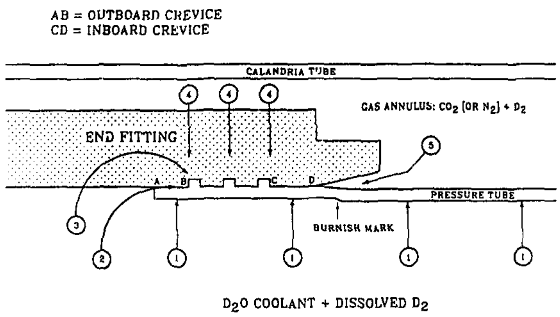

Fig. 4. Schematic Diagram of the Rolled Joint showing the Five Possible Routes for Deuterium Ingress into Pressure Tube at Rolled Joint.

Table 2. The Effect of Increased Wall Thickness on the Deuterium Pickup Rate.

Wall Thickness (mm)	4.2*	4.4	4.6	4.8	5.0	5.2
Deuterium** Pickup Rate (ppmH/8760EFPH)	1.30	1.24	1.18	1.14	1.09	1.05
D Pickup Rate Change(%)	0	−4.6	−9.2	−12.3	−16.1	−19.1

* Reference tube

** Calculated 95% Upper Confidence Level D pickup rate at 310°C by CANDU 6 pressure tubes based on 1992 scrape data.

wall thickness increases. The value is decreased by 19% by changing the pressure tube thickness from 2 to 5.2 mm. The effect of wall thickness on the D pickup rate is shown in Fig. 3.

Deuterium pickup by the pressure tube at the rolled joints is considered to take place via different routes [11], as indicated in Fig. 4. Some of these routes are of more importance than others, but it is clear that since they all involve surface or PT/EF (Pressure Tube/End Fitting) interface effects the total amount of D passing into the pressure tube in a rolled joint will be independent of the wall thickness of the pressure tube. However, the D concentration increase in the rolled joint will be smaller for the thicker tube than for the current tube because the D pickup at the surface will be distributed over more material.

The equivalent hydrogen(Heq) concentrations at the burnish mark in a rolled joint has been calculated. The wall thickness values used were 4.2 and 5.2 mm, the burnish mark was taken to be 63 mm from the end of the tube, and the initial H concentration in the tube was taken to be 5 ppm. The inlet conditions used were 260°C with a TSS(Terminal Solid Solubility) of 37.4 ppmH and a D pickup rate from corrosion at the inside surface of 0.5 ppmD per hot year. The corresponding outlet conditions used were 306°C, TSS 71.1 ppmH and a D pickup rate from corrosion at the inside surface of 2 ppmD per hot year. The rolled joint design was considered to be the same as that in CANDU 6 units with the burnish mark located 63 mm from the end of the tube. The results in Table 3 for 0 to 30 years show that the use of a thicker pressure tube increases the time needed for the Heq concentration at the burnish mark to exceed the TSS and for hydrides to be present during operation.

Table 3. Effect of Increased Wall Thickness on the Heq Concentrations at the Burnish Mark in Rolled Joint for up to 30 Years of Service.

Years	Inlet		Outlet	
	4.06 mm	5.2 mm	4.06 mm	5.2 mm
0	50	5.0	5.0	5.0
1	18.1	15.3	15.8	13.4
2	24.5	20.2	24.5	20.2
3	28.0	23.3	31.1	25.4
4	29.9	25.4	36.6	29.7
5	31.1	27.0	41.3	33.3
6	32.0	28.3	45.4	36.5
7	32.6	29.4	49.0	39.4
8	33.1	30.3	52.4	42.0
9	33.5	31.1	55.5	44.4
10	33.9	31.8	58.4	46.7
11	34.2	32.3	61.1	48.8
12	34.4	32.8	63.6	50.8
13	34.7	33.1	65.4	52.7
14	34.9	33.5	66.7	54.5
15	35.0	33.7	67.6	56.2
16	35.2	34.0	68.3	57.9
17	35.4	34.2	68.9	59.5
18	35.5	34.4	69.4	61.1
19	35.6	34.6	69.9	62.6
20	35.8	34.7	70.3	64.1
21	35.9	34.9	70.6	65.5
22	36.0	25.0	70.9	66.7
23	36.1	35.1	71.3	67.6
24	36.2	35.3	71.9	68.2
25	36.3	35.4	72.8	68.7
26	36.6	35.5	74.1	69.1
27	36.4	35.6	75.8	69.5
28	36.5	35.7	77.7	69.8
29	36.6	35.8	79.9	70.1
30	36.6	35.8	82.4	70.3

3. Effect of a Thicker Pressure Tube on DHC

3.1. Delayed Hydride Cracking Assessment

In this section the effect of using a thicker pressure tube on DHC is examined, using the information con tained in Section 2. There are two different areas to be considered, the body of the tube and the rolled joints.

For delayed hydride cracking to occur it is necessary that the local stress be high so that the stress intensity factor exceeds that needed for DHC (K_{IH}), and that hydrides be present. The use of a thicker tube leads to benefits in both of these factors. In Section 2 it was known that the hoop stress in a tube depends on its thickness and that the use of a 5.2 mm thick tube leads to a reduction in the hoop stress by 19% from that in a 4.2 mm tube. This reduction in hoop stress, σ, means that larger flaws are needed for the initiation of DHC. For DHC initiation, the stress intensity factor must exceed K_{IH}, and the depth, a, of a sharp flaw for this to happen is given by

$$a = \{K_{IH}/(c \times \sigma)\}^2 \text{ (where c is a constant)}$$

which shows that a reduction in the hoop stress, , leads to an increase in the depth of the flaw needed to allow DHC to initiate. For example, with a 19% reduction in the hoop stress from the use of a 5.2 mm thick tube, there is an increase of 50% in the depth of a sharp flaw needed to exceed K_{IH}. The another advantage from the use of a thicker tube is found in the lower Heq concentration in the tube when deuterium is picked up during service. The Heq concentration is given by :

$$Heq = H_{Initial} + 0.5\ D_{picked\ up}$$

Thus a reduction in the deuterium concentration leads to a reduction in the Heq concentration, and the use of a 5.2 mm thick tube leads to a 19% reduction in the deuterium concentration as shown in Section 2. Soon after the unit is commissioned the deuterium concentration will be small, and the Heq will be dominated by the Hinitial value ; but after sevral years the deuterium concentration will become more important in Heq. A lower deuterium pickup rate will delay the time at which the Heq concentration in the body of the tube will exceed TSS at operating temperature ; it will also decrease the temperature to which the pressure tube must be cooled during reactor cooldown before TSS is exceed and DHC can initiate. Thus the amount of crack growth during the cooldowns will be reduced.

The thicker wall thickness can lower average values of stress and hydrogen concentration. But what is the more important is local values at crack tip. As the wall thickness increases the state of stress moves from plane stress to plane strain. Hence the triaxial stress state is favored. Then the hydrostatic tension will increase. Hence the crack tip hydrogen concentration increases to accelerate crack growth rate of DHC.

The stresses in the rolled joints were summarized in Section 2 as follows ;

Total hoop stress = Pressure Hoop Stress + Residual Hoop Stress.

The pressure hoop stress was shown to be slightly reduced in the rolled joint by the use of a thicker tube. The residual tensile stresses in the rolled joints made with thicker pressure tubes are similar to those in joints made with 4.2 mm thick tubes. Thus the use of thicker tubes does not significantly affect the total hoop stress in the rolled joints. However, the thicker tube does affect the Heq concentration at the burnish mark; its effect is to delay the time at which TSS is exceeded at the burnish mark and to reduce the temperature at which hydrides can be present during cooldowns.

3.2. Flaw Tolerance Assessment

The major concerns for flaws in pressure tubes arise from DHC and result in pressure tube fracture. Sharp flaws are acceptable if the following criteria are satisfied [6] ; $K_I < K_{IH}$ and hydrides are not present, the safety margin(K_I/K_I) against fracture initiation is greater than or equal to $\sqrt{10}$ for service level A and B conditions and $\sqrt{2}$ for service level C and D conditions, and the safety margin against plastic collapse is greater than or equal to 3.0 for service level A and B conditions and 1.5 for service level C and D con-

Table 4. Safety Margin against Fracture Initiation in a Flaw Tolerance Assessment

Wall Thickness (mm)		4.2 (Std.)	4.4	4.6	4.8	5.0	5.2
Safety Margin, (K_I/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

ditions. The safety margin for fracture is indicated as K_I/K_I, where K_I is the fracture toughness of Zr-2. 5Nb alloy and K_I is the stress intensity factor. This ratio is the safety margin and it is increased by increasing the wall thickness of the tube.

Table 4 shows the effect of wall thickness on the safety margin for tubes with different wall thickness from 4.2 mm to 5.2 mm. The pressure at inlet and outlet ends used in calculation are 12.7 and 12.03 MPa, respectively. 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 33.29 MPa$\sqrt{m}$ at outlet(318°C) [8]. Using the pressure tube with the increased wall thickness leads to decrease in the hoop stress. As the wall thickness changes from 4.2 mm to 5.2 mm, the stress intensity factors, K_I, reduce from 9.29 to 7.52 MPa$\sqrt{m}$ at inlet and from 8.07 to 6.39 MPa$\sqrt{m}$ at outlet due to reduction of the hoop stress. Therefore, the safety margin is increased by 25% for the 5.2 mm wall thickness tube with sharp flaws. This result means that the service life of pressure tube increases by 25% with using the thicker wall thickness.

4. Conclusion

The effects of an increased wall thickness of Zr-2. 5Nb pressure tube on the stress, deuterium pickup and delayed hydride cracking were studied. The results are as follows :

(1) If the pressure tube wall thickness changes from 4.2 mm to 5.2 mm, the hoop stress and the deuterium concentration are reduced by 19% for thicker pressure tube. The residual hoop stress on the inside surface of thicker pressure tube at the rolled joint region compares well with standard wall thickness tube with zero clearence joint There is an increase of 50% in the depth of a surface flaw needed to exceed the stress intensity factor for DHC. For thicker pressure tube the amount of crack growth during the cooldown is reduced.

(2) DHC initation depends on the stress and the hydrogen concentration in tube. Thus it is assessed from the these results that the safety margins for DHC initation is greatly increased and the reliability of pressure tube during service is improved. However, the crack growth rate of DHC is increased by high hydrogen concentration at the crack tip due to hydrostatic stress in the thicker wall thickness tube.

References

1. G.D. Moan, C.E. Coleman, E.G. Price and S. Sagat ; Int. J. Pres. Ves & Piping, 43, 1 (1990).
2. G.J. Field, J.T. Dunn and B. A. Chedle ; Can. Met. Quartely, 24, No. 3, 181 (1984).
3. P.A. Ross-Ross, J.T. Dunn, A.B. Mitchell, G.R. Towgood and T.A. Hunter ; The Annual Congress of the Engineering Institute of Canada. Manitoba, Sep. 30-Oct. 2, (1975).
4. C.E. Coleman, S. Saget, G.K. Shek, D.B. Graham and M.A. Durand ; Int. J. Pres. Ves. & Piping, 43, 187 (1990).
5. G.D. Moan, J.R. Theaker, P.H. Davies, I. Aitchis-

on and C.E. Coleman ; INS Conference Proceedings, C18-1, Toronto, (1993).

6. 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).
7. S. Venkatapathi, A. Mehmi and H. Wong ; Int. Conference on Expanded and Rolled Joint Technology, H-25, Toronto, (1993).
8. Fitness for Service Guidelines for Zirconium Alloy Pressure Tubes in Operating CANDU Reactors, COG Report No. 91 − 66, 1991 May.
9. Summany of 1992 CIGAR Inspection of Wolsung Unit 1, (1992)
10. E.G. Price ; AECL 8338, Oct. (1984)
11. V.F. Urbanic, G.M. McDougall, A.J. White and A. Bahurmuz ; Int. Conference on Expanded and Rolled Joint Technology, G − 19, Toronto, (1993).