Journal of the Korean Nuclear Society
Volume 30, Number 3, pp.262~272, June 1998

《Technical Note》

A Review of Pressure Tube Failure Accident in the CANDU Reactor and Methods for Improving Reactor Performance

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(Received June, 5, 1996)

Abstract

The experiences and causes of pressure tube cracking accidents in the CANDU reactors and the development of the fuel channel at AECL(Atomic Energy Canada Limited) have been described. Most of the accidents were caused by Delayed Hydride Cracking(DHC). In the cases of the Pickering units 3&4 and the Bruce unit 2, excessive residual stresses induced by an improper rolled joint process played a role in DHC. In the Pickering unit 2, cracks formed by contact between the pressure and calandria tubes due to the movement of the garter spring were the direct cause of the failure. To extend the life of a fuel channel, several R&D programs examining each component of the fuel channel have been carried out in Canada. For a pressure tube, the main concern is focused on changing the fabrication processes, e.g., increasing cold working rate, conducting intermediate annealing and adding a third element like Fe, V, and Cr to the tube material. In addition to them, chromium plating on the end fitting and increasing wall thickness at both ends of the calandria tube are considered. There has also been much interest in the improvement of fuel channel performance in our country and several development programs are currently under way.

1. Introduction

Currently, there are four CANDU type reactors in our country which are Wolsong unit 1 and Wolsong units 2, 3 & 4 that are under construction. The CANDU reactor, first designed and constructed in Canada, uses heavy water as coolant and natural uranium as fuel. The unique design of the CANDU reactor enable fuel to be loaded while the reactor is on power, which makes continuous reactor operation possible. There are 380 horizontal fuel channels in a cylindrical vessel called a calandria and each channel consists of a pressure tube, a calandria tube, an end fitting and a garter spring which maintains the separation between the pressure and calandria tubes. The pressure tube and end fitting are connected by the rolled joint method. The rolled joint process should be carefully performed. If the roller used during fabrication has extended beyond the parallel part

Table 1. Experiences of Pressure Tube Failure Accident in CANDU.

Reactor	Date	Failure Cause	Failure Mechanism	PT/GS Type	Replacement	Shut-Down
Pickering-3	1974.8.10	Over extended RJ	DHC	· Zr-2.5Nb · 2 loose GS	17 PT	7 months +20 days
Pickering-4	1975.5.10	Over extended RJ	DHC	· Zr-2.5Nb · 2 loose GS	52 PT	10 months +8 days
Bruce-2	1982.2.9	Over extended RJ	DHC	· Zr-2.5Nb · 2 loose GS	2 PT	3 months +22 days
Pickering-2	1983.8.1	· GS moved · PT sag · PT/CT contact →Hydride Blister	· PT sag · Hydride Blister	· Zircaloy-2 · 2 loose GS	Whole Channel	
Pickering-3	1985	Over extended RJ	DHC	· Zr-2.5Nb · 2 loose GS	1 PT	
Bruce-2	1986.3	Defect During PT Fabrication	Fabrication Defect	· Zr-2.5Nb · 2 loose GS	1PT/CT	3 months +10 days
Wolsong-1	1994.2	Surface Crack	Fretting	· Zr-2.5Nb · 4 loose GS	3 PT	

PT : Pressure Tube CT : Calandria Tube GS : Garter Spring
RJ : Rolled Joint DHC : Delayed Hydride Cracking

of the end fitting, the pressure tube is strained and excessive residual stresses are produced. These stresses lead to DHC by combining with hydrides that have been already formed. Actually, 17 pressure tubes of the Pickering unit 3[1] were replaced in 1974 because of this problem. After that, a series of similiar accidents happened at Pickering unit 4[2] in 1975, at Bruce unit 2[3] in 1982, at Pickering unit 2[4-5] in 1983, and at Pickering unit 3 in 1985. Through investigation, it was revealed that DHC was the major cause of accident. Excluding the case of the Pickering unit 2, in which the movement of a garter spring had an important role inducing excessive residual stresses, an improper rolled joint was a direct cause of the accident. To avoid a pressure tube rupture accident which is important for the safety and economics of the plant, it is necessary to understand the failure mechanisms, failure causes and eventually to establish prevention techniques. It is our intention to evaluate the cases and causes of pressure tube failure in Canada by reviewing the results of study and to find methods to prevent such accidents in our own country.

2. Structure of the CANDU Fuel Channel

As shown in Fig.1, the fuel channel of CANDU reactors is composed of a pressure tube made of Zr-2.5Nb, attached to the heat transport system by a mechanical joint with a 403 stainless steel end fitting, and surrounded by a thin Zircaloy-2 calandria tube. The pressure tube contains the nuclear fuel and heavy water as coolant, operating at 250 to 300°C at about 10 MPa. There is a gap called the annulus gap between the pressure and calandria tube which is filled with dry CO_2 gas. CO_2 gas provides insulation between the tubes, as

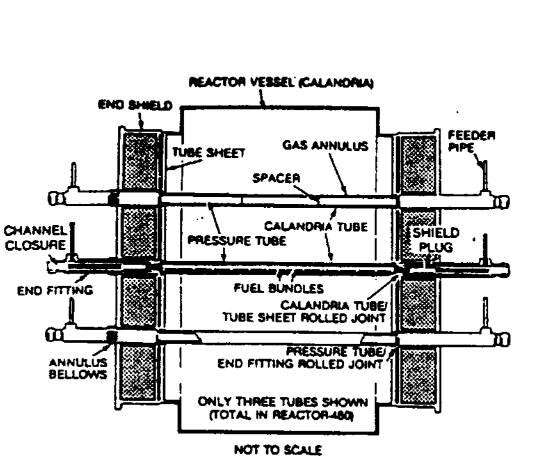


Fig. 1. Schematic of CANDU-PHW Reactor

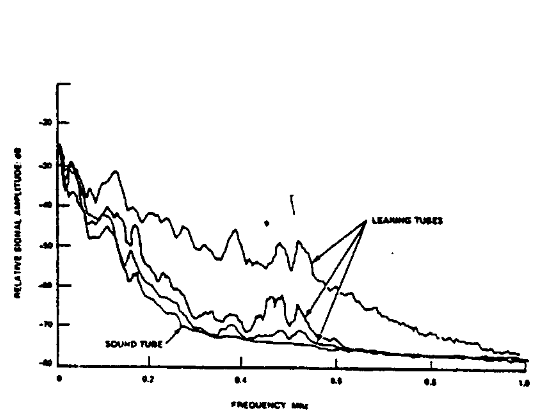


Fig. 2. Characteristic Acoustic Emission Frequency Spectra

well as an effective means of detecting D_2O leakage. To protect against direct contact between the pressure and calandria tubes and to support movement of pressure tube, garter springs are installed between the two tubes. In addition to these components, there is a liner tube and shield plug to facilitate the flow of heavy water. The end of the fuel channel is sealed by a closure plug which opens when the new fuels are loaded.

3. Pressure Tube Cracking Accident

3.1 Experiences during a pressure tube cracking accident(Table 1)

The first pressure tube failure occurred at Pickering unit 3 in 1974. Heavy water was leaking into the sealed annulus between the pressure and calandria tubes. After the accident, a detailed examination of all the pressure tubes was performed and 17 cracked pressure tubes were eventually identified and replaced. At Pickering unit 4 in 1975, two failed pressure tubes and 50 other tubes with deep cracks were found and replaced. Acoustic emission technology was used to detect leakage. Leaking channels could be identified by a characteristic increase in the signal amplitude in the 0.4 - 0.6 MHz frequency range. Fig. 2 shows the variation of frequency spectra of both sound and cracked pressure tube removed from Pickering unit 4. Cracked tubes can be easily found since the frequency differences between sound and leaking tubes are significant. Three tubes at Bruce unit 2 in 1982 were replaced due to a similiar accident. In the stations mentioned above, pressure tubes made of Zr-2.5Nb alloy were installed. However, in the Pickering unit 1&2, which were constructed earlier than the other stations, Zircaloy-2 tubes were used because the superiority of Zr-2.5Nb alloy was not proven at that time. After the pressure tube failure at Pickering unit 2 in 1983 and after verifying the better mechanical properties and lower hydrogen uptake of Zr-2.5Nb than Zircaloy-2, all the Zircaloy-2 pressure tubes in Pickering unit 1&2 were replaced with Zr-2.5Nb tubes. At Pickering unit 3 in 1985, one tube was found to have cracks and replaced.

3.2. Causes of Pressure Tube Failure

3.2.1. Pickering Unit 3 & 4 and Bruce Unit

There had been much effort to find the causes of pressure tube failure after the accident of Pickering unit 3 in 1974. The infrared photograph technique was used to find whether fuel channels

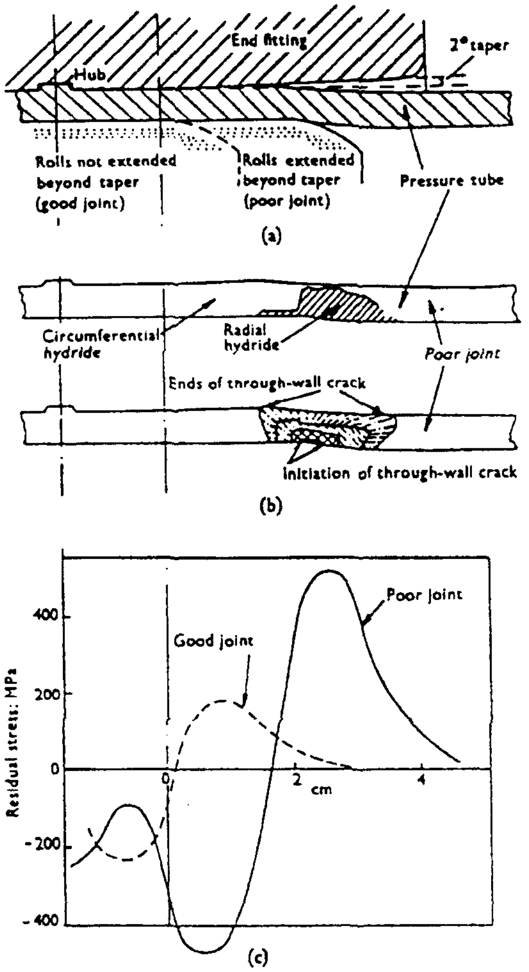


Fig. 3. Pickering Rolled Joint Stresses.
(Hoop Stress on Inner Wall of the Pressure Tube)
a) *Relative Position of Rolling Tool* During Installation
b) Position of Radial Hydrides and Cracks in a Poor Joint
c) Residual Hoop Stress Distribution on the Inner Wall of a Good and Poor Joint

were leaked. This technique could be used since the leaking fuel channel should be cooler than adjacent fuel channels due to loss of heat to the moderator through the water filled gas annulus. To identify which fuel channel was leaking, a sensor was held on each fuel channel in turn, and the noise due to leakage of the primary coolant was recorded using acoustic emission equipment. It was revealed that DHC was the main cause for the failure through the investigation. It was found that DHC occurred due to a combination of excessive residual stresses at the rolled joint position caused by an improperly rolled joint and hydrides formed by hydrogen that existed within the tube over the Terminal Solid Solubility(TSS) limit. According to the analysis of the cracked pressure tube, the rollers used had extended beyond the parallel part of the end fitting so the pressure tube was strained in that area that should not be strained by the end fitting. As can be seen in Fig. 3., the residual stress at the improperly rolled joint position is much higher than that of a good joint. A small amount of hydrogen had been already picked up during manufacturing of pressure tube. Hydrogen content increases continuously during reactor operation by absorbing hydrogen from the corrosion reaction of the pressure tube with heavy water.

Absorbed hydrogen is completely dissolved in the pressure tube at the reactor operating temperature. However, if the temperature is lowered, over saturated hydrogen will be precipitated and hydrides are created. The following results could have been obtained from an investigation of the pressure tube cracking of the Pickering unit 3[2].

(a) All cracks were at the coolant inlet end.
(b) The rolling tool had been inserted about 13 mm too far into the tube.
(c) The cracks started from the inside tube surface, were 15-20 mm long and occurred just inboard of the rolled joints where the tube had been flared out by the joint rolling.
(d) The cracks appeared to progress outward as far as the compressive zone under the hub of the rolled joint and inward as far as the zone of

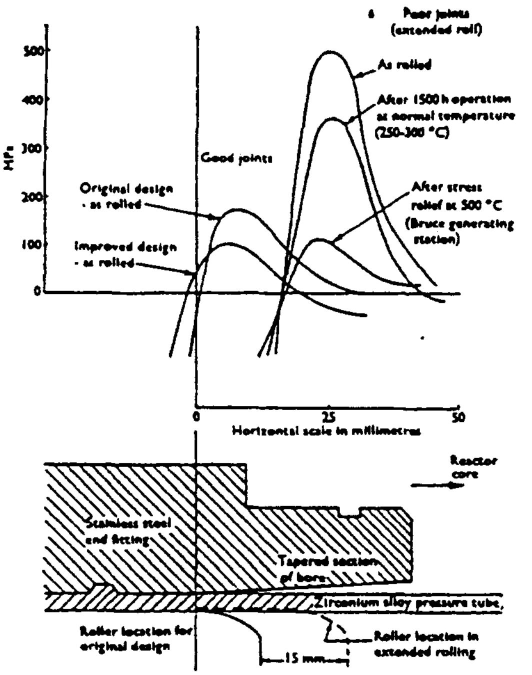


Fig. 4. Variation of Residual Hoop Stress in Pressure Tube Rolled Joints

zero residual stress in the pressure tube.

(e) The length to depth ratio of the cracks was about three.

(f) Three very distinct oxidation bands could be seen on the fracture face.

(g) Electron fractography showed that the fracture was characteristic of delayed hydrogen embrittlement.

(h) Small incipient cracks were present adjacent to the main crack, and radial plate-like precipitates of zirconium hydride were present at the crack tips.

(i) Radial precipitated hydride existed in the cracked region.

Since the orientation of zirconium hydrides within an as-fabricated pressure tube is circumferential, this observation implied that a stress greater than the operating stress must have been present.

Hydrogen in the pressure tube appeared to migrate to high residual stress areas such as a discontinuous site and a small flaw where the stress intensity factor was high enough to initiate cracking. The cracks proceeded through the tube wall by the repeated formation and fracture of the hydride precipitate at the tip of the crack when the heat transport system was at a temperature below that needed for the hydrogen to be in solid solution.

All the pressure tube end fitting joints in Bruce units 1&2 had been rolled at the time of the Pickering problem and they were not very different from those in Pickering. Therefore, stress-relief annealing heat treatments were applied to the Bruce units 1&2 to reduce the residual stress. It was identified that the residual stress up to 772 MPa produced by an improper rolled joint process decreased to 96 MPa after stress relief annealing at a temperature of about 500℃. However, this was a time consuming process. Thus, for Bruce units 3&4, improved rolling processes involving a slight modification in joint design, a tighter rolling tool had been used.

As shown in Fig.4, the residual stresses of a pressure tube rolled using the improved method is similiar to that of the stress relieved tube. Even though the residual stress was relieved by stress relieving annealing, a pressure tube failure accident occurred at Bruce unit 2. Through detailed investigation, it was confirmed that cracks had already existed in the pressure tube and led to the failure of the tube. The results of the studies on the Bruce unit 2 accident performed at Chalk River laboratories of AECL are as follows.[3]

(a) The as-rolled pressure tube had a high residual hoop stresses of about 510-630 MPa

(b) The stress relief operation was successful and had reduced the maximum residual hoop stress to 82 MPa

(c) The deuterium concentration in the pressure tube near the rolled joint was higher than in the

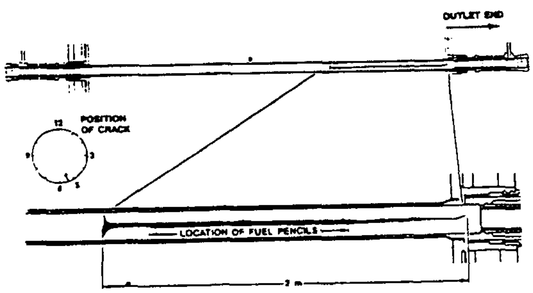


Fig. 5. Location and Orientation on Split in Pressure Tube.

remainder of the tube, as was found in the pressure tubes removed from Pickering unit 4.

(d) Only one crack was found and it was a radial axial crack 27 mm long, originating at the inside surface of the tube just inboard of the rolled area. The origin of the crack was at the axial and radial position of the maximum residual hoop stress existing after rolling.

3.2.2. Pickering Unit 2

The pressure tube cracking accident that occurred at Pickering unit 2 in 1983 was quite different from that of the other plants mentioned above. The size of crack was very long about 2 m and the crack position was different.(Fig. 5) The cause of the failure was associated with both displacement of a pressure tube support spacer during commissioning(Fig.6) and the development of much higher than expected hydrogen concentrations in the Zircaloy-2 pressure tubes as a result of corrosion. All the spacer removed from the cracked pressure tube were in distorted and broken states containing large amount of hydrogen.

The failure procedures of the pressure tube installed in Pickering unit 2 which was shown by the investigation were as follows.[4-5]

(a) The outlet garter spring moved about 1 m inboard from its design location probably during the construction or commissioning phases.

(b) Due to the increased span between supports, the pressure tube sagged into contact with the

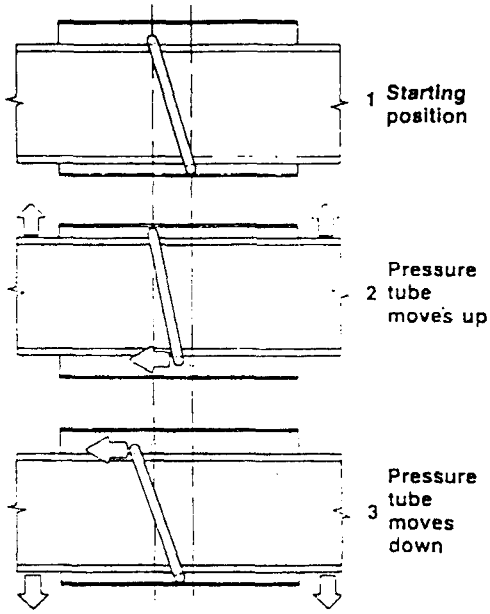


Fig. 6. Illustration of the Movement of Garter Spring by Vibration.

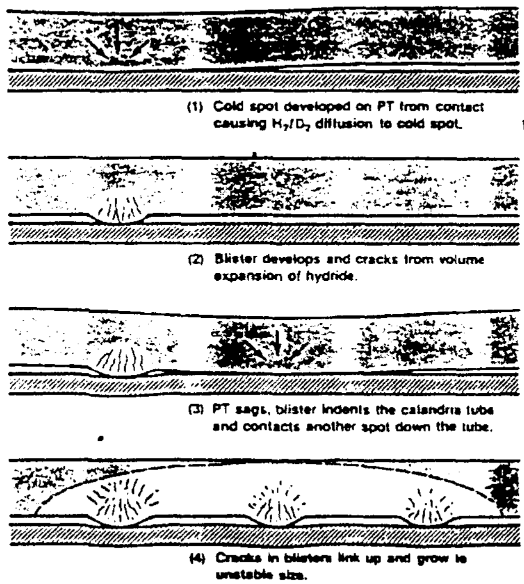
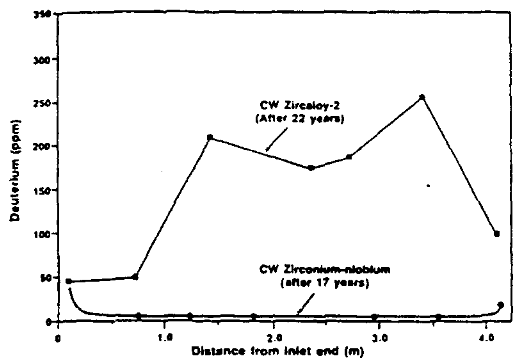
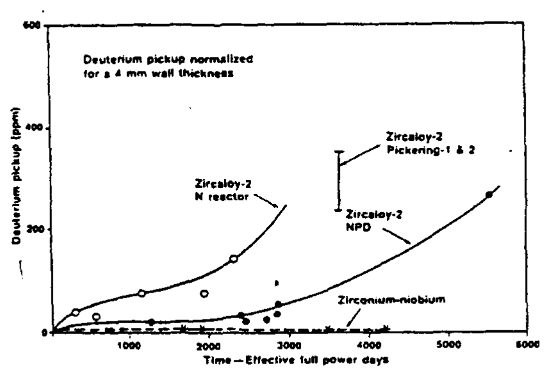


Fig. 7. Probable Sequence of Crack Development from PT/CT Contact.



a)



b)

Fig. 8. Deuterium Pickup in Two Pressure Tubes.
a) Removed from the NDP Reactor
b) Removed from the Different Reactors

calandria tube.

(c) The temperature gradients in the pressure tube wall caused the hydrogen and deuterium to diffuse to the cooler contact area initiating the formation of the blisters.

(d) The enhanced corrosion and deuterium pickup accelerated the growth of the blisters creating high local stresses in an area of high hydride content and initiated a defect.

(e) The defect grew by delayed hydride cracking to form a partial through-wall crack about 100 mm long

(f) When the crack reached a critical size, it suddenly broke through the wall and extended to the 2 m length

There are three essential factors - stress, hydrogen, time - to initiate DHC. If one of them is absent, a crack caused by DHC may not occur. Examination of several Zircaloy-2 and Zr-2.5Nb pressure tubes[6-10] had shown that the heavy water pickup rate of the Zircaloy-2 is much higher than that of Zr-2.5Nb(Fig. 8). Accordingly, all the Zircaloy-2 pressure tubes installed in Pickering unit 2 were replaced with Zr-2.5Nb tubes after the accident.

4. Improvement of Fuel Channel

The fuel channel is one of the most important components in a CANDU reactor because it contains fuel bundles and determines the efficiency and power of the station. Therefore, the integrity of the fuel channel is directly connected to the safety of the whole station. The fuel channel has higher chances to fail than the other components in the station since it operates under severe conditions. Actually, most of the accidents are related to the fuel channel. The AGS(Annulus Gas System) is designed and operated to provided the operator sufficient time to take appropriate action to prevent unstable fracture of a leaking pressure tube. If a leak was to occur through the pressure tube it would be detected by moisture sensors in the AGS. Much effort has been devoted to improve the performance of the fuel channel since Pickering unit 4 pressure tube failure problem in 1974 in Canada. The studies on the development of the fuel channel have also been progressed since some years ago in KAERI.

The following is the method for improving fuel channel performance which are currently being studied.

4.1. Pressure Tube

Currently, the study of the pressure tube is the most active because accidents associated with the fuel channel were mainly caused by the pressure tube. Methods for improving the pressure tube performance can be divided into the following five categories[13]: 1]minimizing the variation of the pressure tube' s dimension(diameter, length), 2]decreasing the defects at which DHC can be initiated, 3]increasing the fracture toughness of the pressure tube, 4]decreasing the corrosion rate and 5]minimizing hydrogen uptake. To reduce dimensional variation, to minimize the defect and to increase the fracture toughness, manufacturing processes should be modified. Several methods, such as increasing cold working rate from 25 to 40% and conducting intermediate annealing and final stress relief annealing are suggested to enhance in-reactor creep property and growth characteristics of the Zr-2.5Nb pressure tube because these properties depend on structural texture, grain shape, dislocation and sub-grain microstructure[12]. Performance test results on the pressure tube manufactured by adopting the methods mentioned above show much lower elongation rates compared to the conventional tube.(Fig. 9) Defects that lead to initiate DHC are created due to large shrinkage produced while the ingot is solidified. A considerable portion of ingot is cropped in current manufacturing processes to reduce this shrinkage. However, much effort is concentrated on developing more advanced, non-destructive methods since microcracks, which are hard to find by conventional non-destructive techniques, may exist. Both the susceptibility of DHC and the crack propagation rate increase with decreasing fracture toughness. Test results showed that Cl-element was a major cause of reduced fracture toughness, so studies to reduce Cl-element in the ingot has been actively persued[14]. Cl is

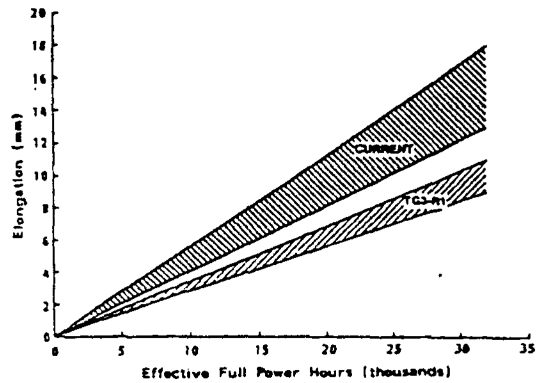


Fig. 9. Comparison of the Elongation of Small Specimens from Improved and Standard Pressure Tubes

removed during melting because it is highly volatile. Therefore, increasing the number of meltings is the most effective way to reduce Cl-ion. Accordingly, quadruple melting is currently used to fabricate pressure tubes instead of double melting.

To prevent DHC, hydride formation should be avoided. Since the solubility limit of hydrogen in zirconium is low, hydrogen concentration in the pressure tube must be lowered in order not to form hydride. Hydrogen is partially absorbed during pressure tube manufacturing processes but most of it is picked up during operation. Although hydrogen can be picked up at each stage of the manufacturing processes, contributions from melting and forging dominate. To reduce the amount of hydrogen absorbed during the melting and forging steps, melting was performed in a vacuum and the surface layer of the pressure tube at which hydrogen was concentrated was machined.

To prevent ingress of hydrogen into the pressure tube during operation, several methods have been studied such as forming a black oxide layer about 1 m thick by autoclaving for 24 hr at 400℃ before installation, changing the microstructure of

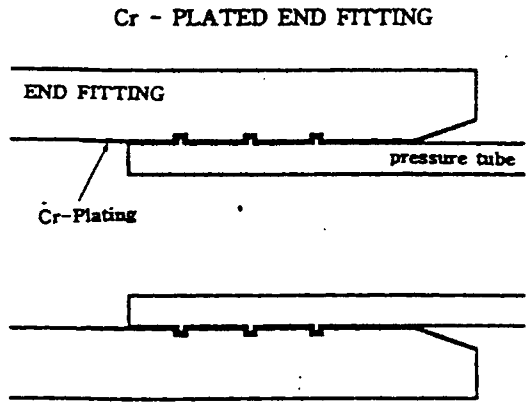


Fig. 10. Schematic Diagram of a Rolled Joint Showing the Chromium Plating on the End Fitting.

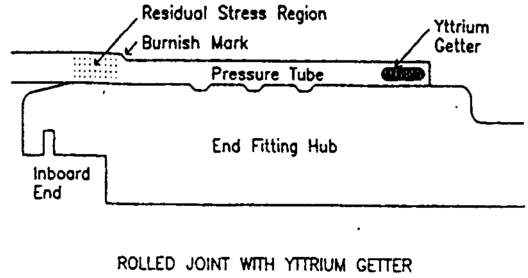


Fig. 11. Schematic Diagram of a Rolled Joint Showing the Yttrium Ring Bonded to the End of the Pressure Tube.

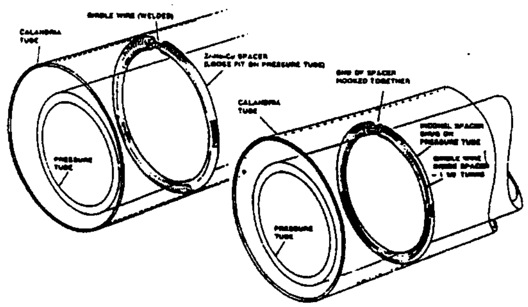


Fig. 12. Schematic Diagram of the Two Designs of Garter Springs Used in CANDU Reactors.

the pressure tube surface using laser or shot peening, adding some elements like Fe, V and Cr which are known to have beneficial effects to reduce hydrogen uptake[13] and coating a thin stress-free zirconium oxide layer on the pressure tube. Among these methods, the zirconia coating technologies are preferred since an oxide layer grown by this method contains fewer cracks than that grown by a thermal oxide layer.

4.2. End Fitting

Hydrogen is absorbed at a higher rate in the rolled joint than in the main body of the tube due to the damage of the oxide barrier during the joint process[1]. Two kinds of methods are suggested to solve this problem. The first method is to put a barrier such as chromium plating between the pressure tube and the end fitting (Fig.10)[13]. Several designs of rolled joints using end-fittings chromium-plated by standard techniques are being tested in a heavy water loop at 300℃. Short term evaluation shows that the reduction in the hydrogen pick-up varies from about 30% to 70%, depending on the design. An alternative method for reducing the hydrogen at the joint position is to place a sacrificial hydrogen getter in a stress free location. Yttrium is known to be an effective getter because it forms a more stable hydride than zirconium(Fig.11). Rings of yttrium are bonded to the ends of the pressure tubes using hydrostatic pressing. Tests on this method are in progress.

4.3. Spacer

The garter spring has the function of separating a hot pressure tube from the cold calandria tube while allowing relative movement of the two tubes without causing wear to either tube5). However, the garter springs were designed to fit to the inside diameter of the calandria tube and this allowed them to move by vibration during

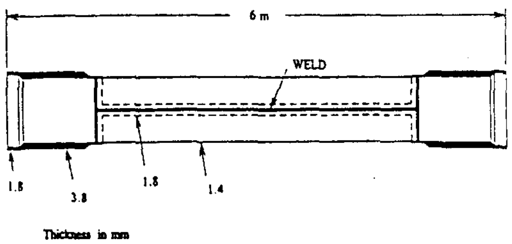


Fig. 13. Schematic Diagram of the Seam-welded Calandria Tube with Thick Weld Region.

installation. This movement and pressure tube sag led to contact between the pressure tube and the calandria tube. This problem could be prevented by using Inconel X750 as garter spring material rather than a zirconium alloy and having an integral internal girdle wire inside the toroid that provides detectability using eddy current techniques (Fig.12)[13].

4.4. Calandria Tube

Calandria tubes should be replaced when they are in danger of contacting with core components located below them or when pressure tube replacement will not be possible due to excessive curvature. Therefore, calandria tube life can be extended by reducing its sag rate. The sag rate can be halved by increasing the wall thickness about 2.5 times for about one meter length at both ends. The burnup penalty associated with such thick ends is only 2 to 4% because the material being added is located in a low flux region of the reactor core(Fig.13). Burst tests on thick-ended calandria tube demonstrated that it did not reduce calandria tube burst resistance, nor induce fracture in the circumferential weld. Currently, properties of thickend calandria tubes are being evaluated[13].

5. Conclusions

Since the fuel channel containing the fuel bundle is operated in severe conditions compared to other components in the plant, chances of an accident in this part are very high. Actually, many accidents that occurred in the plant were related to the fuel channel. Most of them were caused by the failure of the pressure tube. The pressure tube was cracked due to DHC which occurred by combining high residual stresses with pre-existing hydride. Much effort has been given to prevent DHC after the accident. Also, many methods to improve the performance of each component in the fuel channel have been studied. There are two methods to enhance the integrity of the fuel channel. One of them is to improve the properties of each component in the fuel channel by changing the fabrication processes, namely, increasing cold working rate from 25 to 40%, conducting the intermediate annealing and the final stress relief annealing to enhance in-reactor creep property and increasing the number of melting from two to four in order to reduce Cl element which is known to decrease the fracture toughness of the pressure tube. The second method is to prevent DHC by suppressing hydrogen uptake using a barrier such as an yttrium getter between pressure tube and end fitting, Cr-plating on the end fitting and zirconia coating on the pressure tube.

Experiments on each test specimen are currently under way. Since there are already four CANDU type reactors (three reactors are under construction) in our country, more studies are requested on the fuel channel.

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