Module 5

PROBLEMS WITH PRESSURE TUBES

OBJECTIVES:

After completing this module you will be able to:

Page 2 ⇔ 5.1 State two factors contributing to pressure tube elongation.

Page 2 ⇔ 5.2 Explain how pressure tube elongation is handled.

Page 3 ⇔ 5.3 Explain why *excessive* elongation of pressure tubes is a problem.

Page 4 ⇔ 5.4 State two solutions to excessive pressure tube elongation in operating units.

Page 7 ⇔ 5.5 a) Explain how delayed hydride cracking (DHC) causes pressure tube leaks.

Page 9 ⇔ b) Explain how the heat transport system is operated to reduce the occurrences of DHC.

Page 9 ⇔ c) Explain the methods used to reduce the amount of hydrogen ingress into the pressure tubes.

Page 10 ⇔ d) Explain the problem of pressure tube hydride blister formation and the means by which it can be prevented.

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INSTRUCTIONAL TEXT

INTRODUCTION

The operation of large nuclear reactors causes various problems due to materials operating at elevated temperatures in high radiation fields for prolonged periods. This module describes several important pressure tube problems and the steps taken to correct or reduce their effect.

NOTES & REFERENCES

ELONGATION OF PRESSURE TUBES

Obj. 5.1 ⇔

The majority of pressure tube elongation results from two factors: **thermal expansion** and **creep**. During design, allowances were made for the expected elongation from both factors. However, experience with the reactors at Pickering and Bruce has shown that there is *excessive* elongation of pressure tubes. This is due to longitudinal creep.

Module 3 discussed the material requirements for in–core components in the CANDU reactor. It found that zirconium alloys were the most suitable metals. It also noted that zirconium alloys were selected in preference to pure zirconium because of higher strength and increased creep resistance. Despite improved mechanical properties of the alloys, creep is still a major concern for pressure tubes.

Metals operating at elevated temperatures in high neutron fluxes show increased creep. Heat expands the crystal structure of the metal, allowing the defects formed by fast neutron damage to move about the crystal lattice more easily. This means that they are no longer effective barriers to the deformation processes and creep becomes easier.

Previous cold work also influences creep; increased cold work results in increased creep. Since pressure tubes are used in a cold–worked condition (it provides higher strength), the influence of cold work must be considered in the creep properties of the tubes.

Obj. 5.2 ⇔

Pressure tube elongation is handled by an end fitting that floats on a system of bearing journals and sleeves. This arrangement varies from station to station and even within a station, from reactor to reactor. A unit may have pressure tubes with a single fixed end and a single floating end, or it may, instead, have the ability to fix or float either end. Figure 5.1 illustrates this principle.

A normal heat–up and cool–down cycle will result in the pressure tubes growing and shrinking axially due to thermal effects. The permanent axial growth due to radiation effects limits the amount of tube elongation allowable from thermal effects. The elongation limit is reached when the sliding bearing journal is at the end of its support pad (sleeve). Where both ends of the tube can be fixed or free, more tube elongation is easily handled. The floating end fitting is fixed at its maximum travel and the other end fitting released. The tube is now free to expand in the opposite direction. If only one end can be a floating end, a different solution is required. This will be dealt with later in the module.

NOTES & REFERENCES

Obj. 5.3 ⇔

Should the tubes be allowed to elongate until the bearing journals slide off the sleeves, major problems arise. The journal becomes hung up on the sleeve end, preventing its movement* as the tube contracts during cooling. High loads on the pressure tubes and end shields (reactor face) and localized stressing at the end fitting may result during a reactor cool–down. This situation is highly undesirable.

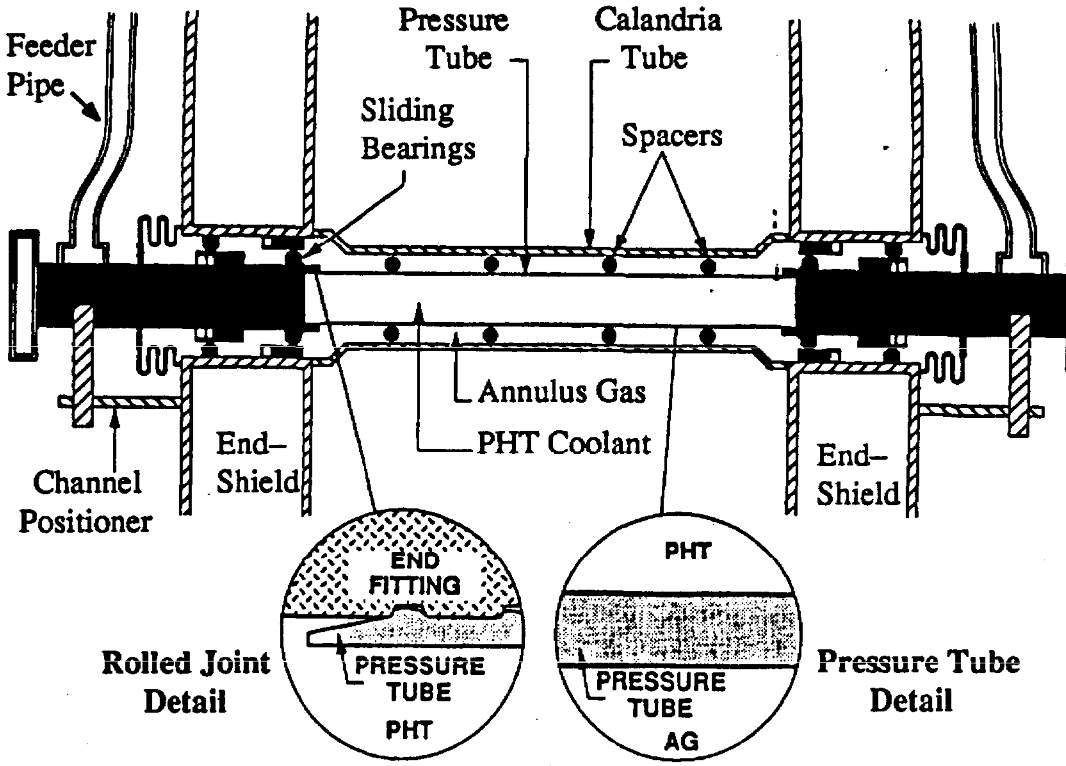

Figure 5.1: Fuel Channel Schematic

Other problems may arise with the main heat transport system feeder pipes. Initially, the feeders are spaced to reduce the possibility of contacting each other due to creep, installation tolerance, and pressure/temperature effects. Axial elongation of the pressure tube is proportional to the fuel channel flux distribution in the reactor core. This means that the axial elongation rates of fuel channels in the outer region are slower than those in the inner region. Large variations in the axial elongation rates between adjacent channels could occur. These variations *reduce* the initial feeder spacings and *increase* the possibility of feeders contacting. Should the feeders contact, fretting and increases in loads on the feeder connection assemblies result. In the extreme case, fretting could compromise the heat transport system pressure boundary.

* *Since the sleeve is fixed within the reactor face.*

Let us compare some actual creep elongation figures with the designed creep allowances*. For many years, regular measurements of creep in pressure tubes have been taken at all operating units. The fastest growing tubes show increases of 3.2 to 4.6 mm per year. Early Pickering and Bruce units had a total axial growth allowance of about 40 mm. Clearly this allowance was inadequate for a thirty year service life. Subsequent units have much larger axial growth allowances (up to 160 mm).

PRESSURE TUBE REHABILITATION PROGRAM

When the design allowance for axial expansion is reached, some method must be found to deal with further elongation. Two possibilities exist.

Obj. 5.4 ⇔

The first, known as REFAB (Repositioning End Fitting And Bearing), involves moving the tubes within the core. Tubes are shifted to put the journals back to the beginning of their travel. The tubes can then grow to the elongation limit a second time. For pressure tubes with a single fixed end, the fixing weld is first cut. The tube is then moved until the floating end fitting bearing is at the beginning of its travel. The fixing weld is remade. Where either end can be floated, one end fitting is pulled outwards completely off its bearings. This means the other end fitting bearing ends up at the beginning of its travel. The off–bearing end fitting is then fixed in place. This allows the free end to extend to its maximum allowance before the process of end fitting relocation is repeated.

A program using the REFAB methodology was applied to units 1–3 at BNGS–A under the name "west shift"(unit 4 has floating bearings at each end, and the pressure tubes were shifted, without cutting and welding, during a short shutdown). "West shift" involved prolonged unit outages over a three year period.

The second approach is to replace all the pressure tubes in a major program known as LSFCR (Large Scale Fuel Channel Replacement). In the mid–1980s, it was decided to perform LSFCR at PNGS–A, albeit for a different reason**. This eight year project (two year shutdown per unit) was completed in late 1992. The elongation allowance should handle the creep of the new tubes for 20–30 more years.

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* *You will not be required to memorize these figures. They are for illustration purposes only.*

** *This was due to a problem of pressure tube cracking. The next section of this module discusses this problem in detail.*

NOTES & REFERENCES

CRACKING OF PRESSURE TUBES

Shortly after returning to full power operation following a maintenance outage, Pickering unit 3 showed indications of through–wall cracking in pressure tubes. The immediate problem was to determine which pressure tube or tubes contained through wall cracks. Acoustic emission techniques proved most successful in this task. The procedure involved listening to the coolant flow* and locating a leaking channel by the different sounds it had from a leak–free channel. Seventeen leaking channels were identified and replaced. From the detection of the leaks in unit 3 to the start–up with the new tubes represented a forced outage of about seven months.

Aside from locating tubes with through–wall cracks, it was necessary to determine which tubes contained partial through–wall cracks. Ultrasonic testing methods were developed for this application. They were used on unit 3 following the replacement of the leaking tubes and later on unit 4. As a result of these examinations and acoustic emissions tests, a total of 52 pressure tubes in unit 4 were replaced (no more tubes were identified for replacement in unit 3).

Laboratory examination of the leaking pressure tubes revealed that the cracks occurred in a region close to the rolled joint**. Measurement of the tube diameter showed an unexpected increase in this area. The change was caused by the method of making rolled joints, and the configuration of the end fitting . To form a joint, the pressure tube wall is squeezed into grooves on the end fitting by rollers, see Figure 5.2. During the rolling operation, the rolling tool was pushed too far (about 13 mm) into the end fitting. The result was to push the pressure tube wall out at the tapered section of the end fitting. This created an extra region of deformation in the tube where high residual stresses were built up, see Figure 5.3. It was found that these stresses were mainly tensile and concentrated at the inner wall of the pressure tube.

Since these problems at Pickering occurred during the construction and commissioning of BNGS–A units 1 and 2, it was necessary to inspect their rolled joints (the joints were already completed in these units). They were found to have been over–rolled. It was decided to stress relieve the over–rolled portion of the pressure tubes. In carrying this out, it was important to use as low a temperature and as short a time as possible to avoid structural damage to the rolled joint or pressure tube. Stress relieving was carried out at 500° C for half an hour. This resulted in a decrease of the residual stress in the pressure tube wall by a factor of 5 to 7 (even somewhat lower than that expected in a correctly rolled joint).

* *With the heat transport system pressurized and main HT pumps shut down, listening for the sound of water exiting a crack.*

** *A rolled joint is used to connect the pressure tube to the end fitting.*

NOTES & REFERENCES

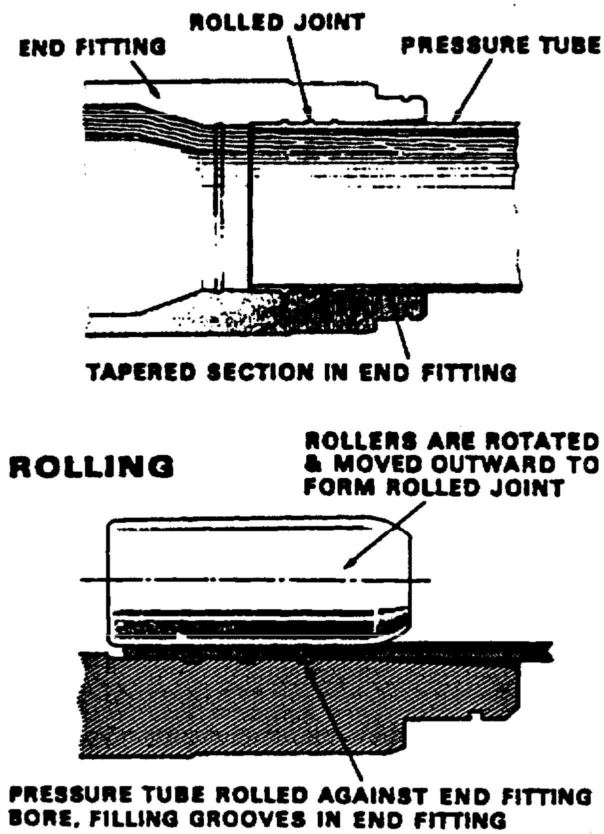

Figure 5.2: Rolled Joint Between Pressure Tube and End Fitting

Unfortunately, early temperature cycles during the commissioning of Bruce unit 2 had already initiated some pressure tube cracks in the rolled joint region. Once the unit entered service, after stress relieving had been performed, these cracks caused several pressure tubes to leak (stress relieving could do nothing to prevent the cracks that had already started).

Subsequent to these problems, improved rolling procedures, and a modified style of joint*, were implemented for all reactors beyond Bruce units 1 and 2. Low levels of residual stress in the rolled joint region were ensured by these improvements.

The laboratory examination of failed pressure tubes showed that zirconium hydride had precipitated out in the tubes. This was expected. What was a surprise was the way in which these hydrides were oriented and the fact that hydrogen appeared to be migrating to the rolled joint area. Under normal conditions, the hydrides were expected to be oriented circumferentially but, in the over–rolled region, they were found to be oriented radially (implying that a stress greater than the operating stress was present).

* *The fuel channel is installed using a very low clearance between the pressure tube and the end fitting.*

NOTES & REFERENCES

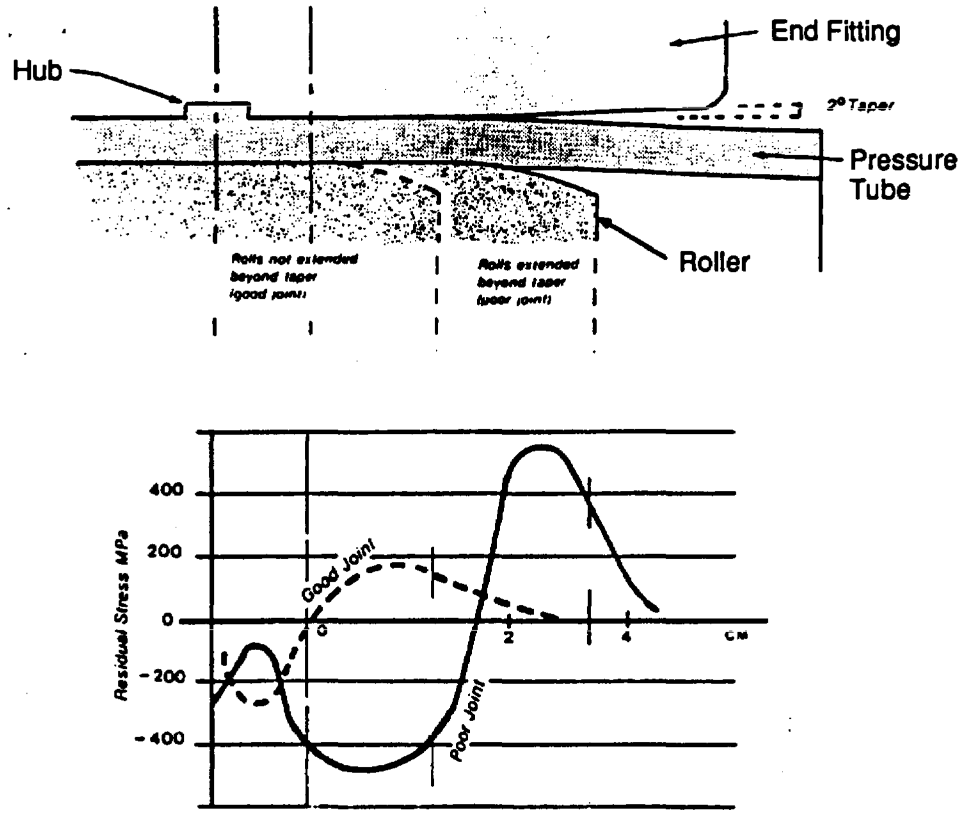

Figure 5.3: Relative Position of Rolling Tool During Installation Causing Residual Stresses in Joint

Why is there zirconium hydride in pressure tubes? How does it facilitate crack formation? Why did the hydrides have a preferred orientation? The answers to these questions will assist the overall understanding of the pressure tube cracking phenomenon, known as **delayed hydride cracking** (DHC).

Obj. 5.5 a) ⇔

Pressure tubes contain about 10 ppm residual hydrogen from the manufacturing process. There is also hydrogen (D_2/H_2*) ingress during the operating life of the pressure tubes which adds to the residual 10 ppm. The region of greatest hydrogen pick–up is the rolled joint area, since this is the highest stressed portion of the tube.

The sources of D_2/H_2 are corrosion (the reaction of D_2O and Zr**), the dissociation of D_2O on the oxidized surface of the pressure tube***, and the radiolytic decomposition of water.

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* *D_2 and H_2 are both isotopes of hydrogen; both terms are used in this section.*

** *Course 224 Chemistry, Module 4 discusses corrosion in the HTS.*

*** *The details of this process are beyond the scope of this course.*

NOTES & REFERENCES

There are also three generic, but distinctly different, mechanisms for D_2 ingress into the pressure tube metal, namely:

a) diffusion of deuterium through and along the stainless steel end fittings (stainless steel is quite permeable to hydrogen),

b) migration of D_2 through the protective oxide layer on the inside wall of the pressure tube,

c) absorption of deuterium gas through the surface oxide on the annulus gas side of the pressure tube – this can be very rapid if surface oxide integrity is not maintained. The deuterium gas will have migrated to the annulus through the end fitting.

Hydrogen that has entered the pressure tube is in solution in the metal if the temperature is above 150° C. Below 150° C, the hydrogen precipitates from solution because the solubility limit decreases (becoming zero at room temperature). As the hydrogen leaves solution, it combines chemically with the metal forming zirconium hydride. The hydride re–dissolves when the temperature is again raised above 150° C. The shutdown and run–up of the reactor cycles pressure tubes through this temperature. Hydrides continuously form and re–dissolve.

Hydrides, like defects in the metal's crystal structure, impose stress on the metal. To minimize this stress, they precipitate in preferred orientations. With the normal stress distribution in pressure tube walls, their preferred orientation is circumferential. This orientation places the hydrides parallel to the largest stress*, providing maximum tensile ductility. Over–rolling alters the stress distribution causing radial orientation of hydrides, ie, they are now perpendicular to the principal stress. This corresponds to a low tensile ductility orientation. Hydride orientation is illustrated in Figure 5.4.

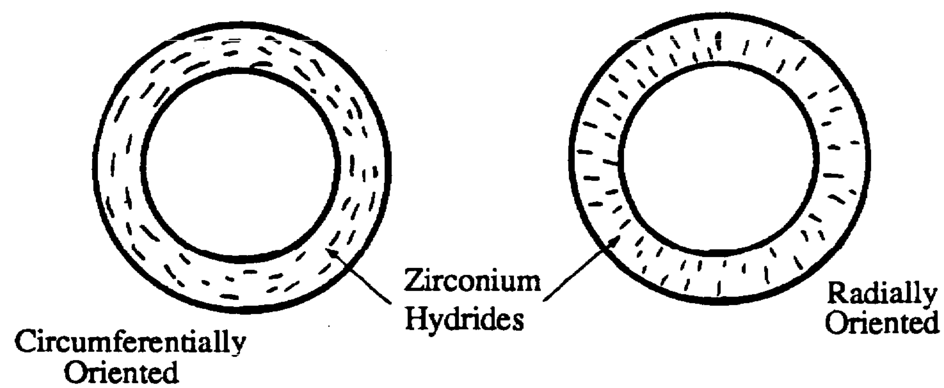

Figure 5.4: Representation of Orientation of Precipitated Zirconium Hydride Platelets in a Pressure Tube

* *This is the stress resisting the tendancy of the pressurized tube to expand outwards.*

NOTES & REFERENCES

Zirconium hydride is extremely brittle and fails readily under tensile loading. Pressurizing fuel channels with radially oriented hydrides present, adds sufficient extra stress to cause the hydrides to crack. Experimental evidence from tests of cold–worked Zr–$2^1/_2$ Nb suggests the whole process occurs in stages. The first step is precipitation and re–orientation of hydride at the crack tip. This is followed by brittle fracture through the hydride precipitate when it reaches a critical size. The crack may not propagate into the more ductile metal, but growth may continue as hydride forming at the new crack tip fails (a further increment of fracture). Figure 5.5 depicts this process.

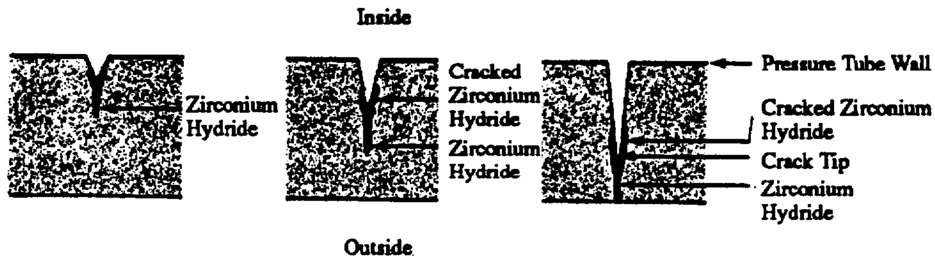

Figure 5.5: Representation of the Growth of a Crack Through Failure of Zirconium Hydride that Precipitates at Crack Tips

How does DHC affect day–to–day station operations? Clearly, zirconium hydride is present in pressure tubes during reactor shutdown. If we accept the possibility that some hydride may be radially oriented, even in correctly rolled pressure tubes, we must be concerned about fully pressurizing the fuel channels before all hydrogen has returned to solution in the metal.

Obj. 5.5 b) ⇔

Experience indicates that the highest risk is present when HTS temperatures are in the area of ~**100–200**°C. Operating procedures are, therefore, designed to **avoid operation** in this region, and also to **pass through** this temperature band as quickly as possible (and in a continuous manner) during both heatup and cooldown of the unit. To further limit stress levels, this transition may occur at pressures lower than normal operating pressure. The hydrides experience tensile stress for a minimum time, thus reducing the probability of through–wall cracks due to DHC.

Obj. 5.5 c) ⇔

Besides the operational restrictions imposed to limit DHC in pressure tubes, there are two means of reducing the amount of hydrogen ingress into the tubes. One applies to the annulus gas side, the other to the heat transport side.

Oxygen is added to the annulus gas system in small concentrations to maintain an oxidizing atmosphere in the annulus gas. This ensures the integrity of the oxide film on the pressure tube surface.

NOTES & REFERENCES

Without O_2 addition, the oxide layer thins and deuterium, if present in the annulus gas, will penetrate into the tube. In a secondary role, the oxygen scavenges any D_2 present (that may have migrated through end fittings).

Oxygen in the annulus gas also recombines with any CO (formed by the radiolysis of CO_2) that may be present. This prevents the CO from accumulating, and further reacting to form tar–like deposits* on the tubes.

Such deposits can create flow restrictions in the "pigtails". Note that any reduction in annulus gas flow due to these restrictions will increase the possibility of hydrogen uptake by the tubes.

An important aspect of chemical control of the heat transport D_2O** is the addition of hydrogen to scavenge excess O_2. Too much oxygen decreases the protective quality of the oxide layer on the tube's inner wall, actually increasing the likelihood of D_2 ingress. The hydrogen addition must be carefully controlled, since too much H_2 in the system can also lead to further hydrogen uptake by the pressure tubes. Thus, too much of either O_2 or H_2 can be detrimental to the pressure tubes.

A program of LSFCR, similar to that implemented at PNGS–A to resolve the DHC problems, will be applied at BNGS–A in the near future. This project will involve extended outages over the next several years.

PRESSURE TUBE – CALANDRIA TUBE CONTACT

In addition to axial creep, the pressure tubes (and calandria tubes) also undergo **creepsag**. Creepsag is defined as the deflection of the tubes in the vertical plane due to a change in curvature caused by flux, stress and temperature. They droop.

Obj. 5.5 d) ⇔

Within the reactor structure, the pressure tubes are separated from the calandria tubes by spacers (garter springs). Should these spacers be mis–located or missing, the hot pressure tube could sag into contact with the colder calandria tube. This establishes a steep through–wall temperature gradient in the pressure tube. Hydrogen present in the tubes diffuses down the gradient, collecting and precipitating from solution at the outside wall of the pressure tube. Blisters then form on the outer surface of the tube. Cracks may initiate and grow (probably by DHC) in this brittle blistered area.

* *The process by which these deposits are formed is beyond the scope of this course.*

** *Refer to course 224 Chemistry, Module 4 for more discussion of hydrogen addition to the HTS.*

The zone of contact between pressure and calandria tubes tends to be long. This may result in strings of blisters forming on the bottom of the pressure tube. The blisters, being extremely brittle, inevitably crack. In August of 1983, a pressure tube in Pickering unit 2 ruptured at a contact location. A string of blisters had formed and cracked. Though this tube was Zr–2 (both Pickering units 1 and 2 were built with Zr–2 pressure tubes), Ontario Hydro began an In–Service Inspection (ISI) program to monitor pressure tube hydriding problems in all its reactors, regardless of pressure tube material.

In addition, the AECB reinforced the requirement that all units have an effective and dedicated leak detection system to warn of leaks which might signal cracked pressure tubes (the annulus gas system achieves this).

In 1987, as part of the ISI program, a pressure tube that was known to be in contact with its calandria tube was removed from Pickering unit 3 and sent for destructive analysis. This tube was found to have hydride levels significantly above those previously found in Zr–Nb tubes.

An important part of the retubing project on the PNGS–A reactors is the move to four garter springs per channel (from two). Spring positions are verified before bringing the unit back into service. At Bruce–A, a project known as SLAR (Spacer Location And Reposition) will be used during planned outages on units 3 and 4 to correctly reposition the four garter springs within each channel. The number of tube contacts with resultant blisters should be reduced, allowing these units to operate until their scheduled retubing (not expected until after the year 2000).

SUMMARY OF THE KEY CONCEPTS

- Pressure tube elongation is caused by thermal expansion and creep. The amount of creep experienced is increased by operating in a high temperature, high radiation environment.
- Insufficient allowance for excessive elongation was made at some early stations. Major modifications to these units were required after construction. Significant design changes were instituted for the stations that followed to handle more elongation.
- Pressure tube elongation is handled by a system of bearings and journals on the end fittings. One or both ends may have the ability to float (with the other end fixed) as the tube grows longitudinally.
- Two approaches to deal with the excessive elongation of pressure tubes in CANDU units are REFAB and LSFCR. REFAB involves relocating the pressure tube and end fittings so they end up at the beginning of the allowable bearing travel. LSFCR is the complete replacement of all the fuel channels in the unit.

NOTES & REFERENCES

- Localized stresses in over–rolled pressure tube/end fitting joints causes zirconium hydride to form and orient radially rather than circumferentially. These hydrides are very brittle and form cracks that eventually propagate through the pressure tube wall.
- To minimize further cracking, operating procedures specify faster heat up and cool down at lower than full pressure through the temperature region of 100–200° C.
- Oxygen is added to the annulus gas system in small concentrations to maintain an oxidizing atmosphere in the annulus gas and scavenge D_2. This prevents the pressure tube's oxide layer from thinning, allowing D_2 to penetrate the outer wall of the tube.
- Hydrogen is added to the heat transport system to scavenge excess O_2. Careful control of H_2 addition minimizes the amount of hydrogen uptake by the tubes.
- Hydride blisters may form at points where pressure tubes have sagged into contact with calandria tubes. The blisters are very brittle, and may crack, causing a pressure tube rupture. Proper spacer placement (through SLAR or retubing) is essential to prevent tube contact and limit blister formation.
- Table 5.1 gives an overview of the various pressure tube problems and methods used to handle them.

NOTES & REFERENCES

Problem	Cause	Accommodation
Pressure Tube Elongation	a) Thermal (each reactor heat–up) b) Creep (entire tube life)	– Sliding end fitting – Adjustable "fixed end" – REFAB
Zirconium Hydride Precipitation	a) Residual stress from over–rolling joints, H_2 ingress into tube, cool down through 150° C, hydride radial orient–ation upon precipitat–ion, cracks form due to brittle fracture b) Pressure tube/Calandria tube contact, cool area on pressure tube, pre–cipitation of hydride in blisters, rupture of tube	– O_2 addition to annulus gas system – PHT H_2 addition control – Heat–up/cool–down procedural restriction – SLAR – 4 Spacers on new tubes (LSFCR units and at Darlington)

Table 5.1 Summary of Pressure Tube Problems

Page 14 ⇔

You can now do **assignment questions 1 – 10.**

ASSIGNMENT

1. State the two primary causes of pressure tube elongation.
2. Explain how is pressure tube elongation is handled.
3. Explain why *excessive* elongation of pressure tubes is a problem.
4. Describe two solutions to the excessive elongation of pressure tubes in operating units.
5. Explain how delayed hydrogen cracking (DHC) causes leaks in pressure tubes.
6. Describe how the heat transport system is operated to minimize further pressure tube cracking.
7. Explain why oxygen is added to the annulus gas system.
8. Explain why hydrogen is added to the heat transport system.
9. Explain how hydride blisters are formed on pressure tubes.
10. Descibe what can be done to limit or prevent blister formation.

Before you move on to the course checkout, review the objectives and make sure that you can meet their requirements.

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