ANALYSIS OF THE PRESSURE TUBE FAILURE AT PICKERING NGS "A" UNIT 2

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INTRODUCTION

About noon on the 1st August 1983, the pressure tube in fuel channel G16 of the Pickering NGS "A" unit 2 reactor developed a critical through wall crack and failed by fast fracture after 342 days of continuous full power operation.

Following removal of the fuel, a TV inspection inside the fuel channel revealed an axial crack in the bottom of the pressure tube approximately 2 metres long, in which two fuel pencils were lodged.

After extracting the fuel pencils, the fuel channel was removed and shipped to the Atomic Energy of Canada Limited's Chalk River Nuclear Laboratories (CRNL) for detailed examination to determine the cause of failure.

Examination of failures normally takes a course of looking at the fracture and gradually refining the work into finer detail to determine the actual origin of the failure. In this case, several other aspects also needed to be examined. The position of the garter spring was very important as was examination of the calandria tube which was subsequently removed. During the inspection several other fuel channels in Pickering "A", Bruce "A" and NPD reactors were inspected and some removed for further assessment at CRNL. All these aspects came together to outline the cause and mechanism of failure. The following gives a very brief review of the salient features of the examination of Zircaloy 2 and zirconium niobium pressure tubes and the implication for operation of subsequent reactors which have zirconium niobium pressure tubes.

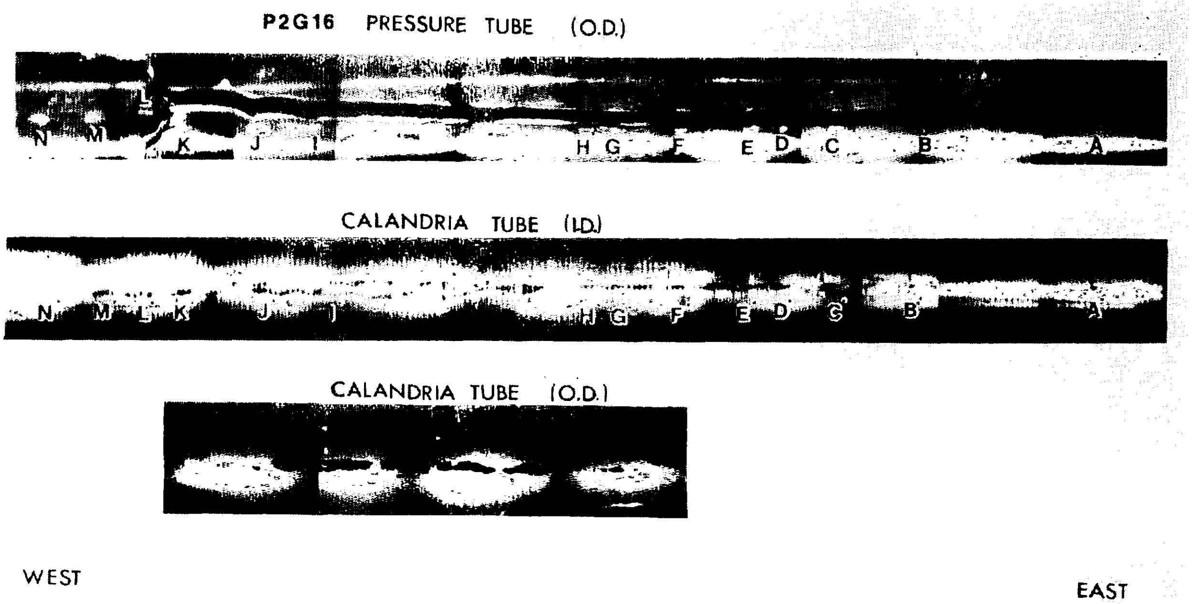

FIGURE 1: BLISTERS ON EAST OUTLET SECTION OF P2 G16 PRESSURE TUBE AND CORRESPONDING CONTACTING SECTION OF CALANDRIA TUBE

EXAMINATION OF PRESSURE TUBE P2 G16

Visual

The examination of the outside of the pressure tube began with a close inspection using a Questar Telescope through 12 feet of water in the fuel bay at CRNL. This was the first time the actual extent of the crack could clearly be seen. The crack was very long extending from just inside the rolled joint to a point about 2 metres along the tube (approximately the design location of the outlet garter spring). It ended at this point in a T configuration of two circumferential tears from the axial crack. Parts of the fracture surface could be seen which showed a radial crack in many areas but developing into a ductile failure towards the outboard end of the crack. Near the T of the crack several dark round marks could be seen which were unexpected. About 14 of these were seen in the zone from about 1.5 metres to 2 metres from the outlet end of the pressure tube. The marks and the crack can be seen in figure 1 along with the inside and outside of the calandria tube which is discussed later.

When the tube was cut lengthwise to allow closer examination the unexpected marks were seen to extend into the pressure tube wall and at the outside surface of the tube had the form of a small crater. For want of a better name they were called blisters. Fourteen clearly identified blisters could be seen together with a fairly large dark patch (later shown to be a concentration of zirconium hydrides near the outside surface of the tube). Figure 2 shows a typical blister before sectioning. The brittle nature of the material in the blister can easily be surmised. The crack ran through several of the blisters but in only one case did it pass through the middle of the blister.

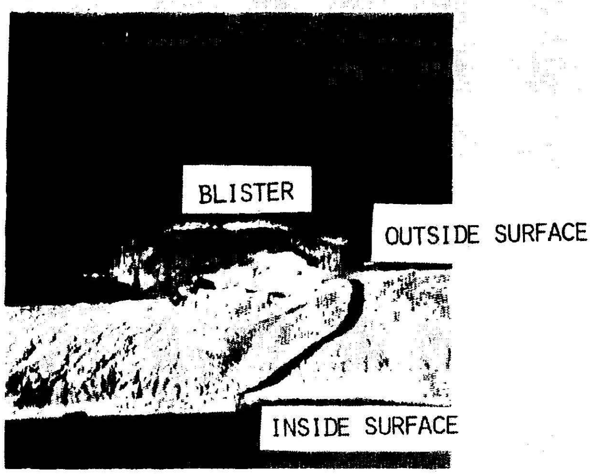

FIGURE 2: TYPICAL BLISTER AT FRACTURE SURFACE

The fracture surface could be divided into three clear zones: Zone I (0.0-0.6m) having a 45 degree shear fracture with markings which indicated propogation toward the outlet end of the tube. Zone II (0.6-1.3m) a flat radial crack surface with intermittent shear lips at the outside and inside surface end of the tube. Zone III a flat radial crack with shear lips on the inside surface of the tube (1.3-2.0m). Markings on the fracture surface indicated that the crack started in this zone. Close examination of the fracture surface around blisters C, D and F revealed what appeared to be the initiating crack which was about 100mm long and at its centre, about 90% through the wall prior to the failure. Subsequent deuterium analysis and metallography of the area showed that the deuterium level close to the inside surface of the wall was very low and this prevented the growth of the crack completely through the wall such that failure was by break before leak. Thus the crack appears to have started at blisters D and E and extended axially along the tube to a critical partial through wall crack about 100mm long. There is still a question remaining of why the crack initiated in the first place. A considerable R and D program has been initiated to determine the behaviour of blisters in pressure tubes.

The historical sequence of a delayed hydride crack can usually be determined by variations in oxide thickness on the fracture surface. In this case however, very little oxidation had occurred suggesting that the crack grew rapidly to the critical size or a lack of oxygen in the annulus gas system prevented the oxidation.

Metallography

The metallography of the tube began with a section through one of the blisters. A typical cross section is shown in figure 3. Here, the white area is seen to be zirconium hydride having a very high deuterium concentration. The dark radiating spikes are areas of high hydride concentration with the general hydride population clearly visible outside this area. This evidence strongly suggested a hydrogen concentrating mechanism. The blister of figure 3 also shows a number of cracks in the zirconium hydride. In general all the blisters examined had this type of crack and preliminary theoretical analysis of stresses around blisters suggests that such cracks are benign, being in an area of compressive stress. One or two blisters in the failed pressure tube had cracks passing through the zirconium hydride area into the base metal of the tube. It is uncertain whether they existed before the tube failure or were a consequence of it. A number of other blistered tubes were examined but only the failed tube had such cracks.

FIGURE 3: CROSS SECTION THROUGH BLISTER

Of all the blisters examined on Pickering "A" NGS units 1 and 2 pressure tubes, most were about 0.5 to 1.3mm deep and 2mm to 5mm in diameter. Their shape was generally circular, but the number varied widely from tube to tube.

Deuterium Analysis

The blisters were shown to be a high concentration of hydrogen or deuterium forming solid zirconium hydride (deuteride) at the surface of the tube. Analyses were initiated to determine the level of these two hydrogen isotopes in the vicinity of the blisters and later along the tube. This was the first Zircaloy 2 pressure tube to be examined after 12 years of service in a power reactor and the levels were much higher than had been predicted. In general the levels had been expected to be below the terminal solid solubility throughout the bulk of the tube but were found to be in excess of 250ppm of deuterium at a peak which occurred about 5 metres from the inlet end of the pressure tube. In order to determine if this deuterium level was an isolated case, a second tube was removed (P2 J15) after ensuring that the garter springs were in the design location and contact between the pressure tube and calandria tube had not occurred. Deuterium levels were found to have a similar distribution but at a slightly lower level. Subsequently several more channels from Pickering "A" unit 2 and unit 1 were removed following their inspection in reactor. Figure 4 shows the general distribution. The P1 K18 pressure tube was found to have been in contact with the calandria tube at the inlet half of the channel and deuterium analysis revealed two peaks, one near the outlet as expected and one at the inlet contact area. On the basis of the oxide thickness at this area (about 15 microns) and some understanding of the corrosion process, it became apparent that the peak of deuterium at this location was not a result of corrosion from the inside surface alone. Diffusion of deuterium into the tube from the annulus gas sytem must have occurred. This appeared to be plausible because the annulus gas system in units 1 and 2 had always operated in a stagnant mode such that deuterium, diffusing through the end fittings, could build up in the atmosphere on the outside of the pressure tube, and subsequently enter the pressure tube.

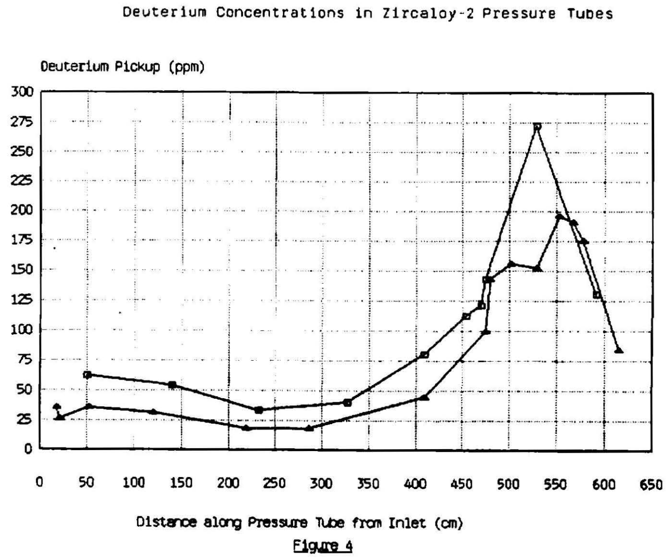

FIGURE 4: DEUTERIUM CONCENTRATIONS IN ZIRCALOY 2 PRESSURE TUBES FROM PICKERING UNITS 1 & 2

The peak in oxide thickness and deuterium level at the outlet of the pressure tubes appears to have arisen from an enhanced corrosion rate which started when the oxide reached a thickness of about 15-20 microns. In effect the local environment within this thick oxide, where the corrosion process was occurring, assumed the worst characteristics of both reducing and oxidizing chemistries and appeared to be independent of the bulk chemistry of the primary heat transport system.

CALANDRIA TUBE EXAMINATION

Visual

At this stage in the investigation, the location of the garter springs prior to the failure was unclear and whilst it was suspected that the failed pressure tube had been in contact with the calandria tube as a result of a misplaced garter spring, there was some evidence that both garter springs were in the correct location - ie. contact where the blisters were seen would not have been possible. Confirmation of contact or gap could only be obtained by careful inspection of the calandria tube and it was subsequently removed and examined at CRNL.

Visual examination of the outside of the calandria tube showed a dark deposit which corresponded with the expected contact location. The deposit was later shown to be a copper oxide corrosion product from materials in the moderator system.

Examination of the inside of the tube revealed dark marks which correlated with the marks on the outside surface of the pressure tube and confirmed that the two tubes had been in contact, figure 1.

Comparison With Pressure Tube Blisters

A careful comparison of the position and spacing of the marks on the two components and their creep and operating history gave a fairly clear historical sequence of events. This clearly shows contact occurring after 9000 Effective Full Power Hours (EFPH) and gradually extending and creating blisters F to N until 52700 EFPH when the fuel channel was shifted relative to the calandria tube by a reactor maintenance operation associated with pressure tube elongation. After this operation, the five most outboard blisters A-E began to form. This time appears to approximately correspond with the onset of enhanced corrosion which resulted in rapid deuterium ingress combined with the formation of a blister due to the contact with the calandria tube. These blisters grew until the crack initiated and the subsequent fast fracture of the tube occurred at 86700 EFPH.

Mechanical Properties

Several tests were carried out on the calandria tube with very encouraging results:

- i. there was no deuterium pickup.
- ii. the contact points showed no detrimental effects on the calandria tube.
- iii. the mechanical properties were as expected in an irradiated material.
- iv. burst testing of three sections gave burst pressures in excess of 13 MPa (Primary Heat Transport System operating pressure is 9.5 MPa).

As with the P2 G16 pressure tube, properties of the P2 G16 calandria tube were under suspicion, having already experienced the pressure tube failure and pressure transient, and a second calandria tube was removed (P2 K13). This had also experienced contact and this area of the tube is currently awaiting a burst test at CRNL to determine if it shows similar behaviour to the P2 G16 calandria tube.

GARTER SPRINGS - EXAMINATION

The two garter springs from channel P2 G16 were badly damaged. Both visual and metallographic examination failed to reveal any reason to believe that the garter springs were broken prior to the pressure tube failure. Sections of the springs were extensively deformed yet still retained reasonable ductility. Deuterium analysis of these and garter springs from other channels showed that the ends of the springs generally had higher values than the centre, levels upto 100 ppm deuterium being typical for ends and about 10 ppm at the centre. These results strongly suggest that the annulus gas system contained deuterium.

All removed garter springs, apart from those in the P2 G12 channel appeared to be in reasonable condition and suggests that the damage to the P2 G16 garter springs occurred either during the incident or during removal of the pieces of pressure tube from the reactor.

Location in Fuel Channel P2 G16

It was essential to determine the location of the garter springs prior to the failure. There was conflicting evidence on the location of the garter springs from the pressure tube and the calandria tube examination at CRNL. However, the two tubes showed obvious signs demonstrating that the tubes had been in contact for a considerable period of time (approximately 68000 EFPH) which implied that the outlet garter spring could not have been in the design location. Very careful examination of garter springs, calandria tube and pressure tube eventually found conclusive evidence that the inlet garter spring was in the correct location. No such clear evidence could be obtained for the outlet garter spring although a dent in the bottom of the calandria tube, the obvious signs of contact and investigation using an analytical approach strongly suggest that the outlet garter spring was about 1 metre inboard of the design location.

FAILURE MECHANISM

The failure mechanism of the P2 G16 pressure tube is now reasonably clear but not fully understood. The events leading to the failure were as follows:

- i. The outlet garter spring moved about 1 metre inboard from its design location probably during the construction or commissioning phases.
- ii. Due to the increased span between supports, the pressure tube sagged into contact with the calandria tube after about 9000 EFPH.
- iii. 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.
- iv. 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.
- v. The defect grew by delayed hyride cracking to form a partial through wall crack about 100 mm long.
- vi. When the crack reached a critical size it suddenly broke through the wall, and extended to the 2 metre length.

In general, the current understanding of the failure mechanism requires at least three conditions to co-exist:

a. high hydrogen/deuterium content in the metal.

b. a means of concentrating the hydrogen/ deuterium at a local area - such as a thermal gradient in the metal.

c. high deuterium ingress rate such that high local stresses are produced in the concentration region, thus creating the necessary preconditions for crack initiation.

ZIRCONIUM NIOBIUM PRESSURE TUBES

The deuterium content found in the Zircaloy 2 pressure tubes of Pickering "A" units 1 and 2 was of considerable concern during the period prior to the decision to retube these units. Laboratory evidence indicated that zirconium niobium pressure tubes might develop similar oxide thicknesses but the deuterium pickup was expected to be about five times lower. However, very little data were available from in-reactor tubes. To obtain some preliminary data the pressure tubes from Bruce "A" unit 2, which had been removed in 1982 for cracks in the rolled joint area were analyzed and found to contain about 5 ppm deuterium. These, however, had only been in service for about 5 years and plans were made to remove two tubes from NPD, one original Zircaloy 2 tube (from 1962) and one of zirconium niobium used as a replacement in 1967. Whilst the operating life and chemistry of the system is different to Pickering "A" it was felt that tubes of the different alloys having seen the same operating conditions would provide a good comparison of their relative oxidation and deuterium pickup rates.

The results were very encouraging for zirconium niobium as can be seen in figure 5. The Zircaloy 2 tube appeared to behave in a similar manner to those in Pickering "A" units 1 and 2 whilst the deuterium level was very low in the zirconium niobium tube - a maximum of 5 ppm.

The "lead" unit, using zirconium niobium pressure tubes in terms of EFPH and fluence, was Pickering "A" unit 3. Preparations were being made throughout 1983 to remove a tube from Pickering "A" units 3 or 4 but the failure of P2 G16 delayed their execution. However, during the recent outage (May 1984), fuel channel P3 J09 was removed and shipped to CRNL for examination.

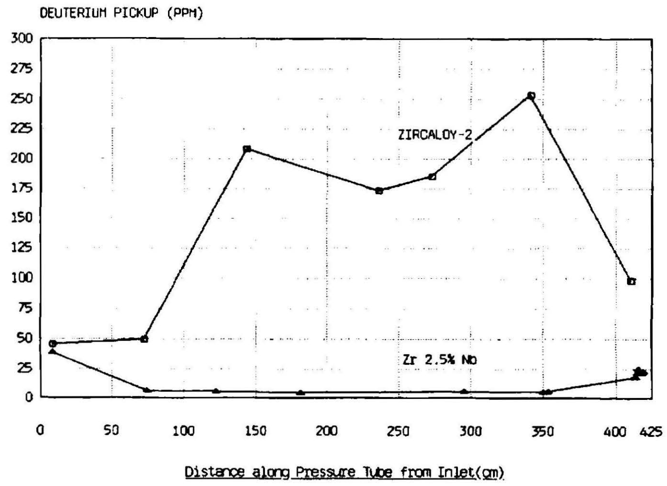

FIGURE 5: DEUTERIUM CONCENTRATIONS IN ZIRCALOY 2 AND Zr 2½%Nb TUBES FROM NPD

This pressure tube had been in contact with the calandria tube for about 4 years and early visual examination of the tube showed evidence of this. The results confirm the data from the Bruce 2 and NPD zirconium niobium pressure tubes in that the deuterium concentration was again approximately 5 ppm along the length of the tube. Metallography of the contact area revealed no signs of hydride concentrations. The deuterium pickup rate for several pressure tubes is illustrated in figure 6.

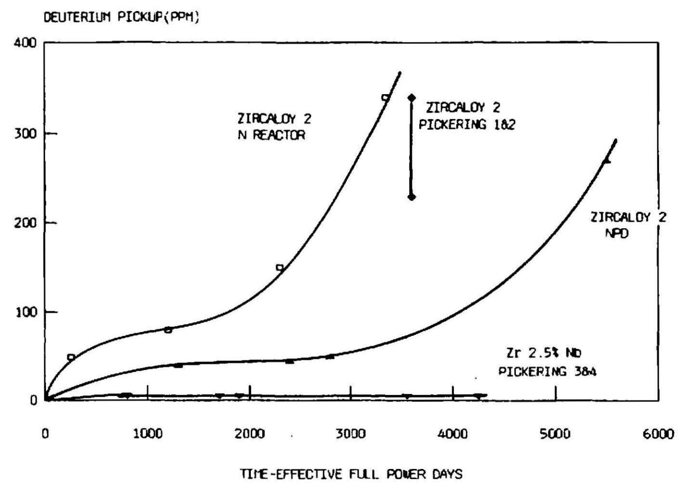

FIGURE 6: DEUTERIUM PICKUP RATES FOR ZIRCALOY 2 AND Zr2½%Nb PRESSURE TUBES FROM DIFFERENT REACTORS

CONCLUSIONS

The failure of the pressure tube in Pickering unit 2 on 1st August 1983 has been found to have been caused by a combination of factors:

a. a fast pickup rate of deuterium from the primary heat transport and annulus gas systems to levels significantly exceeding terminal solid solubility.

b. contact between the pressure tube and calandria tube resulting in significant thermal gradients and deuterium migration.

c. rapid growth of a "blister", the resulting stresses initiating a defect.

d. growth of a delayed hydride crack from the defect, leading to ultimate failure.

Examination of several Zircaloy 2 and zirconium niobium pressure tubes has clearly shown that the deuterium pickup rate of the two materials is significantly different - that of Zircaloy 2 being very high and that of zirconium niobium being very low.

Whilst the pressure tube failure caused a major loss of electricity production from Pickering units 1 and 2, the consequence of the failure and results of the subsequent investigation demonstrate that:

i. sudden pressure tube failure in the CANDU system presents no public safety or worker safety concerns.

ii. the zirconium niobium pressure tubes of all CANDU reactors have absorbed very little deuterium. Even if contact between pressure tube and calandria tube occurs, they do not appear to be susceptible to the type of failure experienced by Pickering unit 2.

ACKNOWLEDGEMENTS

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