

AECL--9939

CA9200406



**AECL CANDU
OPERATIONS**

**Operating Performance of
CANDU Pressure Tubes**

by B. A. Cheadle* and E. G. Price**

presented at:

**The IAEA Technical Committee Meeting
on the Exchange in Operational Safety Experience
of Heavy Water Reactors**

Vienna, Austria, February 20-24, 1989

AECL-9939

April 1989

ATOMIC ENERGY OF CANADA LIMITED



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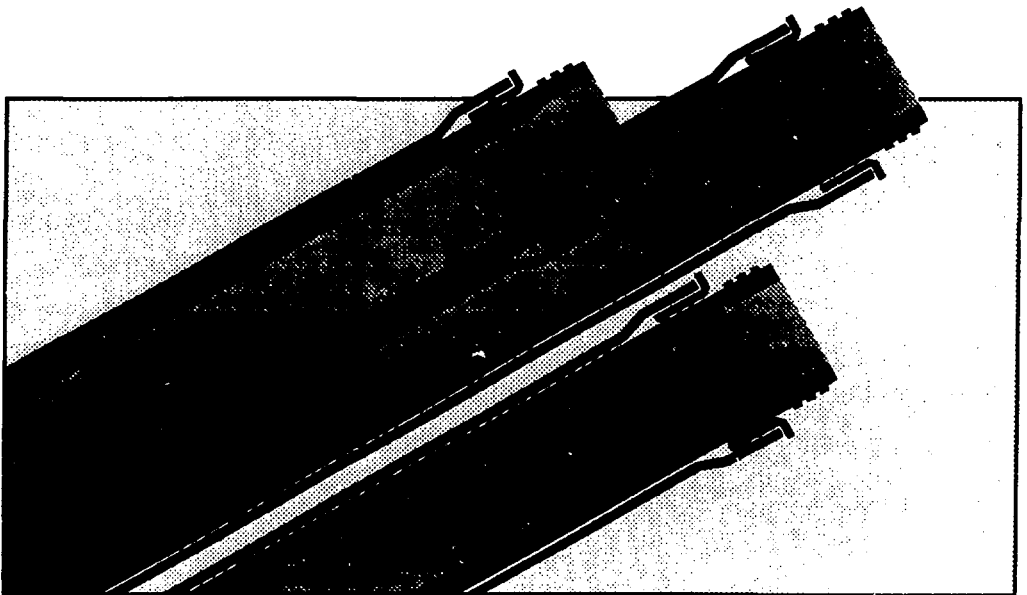
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Abstract

The performance of Zircaloy-2 and Zr-2.5 Nb pressure tubes in Candu reactors is reviewed. The accelerated hydriding of Zircaloy-2 in reducing water chemistries can lower the toughness of this material and it is essential that defect initiating phenomena, such as hydride blister formation from pressure tube to calandria tube contact, be prevented. Zr-2.5 Nb pressure tubes are performing well with low rates of hydrogen pick-up and good retention of material properties.

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Tenue des tubes de force du CANDU en exploitation

B. A. Cheadle*, et E. G. Price**

Présenté à
**l'IAEA Technical Committee Meeting on the Exchange in
Operational Safety Experience of Heavy Water Reactors**
tenue du 20 au 24 février 1989, à Vienne, Autriche

AECL-9939

Avril 1989

Résumé

On passe en revue le comportement des tubes de force en Zircaloy-2 et en Zr-2,5 Nb dans les réacteurs Candu. L'hydruration accélérée du Zircaloy-2 en milieu aqueux réducteur peut réduire la résistance de ce matériau et il est essentiel d'éviter les phénomènes, tels que la formation de pustules d'hydrure par suite du contact entre le tube de force et le tube de cuve, favorisant l'apparition de défauts. Les tubes de force en Zr-2,5 Nb ont une bonne tenue et présentent une faible absorption d'hydrogène ainsi qu'un bon maintien des propriétés du matériau.

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1.0 INTRODUCTION

CANDU pressure tubes are performing very well. Over the last 30 years the CANDU reactor fuel channel has been developed to produce much higher powers and the properties of the tubes have also had to be developed to accommodate the more severe operating conditions, Table 1. This required a change in material from Zircaloy-2 to Zr-2.5 Nb which was fortunate because subsequently it was found that the performance of Zircaloy-2 deteriorated after long term exposure to the reactor environment. After half their predicted service life, Zr-2.5 Nb tubes have excellent corrosion resistance dimensional stability and resistance to failure.

TABLE I

FUEL CHANNEL DESIGN DATA

	NPD	Douglas Point	Pickering 1 and 2	Pickering Kanupp	Pickering 3 and 4	Bruce 1-4	Pickering 5-8	Bruce 5-8	600(1) MW	Darlington 1-4	Cernavoda 1-5	
Power Output, MW (electric)	25	200	540	125	540	750	540	750	600	850	600	
Number of Channels	132	306	390	208	390	480	390	480	390	480	380	
Unit Total			780		780	1920	1560	1920	1520	1920	1900	
Annulus Gas	Air	Air	N ₂	CO ₂	N ₂	CO ₂	CO ₂	CO ₂	CO ₂	CO ₂	CO ₂	
Annulus Spacer Material	1x750	ZrNbCu	ZrNbCu	1x750	ZrNbCu	ZrNbCu	ZrNbCu	ZrNbCu (5-7) 1x750(8)	ZrNbCu	ZrNbCu	1x750	1x750
Number of Spacers	1	2	2	2	2	2 (1,2) 4 (3,4)	4	4	4	4	4	
Coolant Pressure MPa	7.6	9.65	9.65	10.9	9.6	10.2	9.6	10.3	11.1	11.1	11.1	
Coolant Temperature K (maximum)	548	572	570	572	570	581	570	581	585	586	585	
Pressure Tube Material (2)	A	A	A	B	C	C	C	C	C	C	C	
Wall Thickness mm	4.2	3.9	5.0	4.0	4.1	4.1	4.1	4.1	4.2	4.2	4.2	
Internal Diameter mm	82.5	82.5	103	82.5	103	103	103	103	103	103	103	
First Power from Reactor	1962	1967	1971	1971	1972/73	1977/79	1982/85	1984/87	1982	1989/92	1992	

(1) Gentilly-II, Point Lepreau, Embalse, Wolsong.

(2) A is Zircaloy-2, B is heat treated Zr-2.5 wt% Nb, C is cold worked Zr-2.5 wt% Nb.

The excellent performance of the CANDU fuel channels is due to the inherent safety of the design and the principle of Leak-before-Break. If a defect forms and propagates until it is through wall, the small leakage of PHTS heavy water will be detected and the reactor shut down before the defect can grow to the critical unstable size. Since the pressure tubes operate in a high neutron flux at high pressure and temperature their properties change during service and confidence is needed that the properties particularly those that influence leak before break behaviour, remain within acceptable limits.

The CANDU design facilitates non-destructive inspection of the pressure tubes and also the relatively easy removal of individual tubes to monitor the material condition. Inspection and sampling devices have been developed to obtain in-situ, defect, dimensional and compositional information. These results can be referenced to the condition of surveillance tubes, which are removed at intervals using a lead reactor criterion and examined and tested in the laboratories. This ensures that the tubes are in a satisfactory condition and any defect will leak-before-break.

2.0 MONITORING THEIR CONDITION

Four principal factors have the potential to affect the service life of a pressure tube:

- changes in dimensions;
- corrosion and changes in hydrogen concentration;
- changes in mechanical properties;
- change in integrity.

2.1 Dimensions

Thermal creep, irradiation creep and irradiation growth change the shape of pressure tubes during service. The tubes elongate axially, expand in diameter and sag. The rate of deformation is linearly related to fast neutron flux. The dimensional changes establish a definite channel life since there are practical limits that can be accommodated. The diametral expansion limits are established by considerations of the coolant flow through the fuel bundles and elongation can only be accommodated to the design limit of the bearing travel. The limits in sag are determined by interference with other in-core devices or by contact of the pressure tube with the calandria tube between spacers. Sag is unlikely to limit the passage of fuel within the expected life of the channels.

2.2 Corrosion and Hydridding

The products of the chemical reaction between the pressure tube and the PHTS heavy water are zirconium oxide and deuterium. The loss of metal from corrosion is structurally insignificant but some of the deuterium is absorbed by the tubes. Deuterium also enters the tubes via the stainless steel end fittings at each end of the channels. It may also enter from the outside surface of the tube if there is deuterium present in the annulus between the pressure tube and calandria tube and the oxide on the pressure tube loses its effectiveness as an adequate barrier. The increase in deuterium concentration increases the susceptibility to delayed hydride cracking (DHC) and may decrease the fracture toughness.

2.3 Mechanical Properties

Neutron irradiation introduces damage to the crystal lattice that increases the strength and decreases the ductility, but appears to have little effect on the susceptibility to DHC. Fracture toughness decreases due to the damage to the crystal lattice. Hydrogen in solution has very little effect on mechanical properties but when precipitated as hydrides it can reduce fracture toughness and the ductile-brittle transition temperature. The amount of the reduction depends on the number of hydrides and their orientation relative to the stress direction. In the first few years of service, radiation damage causes the mechanical properties to change rapidly but subsequent changes are much more gradual.

2.4 Integrity

Monitoring must ensure that there are not any conditions in the channels which cause localized loss of integrity from unforeseen mechanisms. For example, fretting can cause localized loss of material.

3.0 EQUIPMENT AND PROCEDURES FOR MONITORING

3.1 Inspection in the Reactor

Techniques and equipment have been developed to measure the condition of channels without their removal from reactor. The selection of the tubes for examination is based on either the particular properties of the tubes or on the operating conditions of the channel.

Most inspections are based on the CIGAR (Channel Inspection and Gauging Apparatus for Reactors) device [1] which uses ultrasonics to measure diameter and do volumetric inspection in the body of the tube and the rolled joint, eddy current to determine the position of the spacers, and inclinometer to measure sag. In addition, the following have been developed:

- Eddy current inspection - for detects, spacer location, oxide thickness.
- Ultrasonic inspection - for detects in the rolled joint region.
- Deuterium sampling - Tools remove 50 mg, 0.1 mm thick slivers of material from the inside surface of the tubes which are analyzed for deuterium concentration. These slivers are thinner than the corrosion and wear allowance designed into the tube and leave a shallow, smooth groove.
- Channel elongation - The elongation of each channel is measured at intervals by specific instrumentation attached to the fuelling machines at each end of the channel.

3.2 Tube Removal and Testing

The only way to measure the mechanical properties of a pressure tube is to remove a tube and test samples from it. Ontario Hydro and New Brunswick Power have put into place surveillance programs in which pressure tubes are removed from lead reactors for testing. Various factors such as service time or fluence define a lead reactor.

The physical space in the reactor vault and the availability of suitably sized flasks determines the number of cuts that are made in a pressure tube prior to removal. Typically, three cuts are made, at the centre and near each end fitting to produce four sections. The removal procedures are described in detail by J.T. Dunn et al. [2]. The evaluation of removed tubes in cells includes the following:

- **Visual:** The inside and outside surfaces of the pressure tubes are examined using optical and video equipment for surface damage, appearance of the oxide, marks that show where the spacers were located and evidence of any contact with the calandria tube.
- **Dimensions:** The length of the pieces, their inside diameter and sag profile are measured.
- **Rolled Joints:** The as installed residual stresses in the pressure tube in the rolled joint region are calculated from the inside profile of the tube and the current residual stresses are measured by strain gauge-slitting techniques.
- **Presence of Defects:** Both ultrasonic and eddy current techniques are used to determine if any defects are present.
- **Metallography:** The microstructure, hydride orientation and distribution, oxide thickness and integrity and any defects and damage are assessed using optical and electron microscopes.
- **Mechanical Properties:** Tensile strength, susceptibility to DHC, fatigue resistance, fracture toughness and burst strength are determined using appropriate specimens and equipment. To conserve material and test a wide range of variables, small specimens are used wherever possible. Specimens can be prepared by spark machining, punching or mechanical machining.
- **Chemical Composition:** Small through wall coupons are punched out of the tube at many locations principally for hydrogen and deuterium analyses.

4.0 RESULTS OF INSPECTIONS AND EXAMINATIONS

4.1 Zircaloy-2 Pressure Tubes

In Canada, cold worked Zircaloy-2 tubes were installed in NPD, Douglas Point and Pickering NGS "A" Units 1 and 2, Table 1. These reactors had operated without significant interruptions until the rupture of a pressure tube in Pickering Unit 2 in 1983. Since that incident, an extensive investigation of the behaviour and condition of Zircaloy-2 pressure tubes from NPD and Pickering Units 1 and 2, and correlation with the Hanford-N reactor data has shown that there are serious limitations in the performance of the alloy in reducing chemistry water.

4.1.1 Corrosion

In fluxes $> 10^{17}$ n.m⁻².s⁻¹ (E > 1 MeV) and temperatures above 250°C there is an apparent initial transient period of oxidation followed by a low "secondary" oxidation rate. In NPD the low secondary rate lasted for about 12 years, whereas in Pickering Units 1 and 2, it continued for only about six years, Figure 1 [3]. The initial low rate of oxidation was followed by a gradually increasing rate up to oxide thicknesses of ~ 60 microns when Pickering Units 1 and 2 were shutdown.

The start of the increasing rates occurred when the oxides reached a thickness of 15-20 microns. The tube removed from NPD in 1984 had an oxide thicknesses of 66 microns. Predictions that oxide thicknesses would be 70-80 microns in 1986 were confirmed by an inspection and subsequent removal of a tube in 1987. Figure 2 shows the profile of the oxide thickness along Pickering Unit 2 pressure tubes [3]. The oxide was thickest in regions where flux and temperature are highest. The profile along NPD tubes was less regular with the peak closer to the centre [4].

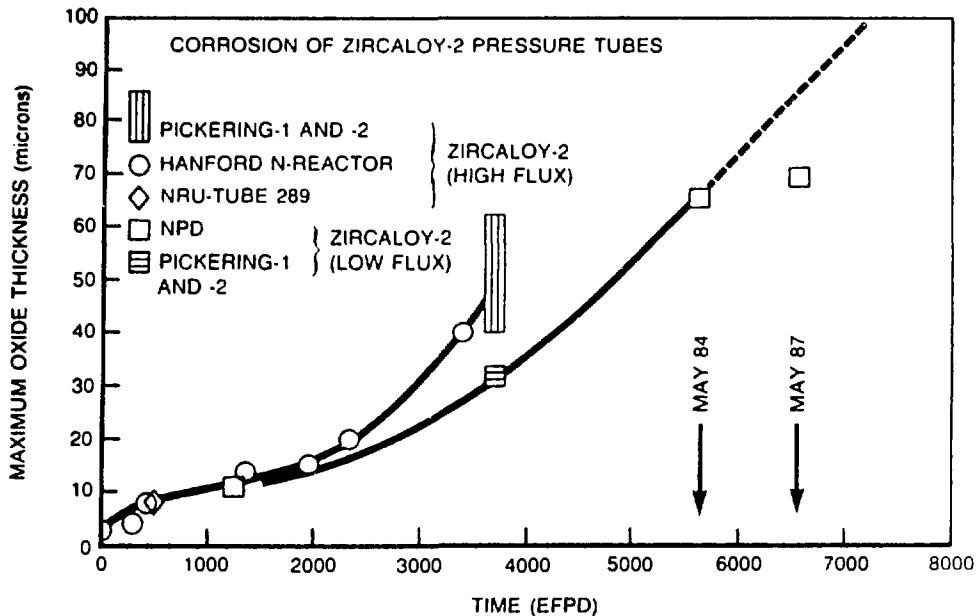


FIGURE 1 WATERSIDE CORROSION OF ZIRCALOY-2 PRESSURE TUBES AS A FUNCTION OF SERVICE LIFE.

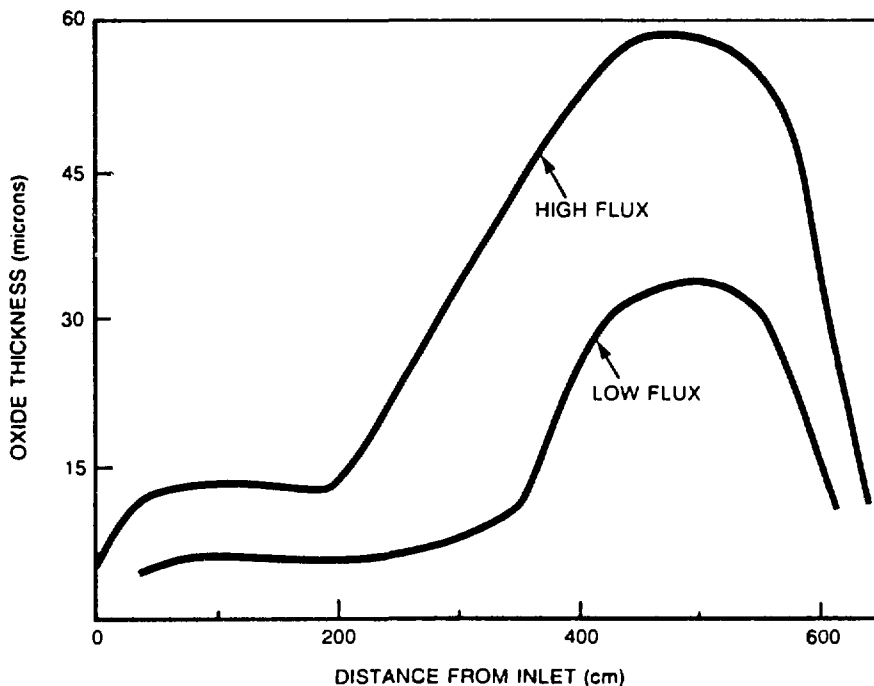


FIGURE 2 PROFILE OF OXIDATION ALONG ZIRCALOY-2 PRESSURE TUBES IN PICKERING A UNITS 1 AND 2

4.1.2 Hydrogen Ingress

Hydrogen (as deuterium) enters the tube from the corrosion reaction with the PHTS heavy water, from crevice or galvanic reactions with the end fittings at the ends of the tubes and sometimes from the gas annulus. The information from surveillance tubes removed from the Hanford N-Reactor confirmed that hydrogen ingress with time followed a similar pattern to corrosion, Figure 3, and hydriding rates of 12 ppm/EFPY are attained [3]. The profile of hydrogen concentration along the Pickering tubes is shown in Figure 4. At the highest temperature

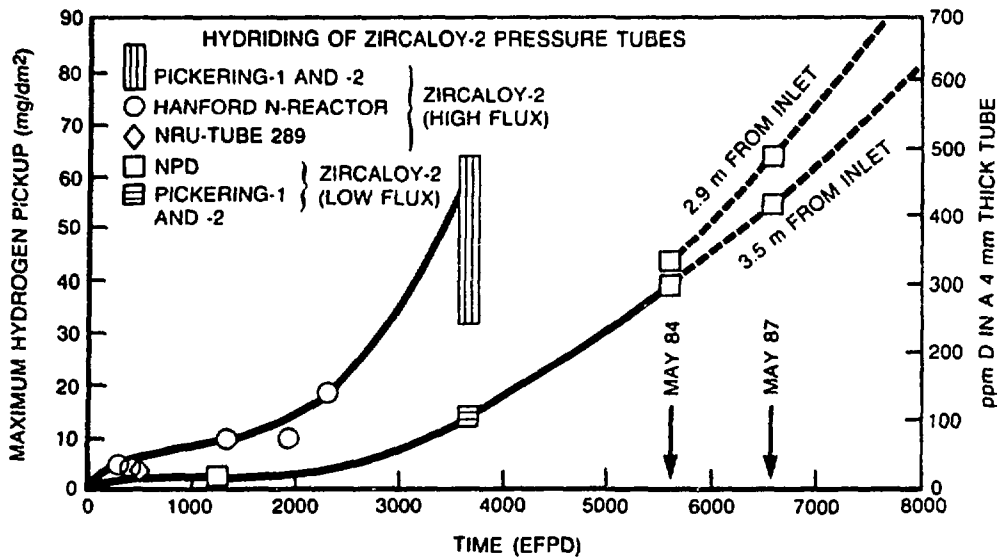


FIGURE 3 HYDROGEN CONCENTRATION OF ZIRCALOY-2 PRESSURE TUBES AS A FUNCTION OF SERVICE LIFE.

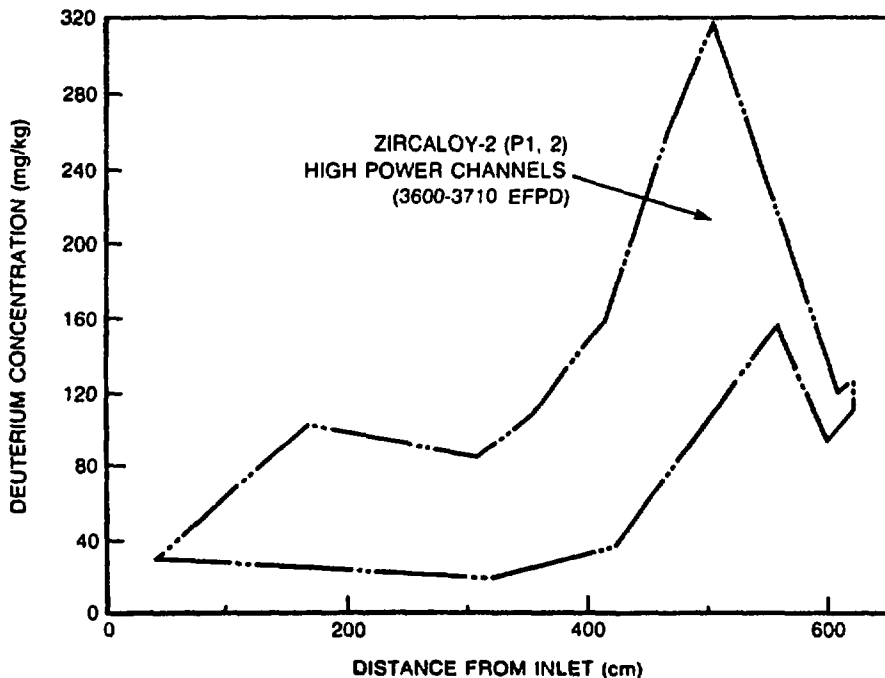


FIGURE 4 PROFILE OF DEUTERIUM CONCENTRATION ALONG ZIRCALOY-2 PRESSURE TUBES IN PICKERING A UNITS 1 AND 2

regions of the channel and at the highest flux positions the hydrogen build-up was greatest. Out of flux the hydrogen concentration was much lower. In NPD tubes, the hydrogen concentration agreed with the pick-up expected from the oxide thickness. In Pickering Units 1 and 2, the pick up on some tubes near the inlet end was higher than could be accounted for by the corrosion on the inside surface.

4.1.3 Microstructural Features

The mode of hydride precipitation was variable. Some tubes from the Pickering reactors showed extensive hydride precipitation on the radial-axial plane as the result of the hydride build-up and the operating stress. Other tubes showed mostly circumferential-axial orientation. As hydride concentration increased, particularly in the NPD tubes, more hydride assumed a radial-axial orientation [4]. At the positions of contact in the Pickering Units 1 and 2 pressure tubes, localized concentrations of hydride ("blisters") had formed [5]. These blisters were typically cracked. There was also a noticeable hydride gradient through the pressure tube wall.

The oxide on the inside surface contained many cracks and had a layered structure. On the outside surface the oxide both on NPD tubes and Pickering A tubes had not significantly increased in thickness since installation. On some Pickering A tubes near the inlet end, the oxide was less than one micron thick indicating little oxidation since start-up but on the NPD tube the oxide was typically six to eight microns thick [3,4].

4.1.4 Mechanical Properties

4.1.4.1 Tensile Properties

Transverse rings and longitudinal tensile specimens were used to measure the transverse and longitudinal tensile strengths of NPD and Pickering A Zircaloy-2

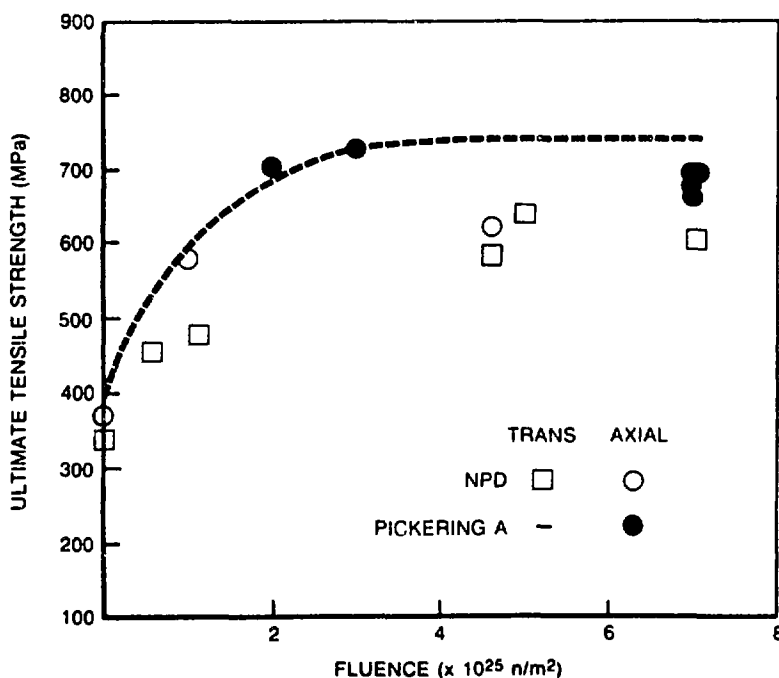


FIGURE 5A EFFECT OF FLUENCE ON THE ULTIMATE TENSILE STRENGTH OF ZIRCALOY-2 PRESSURE TUBES AT 280-300°C

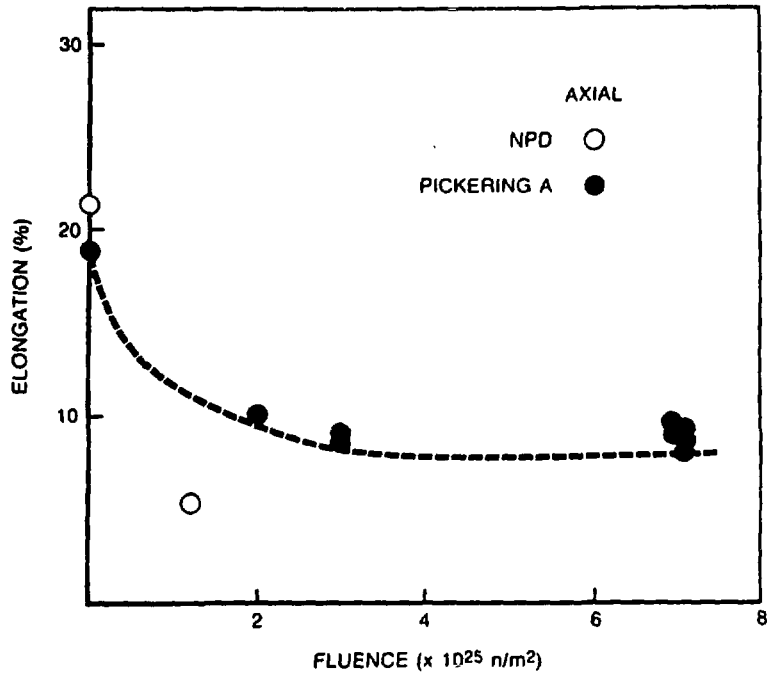


FIGURE 5B EFFECT OF FLUENCE ON DUCTILITY OF ZIRCALOY-2 PRESSURE TUBES AT 280-300°C

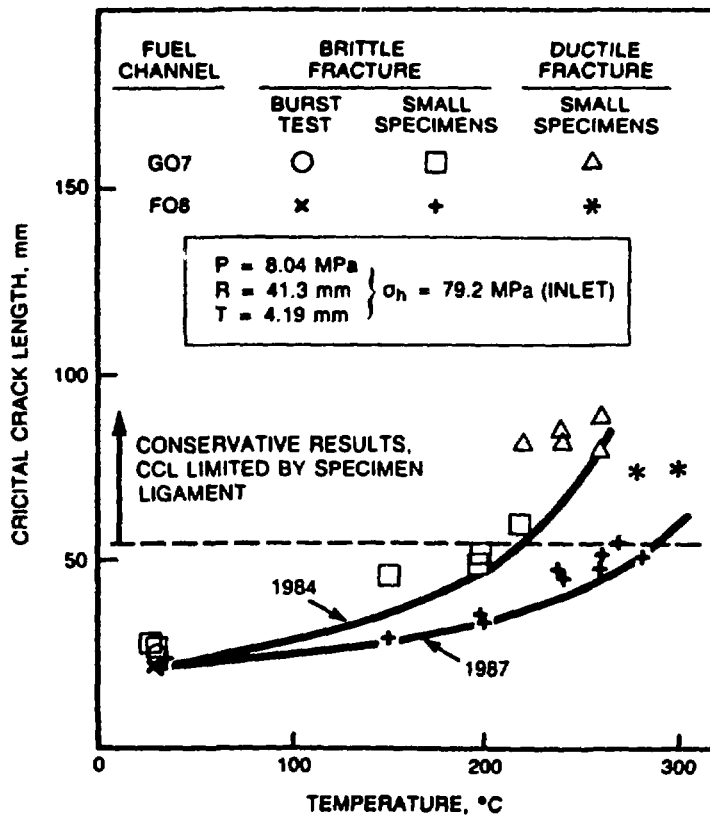


FIGURE 6 ESTIMATED CRITICAL CRACK LENGTH AS A FUNCTION OF TEMPERATURE FOR ZIRCALOY-2 PRESSURE TUBES FROM NPD

pressure tubes. Because the tubes see a varying flux (and temperature) along their length, specimens from varying positions provide an indication of the effect of fluence. There is little increase in strength and decrease in ductility above a fluence of 2×10^{25} n/m², Figure 5 [4,6].

4.1.4.2 Fracture Toughness

Fracture toughness is measured either by testing 17 mm curved compact tension specimens or by bursting 450 mm long tube sections containing an axial, through-wall slit. In both specimens the crack plane is the axial-radial plane and cracking is in the axial direction.

Both the pressure tubes removed from NPD had high deuterium concentrations and many of the hydrides were oriented close to the radial orientation. In the tube removed in 1984 the transition from brittle to ductile fracture behaviour was at about 220°C, Figure 6, which was below the range of reactor operating temperatures, i.e. if a pressure tube in NPD had fractured during reactor operation then the crack would have propagated in a ductile manner. However, the transition temperature of the tube removed in 1987 had increased to about 280°C and if a tube had fractured the crack would probably have propagated in a brittle manner. The change in fracture behaviour of the NPD tubes between 1984 and 1987 was probably due more to the increase in the concentration of radial hydrides than the increase in fluence.

TABLE II
SUMMARY OF FRACTURE TOUGHNESS RESULTS AND SPECIMEN PROPERTIES
OF ZIRCALOY-2 PRESSURE TUBES FROM PICKERING UNITS⁽⁷⁾

Specimen Number	Test Temperature °C	Tough or Brittle	Fracture Toughness K_{IQ} MPa.m ^{1/2}	Yield Stress σ MPa	[H] Equivalent $\mu\text{g/g}$	Critical Crack Length* mm	$2.5 K_{IQ}^2 / \sigma^2$ mm
C5	280	T	54.0a	662	61	71	..
C7	280	T	63.6a	662	59	102	...
C13	280	T	69.7a	662	95	108(LB)	...
C14	280	T	56.9a	662	42	88	...
C16	280	T	63.6a	662	45	95	...
C31	280	T	67.3a	662	58	103(LB)	...
C33	280	T	66.0a	662	42	99(LB)	...
C35	280	T	55.4a	662	...	75	...
C1	230	B	48.7	719	72	49	11
C6	230	B	53.6	719	63	53	14
C11	280	B	75.4	662	110	70	14
C15	230	B	50.3	719	...	50	7.7
C20	280	B	46.0	662	109	47	13
C24	280	B	62.0	662	146	60	12
C36	230	B	40.0	719	81	41	19
C37	230	B	48.5	719	66	49	27

a. Calculated from $K_{IQ} = \sqrt{EJ}$, where J, is read from the first pop-in on the J-resistance curve.

* The values are conservative if the specimen fracture mode was elastic-plastic.

The fracture toughness of the Pickering Units 1 and 2 pressure tubes was measured in regions of relatively high hydrogen concentration and it was apparent that the ductile-brittle transition temperature was between 230°C and 280°C, Table 2 [7]. Again the structure with the greatest amount of radial-axial hydride precipitation exhibited the lowest toughness, but the lowest calculated critical crack length still exceeded 40 mm.

4.1.5 Spacer Location

The NPD channels had one spacer separating the pressure tube from the calandria tube. These spacers were of Inconel X750 and were fabricated as garter springs and at installation were tight on the tube. Four channels were inspected and the spacers were in position. The spacers removed were in good condition.

Similar inspections on Pickering Units 1 and 2 showed that displacement of the spacers had occurred, Figure 7. These spacers were of Zr-2.5 Nb-0.5 Cu but were not tight on the pressure tube to allow for diametral creep. Channel vibration during installation and commissioning caused the spacers to move.

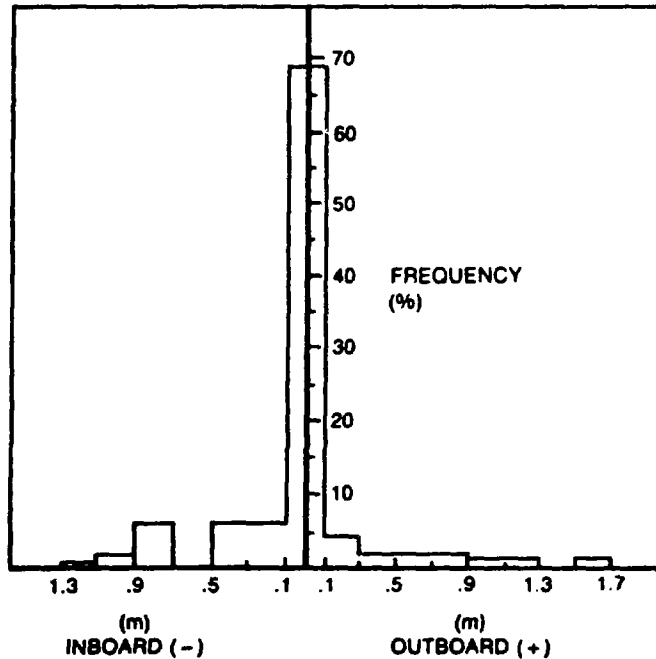


FIGURE 7 HISTOGRAM OF SPACER DISPLACEMENTS IN P1 AND P2 FROM SITE INSPECTIONS

4.2 Cold worked Zr-2.5 Nb

4.2.1 Corrosion

Although one cold worked Zr-2.5 Nb tube was installed in NPD, reactor experience effectively started with the operation of Pickering Units 3 and 4. The majority of the corrosion information has been obtained from tubes from Pickering Units 3 and 4 and Bruce A Units 1, 2 and 3.

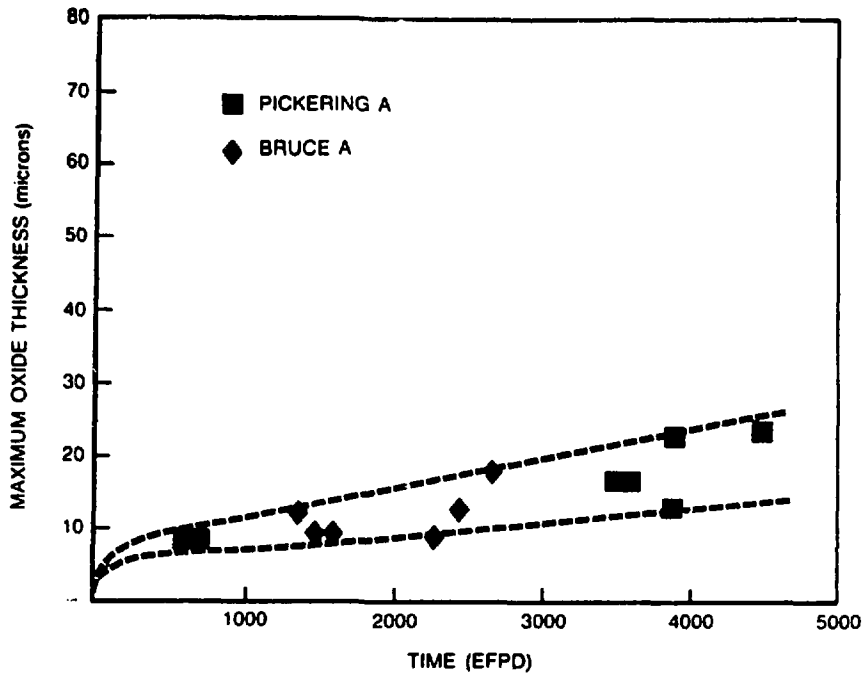


FIGURE 8 WATERSIDE CORROSION OF c.w. Zr-2.5% Nb PRESSURE TUBES AS A FUNCTION OF SERVICE LIFE

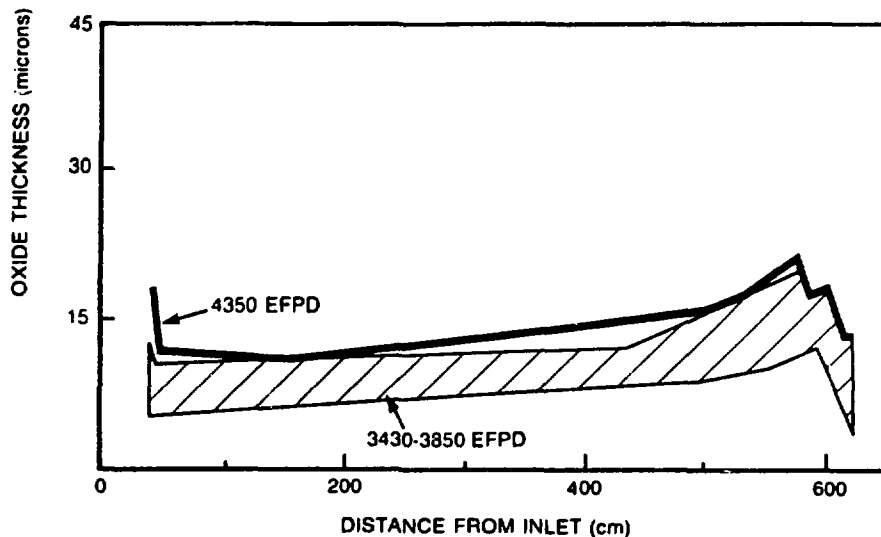


FIGURE 9 PROFILE OF OXIDATION ALONG Zr-2.5% Nb PRESSURE TUBES IN PICKERING A UNITS 3 AND 4

Oxide thickness as a function of service life is shown in Figure 8 [8]. The secondary oxidation rate appears to have stayed constant similar to the secondary rates of Zircaloy-2. These results are from the metallography of tubes removed from the reactors. The eddy current technique developed to measure oxide thickness in-situ indicates similar thicknesses, but the accuracy of the technique is less than that of the metallography due to surface unevenness and other affects. The profile of oxide thickness along Zr-2.5 Nb pressure tubes shows a slight increase near the outlet end (Figure 9).

4.2.2 Hydriding

The maximum local deuterium pick-up with operating time is shown in Figure 10 and along a tube in Figure 11 [8]. The maximum concentrations were at positions near the outlet end. The pick-up of deuterium from the oxidation reaction is considerably less in Zr-2.5 Nb (5%-10% of theoretical) than in Zr-2 (typically > 40%). A small number of tubes in Pickering Units 3 and 4 exhibited higher

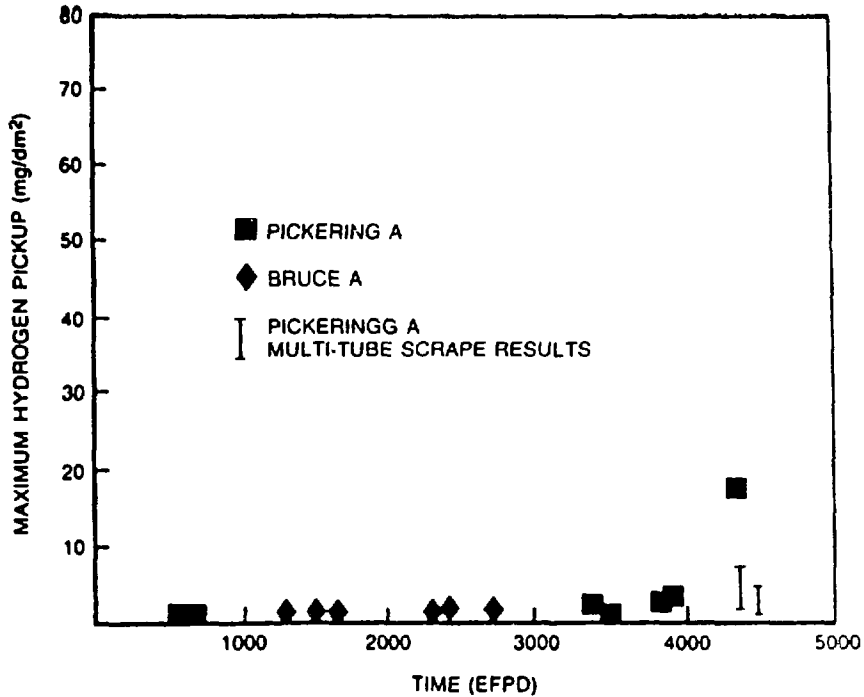


FIGURE 10 MAXIMUM HYDROGEN (DEUTERIUM) PICK UP WITH SERVICE LIFE FOR c.w. Zr-2.5% Nb PRESSURE TUBES

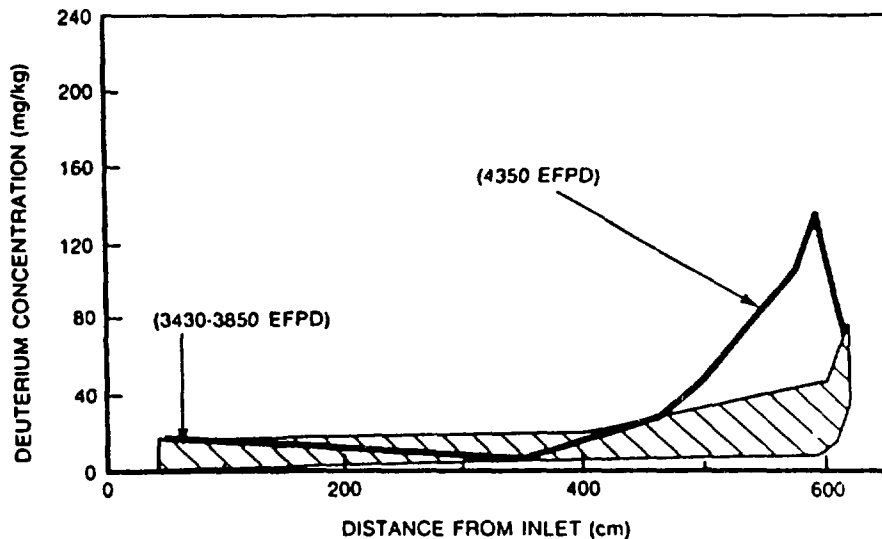


FIGURE 11 PROFILE OF DEUTERIUM CONCENTRATION ALONG PICKERING A Zr-2.5% Nb PRESSURE TUBES

deuterium pick-ups near the outlet end than other tubes. This increase was not matched by an increase in oxide thickness on the inside surface. It is thought this increase may be due to localized ingress from the outside surface. A tube from channel L09 in Pickering Unit 3 had the highest deuterium increase.

The development of a tool to remove a sliver of metal from the top inside surface of an operating pressure tube has enabled a greater amount of data to be obtained [9]. This tool has been used in Pickering Unit 3, Unit 4 (twice) and Bruce Unit 3. Deuterium pick-up rates from waterside corrosion are found to increase with increase in operating temperature.

4.2.3 Metallography

The hoop stress necessary to re-orient hydrides in c.w. Zr-2.5 Nb is in the range 180-220 MPa, and since the operating stress is in the range 130-150 MPa the hydride precipitation mode should remain in the circumferential-axial plane. This has been observed except where high residual stresses near rolled joints caused re-orientation in early reactors.

The oxide morphology on Zr-2.5 Nb is somewhat different to Zircaloy-2. Thick oxides exhibit cracks perpendicular to the surface as well as a tendency to crack parallel and close to the metal-oxide interface.

4.2.4 Mechanical Properties

4.2.4.1 Tensile Properties

Cold-worked Zr-2.5 Nb exhibits an increase in yield and tensile strength with fluence, Figure 12 and a decrease in ductility, Figure 13 [10].

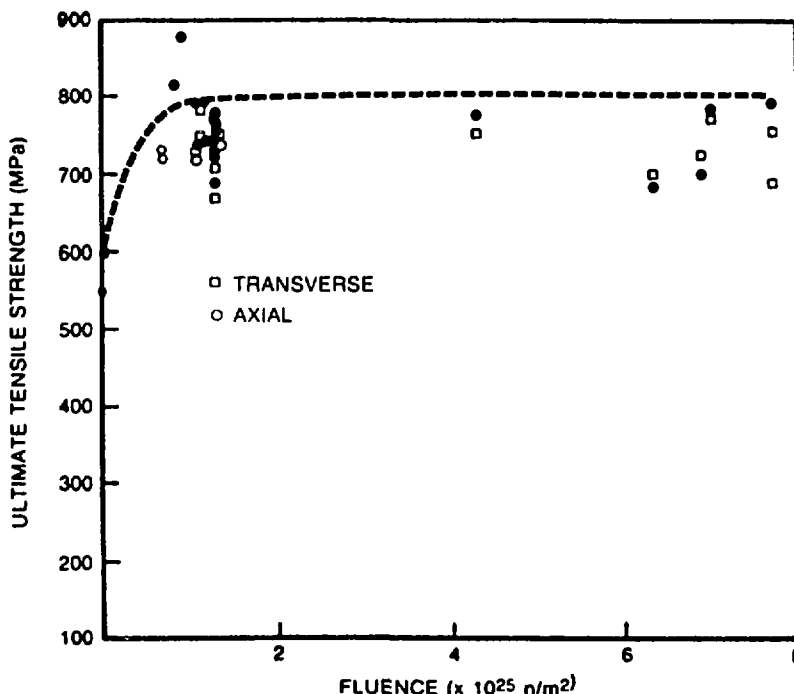


FIGURE 12 EFFECT OF FLUENCE ON THE TENSILE STRENGTH OF c.w. Zr-2.5% Nb PRESSURE TUBES AT 300°C

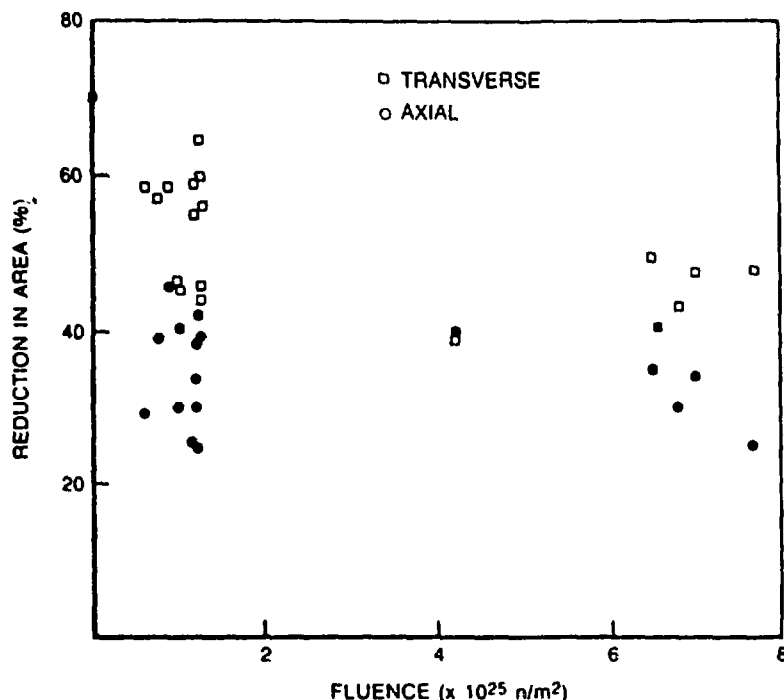


FIGURE 13 EFFECT OF FLUENCE ON DUCTILITY OF c.w. Zr-2.5% Nb PRESSURE TUBES, AT 300°C

4.2.4.2 Fracture Toughness

The development of small specimen fracture toughness test procedures have enabled the trend with fluence to be determined. As with ductility, there is a rapid decrease in early life to about 50% of the as-manufactured value and a much smaller rate of decrease with increasing fluence, Figure 14. Some tubes show significantly higher toughness values than others.

4.2.4.3 Delayed Hydride Cracking (DHC)

The important parameters for DHC are the stress intensity factor K_{IH} for crack initiation, the rate of crack propagation and the temperatures at which cracking can occur. DHC can only occur when hydrides are present in the microstructure, that is, when the hydrogen concentration is above the terminal solid solubility (TSS). New pressure tubes contain less than 20 ppm hydrogen; with this amount TSS is about 220°C and DHC can only occur below this temperature. With the ingress of deuterium, the temperature below which DHC can occur increases until eventually it can occur while the reactor is operating. DHC can occur at reactor operating temperatures much earlier in Zircaloy-2 tubes than in Zr-2.5 Nb because of the higher rate of deuterium ingress.

It is not yet clear if irradiation influences K_{IH} , but it does increase the rate of crack propagation in Zr-2.5 Nb, Figure 15 [11].

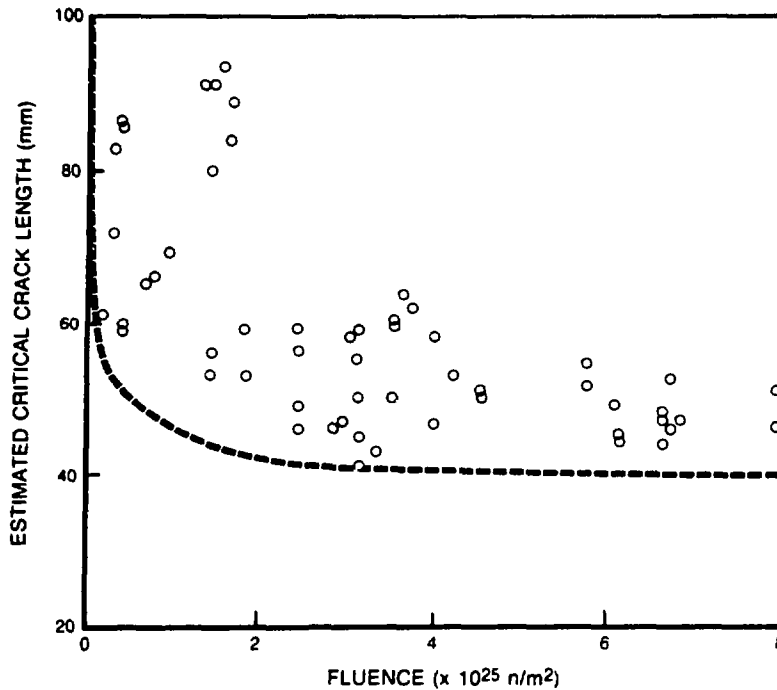


FIGURE 14 CRITICAL CRACK LENGTH OF Zr-2.5% Nb AT 240-300°C ESTIMATED FROM SMALL SPECIMEN FRACTURE TOUGHNESS TESTS

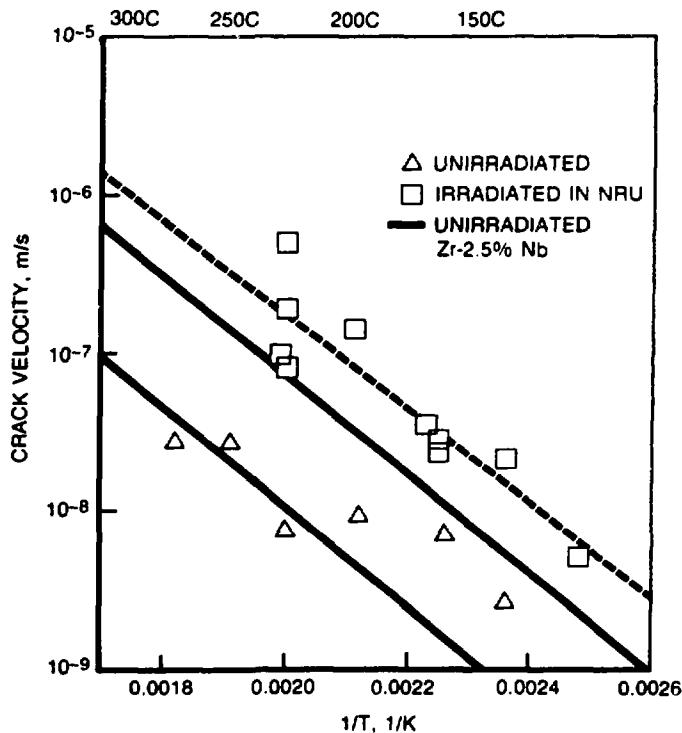


FIGURE 15 THE VELOCITY OF DELAYED HYDRIDE CRACKING IN c.w. Zr-2.5% Nb IN UNIRRADIATED AND IRRADIATED CONDITION

4.3 Heat-Treated Zr-2.5 Nb

Heat-treated Zr-2.5 Nb pressure tubes are water quenched from the ($\alpha + \beta$) phase, cold worked about 12% and then aged at 500°C. This produces a microstructure that consists of about 90% martensitic α' and 10% equilibrium α grains. After the water quench, the martensitic α' is supersaturated in Nb. The subsequent cold work and aging treatment results in a small amount of recrystallization and small β -Nb precipitates are formed. The martensitic α' has a relatively random crystallographic texture and hence the properties of heat-treated tubes are much more isotropic than cold worked tubes.

Compared to cold worked tubes, there is much less information on heat-treated pressure tubes that have been tested after service in reactors. In general, their tensile strength is higher, their ductility, corrosion and hydriding, fracture toughness and susceptibility to DHC are similar, their axial elongation is much less but their diametral expansion is slightly higher.

5.0 OPERATING REQUIREMENTS

For satisfactory operation, the material should remain in an adequately tough condition and any defect generating mechanism should produce a crack whose growth will result in a detectable leak before it becomes unstable: i.e., leak-before-break rather than break-before-leak.

5.1 Leak-Before-Break

For this to occur a number of criteria must be satisfied: the crack must penetrate the tube wall and leak, the leak must be detected and the reactor shut down before the crack grows to the critical length. Thus, the following information is required:

- the maximum length of the crack when it penetrates the wall;
- the crack velocity;
- the critical crack length and its variation with fluence;
- the time to detect a leak.

The first three parameters can be estimated from tests on surveillance tubes. The last parameter is a function of the reactor design and operating procedures.

Delayed hydride cracking in Zircaloy-2 has been studied in the laboratory, but the only occurrence in service was the propagation from blister induced cracking in Pickering Unit 2 channel G-16. A DHC crack in Zircaloy-2 should penetrate the wall with a length about twice the wall thickness. Crack velocity has an Arrhenius relationship with temperature and at operating temperatures cracks could grow to critical lengths in about 24 hours [4]. In NPD the critical crack length was short because of the presence of radial hydrides and the leak detection system with an open annulus may not have detected a leak in time to prevent unstable failure. Since any failure would have been in a brittle mode (Figure 6), reactor operation was terminated in 1987.

In Zr-2.5 Nb pressure tubes, the DHC velocity in the axial direction is twice that in the radial direction. Therefore a crack should penetrate the wall when the crack length is four times the wall thickness. However, in some instances cracks have grown much longer than this before the rate of PHTS heavy water leakage was sufficient to be detected. Nevertheless, the crack detection methods are adequate to detect cracks before they could grow to the critical length.

5.2 Leak Detection and Location

All mechanisms causing leaks in CANDU pressure tubes have been associated with delayed hydride cracking (DHC). This mechanism of crack propagation in zirconium alloys is relatively fast compared to fatigue and the likelihood of inspection detecting a propagating crack is remote.

In early reactors, the annuli were open and leaks could only be detected by a humidity increase in the reactor vault. In later reactors the annulus is sealed and has a gas which is circulated and monitored for moisture content. The system is sensitive to the ingress of small amounts of moisture and leaks as small as a few grams per hour can be detected within an hour from changes in dewpoint.

Leak-before-break is facilitated by reactor temperature manoeuvring after a leak is detected. It has been found that thermal cycling a reactor to about 30 K below the intended hot shutdown temperature, stops crack growth [12]. This procedure enables searches for small leaks to be carried out for a limited time in the hot shutdown condition, where through-wall cracks generally continue to leak. When shutdown to cold conditions, cracks may plug making leaks difficult to locate.

5.3 Break-Before-Leak

This occurs if a crack grows to the critical length before any PHTS leakage is detected, as in Pickering Unit 2 channel G-16 when DHC cracks initiated at blisters. The characteristics of blister formation are substantially similar in Zr-2 and Zr-2.5 Nb. If a region of the pressure tube wall touches the calandria tube it is cooled. If the temperature is below the terminal solid solubility hydride precipitation will occur and the thermal gradients will allow further hydrogen to migrate to the relatively cool zone and build up a mass of hydride. The controlling conditions for blister formation are the temperature of the region, which is determined by the temperatures of each tube and the thermal resistance between them, and the hydrogen concentration in the pressure tube.

The steps in blister formation and cracking are:

- Sag of the pressure tube resulting in contact with the calandria tube. This usually involves limited fretting before loaded contact. The fretting generates a loose oxide.
- Decrease in temperature of the pressure tube at the point of contact.
- Precipitation of hydride if the hydrogen concentration is above the terminal solid solubility (TSS) for the conditions. (If the concentration is below TSS, no precipitation occurs.)

- Build-up of solid hydride to a "blister" shape or layered structure depending on the nature of contact.
- Growth of the blister with time controlled by the total hydrogen concentration.
- Cracking of the blister from volumetric expansion and the hoop stress on the tube during the growth process. The probability of blister fracture and the depth of the crack in the blister increase with blister depth.
- Propagation of the crack outside the blister when a critical depth determined by the stress, is reached.
- Growth of the defect by DHC preferentially in the axial direction due to thermal gradients in the tube wall causing the hydrogen to concentrate near the outside surface.

The higher the hydrogen concentration, the greater the size of blister that can be developed. Thus Zircaloy-2, with an accelerating hydrogen ingress phenomenon, is at risk much earlier than Zr-2.5 Nb.

The timeliness of action to prevent blister formation requires:

- a knowledge of the hydrogen concentration;
- a knowledge of the possibility of contact from the position of the spacers and calculations of sag, or by inspection.

Since determining the position of the spacers is a slow process, warning of possible blister formation is best achieved by measuring the deuterium ingress of tubes that have high initial hydrogen concentrations.

6.0 REVIEW OF FUEL CHANNEL PROBLEMS AND SOLUTIONS

While CANDU fuel channels have operated very effectively a number of problems have had to be resolved. These problems were due to design shortcomings, assembly errors or fabrication flaws.

6.1 Cracks Near Rolled Joints

Incorrectly rolled joints in Pickering Units 3 and 4 resulted in many Zr-2.5 Nb tubes having very high residual stresses in the rolled joint region, and some tubes developed cracks by DHC. The solution was to stress relieve joints already fabricated at the Bruce A reactors and to develop a low stress rolled joint for reactors under construction. However, two tubes at Bruce Unit 2 leaked because cracking had started before the stress relief was done. Stress relaxation during service was sufficient to prevent extensive further crack initiation at Pickering and subsequent to 1975 only one additional tube has developed a leak (in Pickering Unit 3).

6.2 Crack Initiation at Blisters

A Zircaloy-2 pressure tube ruptured in Pickering Unit 2 (G-16). In this instance more than one factor was involved in producing unstable rupture.

Firstly, one of the two spacers had moved out of position allowing the pressure tube to sag and contact the cool calandria tube near the outlet end. Secondly, the Zircaloy-2 pressure tube had built up a high hydrogen content near the outlet end and hydride blisters formed. The blisters cracked and after they had grown to a threshold size the cracks propagated axially and grew to an unstable length. Radial hydrogen gradients in the tube prevented the crack penetrating to the inside of the wall and leaking before the unstable length was reached.

A number of reactors have the zirconium alloy spacer design which can move during assembly and commissioning. Displacement of the spacers increases the length of the unsupported span and allows pressure tubes to touch the calandria tubes prematurely. Contact of the pressure tubes with the calandria tubes is not a serious concern until hydrogen builds up in the tubes beyond a threshold value. In Zr-2.5 Nb tubes this will not occur until the latter half of the design life. The prudent move will therefore be to reposition the spacers during the first half of the design life. An inspection and correction system, (Spacer Location and Repositioning (SLAR)) has been developed to correct this situation. This type of operation will need to be carried out on about eight CANDU units. However, greater time margins are available on these units because they use Zr-2.5 Nb pressure tubes.

However, when only two spacers are present in a channel, the flux enhanced sag in 6 m long channels will allow some pressure tubes to contact calandria tubes before the end of design life. Therefore relocating spacers is of limited benefit in these reactors and they will eventually be retubed and four spacers will be installed.

6.3 Manufacturing Flaws

Two pressure tubes in the Bruce Unit 2 reactor contained defects which had escaped detection during manufacture. Cracks initiated at the defects by DHC. Both leaked and the leakage was detected but one tube failed unstably when it was pressurized cold after shutdown. Improved process control and inspection procedures will eliminate these defects in new pressure tubes.

6.4 Channel Elongation

The design of the Pickering A and early Bruce A fuel channels did not allow for sufficient pressure tube elongation and the bearing travel would be used up before 30 years. When the bearing travel is used up, the channels could be supported at one end outside the normal bearings to allow continued operation. However, since these reactors are also the ones that contain only two spacers, they will be retubed and the elongation allowance will be increased.

6.5 Gas Annulus Hydridding

Surveillance tests on tubes from the Pickering Units 3 and 4 reactors have indicated that some tubes have picked up deuterium near the outlet end faster than expected. The circumstantial evidence favours deuterium ingress from the nitrogen gas annulus due to the degradation of the normally protective oxide. Carbon dioxide is now used in all other units and is expected to prevent degradation. Increased oxygen concentration in the carbon dioxide has now been recommended to ensure that a protective oxide barrier is maintained. These design problems and their solutions are summarized in Table 3.

Table III
Problems Experienced and Rectification

PROBLEM	RECTIFICATION
1. Zircaloy-2 excessive corrosion and hydriding	1. Change to c.w. Zr-2.5% Nb.
2. Displacement of relatively loose Zr-2.5% Nb - 0.5 Cu spacers	2. a) change to Inconel "snug" spacers in new reactors. b) spacer relocation techniques developed.
3. Two-spacers. Contact possible after 17 years	3. Four snug spacers prevent contact for 60 years.
4. Bearing travel only suitable for 15-year service.	4. a) Bearing length and feeder arrangement modified to meet 30-40 yr. service. b) Possible channel bearing relocation off bearing supports at one end of channel.
5. High residual stress rolled joints	5. Low stress joint developed.
6. a) Open annulus. Activation of A ₄₁ . (NPD, Douglas Point). b) Nitrogen Annulus Gas - production of C ₁₄ . c) Annulus Gas - low oxidizing potential. d) Slow response to leakage.	6. a) Closed annulus sealed with Inconel bellows. N ₂ or CO ₂ gas. b) Use of CO ₂ only c) Increased O ₂ concentration. d) Sealed annulus with recirculating gas.
7. High growth rate of c.w. Zr-2.5%Nb	7. Modifications to fabrication process.

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7.0 SUMMARY

Inspection and measurement of properties of Zr-2.5%Nb pressure tubes show that the tubes will operate for their design life in good condition. To date there is no indication that Zr-2.5%Nb could suffer the deterioration seen in Zircaloy-2 material. Channels in out-of-design condition need to be restored to the design condition to ensure that hydride blister induced crack initiation mechanisms cannot be activated.

8.0 CONCLUSION

- (a) Zircaloy-2 in reducing environments can suffer accelerated hydriding within six years of start up.
- (b) The loose spacer design can move during installation and commissioning and produce larger span lengths than designed. Creep sag can cause contact between the pressure tube and the calandria tube.
- (c) Contact can cause hydride blister formation and the conditions for crack growth by DHC which may not result in leak-before-break.
- (d) Contact between pressure tubes and calandria tubes must not occur when the total hydrogen concentration exceeds TSS of the cooled contact zone.
- (e) Cold-worked Zr-2.5 Nb pressure tubes hydride at an acceptable rate and maintain good properties. However, continued contact between these tubes and calandria tubes is undesirable after a hydrogen concentration beyond a threshold level is present.
- (f) A sensitive leak detection system is essential to limit the consequences of pressure tube cracking.

9.0 ACKNOWLEDGEMENTS

The authors wish to record their thanks for use of information generated under CANDU Owners Group development programs and from Ontario Hydro surveillance and inspection programs.

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