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Advances in Fuel Channel Technology for CANDU Reactors

Progrès en technique des canaux de combustible de réacteurs CANDU

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RÉSUMÉ

On met au point les éléments de canaux de combustible de réacteurs CANDU pour qu'ils aient une durée de vie utile de plus de 30 ans et comportent une grande marge de sécurité. Les renseignements provenant des programmes de recherche et l'examen des éléments retirés des réacteurs ont permis d'apporter des améliorations aux tubes de force, espaceurs, tubes de cuve et raccords d'extremité. On a également apporté des améliorations à la conception des canaux pour faciliter le remplacement prévu des tubes.

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Abstract

The components of the CANDU fuel channels are being developed to have service lives of over 30 years with large margins of safety. Information from research programs and the examination of components removed from reactors has enabled improvements to be made to pressure tubes, spacers, calandria tubes and end fittings. Improvements have also been made to the channel design to facilitate planned retubing.

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CONTENTS

1. INTRODUCTION

Since the initial fuel channel design was produced for the Nuclear Power Demonstration (NPD) reactor in 1962, over 10 000 fuel channels have operated in various CANDU[1] reactors. The design has evolved to accommodate increased power output, reaching a maximum of about 6.5 MW in the current generation of fuel channels. A number of design and material problems have arisen, some serious enough to require retubing of reactors before the end of the projected fuel channel design life, but the basic design has been shown to be effective and efficient for safely generating heat for conversion to electricity.

Since 1962, research, together with operational feedback and design development, has contributed to a better understanding of the behaviour of the materials in the reactor environment. This understanding has led to improvements in the materials and designs that form the basis of further evolutionary steps in fuel channel technology.

The emphasis of current evolutionary design efforts is a reactor operational life of 60 years at a high capacity factor and improved behaviour during postulated accidents. These requirements necessitate minimal fuel channel maintenance during the design life (not more than a 1 to 2% contribution to incapability factor), a minimum contribution from inspection needs and design changes to facilitate retubing. Thus the design objective of the future fuel channel will be a guaranteed service life of greater than 30 years at a capacity factor of 90% and a capability for much more rapid retubing.

Because of the effects of temperature and neutron flux on the properties of pressure tubes, the designers see the power of individual fuel channels remaining close to the current values for a number of years. However, in the future, the fuel channel concept will be exploited as a vehicle to burn a wide range of fuels.

This report gives design life predictions, describes the advances in material technology that have enabled improvements to be made, describes the current developments that will enable future improvements, and indicates where design modifications further facilitate channel operation.

2. THE CANDU FUEL CHANNEL DESIGN

The current CANDU fuel channel design, Figure 1, evolved from the prototype design for the NPD reactor, and is a consequence of decisions to:

- use natural uranium fuel,
- use low-temperature, low-pressure heavy water as a moderator,

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[1] CANada Deuterium Uranium™

- use pressure tubes to contain the fuel and heavy-water coolant, and
- use heavy water at high temperature and pressure to remove heat from the fuel.

The consequences that arose from these decisions were:

- the fuel would need to be moved and replaced frequently, on power, to achieve optimum burnup and constant reactivity,
- the hot components carrying the fuel would need to be thermally isolated from the low-temperature moderator,
- the reactor internals would need to be made from low neutron capture cross-section materials, zirconium alloys being the most suitable materials, and
- since knowledge of the long-term behaviour of zirconium alloys was limited, anticipated needs for maintenance made it prudent to allow for relatively easy replacement.

The design of CANDU fuel channels from NPD onwards has evolved to accommodate higher power outputs involving higher temperatures and pressures, Table 1. This has necessitated increases in length and diameter, and an increase in the strength of the pressure tubes.

Table 1: Evolution of the CANDU Design

	NPD	PICKERING	DARLINGTON
Power MW	25	540	850
Number of Channels	132	390	480
Coolant Pressure MPa	7.6	9.6	11.1
Coolant Temperature (Maximum) °C	275	297	313
Pressure Tube Material	Zr-2	Zr-2.5Nb	Zr-2.5Nb
Pressure Tube I.D. mm	82.5	103	103

The components of a fuel channel fall into three categories:

- pressurized components,
- support components, and
- internal components.

The pressurized components comprise the pressure tube, made from Zr-2.5Nb, and the end fittings (including the closure seals and feeder connections). The pressure tubes experience the most severe service of any component, Table 2, and are therefore life controlling. End fittings, by contrast, see a less severe service condition and do not control the life of the fuel channel.

Table 2: The Operating Conditions for Fuel Channel Components

COMPONENT	TEMPERATURE °C	NEUTRON FLUX $n.m^{-2}.s^{-1}$	ENVIRONMENT		MAXIMUM OPERATING TENSILE STRESS
			Outside	Inside	
Pressure Tube Zr-2.5Nb	249-313	3.7×10^{17}	CO_2	D_2O at 9.6-11.1 MPa	120-149 MPa
End Fitting 403 SS	249-313	1.0×10^{16}	CO_2	D_2O at 9.6-11.1 MPa	85 MPa
Calandria Tube Zircaloy-2	70-80	3.0×10^{17}	D_2O	CO_2	~ 5 MPa
Garter Spring Zr-Nb-Cu Inconel X-750	70-313*	3.0×10^{17}	CO_2		

*Thermal Gradient

The support components are the spacers and the calandria tubes. The spacers maintain the separation of the pressure tube from the calandria tube. The spacers also transmit the load of the pressure tube and its fuel and heavy water onto the calandria tube, which operates cold and provides most of the sag resistance of the channel.

The key internal components are the liner tube and shield plug. Both are intended to smooth the entry and exit of the flow of heavy water into and out of the channel. The inlet end is the most important, since turbulence of flow can cause movement of fuel bundles. The ends of the channels are sealed by closure plugs that are removed on power by the fuelling machines to remove fuel and insert new fuel.

To initiate the on-power refuelling of CANDU reactors, the fuelling machines located at each end of the reactor core attach to the two ends of the channel and remove the closure plugs and shield plugs from the end fittings at each end. Two slightly different designs of end fittings have been used in CANDU reactors; the Pickering/CANDU 6 type and the Bruce/Darlington type, as illustrated in Figure 2. The differences between them result from the different fuel handling systems used to fuel the channels. For the Pickering/CANDU 6 design, refuelling is assisted by the coolant flow with new fuel entering the channel from the inlet end. The flow pushes the fuel to be discharged into the fuelling machine attached to the outlet end. After the fuel bundles to be discharged are separated, the string with the new bundles is pushed back into the channel and the shield plugs and closure plugs are reinserted. The fuel is positioned in the core by the coolant flow pushing the string into contact with the shield plug, which is held inside the outlet end fitting. Each fuel string consists of 12 fuel bundles, which are contained inside the pressure tube.

For the Bruce/Darlington type of fuel channels, the fuel string is positioned in the core by having the coolant flow push it into contact with a segmented annular latch located in the outlet end fitting. The fuel string consists of 13 bundles and the bundles at each end extend slightly into the end fittings. During refuelling, fuel is moved through these channels in the opposite direction to the coolant flow, as illustrated in Figure 2. The new fuel bundles are moved in a carrier tube from the fuelling machine into the outlet end fitting and are then pushed into the pressure tube. The fuel bundles being removed are picked up in a carrier tube at the inlet end, and moved into the other fuelling machine. This refuelling results in the pressure tubes experiencing much less fuel movement than for the Pickering/CANDU 6 type of channel, but Bruce/Darlington fuel has exhibited more vibration and hence caused more pressure tube wear.

3. IMPROVING THE SERVICE LIFE OF COMPONENTS

3.1 Pressurized Components

3.1.1 Pressure Tubes

Dimensional Changes

During reactor operation, the conditions of temperature, stress and neutron flux change the dimensions of the pressure tubes. The elongation of Pickering Unit 3 pressure tubes is shown in Figure 3. Enhanced elongation due to irradiation-induced creep and growth was not anticipated, and in early reactors sufficient end fitting bearing travel was provided only for thermal expansion. In these reactors, the fuel channels require axial repositioning, so that they remain adequately supported by their bearings as the pressure tubes elongate. The higher the channel power, the higher the rate of elongation, Figure 4. In the Bruce and later reactors the rate of elongation is 4 to 6 mm per year [1]. In the later units the bearings can accommodate more than 75 mm of elongation at each end of the channel.

Diametral expansion of the pressure tube during service due to irradiation-induced creep, Figure 5, allows more primary heat transport system heavy water to flow around the fuel bundles. The predicted peak diameter changes with service for different reactors are shown in Figure 6. The current maximum diametral expansion rate of Bruce pressure tubes is about 0.1 mm per year [2], and it is not expected to limit their service life.

Prior to service, the pressure tubes have a radius of curvature of over 280 m along the axis. This radius decreases with service time because of sag, but based on projections from current pressure tubes the curvature will never impede the passage of fuel bundles. Except for the first four Pickering units, CANDU reactors have horizontal reactivity control mechanisms at right angles to the fuel channels and some of the calandria tubes need sag only about 50 mm before they contact these mechanisms. Remedial action may have to be taken for about 50 fuel channels located above the horizontal reactivity control mechanism tubes.

The in-reactor creep and growth properties of Zr-2.5Nb pressure tubes are a function of their crystallographic texture, grain shape, dislocation density and sub-grain microstructure. A program was conducted to improve the elongation performance of pressure tubes [3]. Three fabrication routes were designed that would change the microstructure of the finished tubes. These routes used a lower extrusion ratio to produce a thicker walled extrusion and increased the cold work from 25% to 40%, and also had combinations of intermediate anneals and final stress-relieving heat treatments. One of these (Route 1) had a crystallographic texture and α-grain size similar to standard tubes, but a different α-grain substructure and a much lower dislocation density, about $3.0*10^{14}$ m^{-2} compared with $6.0*10^{14}$ m^{-2} for standard tubes. Small specimens from the three routes were tested in research reactors and they showed that Route 1 tubes should have lower elongation rates than standard tubes. This conclusion is being confirmed by axial measurements on a small number of the tubes that have been installed in

Bruce Unit 8, see Figure 7. Diametral creep and sag are predicted to be similar to values in standard tubes.

Defects

Two pressure tubes in Bruce Unit 2 leaked as a result of delayed hydride cracking (DHC) that initiated at flaws [4]. A small number of similar flaws were also discovered by post-installation inspection in other units. The source of the flaws was found to be large shrinkage cavities that formed in the top of ingots during solidification. The cavities were not open to the surface, and although they were closed up by the forging and extrusion processes the surfaces were only partially welded together, and laminar flaws formed at a shallow angle to the surface of the finished tube. These flaws are very difficult to detect by standard non-destructive techniques and also difficult to find metallographically. However, they can open up during service by an oxidation process, and if large enough they can initiate DHC. The manufacturing process has been changed to minimise the size of the shrinkage cavities and concentrate them at the top of the ingot, which is cropped to remove them. Improved ingot inspection also ensures that the cavities are in the section that is removed. Final tube inspection by techniques that can now detect such laminations further decreases the probability of any such defects being present in tubes entering service.

Changes in Fracture Properties

Neutron irradiation introduces damage to the crystal lattice that changes the mechanical properties of metals; the tensile strength is increased and the ductility is decreased, Figure 8. These changes result in a reduction in toughness and a degradation of fracture properties. As fabricated, the tensile strength of CANDU Zr-2.5Nb pressure tubes is higher in the transverse direction than the longitudinal direction, Table 3, as a result of the strong crystallographic texture. With irradiation, the strength increases and ductility decreases rapidly, but after a fluence of about $1*10^{25}$ n/m^2 there is little further change, Figure 9, and there is also little difference between the transverse and longitudinal directions, Table 3 [5]. In zirconium alloys, irradiation slightly increases the susceptibility to DHC, manifest as a decrease in K_{IH}, Figure 10, and increases the velocity of cracking, Figure 11 [6], particularly at the inlet end of the channel as a result of the lower temperature.

If a crack grows undetected, it will become unstable when it reaches the critical crack length (CCL). Fracture toughness controls CCL. As-fabricated pressure tubes are very tough. With irradiation there is an initial rapid decrease in toughness but, as with tensile properties after a fluence of $3*10^{24}$ n/m^2, there is little further change, Figure 12 [7]. There is also a very large range in the toughness of pressure tubes after irradiation, and some tubes retain high toughness levels after 18 years' service, Figure 13 [7,8]. Examination of the fracture toughness specimens revealed that the fracture surfaces of specimens with low toughness, Figure 14, contained more linear features, called 'fissures', parallel to the axis of the tubes, than the fracture surface of a specimen with a high toughness, Figure 15. The toughness decreased with increasing density and the length of the fissures. The fissures were found to be caused

Table 3: The Effect of Irradiation on the Tensile Properties of Zr-2.5Nb Pressure Tubes

		AXIAL DIRECTION	TRANSVERSE DIRECTION
0.2 % Y.S.	U	395	-
MPa	I	696	-
UTS	U	549	604
MPa	I	762	741
Elongation	U	17	-
%	I	4.4	-
R of A	U	-	70%
%	I	35%	55%

U is unirradiated, I is irradiated to 1.3 x 10^{25} n/m^2.

by local accumulations of chlorine and are also associated with high concentrations of carbon. Pressure tubes that contain low concentrations of chlorine have few fissures on their fracture surfaces and have a high fracture toughness [9]. Thus the range of fracture toughness, Figure 13, is partly related to trace amounts of chlorine. The chlorine is a residue of the Kroll process used to refine the zirconium. The fabrication records revealed that the toughest tubes were made from 100% recycled material, and thus the material had been melted four times rather than the normal two times. Quadruple melting the ingots reduces the chlorine concentration to small values and produces tough tubes, Figure 16 [10]. A maximum chlorine concentration of 0.5 ppm has now been inserted into the material specification.

Other trace elements may affect fracture toughness:

- Hydrogen, especially in the form of radial hydrides [11], can be highly detrimental, but with the precautions to be outlined in the next section should not be a factor for toughness.

- Phosphorus forms brittle phosphides that reduce toughness, and for prudence a maximum concentration of phosphorus of 10 ppm has now been included in the specification [9].

Corrosion and Hydrogen Ingress

The design of CANDU pressure tubes incorporates a combined corrosion and wear allowance. During service, the heavy water corrodes the inside surface of the pressure tube. The products of this chemical reaction are ZrO_2 and hydrogen. Some of this hydrogen that is produced at the metal surface is absorbed into the metal and the remainder dissolves in the heavy water. In the alloy Zircaloy-2, up to 80% of the hydrogen is absorbed into the metal, but in Zr-2.5Nb only about 5% of it is absorbed, which results in a much lower rate of deuterium ingress into the pressure tubes during service, Figure 17. The loss of metal from corrosion is very small and after 30 years' service is not predicted to exceed the corrosion allowance.

The hydrogen concentration of the tubes is important, as it affects the DHC and fracture properties. The hydrogen concentration is the sum of the hydrogen concentration in new tubes plus the hydrogen (deuterium) picked up during service.

CANDU pressure tubes are autoclaved at 400°C for 24 hours, which produces a black adherent oxide about 1 μm thick; this oxide is an effective barrier to the entry of hydrogen into the tubes. If the atmosphere in the annulus between the pressure tube and the calandria tube is not sufficiently oxidising, the oxide will deteriorate until it is no longer an effective barrier, and hydrogen that can enter the annulus by diffusion through the steel end fitting can then enter the tube [12]. To avoid pick-up from the annulus gas, it is important to use an annulus gas that has sufficient oxidising species (CO_2 with added O_2 rather than N_2), and to ensure that there is good gas flow through all channel annuli. Pickering Units 1-4 fuel channels used N_2 for the annulus gas before the pressure tubes were changed, and deuterium in the annulus entered the pressure tubes, Figure 17, because of inadequate outside surface oxidation.

When the ends of the tubes are rolled into their end fittings, the oxide is damaged in the rolled joint region and is no longer an effective barrier. The oxide on the inside surface is soon repaired by corrosion with the heavy water, but on the outside surface exposure to air or heavy water is restricted by the end fitting. This results in additional ingress of hydrogen into the tubes via the 403 Stainless Steel end fittings, and a much higher ingress rate at the ends than in the body of the tubes [13]. The rate is higher at the outlet ends than at the inlet ends because of the higher temperature, Figure 18.

The solubility limit of hydrogen in zirconium is low [14]; hydrides are always present at room temperature, while in the range of reactor operating temperatures, hydrides are formed when the hydrogen concentration reaches between 0.3 and 0.5 at.%. Since hydrogen, in the form of brittle hydrides, has been associated with all the cracking or potential cracking in zirconium alloy pressure tubes [15], we are expending much effort to reduce both hydrogen concentration and its effects. Maintaining the concentration below 0.3 at.% will ensure that no hydrides form during reactor operation. The four approaches for minimising the effects of hydrogen in Zr-2.5Nb pressure tubes are:

1. reduce the amount of hydrogen initially present in finished tubes,

2. reduce the rate of hydrogen pick-up during operation,

3. redistribute any hydrogen to innocuous locations, and

4. develop a microstructure that is tolerant of hydrides.

1. The manufacture of Zr-2.5Nb pressure tubes consists of six main steps: production of zirconium sponge, vacuum arc melting into an ingot, forging in two steps, extrusion, cold-working and stress relieving. Hydrogen is picked up at each stage, but contributions from melting and forging dominate [10]. Careful control of melting practice, with particular attention to the vacuum, reduces the hydrogen concentration in the bulk of the ingot. Hydrogen tends to concentrate at the surfaces of both ingots and forgings and judicious machining to remove these hydrogen-rich layers ensures a low hydrogen concentration in the finished tube. The improvement that has been achieved is illustrated in Figure 19. In a typical batch of tubes representing early production, the hydrogen concentration varies from 0.05 at.% to 0.16 at.%, with a mean value of 0.10 at.%, while tubes made by processes incorporating the refinements have a very narrow range of hydrogen concentration at or below 0.05 at.%. The specification for the maximum hydrogen concentration allowed has been changed from 25 ppm (0.23 at.%) to 5 ppm (0.05 at.%) to reflect the improved practice. The consequence for tube lifetime is to increase the time it takes to form hydrides by close to 20 years for tubes at the limits of the specification, assuming that the maximum hydrogen pick-up rate during operation is 0.01 at.% per year.

2. Hydrogen pick-up during reactor operation may be reduced by modifying the concentration of trace elements or modifying the tube surface [16]. Merely reducing the corrosion rate may not be good enough, since hydrogen ingress is not necessarily correlated with corrosion. Laboratory experiments on Zr-2.5Nb-x X, where x is the concentration of element X, show that traces of Fe, V and Cr are beneficial, while traces of Mn, Ni and Sn should be avoided, Figure 20. Surface treatments are also being assessed and the surfaces of the pressure tubes have been modified by local melting with lasers, by shot-peening and by application of a layer of stress-free oxide. With each method, laboratory experiments demonstrate that both the corrosion and amount of hydrogen picked-up per unit of corrosion are reduced. The improvement with laser and shot-peening treatments is attributed to the microstructure at the metal surface containing β-Nb precipitates and α-phase with a concentration of Nb close to the equilibrium value. These microstructural features are produced during irradiation and are thought to be responsible for the reduction in corrosion in a reactor compared with that in the laboratory. The stress-free oxide is produced by depositing a thin layer of colloidal zirconia. This oxide contains fewer cracks than thermally grown oxides, and in laboratory experiments coated specimens corrode independent of the underlying metal microstructure. Specimens with these potential improvements will be evaluated in loops in test reactors.

Hydrogen is absorbed at a higher rate in the rolled joints than in the main body of the tube, Figure 18 [13]. The main contributions come from galvanic corrosion in the outer crevice between the pressure tube and the end-fitting, and from diffusion of hydrogen through the end-fitting. To meet the criterion of no hydrides during reactor operation at vulnerable locations, the hydrogen content in the pressure tube at the rolled joint must be reduced by 80%. Methods of reduction include placing a barrier between the pressure tube and the end-fitting, and reducing the corrosion in the crevice. Chromium plating the end-fitting, Figure 21, may help against both mechanisms [17]. Several designs of rolled joints using end-fittings chromium-plated by standard techniques are being tested in a heavy-water loop at 300°C. Short-term evaluation shows that the reduction in pick-up varies from about 30% up to 70%, depending on the design.

3. An alternative method of reducing the hydrogen at the ends of the pressure tubes is to place a sacrificial hydrogen getter in a stress-free location. Yttrium forms a more stable hydride than zirconium, and is an effective getter when in metallurgical contact. Using hydrostatic pressing, rings of yttrium bonded to and protected by zirconium, then welded to the ends of the pressure tubes, Figure 22, reduce the hydrogen concentration in the attached zirconium alloy to values well below the solubility limit [18]. Demonstration of the efficacy of this method to protect a rolled joint is in progress.

4. The value of the threshold stress intensity factor for DHC, K_{IH}, depends on the ability of hydrides to form with their plate normals parallel to a tensile stress; easy formation of such hydrides implies low K_{IH}. The microstructural feature that controls the stress-induced orientation of hydrides is the distribution of the basal planes, since the habit plane for hydride precipitation is close to the basal plane. Thus basal plane normals should not be parallel to a tensile stress [19]. Material with a high fraction of basal plane normals parallel to a tensile stress has the highest susceptibility to cracking (low K_{IH}) and vice versa, Figure 23. A value of K_{IH} of 10 $MPa\sqrt{m}$ would protect pressure tubes from any defects up to 1 mm in depth, which are easily detectable. Results from experiments on plate materials imply that such values can be attained in pressure tubes by rotating the concentration of basal plane normals away from the transverse direction towards the radial direction, as shown in Figure 23 [20]. Prototype tubes have been made with basal planes more concentrated in the radial direction, and values of K_{IH} greater than 10 $MPa\sqrt{m}$ have been obtained. The full range of properties of these tubes is now being evaluated.

3.1.2 End Fittings

The stainless-steel alloy AISI type 403 is used for end fittings, which are produced as forgings but have also been produced as extrusions and castings. The alloy has been an optimum choice because of the need for strength, corrosion resistance and impact resistance. Improvements to the chemistry and heat treatment of type 403 have reduced the increase in nil ductility temperature with fluence. Impact properties and low-temperature pitting resistance have also benefitted.

The end fitting has given few problems in service. A few small leaks have occurred at the seal faces of the bolted connections to the feeder pipes. For future reactors, it is possible that the feeders will be welded to the end fittings, because of the need to use larger diameter feeders than are currently used to improve critical power rating margins in the fuel bundles. This will also eliminate any leakage at this location. The only other modification being considered for the end fittings is a double set of rolled joint grooves in one end fitting, Figure 24. The outboard set of grooves would be used for the initial pressure tube and the inboard set used for the replacement tube. This would eliminate the need to replace one end fitting, which would facilitate retubing.

3.2 Support Components

3.2.1 Spacers

In early CANDU reactors, the spacers have been the cause of costly maintenance programs. The garter spring design performs the required functions of separating a hot pressure tube from the cold calandria tube, while allowing relative movement of the two tubes without causing wear to either tube. However, in earlier units, the spacers were fitted to the inside diameter of the calandria tube, Figure 25, and this allowed them to move from vibration during installation. Contact between the pressure tube and the calandria tube subsequently resulted from pressure tube sag [21]. The design of spacers has been improved by the use of a spring alloy, Inconel X750, used in the earliest reactors, rather than a zirconium alloy. The spring has an integral internal girdle wire inside the toroid that provides detectability by eddy current techniques, and is a tight fit around the pressure tube, ensuring that the spacer remains in the design location during vibration from installation procedures. In their design locations, contact cannot occur from sag during the design life of the pressure tube.

3.2.2 Calandria Tubes

Several evolutionary improvements for CANDU calandria tubes are being developed based on the proven CANDU calandria tube technology. The calandria tube modifications will decrease the sag rate as well as increase the probability that calandria tube integrity will be maintained during various postulated accidents.

Sag Reduction

The end-of-life for CANDU calandria tubes is reached when their replacement is needed either to prevent them from sagging into contact with core components located below them, or when it will not be possible to perform a pressure tube replacement because of excessive curvature. Therefore, calandria tube life can be extended by reducing its sag rate, with the amount of life extension being proportional to the amount of sag reduction. The target for CANDU calandria tube life is to be twice as long as pressure tube life, so that a calandria tube would not have to be replaced when pressure tubes are replaced.

CANDU fuel channel sag analyses have shown that the sag rate for calandria tubes can be halved by increasing their wall thickness about 2.5 times for about a one-meter length at both ends, as shown in Figure 26. The burnup penalty associated with such thick ends is only 2 to 4% because the material being added is in a low flux region of the reactor core.

One practical way to fabricate a thick-ended calandria tube is to weld thick wall tubing to both ends of a segment of the current calandria tube design. Burst tests on this design have demonstrated that it does not reduce calandria tube burst resistance, nor induce fracture in the circumferential weld. A fabrication process for a seamless thick-ended calandria tube is also being developed. Preliminary full-scale prototypes of seamless thick-end calandria tubes have recently been fabricated and their properties are currently being evaluated.

Increased Burst Resistance

Burst failure for the current seam-welded calandria tube design occurs in its longitudinal weld. Calandria tube burst resistance will increase if this weld is either strengthened, so that failure occurs in the parent material, or eliminated by the use of a seamless tube [22]. As noted above, such a seamless tube is being developed, but before it can be qualified for reactor use it must be shown to have appropriate metallurgical properties.

Another practical way to fabricate a calandria tube with increased burst resistance is to thicken the longitudinal weld region of the current calandria tube design, as shown in Figure 26. Burst testing of many short lengths of thick weld tube has demonstrated that a 25% increase in wall thickness for the weld region of a calandria tube causes burst failure to occur in the parent material, rather than in the longitudinal weld. Such burst failures are associated with about three times more burst strain, and a 20-25% increase in tube stress at burst, than the current calandria tube design, Figure 27. A full-length prototype of a thick weld calandria tube has recently been fabricated and will soon be used in a full-scale burst test, which is the final step in qualifying such a tube for reactor use.

Improved Radiative Heat Transfer

For a postulated large Loss of Coolant Accident (LOCA) plus loss of Emergency Coolant Injection (ECI), the pressure tube temperatures rapidly rise to a high value. The predicted consequences for such an accident are less severe if the peak value for the pressure tube temperature is reduced. This reduction would occur if the radiative heat transfer from the pressure tube to the calandria tube is increased. The absorptivity of the calandria tube can be increased three to four times by shot peening and oxidation of the inside surface of the calandria tube to produce a rough black surface, Table 4. Prototype tubes have been made, but this improvement has not yet been specified for a power reactor.

Table 4: The Effect of Surface Treatment on the Emissivity of Zircaloy-2 Calandria Tube Material

Surface Treatment	Emissivity
Standard (shiny)	0.25
Heated 3 h at 500°C	0.54
Shot blasted	0.55
Shot blasted plus 3 h at 500°C	0.80

Decreased Contact Conductance

For a postulated large LOCA plus loss of auxiliary power, the pressure tube may overheat and balloon into contact with the calandria tube. If the calandria tube overheats it may rupture. If the contact between the tubes is good, the heat conductance is high, producing moderator film boiling, which leads to a high temperature in the calandria tube and poor heat transfer to the moderator. An optimum contact conductance produces nucleate boiling and can be achieved if the inside surface of calandria tubes is roughened by selective pickling to produce a wave form. This process is being developed and tested.

3.3 Internal Components

3.3.1 End Fitting Internals

These components are the channel closure, the liner tube, and the shield plug. Their designs are somewhat different in the two channel designs currently in use (see Section 2), and are illustrated in Figure 28.

The channel closures are mechanisms to open and close the channel for fuelling activities, and are removed from the channel during the fuelling sequence. In the current CANDU 6 design, Figure 29, the channel closures are anchored into the end fitting with radial jaws activated by the fuelling machine ram. In the Bruce design, the plug is torqued into a breech block support, again by the fuelling machine rams. The seal is made by applying a separate axial force to a seal disc, which brings the annular sealing zone of the disc into contact either with the transverse face of a shrink-fitted insert ring on the inside of the end fitting, or with an inside step on the end fitting. A soft nickel coating on the seal face facilitates leak tightness. The designs at the outlet and inlet ends of the channel are similar.

The CANDU 6 liner tube is a simple tube of annealed Type 410 stainless steel that is anchored into the end fitting by roll expansion, Figure 30. It creates an annular flow path for the water coming through the feeder port and prevents excessive crossflow on the fuel bundles as they exit or enter the channel during on-power fuelling. The water leaves the annular passage through a number of holes in the tube at its inboard end. The CANDU 6 liner tube has an inside diameter similar to the pressure tube. The Bruce design is larger in diameter than the pressure tube, to accommodate the carrier for fuelling and defuelling. The Bruce liner tubes are attached to the end fittings with a lock wire. The outlet liner tube incorporates a fuel latch that holds the fuel string in position in the reactor core.

The shield plug, Figure 28, is required to prevent neutron streaming from the fuel into the reactor vault during operation, or gamma streaming during shutdown when maintenance activities may be in progress. In the CANDU 6 design, the shield plug is mostly fabricated from 17-4 pH stainless steel and supports the fuel string at the channel outlet end, and in turn is supported by the liner tube. Concentric support rings on the shield plug ensure that the fuel bundle end plates receive adequate support. Incoming water partly flows through holes in the inboard skirt of the shield plug and partly around the outside of its inboard end before entering the fuel string. In flowing through both the liner tube holes and the shield plug holes, the water transfers some energy into turbulence, but the fuel bundle stability is not affected. In the Bruce design, latches mounted on the end fitting liner tube support the fuel string through their contact with the ends of the outer elements of the outlet and inlet fuel bundles, and the shield plug with a ductile cast iron body is a passive shielding component. In this design, water flows through the liner tube holes and enters four scalloped entry ports on the outer cylindrical surfaces of the plug, which direct the flow through the plug to exit from four nozzles and into the fuel. The outlet and inlet shield plugs are similar but not identical. Both designs of shield plug are latched into a groove in the liner tube by the fuelling machine.

The CANDU 3 fuel channel under development has internal component designs that differ from those discussed, and the designs are not the same at the inlet and the outlet ends, Figure 31. In this channel, fuelling and defuelling is from the outlet end only. The water enters the channel axially, rather than through a side port, but exits through a side port. No closure plug is required at the inlet end. To defuel the channel, a fuel pusher made of Zircaloy, with a force produced by the flow, pushes the fuel to the outlet end. The flow will thus increase as the bundles are incrementally removed, and there is a need to keep the bundles stable under varying flow conditions. Considerable test effort was expended to develop acceptable designs of the inlet shield plug and fuel pusher to meet these requirements. These components have tapered solid sections, to streamline the flow, and, with the exception of the fuel pusher, are made of Type 410 stainless steel. The outlet shield plug, as shown in Figure 31, incorporates similar solid tapered sections, which are supported by a long closure plug with a sealing and latching mechanism similar to the CANDU 6 design.

Other than the CANDU 3 channel, the channel internals for future fuel channels will follow the CANDU 6 design, which has given trouble-free operation over the last 12 years or so.

4. SUMMARY

Since the NPD reactor was designed, the fuel channel and its components have undergone considerable development. This development over the last ten years has been backed by an intensive, integrated materials research program. In addition, a pressure tube surveillance program was instituted that has provided information from operating components, and has provided material for examination, testing, and research. Information from all these sources is now being used to make considerably better fuel channel components that will have longer service lives and greater margins against failure.

The improvements that have been made recently and those that will be made in the future are summarised in Table 5. In the next few years the microstucture and alloy composition of pressure tubes will be tailored to give the optimum combination of dimensional performance and resistance to fracture. Deuterium ingress will be reduced by changes to the surface and probably by chromium plating the end fittings. The development of calandria tubes that are stronger and more sag resistant, and that have improved heat transfer, is almost complete. Specimens from these tubes will be tested in special fuel carrier bundles in power reactors and in special inserts in high flux research reactors, to confirm that the pressure tubes will have a service life greater than 30 years, and the calandria tubes a service life greater than 60 years.

Table 5: Summary of Improvements to Fuel Channel Components

Component and Property	Improvements	Potential Method of Improvement	
	1990-1994	1994 - 2000	Post 2000
Pressure Tubes Zr-2.5Nb			
Dimensions - length, diameter	Low elongation tubes available. Being tested in Bruce 8.	Small changes to microstructure and composition; e.g., Fe increased.	Further improvements to microstructure.
Fracture - toughness	Large improvement by reducing Cl, P, C. Will be installed in Wolsong 3.	Small changes to microstructure.	
- DHC		Small changes to microstructure and composition.	Radial texture.
Deuterium Ingress	As-fabricated hydrogen concentration reduced to < 0.05 at.% (5 ppm)	Modified surface finishes. Small changes to composition. Chromium plated end fittings.	Yttrium sinks. New joint to end fitting. Palladium coating at ends.
Calandria Tubes Zircaloy-2			
Higher burst strength.		Thick welds. Seamless tubes.	
Lower sag.		Thick ends.	
Improved heat transfer and conductance.		Black, rough, wavy inside surface.	
End Fittings 403 SS		Two sets of grooves in one end fitting.	New design for easier replacement.

5. ACKNOWLEDGEMENTS

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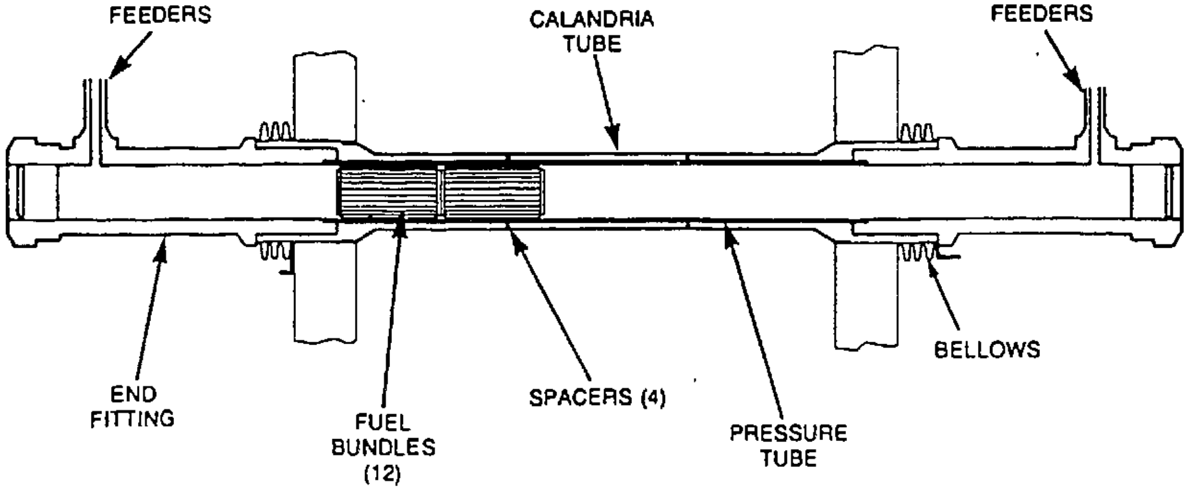
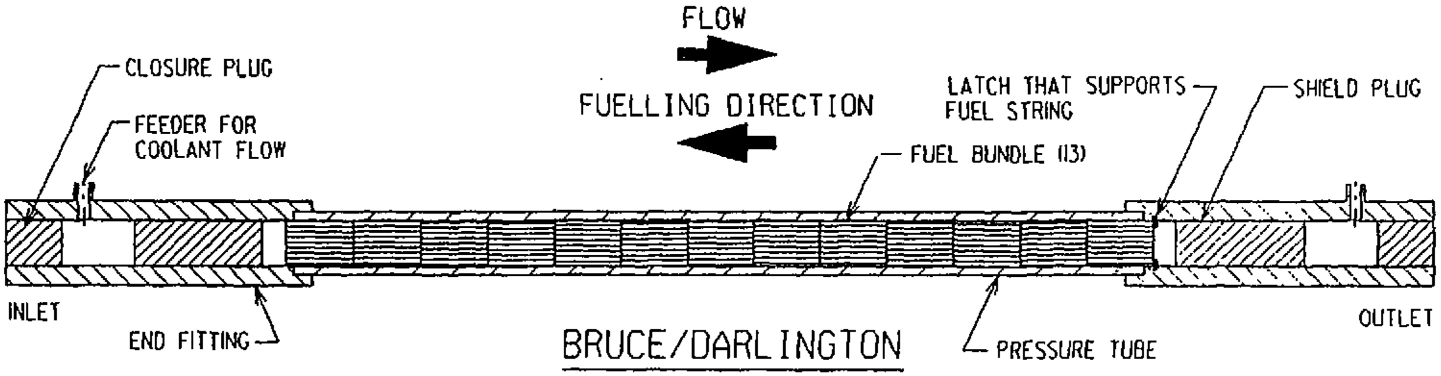
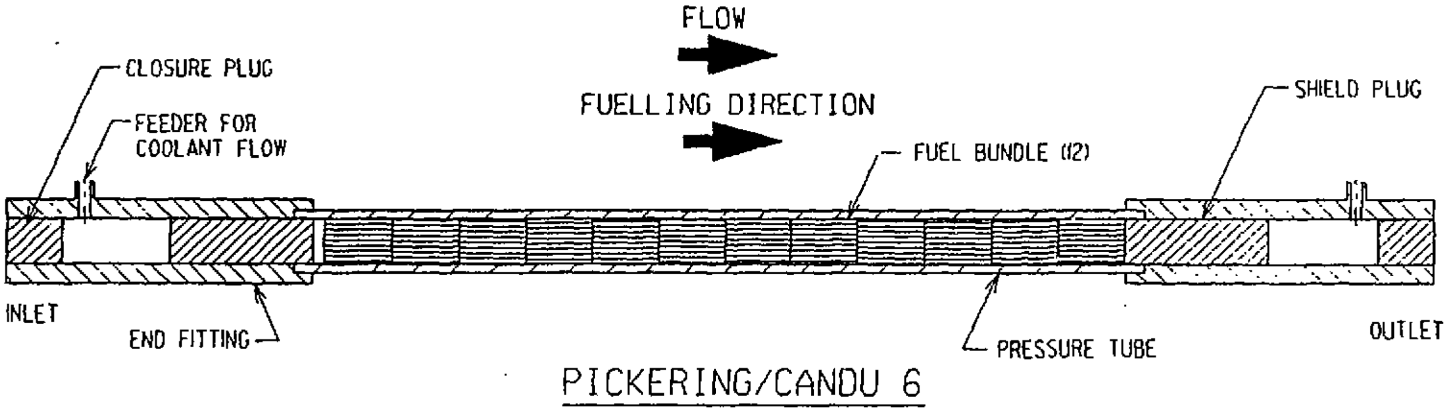


Figure 1: Simplified illustration of a CANDU fuel channel.



BRUCE/DARLINGTON



PICKERING/CANDU 6

Figure 2: Schematic illustration of the two types of CANDU fuel channels.

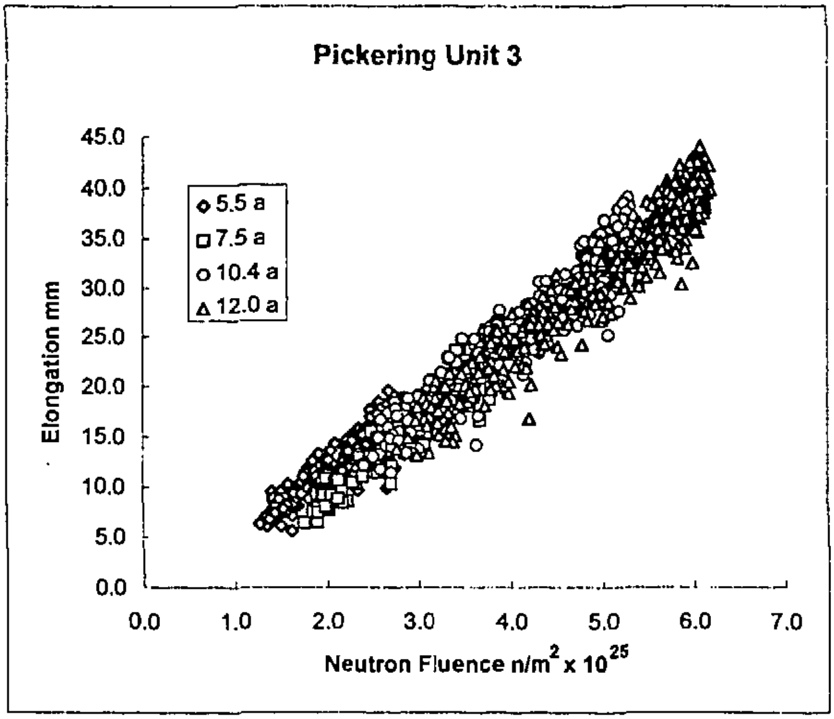


Figure 3: The elongation of fuel channels in Pickering Unit 3 during service.

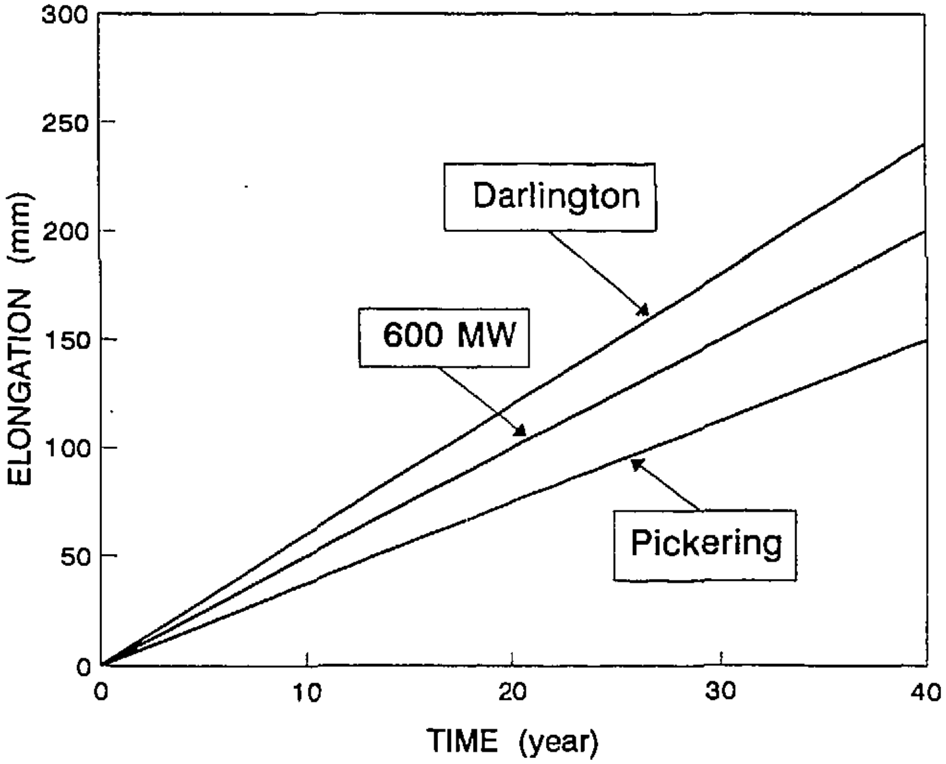


Figure 4: The predicted elongation of fuel channels in CANDU reactors.

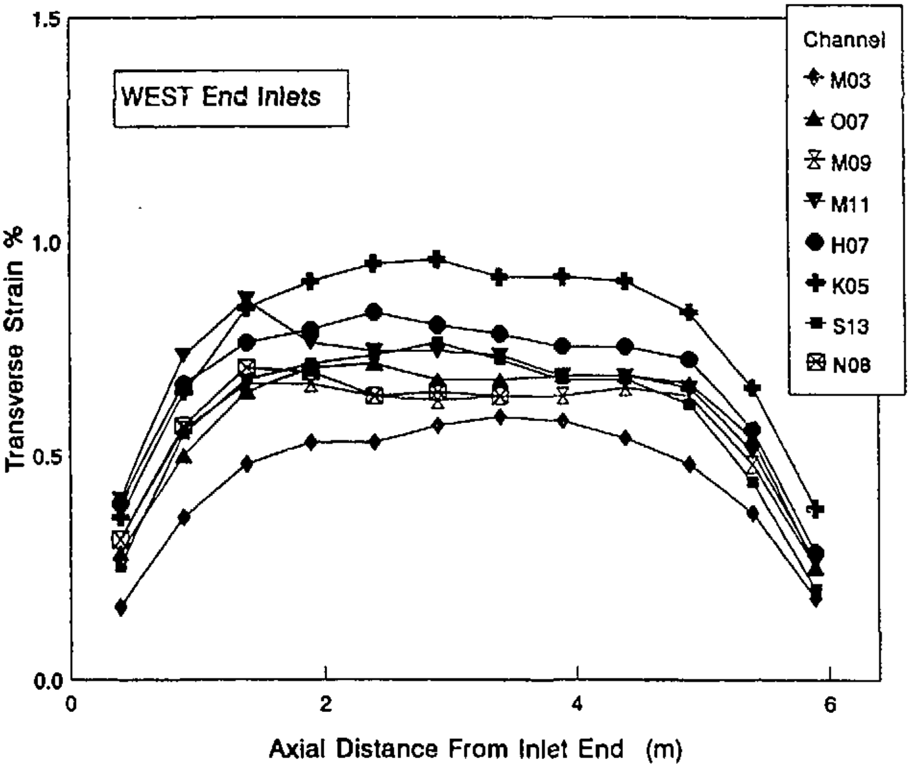


Figure 5: The transverse strain along pressure tubes in Pickering Unit 3 after 17 years' service.

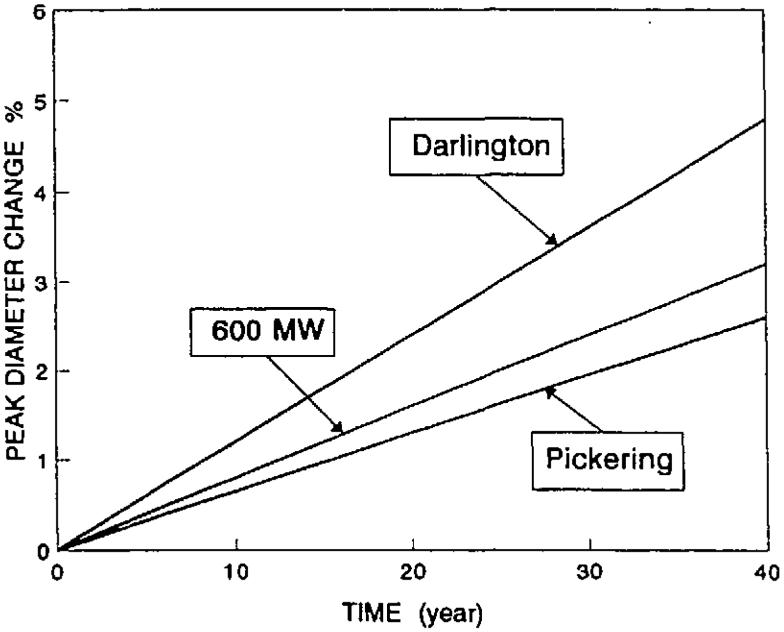


Figure 6: The predicted peak diameter change in Zr-2.5Nb pressure tubes in CANDU reactors.

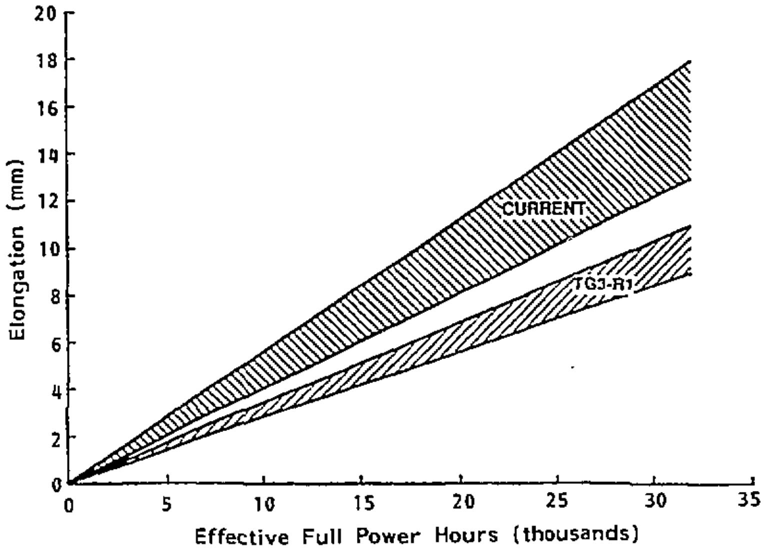


Figure 7: The elongation of small specimens from Route 1 pressure tube compared to a standard pressure tube [3].

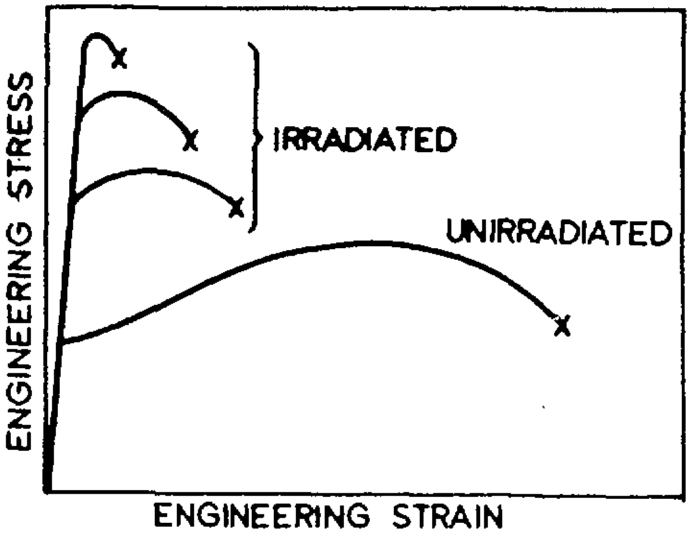


Figure 8: The effect of irradiation on the strength and elongation of metals.

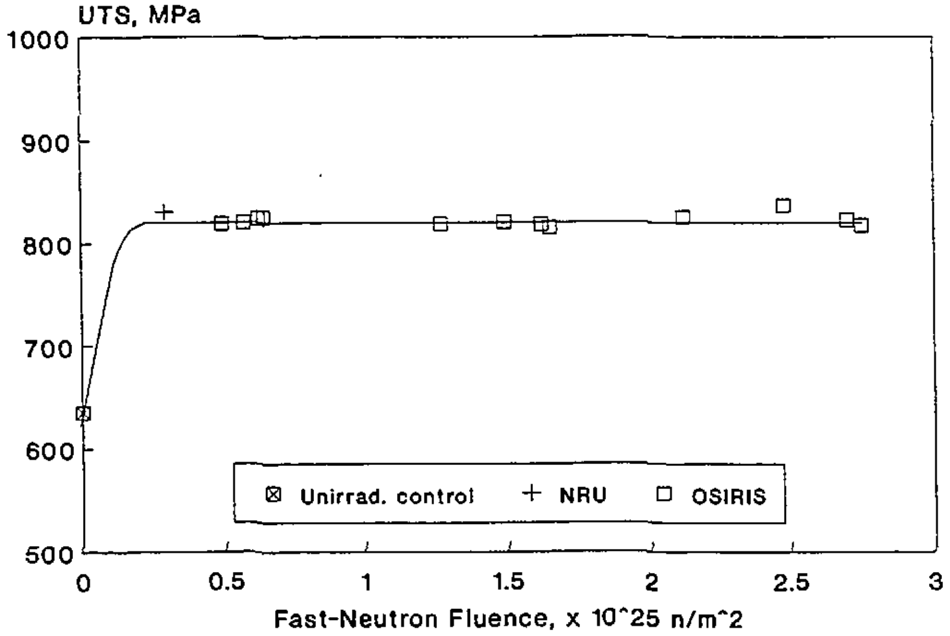


Figure 9: The effect of irradiation on the axial UTS of Zr-2.5Nb pressure tube material.

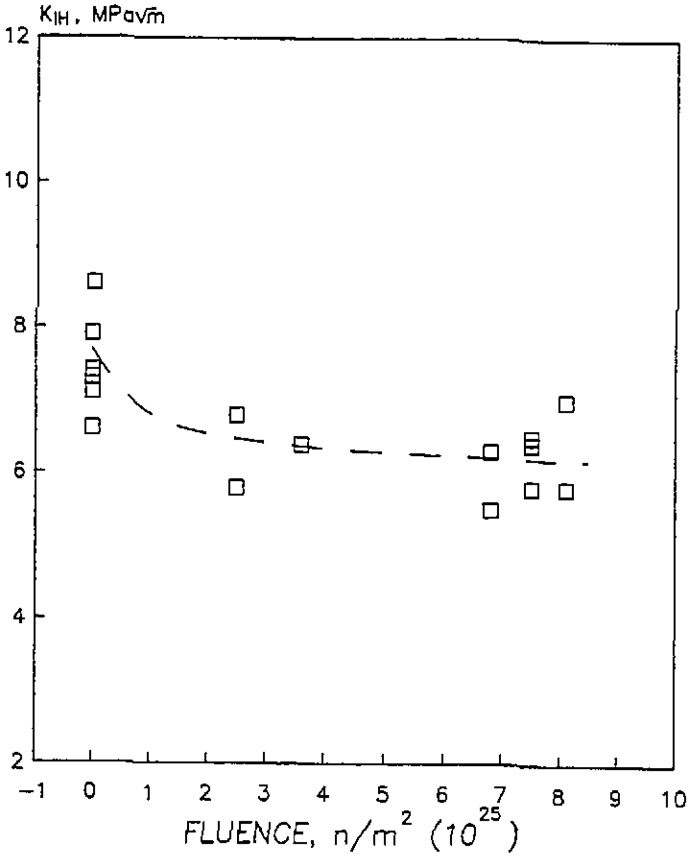


Figure 10: The effect of irradiation on the K_{IH} of Zr-2.5Nb pressure tube material [5].

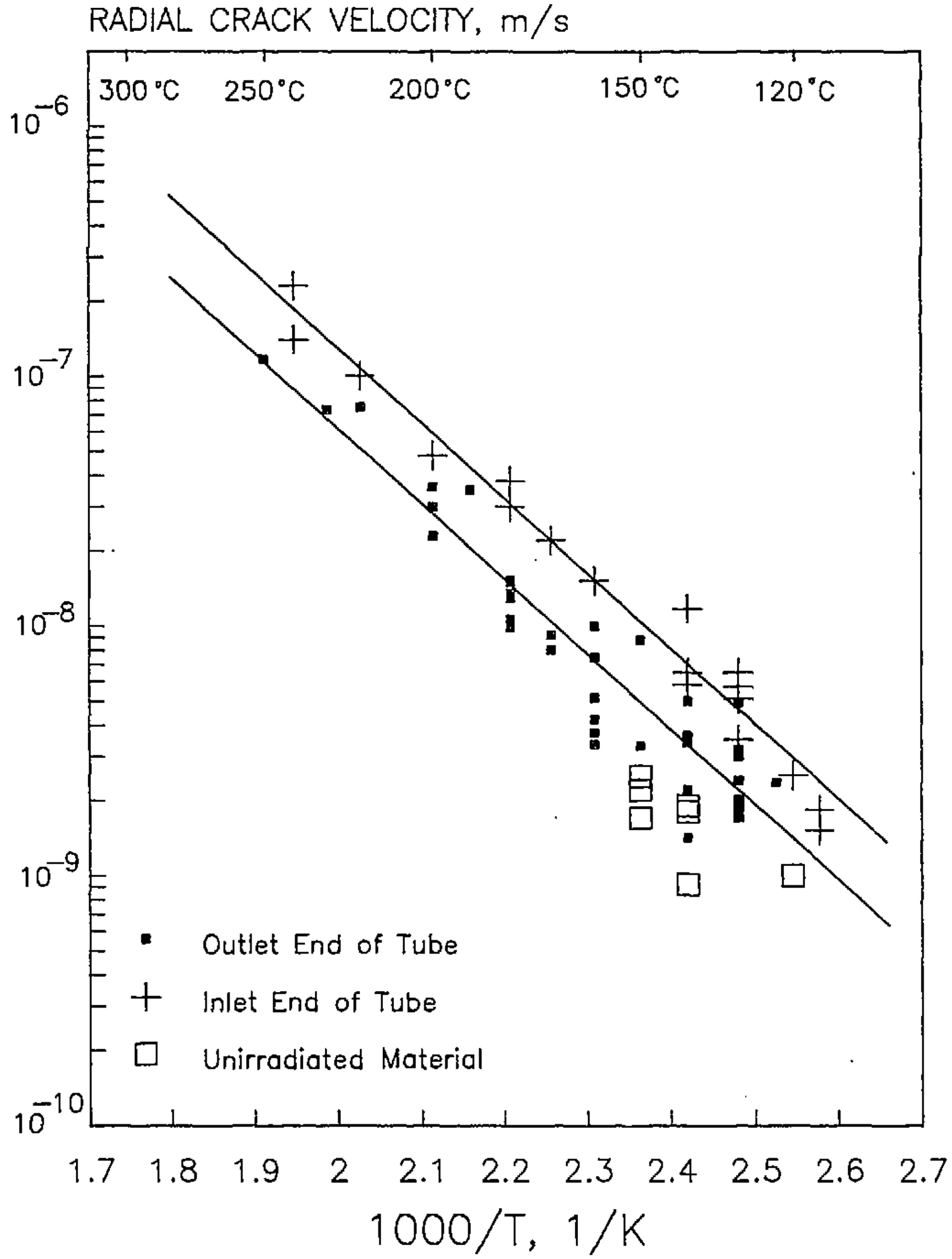


Figure 11: The effect of temperature and irradiation of the velocity of DHC in Zr-2.5Nb pressure tube material [5].

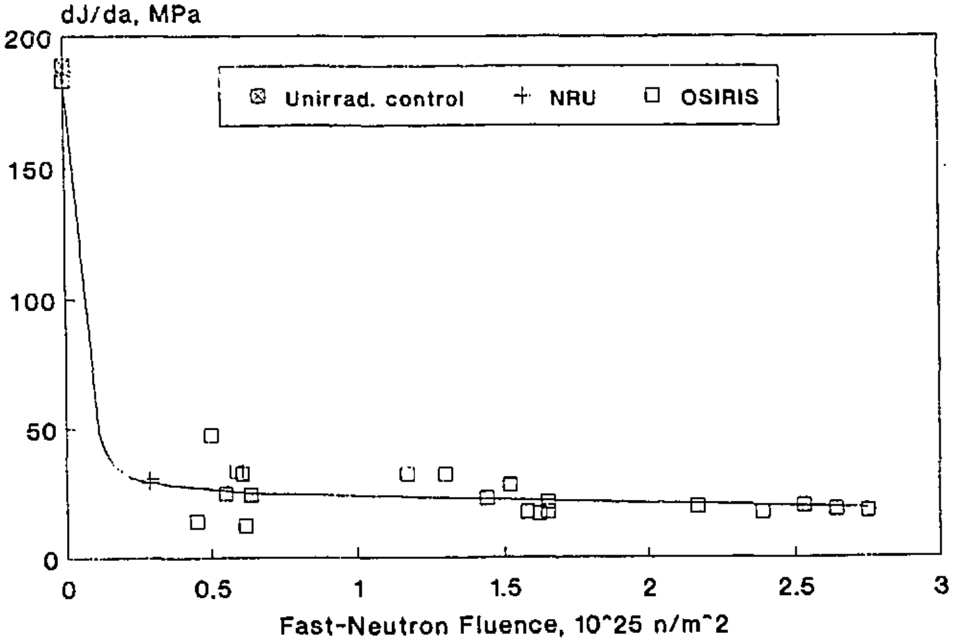


Figure 12: The effect of irradiation on the fracture toughness of a Zr-2.5Nb pressure tube [7].

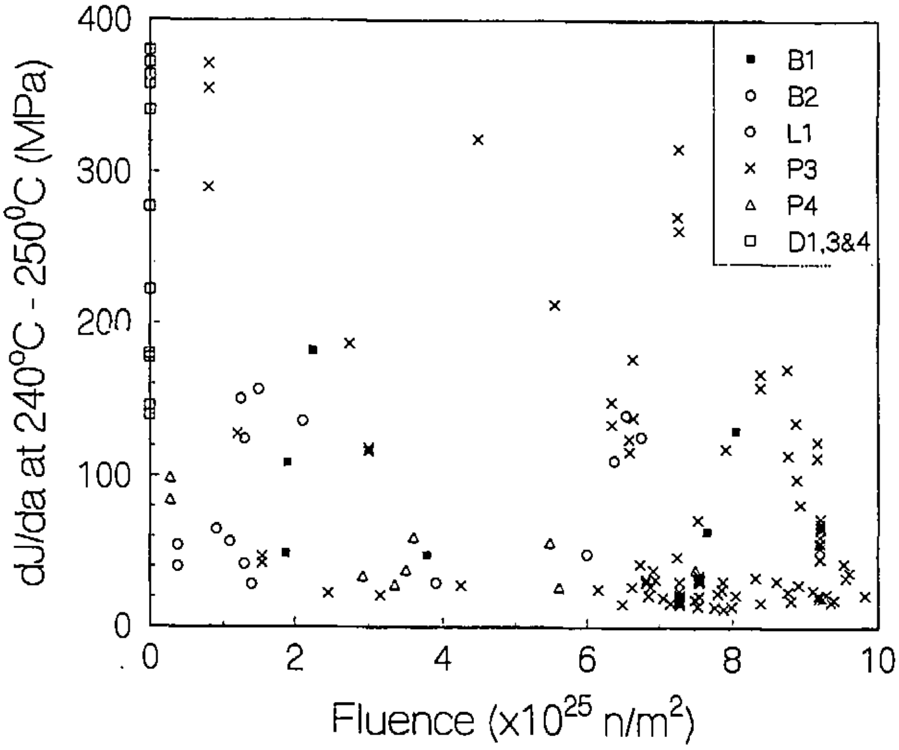
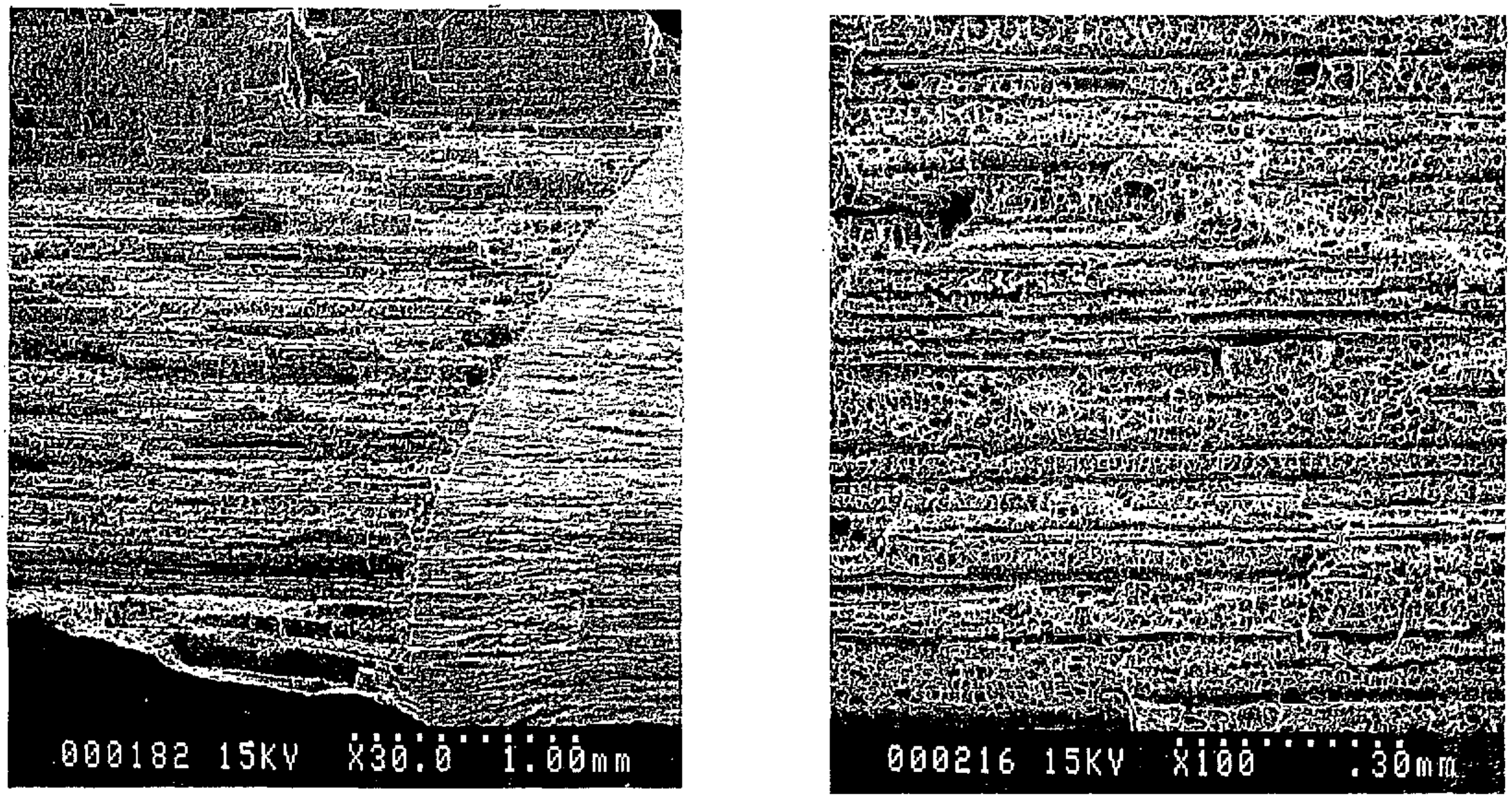


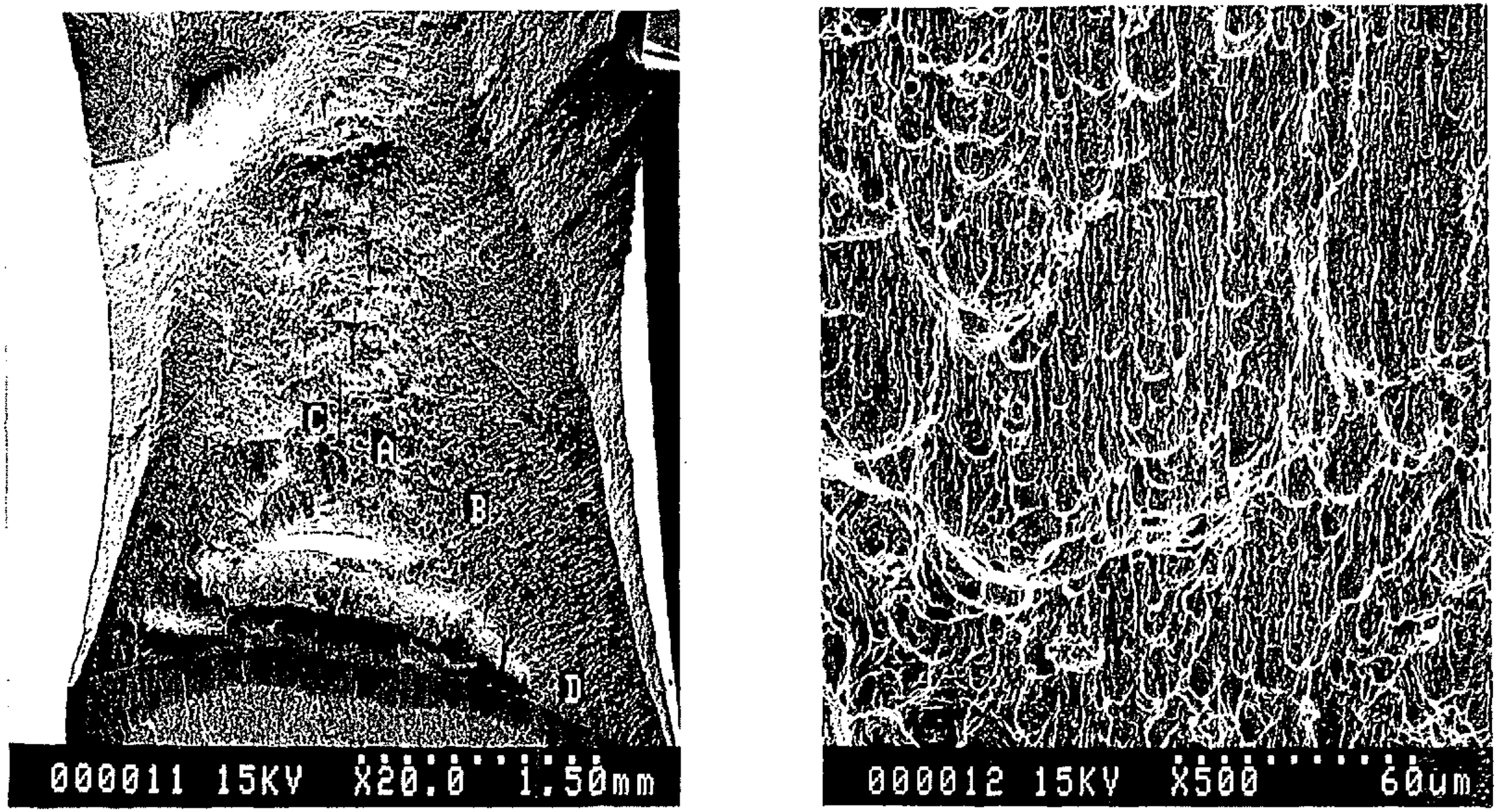
Figure 13: The fracture toughness of Zr-2.5Nb pressure tubes removed from CANDU reactors [7,8].



a. Angle view of fracture near fatigue crack tip

b. Enlarged view of fissures at mid-section

Figure 14: The fracture surface of a compact tension specimen made from the pressure tube removed from channel D18 in Pickering Unit 3 after 18 years' service.



a. Overall view of fracture showing crack branching

b. Tearing dimples in flat fracture zone at mid-section

Figure 15: The fracture surface of a compact tension specimen made from a pressure tube removed from Pickering Unit 3, channel M21, after 18 years' service.

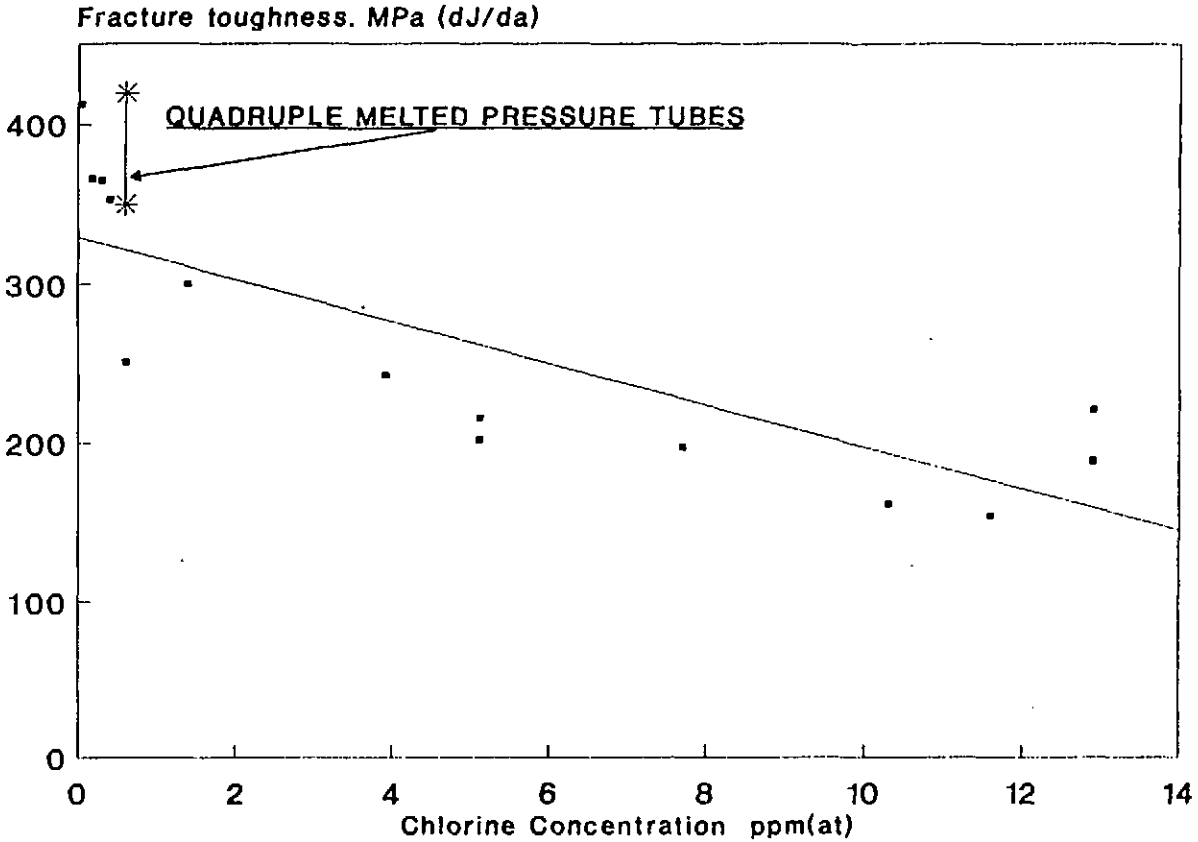


Figure 16: The effect of chlorine on the fracture toughness of Zr-2.5Nb pressure tube material [9].

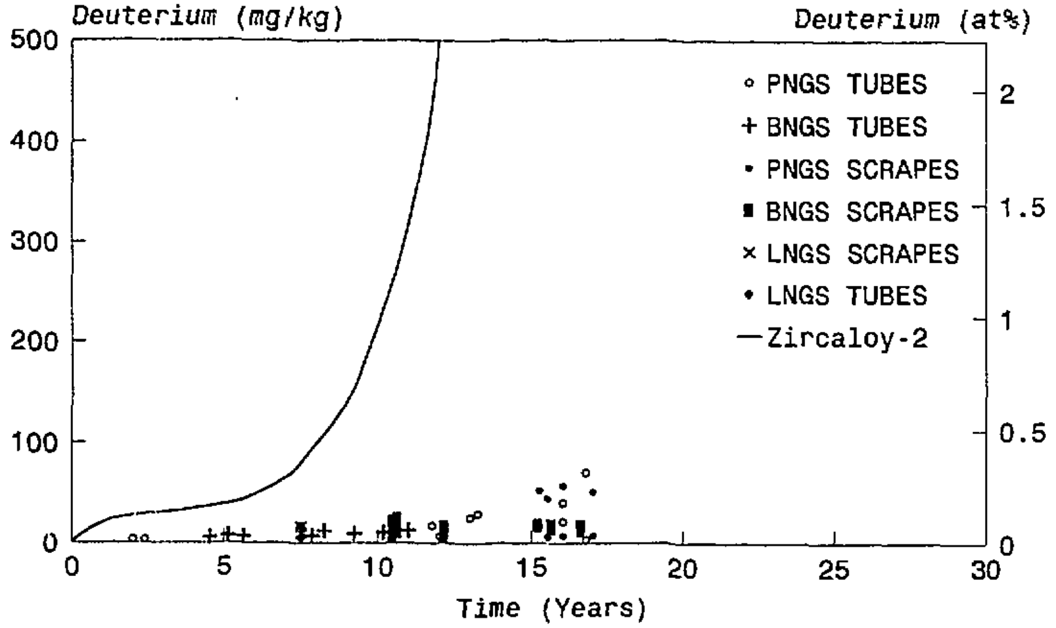


Figure 17: The effect of service on the deuterium concentration of Zr-2.5Nb pressure tubes in CANDU reactors.

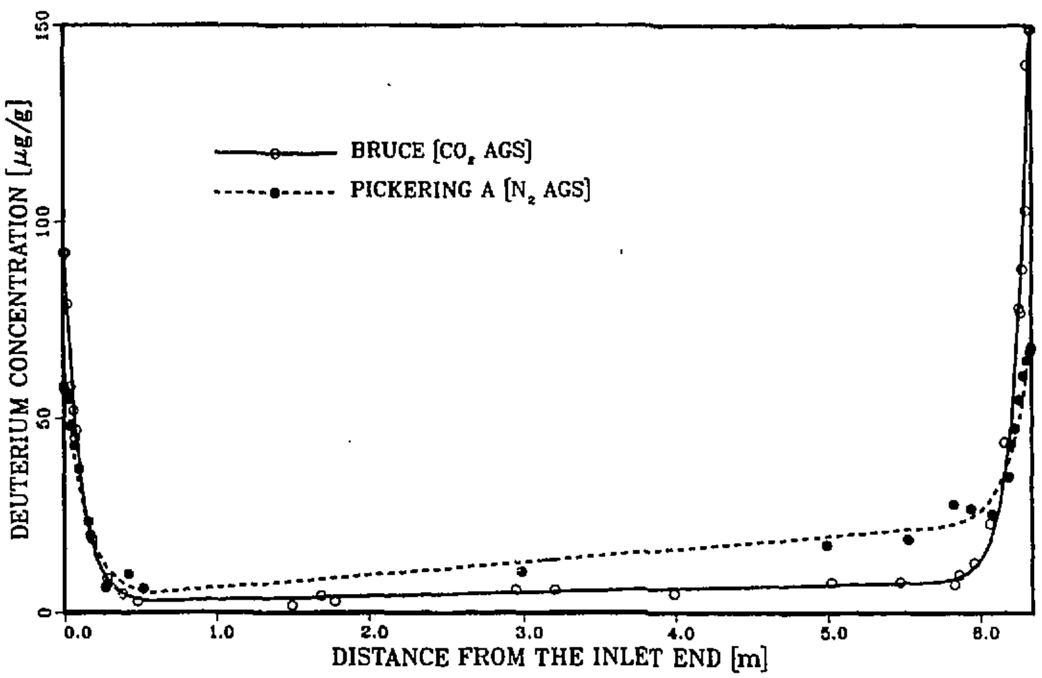


Figure 18: The deuterium concentration along Bruce and Pickering A Zr-2.5Nb pressure tubes after 10 years' service.

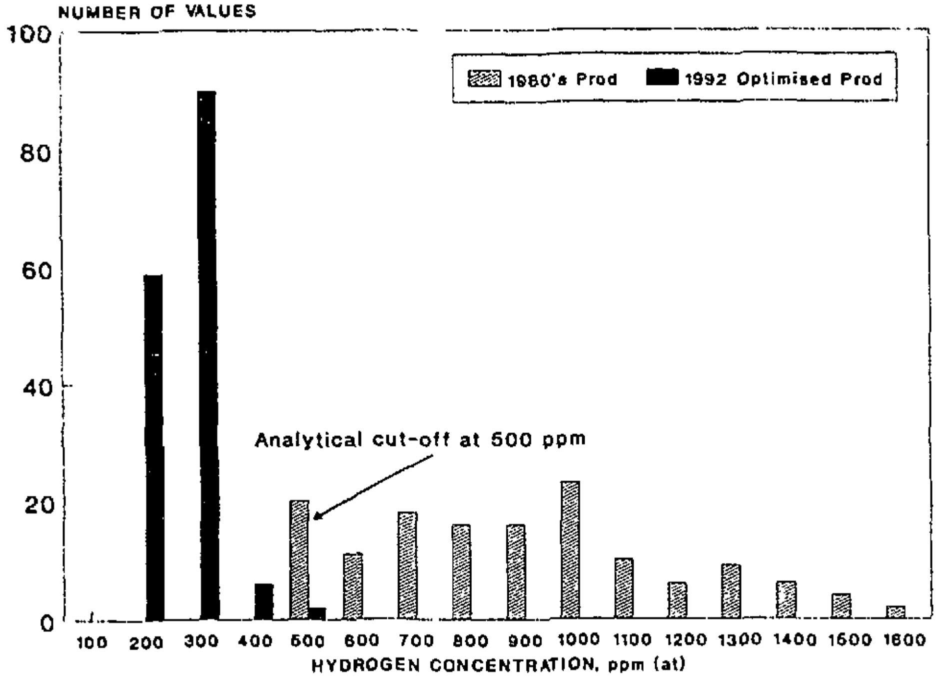


Figure 19: The reduction in as-fabricated hydrogen concentration of Zr-2.5Nb pressure tubes by improved manufacturing practice.

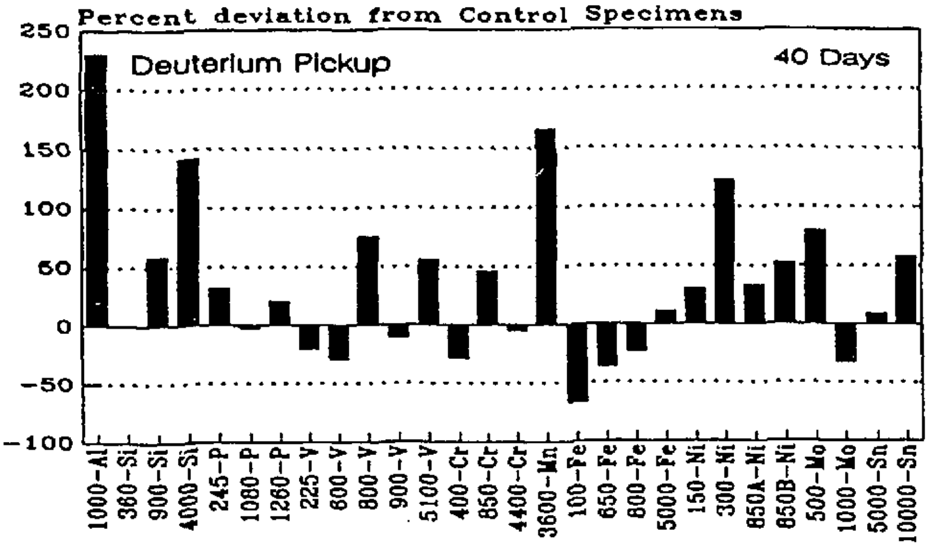


Figure 20: Percent deviation of the deuterium weight gains from the average control specimens behaviour at 40 days' exposure.

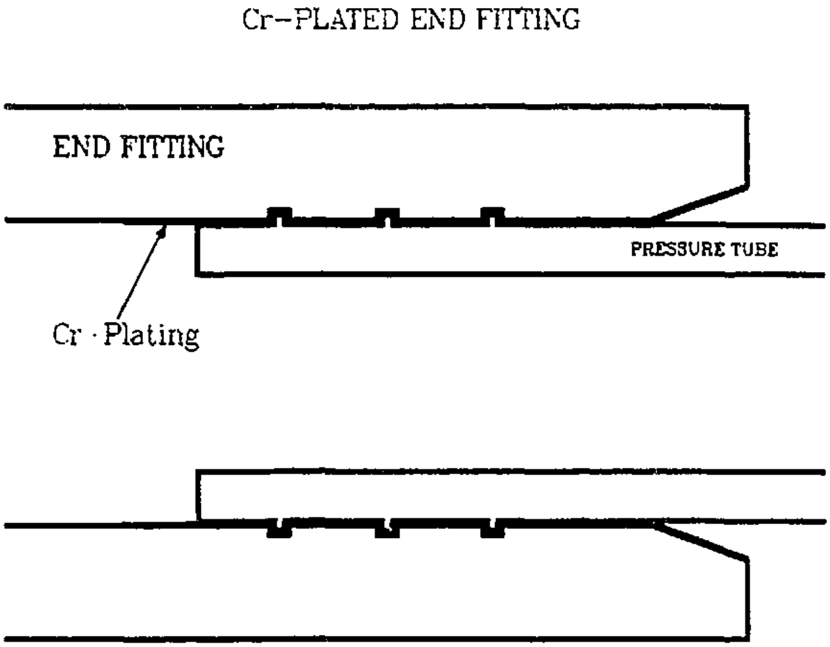


Figure 21: Schematic diagram of a rolled joint showing the chromium plating on the end fitting.

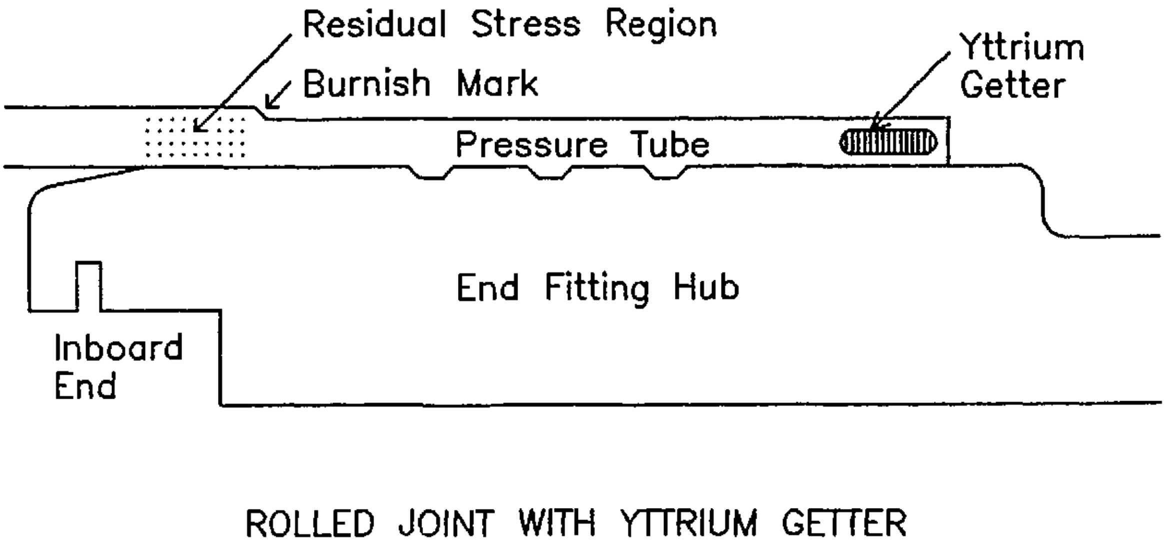
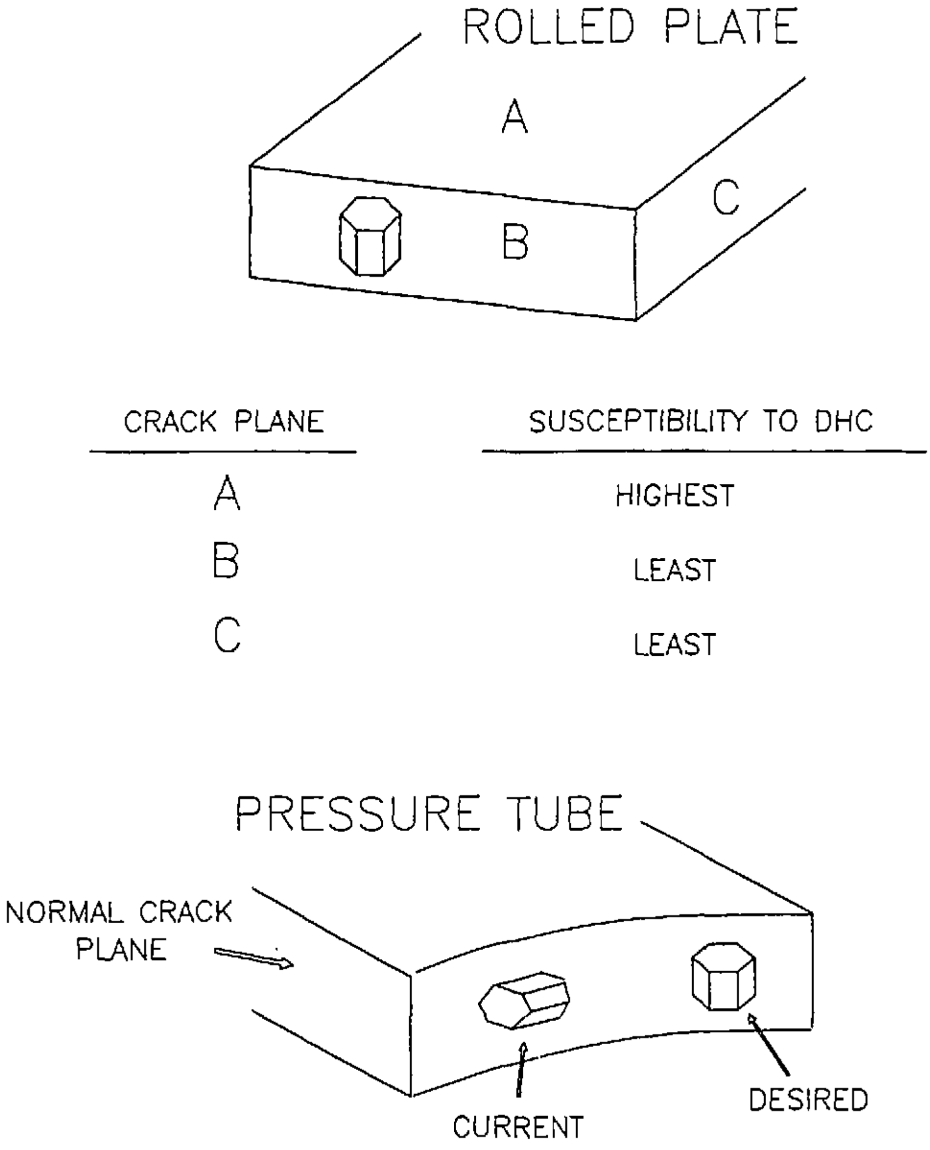
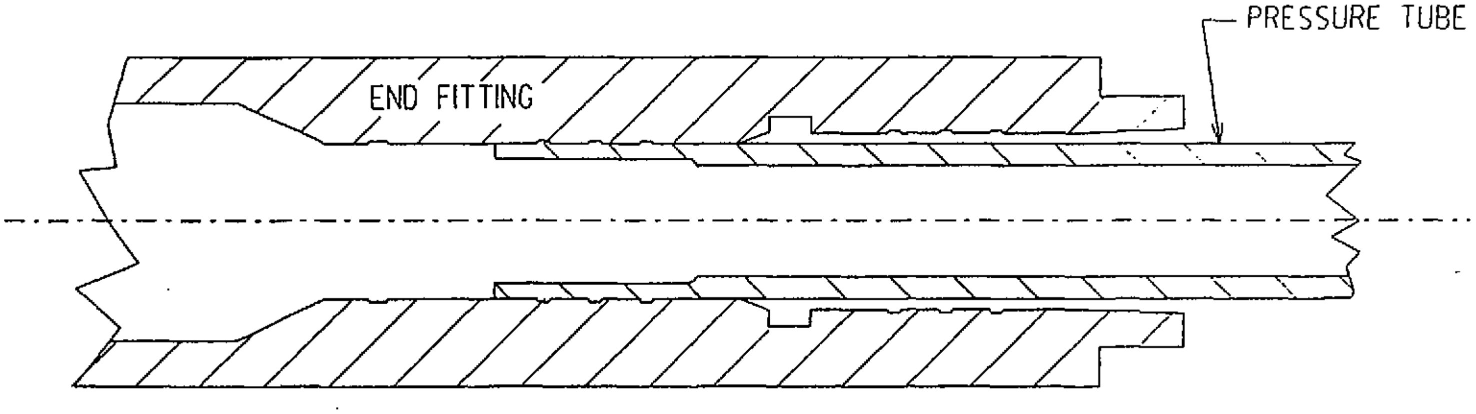


Figure 22: Schematic diagram of a rolled joint showing the yttrium ring bonded to the end of the pressure tube.

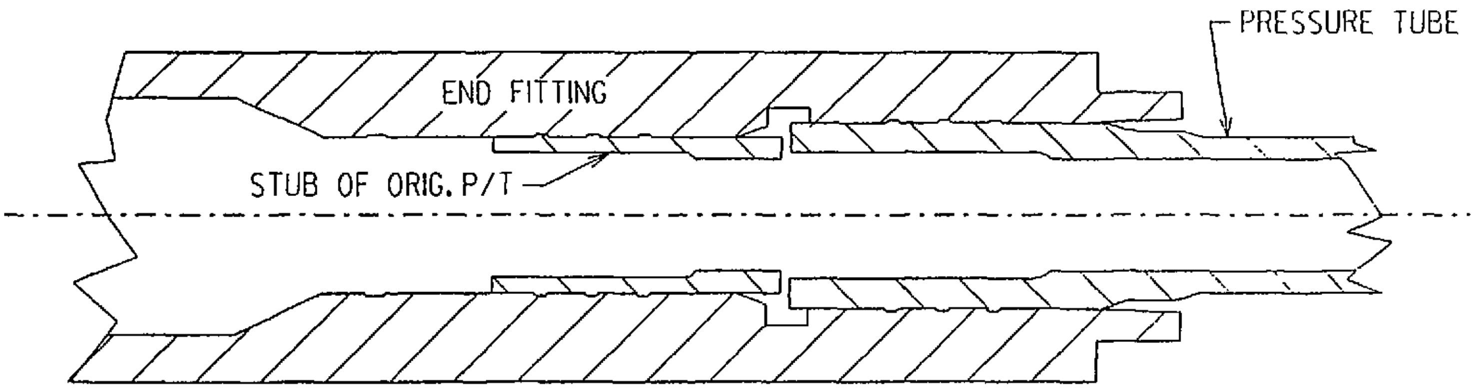


CRACK PLANE	SUSCEPTIBILITY TO DHC
A	HIGHEST
B	LEAST
C	LEAST

Figure 23: Illustration of the effect of crystallographic texture on the susceptibility to DHC.



USE OF OUTBOARD E/F GROOVES



USE OF INBOARD E/F GROOVES IN RETUBING

Figure 24: Schematic diagram of the end fitting with a double set of rolled joint grooves and their use for retubing.

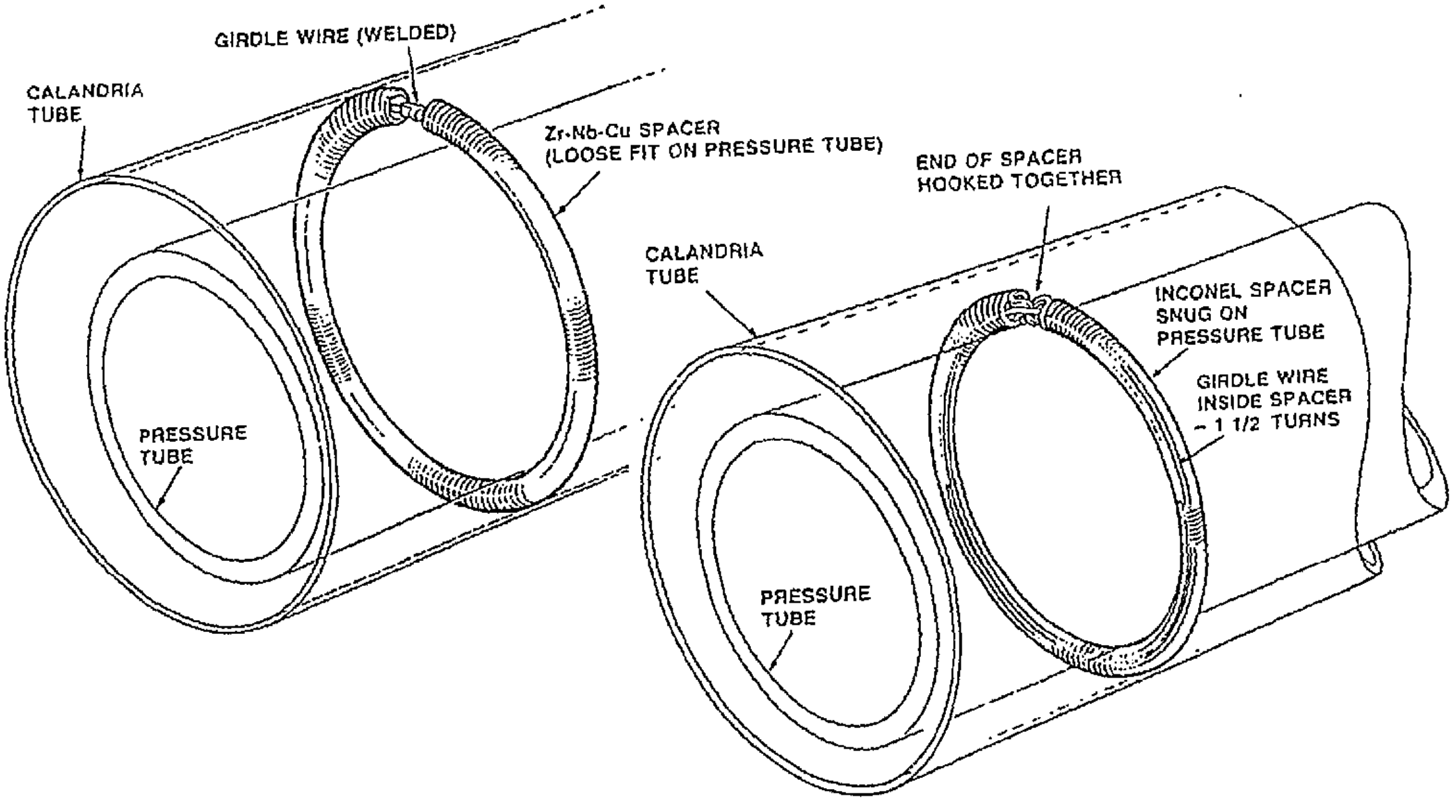
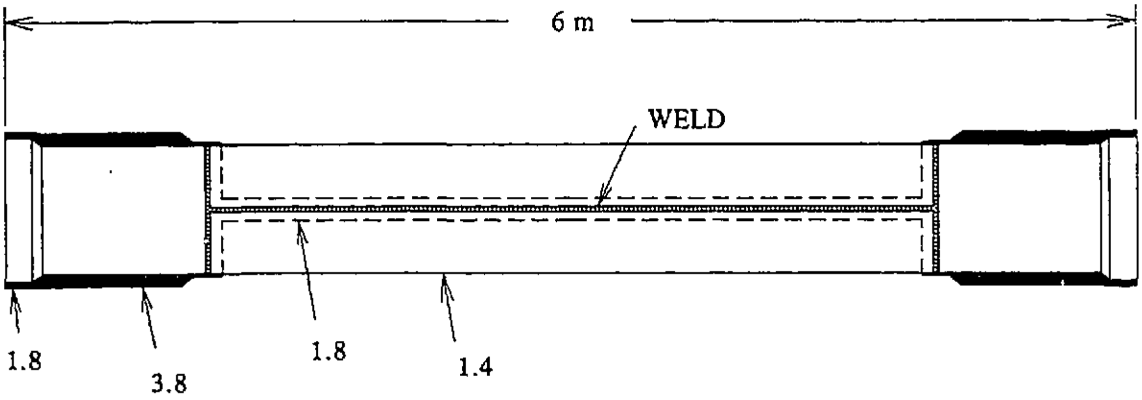


Figure 25: Schematic diagram of the two designs of garter springs used in CANDU reactors.



Thickness in mm

Figure 26: Schematic diagram of a seam-welded calandria tube with thick ends and a thick weld region.

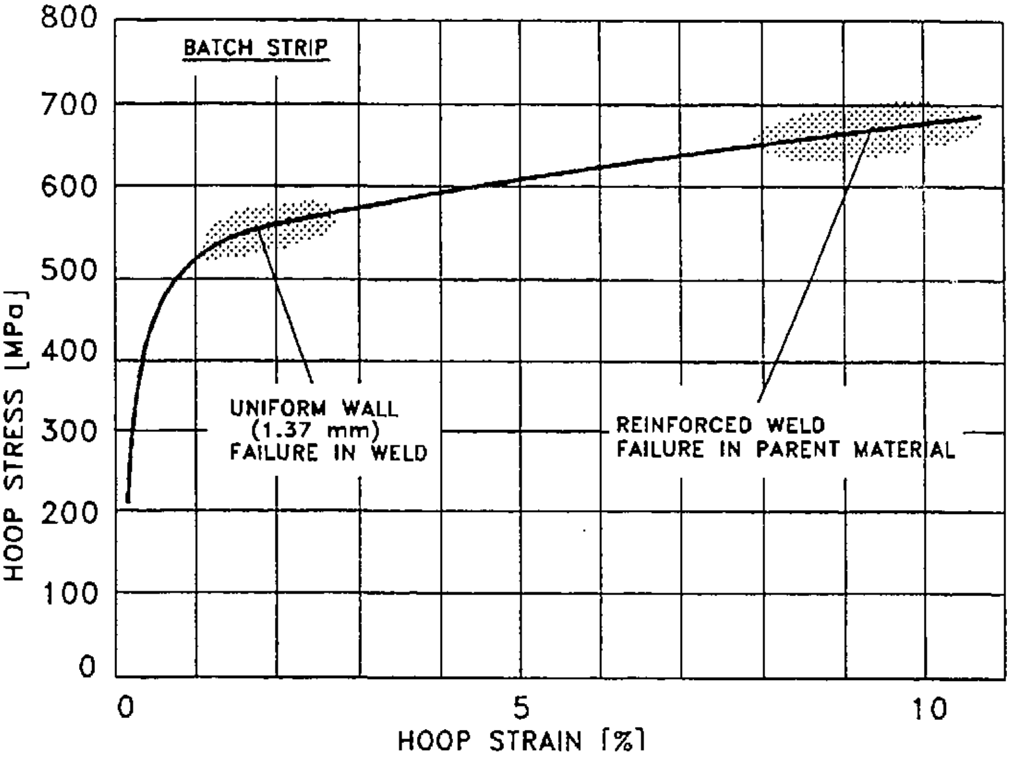


Figure 27: Increase in the burst strength and ductility of Zircaloy-2 calandria tubes by thickening the weld.

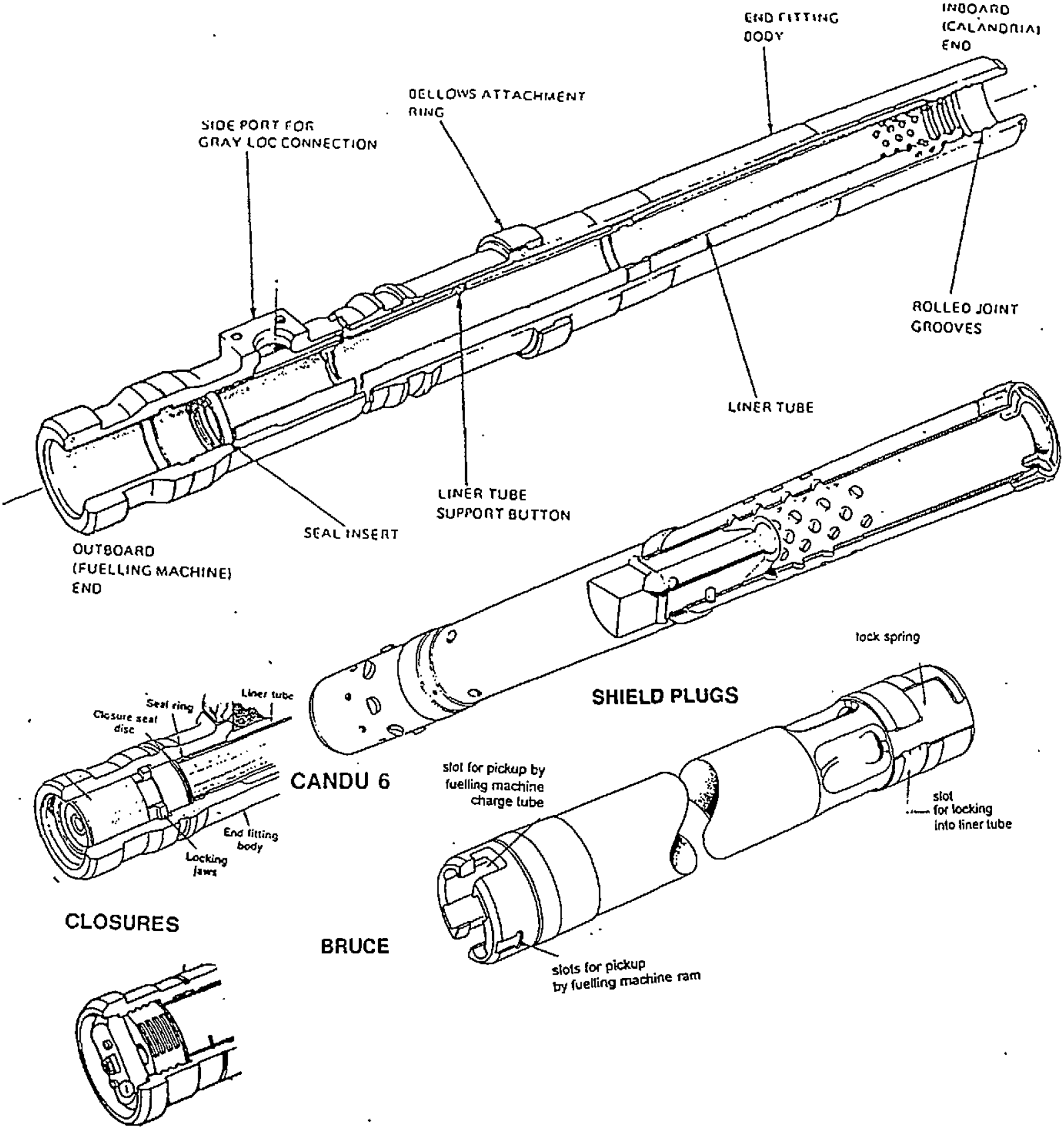


Figure 28: The CANDU fuel channel end fitting showing the two variations in internal component design currently in operation.

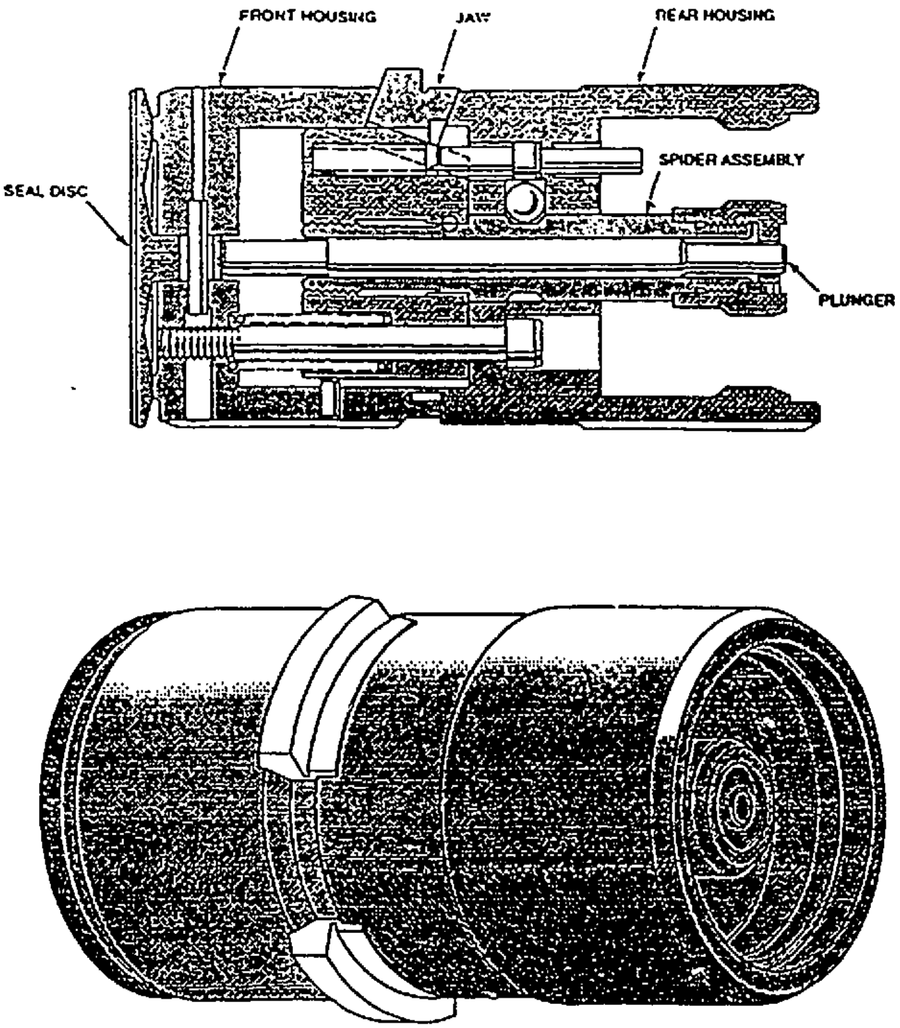


Figure 29: Illustration of the closure plug design used on the CANDU 6 fuel channels.

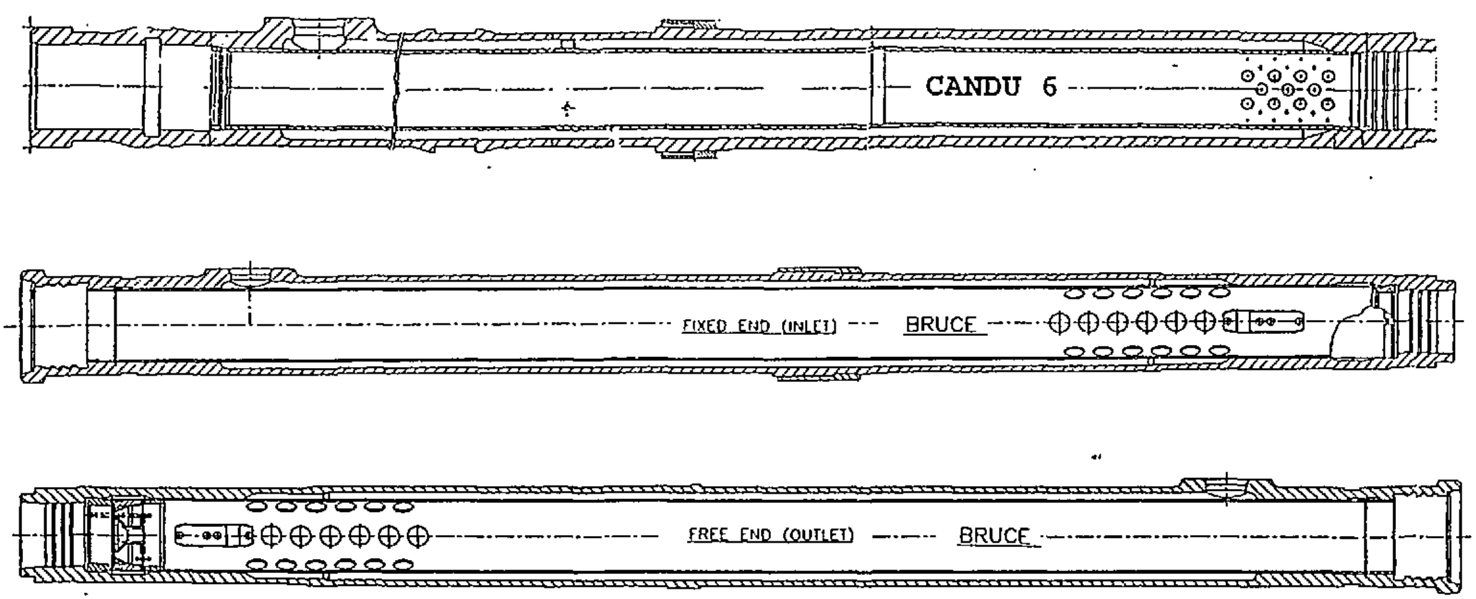


Figure 30: Lengthwise section of the CANDU 6 and Bruce Darlington end fittings, showing the liner tube arrangement.

FLOW-THROUGH INLET SHIELD PLUG

FLOW-THROUGH FUEL PUSHER

OUTLET SHIELD PLUG

LATCHED SPACER PLUG

Figure 31: Illustrations of the internals planned for the CANDU 3 fuel channel.

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