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THIN-WALLED LARGE-DIAMETER ZIRCONIUM ALLOY TUBES IN CANDU REACTORS

by

E.G. Price and P.J. Richinson

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TUBES EN ALLIAGE DE ZIRCONIUM DE GRAND DIAMETRE ET A PAROI MINCE DES REACTEURS CANDU

par E.G. Price et P.J. Richinson

Résumé

On examine les conditions requises des tubes de Zircaloy-2 de grand diamètre et à paroi mince utilisés dans les réacteurs CANDU. La résistance, la configuration des contraintes résiduelles, la texture et les déformations précédentes contribuent à la stabilité de ces tubes. On discute jusqu'à quel point la méthode de fabrication actuelle remplit ces conditions requises.

Ce rapport comprend des sujets qui ont fait l'objet d'un exposé présenté au "Westec 78" de Los Angeles, du 20 au 23 mars 1978.

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Abstract

The requirements of the thin-walled large-diameter Zircaloy-2 tubing used in CANDU reactors are reviewed. Strength, residual stress patterns, texture and prior deformation contribute to the stability of these tubes. The extent to which the present manufacturing route meets these requirements is discussed.

This report contains material made in a presentation to "Westec 78" Los Angeles, March 20-23, 1978.

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FIGURES

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1. INTRODUCTION

Thin-walled large-diameter ($^D/_t \simeq 100$) zirconium alloy *(Zircaloy-2) tubes are important structural components* in the CANDU reactor. They serve two principal functions. One set, the calandria tubes, isolates the pressure tubes, carrying the fuel bundles and the hot pressurized heavy water coolant, from the relatively cool heavy water moderator. The other set, which is incorporated into reactivity mechanism assemblies, act as guide tubes for moving mechanisms or containers for non-moving control devices.

In Figure 1, a reactor cutaway shows the location of the subject tubes. The 380 calandria tubes in a 600 MWe reactor run horizontally between two inner tube sheets. The relevant reactivity mechanism tubes on the other hand are fewer and are vertical components. The reactivity mechanisms penetrate the core between the calandria tubes. The guide tubes hang from the calandria nozzle on the upper wall of the calandria and are fastened at the lower end to the wall of the stainless steel vessel or calandria which forms the reactor core boundary (see Figure 2). There are also reactivity mechanisms which penetrate the core horizontally, but such mechanisms use seamless tubing outside the size range under discussion.

Calandria tubes are typically 129 mm (5.077") diameter, with a 1.37 mm (0.054") wall, and 7 m (20') long. Reactivity mechanism tubing with a high diameter to wall thickness ratio are either 117 mm (4.60") diameter and 1.27 mm (.050") wall thickness, or 127 mm (5.022") diameter and 1.57 mm (0.062") wall thickness. Lengths range up to 8.9 m.

2. DESIGN REQUIREMENTS

2.1 Calandria Tubes

Calandria tubes are designed to meet the intent of American Society of Mechanical Engineers (ASME) Boiler Codes Section III Class I, and are registered to Section III Class III. The significant departure from ASME requirements is the use of Zircaloy-2, a non-code material. The application of low neutron capture cross-section zirconium alloys with their high resistance to corrosion in the service environment, as calandria tube material, is a feature of the CANDU reactor.

The calandria tubes are subjected to loadings due to: head of heavy water (both radial and axial); differential thermal expansion between the austenitic stainless vessel and the Zircaloy tubes; and eventually from the expansion and sag of the pressure tube due to creep. This creep load is transmitted to the calandria tube through spacers inserted between the pressure tube and the calandria tube. These loadings dictate a relatively high longitudinal yield strength in the tube compared to usual American Society of Testing Materials (ASTM) requirements (Table 1).

Table 1 Comparison Between Requirements of Zircaloy-2 Sheet in ASTM B352 and CANDU Calandria Tubing

		ASTM B352 R60802	*AECL SPECIFICATION (Tubing)*
R.T.UTS MPa (kpsi)	LONG	413 (60)	427 (62)
	TRANS	392 (57)	413 (60)
R.T. 0.2% YS MPa (kpsi)	LONG	241 (35)	317 (46)
	TRANS	303 (44)	317 (46)
R.T. Elong^n (% in 2")	LONG	14	20
	TRANS	15	20

The design also caters for postulated accident conditions where overpressure of the calandria vessel is assumed. Under such circumstances the calandria tube must either resist the predicted pressure increase or sustain the collapse onto the pressure tube and spring back to nearly the original shape. The former requirement would dictate a calandria tube thickness that would be a severe neutron penalty; thus the latter criteria has been used to partly establish the adequacy of thinner-walled tubes in recent reactors. Analytical and test work on the tube collapse have shown the advantage of a transverse yield stress in the tube slightly higher than the usual ASTM requirements (see Table 1). A high transverse yield stress also provides greater assurance against increasing ovality due to the cycles of pressure pulses incurred by injecting neutron absorbing material into the moderator to shut down the reactor.

A further requirement of the tube is to form a leak-tight joint onto the end shield material (type 304L stainless steel) by means of a sandwich rolled joint. The ends of the calandria tube are belled (expanded) to allow the joint to be formed without interferring with the ability to insert the pressure tube-spacer combination. The annulus between the calandria tube and the pressure tube is filled with either nitrogen or carbon dioxide at a pressure just above atmospheric (Figure 3).

2.2 Reactivity Mechanisms

The larger-diameter thin-walled tubes are in devices such as shutoff rods, booster rods, adjuster rods, control absorber rods and zone control assemblies. These assemblies are not heavily loaded and generally are not pressure boundary parts although ASME Section III Class III is used as a guide in design. The devices are fastened on the opposite side of the calandria vessel and a small axial tension load is applied to promote straightness and change the vibration frequency of the tubes. Guide tubes can be solid tubes (boosters and zone control assemblies) or perforated tubes (shutoff rods and absorbers). Figure 4 illustrates, schematically, typical devices. Figures 5 and 6 are photographs inside a reactor illustrating penetrations between the calandria tubes.

3. MANUFACTURING

For the tubes under discussion, the selection of a manufacturing route is dictated by a number of considerations. These are:

(a) Economy both in manufacturing cost and potential fuelling cost from parasitic material in the core. The latter requirement plus manufacturing capability has resulted in an allowable wall variation of 0.002" (0.05 mm) in calandria tubing.

(b) The need to avoid distortion in service without weakness to buckling loads imposes a requirement for a homogeneous microstructure in the tube and either a uniform residual stress pattern or a low residual stress.

(c) A requirement for a low irradiation extension by growth and creep in service. To this requirement can be added the desirable small variation in such properties from tube to tube, *i.e.*, as far as possible a uniform manufacturing process.

The requirements to date have been closely met with seam welded tubes. Zircaloy strip is rolled to a thickness tolerance close to the required + .002" to -0.000" (+0.05 mm to -0.00 mm). The strip is brake formed and gas tungsten arc (GTA) welded to obtain the tube shape. Following bead levelling and annealing the tubes are required to possess a structure in the weld zone as shown in Figure 7. This microstructure, although containing some Widmanstatten alpha, more closely resembles the parent metal than the cast weld structure, but it does tend to be isotropic over a narrow zone compared to the textured parent metal. Because of the diameter to wall thickness ratio the tubes are sized by sink draws rather than plug draws. End belling is by bulge forming.

Other manufacturing routes have been considered and actually used. One reactor set of calandria tubes was fabricated by extrusion and cold drawing. However the wall thickness variation resulting from this process does not make it attractive. Seamless fabrication by roll extrusion has been studied. Preliminary results indicate a better wall thickness tolerance than can be obtained from strip, and roll extrusion will give a texture similar to strip. A slight disadvantage is a residual stress pattern that is negative in the circumferential direction.

4. TUBE QUALITY

Because of the high cost both in down time and manrem expenditure to replace either a calandria tube or a reactivity mechanism tube after initial service, the quality demanded is high. Tolerance on surface irregularities adjacent to welds and in the parent material are imposed to avoid a leak path developing at the rolled joint. Defect size acceptance criteria are set against a 0.003" x 0.030" (0.08 mm x 0.8 mm) ultrasonic defect standard. Dye penetrant inspection of strip, high resolution radiography of the welds, and ultrasonic examination of the tube are employed to ensure a high standard is met. Analysis of defect propogation rates from expected vibrational loading or static loading indicates the defect limits are conservative. Dimensional requirements for bow, end skew and ovality are imposed to obtain a tube that when installed gives maximum clearance between horizontal and vertical tubes.

5. CHARACTERISTICS OF THE SEAM WELDED TUBES

5.1 Texture

The texture seen in the seam welded tubes is substantially that of the rolled sheet from which they have been fabricated. The fabrication procedure on the sheet, which involves beta forging, beta and alpha rolling, and cold rolling to finish with intermediate anneals, leaves a texture in which the hexagonal axes of the grains are normal to the sheet (Figure 8). The number of deformation systems in Zircaloy is limited and slip on the (1010) planes, *i.e.* the prism planes, in the ⟨1120⟩ direction, determines that for tensile deformation the longitudinal and transverse directions of the sheet and subsequent tube are similar and result in similar properties.

5.2 Residual Stress

The deformation the tube receives from sinking to obtain rounding and final dimensions results in a residual stress pattern that has a magnitude approximately proportional to the degree of diametral sinking. It is biaxial with the longitudinal residual stress about twice the magnitude of the transverse residual stress. The residual stresses have an important effect during tube qualification tensile testing. The tests are made on transverse specimens, since this is the maximum stressed direction, and it has been found that the residual stress causes lowering of the apparent yield stress obtained due to the Bauschinger effect.

The uniformity of this residual stress is of concern since under irradiation there is relief of stress. Nonuniform stress patterns could result in a tendency to distort in reactor. Thus, the manufacturer is required to demonstrate the stability of the tubes on preproduction samples by simulating the irradiation stress relief with a thermal stress relief.

5.3 Strength

Histograms showing distribution of mechanical properties in current production calandria tubes are shown in Figure 9. The tubes have a mean transverse Ultimate Tensile Strength (UTS) of 460 MPa and a mean transverse 0.2% yield strength (YS) of 345 MPa. The mean tensile elongation is 33%.

6. SERVICE CHARACTERISTCS

6.1 General

In service, calandria tubes and reactivity mechanism tubes undergo two significant changes. In common with most metals, the neutron fluence will increase the strength and decrease the ductility of the annealed Zircaloy-2. In addition the tubes will creep and grow. Corrosion is not expected to be of concern.

The increase in strength of annealed Zircaloy-2 tubes is not used in design but it occurs within a few weeks of start up. After about 1 year the strength reaches an apparently limiting value with a greater increase in yield than in UTS. Figure 10(a) outlines the changes that occur.(1)(2) Simultaneous to the increase in strength is a loss in ductility which is shown by a reduction in the amount of deformation prior to fracture in a tensile test. As shown in Figure 10(b), however, the material retains a significant level of ductility even after the equivalent of 30-years service. The ductility reduction is greatest in uniform elongation. The necking ductility occurring during a tensile test is less affected. The weld material exhibits similar behaviour under irradiation.(3)

In-reactor creep and growth occurring in zirconium alloy components has become of interest in recent years. The creep of zirconium alloys under irradiation is higher than it is out-reactor for the same stress. Creep of Zircaloy-2 is quite low at moderator temperatures (350 K). Stresses in the range 20 to 70 MPa produce a creep rate of approximately 1×10^{-8} h^{-1}.(4) Growth of zirconium alloys is less dependent on temperature. It is, however, dependent on the texture, the amount and direction of prior working, and on the residual stress present. The details of these effects are not yet clear. General trends indicate zirconium alloys will grow more in a direction perpendicular to the hexagonal axis than parallel to the hexagonal axis of the grains. More growth will occur in the direction of prior working than perpendicular to that direction. The higher the dislocation density or amount of working, the greater the growth. Residual stress in the material mostly affects the behaviour in the early "transient" stage. Available information suggests that the annealed condition of the present tubing is the most stable of the options available.(5)

6.2 Calandria Tubing

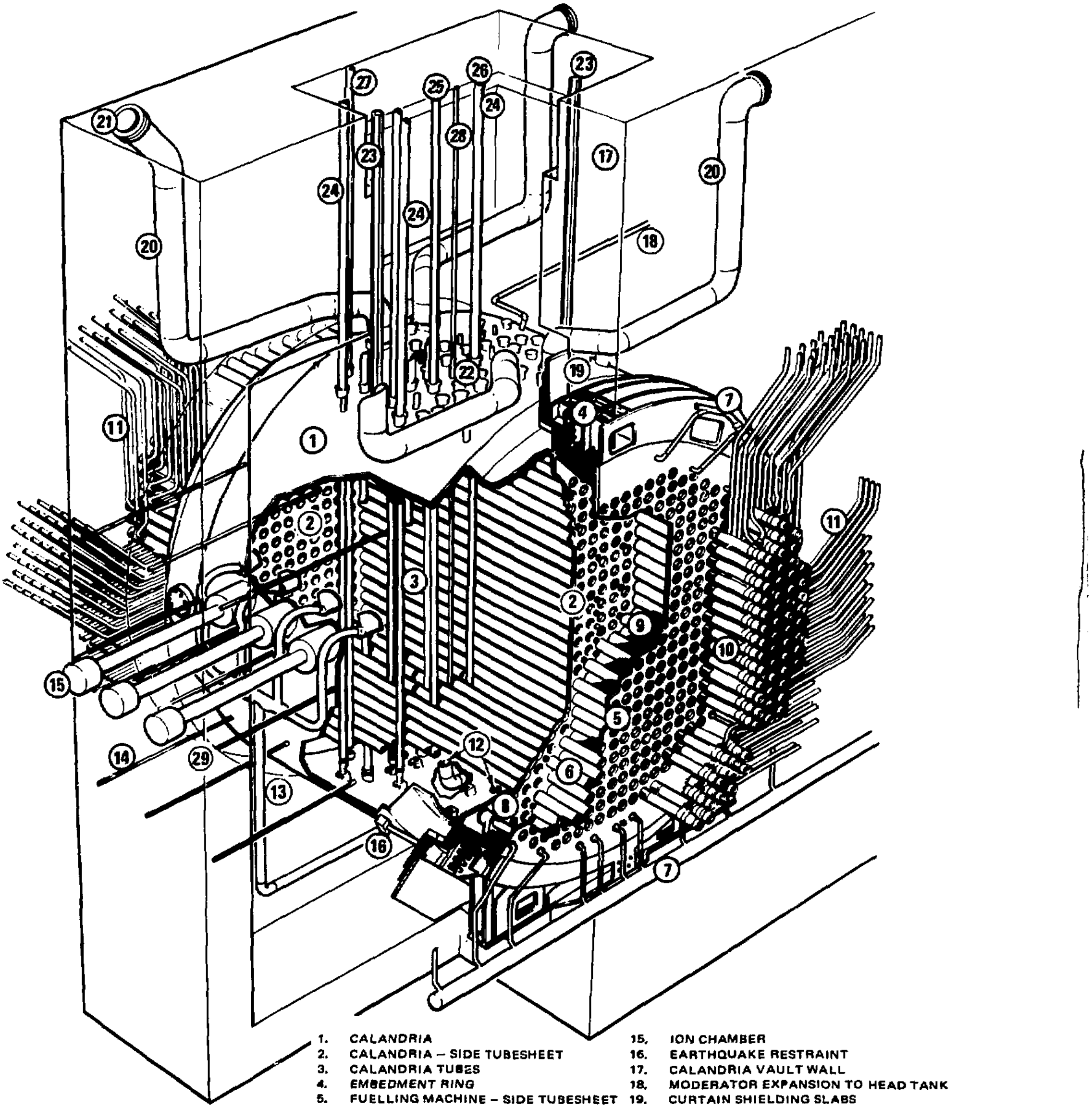
The complex loadings of calandria tubes and the extensive growth transients occurring in early life make predictions of dimensional changes subject to some uncertainty. Axial growth can be expected to change loadings on the end shields or be reflected in calandria tube sag. However, to date no movements on the end shields have been detected.

6.3 Reactivity Mechanism Tubing

The reactivity mechanism tubes are not heavily loaded components. As pointed out an axial spring load is applied to promote straightness and to alter the natural frequency of the tubes. Growth and creep of these tubes is mostly axial and the design adequately allows for the predicted extensions. Dimensional stability with respect to bowing is particularly important because of clearance limits between guide tubes and calandria tubes, and between the moving elements and the shutoff and absorber devices. This necessitates considerable attention to residual stresses in the tubes.

7. CONCLUSION

The present manufacturing route for the fabrication of thin-walled large-diameter Zircaloy-2 tubes used in CANDU reactors produces a high quality product that has performed the designed functions. The characteristics of the product and present knowledge indicate it is the most stable relative to the options available. Further knowledge of growth characteristics may, however, result in modifications to the manufacturing route.



1. CALANDRIA
2. CALANDRIA – SIDE TUBESHEET
3. CALANDRIA TUBES
4. EMBEDMENT RING
5. FUELLING MACHINE – SIDE TUBESHEET
6. END SHIELD LATTICE TUBES
7. END SHIELD COOLING PIPES
8. INLET-OUTLET STRAINER
9. STEEL BALL SHIELDING
10. END FITTINGS
11. FEEDER PIPES
12. MODERATOR OUTLET
13. MODERATOR INLET
14. HORIZONTAL FLUX DETECTOR UNIT
15. ION CHAMBER
16. EARTHQUAKE RESTRAINT
17. CALANDRIA VAULT WALL
18. MODERATOR EXPANSION TO HEAD TANK
19. CURTAIN SHIELDING SLABS
20. PRESSURE RELIEF PIPES
21. RUPTURE DISC
22. REACTIVITY CONTROL UNIT NOZZLES
23. VIEWING PORT
24. SHUTOFF UNIT
25. ADJUSTER UNIT
26. CONTROL ABSORBER UNIT
27. ZONE CONTROL UNIT
28. VERTICAL FLUX DETECTOR UNIT
29. LIQUID INJECTION SHUTDOWN NOZZLE

FIGURE 1 REACTOR ASSEMBLY

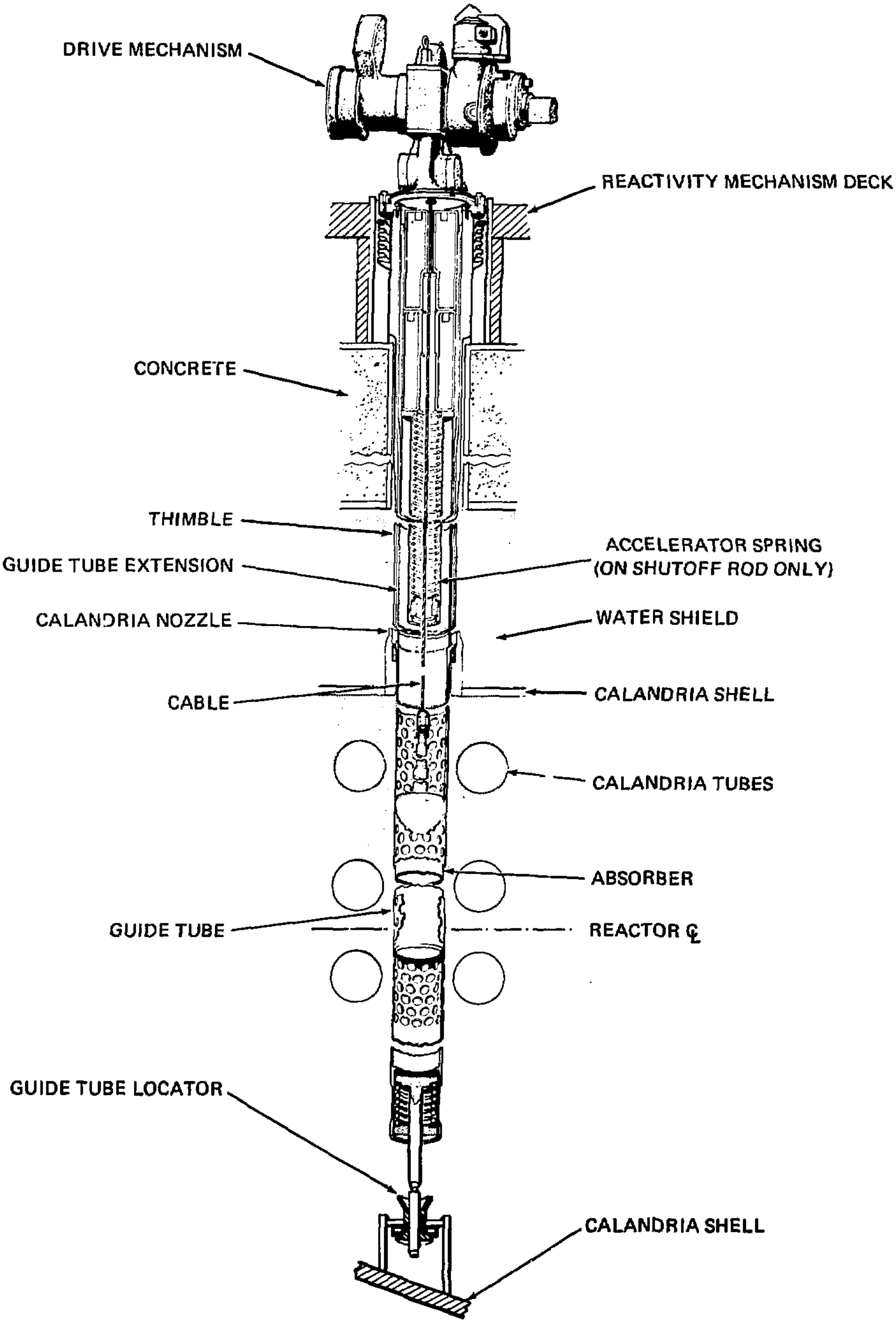


FIGURE 2 SHUTOFF AND SOLID CONTROL ABSORBER UNIT

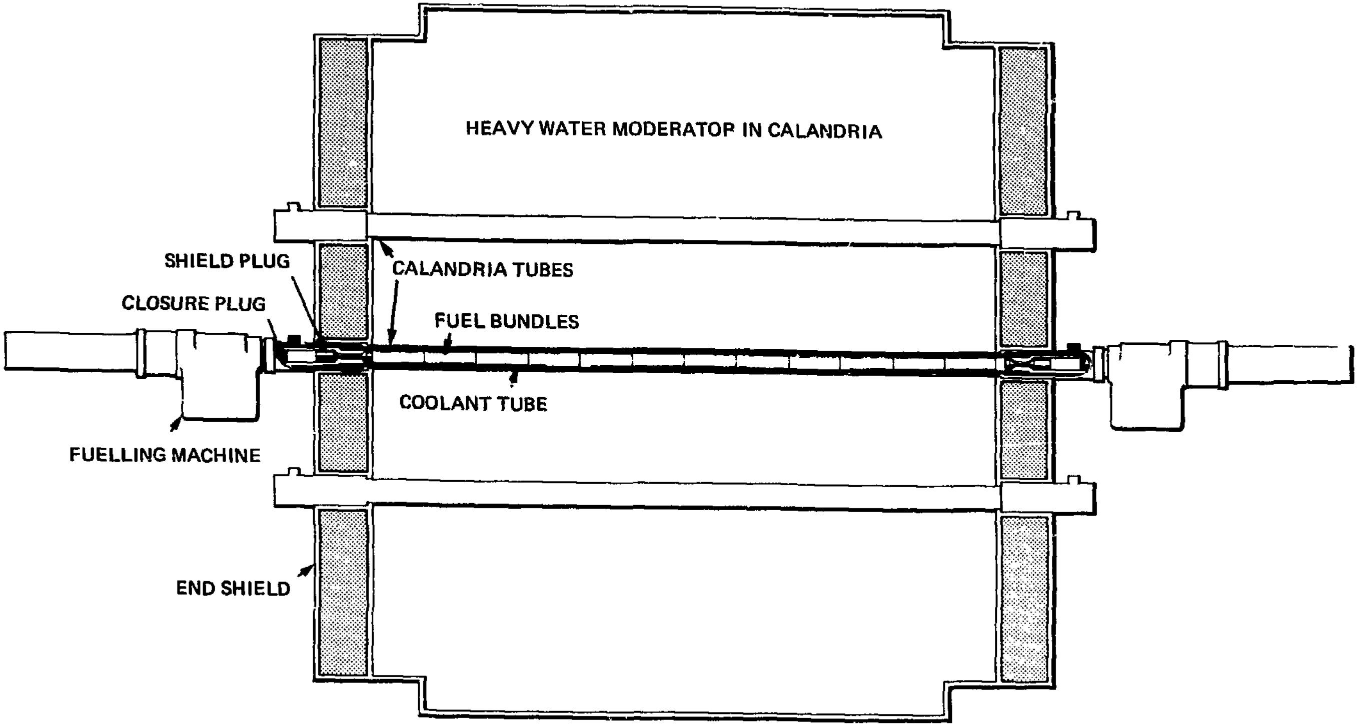


FIGURE 3 SCHEMATIC OF CANDU-PHW REACTOR

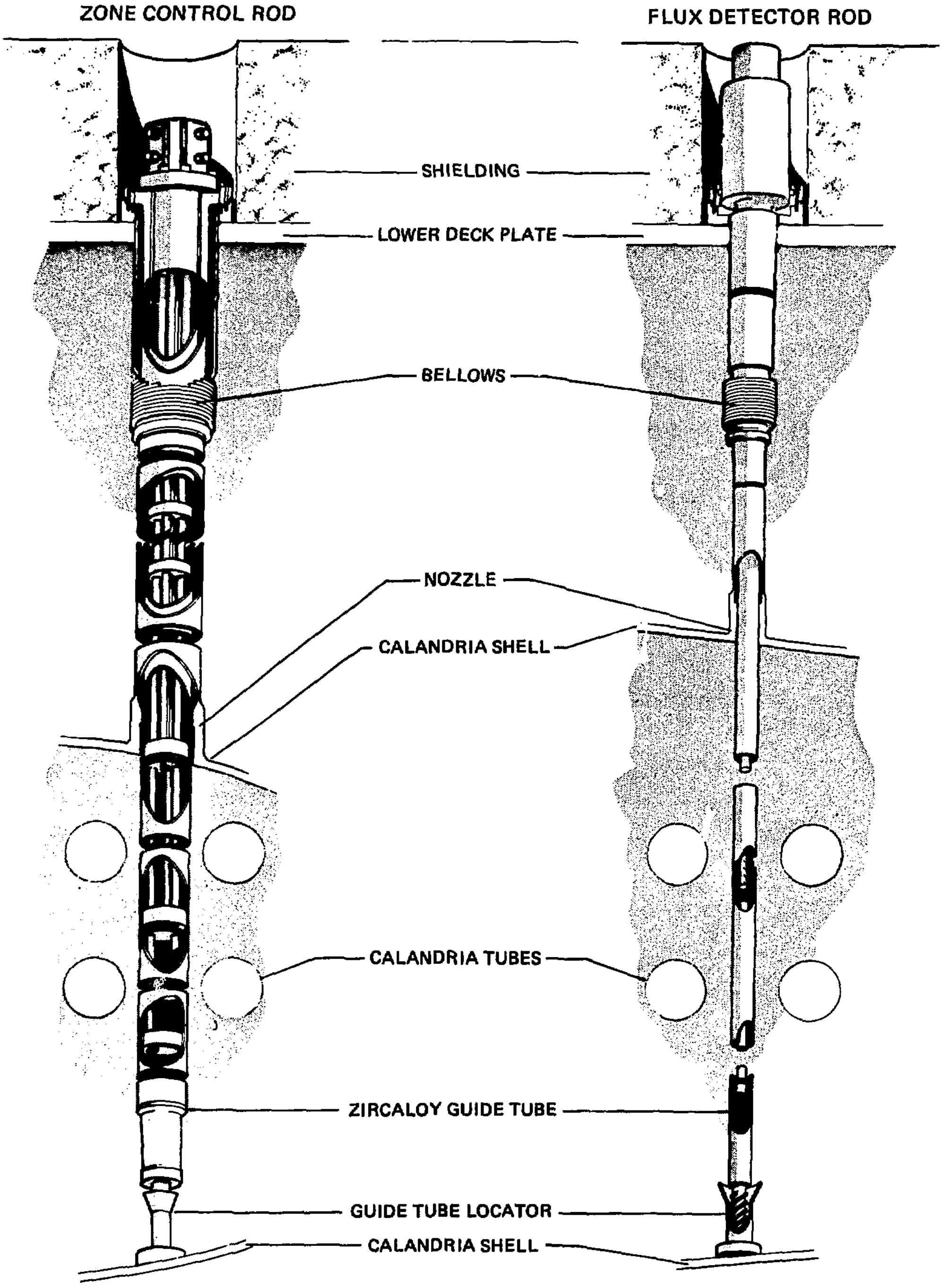


FIGURE 4 ZONE CONTROL AND FLUX DETECTOR RODS

FIGURE 5 VERTICAL SHUTOFF GUIDE TUBE PENETRATING THE REACTOR CORE BETWEEN ROWS OF CALANDRIA TUBES

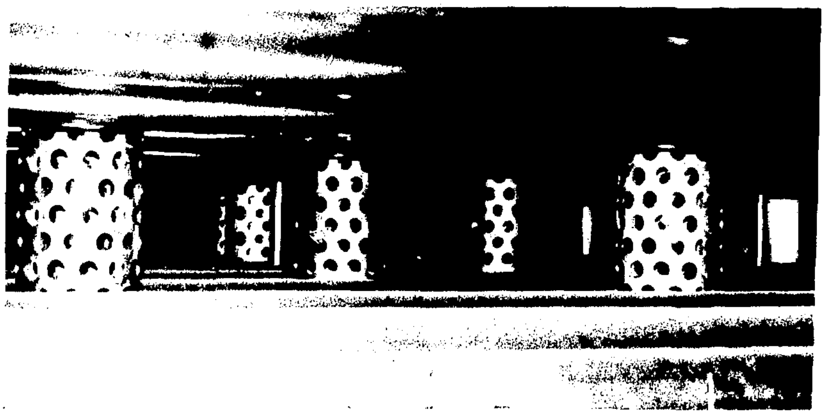


FIGURE 6 VIEW LOOKING HORIZONTALLY BETWEEN ROWS OF CALANDRIA TUBES SHOWING THE VARIETY OF VERTICAL PENETRATIONS

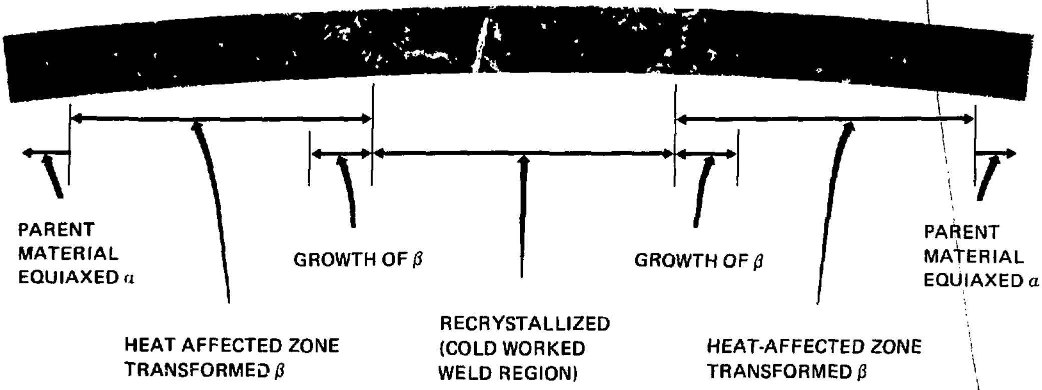


FIGURE 7 WELD CROSS SECTION FROM WELDED, SEAM-LEVELLED AND ANNEALED ZIRCALOY-2 CALANDRIA TUBE

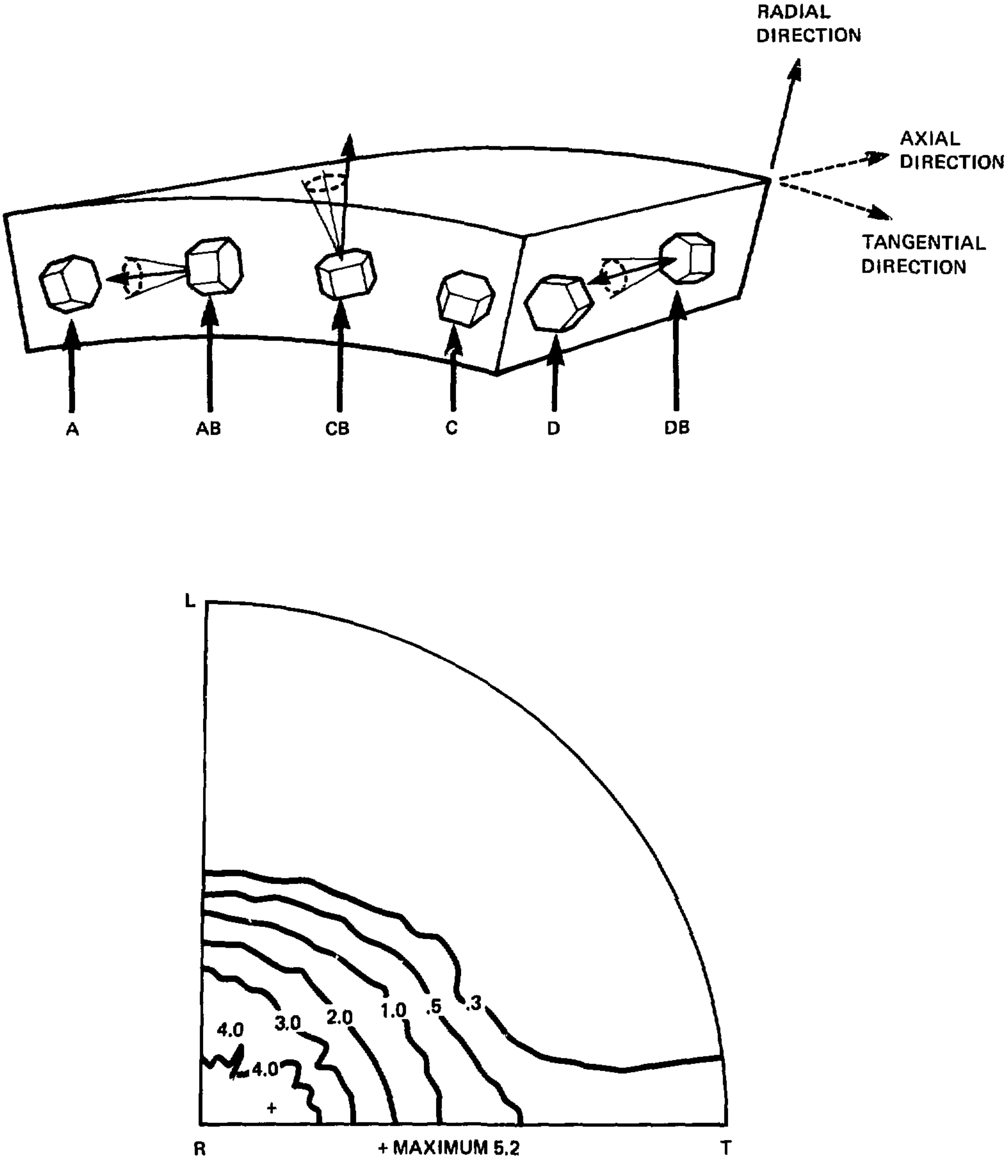
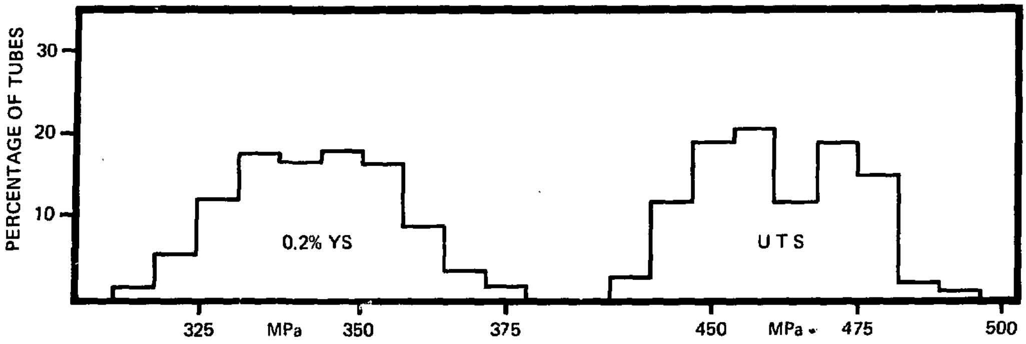


FIGURE 8 IDEALIZED ORIENTATIONS OF GRAINS IN ZIRCONIUM ALLOY TUBING TOGETHER WITH A POLE FIGURE FROM CURRENT CALANDRIA TUBE PRODUCTION



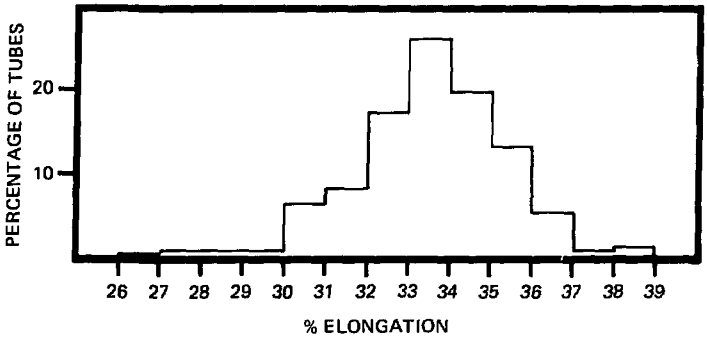


FIGURE 9 DISTRIBUTION OF PROPERTIES IN CALANDRIA TUBES MANUFACTURED FOR A 600 MWe CANDU REACTOR

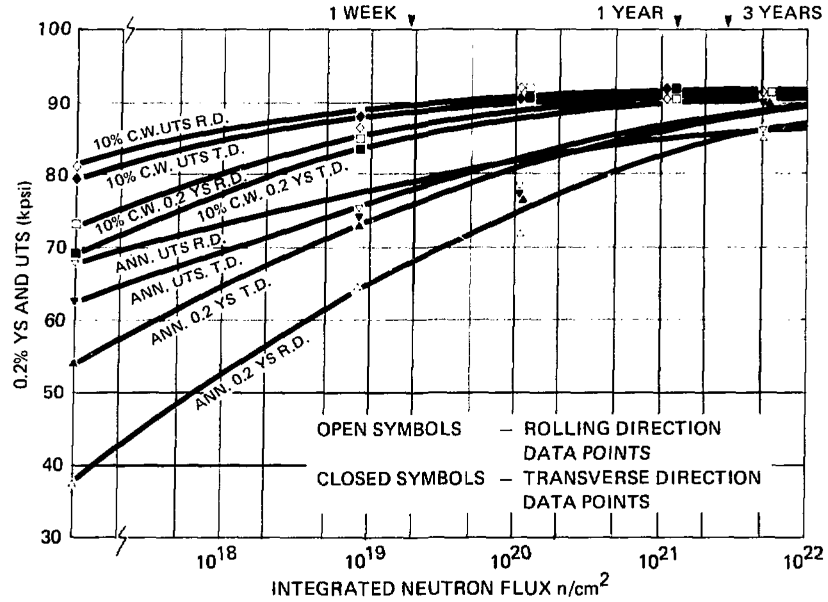


FIGURE 10(a) INCREASE IN ROOM TEMPERATURE TENSILE 0.2% YS AND UTS OF ANNEALED AND 10% COLD WORKED ZIRCALOY-2 WITH IRRADIATION AT ~ 320 K.

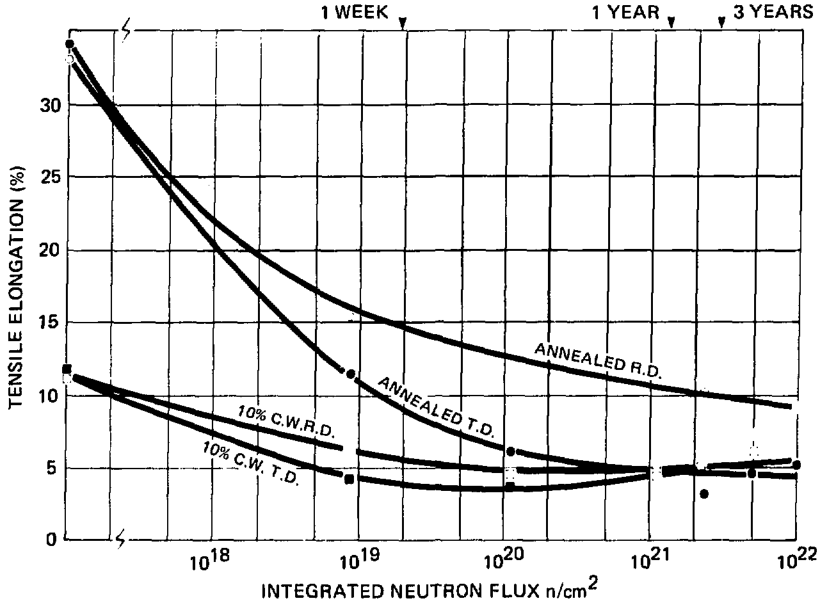


FIGURE 10(b) DECREASE IN ROOM TEMPERATURE TENSILE DUCTILITY (TOTAL ELONGATION) OF ANNEALED AND 10% C.W. ZIRCALOY-2 SHEET WITH IRRADIATION AT ~ 320 K.

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The International Standard Serial Number

ISSN 0067–0367

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