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ASSESSMENT OF THE INTEGRITY OF KANUPP FUEL CHANNELS

B.A. Cheadle[+], A. Celovsky[+], M. Ghafoor[*] and W. Butt[*]

[+]Reactor Materials Division
Chalk River Laboratories
Chalk River, Ontario K0J 1J0

[*]Karachi Nuclear Power Plant
P.O. Box 3183
Karachi-29, Pakistan

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ABSTRACT

The KANUPP reactor first produced power in 1972. In 1983 one of the fuel channels, G12 was difficult to refuel due to the South end fitting being retracted relative to the adjacent channels. In November 1993, eight fuel channels were inspected non-destructively for defects. The dimensions and shape of the pressure tubes were measured, and channel G12 was removed for examination and testing at the Chalk River Laboratories.

Examination of channel G12 showed that the South end calandria tube rolled joint had been leaking moderator heavy water into the annulus. The inborad bearing was completely corroded away which resulted in the South end fitting seizing in the debris. The Inconel X750 garter springs were both completely broken into small rings due to Stress Corrosion Cracking (SCC) in acids produced by radiolysis of the moderator heavy water.

The inspection of the eight fuel channels did not reveal any serious defects. The length and diameter changes in the pressure tubes were both small. The deuterium ingress had been low with the result that the hydrogen isotope concentration of the pressure tubes was below Terminal Solid Solubility (TSS) even close to the end fittings. Irradiation had increased the strength and reduced the ductility and fracture toughness of the tubes and the Delayed Hydride Cracking (DHC) properties were similar to irradiated cold worked Zr-2.5Nb pressure tubes.

The examination and testing showed that the KANUPP pressure tubes are all probably in good condition and fit for several more years service.

1. INTRODUCTION

KANUPP is a 137 MW(e) CANDU reactor that was constructed in Pakistan by Canadian General Electric. The reactor first produced power in 1972 and has generally been operated at less than 100 MW(e). A comparison with other CANDU fuel channels is given in Table 1. In 1993 November, the reactor had operated for 60 962 Effective Full Power Hours (EFPH) and 103 387 hours hot. In 1983, one of the fuel channels was difficult to refuel due to the South end fitting being retracted relative to the adjacent channels. In 1989, channel F15 was also found to be retracted relative to its adjacent channels. The investigation into the cause of this behaviour in 1989 by an IAEA ASSET team concluded that the South end fittings of these channels were locked, and not able to move on their bearings as a result of corrosion of the grey cast iron bearings and the carbon steel sections of the lattice tubes. The team recommended that channels G12 and F15 should be isolated from the Primary Heat Transport System (PHTS) and supplied with their own cooling system; the pressure tube, end fittings and calandria tube from channel G12 should be removed and examined to determine the cause of the axial elongation behaviour; and the pressure tube be chemically analysed to determine the extent of deuterium pickup and tested to determine its mechanical properties.

In 1990, AECL made an additional assessment of the behaviour of these two channels and the probable condition of all the fuel channels. A contract was negotiated with AECL to inspect eight pressure tubes, remove the pressure tube, end fittings and garter springs from channel G12, test the pressure tube and garter springs, and based on the results, assess the condition of the pressure tubes in the reactor and recommend if they were suitable for further service.

2. BEHAVIOUR OF CHANNEL G12

In 1983 when the fuelling machine would not lock onto the South end of channel G12 because the end fitting was displaced inboard relative to the neighbouring channels, changes were made to the fuelling machine to enable it to lock on and refuel the channel. In 1987, the position of the South ends of several channels were measured both at 50^{0}C and again at 281^{0}C. At 50^{0}C, G12 was retracted 10.2 mm relative to its neighbours and on heating to 281^{0}C it only moved 4.5 mm compared with 14 mm for the other channels. Thermal expansion should move the free ends of the channels at least 12 mm when they are heated from 50^{0}C to 281^{0}C. In 1989, channel F15 was also found to be retracted 9.5 mm relative to its neighbours. The IAEA ASSET team concluded that the South end fitting of channel G12 was locked on its bearings due to the corrosion of the carbon steel lattice tube. They suggested that the corrosion was due to problems with moisture in the annulus gas system and even possibly moist salty air occasionally getting into the annulus gas system. Channels G12 and F15 were isolated from the PHTS and provided with their own Empty Channel Cooling System (ECCS). An assessment by AECL, suggested that it was more likely that corrosion of the cast iron bearings was causing the problem as the bearing clearances were only 0.76 mm compared to a 1.5 mm clearance for the lattice tube.

The North end fitting was removed easily but special tooling had to use a combination of several thousand pound axial pull, plus impact and vibration to remove the South end fitting. After the pressure tube and end fittings had been removed, the channel was cleaned by pushing a swab through from the North end. The lattice tube, bearings and calandria tube were then examined using a video camera. At the North end (fixed end) there was some loose debris along the bottom of the lattice tube but the single inboard bearing appeared to be in good condition. The South end lattice tube had a lot of debris along the bottom in the smaller diameter section. The outboard bearing appeared in reasonable condition, but the inboard bearing was essentially completely corroded away.

The video examination of the calandria tube showed that the garter springs were broken into small rings and many of these rings had been pushed into the calandria tube extension sleeves, by the pressure tube removal operation and the swabbing operations. The failure of the Inconel X750 garter springs probably failed from stress corrosion cracking. Moderator heavy water leaked into the annulus from the South end calandria tube rolled joint and radiolysis probably formed several acids that cause stress corrosion cracking in Inconel X750.

Hence the problems in channel G12 were caused by the South end calandria tube rolled joint leaking moderator heavy water into the annulus. The water resulted in the complete corrosion of the inboard bearing. This resulted in the South end fitting seizing in the bearing and prevented the axial movement of the end fitting.

3. INSPECTION AND TEST RESULTS

The service life of CANDU pressure tubes is determined by the allowable dimensional changes as shown by diametral increase and length extension of the pressure tube and sag of the fuel channel, and by the capability to satisfy the Leak-Before-Break (LBB) criteria developed for CANDU pressure tubes. New pressure tubes meet all the dimensional requirements, but during service the tubes change due to creep and irradiation growth, and at some point they may no longer meet the design requirements for the reactor. As a result of deuterium ingress, changes in mechanical properties due to irradiation and any fretting damage, the probability of LBB can decrease to a level that the tubes are no longer suitable for further service. If the tubes do not meet any of these requirements they must be replaced as has been done in Pickering Units 1- 4, or the reactor decommissioned as in the case of NPD.

The dimensions of the pressure tubes can be monitored during service and future changes predicted based on their previous behaviour and models that have been developed. The change in probability of LBB is more difficult. The important properties are:

- Presence of damaging defects that could initiate Delayed Hydride Cracking (DHC).

- Change in the concentration of hydrogen isotopes due to deuterium ingress during service.

- Changes in mechanical properties, particularly susceptibility to DHC and reduction in toughness from irradiation induced microstructural changes.

The presence of defects and concentration of hydrogen isotopes can be measured non-destructively but the changes in mechanical properties must be measured on tubes removed from the reactor. Eight channels were inspected, Table 2, and material from the G12 pressure tube tested, Table 3, to provide the information needed to assess the condition of the KANUPP pressure tubes and their suitability for further service.

3.1 Presence of Defects

The potential sources of defects in pressure tubes are:

- The fabrication process. The casting, extrusion and cold drawing processes can all introduce defects. Any such defects are usually found by the manufacturing inspection. However the equipment available when the KANUPP tubes were inspected is not as sensitive as current equipment and it is possible that some defects were not detected.

- The installation procedure, particularly making the rolled joint.

- Debris introduced into the PHTS during reactor construction or during service can be trapped between the fuel bundles and the pressure tube and cause fretting damage.

- Fuel bundle bearing pads scratch the inside surface when the bundles are pushed along the channel and the pads can also cause crevice corrosion of the pressure tube.

None of the eight channels inspected contained any injurious defects. The only marks detected were very small grooves/scratches on the inside of the pressure tubes that are caused by the fuel bundles bearing pads. Although the inspection of eight channels only gives an indication of the probable condition of all the 208 channels, the fact that no defects were detected indicates that there has not been any serious fretting problems from debris in the PHTS and the fuel bundles and fuelling operations have not caused any unusual damage to the pressure tubes.

3.2 Changes in Dimensions

The sag, maximum transverse strain and length change of the eight channels are shown in Figures 1, 2 and 3. Since the channels were not measured after they were installed, there is no zero point and it is difficult to estimate the exact change with service or the exact deformation rates. The maximum estimated increases excluding channel G12 are: diameter 0.8%, elongation 5 mm and sag 23 mm. The elongation is much less and the increase in diameter is greater than would have occurred in cold worked Zr-2.5Nb pressure tubes operating under the same conditions. This is due to the effect of the much more random crystallographic texture of the heat treated tubes.

3.3 Hydrogen Concentration, Corrosion and Deuterium Ingress

The initial hydrogen concentration of heat treated Zr-2.5Nb pressure tubes is usually higher than cold worked tubes because hydrogen is picked up during the water quenching and aging heat treatments. These treatments also increase the variability both along a tube and between tubes. The hydrogen concentrations of the eight tubes ranged from about 6 ppm to about 23 ppm and there was often a significant variation along the tubes. These values are typical of heat treated Zr-2.5Nb pressure tubes.

The oxide thicknesses measured are similar to those observed on other heat treated Zr-2.5Nb pressure tubes and less than has been observed on cold worked pressure tubes after the same hot service time, Figures 4 and 5. The deuterium concentrations of the KANUPP tubes, both at the ends and in the bulk of the tubes were either similar or lower than observed in cold worked Zr-2.5Nb pressure tubes after the same hot service time, Figures 6 and 7. This is due to the lower operating temperature and also possibly the behaviour of heat treated material compared with cold worked material. The deuterium ingress rates are sufficiently low, that even with some of the tubes having high hydrogen concentrations, none of them should reach TSS at operating temperature in the next 10 calendar years, even in the rolled joint regions.

The second important hydrogen isotope concentration is the blister threshold value. If a pressure tube is in contact with the calandria tube then at the contact it is cooled as the calandria tube is at the moderator temperature and there is a temperature gradient through the wall of the pressure tube. Hydrogen diffuses down a temperature gradient and if the concentration is above the threshold value will precipitate and form a hydride blister. This value depends on the location of the contact along the channel because of the change in temperature of the pressure tube. All KANUPP pressure tubes that had an as fabricated hydrogen concentration greater than 10 ppm now have hydrogen isotope concentrations greater than the threshold values for blister formation.

3.4 Mechanical Properties

In Zr-2.5Nb, the quenching and aging heat treatment produces a higher strength than cold working. The tensile strength of the KANUPP pressure tubes were generally higher than the similar Gentilly 1 heat treated pressure tubes and also higher than cold worked pressure tubes, Figure 8. As expected, irradiation increased the strength of G12, Figure 9 and lowered its ductility, but the % elongation values were still close to the specifications for the as fabricated tubes.

The fracture toughness of G12 was less than average cold worked Zr-2.5Nb pressure tubes but above the lower bound values, Figure 10. The toughness of the KANUPP tubes is low but probably no worse than in many of the cold worked Zr-2.5Nb pressure tubes operating in other CANDU reactors.

The two important properties for DHC are the susceptibility to crack initiation as measured by K_{IH} and the velocity of a growing crack, DHCV. The K_{IH} for G12 was near the lower bound of values for cold worked Zr-2.5Nb pressure tubes, Figure 11. The DHCV values were less anisotropic than those of cold worked tubes, being near the upper bound for cold worked Zr-2.5Nb in the radial direction and near the lower bound in the axial direction, Figure 12. This difference in behaviour is probably due to the difference in the microstructures of the tubes.

The KANUPP pressure tubes have been irradiated to fluences greater than 4×10^{25} n/m^2 and since the changes in mechanical properties in cold worked Zr-2.5Nb due to irradiation damage saturate after fluences of about 10^{25} n/m^2, then by analogy there should be no further change in the mechanical properties of the KANUPP pressure tubes.

4. ASSESSMENT OF THE INTEGRITY OF THE FUEL CHANNELS

4.1 Dimensional Changes

An increase in pressure tube diameter results in a larger proportion of the coolant flowing around the fuel bundles rather than through them. When the increase in inside diameter is above about 4% this can cause Critical Heat Flux (CHF) and Critical Channel Power (CCP) concerns. Hence an increase of 0.8% after 7 EFPY is not a concern and the projected increase to about 1.7% after a further 10 calendar years service is also not a concern.

The allowable increase in the axial length of fuel channels is only of concern with respect to the axial travel of the bearings. The KANUPP end fittings are clamped at their outlet ends and the bearings at the inlet ends are designed for 25 mm of travel. The maximum elongation measured on the channels was less than 5 mm and after a further 10 years service is estimated to increase to about 10 mm. Hence neither of these elongations are of any concern.

In CANDU fuel channels, the pressure tube is supported by the calandria tube. Since the calandria tube operates at a lower temperature than the pressure tube, the increase in sag during service is mostly a function of the sag resistance of the calandria tube. The maximum sag of 23 mm does not cause any concerns and since this reactor does not have any horizontal reactivity mechanism tubes, the estimated sag of 54 mm after a further 10 calendar years service will not cause any problems. Curvature of the channel can eventually cause problems with fuel bundles sliding through the pressure tubes but a sag of 54 mm is not expected to cause any problems.

The other concern is the sag of the pressure tube between supports. In the KANUPP fuel channels, the supports are the bearings on the end fittings and the two garter spring spacers. If there were no garter springs, they were not close to their design location or they were broken, then the pressure tube could sag into contact with the calandria tube. This situation is only of concern if the hydrogen isotope concentration is sufficiently high for hydride blisters to form in the pressure tubes because large blisters can initiate DHC, and this is the case for all the tubes that had initial hydrogen concentrations greater than 10 ppm. Therefore it is important to be sure that the garter springs are present, close to their design locations and not broken. Since the garter springs are made of Inconel they cannot be detected with the eddy current equipment developed for the Zr-Nb-Cu garter spring spacers used in many CANDU reactors. Unfortunately the pressure tube to calandria tube gap measurements and the pressure tube sag profiles could not be used to confirm that the garter springs were intact and close to their design location. However, there is also no evidence to imply that they are not intact and in their design location. The failure of the garter springs in channel G12 was due to the leakage of moderator heavy water through the calandria tube rolled joint into the annulus. Radiolysis of the heavy water produced an acidic environment that caused stress corrosion cracking to occur in the Inconel X750.

4.2 Leak-Before-Break

The concept of LBB is that if a defect is present in a pressure tube and initiates a crack, the crack will grow through the wall and leak PHTS heavy water, the leakage will be detected and the reactor shut down before the crack grows to the critical unstable length and the tube ruptures. The probability of LBB decreases during service (the probability of Break-Before-Leak increases). In new pressure tubes, the hydrogen concentration is below the TSS at operating temperatures, DHC can only occur when the reactor is shut down and then the PHTS pressure is usually reduced which reduces the stress.

During service, deuterium ingress will eventually raise the hydrogen isotope concentration above the TSS, and then if there are any sufficiently large defects present, DHC can occur during reactor operation. The defects could have been introduced during fabrication, be introduced during service if debris is introduced to the PHTS during maintenance, or the defects could be hydride blisters. Irradiation damage increases the susceptibility of the material to DHC (decreases the size of harmful defects) and reduces the toughness and the Critical Crack Length (CCL) of the material. Hence the important parameters are:

- The presence of defects and their size.

- The concentration of hydrogen isotopes due to deuterium ingress.

- The possibility of forming hydride blisters. Pressure tubes in contact with calandria tubes and their hydrogen isotope concentration greater than the blister threshold value.

- The change in susceptibility to DHC (the size of a defect that could initiate DHC).

- The reduction in CCL.

- The capability of detecting small leaks into the annulus gas system.

No defects were detected in the eight tubes inspected. If any defects were present in the main body of any of the other tubes, the defects would have to be greater than 0.4 mm deep and have a very sharp profile before they could initiate DHC. Since the rate of deuterium ingress has been low, none of the tubes should have hydrogen isotope concentrations above TSS at operating temperatures and therefore if any such defects were present, DHC is very unlikely to be able to occur during reactor operation.

However if a crack did initiate and grow during reactor operation then the time 't' to detect the leak and shut the reactor down before the crack grows to the CCL can be calculated by:

$$t = (CCL - L_p)/2V \quad (1)$$

where L_p is the length of the crack that penetrates the wall and V is the axial crack growth velocity.

The CCL of the G12 pressure tube was not measured in any burst tests and a minimum value of 44.7 mm at 245°C was calculated from the small specimen fracture toughness values, (for a pressure of 10.3 MPa). Small fracture toughness specimens give conservative estimates of CCL compared to burst tests. A crack velocity activation energy of Q=55 330 kJ/mol and the maximum axial velocity measured at 130°C were used to estimate the crack velocity at 245°C as 2.4×10^{-7} m/s. The crack penetration length used in LBB analyses in cold worked Zr-2.5Nb pressure tubes with the same 4 mm wall thickness is 20 mm.

Substituting these values into the equation, the time 't' at 245°C (the inlet operating temperature) is 15 h. This is the time available for reactor operators to detect the leaking channel and shut the reactor down. This prediction is conservative because it is based on the worst fracture and DHC properties. If burst tests were done, the CCL would probably be about 20% higher which would increase the time to about 20 hours. Therefore in the event of a crack initiating, to ensure that LBB will occur, the annulus gas leak detection system must be maintained in good condition.

Large hydride blisters can initiate DHC. If there is either a long blister or a series of blisters close together, a long DHC crack can form that grows to the CCL before it grows through the wall and leaks. All pressure tubes that had as fabricated hydrogen concentrations greater than 10 ppm now have hydrogen isotope concentrations greater than the blister threshold value. However we have no evidence that shows that the garter springs are not in good condition and in their design location. If this is correct, contact between the pressure tubes and calandria tubes is not possible and blisters cannot form.

5. CONCLUSIONS

1. The inboard displacement of the South end fitting of fuel channel G12 relative to the neighbouring channels was due to seizing of the inboard bearing. The South end calandria tube rolled joint leaked moderator heavy water into the annulus which resulted in the bearing corroding away and the end fitting seizing in the debris. Both the garter springs probably failed by Stress Corrosion Cracking (SCC) in acids produced by radiolysis of the heavy water and the carbon dioxide annulus gas.

2. The inspection of eight fuel channels and the examination and testing of channel G12 did not detect any serious defects, the dimensional changes in the pressure tubes were small and the deuterium ingress had been low. The mechanical properties are satisfactory and should change little with further service. Hence all the pressure tubes are probably in good condition and suitable for at least a further 5 years service from 1993 and probably a further 10 years service.

3. Due to the low rate of deuterium ingress, DHC should not be able to initiate at any defects during reactor operation. However, if a defect was present in a tube and that tube did have a sufficiently high hydrogen isotope concentration that DHC could occur, the reactor operators should have at least 15 hours to detect the leaking crack from moisture in the annulus and shut the reactor down before the crack grew to the critical length and the tube ruptured (Leak-Before-Break).

4. Many pressure tubes now have sufficiently high hydrogen isotope concentrations that if they contact their calandria tubes, hydride blisters could form. A string of blisters could then initiate DHC and result in pressure tube rupture and Break-Before-Leak. The inspection of the channels was not able to confirm that the garter springs were in their design position and maintaining the pressure tube to calandria tube gap.

TABLE 1: COMPARISON OF KANUPP FUEL CHANNELS WITH OTHER CANDU REACTORS

	KANUPP	NPD	DOUGLAS POINT	PICKERING-A UNITS 1 & 2*	BRUCE-A UNITS 1 & 2	PT. LEPREAU CANDU-6
Gross Electrical Output, MWe	137	25	218	542	815	680
In-Service Date	1971	1962	1967	1971	1977	1983
Shutdown Date	In-service	1987	1984	Re-tubed 1987/88	In-service	In-service
No. of Fuel Channels	208	132	306	390	480	380
Lattice Type	Square	Square	Square			
Lattice Pitch	9.25"	10.25"	9"	11.25"	11.25"	11.25"
No. of Bundles/Channel	11	9	12	12	13	12
Fuel Elements/Bundle	19	19	19	28	37	37
Channel Closure Type	Twist Type	Twist Type	Axial Type	Axial Type	Twist Type	Axial Type
Fuel Latch	Yes	Yes	No	No	Yes	No
PRESSURE TUBE						
Material	HT Zr-2.5Nb	CW Zircaloy-2	CW Zircaloy-2	CW Zircaloy-2	CW Zr-2.5Nb	CW Zr-2.5Nb
ID	3.25"	3.25"	3.25"	4.0"	4.0"	4.0"
Wall Thickness (Min.)	0.160"	0.165"	0.155"	0.195	0.160"	0.164"
Length	208"	164"	211"	248"	249"	
CALANDRIA TUBE						
Material	Zircaloy-2	Aluminum	Zircaloy-2	Zircaloy-2	Zircaloy-2	Zircaloy-2
ID	4.0"	4.0"	4.2"	5.1"	5.1"	5.1"
Wall Thickness	0.050"	0.050"	0.049"	0.061"	0.054"	0.054
GARTER SPRING						
Material	Inconel X750	Inconel X750	HT Zr-Nb-Cu	HT Zr-Nb-Cu	HT Zr-Nb-Cu	HT Zr-Nb-Cu
Type	Snug Fit	Snug Fit	Loose	Loose	Loose	Loose
No./Channel	2	1	2	2	2	4
ANNULUS GAS						
Type	Closed	Open		Closed	Closed	Closed
Gas	CO_2	Air		CO_2	CO_2	CO_2
END FITTING						
RJ Region Material	Inconel	Ty 403 SS	Ty 403 SS	Ty 403 SS	Ty 403 SS	Ty 403 SS
Type of RJ Clearance	Normal		Normal	Normal	Normal	Zero

*Prior to re-tubing
Blanks indicate data not readily available.

TABLE 2: ON-SITE INSPECTIONS PERFORMED BY AECL

Channel	UT	ET	GAP	Sag 6-12 o'clock	Deflect. 3-9 o'clock	Dia.	RJ and Length	Surf. Rough.	Video	Scrape Sample	Photo-graphic OD
F-15 P/T	X		X	X	Y	X	X	X	Y	4	
G-12	X		X	X	Y	X	X	X	Y	4	
F-06		X	X	X		X	X	X		4	
G-08		X	X	X		X	X	X		4	
J-10	Y	X	X	X		X	X	X		6	
G-09		X	X	X		X	X	X		4	
K-09		X	X	X		X	X	X		4	
N-03		X	X	X		X	X	X		4	
G-12 C/T									X		
G-12 N Lattice Tube									X		
G-12 S Lattice Tube									X		
G-12 P/T											X

"X" & "Y" - denote exam performed.
"X" denotes part of original baseline inspection
"Y" denotes addition to original baseline inspection
No. indicates number of scrape samples taken

P/T - Pressure Tube
C/T - Calandria Tube
N - North
S - South

TABLE 3: TEST MATRIX FOR MECHANICAL AND METALLURGICAL TESTS ON MATERIAL FROM THE G12 PRESSURE TUBE

Nominal Test Temp ^{0}C	Tensile		Fracture Toughness		Delayed Hydride Cracking Velocity			K_{IH} Tests
	Trans.	Long.	Trans. (Circum.)	Long. (Axial)	Circum.	Axial	Radial	
30	1	1	1	2	-	-	-	
100	1	1	1	1	-	-	-	
130	-	-	-	-	6	8	5	
200	1	1	1	1	-	-	-	
240	1	1	1	2	-	-	-	
300	1	1	1	2	-	-	-	
Below Solvus Temp	-	-	-	-	-	-	-	7
Totals	5	5	5	8	6	8	5	7

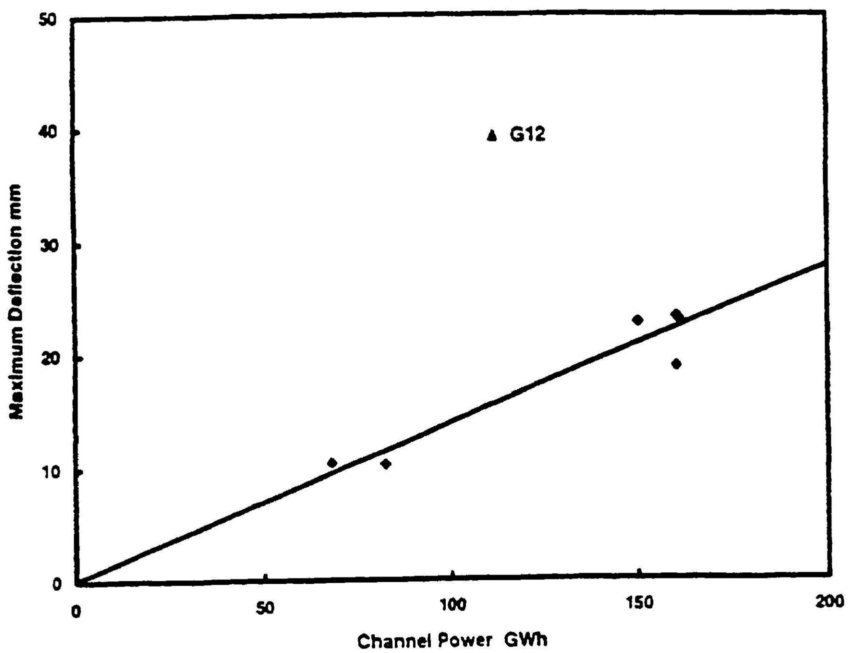

FIGURE 1: MAXIMUM VERTICAL DEFLECTIONS VERSUS TOTAL CHANNEL POWER. LEAST SQUARES LINE DOES NOT INCLUDE G12.

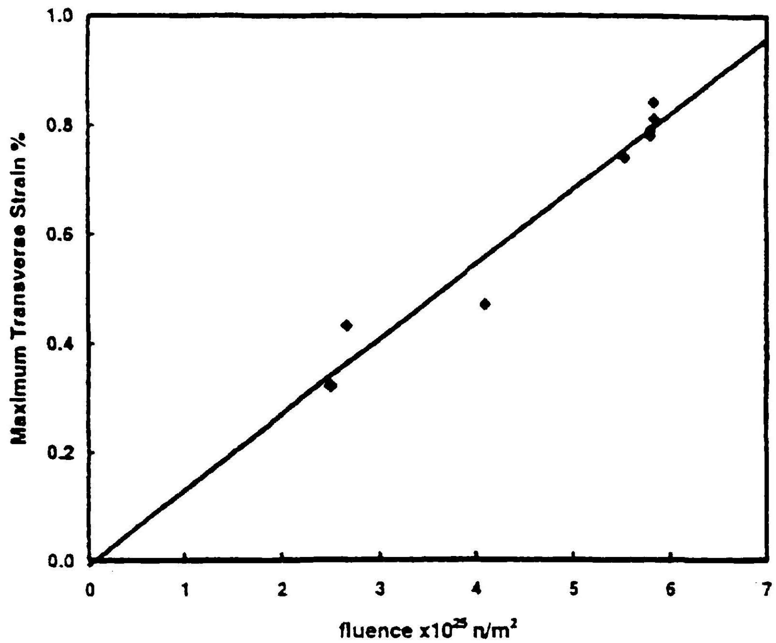

FIGURE 2: MAXIMUM TRANSVERSE STRAIN VERSUS MID-BUNDLE FAST NEUTRON FLUENCE, WITH LEAST SQUARED FIT LINE.

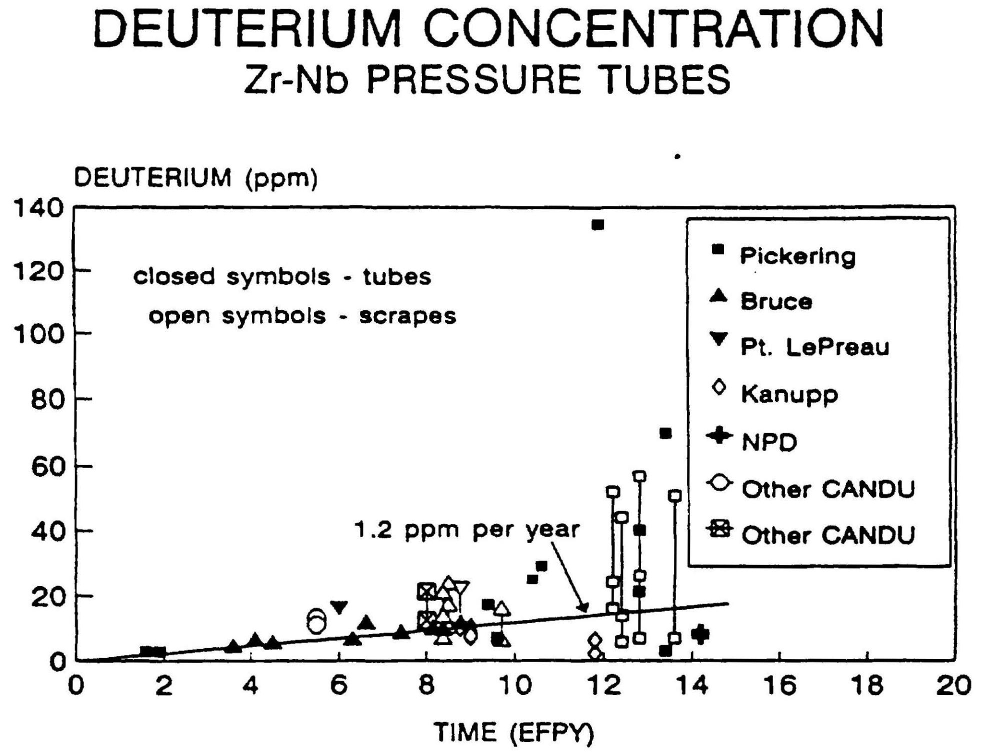

FIGURE 7: COMPARISON OF DEUTERIUM INGRESS IN KANUPP TUBES WITH OTHER Zr-2.5Nb PRESSURE TUBES FROM CANDU REACTORS.

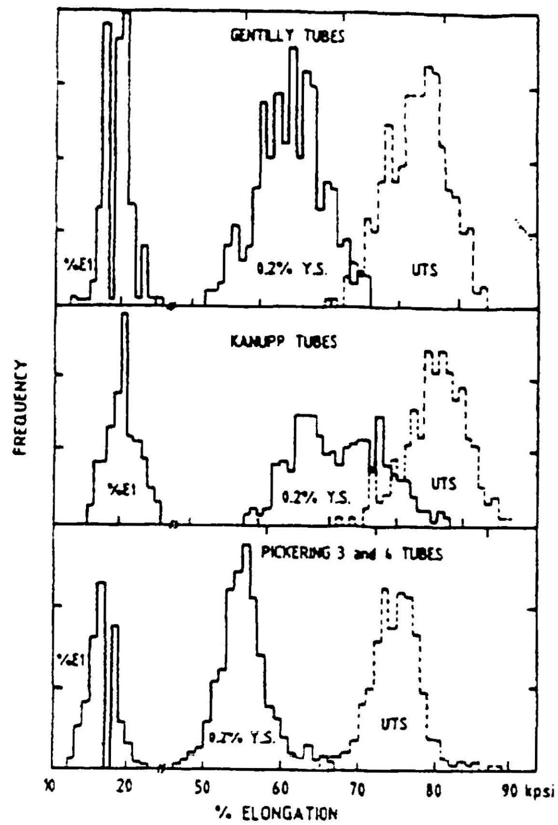

FIGURE 8: THE LONGITUDINAL TENSILE PROPERTIES OF KANUPP, GENTILLY 1 AND PICKERING UNITS 3 AND 4 PRESSURE TUBES.

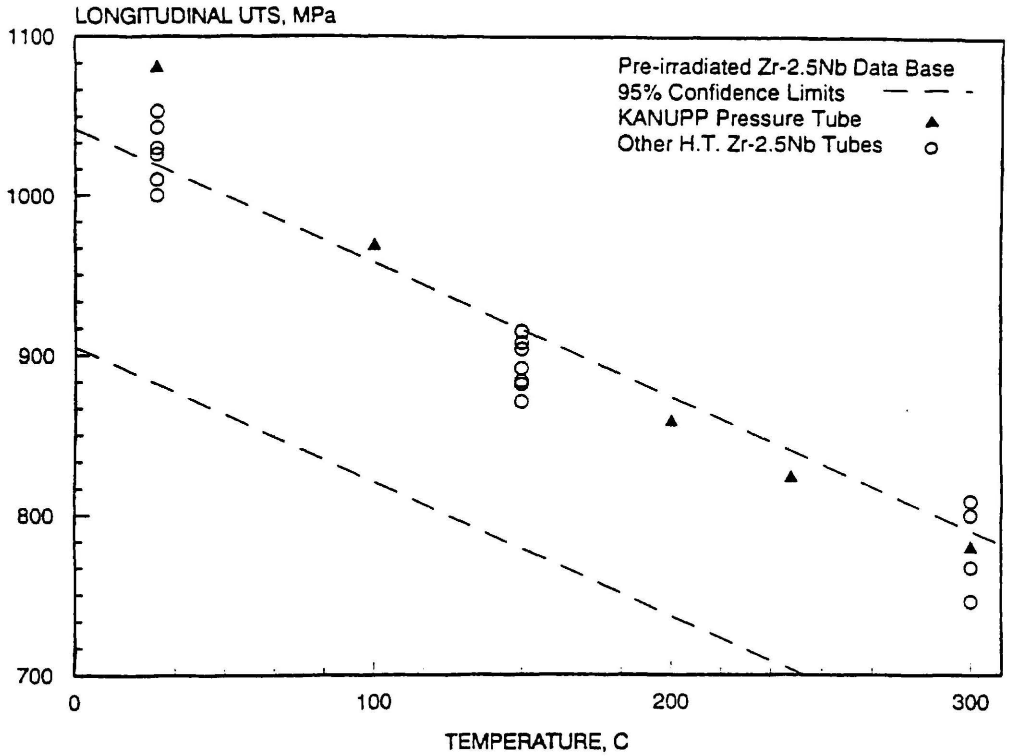

FIGURE 9: LONGITUDINAL TENSILE PROPERTIES OF KANUPP PRESSURE TUBE MATERIAL AS A FUNCTION OF TEMPERATURE COMPARED WITH IRRADIATED COLD-WORKED Zr-2.5Nb AND HEAT-TREATED Zr-2.5Nb MATERIALS.

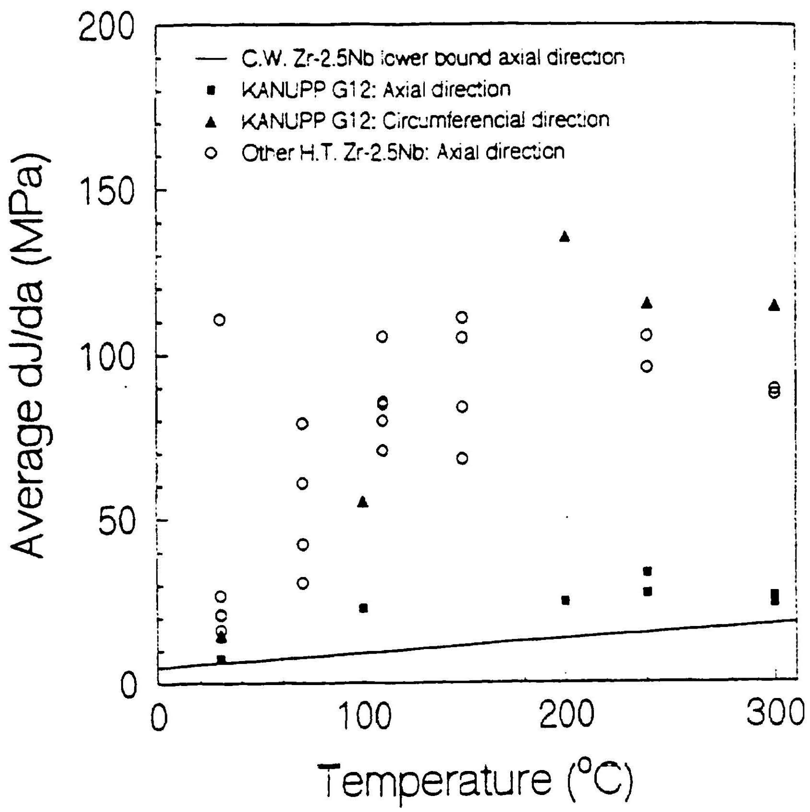

FIGURE 10: FRACTURE TOUGHNESS OF G12 MATERIAL AS A FUNCTION OF TEMPERATURE COMPARED WITH OTHER Zr-2.5Nb MATERIALS.

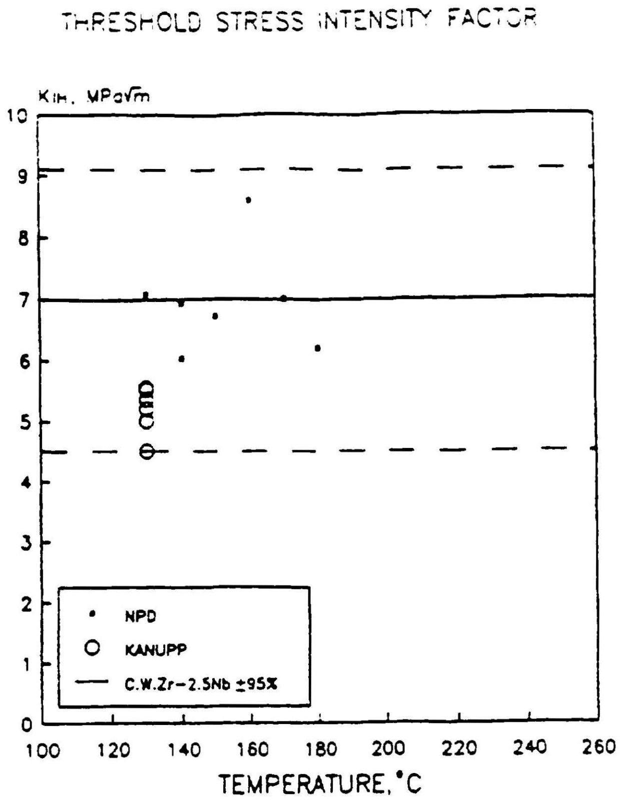

FIGURE 11: COMPARISON BETWEEN K_{IH} IN THE G12 TUBE AND OTHER DATA ON HEAT-TREATED PRESSURE TUBE AND COLD-WORKED Zr-2.5Nb PRESSURE TUBES.

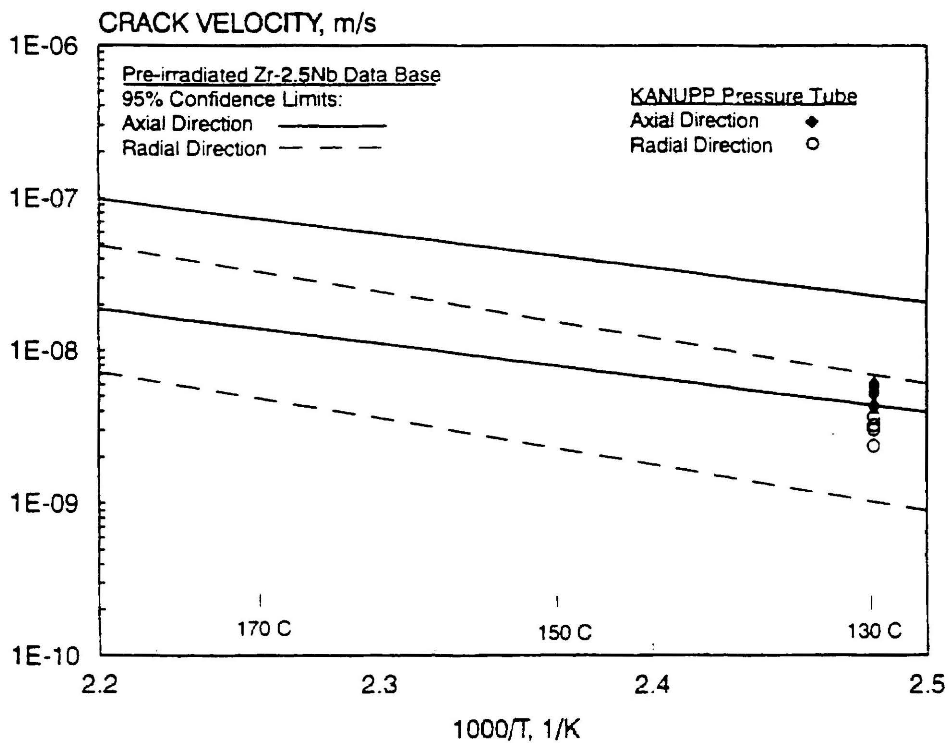

FIGURE 12: COMPARISON BETWEEN THE AXIAL CRACK VELOCITY, OBTAINED AT 130°C, IN THE KANUPP TUBE AND OTHER DATA ON HEAT-TREATED PRESSURE TUBE AND COLD-WORKED Zr-2.5Nb PRESSURE TUBES.