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PLATING END FITTINGS TO REDUCE HYDROGEN INGRESS AT ROLLED JOINTS IN CANDU REACTORS

REVÊTEMENT DES RACCORDS D'EXTRÉMITÉ POUR LA RÉDUCTION DE L'ENTRÉE D'HYDROGÈNE DANS LES JOINTS DUDGEONNÉS ENTRE LES TUBES DE FORCE ET TUYAUX DES RÉACTEURS CANDU

**A.J. WHITE, V.F. URBANIC, A.A. BAHURMUZ, W.R. CLENDENING,
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Presented at the International Conference on Expanded and Rolled Joint Technology
Toronto, Ontario, 1993 September 13-14

Chalk River Laboratories

Laboratoires de Chalk River

Chalk River, Ontario K0J 1J0

October 1993 octobre

AECL Research

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A.J. White[1], V.F. Urbanic[1], A.A. Bahurmuz[1], W.R. Clendening[2],
R. Joynes[1], G.M. McDougall[1], B.C. Skinner[3] and S. Venkatapathi[1]

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[1]AECL Research, Chalk River Laboratories, Chalk River, Ontario, K0J 1J0
[2]AECL CANDU, Sheridan Park Research Community, Mississauga, Ontario, L5K 1B2
[3]AECL Research, Whiteshell Laboratories, Pinawa, Manitoba, R0E 1L0

Fuel Channel Components Branch
Chalk River Laboratories
Chalk River, Ontario, K0J 1J0
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RÉSUMÉ

Les tubes de force d'alliage de Zr-2,5Nb des réacteurs nucléaires CANDU absorbent de l'hydrogène qui est produit à une faible vitesse par l'eau du système caloporteur primaire circulant dans les tubes. L'excédent d'hydrogène est retenu aux joints dudgeonnés entre les tubes de force et les tuyaux d'acier hors coeur. Cette entrée d'excédent d'hydrogène pourrait contribuer à la fissuration des tubes de force aux joints dudgeonnés incorrectement. On a diminué le risque de rupture des tubes de force en assurant la réalisation correcte de joints et on pourrait le diminuer davantage en réduisant l'entrée d'hydrogène dans les joints dudgeonnés. Dans cette communication, on examine l'avancement des recherches vers la réalisation de raccords d'extrémité (embouts) à revêtement pour réduire l'entrée d'hydrogène dans les joints dudgeonnés.

Au cours d'essais ayant pour but de comprendre le mécanisme d'entrée dans les joints dudgeonnés, on a constaté qu'en revêtant de chrome le raccord d'extrémité, au point de contact avec le tube de force, on pouvait réduire l'entrée d'hydrogène. On a donc lancé un programme pour mettre au point des raccords d'extrémité à revêtement à des fins d'utilisation dans les réacteurs CANDU. La mise au point met en jeu plusieurs aspects. On effectue des essais sur des joints à revêtement en grandeur réelle quant à la réduction de l'entrée d'hydrogène et conformité aux critères de conception des réacteurs CANDU. On effectue également des essais quant au rôle du revêtement dans la réduction de l'entrée d'hydrogène et à la réalisation de meilleurs revêtements.

Les résultats obtenus sont encourageants dans le cas des raccords d'extrémité à revêtement de 18 μm de chrome dans la région des joints dudgeonnés. L'entrée d'hydrogène est de 30% à 60% de moins, à court terme, aux joints revêtus de chrome et peut-être de 95% de moins, à long terme, qu'aux joints normaux. En outre, les joints à revêtement peuvent respecter les critères de conception quant à l'étanchéité, à la résistance à l'arrachement et aux contraintes résiduelles. Néanmoins, il faudra apporter d'autres améliorations. On devrait porter le pourcentage de réduction de l'entrée d'hydrogène à 80% pour assurer 30 ans de protection aux tubes de force, à l'endroit des joints dudgeonnés. De plus, certains types de joints pourraient demander une meilleurs étanchéité. On cherche à apporter des améliorations à l'aide d'autres métaux de revêtement et d'autres techniques.

Service des Composants de canaux de combustible
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ABSTRACT

Zr-2.5Nb pressure tubes in CANDU nuclear reactors absorb hydrogen at a low rate from the primary heat transport water circulated through the tubes. Extra hydrogen is picked up at the rolled joints that connect the pressure tubes to out-of-core steel piping. This enhanced ingress may contribute to pressure-tube cracking at incorrectly assembled joints. The risk of pressure-tube failure has been decreased by ensuring correct joint assembly, and could be further decreased by reducing hydrogen ingress at rolled joints. This paper reviews progress toward using plated end fittings to reduce rolled-joint hydrogen ingress.

During experiments designed to understand the mechanism for rolled-joint hydrogen ingress, it was found that chromium plating the end fitting, where it contacted the pressure tube, could reduce hydrogen ingress. As a result, a program was initiated to develop plated end fittings for use in CANDU reactors. There are several aspects to this development. Full-scale plated joints are tested for reduction in rolled-joint hydrogen ingress, and for compliance with CANDU design criteria. Experiments are also conducted to determine the role of plating in reducing ingress, and to develop improved coatings.

Results are promising for end fittings plated in the rolled-joint region with 18 µm of chromium. Hydrogen ingress is between 30% and 60% less at chromium-plated joints in the short term, and possibly more than 95% less in the long term, than at standard joints. Also, plated joints can comply with design criteria for leak tightness, pull-out strength and residual stresses. Nevertheless, there is room for improvement. The benefit of plating should be increased to an 80% reduction in hydrogen ingress to provide 30 years' protection for pressure tubes at rolled joints. In addition, some joint designs may require better leak tightness. Improvements are being sought with alternate plating materials and procedures.

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VALUE AND IMPLICATIONS

Pressure tubes pick up more hydrogen at their ends, where they are rolled into end fittings, than they pick up in the rest of the tube. This extra hydrogen increases the risk of delayed hydride cracking (DHC) at rolled joints. To prevent DHC in pressure tubes we require that hydrides should not be present for the life of the fuel channel. One possible method of reducing hydrogen ingress at rolled joints is to place a chromium layer between the end fitting and the pressure tube. Good progress has been made to develop a coating and distinct benefits have been demonstrated. However, further improvements are needed to achieve a consistent low hydrogen ingress (target of 80% reduction) and to ensure a leak-tight joint.

CEColeman

C.E. Coleman
(Branch Manager)

Fuel Channel Components Branch
Chalk River Laboratories
Chalk River, Ontario K0J 1J0

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1. INTRODUCTION

CANDU (CANada Deuterium Uranium, registered trademark) nuclear power reactors are a pressure-tube design. The reactor core consists of a large calandria filled with heavy-water moderator and penetrated by a lattice of about 400 horizontal fuel channels. Each fuel channel comprises a calandria tube that is separated from a smaller pressure tube by an insulating gas annulus. The natural uranium oxide fuel used in CANDU reactors is assembled into short fuel bundles that are inserted, end to end, into the pressure tubes. During operation, the heat from the fuel bundles is collected by circulating hot, high-pressure heavy water through the pressure tubes.

The in-core reactor components are made from zirconium alloys combining low neutron capture cross-section, high strength and good corrosion resistance. Zircaloy-4 is used to sheath the fuel; the pressure tubes are made from Zr-2.5Nb and the calandria tubes are made from Zircaloy-2. As the pressure tubes are the in-core primary pressure boundary, they are subjected to a severe operating environment. Over time, a pressure tube's material properties change due to a combination of irradiation effects, thermal aging and corrosion. In particular, hydrogen[1] picked up from the primary heat transport water may increase susceptibility to fracture. The cracking process (delayed hydride cracking) requires a crack starter, high tensile stresses and the presence of zirconium hydrides. Consequently, the risk of pressure-tube cracking can be reduced by removing one or more of these three factors.

Outside of the core, where neutron economy is not a concern, heat transport components are typically steel. The primary heat transport piping is made from carbon steel, and 403 stainless-steel end fittings make the transition between the out-of-core piping and the pressure tubes. These end fittings allow access to the fuel channels during on-power fuel maneuvering. The connection between pressure tubes and end fittings is made with rolled joints (Figure 1). These joints must provide a strong and leak-tight connection for the life of a fuel channel. To ensure good performance of the rolled joints, design criteria have been established for leak tightness and pull-out strength (the axial load required to separate the pressure tube and end fitting) [1].

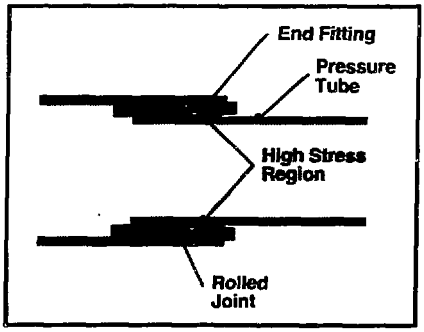

Figure 1: Schematic Diagram of a Rolled Joint

Prevention of pressure-tube failure at rolled joints is also a concern. More hydrogen from

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[1] Hydrogen isotopes will be collectively referred to as hydrogen.

the primary heat transport water is picked up at the rolled joints than is picked up by the rest of the pressure tube [2]. This enhanced ingress has contributed to pressure-tube cracking at incorrectly manufactured joints. As a result of this experience, tensile stresses left in the pressure tube from the rolling procedure are now minimized by ensuring correct joint assembly, and by optimizing the fit between the pressure tube and end fitting. A zero-clearance (ZC) rolled joint, with a fit range of -0.18 mm to +0.05 mm, is used for fuel channels in new reactors. Consequently, the end fitting must be heated for pressure-tube insertion prior to rolling. For replacement fuel channels in existing reactors, where heating the end fitting is not practical, a low-clearance (LC) rolled joint is used, with a fit range of +0.13 mm to +0.26 mm.

Techniques for reducing hydrogen ingress at rolled joints are being pursued to increase protection against pressure-tube failure (see also Cann et al. [3]). This paper describes a promising technique based on chromium plating the region of the end fitting in contact with the pressure tube (Figure 2). Preliminary results that demonstrated feasibility of the technique are outlined, and the program being followed to develop plated end fittings is described.

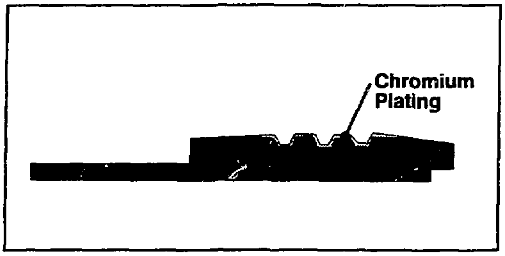

Figure 2: Schematic Diagram Showing Plated Region of the End Fitting

2. PRELIMINARY RESULTS

Rolled joints made with end fitting hubs (a hub is a short length of end fitting material used in rolled-joint tests) plated with 18 μm of chromium, using standard commercial practice, were first tested as part of a program investigating the mechanism for rolled-joint hydrogen ingress (subsequently referred to as "mechanistic tests"). The purpose of the chromium layer was to act as a barrier to hydrogen at the surface of the steel hub. Two quarter- and one full-size rolled-joint assemblies were exposed on an out-reactor water loop. The loop simulated the conditions experienced by a rolled joint in a power reactor without the irradiation.[2] Each assembly had one plated and one unplated end fitting hub.

One quarter-size assembly was removed and destructively examined after 120 days, and the other was removed and destructively examined after 240 days. In both assemblies, hydrogen ingress was less at the plated hub (Table 1). There was, however, only a small benefit (defined as the percentage decrease in ingress at plated

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[2] The radiation fields at rolled joints are small, and should not affect hydrogen ingress.

hubs) of chromium plating in the 240-day test. The full-size assembly was exposed to light water for the first 568 days, and to heavy water for a further 568 days.[3] In contrast to the shorter-term test results, this longer-term test demonstrated a clearer benefit for chromium plating (Table 1). There was little hydrogen uptake at the full-size chromium-plated hub compared with uptake at the unplated hub. The source of the variability in these results is not known.

Table 1: Hydrogen Ingress at Chromium-Plated Rolled Joints

Joint Type	Exposure Time (d)	Hydrogen Uptake (mg of D)		Benefit
		Plated	Unplated	
quarter-size	120	0.2	1.1	80%
quarter-size	240	0.7	0.8	10%
full-size	1136	<0.5*	7.9*	>95%

*The deuterium uptake does not include hydrogen picked up during the first 568 days.

These first results demonstrated that plated end fittings could reduce hydrogen ingress at rolled joints. To further assess their suitability for use in-reactor, three full-size trial joints were made to determine their compliance with design criteria for leak tightness and pull-out strength. Because it is difficult to ensure uniform plating thicknesses, these joints were made with three different thicknesses bracketing the 18 μm used for the mechanistic assemblies.

After fabrication, the helium-leak tightness of all three joints was measured using a standard test [1]. The joints were found to meet the acceptance limit of 2×10^{-5} cm^3/s of helium at atmospheric pressure (Table 2) but one joint was found to have a relatively high leak rate. The pull-out strength of this joint was measured under reactor operating conditions, at a temperature of 300°C and an internal pressure of 10 MPa. The force required to pull out the pressure tube was 650 kN, which is within the range expected for unplated joints (see section 4).

Table 2: Preliminary Leak Rates and Pull-Out Strengths for Plated Joints

Plating Thickness (μm)	Helium Leak Rate (cm^3/s)	Pull-Out Strength (kN)
15	5.4×10^{-10}	-
28	5.9×10^{-6}	650
58	1.6×10^{-10}	-

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[3] The loop was converted to heavy water halfway through the test.

3. DEVELOPMENT PROGRAM

On the basis of the promising preliminary results, a program was initiated to develop plated end fittings for use in CANDU power reactors. The objective is to develop a plated end fitting that reproducibly reduces hydrogen ingress at rolled joints, and that is acceptable for use in a fuel channel. To achieve this objective, full-scale rolled-joint assemblies are being tested for reduction in hydrogen ingress at rolled joints, and for compliance with CANDU fuel-channel design criteria.

Standard chromium plating, 5, 18 and 30 µm thick, is being tested for the first phase of the program. This is the plating used for the mechanistic tests (see section 2) and used on the outboard end of end fittings to minimize wear from contact with feeling machines. Potential improvements in this coating are being sought in subsequent phases.

The hydrogen-ingress tests are performed on an out-reactor loop that circulates heavy water under conditions similar to those in a power reactor fuel channel. Hydrogen ingress at rolled joints is determined from deuterium concentration profiles (Figure 3). These profiles can be generated by destructive sampling, as used for the mechanistic tests, or by non-destructively scrape sampling the pressure tubes [4]. Non-destructive sampling allows joints to be returned to test, to determine the time dependence of hydrogen ingress. Compliance with design criteria is determined by testing full-scale rolled joints (following established test procedures [1]) for helium-leak tightness, pull-out strength and residual tensile stresses in the pressure tube. The test matrix for Phase I is shown in Table 3.

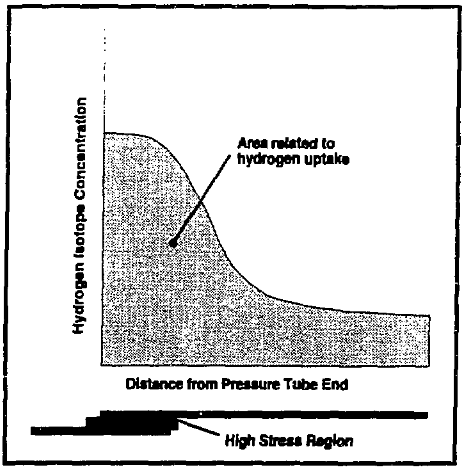

Figure 3: Typical Hydrogen Isotope Distribution at a Rolled Joint

4. PHASE I EXPERIMENTAL RESULTS

Plated joints have acceptable pull-out strength and residual stresses, and the loop tests have shown that plating reduces hydrogen ingress. Improvements in the leak tightness of zero-clearance joints is desirable.

Table 3: Phase I Test Matrix

Joint Type	Plating (µm)	Number of Rolled Joints Tested			
		Residual Stresses	Pull-out Strength	Helium-Leak Rate	Loop Exposure
ZC	none	-	-	4	3
ZC	5	-	-	-	1
ZC	18	1	3	9	3
ZC	30	-	-	-	1
LC	none	-	-	4	3
LC	5	-	-	-	1
LC	18	2	3	7	3
LC	30	-	-	-	1

Chromium plating the end fitting hub does not affect pull-out strength. In Figure 4, the pull-out strengths for chromium-plated rolled joints are compared with the database of unplated rolled joints. The results for plated joints are shifted from a pressure-tube wall thickness of 4.2 mm to 4.0 mm to distinguish them from the other data points. The figure shows that pull-out strength is not affected by the presence of a chromium layer.

Chromium-plated rolled joints also have acceptable residual tensile stresses. In Figure 5, the database for peak residual hoop tensile stress is plotted as a function of the rolled-joint fit (negative values indicate an interference fit), and the data points for chromium-plated joints are amid the scatter. The figure

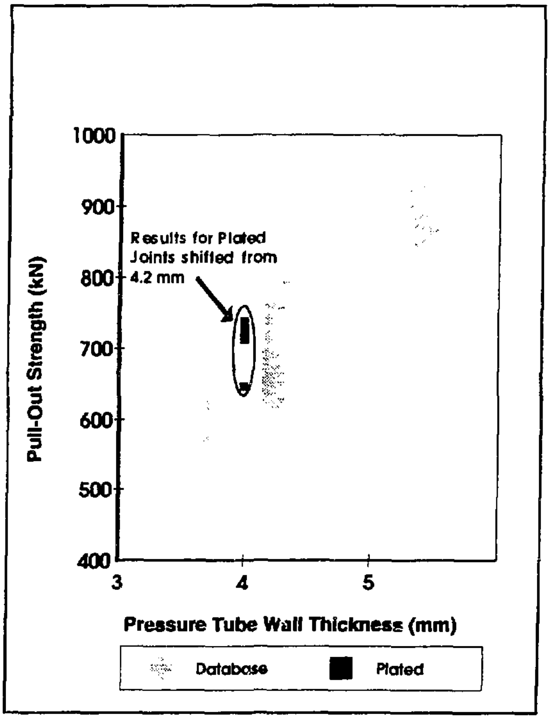

Figure 4: Pull-out Strength Plotted Against Pressure-Tube Wall Thickness

also illustrates the increase in residual stress with rolled-joint clearance, and hence the benefit of zero-clearance joints.

Chromium-plated rolled-joint assemblies have been tested in an out-reactor loop for more than 500 days. These assemblies were non-destructively sampled for deuterium concentration profiles after 108, 220 and 408 days. The hydrogen uptake results showed that less hydrogen is picked up at plated joints, and that plating thickness does not affect uptake. The results are summarized in Table 4. The variability in the benefit of chromium plating is similar to that observed previously (see section 2).

Low-clearance rolled joints made with plated hubs meet the design criterion for helium-leak tightness, but zero-clearance rolled joints tend to have unacceptable leak rates (Table 5). Also summarized in Table 5 are the results for the other compliance tests. The leakage results are discussed further in section 5.

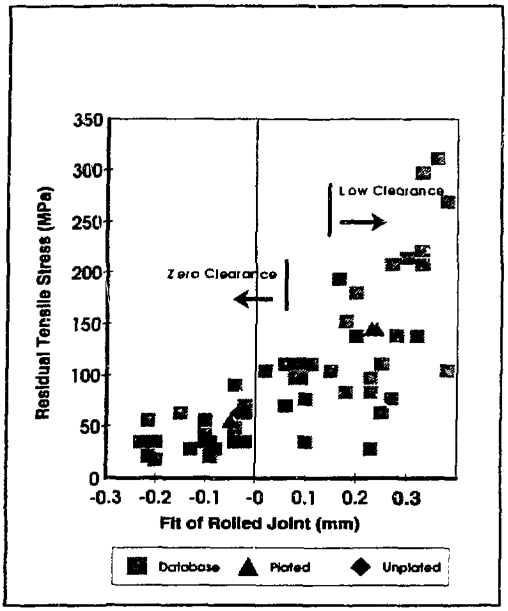

Figure 5: Residual Tensile Stress as a Function of Rolled Joint Fit

5. DISCUSSION

5.1 Hydrogen Ingress

Variability makes the hydrogen ingress results difficult to interpret. The apparent decrease in hydrogen ingress after 220 days (Table 4) is especially puzzling. Since it is unlikely that the pressure tubes actually lost and then regained hydrogen, the method of nondestructively determining the deuterium profiles is suspected as one source of variability in ingress results. Tests are underway to quantify the contribution of the sampling technique to variability.

Notwithstanding the variability and uncertainties in the sampling technique, the results still demonstrate that less deuterium is picked up at plated end fittings. Calculations of the evolution of hydrogen profiles at rolled joints have shown that a benefit of more than 80% reduction in ingress at plated joints is required to provide protection for the lifetime of a pressure tube. As a result, a coating is being sought that will provide a consistently larger benefit. Currently, variations in chromium plating are being loop tested, and other coatings are being investigated for potential future testing.

Table 4: Summary of Phase I Hydrogen Ingress Results

Joint Type	Exposure Time (d)	Hydrogen Uptake (mg)[*]		Benefit
		Plated[†]	Unplated[†]	
ZC	108	7.7 ± 1.7	12.7 ± 0.4	40%
LC	108	5.7 ± 1.1	8.8 ± 1.1	36%
ZC	220	3.8 ± 1.3	8.7 ± 4.6	57%
LC	220	3.4 ± 0.3	5.0 ± 0.2	32%
ZC	408	7.1 ± 2.4	15.4 ± 5.3	54%
LC	408	10.0 ± 2.1	10.8 ± 1.5	7%

[*] Given as an average ± one standard deviation.

[†] Average of five plated or three unplated joints.

Table 5: Compliance of Chromium-Plated Rolled Joints with Design Criteria

Factor	Joint Type	Plated?	Test Results (# of tests)	
			Acceptable	Unacceptable
Residual Stress	ZC	yes	1	
Residual Stress	LC	yes	2	
Pull-out Strength	ZC	yes	3	
Pull-out Strength	LC	yes	3	
Leak Tightness	ZC	yes		9
Leak Tightness	ZC	no	2	2
Leak Tightness	LC	yes	6	1[*]
Leak Tightness	LC	no	4	

[*] Leak rate of 2.2×10^{-5} cm^3/s compared with the acceptance limit of 2.0×10^{-5} cm^3/s.

5.2 Leakage at Plated Rolled Joints

In our tests, zero-clearance joints tend to have higher helium leak rates than low-clearance joints, and chromium plating increases the likelihood of exceeding the acceptance limit for helium-leak rate. The reason for higher leak rates at unplated zero-clearance joints is not fully understood, but one contributing factor is believed to be a non-standard heat treatment used in the manufacture of the test assemblies. For the plated zero-clearance joints, inserting the pressure tube appears to create long axial cracks in the chromium layer that could act as leak paths. Therefore, a thinner layer that is less prone to cracking may result in a more leak-tight joint.

The water leak rate of the loop test joints is being monitored to gain data on the relationship between helium and water leak rate. Some of the initial water leak rates were about 100 mg/h for joints that had helium leak rates above 10^{-4} cm^3/s. The water leak rates of all joints decreased with time. After 5000 h of operation, the water leak rates were between 0.1 and 1 mg/h, independent of helium leak rate (Figure 6). Therefore, water leak paths in a rolled joint may seal early in life.

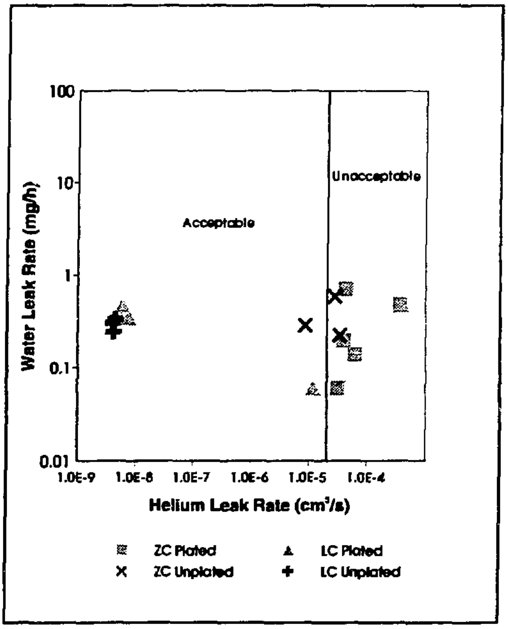

Figure 6: Water Leakage of Loop Test Joints Plotted Against Initial Helium Leak Rate

6. CONCLUSIONS

Chromium plating the end fitting hub is a promising technique for decreasing the amount of hydrogen picked up by the pressure tube at the rolled joints in CANDU fuel channels. Improvements in the coating are being sought to ensure that coated rolled joints meet design criteria for use in a reactor, and to gain a consistently greater reduction in hydrogen ingress.

7. ACKNOWLEDGEMENTS

The work reported in this paper was supported by the CANDU Owners Group. The authors would also like to thank their many colleagues who have contributed to this program.

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Cat. No. CC2-10965E
ISBN 0-660-15384-X
ISSN 0067-0367

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