DEVELOPMENT OF FLUSH ROLLED JOINTS FOR BRUCE NGS A LSFCR* PROGRAM

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ABSTRACT

Current rolled joint design and fabrication procedures produce a step change (burnish mark) in the inside diameter of the pressure tube inboard of the rolled joint. This can result in abnormal fuel support at the inlet rolled joint of a Bruce-type (with fuel latch-type fuel changing process) fuel channel. It has been recommended that the burnish mark step be reduced between the rolled and unrolled regions of the pressure tube for inlet rolled joints.

The flush rolled joint concept involves the use of a pressure tube with a thick end, achieved by decreasing the inside diameter. Dimensions of the thick end are chosen so that when rolled into the inlet end fitting, the rolled joint bore will be flush with the unrolled region of the pressure tube.

This paper details the program to develop and qualify the flush rolled joint design for installation in a commercial power reactor. Specific attention has been given to the material properties of the thick-ended pressure tube, the geometry of the inside surface of the pressure tube at the rolled joint, pressure tube residual stresses in the roll expanded region, pullout strength, and helium leak rate across the rolled joint.

The above results are evaluated using the database on CANDU pressure-tube-to-end-fitting rolled joints as the frame of reference.

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* LARGE SCALE FUEL CHANNEL REPLACEMENT

INTRODUCTION

Current rolled joint design and fabrication procedures produce a step change in the inside diameter of the pressure tube inboard of the rolled joint (burnish mark). This can result in abnormal fuel support at the inlet rolled joint of the fuel channel. It has been recommended that the burnish mark step between the rolled and unrolled regions of the pressure tube for inlet rolled joints be reduced (Figure 1).

The "flush" rolled joint concept involves the use of a pressure tube with a thick end, achieved by decreasing the inside diameter. Dimensions of the thick end are chosen so that when rolled into the inlet end fitting, the rolled joint bore diameter of the pressure tube will be flush with the unrolled inboard region of the pressure tube.

PROOF-OF-PRINCIPLE TESTS

To evaluate the flush rolled joint concept, three rolled joints were fabricated.

For expediency, standard (4.19 mm (0.165") nominal thickness) uniform wall pressure tube spool pieces were used. The thick end of the pressure tube was achieved by machining the spool pieces. The inside diameter of the pressure tube in the machined region (representing the unrolled body of the pressure tube) was made equal to the required rolled joint bore diameter with 13.5% nominal wall reduction at the thick end.

The three rolled joints were fabricated with the apparent wall reductions at the nominal value and the two extremes of the specified range, 13.5% ± 1.5%

Evaluation of the feasibility test results showed that the transition between the rolled and unrolled regions of the pressure tube was as smooth as the rolled region of the pressure tube (with typical surface undulations at the end fitting lands and grooves in the rolled region). The rolled joints had low helium leak rates during the soak-type helium leak tests.

FLUSH ROLLED JOINT QUALIFICATION PROGRAM

Based on the encouraging results of the proof-of-principle tests, a comprehensive test program was undertaken to qualify the flush rolled joint design for power reactor installation.

The qualification program consisted of:

(1) Tests to qualify pressure tubes.
(2) Tests to qualify the inlet flush rolled joint design (rolled joint bore geometry, residual stress evaluation and hot pressurized pullout strength).
(3) Development of production nondestructive examination (NDE) techniques to inspect the inlet end (thick end and the transition) of the pressure tube.
(4) Measurement of the as-manufactured residual stress distribution at the thick end and the transition of the pressure tube, using the neutron diffraction technique.

The Qualification of Thick-Ended Pressure Tube Manufacture

The pressure tube manufacturing qualification program was divided into two phases:

Phase 1 Demonstrate the feasibility of production and NDE of the pressure tube to the specified dimensional requirements.

Phase 2 Manufacture, inspection and testing of pressure tube spool pieces for the pressure tube and rolled joint qualification program.

Phase 1 - Demonstration of production feasibility. The geometry at the inlet end of the pressure tube is different from that of all the pressure tubes previously manufactured by the qualified supplier of pressure tubes. The manufacturing plan and dimensions of the pressure tube had to be changed from that used for producing conventional pressure tubes. The change in the geometry of the pressure tube required modifications to the procedures and the hardware for ultrasonic and eddy current inspections.

Phase 1 of the pressure tube production program evaluated the feasibility of the manufacturing process to produce pressure tubes to specified dimensional requirements. The manufacturing process was also optimized during Phase 1. Procedures for NDE of the transition zone in the pressure tube were also developed. The NDE hardware and procedure modification were implemented.

In order to ensure that the manufacturing and inspection processes were repeatable, a sufficient quantity of samples (6) were manufactured.

Phase 2 - Production of test spool pieces for the qualification program. The objective of Phase 2 was to manufacture pressure tube spool pieces for the following:

(1) Qualification of thick-ended pressure tubes for use in power reactors.
(2) Qualification of the flush rolled joint design for use in power reactors.

The pressure tube spool pieces were made to be representative of reactor-grade pressure tubes. They were inspected and tested by the supplier to the technical specifications and drawings used for the manufacture of pressure tubes for reactor installation.

Pressure Tube Properties

The pressure tube spool pieces, including the thick end and the transition zone, were fabricated using the standard cold-drawing process.

Residual stress measurement - as-manufactured pressure tube. The residual stress distribution in as-manufactured pressure tubes was measured using the neutron diffraction technique. The highest magnitude of the residual stresses (130 MPa compressive) was found to be in the hoop direction occurring near the centre of the thick-thin transition.

Mechanical properties. In accordance with the governing specifications, the hardness of the pressure tube spool pieces was measured by the supplier, using the hardness rings from the 4.95 mm (0.195") thick end and the 4.19 mm (0.165") thick end of all the spool pieces covered by Phase 2.

The pressure tube manufacturer performed longitudinal tensile tests at 300°C on all the spool pieces covered by Phase 2, in accordance with the specifications. The tests were performed on the offcuts taken from both ends of each pressure tube spool piece. The ultimate tensile strength, 0.2% offset yield strength and percent elongation were reported. The results did not exhibit any anomalous behaviour.

In addition, axial tensile tests at room temperature were performed at AECL CANDU on samples taken from the tensile offcuts from the thick and thin ends of four pressure tube spool pieces. The results showed that the thick and thin ends of the pressure tube behaved as expected.

The transverse tensile tests, needed for fracture toughness assessment, were performed at room temperature by AECL. The specimens were taken from the tensile test offcuts from the thick and thin ends from four pressure tube spool pieces.

The results were similar to those obtained for the conventional uniform-wall pressure tubes.

Chemical composition. The supplier of Zr-Nb pressure tube ingots performed chemical analyses on all the ingots used to manufacture the billets used for the pressure tube spool pieces in the development program. The results, along with ingot and billet NDE results, were reported in the ingot test reports. The results met the technical specifications.

Chemical check analyses per the technical specification were done on an offcut from one pressure tube from each ingot.

Corrosion tests - specification tests. The corrosion tests, in accordance with the technical specifications, were performed by the supplier on the samples taken from the thick and thin end of each pressure tube spool covered in Phase 2. The results at the thick end and the body of the pressure tubes met the specifications.

Long-term corrosion properties. In addition to the corrosion tests performed by the supplier, long-term autoclave corrosion tests were performed on samples taken from the offcuts from the thick and thin ends of four pressure tubes. The results were similar to those of standard pressure tubes.

Delayed hydride cracking (DHC) properties. DHC tests were performed on sections taken from the thick and thin ends of four pressure tube spool pieces. The K_{IH}, and DHC velocity were measured for each sample. The results indicated that the DHC behaviour of the thick-ended pressure tubes was similar to that of standard pressure tubes.

Fracture toughness tests at 250°C were performed on samples taken from the thick and thin ends of four pressure tube spool piece sections. The thick end of the pressure tube had slightly higher fracture toughness, as expected, since the thick end had been subjected to a lower cold-work than the body of the pressure tube. Fracture toughness values were similar to those found in current pressure tubes.

Hydride reorientation tests were done on samples from the thick and thin ends taken from four pressure spool pieces. The hydride orientation behaviour was as expected for a pressure tube with a lower cold-work at the thick end.

Microstructure. Texture measurements were done on samples from the thick and thin ends of four spool pieces. The data did not show any significant difference between the thick end and the body of the pressure tube. The results were similar to those of conventional pressure tubes.

Rolled joint hydride distribution. One low-clearance rolled flush joint was hydrided and heated to operating conditions to allow the hydrogen to diffuse. The joint was sectioned and examined for hydride distribution. The hydride reorientation behaviour was similar to that seen in conventional pressure tubes.

Rolled Joint Development Tests

The rolled joint development tests included:

(1) Axial profiles of the inside surface of the rolled region, transition ("burnish mark") and unrolled body of the pressure tube.
(2) Measurement of residual stresses in the pressure tube (after roll expansion) using the strain gauging and slitting technique.
(3) Measurement of pullout strength at the design temperature and internal pressure. The rolled joints were subjected to the standard temperature soak and cycle and helium leak test prior to the pullout test.
(4) Fabrication of double-ended rolled joint assemblies for long-term loop tests.
(5) Fabrication of one double-ended assembly for the rolled joint hydride distribution test.

Test Matrix

Table 1 shows the recommended test matrix for residual stress evaluation.

The matrix includes:

(1) The inlet (flush) Zero Clearance Rolled Joint (ZCRJ), to be used at the first end of the fuel channel (and roll-expanded in the component building).
(2) The inlet (flush) Low Clearance Rolled Joint (LCRJ), to be used at the second end of the fuel channel (and roll-expanded at the reactor face).

The extreme inboard and outboard axial locations of the transition between the thick end and the body of the pressure tube were included as test variables for the LCRJs (which are the in-reactor rolled joints where the calandria condition will affect the pressure tube axial location in the roll-expanded region). Twenty-four single-ended rolled joints were fabricated and strain gauged.

Table 1 Residual Stress Evaluation - Test Matrix					
Location of Pressure Tube Transition Before Rolling		Number of Joints			
		Extreme Outboard		Extreme Inboard	
Required Rolled Joint Bore Diameter (mm)		103.66	103.76	103.66	103.76
Average Diametral Fit (mm)	0.25 Clearance (LCRJ)	2	2	2	2
	0.13 Clearance (LCRJ)	2	2	2	2
	0.05 Clearance (ZCRJ)	2	2	-	-
	0.18 Interference (ZCRJ)	2	2	-	-

Four rolled joint assemblies, per Table 2, were fabricated for pullout strength evaluation. The assemblies had an inlet rolled joint at one end and a dummy rolled joint (for installation in the pullout test rig) at the second end.

Table 2 Pullout Strength Evaluation - Test Matrix			
		Number of Joints	
Required Rolled Joint Bore Diameter (mm)		103.66	103.76
Average Diametral Fit (mm)	0.25 Clearance	1	1
	0.18 Interference	1	1

In addition, two double-ended rolled joint assemblies were fabricated for long-term loop testing. Each assembly had an inlet rolled joint at one end and a low clearance dummy rolled joint at the other end, to facilitate installation in the loop. One assembly had an inlet (flush) LCRJ and the other had an inlet (flush) ZCRJ.

Also, one double-ended assembly, with a low clearance inlet (flush) rolled joint at one end and a low clearance dummy rolled joint at the other end, was fabricated for the rolled joint hydride distribution test.

Rolled Joint Components

Pressure tube spool pieces. Spool pieces for the pressure tube representing the inlet end geometry, transition zone and body were fabricated to the dimensional requirements of the LCRJ and ZCRJ, respectively (Figures 2 and 3). The pressure tube spool pieces were manufactured and inspected according to the governing technical specifications.

End fitting hubs. The geometry of the end fitting hub is shown in Figure 4. The end fitting hubs were fabricated by the qualified supplier of end fittings for CANDU commercial power reactors. The end fitting hubs were manufactured and inspected according to the governing technical specifications.

Rolled Joint Evaluation Tests

Axial profile of the rolled joints. The axial profile of the rolled joint bores, covering rolled and neighbouring unrolled regions of the pressure tube, was plotted at six circumferential locations, 60° apart.

Helium leak tests. All rolled joints were subjected to a soak-type equilibrium helium leak test in the as-rolled condition. In addition, the rolled joint assemblies to be pull tested were subjected to an identical helium leak test after the standard temperature soak and cycle thermal treatment.

Rolled joint defect detection examinations. After the helium leak test in the as-rolled condition, the rolled joints were inspected using ultrasonic and eddy current techniques, to ensure that there were no lap indications on the inside surface.

The defect standards were made using spool pieces taken from a 4.95 mm (0.195") thick pressure tube manufactured for tool proving and crew training during Pickering NGS A, Unit 1 and 2 LSFCRP. The spools were machined to have abrupt steps of varying severity in the inside diameter, and were roll expanded into a hub. The resulting intentional laps were used as defect standards. After characterizing of these defects using NDE, axial strips of the pressure tubes were removed from the joints. The dimensions of the intentional defects were established by metallographic examination of these axial strips.

Axial strips from the strain-gauged rolled joints were also subjected to a metallographic examination, to confirm the results of NDE.

Pressure tube residual stress evaluation (as-rolled condition). Twenty four single-ended rolled joints were fabricated. The residual stresses were measured by the strain gauge and slitting technique.

The following process flow outline was used:

1. Perform dimensional receiving inspection and hardness measurements of pressure tube spools and hubs.
2. Profile the hub groove geometry.
3. Profile the pressure tube transition and concentricity before rolling.
4. Trim the pressure tube to achieve the required location of the interface between the thick end and the transition in the pressure tube before rolling. Prepare the ends.
5. Align and insert the pressure tube.
6. Roll expand and measure the spring back, extrusions, twist and outside diameter growth at the rolled joint and at the location of the inboard journal ring.
7. Profile the rolled joint inside surface.
8. Perform a helium leak test (soak-type equilibrium leak test).
9. Perform NDE of the pressure tube at the transition between the rolled and unrolled regions.
10. Install strain gauges, slit, measure strains and calculate residual stresses.
11. Profile hub grooves for groove deformation.
12. Measure pressure tube thicknesses in the rolled region, to calculate ridge height and actual wall reduction. Profile the pressure tube outside surface at the roll-expanded zone for ridge profile and oxide condition.
13. Perform metallographic examination of the axial strips.

Pullout strength evaluation. Rolled joints for the pullout strength evaluation were fabricated and tested using the following process flow outline:

1. Perform dimensional receiving inspection and hardness measurements of pressure tube spools and hubs.
2. Profile the hub groove geometry.
3. Profile the pressure tube transition and concentricity before rolling.
4. Trim the pressure tube to achieve the required location of the interface between the thick end and the transition in the pressure tube before rolling. Prepare the ends.
5. Align and insert the pressure tube.

6. Roll expand and measure the spring back, extrusions, twist and hub growth. Roll expand the dummy end.
7. Profile the rolled joint inside surface.
8. Perform a helium leak test (soak-type equilibrium leak test).
9. Perform NDE of the rolled joint.
10. Perform a temperature soak and cycle. (The assemblies were cycled 5 times between 300°C and 100°C. The joints were held at 300°C for a minimum of 100 hours.)
11. Perform a helium leak test (soak-type equilibrium helium leak test).
12. Perform a hot pressurized pullout test (temperature: 300°C; internal pressure: 11 MPa (1600 psi) gauge).

Test Results

Rolled joint profiles. The inside surfaces of all flush rolled joints were profiled. A typical axial profile is shown in Figure 5. The figure also shows an axial profile from a conventional rolled joint for comparison.

As shown in Figure 5, the inside surface variations in the flush rolled joint are negligible compared to those in the standard CANDU 6 rolled joints.

Helium leak test results. The equilibrium helium leak rates across the flush rolled joints, in the as-rolled condition and after the temperature soak and cycle thermal treatment, were extremely low (i.e., in the 10^{-9} atmospheric cm^3 per second Helium range).

Pullout strength. The rolled joints were subjected to a hot pressurized pullout test at 300°C, with an internal (nitrogen) pressure of 11 MPa (1600 psi) gauge.

Figure 6 compares the results of hot pressurized pullout tests of flush rolled joints with those from various rolled joint development programs. The pullout strength of the flush rolled joint conforms to the trend observed in standard CANDU 6 rolled joints.

Pressure tube residual stresses in the rolled joints. The maximum tensile residual hoop stress at the inside surface of the pressure tube of the flush rolled joints is compared with those of the conventional under-extended rolled joints in Figure 7. The maximum tensile residual hoop stress at the inside surface of flush rolled joints is in the same range as that measured in conventional under-extended rolled joints.

NDE of the pressure tube in the rolled joint. All rolled joints were subjected to an eddy current examination.

Five rolled joints, chosen at random, were examined using ultrasonic techniques.

The NDE did not reveal any relevant unacceptable indications.

Selected rolled joints were subjected to a dye penetrant examination. No relevant indications were identified.

An axial strip from each strain-gauged rolled joint was subjected to a metallographic examination. No flaws were found in any of the sections.

CONCLUSIONS

The results of the development program show that the pressure tube and the flush rolled joint meet the requirements for installation in the fuel channels in a commercial power reactor. The design is being recommended for implementation during the large-scale fuel channel replacement program at Bruce NGS A.

ACKNOWLEDGEMENTS

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This paper is dedicated to the memory of P.G. Beston, one of the pioneers in the application of roll expanded joints in CANDU commercial power reactors.

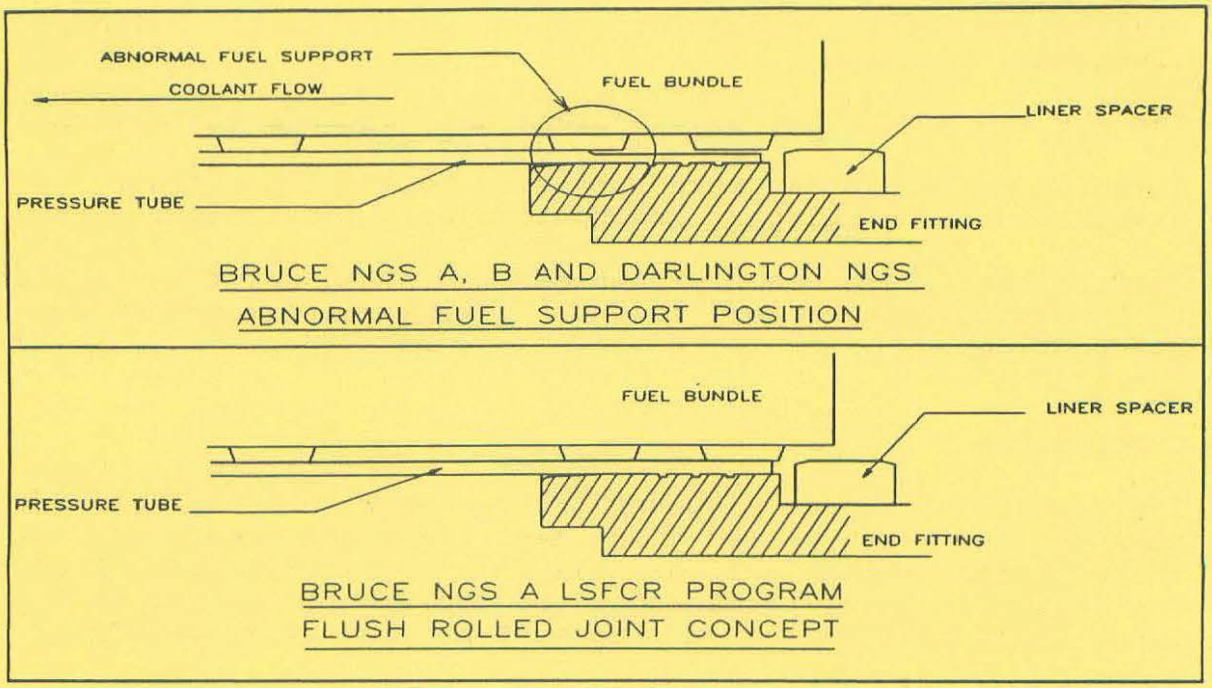

Figure 1: Abnormal Fuel Support and Flush Rolled Joint Concept

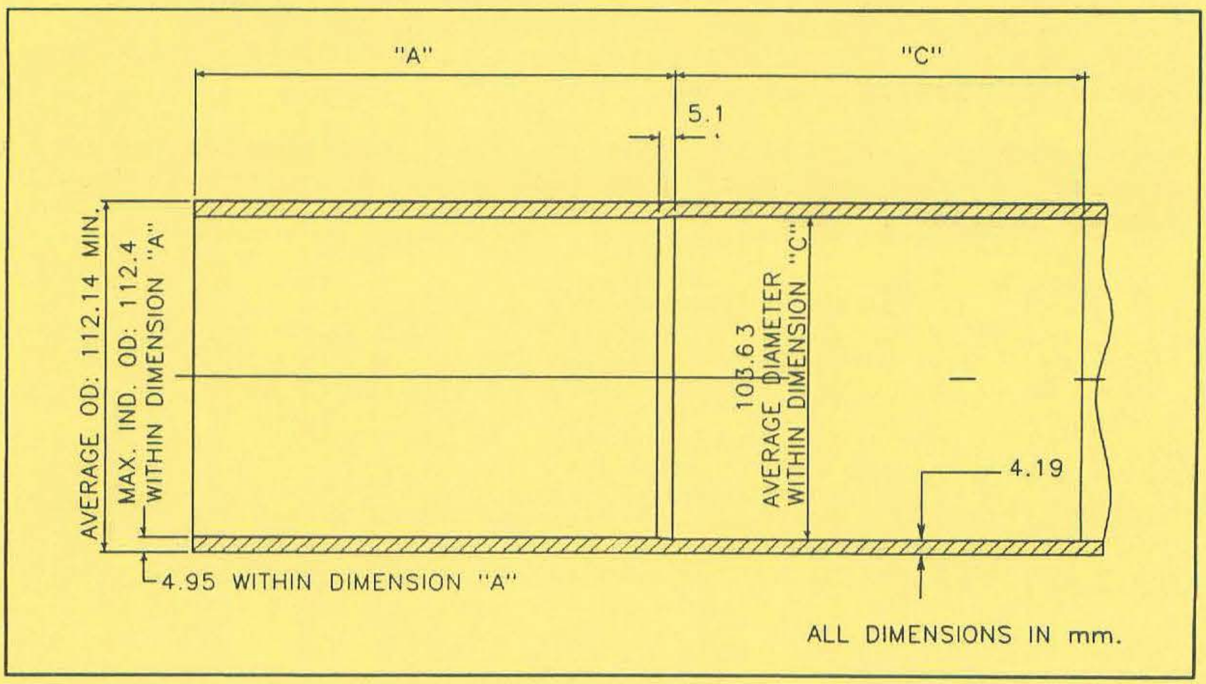

Figure 2: Pressure Tube Geometry - Spools for LCRJ Fabrication

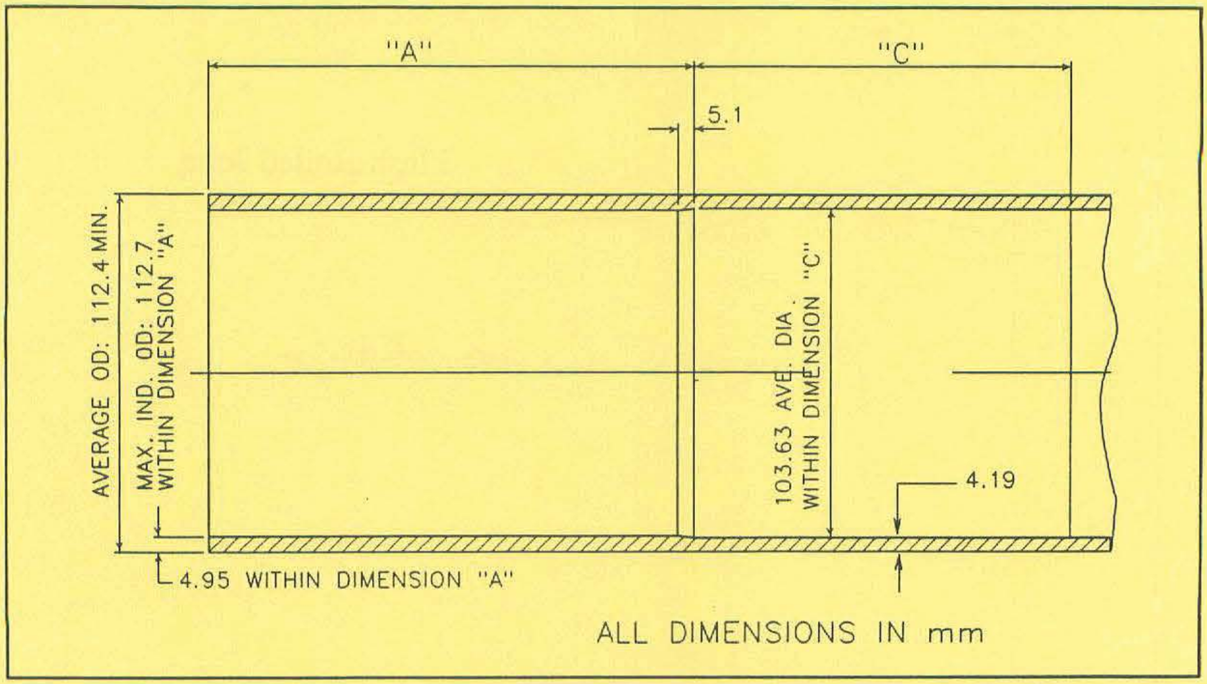

Figure 3: Pressure Tube Geometry - Spools for ZCRJ Fabrication

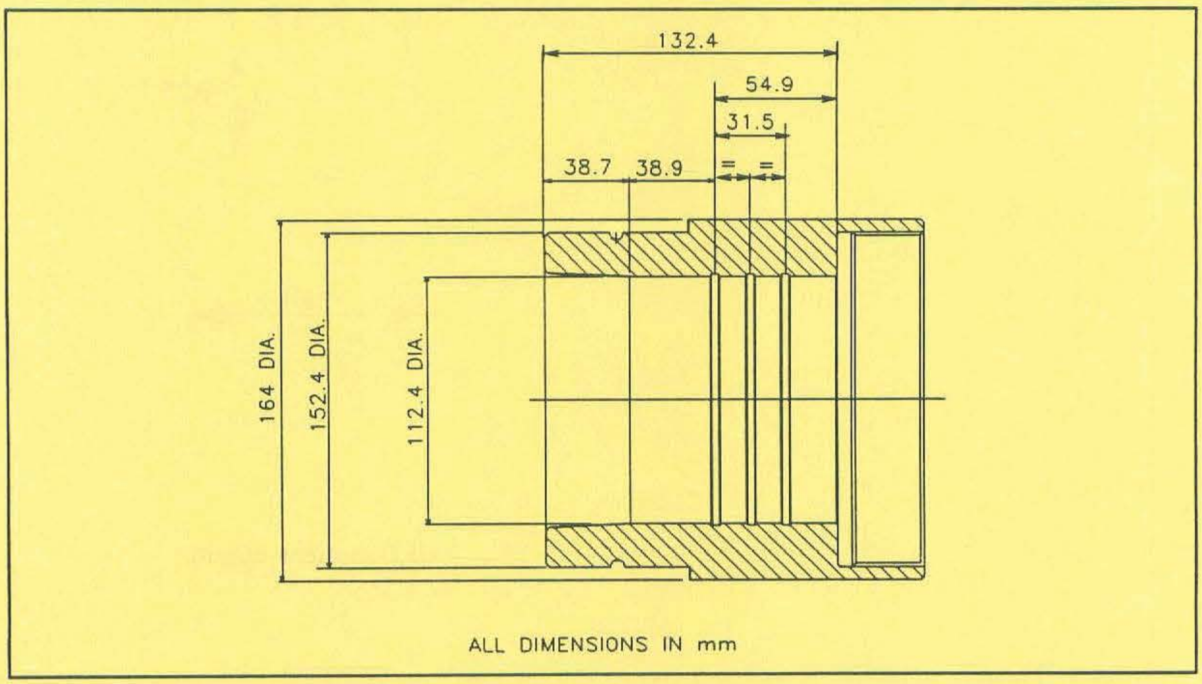

Figure 4: End Fitting Hub Geometry

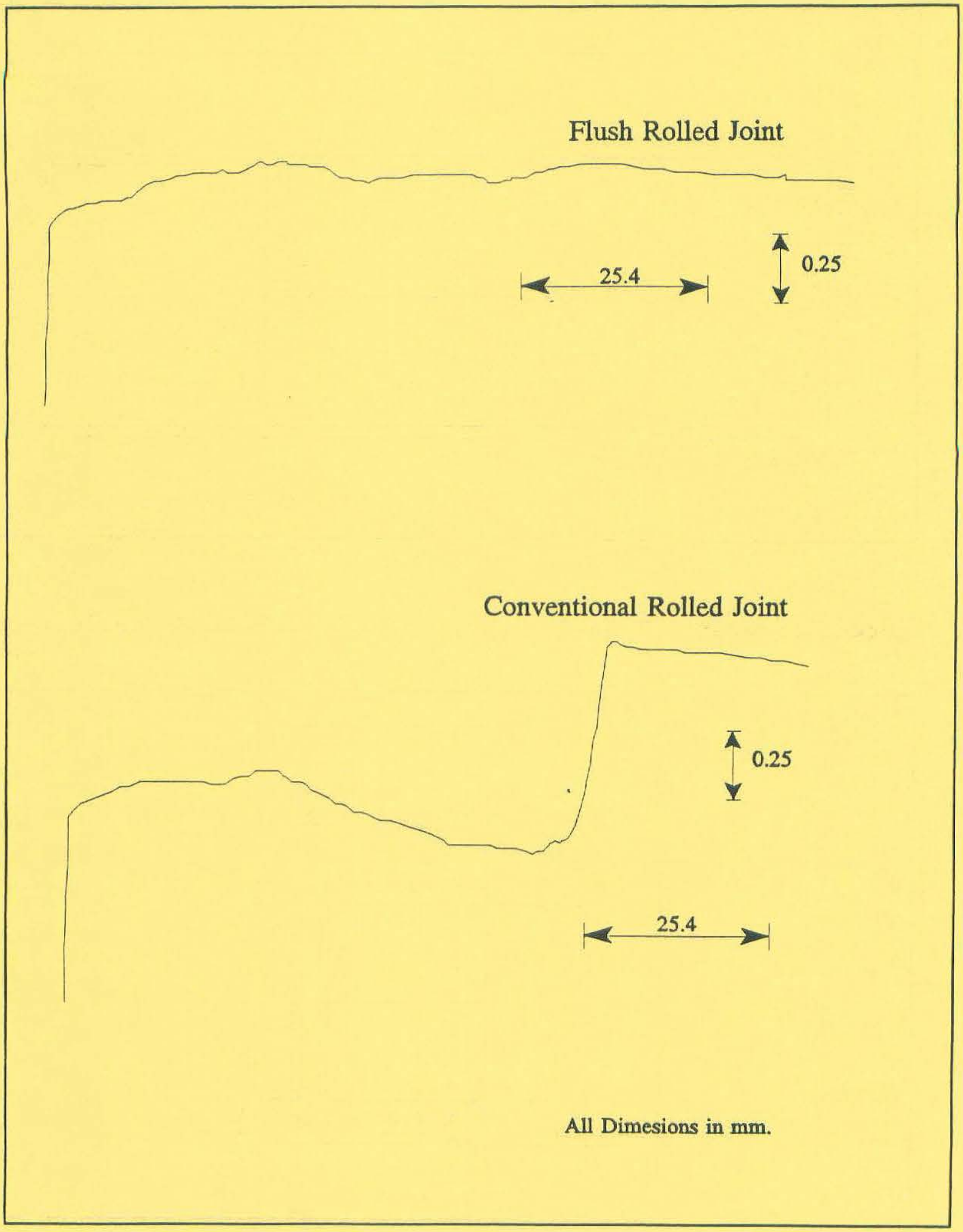

Figure 5: Axial Profiles of the Rolled Joint Regions

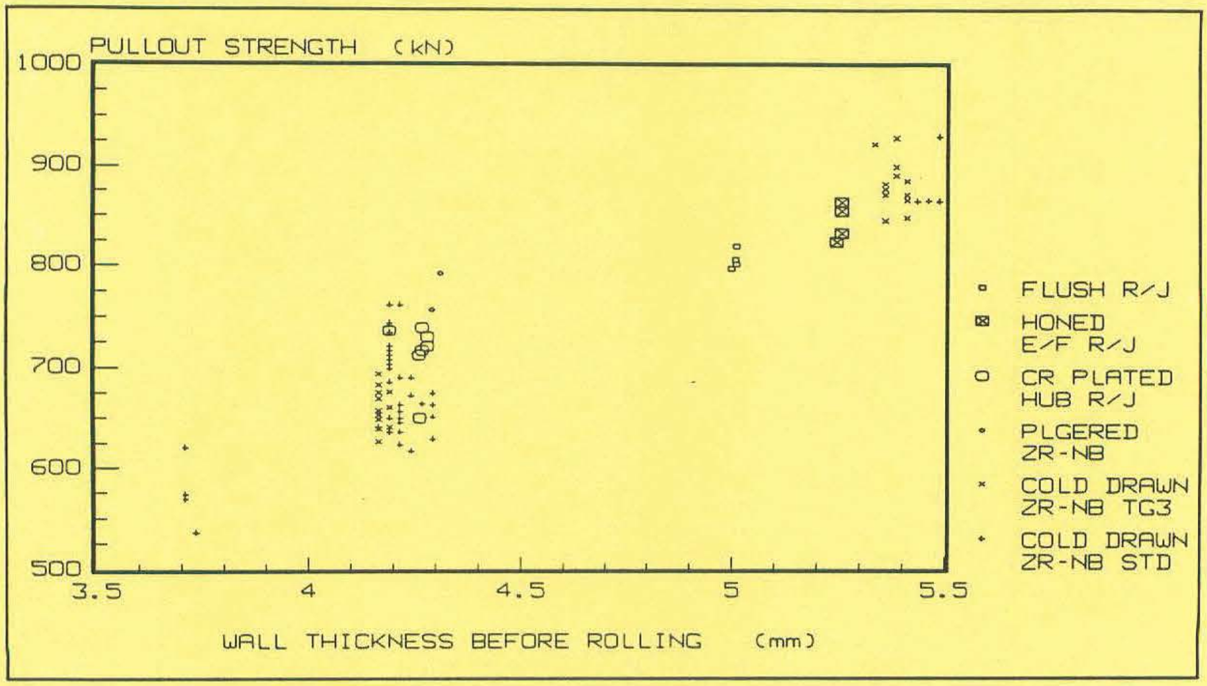

Figure 6: Hot Pressurized Pullout Test Results

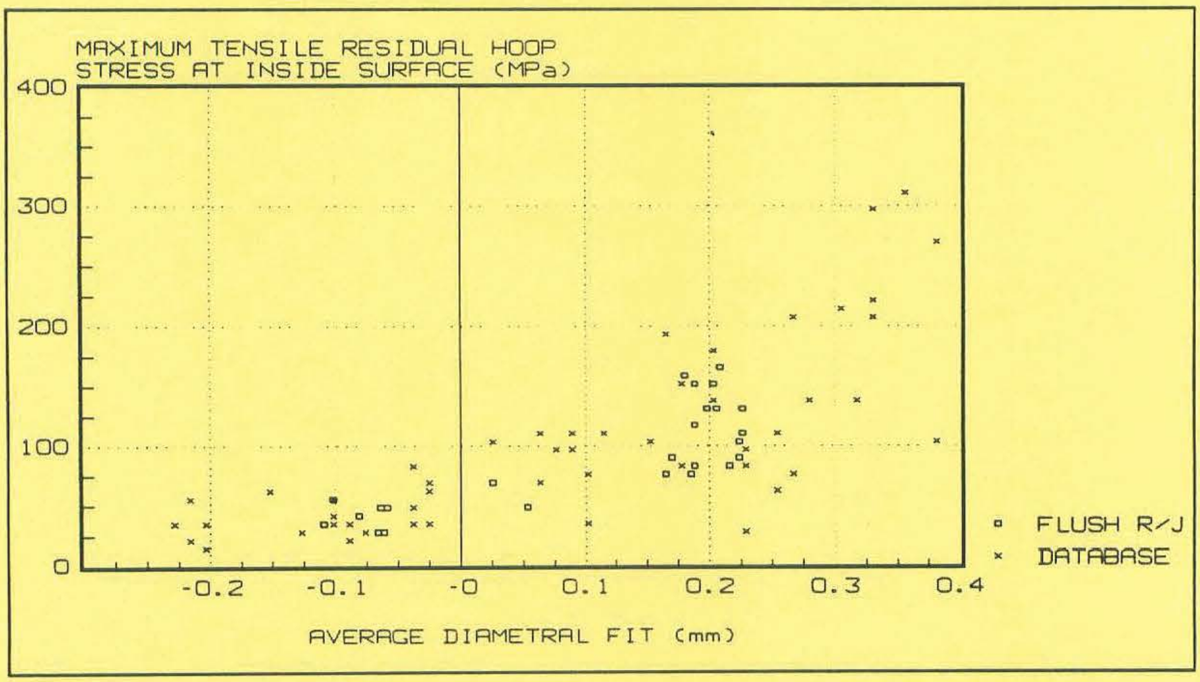

Figure 7: Maximum Tensile Residual Hoop Stress at the Inside Surface of the Pressure Tube