SMiRT-12 / K. Kussmaul (Editor)
1993 Elsevier Science Publishers B.V.

F07/4

EXPERIMENTAL DEVELOPMENT OF ROLLED JOINTS FOR ZR-2.5 WT% NB PRESSURE TUBES FOR USE IN INDIAN PHWRS

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ABSTRACT

In Pressurised Heavy Water Reactors (PHWRs) the fuel bundles are located in horizontal pressure tubes, which are joined at both their ends to S.S. end fittings through rolled joints. In the current generation of Indian PHWRs the material of the pressure tube is changed to cold worked high strength Zr-2.5% Nb alloy. In order to reduce the tensile residual stress near the rolled joints, the concept of low clearance/interference type joints was accepted. This necessitated the development of a new design of rolled joint and optimisation of different parameters involved. As many as fifty eight joints were assembled and subjected to different tests viz. helium leak test, pull-out test. The paper gives details of the new design of the rolled joint and an analysis of the test results obtained.

1.0 INTRODUCTION

In Pressurised Heavy Water Reactors (PHWRs), the fuel bundles are lacated in horizontal pressure tubes which are joined at both their ends to SS 403 end fittings through rolled joints (Fig. 1 and Fig. 2). Rolled joint is a mechanical joint in which the tube is expanded to deform plastically using rollers so that it flows into the grooves on the end fitting and developes the required contact pressure. In the current generation of Indian PHWRs (KAPP-2 onwards) the material of the pressure tube is changed from cold worked Zircaloy-2, used earlier, to cold worked Zr-2.5 wt% Nb alloy. Since the latter has higher strength there is a reduction in tube wall thickness. This necessitated the development of a new groove design and optimisation of rolling parameters to meet the specifications for the rolled joints.

A major problem associated with Zr-2.5% Nb alloy is its susceptibility to delayed hydride cracking (DHC). The mechanism of DHC near rolled joints is described elsewhere [1]. In the case of Zr-2.5% Nb joints with large initial assembly clearance there will be high residual tensile stress near the rolled joint making the joint vulnerable to failure due to DHC. This necessitated the development of a low clearance/interference joint where the initial assembly is to be achieved by induction heating of the end fitting.

2.0 SPECIFICATIONS OF THE ROLLED JOINT

In the case of 220 MWe PHWRs, the rolled joint between pressure tube and end fitting has to meet the following specifications:

1. Pull-out strength at room temperature greater than 50 Te.

2. Pull-out strength at 573 K greater than 27 Te.
3. Helium leak rate at room temperature not more than 3E-08 std. cc/sec.
4. The joint has to qualify hydro test at 20 MPa for 10 minutes without any leakage.

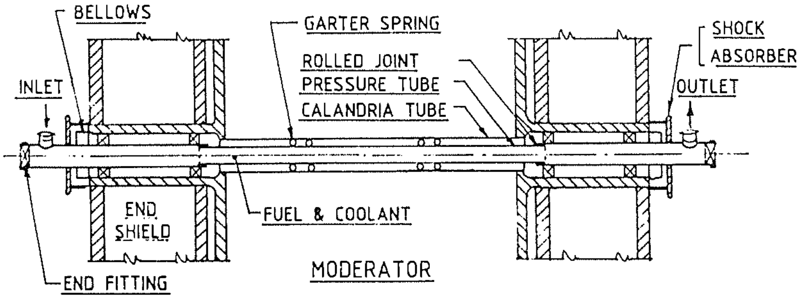


FIG. 1 COOLANT CHANNEL ASSEMBLY

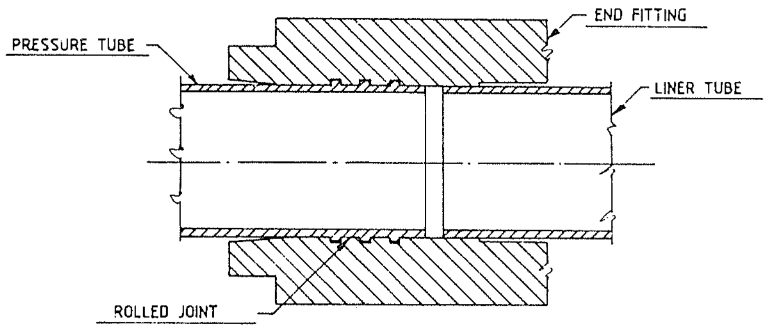


FIG. 2 - PRESSURE TUBE TO END FITTING ROLLED JOINT

3.0 AN OVERVIEW OF THE EXPERIMENTAL PROGRAMME

Short length pressure tube spool pieces (Inside dia. = 83 mm, Wall thickness = 3.32 mm and Length = 300 mm) and sleeves representing the end fitting rolled joint area were used for the developmental trials. The joints assembled were rolled using a special rolling set up and a tool having five rollers. The pressure tube spool pieces were selected from eleven different batches with different mechanical properties as given in Table 1.

Table 1
Mechanical properties of different batches of pressure tube spool pieces

Batch No.	1	2	3	4	5	6	7	8	9	10	11
				Yield stress at room temperature							
Transv. dir.		428	658	767	488	609	578	573	511	550	396
Longit. dir.	679										
				UTS at room temperature							
Transv. dir.		645	933	953	720	811	827	838	771	812	572
Longit. dir.	938										

Note: Underlined properties are at 573 K

The sleeves were categorised into four different types based on groove geometries as given in Table 2. All the joints assembled were subjected to one or more of the following tests:

1. Helium leak test at room temperature and at high temperature.
2. Thermal cycling from room temperature to 573 K and then back to room temperature for one or more cycles followed by helium leak testing.
3. Pull-out test at room temperature/high temperature.
4. Post-sectioning examination of groove geometries and tube metal flow into the grooves.
5. Hydro test at 20 MPa for 10 minutes.

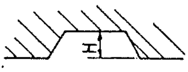
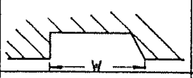
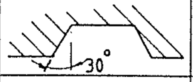
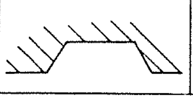
4.0 TEST RESULTS OF JOINTS

During the entire developmental programme fifty eight joints were assembled, rolled and subjected to one or more of the tests described in the previous paragraph. A discussion of the test results is given in the following sections.

4.1 Groove geometry and PTWR

Initially, for the first fourteen joints, 'A' type groove geometry was used. During subsequent tests they showed deteriorating leak rates after thermal cycling. Then type 'E' was used which also showed poor leak tightness. Joints with 'F' type groove geometry showed wide scatter in the helium leak rates after thermal cycling. While a few of the joints maintained excellent leak tightness (less than 1E-09 std.cc/sec), some others degraded seriously, to provide a leak rate greater than 3E-06 std. cc/sec. Then the geometry was modified to 'F1' type. Eight joints in this category showed high leak rates after thermal cycling. A major reason for this could be the higher strength of the tubes. A large fraction of joints with 'F1' type groove geometry and rolled with optimised procedure gave an extremely low post thermal cycling helium leak rate (less than 1E-09 std. cc/sec). The helium leak rate is shown as a histogram in Fig. 3. Leak rates after a min. of five thermal cycles were considered for this preparing this histogram.

Table-2
Different groove geometries of sleeve

Sleeve type	Groove Geometry	Nominal Dimensions (mm)
A		W = 3·6 H = 0·8
E		W = 3·6 H = 0·8
F		W = 4·0 H = 1·0
F1		W = 4·0 H = 1·1
No. of grooves per sleeve = 3 Distance between the ℄ of grooves =16 mm		

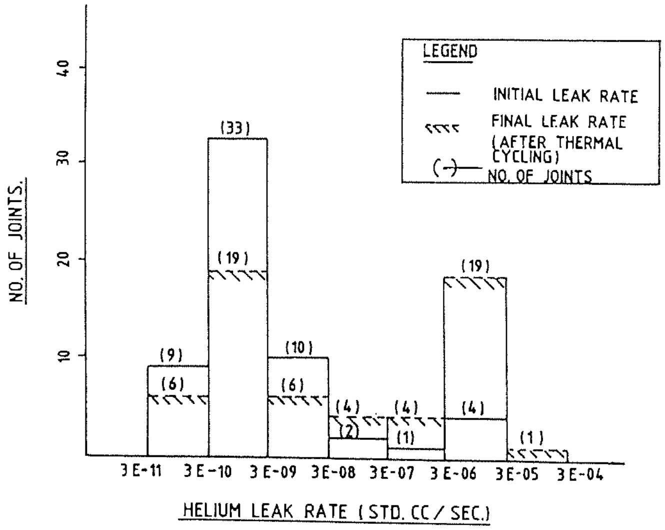


FIG. 3 HISTOGRAM FOR HELIUM LEAK RATE WITH NUMBER OF JOINTS TESTED.

The pull out test results indicate that joints rolled with Percentage Tube Wall Reduction (PTWR*) in the range 11 to 13.5% met the strength requirements both at room temperature and at 573 K. Pull-out test results is given in the form of a histogram in Fig. 4.

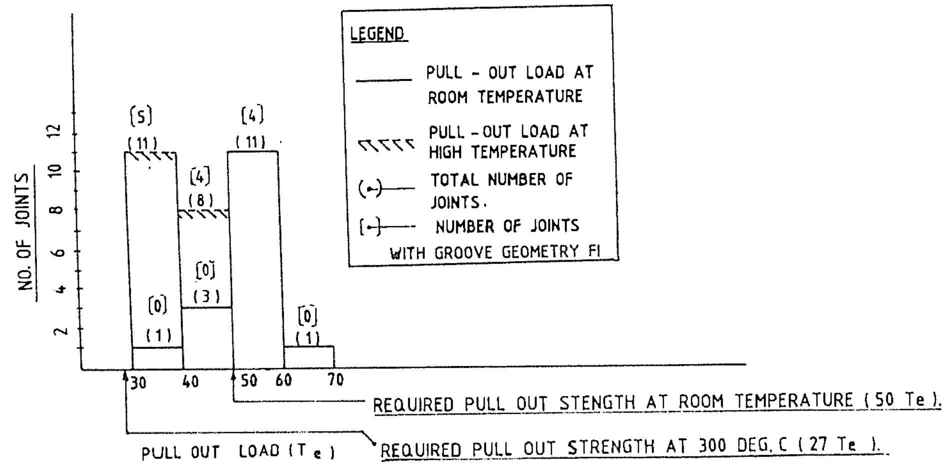


FIG. 4 HISTOGRAM FOR PULL-OUT LOAD WITH NO. OF JOINTS TESTED.

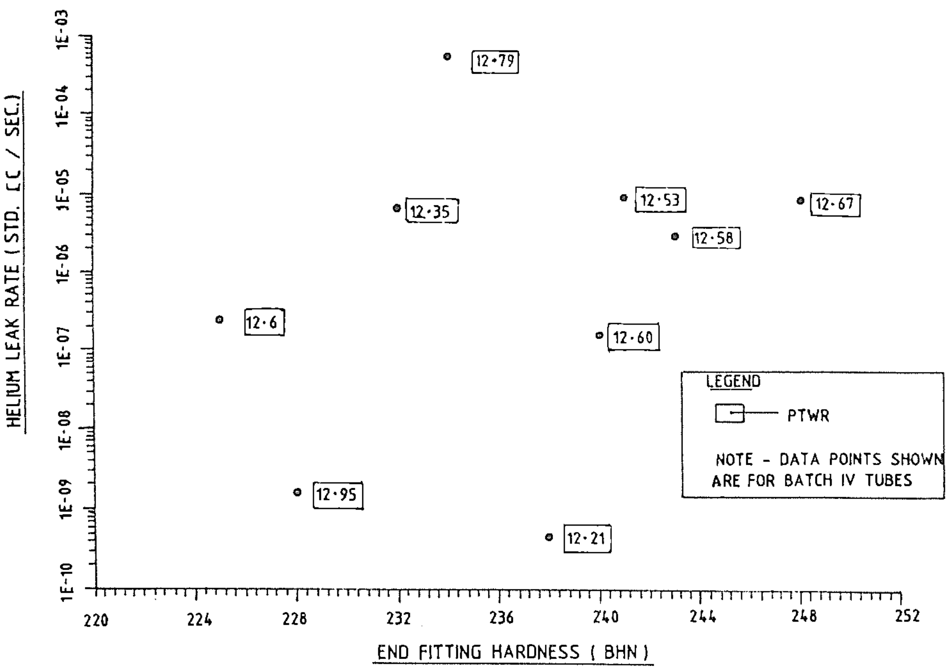


FIG. 5 VARIATION OF AVERAGE HELIUM LEAK RATE WITH SLEEVE HARDNESS GIVEN AS DATA POINTS.

Note:
* PTWR = (Final ID of the tube - Zero-nip dia.) / (2 * WT of tube) * 100
where,
Zero-nip dia. = Sleeve ID - 2 * Avarage wall thickness of tube.

In view of the above, 'F1' was selected as the desired groove geometry and PTWR was selected as 11 to 13.5%.

4.2 End fitting hardness vs. helium leak rate

An examination of test results of rolled joints indicate that there is no apparent relationship between the hardness of end fitting in the range 221-252 BHN and the helium leak rate of the rolled joint even for the same batch of tubes, as shown in Fig. 5. Apparently the extent of plastic deformation of end fitting bore during rolling is insignificant. This was confirmed earlier during rolling through measurements.

4.3 Room temperature mechanical properties vs. helium leak rate

A scrutiny of rolling test results indicate that there is a wide scatter in the helium leak rate with room temperature mechanical properties of the tube. On account of such scatter, it is necessary to have a large population of joints from which a statistically significant information could be drawn. Also, while drawing any conclusion on the helium leak rate it is logical that a higher weightage must be given to joints with higher leak rate. With this in mind, and based on the assumption that transverse mechanical properties are propotional to longitudinal properties, a general trend is discernible in the plot for upper bound average helium leak rate with mechanical properties. Geometric mean of the helium leak rate of each joint for a particular batch of tube was considered for this purpose. The trend shown in Fig. 6 and Fig. 7 is explained by the higher elastic spring back and consequent reduction in contact pressure for stronger tubes.

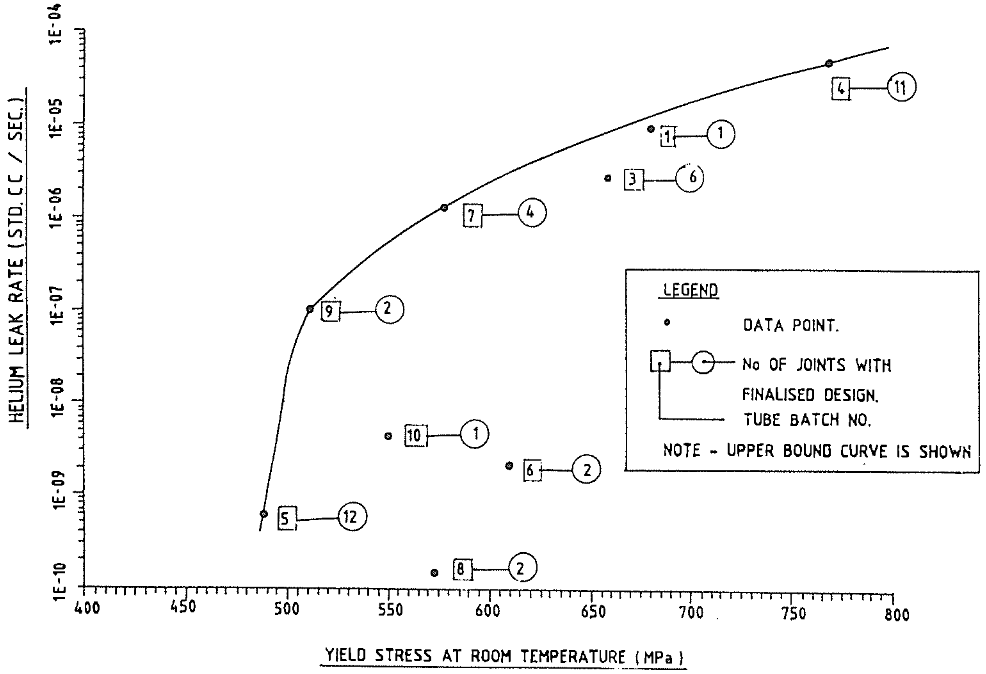


FIG. 6 VARIATION OF AVERAGE HELIUM LEAK RATE WITH ROOM TEMPERATURE Y.S FOR ROLLED JOINTS OF FINALISED DESIGN.

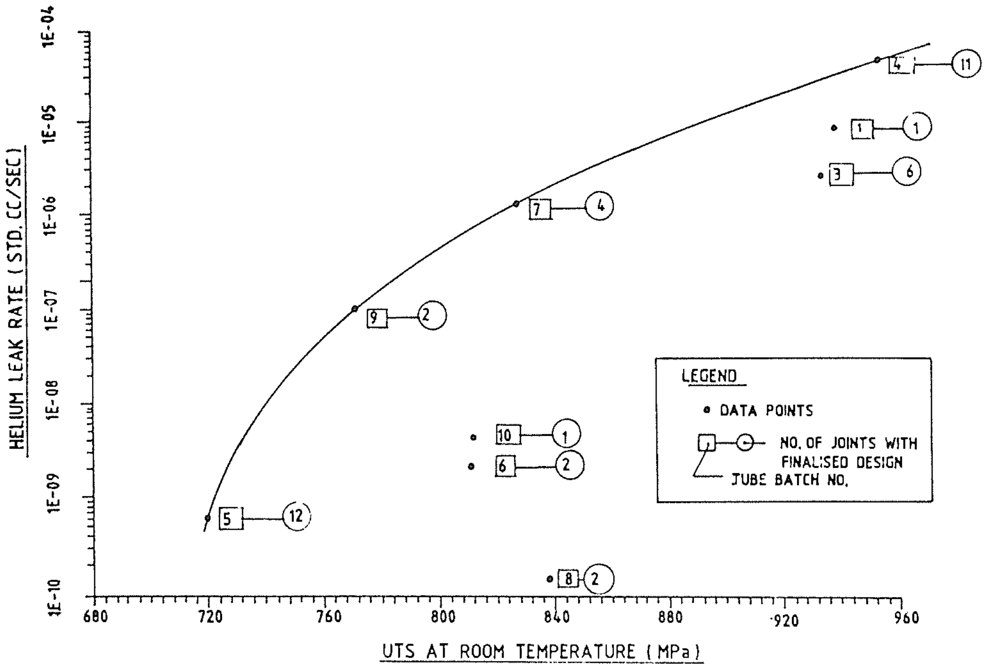


FIG. 7 - VARIATION OF AVERAGE HELIUM LEAK RATE WITH ROOM TEMPERATURE UTS FOR ROLLED JOINTS OF FINALISED DESIGN.

5.0 CONCLUSION

1. Based on the rolling trials and test results, 'F1' type groove geometry with nominal PTWR in the range 11 to 13.5% was found suitable for meeting the specifications for the rolled joint.
2. No correlation exists between the helium leak rate of rolled joint and end fitting hardness in the range 221 to 252 BHN.
3. Upper bound helium leak rate increases with increase in room temperature mechanical properties.

6.0 REFERENCES

1. Perryman, E.C.W. 1978. Nuclear Energy. 17, April, No. 2. pp 95-105.
2. R.K. Sinha, K. Madhusoodanan et. al., Report No. RED/RCCS/KM/910520.