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DESIGN AND DEVELOPMENT OF ROLLED JOINT FOR MODERATOR SPARGER CHANNEL OF AN INDIAN PRESSURISED HEAVY WATER REACTOR

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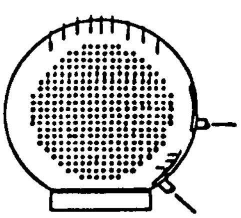
1. INTRODUCTION

Indian Pressurised Heavy Water Reactors are natural uranium fuelled heavy water moderated and cooled reactors. As per the conventional scheme, as shown in Fig.1, the moderator enters through one or more inlet nozzles penetrating the calandria shell and flows out through outlet nozzles. Baffles are fixed at the inlet nozzles for proper distribution of moderator in the calandria and to avoid the impact of the jet on the neighbouring calandria tubes.

An alternate scheme for moderator inlet, as shown in Fig.2., has been conceived and engineered in which three lower peripheral lattice locations of the reactor are converted into moderator inlets. This is achieved by moderator sparger channels each containing a 5 m long perforated zircaloy-2 sparger tube rolled to the calandria tube sheets and extended by stainless steel tubular components (inserts) at both ends of a sparger channel. Moderator enters the sparger channel at both ends and flows into the calandria.



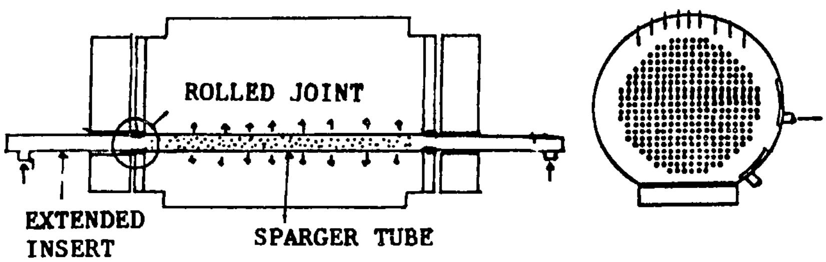


Fig. 1. Conventional Moderator Circuit

Fig. 2. New Scheme with Sparger Channel

In the absence of standard codes for the design of rolled joints, it was required to develop these joints based on trials followed by various tests. This paper discusses the details of the rolled joint developed for this purpose, the details of the trials with test results and optimisation of rolling parameters for these joints.

2. SPECIFICATION

Specificatioons set for this joint are as follows.

1. Pull out strength of 27000 kgf (min) between tube & sleeve
2. Pull out strength of 5000 kgf (min) between tube & insert
3. Helium Leak Rate : 1 E -6 cc/sec (max).
4. The joint should withstand 5000 flexing cycles of 0 to 30 MPa bending stress on tube side & 5000 cycles of ±47 MPa bending stress on insert side without any deterioration beyond the values given in 2 (i), 2 (ii) & 2 (iii).

3. JOINT DESIGN

Usually rolled joints used in PHWRs are either conventional grooved joints or sandwich joints. In conventional grooved joints, tube is rolled into a fitting or tube sheet having 2 to 3 trapezoidal grooves. Plastic flow of tube material into the grooves enhances the joint strength and pinching of tube at the groove edges results in leak tightness. This type of joint can be successfully made if the tube diameter to wall thickness (D/t) ratio is below about 25 and the fitting or tube sheet yield stress is at least equal to the tube yield stress. At the other end, for very thin walled (D/t > 50) tubes landed insert sandwiched joint [1] is used. In such cases, joint is made by sandwiching the tube between fitting and an insert of sufficient thickness. In the case of sparger tube (D/t ratio = 31 and tube sheet yield stress < tube yield stress) the contact pressure and pull out strength was found to be very small if conventional joint was used and use of usual landed insert sandwich joint is impractical. The tube if rolled directly into the tube sheet, does not develop enough strength and leak tightness unless a backing insert is rolled into the rolled bore of the tube subsequently. Similar joints (Plain Insert Sandwiched Joints) have been developed earlier for the Dhruva research reactor [2]. The three different types of joints are illustrated in Fig. 3.

To achieve such a joint Zircaloy-2 tube (121 mm OD X 3.9 WT) is rolled into the lattice bore of Calandria tube sheet having 3 numbers of narrow circumferential grooves as shown in Fig 4. An SS 304L insert with projections on its OD corresponding to the grooves in the calandria lattice bore is rolled inside the rolled zircaloy-2 tube sandwiching the tube between calandria tube sheet and the SS 304L insert. The insert acts as backing ring thereby improving the strength of the joint considerably.

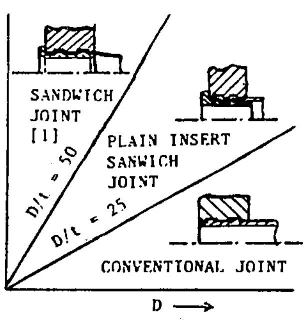


Fig. 3. Differnt types of Joints.

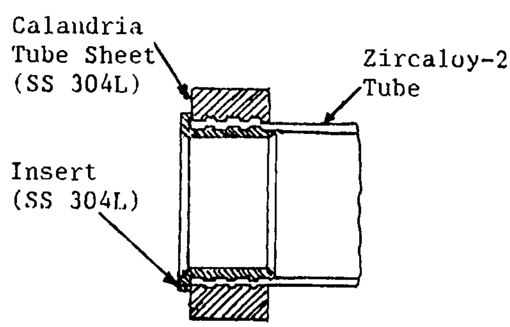


Fig. 4. Joint Assembly

4. MATERIALS

Zircaloy-2 tube spools of two different types I and II were used for the trials. The UTS and YS of Type-I tube was 625 MPa and 490 MPa and Type-II tube was 570 MPa and 410 MPa respectively. The inserts were machined from a solution annealed SS 304L hollow bar. The sleeves were machined from a SS 304L plate. The boring and grooving of sleeves were done initially in a lathe and subsequently using a remote boring and grooving machine developed by BARC.

5. ROLLING PROCEDURE

The joint is made by rolling in two stages. In the first stage the tube is rolled inside the tube sheet up to the specified percentage tube wall reduction (PTWR). In the second stage the insert is placed inside the tube and rolled to the specified percentage insert wall reduction (PIWR).

6. TESTING PROCEDURE

The joints are subjected to the following tests.

1. Helium leak test by vacuum method immediately after tube rolling and after insert rolling.
2. Thermal cycling, RT- 90° C - RT, of joint with helium leak test at 90° C as well as at room temperature (RT).
3. Cyclic Bending Test, 0-30 MPa on tube side and ±47 MPa on insert side with intermediate helium leak test.
4. Pull Out Test to determine pull out strength of the tube w.r.t. the sleeve and of the tube w.r.t. the insert.
5. Post-sectioning examination of selected joint assemblies.

7. RESULTS

Twenty five rolled joints were assembled. These joints were rolled to diffeent percentages of wall reduction. They were subjected to various tests as described under section 6 of this paper. A number of parameters associated with rolling viz. percentage tube wall reduction (PTWR), percentage insert wall reduction (PIWR), initial and intermediate Helium leak rates and pull out strength were measured/evaluated while rolling different joints. Post sectioning examination was done on a joint to determine true wall reduction of tube and insert and depth of metal flow in each groove.

8. DISCUSSION OF RESULTS

8.1 Effect of PTWR and PIWR on pull out strength of tube

During the trials PTWR has been varied from 8.2 to 13.3 and PIWR from 6.5 to 11.03. Pull out strength of tube with respect to sleeve vs PTWR is plotted in Fig 5. It can be noticed that higher pull out strength can be achieved for the same PTWR with higher PIWR. This is as expected as the insert rolled inside the rolled sparger tube acts as a backing ring as explained earlier in section 3. Based on the experience gained from the trials, it has been found that PTWR and PIWR in the range 8 to 10 and 7 to 9 respectively, with an over rolling margin of 2 %, a joint meeting the specifications can be made.

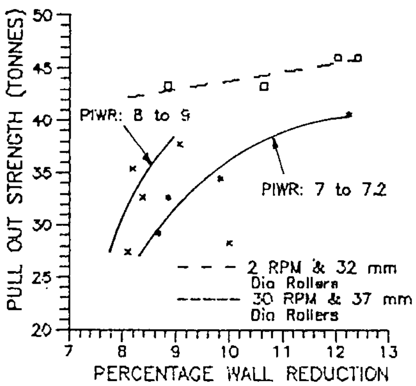


Fig. 5. Pull out Strength of Tube Vs PTWR

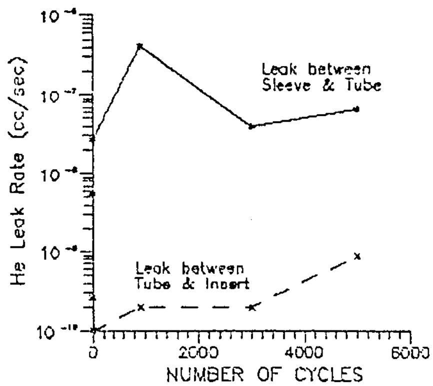


Fig. 6. Leak Rate Vs Number of Bending Cycles

8.2 Effect of roller diameter and RPM of Tool

It is evident from Fig 5 that higher pull out strength can be obtained for the same PTWR with a smaller roller diameter (32 mm diameter) and lower tool rpm (2 rpm). With a smaller diameter roller radial force applied by the tool is distributed over a smaller area resulting in better plastic flow of the material into the grooves.

8.3 Spring Back

Spring back increases with yield stress of the tube material and tube wall reduction. This varied from 0.5 to 0.55mm for trials with spools from Type-I tubes and from 0.38 to 0.69mm for PTWR variation of 8.68 to 13.26 for spools from Type-II tubes.

8.4 Extrusion, Rotation and Torque

Sparger Tube forward (towards operator) extrusion was not observed after the use of Sparger Tube Extrusion Controlling Fixture. Sparger Tube back extrusion was showed a large variation and the maximum value was 2.0mm. Contribution of insert rolling on sparger tube back extrusion was in general negative but a maximum value of +0.3mm was observed. Insert extrusion was found to be 1.0 ± 0.2 mm with an exception where an higher value of 2.85 mm was noticed, which is attributed to the release of EI Pressing Fixture immediately after Zero Nip rolling.

Sparger tube rotation was 3.64° to 3.8° during sparger tube was rolling and 10' to 33' during insert rolling, both against the direction of rotation of tool mandrel. Insert did not show any noticeable rotation.

Torque required for rolling sparger tube was 65 ±10 kg-m and for rolling insert was 63 ±2 kg-m.

8.5 Effect of Cyclic Bending Moments

Leak rate between tube & sleeve and leak rate between insert & tube Vs number of bending cycles for a typical joint is plotted in Fig 6. In general it has been found that the leak rate increases with the number of bending cycles. The initial rate of deterioration is found to be higher folowed by either a lower rate of deterioration or a slight improvement in leak tightness followed by a slower rate of deterioration. This phenomenon has not been studied in depth but it may be due to the combined effect of reduction in contact pressure due to cyclic bending resulting in higher leakage and sealing effect of wear products. After 5000 bending cycles each of 0 - 30 MPa on tube and ±47 MPa on insert, one joint has been subjected to 500 bending cycles of ±100 MPa on insert. This resulted in sudden increase in the leak rate between sleeve & tube as well as tube & insert 6.8 E-6 and 7 E-5 std. cc He/sec. respectively. The cyclic bending moments has resulted in lower pull out strength also (29 T). Thus it can be concluded that cyclic bending stresses will degrade the rolled joints - increase in leak rates and lower pull out strength. The results of cyclic bending test for a typical joint rolled to 11.63 PTWR and 11.03 PIWR is tabulated in Table-1.

Table-1. Leak Rate of the Joints after Cyclic Bending Tests

No. of bending cycles of 30 MPa on tube and 47 MPa on Insert	900	1500	3000	5000	After additional 500 cycles of ± 100 MPa on insert.
Leak between Tube & Sleeve	2.2 E-7 cc/sec.	5.8 E-8	4 E-8	6.6 E-8	6.8 E-6
Leak between Insert & Tube	5 E-10 cc/sec.	2 E-10	2 E-10	8 E-10	7 E-5

9. ADDITIONAL STUDIES RELATED TO SPARGER CHANNEL ROLLED JOINTS

9.1 Effect of Additional cold work on Calandria Tube sheet material with regard to its susceptibility to IGSCC

During the process of rolling it is expected that a layer of material at the bore of Calandria Tube sheet will undergo plastic deformation. The extent of cold work will be limited on account of surrounding elastic zone. Actual measurements were carried out on four sparger tube sleeves from which tubes and insert were removed after rolling and one 235 Mw(e) calandria tube sleeve with the objective of determining the extent of cold work and work hardening. It has been experimentally found that the increase in the tube sheet bore diameter due to sparger tube rolling is 0.4mm (0.33% plastic hoop strain) and the hardness on the bore of the tube sheet increases only from HRB 74 σ 1.0 to HRB 77.4 σ 1.7. Thus induced cold work as well as work hardening of tube sheet material due to sparger tube rolling is extremely small and is comparable with the same for calandria tube rolled joint (HRB 73.5 σ 1.0 to HRB 77.7 σ 1.5).

To examine the possibility of increase in IGSCC susceptibility due to cold work in rolled joints, a full size proto-type rolled joint assembly was boiled for 24 hours in magnesium chloride solution at 154° C, and no damage to the joint was observed. Thus it is concluded that cold work generated in tube sheet due to the process of rolling will not lead to enhancement in its susceptibility to IGSCC.

9.2 Effect on the Integrity of Neighbouring Calandria Tube

During the process of rolling of the sparger channel, in a composite assembly consisting of a rolled calandria tube and sparger channel, change in diameter of the rolled joint of neighbouring Calandria Tubes (109.5 mm) has been observed to be only 100 micro strains. It was also observed that the leak rate of the calandria tube rolled joint was impoving from 2.4 E-7 to 3 E-9 cc/sec after rolling the sparger channel to 10.8 PTWR and 7.65 PIWR. It is thus concluded that at the location of neighbouring calandria tube the strains in the tube sheet are extremely small and that the forces transmitted to the neighbouring Calandria Tubes are negligible enough to affect their integrity.

10. CONCLUSIONS

The main findings of the study are listed below.

1. Plain insert sanwich joint meeting the specification can be made for joining the sparger tube to calandria tube sheet.
2. Insert is required for achieving the specified pull out strength of the joint.
3. For the same PTWR, joint strength can be increased with higher PIWR.
4. Joints rolled with a tool with smaller roller diameter and at lower speed will be stronger for the same PTWR.
5. Joint integrity rapidly deteriorates with cyclic bending causes max. stress greater than 0.47 YS of insert.
6. This can be adapted for operating reactors as rolling of sparger tube into the calandria tube sheet will not affect the integrity of neighbouring calandria tube rolled joints.

11. REFERENCES

1. Westwood R. and Paterson D. L., Development of a tube-to-tube sheet joint for the Douglas Point Reactor Calandria. AECL 1611.
2. Sinha R. K. and Kakodkar A., Semi-analytical technique for the design of rolled joints, Paper G10/5, SMIRT 5, Berlin, 1979.