QUALITY CONTROL & QUALITY ASSURANCE FOR TUBE TO TUBESHEET JOINTS AND SHELL WELD JOINTS OF STRAIGHT TUBE DESIGN DECAY HEAT EXCHANGERS FOR 500MWE PROTOTYPE FAST BREEDER REACTOR

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ABSTRACT

Prototype Fast Breeder Reactor (PFBR) is a 500MWe pool type sodium cooled nuclear reactor, which is presently under construction at Kalpakkam, India. Nuclear decay heat generated in the core after reactor shutdown has to be removed to avoid core melt down and maintain the structural integrity of the reactor components. As per the safety guidelines, failure probability of decay heat removal function shall be less than $10^{-7}$/ry. In order to achieve this value, highly reliable Safety Grade Decay Heat Removal (SGDHR) system is provided in PFBR. Decay Heat Exchanger (DHX) which is a part of SGDHR system has to be designed and manufactured with stringent specification requirements to achieve high reliability. Decay Heat Exchanger is a vertical, shell and tube type, counter flow, sodium to sodium heat exchanger in which heat from the radioactive primary sodium is transferred to non-radioactive intermediate sodium in SGDHR circuit. Austenitic SS316LN material is selected as principal material of construction for DHX. As operating temperature is high and DHX forms part of SGDHR circuit, very high degree of reliability against failure is emphasized during design, material selection and manufacturing. To enhance the reliability, specification for SGDHR circuit components are made stringent compared to specification used in other industrial applications.

The tube bundle of DHX consists of 108 nos. of seamless tubes of OD24mmX1mm wall thickness, rolled & welded at either end with top & bottom tubesheets by autogenous pulsed Gas Tungsten Arc Welding (GTAW) process. During material procurement, ultrasonic test is done on the entire length of each tube in accordance with ASME Sec.III Class I. In addition, each tube is subjected to hydro test as per PFBR specification to ensure integrity of tubes before component manufacture. The tube to tubesheet joints is subjected to various examinations and testing at different stages of manufacture for quality assurance. After completion of tube bundle assembly, shell integration is carried out by GTAW process. Each production weld joints of shells are subjected to thorough Visual Examination, Liquid Penetrant Examination (LPE) and Radiography Examination (RE). In case radiography is not possible, layer by layer LPE and Ultrasonic Examination (UE) is carried out to evaluate soundness of the welds. After completion of manufacture, the tube side of DHX undergoes pneumatic testing and Helium leak testing to ensure integrity. This paper details the quality control and quality assurance for the tube to tubesheet joints and shell weld joints of Decay Heat Exchangers for 500MWe Prototype Fast Breeder Reactor.

Keywords: Tube to Tubesheet Joint; Quality Assurance; Safety Grade Decay Heat Removal System; Decay Heat Exchanger;

INTRODUCTION

PFBR is provided with two independent and diverse Decay Heat Removal (DHR) systems viz., Operating Grade Decay Heat Removal System (OGDHR) and Safety Grade Decay Heat Removal System (SGDHR). OGDHR utilizes the secondary sodium loops and steam–water system for decay heat removal. In order to improve the reliability of DHR function, a passive Safety Grade Decay Heat Removal System (Figure-1) containing four independent loops of each 8MWt heat removal capacity is provided. Two SGDHR loops are provided with straight tube design sodium to sodium heat exchanger which is called as Decay Heat Exchanger (DHX-Type A) and serpentine tube design sodium to air heat exchanger which is called as Air Heat Exchanger (AHX-Type A). The other two loops are having diversity in design to avoid common cause failure during reactor operation. These two loops consists of U tube design DHX-Type B & straight tube design AHX-Type B. Driving force for the natural convection flow is obtained by the elevation difference between DHX and AHX of ~41 m and by a stack of height 30m over AHX. Decay Heat Exchanger is a very important component of
reactor, as it transfers the heat from radioactive primary sodium to non-radioactive intermediate circuit sodium. Heat from the intermediate circuit sodium is rejected to atmospheric air through AHX. The specification requirements are stringent to ensure high degree of reliability for the design service life of 40 years.

**DESCRIPTION OF DECAY HEAT EXCHANGERS (TYPE A)**

Decay Heat Exchanger (Figure-1) is supported on roof slab in the reactor assembly inside the Reactor Containment Building (RCB) and is dipped in hot pool primary sodium of the reactor. DHX is a vertical, shell and tube type, counter flow, sodium to sodium heat exchanger. The major material of construction for DHX is austenitic stainless steel of type 316LN. This is a low carbon stainless steel chosen to ensure freedom from sensitization during welding of the components. This steel has excellent mechanical & creep properties and has good compatibility with liquid sodium coolant. The DHX tube bundle consists of 108 nos. of seamless tubes of OD24mmX1 mm wall thickness arranged in a circular pitch. The tubes are rolled & welded to top & bottom tubesheets.

The primary hot sodium flows from top to bottom on the shell side and intermediate sodium flows on the tube side. The tube bundle shell is perforated for a height of 1.76m at the primary sodium inlet to enable primary sodium flow on the shell side even if there is a fall in hot pool sodium level due to unexpected sodium leak incident if any in the reactor. Tubes are held at regular intervals by anti vibration belts to minimize the phenomenon of flow induced vibration. A small bend on each tube is provided at the top to accommodate differential thermal expansion among tubes.

**QUALITY ASSURANCE OF TUBE TO TUBESHEET JOINTS**

The tubes, tubesheets and tube to tubesheet joints which separates radioactive primary sodium and non-radioactive intermediate sodium are the most critical items in DHX. The raw materials for tubes and tubesheets were produced by electric arc melting process with tight control on inclusion content. High quality control in inclusion content during melting process helps in achieving sound weld joint between tube & tubesheet during autogenous welding process. Decay Heat Exchanger consists of 36mm thick top & bottom tubesheets in which tube holes are drilled in a circular pitch. Each hole is provided with two inside grooves at a distance of 10mm & 20mm from the inner face of tubesheets for additional longitudinal load resistance of tubes. The tubes are rolled & seal welded to tubesheets at both the ends. The specification requirements and acceptance criteria for tube to tubesheet joints are stringent. The strength rolling (7-10% thinning) of tubes is carried out during which expanded tubes grips inside the grooves. This arrangement also acts as a mechanical seal for arresting the entry of primary sodium into the gap between the tube OD & tubesheet hole. Thus, deep crevices are eliminated in the design by strength rolling of tubes in the tubesheets. Face grooves are machined with tight tolerances on face of each hole on the tubesheet which provides a thinner section for seal/lip welding to get the desired weld profile. This also helps in minimizing the heat input required for seal welding and makes a perfect fusion of the base materials (tube & tubesheet).

Even though conventional heat exchanger tube to tubesheet joints are executed first by welding and then rolling, PFBR tube to tubesheet joints were done first by rolling by using
mechanical tube expanders and then single pass seal welding by automatic pulsed TIG welding process without addition of filler wire (Figure-2). This is to avoid probable stresses induced in the welds during tube expansion step which may result in subsequent failure of the weld joints during transient reactor operating conditions. The automatic welding process ensures repeatability & consistency in quality of tube to tubesheet weld joints. The process parameters of welding include pre purge time, up slope, speed of welding, down slope, post purge time. The weld quality with respect to shape and soundness are controlled by process parameters.

The process of rolling & welding is qualified in a qualification block simulating job conditions before starting this process on the actual job. The expanded tubes in the qualification block are subjected to pullout tests at room temperature. The rolled tubes are longitudinally sectioned and subjected to hardness survey, check for % thinning, thorough visual examination for scratches, cracks, peels etc., and micro examination for the smooth transition of rolled region to the unrolled region. Tube to tubesheet seal welding is carried out by autogenous pulsed TIG process after rolling. The seal weld is subjected for visual examination, Helium Leak Test (HLT) and fluoroscent LPE as per ASTM E-165 type-1, method C for examination of lack of fusion at the edge of hole in the tubesheet, surface pores, cavities, cracks etc.

After completion of non-destructive examinations, the pullout test is repeated on the expanded & welded tubes and few welded tubes are sectioned for micro & macro examination. The mean dimension of the throat shall not be less than 0.9t and no individual throat dimension shall be less than 0.66t,

<table>
<thead>
<tr>
<th>Test / Examination</th>
<th>Parameter</th>
<th>Acceptance Standard</th>
</tr>
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<tbody>
<tr>
<td>Visual/profile</td>
<td>Lack of fusion at the edge of the hole in tubesheet</td>
<td>NIL</td>
</tr>
<tr>
<td></td>
<td>Surface pores, cavities</td>
<td>NIL</td>
</tr>
<tr>
<td></td>
<td>Cracks</td>
<td>NIL</td>
</tr>
<tr>
<td>Weld bead &amp; weld surface</td>
<td>Uniform &amp; smooth</td>
<td>NIL</td>
</tr>
<tr>
<td>Floroscent LPE (as per ASTM E-165 type-1, method C)</td>
<td>Indications in the weld</td>
<td>NIL</td>
</tr>
<tr>
<td></td>
<td>For zone adjoining weld metal: indication &gt;1.5mm and indication &lt;1.5mm if they are less than 3mm apart</td>
<td>NIL</td>
</tr>
<tr>
<td>Helium Leak Testing (as per PFBR specification)</td>
<td>Local leak</td>
<td>≤10⁻⁶ Pa·m³/s</td>
</tr>
<tr>
<td></td>
<td>Global leak</td>
<td>≤10⁻⁷ Pa·m³/s</td>
</tr>
</tbody>
</table>

where ‘t’ is tube wall thickness. Macro examination is done at 20X on the cut sections to verify that there are no cracks at base of the weld bead. The weld is ground off starting from the top and a micro examination is done at 100X for every 0.2mm till the base metal is reached to check the porosities/inclusions. Cracks on the welds are not permitted. The minimum porosities/inclusions are tolerated only if the
difference between major diameter of weld and the sum of
diameter of porosities/inclusions shall be greater than 0.66t
and any case no pore diameter shall be greater than 0.2mm in
maximum dimension.

Rolled tubes on the actual job are subjected to thorough visual
examination and check for specified % thinning. After the seal
welding, visual inspection, fluoresce LPE and Helium leak
testing (Figure-3) are done on the production tube to tubeshot
joints. The non-destructive examinations and testing
requirements on production joints are stringent. Acceptance
criteria of tube to tubeshot weld joints are given in Table 1.
All specification requirements were met during tube to
tubeshot welding procedure qualification and during
fabrication on the actual job.

HELLEUM LEAK TESTING OF TUBE TO TUBESHEET
JOINTS

Nothing man made is truly leak tight. So there is a necessity
to establish & specify a practical leakage rate that is acceptable
for a component under test. The end purpose of leak testing is
to ensure reliability and serviceability of component to prevent
premature failure of systems containing fluids under pressure/ vacuum. As a part of quality assurance program of DHX,
Helium leak testing is carried out at tube bundle stage to ensure
leak tightness of tube to tubeshot joints before proceeding with
further fabrication. HLT trials were conducted on the
mock up for evaluating the leak tightness of rolled/expanded
tube to tubeshot joints before seal welding. As rolled/
expanded joints (without seal welding) itself found to be leak
tight, it was extremely challenging task to evaluate the leak
tightness of seal weld (after rolling). Special fixtures were
designed & developed for bombarding the Helium on rolled
& welded tube to tubeshot joint from outside. Subsequently,
HLT is performed for the seal weld by vacuum method. After
successful completion of above trials, HLT is carried out on
the production joints. The leak rate achieved after expansion
as well as after seal welding of tube to tubeshot joints found
to be less than $10^{-8}$ Pa-m$^3$/s which is meeting the specification
requirement. The above exercise and quality assurance has
given highest confidence on leak tightness and reliability of
tube to tubeshot joints.

QUALITY ASSURANCE FOR THE WELD JOINTS OF
COMPONENTS/SHIELDS

After completion of tube bundle activities, shell assembly is
carried out for top & bottom portion. The welding of DHX
shells/components is done only by Gas Tungsten Arc Welding
(GTAW) even though Shielded Metal Arc Welding (SMAW)
process is permitted as per specification to ensure highest
degree of cleanliness & quality.

Before welding, LPE is carried out for Weld Edge Preparation
(WEP) of the shells to ensure no surface defects. The welding
procedure is qualified with stringent destructive and non-
destructive examinations & testing before executing welding
on the actual job. The qualification test coupons are subjected
to all the non-destructive examinations applied in fabrication
of actual job. As per specification, qualification weld joints
shall be subjected to thorough visual examination, LPE,
radiography examination, longitudinal tensile test at room
temperature, transverse tensile test at room temperature and
elevated temperature, bend tests (root, face & side), Charpy U
notch impact test, delta ferrite content test, IGC and
metallurgical examination for the complete transverse section
of the weld. Thorough visual examination, root and final pass
LPE and 100% radiography examination is done for all the
possible production weld joints. In case radiography for the
production weld joint is not possible, the quality of the weld
joint is evaluated by ultrasonic examination. Specification
requirements were met during various welding procedure
qualification with excellent test results. The mechanical test
results observed during welding procedure qualifications were
much more than the minimum requirement. Bend tests results
were found to be satisfactory.

No re-rolling is permitted as per specification after welding
on the components which may induce un-quantified stresses
on weld joints. Production test coupons are welded for every
20m of production weld length for each type of weld joint
adapting same process parameters of job welds to control &
monitor the quality of welds. The production test coupon
undergoes all the destructive and non-destructive examinations
& testing carried out during procedure qualification. The QA,
QC and inspection stages are covered in a systematic manner
on base materials as well as weld materials at various stages
and are critically documented.

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Fig. 4 : Pneumatic test of complete fabricated DHX
PNEUMATIC TEST AND HELIUM LEAK TEST FOR DHX

On completion of DHX fabrication, the tube side is subjected to pneumatic test (Figure-4) at 7.8 bars gauge pressure for minimum of 10 minutes hold time to check the integrity of component. The double envelope of intermediate sodium inlet-outlet portion is subjected to pneumatic test at 0.125 bar gauge pressure. No drop in pressure is acceptable. All the accessible welds are subjected to soap bubble test. No leak is acceptable during the test.

After completion of pneumatic test, DHX tube side is subjected to Helium leak test under vacuum as per PFBR specification during which global leak rate shall not be more than $10^{-7}$ Pa-m³/s and local leak rate shall not be more than $10^{-8}$ Pa-m³/s.

CONCLUSION

Enhanced reliability of welded components can be achieved mainly through quality control and quality assurance procedures in addition to design, adequate appreciation of materials & their weldabilities, properties of welding consumables and characteristics of welding processes. The diverse and redundant inspections in terms of both operator and technique are required for components where zero failure is desired & claimed. Very high standard quality control and quality assurance during material procurement, welding, fabrication and testing has given high confidence for trouble free service from Decay Heat Exchangers for the design service life of 40 years.

REFERENCES

