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QUALITY MANAGEMENT DURING TUBE BUNDLE FABRICATION OF HEAT EXCHANGERS FOR 500 MWe 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 in an advanced stage of construction. Prototype Fast Breeder Reactor consists of Primary Sodium Circuit (PSC), Secondary Sodium Circuits (SSC), Safety Grade Heat Removal Circuits (SGDHRC) and Steam-Water Circuit (SWC). The primary sodium circuit removes the nuclear heat generated in the core and transfers it to the secondary sodium circuits through Intermediate Heat Exchangers (IHXs). The secondary sodium circuits, in turn, transfers the heat to steam/water circuit through Steam Generators (SGs). The decay heat is removed by sodium to sodium heat decay heat exchanger (DHX) and in turn sodium to air heat exchanger (AHX). The boundaries of sodium systems of Prototype Fast Breeder Reactor is designed so as to have an extremely low probability of leakage, rapidly propagating failure and rupture under the static & dynamic loads expected during various operating conditions. The degradation of material properties (e.g. effect of sodium, temperature and irradiation), transients, residual stresses, flaw size etc. are the important considerations, which were taken into account. Austenitic stainless steels of grade 316LN were used as major structural materials for IHX & DHX and modified 9Cr-1 Mo was used as the principal material of construction for the SG & AHX. Most of the Nuclear Steam Supply System (NSSS) components are thin walled and require manufacturing in separate nuclear clean halls to achieve high levels of quality. The welding standards and acceptance criteria of PFBR equipment are more stringent compared to ASME/other International standards. Various control measures and quality assurance are instituted during each and every stage of raw material procurement, welding, fabrication, non-destructive examinations, testing, handling, erection and post erection preservation to ensure high degree of reliability against failure for the design service life of 40 years. This paper highlights the challenges involved in welding and fabrication of various heat exchangers for 500MWe Prototype Fast Breeder Reactor.**

Keywords: **Quality Management, Welding, Non-destructive examination, Sodium systems.**

1. INTRODUCTION

The design and construction of PFBR is based on the French code RCC- MR which is highly sophisticated and specific to the fast breeder reactors in comparison to the conventional boiler and pressure vessel code of ASME. The principal material of construction being stainless steel shall be handled with care following best engineering practices coupled with stringent QA requirements to avoid stress corrosion cracking in the highly brackish environment. Intergranular stress corrosion cracking and hot cracking are additional factors to be addressed for the welding of stainless steel components. Pickling and passivation, Testing with chemistry controlled demineralized water are salient steps in

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manufacturing. Corrosion protection and preservation during fabrication, erection and post erection is a mandatory stipulation in the QA programme. The standards are very much similar and tight for chrome-moly components too. Enhanced reliability of welded components can be achieved mainly through quality control and quality assurance procedures in addition to design and metallurgy. The diverse and redundant inspections in terms of both operator and technique are required for components where zero failure is desired & claimed.

2. INSIGHT INTO THE HEAT TRANSPORT SYSTEM OF PFBR

The primary liquid sodium is radioactive. Therefore, radioactive primary sodium is not used directly to produce the steam. In addition, the secondary sodium circuit in between primary sodium circuit and steam-water circuit is envisaged to prevent carryover of hydrogenous materials and reaction products (water, steam, hydrogen, sodium hydroxide) into the core, in case of a sodium-water/steam reaction incident in the Steam Generators. The primary sodium circuit consisting of core, primary sodium pumps (PSP), intermediate heat exchangers (IHXs), primary pipe connecting the pumps and the grid plate, is contained in a single large diameter vessel called Main Vessel (MV).

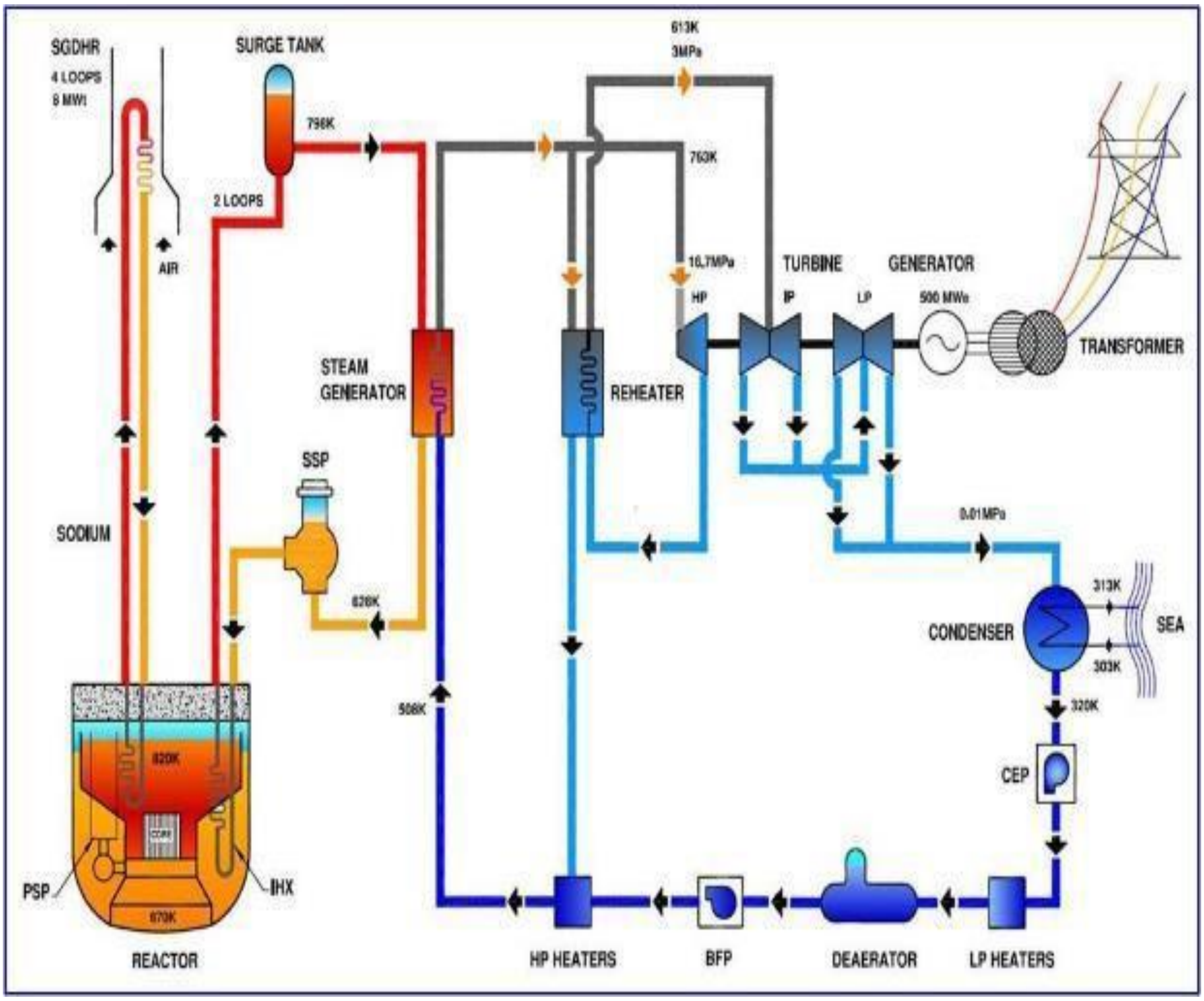

Figure.1: Prototype Fast Breeder Reactor flow chart

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 -7 removal functions shall be less than 10 /ry. Prototype Fast Breeder Reactor is provided with two independent and diverse Decay Heat Removal (DHR) systems viz., Operating Grade Decay Heat Removal System (OGDHRS) and Safety Grade Decay Heat Removal System (SGDHRS). OGDHRS in PFBR utilizes the secondary sodium loops and steam–water system for decay heat removal.

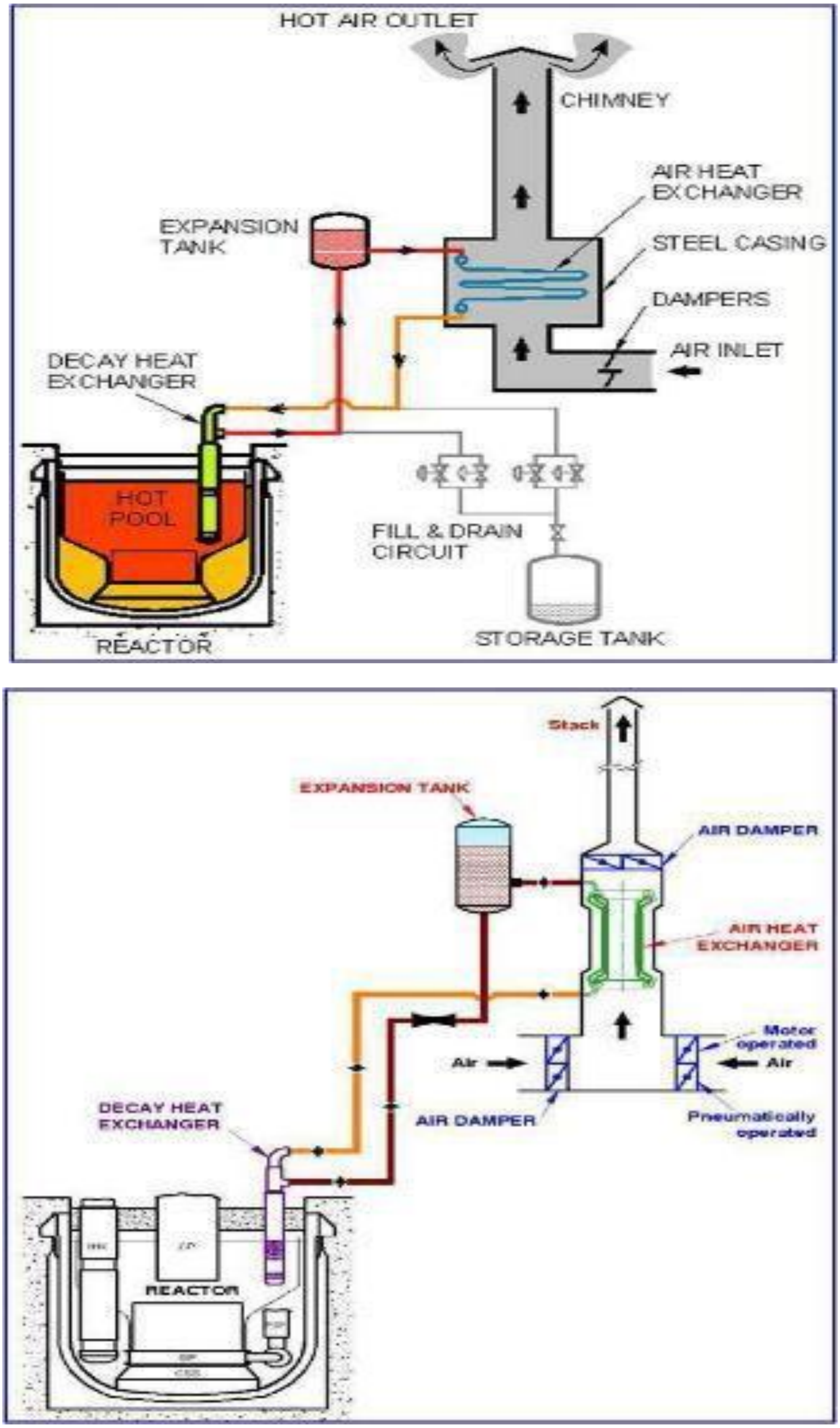

Figure.2: SGDHR

In order to improve the reliability of decay heat removal function, a passive Safety Grade Decay Heat Removal System (Figure-2) consisting of four independent loops of each 8MWt heat removal capacity in natural convection mode is provided. Two SGDHR loops are having one design of Sodium to Air Heat Exchangers (AHX) & Decay Heat Exchangers (DHX) [Type–A] and other two SGDHR loop AHX & DHX are of different design [Type-B] concept to avoid common cause failure. Decay heat exchangers transfers' heat from the primary radioactive hot pool sodium to intermediate circuit sodium. Heat from the intermediate circuit sodium is transferred to atmospheric air through AHX and by natural convection.

3. QUALITY MANAGEMENT DURING IHX TUBE BUNDLE FABRICATION

The major material of construction is austenitic stainless steel grade 316LN (Cr: 17-18%, Ni: 12-12.5%, Mo: 2.3-2.7%, Mn: 1.6-2.0%, C: 0.024-0.03, N: 0.06-0.08%). This is a low carbon stainless steel chosen to ensure freedom from sensitization during welding and Intergranular corrosion of the components. In addition, this steel also possesses excellent mechanical and creep properties. SS316LN materials were procured in solution annealed, pickled and passivated condition. During material procurement, specimens of the plates were subjected to chemical examination, metallographic examination, test for delta ferrite, inclusion content test, Intergranular corrosion test as per ASTM A262, Practice E. During material procurement, plates were subjected to thorough Visual Examination/Liquid Penetrant Examination (LPE) and 100% Ultrasonic Examination (UE) with minimum 10% overlap of previous scan to ensure soundness of the plate. Grain size and chemical composition of plate material has been precisely specified with upper & lower values to optimize the mechanical & creep properties. During plate procurement, high temperature tensile test is also carried out in addition to tensile test at ambient temperature on specimens to evaluate & ascertain the properties for service conditions

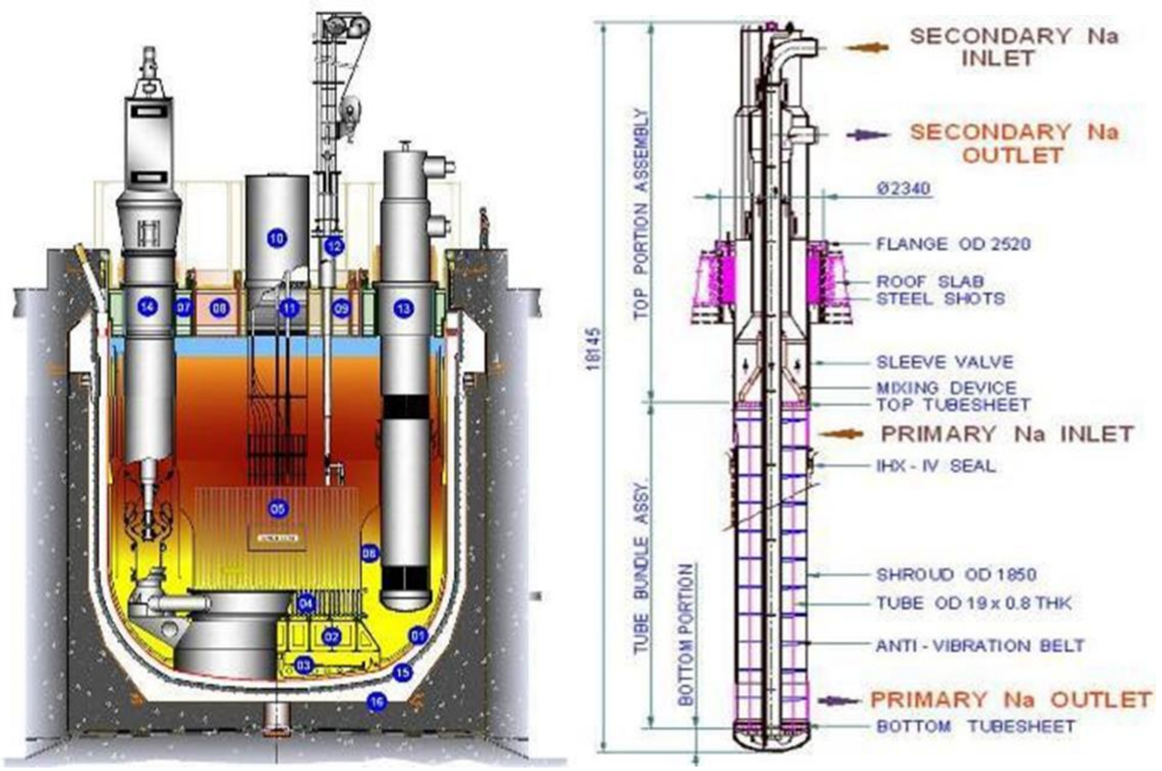

Figure.3: Primary reactor assembly and Intermediate Heat Exchanger of PFBR

The tubes are seamless and both tubes & tubesheets are produced by electric arc melting with tight control on inclusion content to achieve sound weld during autogenous welding process between the tubesheet and tube. Ultrasonic test is done on the entire length of each tube in accordance with ASME Sec.III Class I. Each tube is subjected to hydro testing as per PFBR specification to ensure the integrity. Tube bundle activities of IHX were done in separate nuclear clean hall conditions as per the class-1 component requirements of PFBR. The tube to tubesheet joints are rolled and subsequently seal welded by autogenous pulsed Gas Tungsten Arc Welding (GTAW) process. Even though conventional heat exchanger tube to tubesheet joints are done first by welding and then rolling, PFBR tube to tubesheet joints are executed first by rolling using mechanical tube expanders and then welding to avoid stresses on the welds during tube expansion step. After completion of tube bundle, IHX tube bundle is subjected to Helium Leak Test (HLT) under vacuum as per PFBR specification during which the global leak rate shall not be more than 10^{-7} Pa-m^3/s

Figure.4: Tube to tubesheet rolling and welding of Intermediate Heat Exchanger

4. QUALITY MANAGEMENT DURING DHX TUBE BUNDLE FABRICATION

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 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-5). 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.

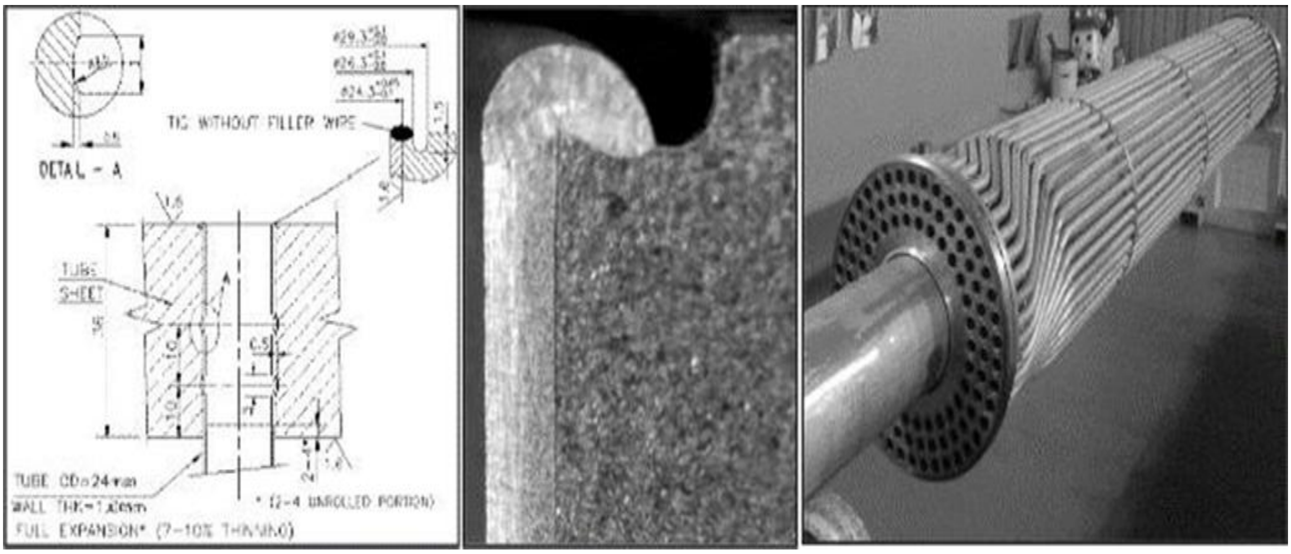

Fig.5: Tube to tubesheet joint details and tube bundle of DHX.

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 florescent 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, 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, floroscent LPE and Helium leak testing (Figure-3) are done on the production tube to tubesheet joints. The non-destructive examinations and testing requirements on production joints are stringent. Acceptance criteria of tube to tubesheet weld joints are given in Table 1. All specification requirements were met during tube to tubesheet welding procedure qualification and during fabrication on the actual job.

5. QUALITY MANAGEMENT DURING AHX TUBE BUNDLE FABRICATION

The tube to tube weld joint is carried out by autogenous pulsed GTAW process in 5G position. The development program for tube to tube welding was a concentrated effort of almost 18 months. Various different types of trials were conducted on the mock up by welding enormous nos. of joints. As there is no past experience of welding on higher thickness by autogenous welding process, the technology development for tube to tube welding was an exigent task. Welding on higher thickness (as received tube thickness was in the range of 2.8-2.9mm which was within the positive tolerance of specification requirement) by autogenous welding process specifically on modified 9Cr-1Mo material is carried out for the first time in the country and no open literatures are available on above topic. The major defects observed during welding procedure qualification are inconsistent penetration and depressions on face of the weld. These defects have been overcome by trial and error method by adjusting various welding process parameters. The optimized autogenous pulsed GTAW process parameters includes square butt type tube to tube setup before welding, 6 sector programming in the welding machine, use of 1.2mm diameter 2% thoriated tungsten electrode with ultra-high purity (99.999%) argon gas for shielding and back side purging. Liquid Penetrant Examination (LPE) is carried out for WEP before setup of tubes to examine the surface indications if any before start of welding. During qualification, weld joints were subjected to thorough visual examination before & after PWHT, LPE before & after PWHT, Magnetic Particle Examination (MPE) before & after PWHT, radiography examination before & after PWHT, transverse tensile test at room temperature and high temperature (550°C), bend tests (face bend & root bend), hardness survey (Before& after PWHT) and metallographic examination at 200X magnification to ensure that weld is free from micro cracks. No indication is the acceptance criteria for WEP and tube to tube welds during liquid penetrant examination. The acceptance criteria for balance examinations are stringent compared to acceptance criteria of ASME

Fig.6: Tube bundle fabrication of AHX- B.

The tube bundle is assembled using fixture in such a way that the entire tube bundle is supported by the centre shaft (Figure-6) which can be rotated during fabrication for accessibility and feasibility. Tube bundle fabrication starts with tube to tube welding of straight finned tubes. The complete massive tube bundle is rotated for finned tube to tube welding process, which requires extraordinary precautions and safety measures. After completion of all straight finned tube to tube welding, pullout header sectors are positioned for straight finned tube to bend tube welding and bend tube to header pullout welding. The header pullout to bend tube welding (Figure-6) is carried out by manual GTAW process using ER 90S B-9 filler wire. Each bend tube to header pullout joint is welded in three passes manually.

In the case of AHX-A, there are 116 nos. of Modified 9Cr-1Mo tubes of OD 38.1mm and 2.6mm wall thickness. Tube bundle activities are carried out in separate nuclear clean hall conditions as per class-1 component requirements of PFBR to ensure the quality. Due to complex constructional features, the heat treatment is not straight forward. The PWHT of individual tube to tube weld joint is carried out by electrical resistance method using metallic split cartridge. Enormous nos. of trials were conducted to establish the procedure for local PWHT of header pullout to tube weld joints using metallic split cartridge. The temperature control was extremely difficult due to asymmetric shape and non-uniform mass of pullouts. Hence, it was decided to carry out PWHT of header pullout to tube weld joints along with PWHT of 12mm thick header weld joints. After fabrication of complete cylindrical header, PWHT is carried out at 760±10 deg C for 2 hours for 12mm thick longitudinal & circumferential weld joints. Then, welding of middle row header pullout to tube joint is carried out and complete header assembly is again heat treated at 760±10 deg C for 1 hour soaking time. Subsequently, inner and outer row header pullout to tube welding is carried out and complete header is again subjected to heat treatment for another 1 hour soaking time.12mm thick weld joints undergoes heat treatment for total 4 hours, Middle row header pullout to tube weld joint undergoes heat treatment for total 2 hours soaking time, Outer & inner row header pullout to tube weld joint undergoes heat treatment for 1 hours soaking time.

Fig.7: Tube bundle fabrication of AHX- A.

6. QUALITY MANAGEMENT DURING SG TUBE BUNDLE FABRICATION

Each SG (Figure -8) has 547 nos. of seamless tubes of 17.2 mm OD, 2.3 mm wall thickness and 23meter in length welded to top and bottom tubesheets at the ends. Autogenous internal bore pulsed Gas Tungsten Arc Welding (GTAW) with raised spigot design (Fig. 2) is selected for tube to tubesheet joints over the traditional rolled & welded joint to keep the welds in a low stress region and this design permits radiography & post weld heat treatment of individual tube to tubesheet weld joints which is specified to avoid risk of stress corrosion & reheat cracking. Tube bundle activities of the steam generator are done in separate Nuclear Clean Hall conditions as per the class-1 component requirements of PFBR.

The welding process for tube to tubesheet selected is inside bore, autogenous pulsed GTAW process. Each tube to tubesheet joint is preheated to 200-250 deg C and subjected to Post Weld Heat Treatment (PWHT) at 760±100 deg C for 30 minutes. Each tube to tubesheet joint is subjected to thorough visual examination, LPE, radiography using micro-focal rod anode x ray, profile check (concavity, convexity and wall thickness), pressure testing and helium leak testing. Specially designed dial gauge is used to check the weld profile from inside for all the joints. Replica technique is also used to crosscheck the internal weld profile for 1% of the total joints in addition to dial gauge measurement. External profile measurement is done by replica technique for all the weld joints. After completion of tube bundle, the row wise hydro test is done to check the integrity. Subsequently, shell assembly is carried out around the tube bundle.

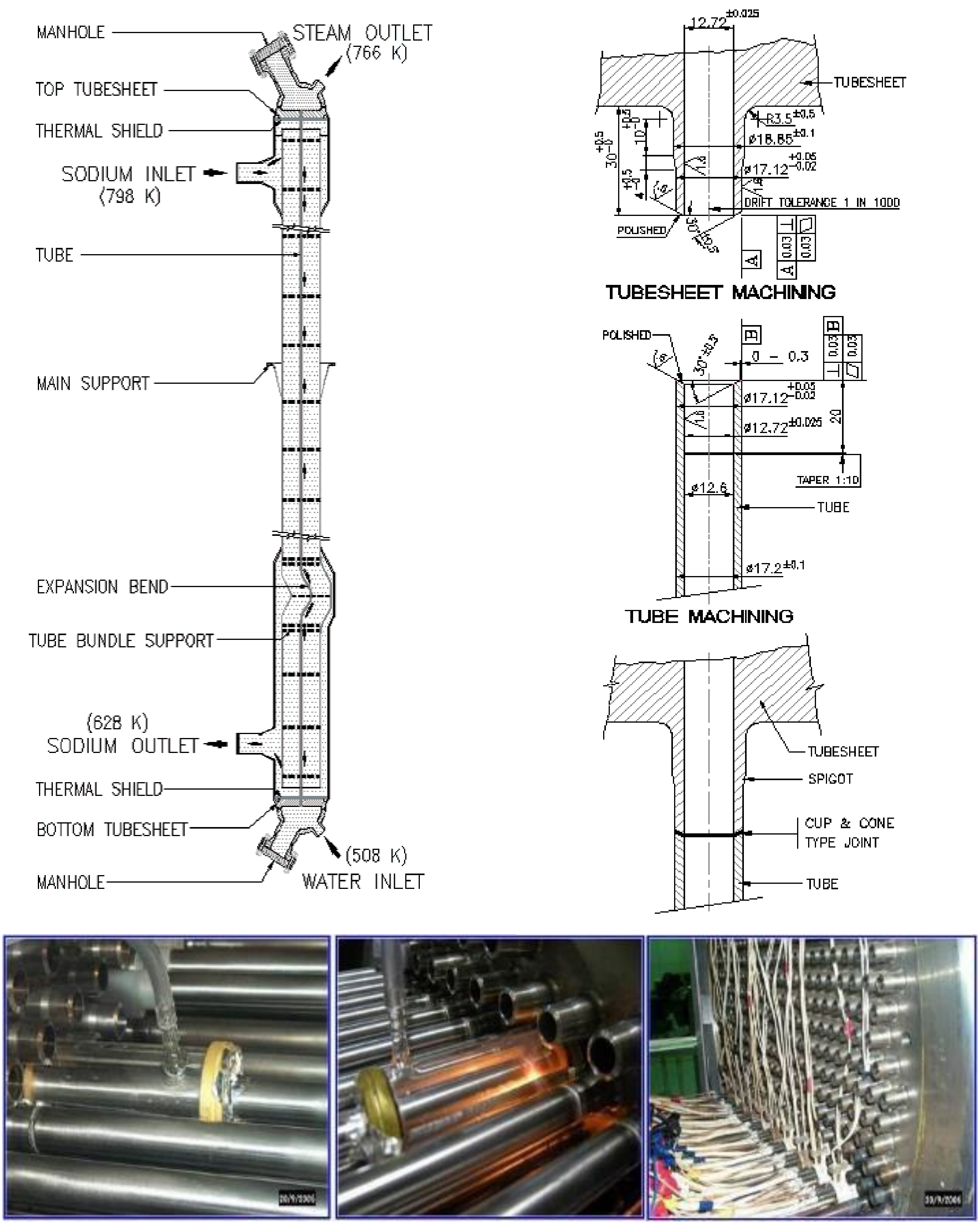

Figure.8: Tube to tubesheet welding of SG and local PWHT of joints

The development program for the tube to tubesheet welding was a concentrated effort of almost 10 months. Extensive 22 different types of tube to tubesheet welding trials were conducted by welding over 500 joints. The major defects observed in the tube to tubesheet welds are porosities. Lack of fusion, Lack of penetration, linear indications and profile deviations were also observed in the tube to tubesheet welds during development. During initial trials the tube and spigot ends were cleaned with the help of abrasive cleaning followed by swabbing with white cloth dipped in acetone. Around 25% of the joints were found to have porosities with the above cleaning procedure. In order to improve the quality of welds and to achieve consistent results, different cleaning procedures were studied. Finally, it was concluded to carry out 0.1mm skim cut of spigot & tube ends and SS wire brush cleaning of the tube & spigot ends followed by acetone cleaning by using lint free cloth. It was learnt that very high level of cleanliness is required to achieve porosity free joints. Approximately 10% of the joints showed profile deviation during initial trials. Further analysis revealed that the problem was localized and related to setup methods & offset produced during the setup. Initial design of the square butt of tube and spigot weld edge preparation (WEP) is changed to cup & cone type butt joint to facilitate better setup. Offset check was introduced at the setup stage before start of tube to tubesheet welding. Considerable improvement was observed in the profile after the above development and design change.

7. CONCLUSION

Manufacture of heat exchangers and tube bundle fabrication for PFBR has been a great challenge. The specification requirements, dimensional tolerances and acceptance criteria for PFBR are far more stringent than ASME or many other international standards. It is heartening that the design features have been correctly translated into welding and manufacture in PFBR. The achievement in welding science and technology during construction of Prototype Fast Breeder Reactor is a matter of pride to the nation. Very high standard quality control & quality assurance during welding and fabrication has given adequate confidence on trouble free service from Prototype Fast Breeder Reactor for the designed service life of 40 years

REFERENCES

[1] Aravinda Pai, T.K.Mitra, T.Loganathan and Prabhat Kumar, “Design and fabrication of serpentine tube type sodium to air heat exchangers for PFBR SGDHR circuits”, International conference on fast reactors and related fuel cycles (FR-2013), 4-7 March 2013, Paris, France

[2] T.K.Mitra, Aravinda Pai and Prabhat Kumar, “Manufacturing experience of hardfacing of Intermediate Heat Exchangers-Inner vessel seal assembly for 500MWe Prototype Fast Breeder Reactor”, IIW-2009, 16- 17 July 2009, Singapore.

[3] Aravinda Pai, T.K.Mitra and Prabhat Kumar, “Manufacturing experience of tube to tubesheet joints of PFBR Intermediate Heat Exchangers”, Proc National Welding Seminar, February 2009,Mumbai, India.

[4] T.K.Mitra and S.C.Chetal, Design And Manufacture of PFBR Steam Generator, Proc. International Conference on Pressure Vessels and Piping (OPE 2006), pp 7-9, Feb. 2006, Chennai, India.

[5] A.John Arul, C.Senthil Kumar, S.Athmalingam, Om Pal Singh and K.Suryaprakasa Rao “Reliability analysis of safety grade decay heat removal system of Indian prototype fast breeder reactor, Annals of Nuclear Energy-33, pp 180–188, 2006.