Challenges during Manufacture of reactor components of PFBR

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Abstract. BHAVINI is constructing Prototype Fast Breeder Reactor (PFBR), forerunner of FBRs, a 500 MWe sodium cooled, pool type, mixed oxide (MOX) fueled reactor at Kalpakkam. Presently PFBR is in the commissioning phase. Reactor assembly consists of large dimensional vessels viz., Safety Vessel, Main Vessel and Inner Vessel made of Austenitic stainless steel. Top shield is a box type structure comprising of Roof Slab, Rotatable plugs viz., Large and Small plugs made of Carbon steel A48P2 material and Control Plug at the center. The entire core is placed over the Grid Plate which in turn is supported by Core Support Structure equipped with Core Catcher at the bottom. The control and shutdown mechanisms are housed inside the Control Plug with necessary provisions for core instrumentation. The vessel houses the primary heat transport circuit which consists of Primary sodium pump, Primary Pipe and Intermediate heat exchanger transferring the primary heat from the core. The in-vessel and ex-vessel core handling are performed by Transfer Arm and Inclined Fuel Transfer machine. The decay heat is removed by passive systems consisting of Decay Heat Exchanger and associated components. The reactor is equipped with in-vessel and ex-vessel in-service inspection devices. These components had undergone many stages of manufacturing viz. forming, rolling, welding, machining etc. meeting the stringent specification requirements as neither repairs nor replacement can be possible at the later stages of reactor operation for major components. The dimensional tolerances were respected at various stages of manufacture and the interfaces of these Over Dimensional Components were meticulously matched to avoid interferences during final assembly inside the reactor vessel. This paper presents the challenges faced during the manufacture of critical reactor components which serve as a vital input to future fast reactor program in India.

Key Words: forming, rolling, welding, machining.

1. Introduction

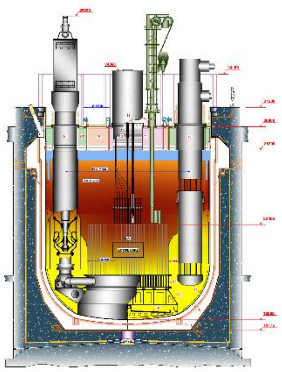

Fig 1: PFBR Reactor Assembly

Prototype Fast Breeder Reactor (PFBR) 1250 MW t / 500 MWe is presently under advance stage of commissioning at Kalpakkam site. Being a pool type reactor, it requires large diameter vessels and internals. Reactor assembly of PFBR, consists of primary sodium circuit contained by main vessel (MV) made of SS 316 LN material supported at the top with top shield containing roof slab, large and small rotatable plugs and control plug. The core subassemblies are supported on grid plate (GP) and their collective load is transferred to main vessel through core support structure (CSS). Safety Vessel (SV) made of SS 304 LN with Ø13.5 m and 12.5 m height is positioned concentric to main vessel on outer side. Inner vessel (IV) separates the hot and cold pools of primary sodium and houses primary sodium pumps (PSP - 2 Nos.) and intermediate heat exchangers (IHX - 4 Nos.) at the bottom end.

Reactor assembly is housed in a concrete vault lined with carbon steel. The roof slab integrated to top end of main vessel is hung from a cylindrical support shell, which in turn is welded to an embedment provided in the reactor vault concrete. Fig. 1 shows the cross section of PFBR reactor assembly. Two thermal baffles, outer and inner form a part of the main vessel cooling system and welded concentric to inside of MV at optimum elevation. Altogether weight of components and sodium is carried by main vessel. This paper discusses the manufacturing challenges of reactor assembly components at PFBR site towards meeting the stringent tolerances on various dimensions and NDE requirements.

2. Design features

High operating temperature of the system and use of sodium as coolant due to its good heat transfer property, and the associated stresses developed due to thermal transients necessitate use of thin walled structure. Sensitisation of stainless steel materials is to be kept low to avoid intergranular corrosion, pitting corrosion, intergranular stress corrosion cracking, loss of ductility etc., Distortion during weld is to be kept minimum to avoid stress concentration and to maintain dimensional stability. Minimum heat input is to be used during welding. Delta ferrite shall be maintained at the minimum level to avoid sigma phase formation during operation at high temperature. All the above lead to specify more stringent requirements than those required for other thermal reactors.

2.1. Material Specification

The material chosen for construction is SS 316 LN (MV, IV & TB) for its high temperature strength and compatibility with sodium. Low carbon grade has been chosen to ensure freedom from sensitisation during welding of the components and hence to avoid risk of chloride stress corrosion cracking during storage in coastal site. Nitrogen is specified as an alloying element to improve the mechanical properties so that the strength is comparable to that of SS 316. Although SS 316 L (N) specified by ASME has nitrogen in the range of 0.10 to 0.16 wt%, for PFBR, nitrogen content is limited to 0.08 wt% in view of improved weldability and for minimising scatter in mechanical properties.

Phosphorus, sulphur and silicon are treated as impurities, as they have adverse effects on weldability. Therefore, acceptable maximum limits are reduced to values that can be achieved in steel making practice. Considering the adverse effects of titanium, niobium, copper and boron on weldability, maximum permissible limits have been imposed. A minimum level has been specified for manganese to improve weldability.

Additional mechanical tests like impact strength at room temperature in solution annealed and embrittled condition, tensile test at elevated temperature, control on delta ferrite, stringent control over inclusion content etc., are specified.

2.2. Dimensional requirements

Thin walled vessels designed to withstand leading thermal stresses due to usage of sodium as a coolant requires tight tolerances on shells to provide rigidity against buckling. Major dimensional tolerances for cylindrical shells and dished end like form tolerance, local deviations roundness & straightness, contour are stringent compared to RCC – MR. Additional supplementary controls are also specified on straightness of the generatrix, weld mismatch, circumference control etc., to control the deviations in forming of the shells.

2.3. Welding requirements

Design requirements to be respected during welding are stringent when compared to other codes.

Distortion and shrinkage during welding is to be minimized for avoiding stress concentration and to achieve dimensional accuracy. The following methods are used to minimize distortion and shrinkage;

i. *Minimum heat input/unit length of weld.*
ii. *Welding on both sides wherever possible.*
iii. *Sequencing of welding.*
iv. *Simultaneous welding by two (or) more welders in case of large length welds and large dia pipes.*
v. *Use of minimum bevel angles.*
vi. *Use of special fixtures wherever required.*
vii. *Limiting number of repairs.*

The qualification production test coupons must undergo all the destructive and non-destructive examinations applied in fabrication to the joints it qualifies and must satisfy the highest quality level requirements applicable to these joints. These examinations are visual examination, NDT examination and various destructive tests. These requirements make the procedure qualification more difficult than that qualified by only tensile and bend tests required as per ASTM.

2.4. Requirement of hard facing

The interfacing surfaces between various reactor assembly components (Core Catcher to Main Vessel, Core Support Structure to Grid Plate and Primary Pipe, Grid Plate to Core Subassemblies may be subjected to galling or self-welding during reactor operating temperature of 670K. During reactor operation, there will be relative radial thermal expansion between the adjacent components due to thermal transients. Hence, radial movement should be permitted to avoid harmful thermal stresses being developed at these locations. Therefore hard facing was carried out at the interfacing surfaces. These hard faced coating shall have sufficient bond strength during thermal cycles without flaking. Any cracks in the hard facing surface will severely affect the functioning of the components. Achieving crack free deposition was therefore crucial. Dimensionally, the hard facing profile, thickness, horizontality of hard facing tracks, the relative height between the two hard faced tracks were highly respected during implementation of hard facing.

2.5. Welding Procedure qualification for hard facing

The welding parameters were optimized to minimize the magnitude of residual stress, to eliminate the risk of micro cracking, dilution of deposit and de-lamination of the hard face deposit. The preheat temperature, coating thickness, heat input, deposition process and the geometry of the component were finalized bases on extensive mock up. Accordingly travel speed, oscillation distance, gas supply were decided to achieve the desired metallurgical and dimensional results. The welded coupons were subjected to metallographic examination, micro hardness (tangential & longitudinal), surface hardness, thickness measurements, IGC & bend test and chemical analysis. This methodology was adopted for performing hard facing in all the reactor assembly components viz., Core Catcher, Core Support Structure, Grid Plate and Primary Pipe. The test results met the specification requirements.

3. Manufacturing Challenges

3.1.1 Primary Pipe with Spherical Header

The spherical header was required to be made in not more than three formed parts welded together. It was intended to be formed with three pull outs for the vertical pipes and two horizontal pipes. However, during trial, it was found difficult to make pull outs in the formed spherical header segments. Hence, rolled and welded plates for horizontal pipes were revised to forged nozzles accommodating the pull out region of the header. The configuration was thus achieved after meticulous efforts to meet the final dimensional requirements.

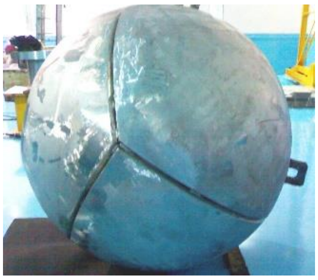

Fig. 2. Spherical Header

3.1.2 Branch Pipe Bends

The branch pipes interconnects the horizontal nozzles provided in the spherical header with the nozzles provided in the Grid plate Shell. The branch pipe bends were cold formed in two halves. Procedure qualification was performed for cold forming. Die and Punch was qualified before actual forming and contact with carbon steel was avoided. Half segment forming was carried out on press using full size die and punch. Hardness and thickness of segments were checked and grid lines were also checked to calculate strain. Mechanical testing from the end extra portion was taken up. On satisfactory results, the two segments were welded to achieve the required branch bends.

3.1.3 Flow baffles

The flow baffles were necessary to have smooth propagation of sodium flow and hence to reduce the pressure drop in the sodium discharge from the primary sodium pump. The assembly of flow baffles consists of a central cone in the header and a non axi–symmetric baffle (3D baffle). The baffle joins the Central cone at the central horizontal plane of Spherical header and it joins the header at the bottom location of the discharge pipes. The baffles were hot formed to the required profile. The profile of baffle plates were checked at locations on 4 concentric circles along 24 generators 15° apart and they met the stringent dimensional tolerances.

3.1.4 Critical interfaces locations:

The critical dimensional interfaces were to be respected to facilitate assembly of various reactor assembly components inside main vessel. Some of the interfacing parameters of Primary pipe with other adjacent components viz., Core Support Structure, Primary sodium pumps & Grid Plate are indicated below:

a) Inner radius w.r.t. outer radius of mating component (hardfaced location)
b) Diameter of bend pipes after forming.
c) Diameter of nozzle after welding
d) Parrallelism of nozzle pipes
e) Concentricity of nozzle to bend pipes

3.2 Grid Plate

After subjecting the raw materials to various severe testing requirements, welding of higher thickness Plates were taken up for the manufacture of top and bottom plates of Grid Plate. Stress relieving heat treatment (1065°C) were carried out and subsequently, Radiographic examination of weld joints were performed to qualify the weld joints. Machining Operations which include Gantry milling, drilling & boring operations and subsequent Stabilizing heat treatment at 530°C and finish milling to required thickness. The Finish Assembly Boring operation was performed on on top plate with three different diameters accounting 609, 417, 732 holes. The finished plates were subjected to final Inspection and all the achieved values of parallelism, perpendicularity, flatness and surface finish met the respective drawing requirements. There were totally 32 crucial manufacturing operations in top plate and 43 in bottom plate of Grid Plate. Integration of Grid Plate with the adjacent components was successfully carried out without any interfacing issues and the machining accuracies achieved during manufacture yielded the desired results.

3.3 Core Support Structure

The Core Support Structure was manufactured taking into consideration of the stiffness requirements and the permissible slope (in conjunction with Grid Plate) so that the misalignment during subassembly handling and insertion of shut down rods is within the required limits. Since the Core Support Structure supports the concentrically placed grid plate along with the inner vessel, the dimensional accuracies were achieved starting from meeting the form tolerances during petal forming till finish machining of 7.83m diameter structure. The CSS structure consists of top plate and bottom plate interconnected by number of vertical stiffeners. At the 4 corners of the square grid, forged members were welded to the vertical stiffeners to avoid tri-junction welds. Suitable staggering and sequencing of welds were to avoid buildup of residual stresses and distortion especially of circular welds of shells. Distortion control measures were taken considering the sequence of assembly, welding, heat input to weld etc., The shrinkage and distortions of the welded joints were carefully analyzed and the average heat input were controlled by properly controlling the voltage, current and welding speed during welding to meet the mechanical and metallurgical properties of the weldment. Production test coupons were made for longitudinal and circumferential welds and these test coupons were subjected to all the tests and heat treatments as applicable and met the specification requirements.

3.4 Primary Sodium Pump

The primary sodium which transfers the heat from the core to the secondary sodium is circulated by two primary sodium pumps (PSP) located in the cold leg of the primary pool. PSP is a mechanical, centrifugal, vertical type pump. The pump has to develop a head of 75 mlc and the flow required is 4.13 m^3/s. The PSP shaft was one of the most challenging task among other manufacturing constraints faced during the assembly and testing of PSP. The total length of the shaft is 11.3 m and it weighs 6 t. The shaft was manufactured to stringent requirements concentricity between the top and bottom bearing locations, spaced 8 m apart. To achieve dimensional stability, the shaft was stress relieved at 980°C in vertical condition under controlled atmosphere. Holes of 2 m deep were drilled on top and bottom of the shaft with high precision. Finally the hollow portion of the shaft was evacuated to 0.133 kPa and seal welded to retain the vacuum. The shaft was balanced to ISO grade 1. The pump was tested at different speeds and monitoring of the hydraulics and mechanical performances were established and endurance tested. The performance results were in line with the requirements.

3.5 Forming of Dished End & Conical Petals

Fig. 3. Safety Vessel Dished End with Swing Arm Gauge

Safety vessel dished end consists of knuckle and crown portion. Due to its inherent size of the vessel, the knuckle portion of radius IR 4815 is divided into two halves in meridional direction and total of 22 petals in longitudinal direction. The crown of radius IR 19650 mm is divided two halves in meridional direction and total of 7 petals in longitudinal direction constituting overall total of 29 petals for dished end. Main vessel has 39 Nos. of petals (2 tiers of crown region having 7 petals of 30 mm thick, 1 tier of transition region having 10 petals of 40 mm thick and 2 tiers of knuckle region having 22 petals of 30 mm thick). Inner vessel has 14 special shape conical petals with double curvature at the top and bottom end. The diameter at top is 12200 mm and at 6350 mm at bottom with an overall height of 3294 mm. Redan petals are trial assembled at manufacturer works on row by row basis without the closing petals. Full trial assembly was carried out, dismantled and then brought to site for reassembly and welding. Fig.3. shows the safety vessel dished end with swing arm gauge.

Prior to procedure qualification, mock-up of petal pressing was carried out using carbon steel material of 20 mm thick to check the feasibility of pressing without point pressing and thereby qualify the vendor. On successful completion of mock-up, procedure qualification was carried out on SS material for typical regions of dished end petals. Further to template measurement, basket gauges were used for checking the profile of petals as a yard stick to reduce cycle time. Full size die and punch were deployed, incorporating the spring-back allowances for pressing, since point pressing was not recommended.

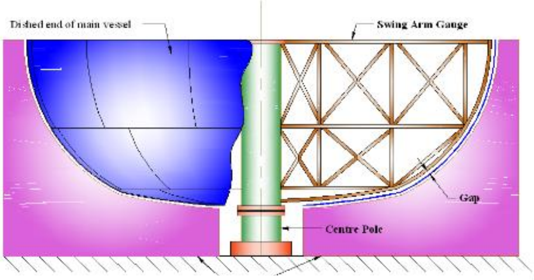

Fig. 4. Schematic Diagram of Swing Arm Gauge

Profile inspection of these large sized petals requires a special technique of inspection by using templates and employing non-contact method. During assembly, special inspection method such as Swing Arm Gauge and Electronic Coordinate Determinate System are used for accurate inspection of these large dished end vessels. All the welds are ground flush with the base material or to required radius and are examined by visual, liquid penetrant inspection on weld edge preparation (before weld fit up), root pass, back gouge and on the finished weld. 100% of the weld length is examined by radiography inspection methods and helium leak tested under vacuum by jacket method.

3.5.1 Circumference Matching

Cylindrical portion of safety vessel, main vessel & Inner vessel consists of 3, 4 & 2 shell courses respectively. Initially shell segments were taken up for fit up and then welding was carried out sparing one shell segment space open. After completion of segments welding, the last/ closing segment is trimmed accordingly to maintain the circumference specified. Subsequently the weld edge preparation for the last segment was made after fixing the length for meeting the required circumference considering the root gap and weld shrinkage and then welded to form the shell course. On completion of shell courses, shell course-1 and shell course-2 were welded circumferentially, followed by shell course-3 welded with assembly.

3.5.2 Weld Overlay at Transition Region

To facilitate the weld between core support structure support shell and transition region, weld deposition was carried out on the inside surface of transition region of main vessel along the circumference. This 25 m circumferential weld deposit was carried out in a sequential manner by continuous monitoring on the heat input, interpass temperature and other weld parameters. The contour and profile was achieved as per drawing respecting the elevation requirements by grinding. Transition region was cleared by ultrasonic examination before and after overlay.

3.6 Welding of Core Support Structure Support Shell

Welding of Core support structure support shell on weld overlay in main vessel was carried out in a phased manner. This support shell of 3900 mm radius with 30 mm thick consists of three segments. 24 holes were drilled on the circumference of the shell prior to welding to transition region considering the root gap & shrinkage allowance. Dimensional requirements of the shell including the elevation of 24 Nos. of holes, orientation of holes matching with thermal baffle support plate located at middle of main vessel, circumference of the shell matching with circumference of CSS component were achieved with in the tolerances specified. Utmost care was taken to maintain the circumference and verticality during welding of core catcher support plate inside the shell. This facilitated easy welding of main vessel cooling pipes to thermal baffle support.

3.7 Integration of Thermal Baffle with Main Vessel

Two concentric shells of diameter 12440 mm and 12670 mm with total height of baffle 4930 mm was lifted with suitable lifting spider and integrated with main vessel. The requirement on horizontality of thermal baffle was stringent due to its system requirement. The annular space between thermal baffle and main vessel was maintained by maintaining the horizontality of baffles. Controlled heat input and sequencing of welding was key parameters to respect the specified tolerances.

3.8 Hard facing of inner vessel standpipes

Fig. 6. Stand Pipe Weld on Inner Vessel

inner vessel

Fig. 5. Stand Pipe Weld on Inner Vessel

There are four hard faced standpipes in inner vessel (Fig.5) through which intermediate heat exchangers pass. These standpipes form part of mechanical seals to minimise leakage of hot sodium into cold pool. After hard facing of the first standpipe, defects were noticed. The root cause analysis was carried out and the first standpipe was rejected and the following improvements were made in the hard facing of other standpipes. The hard facing groove configuration was modified. For preheating and PWHT, the cooling, heating and holding were rigorously controlled so as to be uniform throughout the standpipe, the insulation thickness and effectiveness were improved, rigid circumferential and longitudinal restraints were tack welded to the outside of standpipes, deposition parameters were suitably modified etc. With these changes, the ovality could be respected.

3.9 Quality Assurance

Quality assurance activities on these over dimensional vessels commenced from the procurement stage of raw material to final dimensional inspection and non-destructive examinations viz., LPE, UE, RE & Helium leak test for joints. Apart from conventional dimensional measurements, ECDS measurements were taken on all the vessels.

4. Conclusions

The challenges in manufacture of over dimensional vessels of such large size made the Indian industries to fine tune the manufacturing processes. The experience in manufacturing of over dimensional components has given boosting to the Indian industries. The feedback experiences will be useful for the future FBR programme start from design to manufacture and installation of large sized reactor components towards reducing the construction time.

Appendix 1: References

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