Quality Management during Manufacture of Block Pile Components 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 in an advanced stage of construction. 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 the primary and secondary sodium systems of PFBR. Versatile types of systems and varieties of components with complex constructional features require diversities in welding and fabrication processes for the PFBR components. The quantum of welding and fabrication too are fairly large for the large reactor equipment of PFBR. High operating temperature of various systems causing high stresses are minimized by designing thin walled structure. 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. High distortion in stainless steels due to high thermal expansion and low thermal conductivity offers challenge to the fabricators to achieve stringent tolerance in large size PFBR components. 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 for reactor equipment 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 few of critical nuclear reactor equipment/systems of 500MWe Prototype Fast Breeder Reactor.**

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

I. INTRODUCTION

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 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 manufacturing.

International Journal of Engineering Research and Reviews ISSN 2348-697X (Online)
Vol. 4, Issue 2, pp: (45-51), Month: April - June 2016, Available at: www.researchpublish.com

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.

II. INSIGHT INTO THE NSSS COMPONENTS 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).**

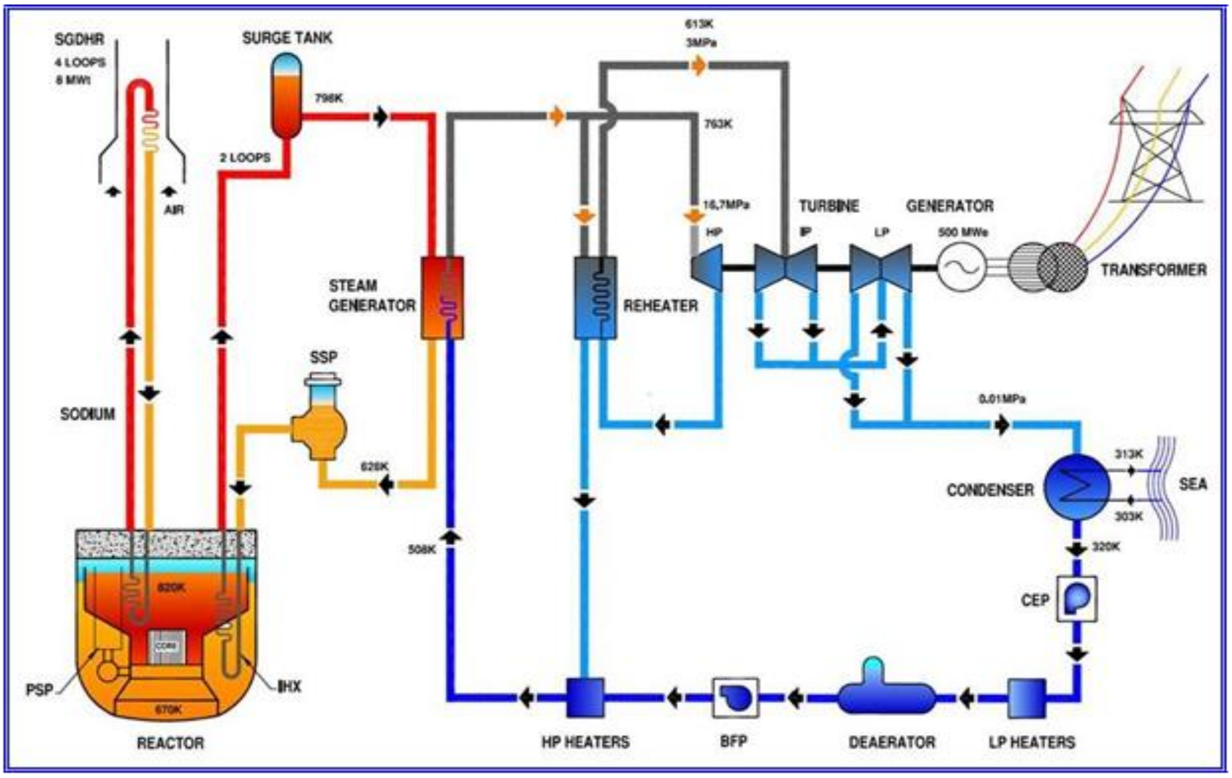
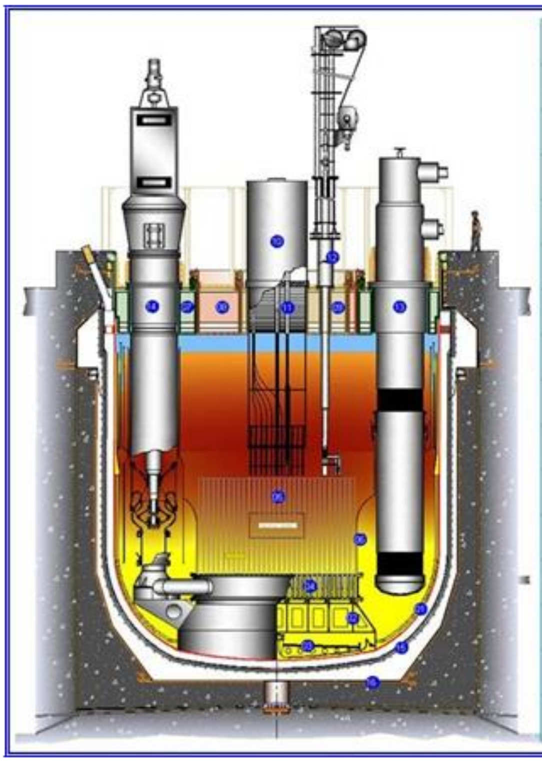


Figure-1: Prototype Fast Breeder Reactor flow chart

The main vessel has no penetration and is welded at the top to the Roof Slab (RF). The main function of Roof Slab (RS) is to provide thermal and biological shielding in the upper axial direction from the hot sodium pool and acts as a part of primary containment boundary supporting various reactor components. The core subassemblies are supported on the Grid Plate (GP), which in turn is supported on the core support structure (CSS). As a matter of abundant precaution, a Core Catcher (CC) is provided just below the core support structure. The Core Catcher is designed to prevent the core debris reaching the main vessel when seven fuel assemblies melt and ensures the cooling of the debris by natural convection of sodium. The Main Vessel (MV) is surrounded by the Safety Vessel (SV) closely following the shape of the Main Vessel, with a nominal gap of 300mm which is large enough to permit ultrasonic inspection of the vessels using a robotic inspection vehicle. The space between the Main and Safety Vessels is small enough to keep the sodium level above the inlet windows of IHX ensuring continued cooling of the core in case of a leak of main vessel. Liquid sodium at 397°C is circulated by two primary sodium pumps through the core and in turn gets heated to 547°C. The non-radioactive secondary sodium is circulated through two independent secondary loops, each having a secondary sodium pump, two IHX's and four steam generators (SG's). The primary and secondary sodium pumps are vertical, single stage and single suction centrifugal type with variable speed AC drives. The Steam Generators (SG) are a vertical, once through, shell and tube type heat exchangers with liquid sodium flowing in the shell side and water/steam flowing in the tube side. PFBR has 181 fuel sub-assemblies arranged in a triangular pitch. Alloy D9 in 20% cold worked condition (20CW D9) has been chosen for clad and wrapper tubes of PFBR due to its high resistance for swelling and irradiation creep. The PFBR also has enhanced negative reactivity in the core, which is an important inherent safety feature of the reactor.



01	Main Vessel
02	Core Support Structure
03	Core Catcher
04	Grid Plate
05	Core
06	Inner Vessel
07	Roof Slab
08	Large Rotating Plug
09	Small Rotating Plug
10	Control Plug
11	CSRDM / DSRDM
12	Transfer Arm
13	Intermediate Heat Exchanger
14	Primary Sodium Pump
15	Safety Vessel
16	Reactor Vault

Figure-2: Reactor assembly components of PFBR

TABLE I: COMPONENTS AND MATERIAL OF CONSTRUCTION

Sl. No	Components	Materials of construction
1	Fuel clad & subassembly wrapper	20% CW D9
2	Main vessel, Safety vessel, Inner vessel, Core support structure, Grid plate, Intermediate Heat Exchanger, Secondary sodium main piping	SS 316 LN
3	Roof slab, Large Rotatable plug, Small Rotatable plug	A48P2 (C.S.)
4	Primary sodium pumps, Secondary sodium pumps, tanks and auxiliary piping	SS 304 LN
5	Steam Generator, Sodium to air heat exchangers	Modified 9Cr-1Mo (Grade 91)

III. WELDING QUALITY MANAGEMENT OF NSSS COMPONENTS

Diversity of activities, diversity of environment at different places of works, ever changing scenarios, difficult field conditions to work and perform, diversity of people and skills at different periods of project activities are only a few of the complexities that a mega project like PFBR encounters. Large size thin wall reactor vessel fabrication at site, handling and erection, complex geometry of grid plate, roof slab, control plug, control rods, stringent form, position and dimensional tolerances during fabrication and erection and very stringent weld specification make PFBR construction extremely exciting. The quality requirements in every arena of PFBR are far in excess of conventional engineering projects. BHAVINI Quality management has gone beyond the specification requirements whenever required irrespective of the cost involved for high quality steel production for reactor equipment with stage by stage inspection from laddle to product for raw materials, deployment of high quality welding consumables, deployment of highly skilled & qualified welders and creation of Nuclear Clean Halls for equipment Manufacture. Highest level of quality control measures are imparted during every stage of welding, fabrication, Non-Destructive Examinations (NDE), testing, handling, erection and post erection preservation of reactor components. The positive experience of achievements in the field of new technology is the matter of pride to the nation. The PFBR has overcome many high technology manufacturing challenges by successful fabrication of critical, over dimensional reactor equipment with close tolerances. Many new and innovative procedures/techniques were developed for erection of reactor equipment meeting all the stringent specification requirements. The project has moved with robust demonstration of Indian technological capability.

The major factors considered for the selection of materials include operating environment, availability of design data in nuclear codes, International experience, and quality & safety parameters. The principal 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 low carbon nitrogen alloyed stainless steel provides required material properties, ensures freedom from sensitization during welding and inter- granular corrosion of the components. In addition, this steel also possesses excellent high temperature mechanical properties. SS316LN plates were procured in solution annealed, pickled and passivated condition. During material procurement, specimens of the materials 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 materials have been precisely specified with upper and lower values to optimize the mechanical and creep properties. During material procurement, high temperature tensile test is also carried out in addition to tensile test at ambient temperature on the specimens to evaluate and ascertain the properties for service conditions. The raw materials like plates, forgings, tubes, pipes, bars etc. are procured as per approved quality assurance plan with stage by stage inspection to assure the quality even though failure probability for raw material is low.

TABLE II: ACCEPTANCE CRITERIA OF WELD JOINTS

SL.No	Defects	Tolerance
1	Mismatch (For Both Sides weld)	For $t < 5mm$, t/4mm max.
		$t \geq 5mm$, t/10 + 1mm with 4mm max.
	Mismatch (For single Side weld)	FOR $t < 5mm$, t/4mm max. $t \geq 5mm$, t/20 + 1mm with 3mm max.
2	Slope on welding materials of different thickness	Slope $\leq 1/4$
3	Reinforcement (Face side)	Reinforcement $\leq$ Width/10 + 1mm
4	Reinforcement (root side) without back gouging	Reinforcement $\leq$ t/20 +0.5mm OR 1.5mm max.
		t= thickness of thinner part
5	Unfilled groove/root concavity, Undercut, Arc bite, Lack of penetration, Lack of fusion, Any type of crack, Arc spatter	NIL

The welding and fabrication of PFBR equipment are carried out by combination of Gas Tungsten Arc Welding (GTAW) and Shielded Metal Arc Welding (SMAW) processes. The welding is carried out using 16-8-2 filler wires and E 316-15 electrodes with controlled heat input to minimize the distortion and dimensional deviations. The welding procedure is qualified with stringent destructive and non- destructive examinations & testing before executing welding on the actual job. The acceptance limits for the joints are indicated in the Table-II. The qualification test coupons were subjected to all the non-destructive examinations applied in fabrication of actual job. During qualification, weld joints were subjected to thorough visual examination, liquid penetration examination (LPE), radiography examination (RT), longitudinal tensile test at room temperature, transverse tensile test at room temperature and high temperature (550°C), bend tests, Charpy impact test, delta ferrite content test, Inter Granular Corrosion (IGC) test and metallographic examination for the complete transverse section of the weld. The QA, QC and inspection stages are covered 100% on all welds at various stages of manufacture. Root and final pass LPE and 100% radiography examination are done for all the job weld joints. In case radiography for the job weld joint is not possible due to practical limitations, the volumetric examination of weld joint are carried out by ultrasonic examination. Production test coupons are welded for every 20m of production weld length for each type of weld joints adapting same process parameters of job welds for controlling and monitoring the weld quality during fabrication. The production test coupon undergoes all the destructive and non-destructive testing carried during procedure qualification. No re-rolling is permitted after welding on the components which may induce un-quantified stresses on the weld joints

IV. QUALITY ASSURANCE DURING MANUFACTURE OF BLOCK PILE COMPONENTS

The manufacture of reactor equipment is carried out in separate nuclear clean hall conditions as per PFBR specification. The reactor assembly components and sodium system equipment fabrication has been a great challenge. The welding with stringent tolerances along with high distortion tendency of stainless steels makes the fabrication extremely challenging. Manufacture of over dimensional components such as Main Vessel (12.9m diameter, 12.8m height, thickness varying from 25mm to 40mm, weight 135t), Safety Vessel (13.5m diameter, 12.5m height, thickness varying from 15 to 20mm, weight 110t), Inner Vessel (12.2m/6.35m diameter, 9.1m height, thickness varying from 15 to 20mm, weight 60t) involve die pressing of large size dished end and conical petals. The solution annealing of cold worked petals is a mandatory requirement if strain exceeds 10%. Innovative welding techniques were deployed for defect reduction, distortion control and reduction of heat affected zone. The forming techniques and bending methods were qualified with various examinations and testing and many trials were conducted on the mock-up for establishing the process parameters prior to taking up the actual job. Profile measurement of large sized petals requires a special technique of inspection employing non-contact type Swing Arm Gauge.

Main Vessel has three cylindrical shells with outer radius of 6450 mm & 25mm thickness and having dished end at bottom with three different radius and curvatures. The design and fabrication of Main Vessel has the typical weld joints of single 'V', Double 'V', Intricate 'K' Type and Triple point weld joints. Due to large diameter to thickness ratio, utmost care is required during welding to avoid distortion and for maintaining the dimensions within the tolerance. Distortion during welding is minimized by ensuring minimum heat input/unit length of weld, welding on both sides wherever possible, sequential welding, simultaneous welding by two or more welders in case of large length welds, use of minimum bevel angles etc. The tolerance achieved during manufacture of above vessels is within specified 10mm for the 12 meters diameter, which is one of the great accomplishments in PFBR. This was possible only due to special welding techniques and various step by step controls during fabrication. In addition to radiography examination of Main Vessel weld joints, ultrasonic examination is specified as an additional requirement for generation of Pre-Service Inspection (PSI) data, which could be later used as base-line data for In-Service Inspection (ISI). After completion of fabrication, the weld joints of Main Vessel were subjected to Helium Leak Test (HLT) during which the local leak rate has not exceeded $1X10^{-8}$ Pa-m^3/Sec. Figure-3 shows the fabricated Main Vessel and Safety Vessel at specially constructed site assembly shop at PFBR site at Kalpakkam.

Figure-3: Main Vessel and Safety Vessel of PFBR fabricated at Kalpakkam site

Thermal Baffle (Figure-4) in PFBR has two large concentric cylindrical shells, inner and outer shells of diameters 12.4m (thickness 20, 25mm) and 12.6m (thickness 20, 25 and 50mm) respectively and fabrication is one of the difficult and challenging task.

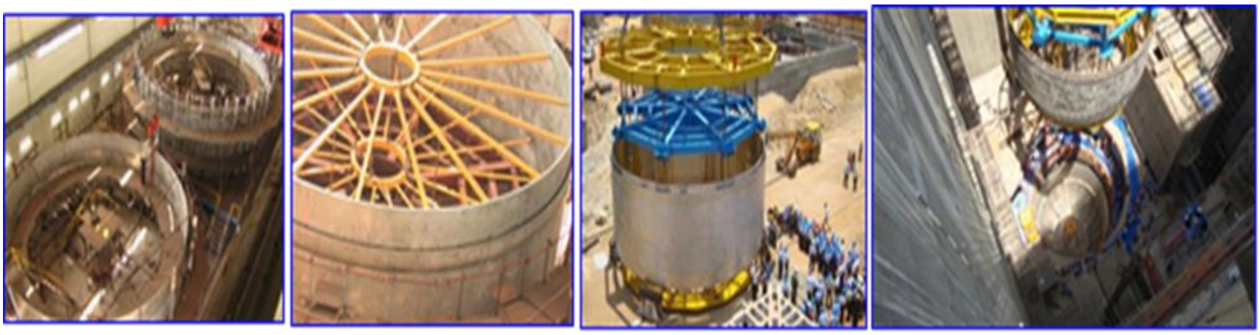


Figure-4: Thermal Baffle

Roof Slab (RS) is a box type massive structure of ~230 tones made mostly from special carbon steel plates confirming to AFNOR- A48P2 (modified) material. The RS acts like a top shield above the main vessel and supports components such as intermediate heat exchangers, decay heat exchangers, large rotatable plugs, small rotatable plugs, control plug etc. PFBR also involves dissimilar joint welding between the carbon steel (A48P2) and austenitic stainless steel (316LN) at integration location of the Roof Slab and Main Vessel. This welding is carried out by combination of GTAW and SMAW processes using ER 309L and E 309-16 welding consumables with controlled heat input to minimize the dilution of carbon. As about 2500 tons of load would act on the critical integration weld joint between the main vessel and roof slab, qualified welding procedure with foolproof quality is inevitable. The weld between sodium component i.e. primary pipe and grid plate (Figure-5) that supports the fuel subassemblies cannot be accessed for In-Service Inspection and therefore requires extra-ordinary skilled welders. Any failure of above weld during reactor operation would lead to inefficient decay heat removal from the reactor core, which must be avoided. Space constraints and lack of accessibility make the welding and inspection challenging. Highly skilled welders were deployed for welding between the primary pipes to grid plate meeting arduous specification requirements.

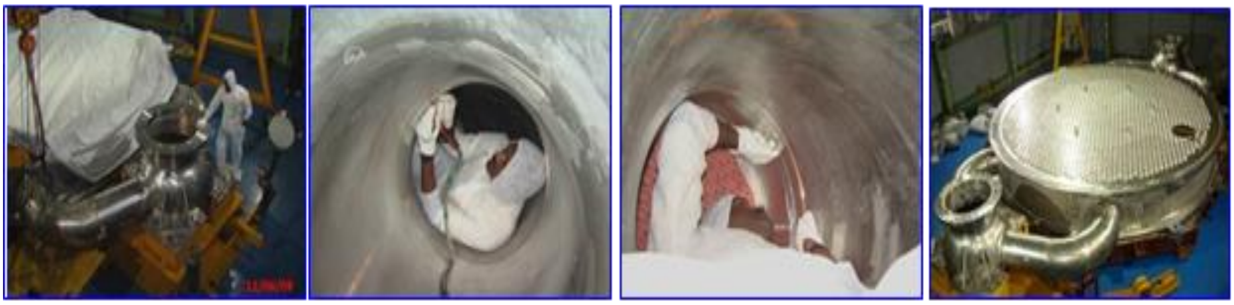


Figure-5: Welding of Grid Plate to Primary Pipe

PFBR has 181 fuel subassemblies. Core catcher is an in-vessel cooling device for post-accident heat removal of the core debris resulting from Beyond Design Basis Event (BDBE) of total instantaneous blockage to a single fuel sub-assembly. During a single sub assembly melt-down accident, the molten fuel along with structural material (core debris) in contact with liquid sodium will be fragmented and are expected to settle on the bottom surface of main vessel (MV) in the absence of core catcher. The decay heat generated within debris bed may lead to possible failure of main vessel. Hence, the core catcher serves as an in vessel core debris retention device and provides Post Accident Heal Removal (PAHR) of debris by natural circulation. Considering its importance, high standard quality control is essential during fabrication. The core support structure (CSS) is an important structure, provides support for the core. The maximum diameter of the core support structure is 7.83 meters. The CSS consists of top plate and bottom plate interconnected by number of vertical stiffeners. The vertical stiffeners are arranged in square grid pattern at the center and in radial pattern at the periphery of the structure. A number of cutouts are provided in the top and bottom plates and in vertical stiffeners to enable access for welding to all the regions during manufacture and to reduce the total weight without affecting the overall stiffness of the structure. Figure-6 shows the welding and fabrication activities of core support structure and integration with MV in the site assembly shop at PFBR site. It is nearly impossible to repair any defect in the Core Catcher and Core Support Structure after their installation in the reactor. Hence, these components have to be fabricated with utmost care to a very elaborate quality control scheme.

The amount of welding involved during manufacture of CSS is too large. In case of distortion of CSS during reactor operation due to residual stresses, it may cause disturbance of the core assemblies and its control mechanisms. Therefore, the entire core support structure after rough machining of the flange underwent stabilization heat treatment at 530^{0}C for 660 minutes for dimensional stability. The heat treatment was carried out with nitrogen purging to minimize the oxygen affects. After completion of heat treatment, the surfaces of austenitic stainless steel were subjected to pickling followed by passivation. Mixture of 70% concentration nitric acid (HNO3) solution (10-20% volume), 40% concentration hydrofluoric (HF) acid (1-3% by volume) and de-mineralized (DM) water (balance volume) is used for pickling operation. Mixture of 70% concentration nitric acid (HNO3) solution (10-20% volume) and DM water (balance volume) is used for passivation to get homogenous passive chromium oxide layer on the surfaces

Figure-6: Welding and fabrication of Core Support Structure and integration with MV

V. CONCLUSION

Manufacture of block pile equipments 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 achievements 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

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