QUALITY ASSURANCE ASPECTS DURING MANUFACTURING OF ROOF SLAB FOR 500 MWE PROTOTYPE FAST BREEDER REACTOR

Shripal, T.Loganthan, S. Ramesh, R.V.R. Govindarajulu, A. Ramu and Prabhat Kumar

Prototype Fast Breeder Reactor (PFBR) Project
Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI)
Department of Atomic Energy, Kalpakkam-603102, Tamil Nadu, INDIA

ABSTRACT

The construction of 500 MWe Prototype fast Breeder Reactor is nearly in final stage of completion at BHAVINI, Kalpakkam, Tamil Nadu-603102. Roof slab, a critical component of PFBR, consists number of penetrations with specified PCR, angular orientation, and flatness which need stringent dimensional requirements and the same are controlled by conventional and ECDS system. The plates for roof slab shell segments are produced by electric arc melting with tight control on inclusion content to achieve sound weldments. The weldments of similar and dissimilar metals are examined and evaluated by various NDE methods such as visual, LPE, radiographic examination, ultrasonic examination, PSI (pre-service inspection) ultrasonic examination and finally tested for pneumatic and helium leak testing. The highly radioactive concentration, radioactive nature of primary sodium and cover argon gas necessitates boundaries with a high degree of reliability against failure for the roof slabs. Therefore, PFBR specifications requirements are stringent compared to specifications of other industrial applications to enhance reliability. This paper details the overview of the steps taken for implementing the quality assurance aspects during manufacture of roof slab for 500MWe PFBR project.

Keywords: Ultrasonic, Radiographic, helium Leak testing, Electronic Coordinate Determination System.

INTRODUCTION

Top shield consist of roof slab (RS), rotatable plugs and control plug. The main function of roof lab (RS) to provide thermal and biological shielding in the upper axial direction from the hot sodium pool to facilitate personnel access above and acts as part of primary containment boundary. It supports various components such as main vessel (MV), large rotatable plug (LRP), small rotatable plug (SRP), primary sodium pumps (PSP), intermediate heat exchanges (IHX), decay heat exchanges (DHX), delayed neutron detectors (DND), level detectors & other associated auxiliary equipments. Roof slab is a box type structure made mostly from special carbon steel plates confirming to AFNOR-A 48P2 (Mod.). It is selected as a principle material of construction to meets the requirements of good through thickness ductility, high toughness, and good resistance to lamellar tearing. The structural arrangements consist of a top and bottom plates inter-connected by inner shell, outer shell, and radial stiffener plates.

DESCRIPTION OF ROOF SLAB AND NEED FOR QUALITY ASSURANCE

Roof slab is massive structure in weight, ~230 tonne, and in size with the outer/inner diameters of 12900/6210 mm. It has six major penetrations at pitch circle diameter (PCD) of 9760mm for supporting primary sodium pump (two with ID 1900mm) and intermediate heat exchanger (four with ID 2200mm). It has twenty other penetrations for supporting decay heat exchangers (four with ID 600mm), delayed neutron detectors (eight with ID 350 mm), cold pool level detector (one with ID 600mm), hot pool level detector (one with ID 203mm), sodium purification lines (one with ID 480 mm), argon lines (two with ID 203mm), clad rupture detection argon lines (two with ID 203mm), and an inclined (17° inclination with vertical and ID 600mm) penetration for in-out transfer of sub-assemblies. All the penetrations except the penetration for argon lines have machined support flanges with stringent dimensional and geometrical tolerances. It also have ten cooling boxes, eighty-six spacer pads to avoid core disruptive accident, eighty-six concrete filling pipes for filling high density concrete, three hundred ten of thermocouples, hundred and forty-four tie rods holes, two hundred eighty-nine stiffeners, and thermal shield. It has twenty-one inlet and outlet coolant pipes, four horoscopes near IHX locations, four horoscopes near LRP location and twenty-eight support pads and gear mounting pads. Fig. 1 digital image during fabrication of roof slab.

Roof slab have large diameter to thickness ratio. Its manufacture needs many innovate methods for fabrication,
welding, and machining to control distortion, to achieve stringent weld profile, and stringent geometrical (IS 2102, part 1, fine class) and dimensional (IS 2102, part 2, H class) tolerances after onsite machining. There is a need for devising many QA procedures and methods for accurate and reliable inspection and development of non-destructive examination techniques to ensure these requirements. The welding of special carbon steel, modified SS316LN, and modified SS304LN plates need special types of welding electrodes and filler wires, which are not readily available and classified by AWS. These modified electrodes and filler wire developed after very extensive tests and validations. The main requirements of special carbon steel welds to have low nil ductility temperature and impact strength. The main requirements for austenitic stainless steel welds are to have resistance to thermal shock and resistance to embrittlement due to fast neutrons. PFBR specifications demands large additional numbers of tests/inspections/examinations with much more stringent requirements than ASME, Section III, Division 1, subsection NB.

QUALITY ASSURANCE DURING PROCUREMENT OF RAW MATERIALS AND WELDING CONSUMABLES

The principal material of construction is special carbon steel conforming to AFNOR-A 48P2 (modified) except roof slab outer shell, step plate and thermal shield panels that are made of modified stainless steel SS316LN and SS304 LN as per PFBER specifications. For welding of special carbon steel material for roof slab, with SMAW process special low hydrogen carbon steel electrode is used. Carbon steel plates, stainless plates, and welding consumables demands a very narrow range chemical composition of plates and welding consumables as per PFBR specifications. For dissimilar weld between carbon steel and stainless steel, electrode and filler wire conforming to AWS classification E309 and ER309 of SFA 5.4 is used.

Carbon steel plates AFNOR A 48 P2: Carbon steel plates with specific ductility requirements in short transverse direction used in the fabrication of roof slab. Plates made by electric arc furnace melting process. Plates supplied in
normalised, killed and vacuum degreased condition for controlled inclusion content. Reference nil ductility temperature (RT_{NDT}) of these plates determined as PFBR specifications. Each plate tested for room temperature tensile test- long transverse and short transverse test, RT_{NDT}, impact test, tensile after simulated stress relieving heat treatment, bend test. Plates under goes 100% ultrasonic examination in accordance with ASTM A -578.

Modified Austenitic stainless steel 316LN and 304LN plates: Stainless plates supplied in solution heat-treated, pickled, and passivated condition and manufactured using electrical arc furnaces melting process. Plates undergoes chemical analysis, room temperature tensile test, tensile test at elevated temperature, impact in solution annealed condition and embrittled condition, intergranular corrosion test, inclusion test, delta ferrite (less than 1%), metallographic examination, grain size (finer than ASTM no. 2) determination as per PFBR specifications. Plate are visually examined (in case doubt by liquid penetration examination) to ensure that are free from scratches, blowholes, scales, cracks, hairline flaws. All plated undergoes 100% ultrasonic examination with 10% overlap by longitudinal waves using pulsed-echo technique at a probe frequency of 2 MHz.

Austenitic stainless steel electrodes and wires: Austenitic stainless steel modified electrode E316-15 of SFA5.4 and 16-8-2 filler wires undergoes additional/modified examinations and testing to ensure the service conditions of the components. These includes slag detachability, radiographic examination, all weld metal tension test, impact test, tensile test at ambient temperature, tensile test at elevated temperature( 823K), intergranular corrosion test in as welded state, fillet weld test, delta ferrite check, crack susceptibility test, and creep test.

Carbon steel electrodes and filler wires: carbon steel modified electrodes of SFA 5.1 and modified filler wire of SFA 5.18, undergoes additional / modified examination and testing. These includes all weld tensile test at room temperature, Charpy impact test at -20°C, radiographic examination, nil ductility transition temperature determination, coating moisture test and fillet weld test.

QUALITY ASSURANCE DURING MANUFACTURING OF ROOF SLAB (ROLLING, FABRICATION, AND MACHINING)

LRP support flange (made in sectors and integrated) and all other flanges cut from a single plate are integrated to roof slab and has undergone heat-treatment at the holding temperature of 873K±10K. Holding time is 2 minutes per mm of thickness with minimum of 30 minutes and maximum of 120 minutes. The temperature of loading in furnace is less than 200°C. Heat and cooling rate shall not exceed the greater of two values (1) 220K/h divided by the maximum thickness in multiple of 25 mm or (2) 55K/h. Other welds of thickness ≤ 35 mm are under-gone to heat treatment. Stainless steel surfaces under-goes passivation as per PFBR specifications. On site, machining (Fig. 2) was performed using special purpose machines in one setting without disturbing the roof slab. Dimensions of machined flanges ranges from 200mm to 7000 mm in diameter with flatness requirement of 0.1 mm to 0.3 mm. Bottom surface of support ring of support assembly of diameter 13600mm also finish machined.

QUALITY ASSURANCE DURING WELDING OF ROOF SLAB

Recommended welding process is shielded manual arc welding (SMAW). For joints where back gouging is not possible, the root pass made by GTAW process using argon gas purging on the back side. The qualification of welding procedure and welders for welding of carbon steel, stainless steel components, and dissimilar metal weld had done as per PFBR specifications that are much more stringent than code ASME Section III, Division 1, subsection NB and demands large number of additional tests, inspections, and examinations. During welding procedure qualification for carbon steel, reference nil ductility temperature transition temperature (RT_{NDT}) is determined as per ASME Section III, class I component with PFBR specification requirements. Specimens taken from base metal, heat affected zone and weld metal with a requirement of RT_{NDT} temperature -15°C or lower. After determining RT_{NDT} temperature as per ASTM E 208 by drop weight test, impact
tests carried-out at the determined RT<sub>max</sub> temperature +33°C with the requirement of 68J energy minimum and lateral expansion of 0.9 minimum for all specimens. Fig. 2 digital image during welding of roof slab.

Welds are either ground flush or to required radius as indicated in drawings. At other locations, reinforcement on the welds controlled as per PFBR specifications. The surface finish requirements are better than 6.3 micron (CLA) on welds ground flush and ground surfaces. Sector integration weld are suitably staggered with a minimum distance of 100 mm between them and sequenced to avoid build up of residual stresses and distortion. Written procedures made to control distortion for each typical joint giving sequence of assembly, sequence of welding, and heat input to welds. The shrinkage and distortion of all weld joints measured and recorded. During welding heat input, nearly 0.8 to 1.2 kJ/mm and 1.5 to 2 kJ/mm reported for stainless steel welds and carbon steel welds respectively. The number of repairs permitted for welds is limited to maximum two times at any location. The mismatch limit required at fit-up stage is as low as possible to achieve the tolerances specified on the geometrical shapes of the components. The mismatch at fit-up stage is limited to (t/20) +1 mm with maximum of 3 mm, where t is the thickness of the plate. Production test coupons (PTCs) of about dimensions of 150×1000mm welded to extension of plates for the job. PTCs welded simultaneously along with the job and same welding parameters, heat treatment, destructive, and non-destructive testing followed as for the production welds. Total thirteen PTCs prepared.

**NON-DESTRUCTIVE EXAMINATION OF ROOF SLAB**

The systematic and sequential methodology applied for ensuring soundness of welds. All welds undergo 100% non-destructive examinations.

**Visual examination:** All welds undergoes visual examination to ensure that welds are free from surface defects e.g. under cut, unfilled groove, slag, excessive penetration, lack of fusion, lack of penetration etc.

**Liquid Penetration Examination of welds:** All welds of roof slab subjected to solvent removal visible LP examination with written procedure for detecting surface discontinuities e.g. surface cracks, surface porosity, weld spatter etc. Welds subjected to edge, root pass, final pass and one/two layer (for some weld seams) LPE with evaluation and acceptance criteria as per PFBER specifications. All liquid penetrant materials used on austenitic stainless steel welds analysed batch wise for sulphur (≤1%) and halogen content (≤25 ppm). All welds with the temporary closures, fixtures etc., subjected to LPE and welded by qualified welder (Fig. 3).

**Ultrasonic Examination:** Many butt and fillet welds of roof slab undergo ultrasonic examination with written procedure with evaluation and acceptance criteria as per PFBR specifications. Weld surfaces merged smoothly in to surface of base metal. The surfaces adjacent to the weld shall be ground to eliminate any weld defect like arc strikes, weld spatter and to achieve surface not exceeding 6.3μm (CLA). Couplants (oil/grease) when used on austenitic stainless steel welds, analysed batch wise for sulphur (≤1%) and halogen content (≤25 ppm). In principle, frequency of examination is 2MHz. The reference block for carbon steel welds is same as base material. For austenitic stainless steel simulated weld coupon used. Reference block with 2 mm side drilled hole employed for establishing reference echoes height and DAC curves. Any echo with amplitude equal to greater than 50% of the reference echo recorded. Further, for joints with different thickness and dissimilar materials, suitable mock-ups have performed to establish the ultrasonic examination sensitivity (Fig. 3).

**Radiographic Examination:** Many butt as well as T-Joint welds of roof slab subjected to radiographic examination with written procedure with evaluation and acceptance criteria as per PFBR specifications. X-ray equipment used as radiation source up to 20 mm thickness. For thickness higher than 20 mm, X-ray or suitable γ-ray source used. In general, class-2 or class-1 films along with lead intensifying screens used. All weld surfaces merged smoothly into the base metal surface. For all films radiographic films density measurements performed. Geometrical un-sharpness requirements for X-rays

Fig. 4 : Digital images during ECDS measurement and helium leak testing of roof slab
up to 400kV or Ir-192 or Tm-170 are less than 0.3 mm and for Co-60 is less than 0.6 mm. The finished surface of the reinforcement of any butt welds flushed with the plate. The maximum reinforcement permitted is less than W/10+1 mm. Where W is the width of the weld seam in mm. Welds, radio graphed with techniques, to achieve the sensitivity as per PFBR (ranging from 2-1T to 2-2T) specification. Sensitivity and acceptance criteria as per PFBR specifications are much more stringent than ASME, section III, division, subsection NB.

**FINAL INSPECTION OF ROOF SLAB BY “ECDS”**

Dimensional and alignment inspection of roof slab performed with written dimensional and alignment inspection procedure satisfies/generate data to meet all the requirements specified in the drawings. It includes both conventional and electronic co-ordination detection system (ECDS). ECDS measurements performed for verification of conventional measurements (Fig. 4).

**PRE-IN-SERVICE INSPECTION (PSI) ULTRASONIC EXAMINATION OF WELDS OF ROOF SLAB**

Pre-in-service inspection (PSI) ultrasonic examination performed on welds of outer shell A₁ and outer shell A₂ from external surface to generate baseline data for the purpose of comparison of these data during in-service inspection. The signals stored in retrievable digital form with appropriate weld/location identification.

**LEAK TESTING OF ROOF SLAB**

Welds of roof slab tested by pneumatic testing. An internal pressure of 0.06MPa applied for 10 minutes and welds checked for leaks. Then, pressure reduced to 0.5Mpa and roof slab is hold at this pressure for 60 minutes to ensure that there is no pressure drop and soap bubble (lissapol) solution applied to detect the leaks. The soap solution checked for ionic chloride content not more than 25ppm and sulphur content not more than 1% by weight for application on stainless steel parts of roof slab. Additionally, helium leak testing (HLT) under pressure of 0.06MPa performed on the welds of roof slab. During testing, it is ensured that global leaks shall not exceed $1\times10^{-6}$ Pa-m³/s per m³ of the internal volume and local leaks not exceed $1\times10^{-7}$ Pa-m³/s. Before testing, it is ensured that concentration of helium inside the roof slab is at least 60% in volume. This had ensured by lab tests (Fig. 4).

**CONCLUSIONS**

The innovate methods for; manufacture, fabrication, integration of cooling boxes, alignments of various parts/sectors of roof slab, welding techniques, machining methods, non-destructive examinations, and leak testing all successfully employed to achieve required quality levels for roof slab -a box type hollow structure with very large outer diameter and large diameter to thickness ratio. This had achieved by implementing the effective quality assurance methodologies. A well-planned inspection approach including ECDS methods, PSI-UT, and large number of mock-up etc. facilitated in achieving desired tolerances and stringent NDE requirements for roof slab and hence, meeting the challenges in manufacturing the roof slab.