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Quality Management During Welding, Fabrication & Erection of Austenitic Stainless Steel Piping for Sodium Circuits of 500MWe Prototype Fast Breeder Reactor

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Abstract: **Prototype Fast Breeder Reactor (PFBR) is a 500MWe pool type, sodium cooled, first of its kind nuclear reactor which is presently in advanced stage of construction by BHAVINI at Kalpakkam, India. The boundaries of the sodium systems are designed so as to have an extremely low probability of abnormal leakage, rapidly propagating failure and gross rupture under the static & dynamic loads expected during various operating conditions. Therefore, design for the above shall include considerations of degradation of material properties (e.g. effect of sodium, temperature and irradiation), transients, residual stresses, flaw size etc. The principal material of construction for sodium piping circuits is austenitic SS316LN/SS304LN. All sodium pipelines inside Reactor Containment Building (RCB) of PFBR are provided with hot guard pipe and are inerted with nitrogen. The guard piping and the containment penetrations require sequential welding and NDT which are unique to PFBR. Limited space at site for the erection of sodium piping along with welding at inaccessible areas with confined space makes the work all the more challenging. Manufacturing of thin and big bore piping with tight tolerances along with the high distortion in stainless steels due to high thermal expansion and low thermal conductivity makes fabrication extremely challenging. With strict rules of sloping to be given to the piping to make conducive for full draining of the sodium loops, the fabrication challenges becomes multi fold. The welding standards and acceptance criteria of PFBR sodium piping system is very stringent compared to conventional piping systems. The welding of sodium piping systems are carried out by combination of Shielded Metal Arc Welding (SMAW) and Gas Tungsten Arc Welding (GTAW) process as per stringent PFBR specification requirements. Due to complex constructional features of the sodium piping systems, the argon gas purging, welding and non-destructive examinations are extremely difficult and challenging task. Various special tools and fixtures were designed, developed and used for welding & fabrication to ensure high degree of reliability against failure. This paper highlights on welding aspects, challenges faced by BHAVINI management and innovations during fabrication activities of sodium piping circuits for 500MWe Prototype Fast Breeder Reactor.**

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

I. INTRODUCTION

PFBR piping consists of Primary Sodium Circuit (PSC), Secondary Sodium Circuits (SSC), Safety Grade Heat Removal Circuits (SGDHRC) and Steam-Water circuit. The primary sodium circuit removes the nuclear heat generated in the core and transfers it to the SSC through Intermediate Heat Exchangers (IHXs). The secondary sodium circuits, in turn, transfer the heat to steam/water circuit (SWC) through Steam Generators (SGs). Decay Heat Removal is through independent SGDHR circuits when either SWC or the SSCs are not available. The Sodium piping in Prototype Fast Breeder Reactor is thin walled and is manufactured as per stringent PFBR specification with SS 316LN/SS304LN stainless steel as material of construction. The sodium loops consists of main circuit, fill and drain, purification and allied circuits like argon and nitrogen. The entire sodium piping and its components are located in the Reactor containment Building (RCB) and in Steam Generator Buildings (SGB). The piping is connected to small sodium components such as exchanger economizers, flow meters, thermal mixers, E.M. pumps, catch pots and relief pots etc. Materials, Welding, inspection and testing of sodium piping systems are more stringent than ASME B 31.1. 'K' type surface thermocouples, ECR type surface heaters, leak detectors are provided on these piping. The piping is finally insulated with bonded mineral wool and with SS/aluminum cladding. The sodium piping is supported with structural supports and spring supports. In addition snubber supports are provided in certain locations. Sodium piping is a low pressure system and is prone to thermal shock due to the inherent fluid (liquid sodium) properties. This necessitates optimized thickness of the pipes. The compromise between economy and pressure temperature characteristic makes the pipes thin. Manufacturing of these thin and big bore piping with appropriate tolerance along with the high distortions in stainless steels makes fabrication extremely challenging. The stringent 3 stage helium leak testing - spool stage, after spool erection and after integration with the terminal components is adopted to ensure leak tightness of the system. Limited space at the site for the erection of sodium piping along with welding at inaccessible areas and confined space makes the work all the more challenging. All the butt welds in the pressure boundary are subjected to 100% Radiographic Examination (RE). In case radiography for the weld joint is not possible due to practical limitations, the quality of weld joint are evaluated by ultrasonic examination. All the pipe spools are subjected to hydro test/pneumatic test and helium leak test under vacuum. This paper brings out the glimpses of challenges in fabrication and erection of Sodium piping for PFBR.

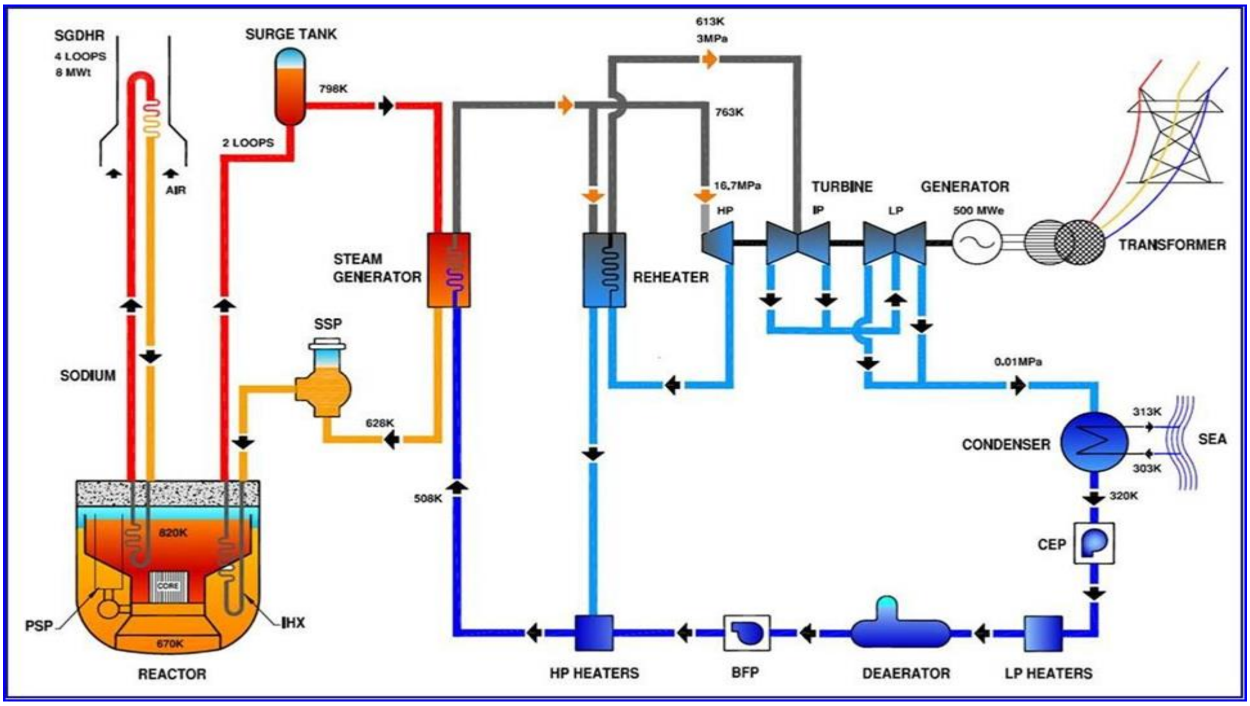

Figure-1: General flow sheet of PFBR heat transport system

II. SALIENT FEATURES OF SODIUM PIPING AND SAFETY ASPECTS

- Material of construction is SS 316LN/SS 304LN modified as per PFBR specification.

- Welding consumables, Inspection, Testing, Non-destructive examinations, welder qualification, procedure qualification and acceptance criteria are all specific and stringent than any ASME code or RCC-MR code.

- The sodium pipe lines are thin walled. Maximum thickness of the pipe line is 10 mm for OD of 800 mm.

- Completely butt welded construction with 100 % Radiographic examination and not having any flange or socket joints. Three stage HLT ensures high degree of leak tightness for sodium containment.

- Bellow sealed globe valves for small bore piping and frozen seal valves for large diameter piping is used. Valves are welded connection with 100% RE. For the construction material, forgings are used instead of castings

- All sodium pipe lines inside Reactor Containment Building (RCB) are provided with hot guard pipe and is inerted with nitrogen. All the sodium lines with or without guard pipe are provided with sodium leak detectors. Guard pipes are compartmentalized to identify leak location. Leak detectors of specific length provided on single walled pipe can identify the pipe length in which sodium leaks. Sodium fire inside RCB is beyond design basis event.

- Bends are preferred over bellows in the main pipe to take care of thermal expansion. Guard pipes are provided with bellows to accommodate differential expansion of main pipe and guard pipes and also the wall penetrations
- Thermowells are welded to the pipe lines for measurement of centreline mean temperature. This welding need to be robust and sound as earlier failure experience in Monju reactor in Japan poses a great threat. Both design validation and welding qualifications are commensurate to the critical failure mode (Flow induced Vibration).
- Entire sodium pipe lines are provided with ECR (Extruded Cold Region) type surface heaters for preheating the lines. These heaters are duplicated and triplicated based on the accessibility criteria. Welding of heater holding cleats are ensured before the final integrity testing.
- 3% slope is strictly ensured for effective draining of sodium during any leaks. The 3D pipes are rotated appropriately to accommodate the sloping and the 2D spools are given miters for the same.
- Rupture discs are provided to take care of huge pressure transient arising out of Sodium Water Reaction (SWR) in steam generators. Dedicated circuit for handling the reaction products of sodium water reaction is available.
- No vent and drain points are provided in the circuit for integrity testing as pneumatic is preferred over hydro in the erected pipe spools owing to corrosion issues and sodium being stored in the nearby tanks.
- All the sodium tanks and pumps have free sodium level and use of argon gas which prevents air coming in contact with sodium leak
- In order to minimize the sodium side corrosion on the pipelines the sodium purity is maintained at a desired level by purification circuit.
- For fast dumping of sodium in to the storage tank is provided in case on any accident. The dump valves are duplicated to increase the reliability.
- Irrespective of the safety class all the piping circuits are seismically qualified (seismic class-1

III. SODIUM PIPING FABRICATION AND ERECTION

The scope of piping fabrication work is too large due to versatile types of system with varieties of pipes, fittings, valves etc. involved. The pipe size ranges from 15 NB to 800 NB and as long as maximum of 35 meters in length. The piping is connected to large sodium tanks as well as small sodium components such as exchanger economizers, flow meters, thermal mixers, EM pumps, catch pots and relief pots etc. which forms the terminal joints of the sodium piping system. Material selection is a vital link between the code and QA requirements considering the coastal environment and operating conditions. The material requirements are characterized by narrow ranges of chemical composition for alloying elements like Cr, Ni, Mo & Mn. Lower permissible limits for impurities and residual elements like S, P, B, Si, Nb, Ti, Co were stipulated and controlled. Addition of nitrogen with reduction of carbon to maintain the strength of austenitic SS materials at high temperature and at the same time to have good resistance for sensitization and was done. Additional mechanical tests like impact at room temperature in solution annealed and embrittled condition, tensile test at elevated temperature, control on delta ferrite (less than 1%), stringent control over inclusion content etc., were specified.

The welding standards and acceptance criteria of PFBR sodium piping system is very stringent compared to conventional piping systems.

TABLE I: 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

Various constraints due to change of layout, civil modifications, electrical panels & air ventilation systems rooting etc. posed several challenges to sodium pipe line erection. The systematic and sequence methodology of stage by stage inspection & testing of weldments for its soundness and quality level is enforced and results achieved are to the highest feasible quality. Utmost care is to be taken to avoid mixing of welding consumables, tools/tackles maintaining the nuclear clean environments. The welding of sodium piping systems are carried out by combination of Shielded Metal Arc Welding (SMAW) and Gas Tungsten Arc Welding (GTAW) process as per stringent PFBR specification requirements. Before welding on the actual job, welding procedure qualification is done meeting various non-destructive & destructive examinations/testing on the test coupons. Various special tools and fixtures were designed, developed and used for welding & fabrication to ensure high degree of reliability against failure. After completion of welding and fabrication, various systems are subjected to pneumatic test and helium leak test to ensure the integrity of the welds. Rigorous Foreign Material Exclusion (FME) practices adopted during each and every stage of fabrication to ensure absence of foreign material inside the piping before helium leak testing. Boroscopic inspection of pipe lines is carried out in the inaccessible areas to ensure FME in the complete piping systems. In contrast to the other process piping, there is no possibility of flushing the piping with DM water due to risk of moisture in the spools. FME is more stringent due to this reason.

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-1. 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

TABLE II: COMPARISON OF WELDING PROCEDURE QUALIFICATION

Sl.No	Tests	ASME	PFBR
1.	Longitudinal tensile test at RT (t>10 mm)	Not asked	Yes
2	Transverse tensile at RT	Yes	Yes
3	Transverse tensile test at high temp	Not asked	Yes
4	Bend test	Yes	Yes
5	Impact test t<10 mm	Yes	Yes
6	IGC test	Not asked	Yes (for C>0.035%)
7	Micrography	Not asked	Yes
8	Delta ferrite test	Not asked	Yes

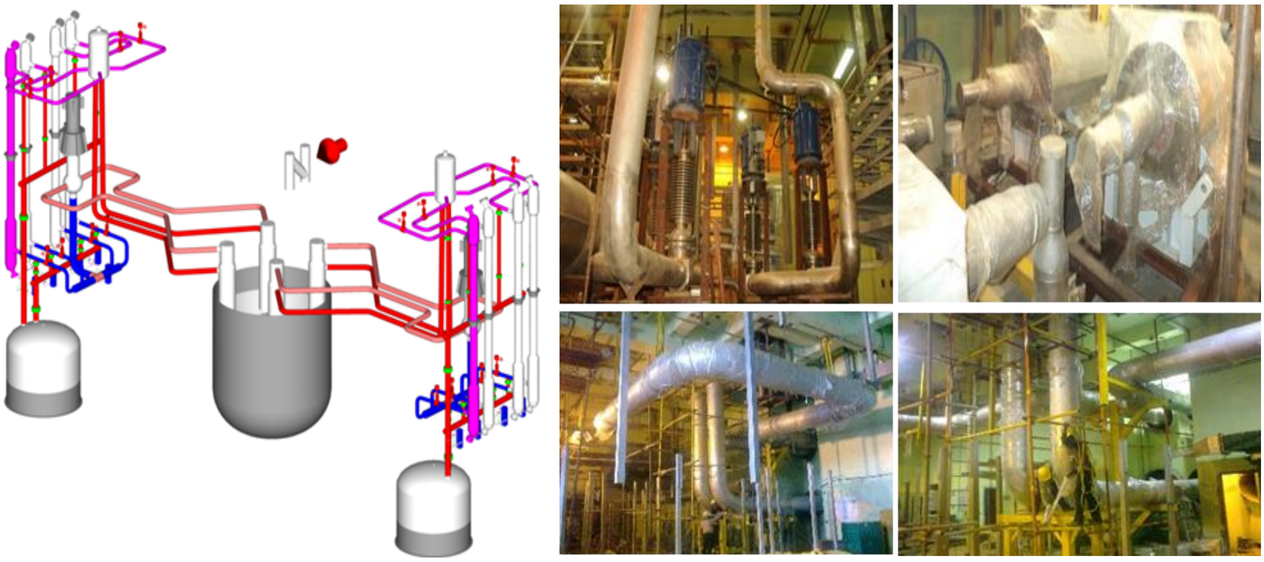

Figure-2: Secondary Sodium piping during erection and 3-D Isometric

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IV. SEQUENTIAL WELDING OF PIPE IN PIPES

All sodium pipelines inside RCB are provided with hot guard pipe and are inerted with nitrogen. Differential thermal expansion between main pipe and guard pipe is taken care of by bellows on the guard pipe. Guard pipes are compartmentalized to identify leak location. MI type and spark plug type leak detectors are provided for each guard pipe / vessel compartment to detect any sodium leak giving sufficient time for shutting down the system.The guard piping and the containment penetrations require sequential welding and NDT which are unique to PFBR. The sequencing method is achieved by many mock-ups addressing all the accessibility issues.Double barrier piping penetrations are generally provided for all the piping which passes through the containment of a nuclear reactor. Several pipes may pass through the same sleeve to minimize the number of containment penetrations required.

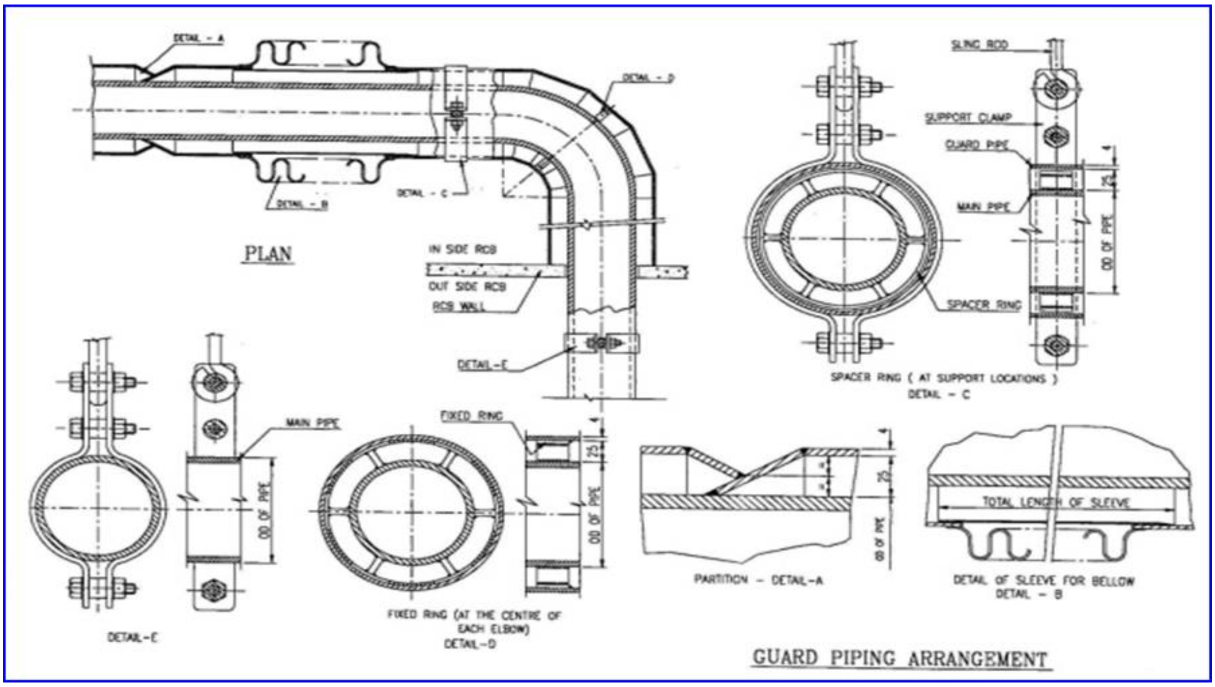

Figure-3: Intricacies of guard pipe system

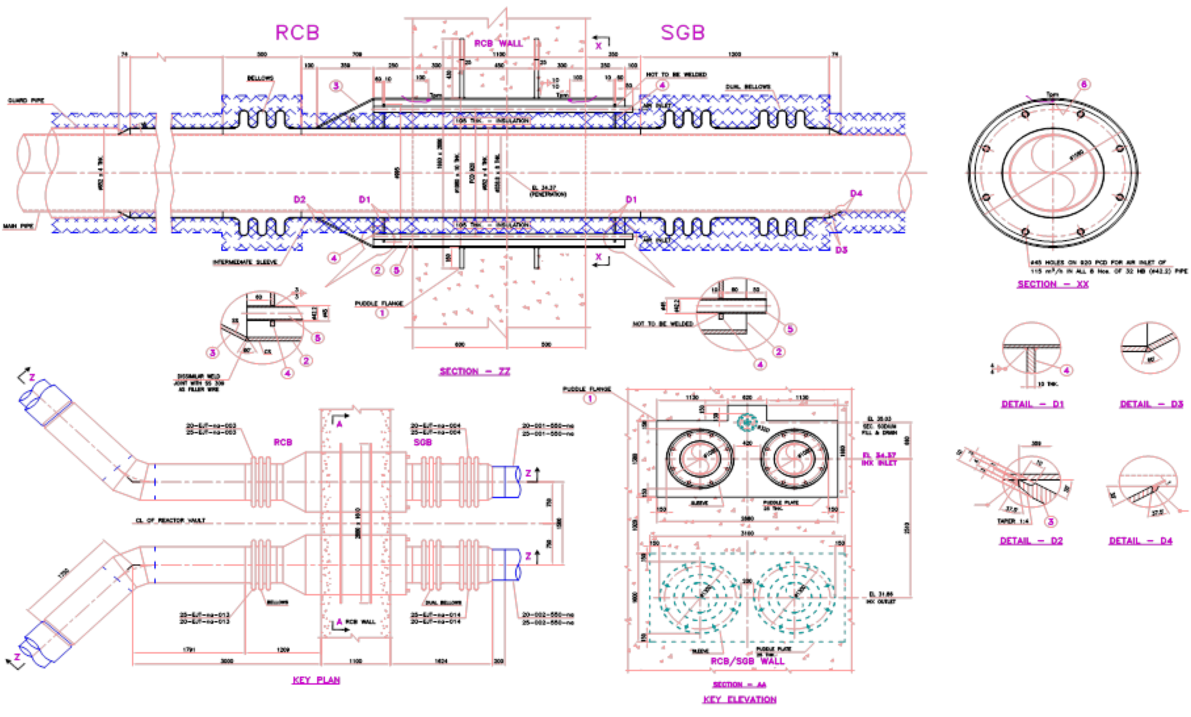

Figure-4: Pipe penetration scheme

The welding of Pipe in pipes shall be meticulously carried out sequentially as per the approved fabrication procedure failing which repair and rectification works are much difficult. The elbows and mitres shall be inserted first and also the spacers shall be welded at relevant locations in the main pipe. The bellows are inserted at last and the closing seam of the guard pipe is usually in two halves. The spacer locations in the main pipe shall be carefully transferred to the guard pipe so as to handle the spool without transmitting the load to main pipe.

Figure-5: Sodium pipe penetration in RCB wall

V. CONCLUSION

The welding and fabrication of sodium piping system is extremely difficult and challenging due to varieties of pipes, valves, bellows, sweepolets, fitting involved. BHAVINI management has gone beyond stringent specification requirements wherever required to ensure high standard quality assurance during fabrication and erection activities of sodium piping systems. Trouble free service is expected from various sodium piping components and systems for the design service life of 40 years.

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