Development of Welding and Hardfacing Technology for the Fast Reactor Programme in India

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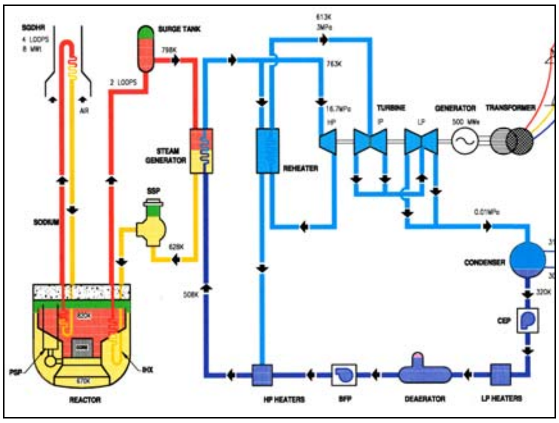
1. Introduction

The mission of the Indira Gandhi Centre for Atomic Research (IGCAR) is to make India self-sufficient in all areas of Fast Breeder Reactor (FBR) technology. In the early days of IGCAR, the emphasis was on construction of Fast Breeder Test Reactor (FBTR) and its operation. This was to demonstrate the capability of constructing and operating the liquid-sodium cooled FBR successfully, and also to gain valuable experience in liquid-sodium technology before taking up construction of liquid sodium cooled FBR for power production. In parallel, complete indigenous design of 500 MWe Prototype Fast Breeder Reactor (PFBR) was also taken up. With R&D activities spanning over almost three decades, successful operation of FBTR for two decades and demonstration of capability of Indian industries to fabricate all components for PFBR Project, IGCAR gained confidence that India is ready for building and operating 500 MWe FBRs. Accordingly, Government of India accorded financial sanction for construction of PFBR in September 2003 and construction of the reactor. While the indigenous design and development activities for PFBR were carried out at IGCAR, Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI), a government company formed in 2003, is implementing the PFBR project. A rigourous technology development phase though proactive interactions with the fabrication industry, backed by wide-spectrum R&D in welding science and technology and mechanical property characterisation, was essential to ensure that a robust fabrication technology is established for each of the components. This enabled successful fabrication of all the components of PFBR by Indian fabrication industries. Presently, PFBR is in advanced stage of construction at Kalpakkam, and almost all the components for the reactor is fabricated in India by different fabricators both in public and private sector.

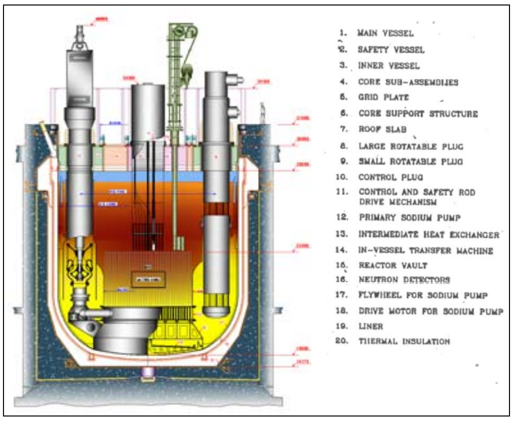
PFBR is a pool-type liquid-sodium-cooled reactor having two separate sodium circuits with the intermediate heat exchanger (IHX) providing thermal contact between the primary pool and the secondary circuit. The secondary sodium circuits transfer heat from the IHX to the steam generator (SG), the steam from which drives the conventional steam turbines. The minimum sodium temperature in the primary pool during normal operation is 400°C, while the mean above-core temperature is 550°C. The minimum and maximum sodium temperatures in the secondary circuit are 355 and 525°C, respectively. The steam temperature is 490°C at 16.6 MPa pressure. Figure 1 shows a schematic of the heat transport flow sheet of PFBR and Fig. 2 shows the major components in the reactor assembly [1].

R&D activities on the science and technology of welding and hardfacing at IGCAR are closely associated with the developments in PFBR technology. Austenitic stainless steel (SS) is the major material of construction for PFBR. The Main Vessel, Inner Vessel, Grid Plate, and Primary Piping, etc., whose service temperatures are above 427°C, are made of

316LN SS containing 0.06-0.08% nitrogen. The Safety Vessel, IHX etc., whose service temperatures are below 427°C, are made of 304LN SS; Fig. 3 shows the photograph of the safety vessel being lowered into the reactor vault at the construction site. The reactor core components, the clad tube which contains the mixed-oxide fuel pins and the fuel subassemblies in which these clad tubes encased are made of alloy D9, an austenitic stainless steel with enhanced resistance to radiation swelling. The Roof Slab, which covers the top of the reactor, from which many of the reactor components like fuel handling machine, sodium pump etc. are suspended, is made of carbon steel (Fig. 4). The steam generators of PFBR are made of modified 9Cr-1Mo steel; Fig. 5 shows one of the steam generators. There are many other structural materials like boron-containing stainless steels, precipitation-hardened steels, nickel-base alloys etc. that are also used in PFBR in much smaller proportion than the major alloys mentioned above.

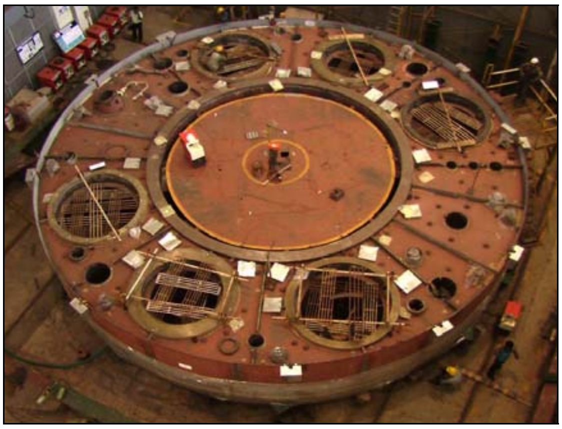


<u>Fig. 1</u>: *Schematic of heat transport flow sheet of PFBR*



<u>Fig. 2</u>: *Reactor assembly of PFBR – major components*

<u>Fig. 3</u>: *PFBR safety vessel being lowered into the reactor vault*



<u>Fig. 4</u>: *Roof slab of PFBR*

The size and thickness of the major reactor components vary widely. The Safety Vessel, which is the outermost vessel that contains the reactor core, has 13.5 m inner diameter, 12.5 m in height and wall thickness of 20 mm for the cylindrical portion. The Main Vessel is slightly smaller in diameter (12.9 m inner diameter) and larger in height (12.94 m) and is made of 25 mm thick plates for the cylindrical portion. The Grid Plate assembly, in which the fuel subassemblies rest, is made of two large circular plates of more than 6 m diameter and 60 mm thickness. The Roof Slab (Fig. 4) is a massive box-type structure (12.9 m diameter and 1.8 m height), in which the top and bottom plates interconnected by vertical cylindrical shells and radial stiffeners welded to them, is fabricated mostly from 30 mm thick carbon steel plates but also has some components made from plates of much higher thickness. Similarly, the once-through type steam generators (SG) made of modified 9Cr-1Mo (grade 91) steel are 25 m in length, and are made from 12 and 30 mm thick plates for the shells and headers, 150 mm thick forgings for the tubesheet and of 23 m length and 2.6 mm wall thickness (547 tubes per SG). As with the SG tubes not all components are thick. The fuel clad tubes are only 0.43 mm in wall thickness and hexagonal shaped fuel subassembly is only 3 mm thick.

Fabrication of the many of the components is already complete and major components like the Safety Vessel and Main Vessel have been installed in the reactor site and other components like roof slab, IHX are now in the site assembly shop, ready of installation. Needless to say that welding is one of the important modes of fabrication and different welding consumables and processes were used in the fabrication of the components. As material specifications are stringent, indigenous development of materials and welding consumables, development of welding procedures and technology, and evaluation of weldability and properties of the materials involved were important components of technology development. Figure 6 shows the various welding consumables and processes used in the fabrication of the various components and piping of PFBR.

Fig. 5: *Steam generators under fabrication*

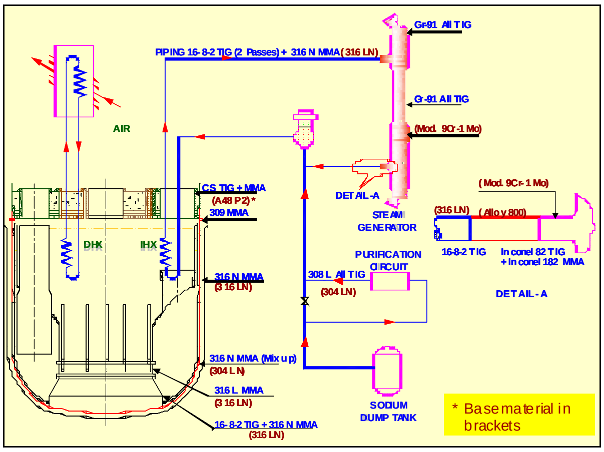


Fig. 6: *Welding consumables used in different components and piping of PFBR*

In PFBR, as already mentioned, 316LN SS is the structural material for components operating above 427°C. The liquid sodium coolant acts as a reducing agent and removes the protective oxide film present on the SS surface of the in-sodium components. Many of these components would be in contact with each other or would have relative motion during operation, and their exposure at high operating temperatures (typically 550°C) coupled with high contact stresses could result in self-welding of the clean metallic mating surfaces. In addition, the relative movement of mating surfaces could lead to galling, a form of high-temperature wear, in which material transfer occurs from one mating surface to another due to repeated self-welding and breaking at contact points of mating surfaces. Further, susceptibility to self-welding increases with temperature for 316 SS [2]. Hardfacing of the mating surfaces has been widely used in components of water-cooled and liquid-sodium cooled FBRs to avoid self-welding and galling [3,4]. Cobalt-base hardfacing alloys (e.g. Stellite©) have been traditionally used very extensively for high temperature application in many critical hardfacing applications due to their excellent wear-resistance properties [5]. However, when cobalt-base alloys were used in a nuclear reactor environment, the cobalt-60 isotope formed due to irradiation enhances the radiation dose rate to operating personnel during handling, maintenance or decommissioning of the hardfaced components. Hence, there is an emerging trend of avoiding the use of cobalt-base alloys for hardfacing of nuclear power plant components. Nickel-base hardfacing alloys (e.g. Colmonoy©) were developed mainly to replace the cobalt-base alloys for avoiding induced radioactivity problems in thermal and FBR applications. Accordingly, for PFBR, selection of suitable hardfacing materials for various components was preceded by detailed induced radioactivity, dose rate and shielding computations to ensure that induced radioactivity from hardfaced components is kept to the minimum for maintenance and decommissioning purposes, and also to reduce the shielding thickness requir ed for the component-handling flask, which in turn would reduce the flask weight, size of handling crane and loads on civil structures [6].

On looking back at R&D in the areas of welding and hardfacing it can be noticed that IGCAR gained from developments in these fields worldwide and in turn contributed significantly to these technologies. This paper highlights the application of the science and technology welding and hardfacing for the 500 MWe PFBR, as also the challenges encountered during fabrication of different reactor components and structures.

2. Welding of Austenitic Stainless Steels

Various codes for fabrication, such as RCC-MR and ASME Section III, provide for hot cracking tendency of austenitic SS during welding by either specifying limits on ferrite content in weld metal or by weldability tests. RCC-MR specifications for welding filler materials make a distinction for ferrite content based on service temperature. As per RS 3334, 5-15% ferrite is specified for components operating below 375°C. For components operating above this temperature, these limits do not apply and the user must specify ferrite limits. Weld ferrite content is determined by either Schaeffler or DeLong diagram or by magnetic saturation method. When ferrite content of the deposited weld is below 5%, RS 2536 stipulates a groove cracking test for qualification of welding consumables as per RS I 900 or 930. The test consists of depositing (undiluted) 5 lengths of weld metal (50 or 60 mm length) within an 80° groove. The deposits are then examined for cracking using liquid penetrant test. Filler materials or electrodes must ensure freedom from cracking, including crater cracking. ASME Section III NB-2433.2 does not make a distinction based on service temperature but accounts for hot cracking tendency by specifying a minimum ferrite level as per WRC-92 ferrite diagram. Delta-ferrite is restricted in weld metals intended for elevated temperature service because it results in poor creep properties due to its microstructural instability under service conditions.

The current code stipulations rely on conservative tests and additional requirements such as ferrite level specification to provide for resistance to cracking susceptibility. However, the codes do not address adequately the necessary tests for hot cracking behaviour of weld metals intended for high temperature service. The possibility of heat affected zone (HAZ) cracking in the base metal and multipass SS weld metal are not taken into account in the codes. There was, therefore, a need for detailed weldability evaluation to obtain clear quantitative guidelines for excluding the possibility of cracking while at the same time avoiding excessive conservatism.

2.1 Development of special-purpose electrodes

The specifications for welding consumables were drawn up to ensure good resistance to cracking, and also included nitrogen level (0.06-0.10%) comparable to that of the base metal to ensure creep properties comparable to that of the base material. This necessitated developing special welding consumables for PFBR components. For GTAW, which is used mainly in root pass and in thin section piping, 16-8-2 wire, which is accordance with AWS/ASME specification. Choice of this consumable was mainly based on the experience during construction of FBTR. This filler was developed indigenously and used for GTAW in fabrication of all components and piping of 304LN and 316LN SS. However, the weld metal composition for the SMAW electrodes for PFBR is significantly different from the corresponding AWS/ASME specification (Table 1). Carbon and nitrogen levels are chosen to ensure $(C+N)_{min}$ is 0.105% to ensure weld creep rupture strength at least equal to base metal. Also, titanium + tantalum + niobium contents are limited to ensure good weldability. These E316-15M electrodes meeting the PFBR specifications were developed and manufactured in collaboration with Indian electrode manufacturers [7]. This developmental experience has shown that the identification of critical problems in production and their resolution through collaborative efforts, wherever necessary, have contributed to the success. During this developmental work it also became necessary to develop an artificial neural network (ANN) based methodology to accurately estimate the delta-ferrite content taking inputs from the chemical composition of the stainless steel weld metal [8]

Table 1: *Composition of welding consumable for PFBR E316-15M and ASME SFA 5.4 E316L-15 specifications*

Element	C	Cr	Ni	Mo	N	Mn	Si	P	S	Ti +Nb +Ta	Cu	Co	B	FN
ASME	0.04 max	17-20	11-14	2-3	NS	0.5-2.5	0.9 max	0.04 max	0.03 max	NS	0.75 max	NS	NS	3-10
PFBR	0.045-0.055	18-19	11-12	1.9-2.2	0.06-0.10	1.2-1.8	0.4-0.7	0.025	0.02	0.1	0.5	0.2	0.002	3-7
Weld metal	0.05	18.5	11.1	1.9	0.1	1.4	0.46	0.006	.025	< 0.1	< 0.05	< 0.05	0.001	3.0-3.9

The property requirements as specified and achieved for these electrodes are given in Table 2. The most challenging part of this development was to achieve the toughness specified after the ageing heat treatment at 750°C for 100 hours. This requirement was included to assess the susceptibility of the weld metal to embrittlement by sigma-phase formed during high-temperature exposure by transformation of the delta-ferrite. It was found that the molybdenum content has to be carefully controlled in the lower limit of the specification to ensure this. Another challenge was to improve the slag detachability of the deposited weld metal. Poor slag detachability of the weld metal often necessitates extensive grinding and rework. Many trials batches were made to optimize both the composition of the weld metal and flux to meet these demanding requirements. All the welding of various reactor components made of 316LN SS is carried out by the electrodes supplied by the Indian electrode manufacturers who have successfully developed this electrode.

Table 2: *Mechanical properties of E316-15M electrodes of PFBR*

Properties	YS(MPa)	UTS(MPa)	Elongation (%)	Charpy U-notch Toughness(daj/cm^2)	
				As welded	1023K/100h aged
Specified	350 min.	550 min.	35 min.	7.0 min.	3.0 min
Achieved	504	621	40	8.2	4.0

2.2 Weldability evaluation

Detailed weldability assessment of Alloy D9, 316LN SS, E316-15M weld metal and 316L SS (for comparison) was carried out by application of strain during welding and assessing the deposited weld for cracking using the Varestraint test in which the criteria used included Total Crack length (TCL), Maximum Crack Length (MCL) or Brittleness Temperature Range (BTR). In stainless steels, the BTR, which is the temperature range over which weld metal is prone to cracking during solidification due to presence of low-melting eutectics, and solidification cracking are strong functions of the solidification mode given by WRC Cr_{eq}/Ni_{eq} ratio. The BTR values are low for high $Cr_{eq}/Ni_{eq} > 1.3$, which corresponds to ferritic solidification mode. SS base and weld metals solidifying in FA mode of solidification have BTR ≤ 30°C and are highly resistant to solidification cracking. The cracking tendency increases with decreasing Cr_{eq}/Ni_{eq} ratio, i.e. decreasing ferrite content, while solidification mode changes to AF (austenitic/ferritic) and to "A" (fully austenitic). The PFBR specified E316-15M weld metal with limits of ferrite content of 3-7 FN is located in the safe regime of FA mode of solidification (Fig. 7) and would essentially be free from hot cracking in the weld metal and HAZ.

Solidification cracking is also a function of the level of impurity elements, sulphur and phosphorus, and minor elements such as titanium and silicon. Although direct correlation between the composition, impurity levels and cracking was not available, the diagram of Kujanpaa et al, viz. Hammar-Svensson (H-S) Cr_{eq}/Ni_{eq} vs. P+S content was used [9]. In this diagram (Fig. 8), susceptible compositions lie in the region of $Cr_{eq}/Ni_{eq} < 1.5$ and P+S > 0.015%. Much higher impurity levels can be tolerated for higher Cr_{eq}/Ni_{eq} ratios and such compositions were not susceptible to cracking. The unstabilised stainless steels fit reasonably well into the diagram, with low-BTR compositions finding a place in the less susceptible regions and the high-BTR compositions are placed in the "highly susceptible" portion.

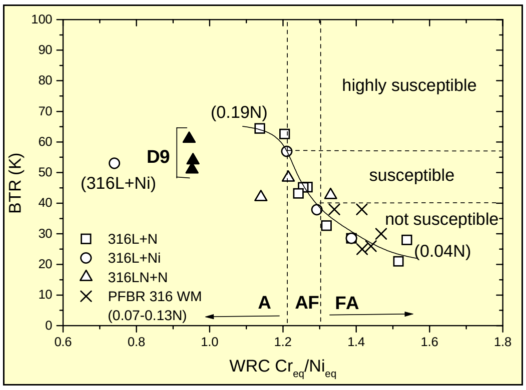


Fig. 7: *Solidification cracking in 316LN and E316-15M weld metal as function of WRC Cr_{eq}/Ni_{eq} ratio; (Solidification mode: A-austenitic, F-ferritic)*

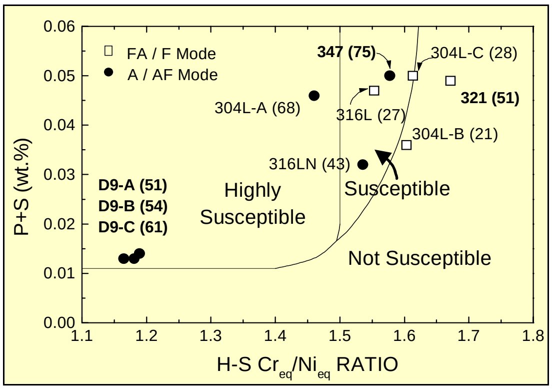


Fig. 8: *Modified Suutala diagram showing hot cracking behaviour as function of Hammar-Svensson Cr_{eq}/Ni_{eq} and P+S content (BTR at 4% strain in brackets)*

Extensive studies were carried out on the effect of nitrogen on fusion zone and HAZ cracking in these materials [10], and are well represented in Fig. 8 in which data for two types of weld are shown; nitrogen-added 316 and 316LN with 0.04-0.19%N, and E316-15M weld metals with 0.07-0.12%N while maintaining Cr_{eq}/Ni_{eq} constant. The essential observations from these data are that nitrogen has no detrimental effect on cracking if Cr_{eq}/Ni_{eq} is maintained to obtain a favourable solidification mode in the weld metal. Nitrogen could be detrimental if ferrite is absent or solidification mode becomes austenitic ("A" mode) and for S > 0.01%. This situation is possible during autogenous welding of base metal or when HAZ cracking is envisaged. During structural welding of components, the risk of cracking during autogenous welding is small due to stringent specifications, particularly for impurity elements. HAZ cracking is a strong function of ferrite content or ferrite potential of the underlying material, but is likely only in extremely high restraint situations. Both these factors are therefore not a serious concern during structural welding.

The fuel clad tubes, which contain the fuel pellets, are made of the alloy D9. On both the ends of the clad tube, end-caps are inserted and welded to seal the tube after filling it with the fuel pellets. Being fully austenitic, alloy D9 is highly susceptible to hot cracking. It is clear from Figs. 7 and 8 that D9 alloys have BTR values that make them fall in "susceptible" to "highly susceptible" regions of the diagram. Hot cracks observed in alloy D9 during Varestraint test is shown in Fig. 9. Since alloy D9 is highly susceptible to hot cracking, it is found that end-cap weld would crack, if both the clad tube and end caps are made from alloy D9. However, if 316LN SS is used as the end-cap material, cracking could be avoided, with careful choice of the welding parameters. Welding is carried out using pulsed GTAW process and major problems faced during end-cap welding were the HAZ cracking and non-uniform weld penetration. Welding parameters like peak current and background current and welding speed were carefully varied to obtain defect-free welds. Recently technology has also been developed for end-cap welding of clad tubes using laser welding techniques.

Application of Varestraint test criteria such as crack lengths and BTR to practical welding situations is complicated by the fact that in the actual case, strain, strain rate and stress are difficult to quantify as a function of weld geometry. Investigations at IGCAR show that the TCL parameter is subject to variations because of weld bead geometry, while BTR is not influenced by these factors that are related to fluid flow effects in the weld pool. It has been shown (Fig. 10) that if TCL is normalised using the weld-width (W), i.e. TCL/W, the correlation with BTR is very good.

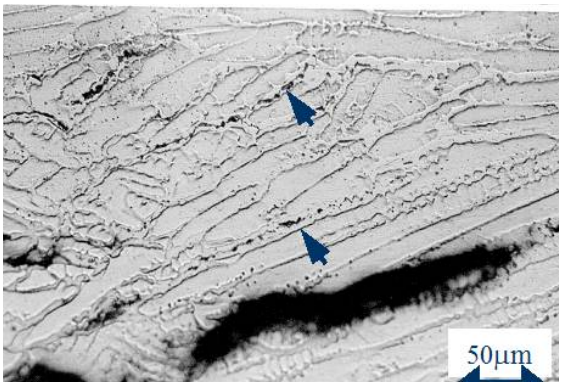


Fig. 9: *Hot cracking in alloy D9 after during Varestraint test*

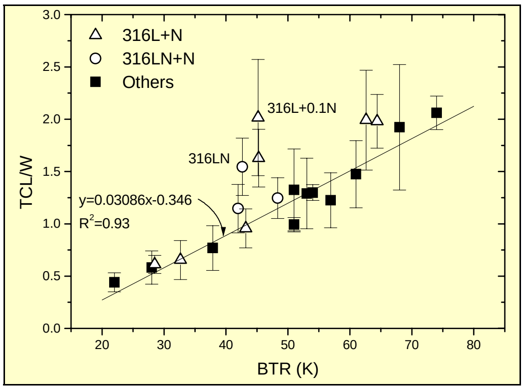


Fig. 10: *Correlation between TCL/W and BTR criteria*

2.3 Tube-to-Tubesheet Welding in Intermediate Heat Exchangers

PFBR has four IHXs in the primary circuit, which transfers heat generated in the reactor core to the secondary sodium. The IHXs are of shell and tube type, counter-current, sodium-to-sodium heat exchangers. The IHXs are very important components of the reactor, as it forms the boundary between radioactive primary sodium in the reactor pool and non-radioactive secondary sodium. The primary sodium of the reactor flows through the shell side and secondary sodium flows in the tube side. The principal material of construction of IHX is 316LN SS. Each IHX has 3600 straight seamless tubes welded to either ends of the top and bottom tubesheets. Expanded and seal welded joint are specified for tube and tubesheet of IHX (Fig. 11). The material specification for both tubesheets

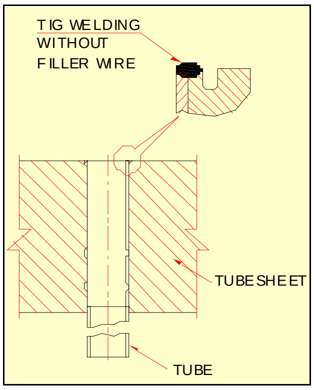


Fig. 11: *Tube to tube joint in IHX*

and tubes are stringent to ensure good welding. It is found that aluminium, a deoxidizing element added during steel making, can increase the fluidity of the molten pool causing sharp changes in the weld pool contour. Further, at high aluminium levels, oxide that is formed on the weld surface can crack off and carried to the pump bearing. Considering these, the aluminium content in both the tube and tubesheet is maintained below 0.07%, with the upper limit chosen based on experience of IHX fabrication of the Fast Flux Test Facility in USA, in which tubes with aluminium content higher than 0.07% was replaced with tube of lower aluminium content. Hence both the tubes and tubesheets are produced by electric arc melting with tight control on inclusion content to achieve sound welds. Ultrasonic testing is done on the entire length of each tube in accordance with ASME Section III Class I. Each tube is subjected to hydro-testing as per PFBR specification to ensure the integrity of tubes. Grain size and chemical composition of tubes and tubesheets have been precisely specified with upper and lower values to optimize mechanical and creep properties.

The IHXs consist of 150 mm thick 316LN SS tubesheet made of forging at the top as well as at bottom end. Each tubesheet is drilled with 3600 holes in a circular pitch. Each hole is provided with two inside grooves at a distance of 20 and 45mm from the bottom face of top tubesheet and from the top face of bottom tubesheet for additional longitudinal load resistance. The strength rolling of the tubes is carried out on these grooves, during which expanded tube grips inside the grooves are used. This arrangement also acts as a mechanical seal for arresting the entry of primary sodium into the gap between the tube outer-diameter and tubesheet hole. Thus, deep crevices are eliminated in the present design by strength and contact rolling of the tubes in the upper and lower regions of the tubesheets. The face grooves are machined with very tight tolerances on the face of each hole on the tubesheet which provides a thinner section across the seal/lip welding to get the desired weld profile. This helps in minimizing the heat input required for seal welding and makes a perfect fusion of the base materials (tube and tubesheet). The thickness of thinner section on the face groove is approximately same as that of tube wall thickness.

The straight tubes are inserted in the tubesheet hole such that the ends of tubes are flushed with the face of the tubesheet. Tubes are held at regular intervals by anti vibration belts to minimize the effect of flow induced vibration. Even though conventional heat exchanger tube-to-tubesheet joints are done first by welding and then by rolling, PFBR tube-to-tubesheet joints are executed first by rolling by using mechanical tube expanders and then single-pass welding by automatic pulsed GTAW process without filler wire, to avoid induced stresses and cracks on the welds during tube expansion step and subsequent failure of the weld joints during transient reactor operating conditions. The weld is executed in 5G position (tube axis horizontal). The process parameters of welding include pre purge time, up slope, speed of welding, down slope, post purge time. The weld quality with respect to shape and soundness are controlled by process parameters. The welds produced satisfying the non-destructive test requirements were also subjected to pullout test and found to have strength of about 29 kN. The IHXs of PFBR with these tube-to-tubesheet joints have been successfully fabricated and are now ready for installation.

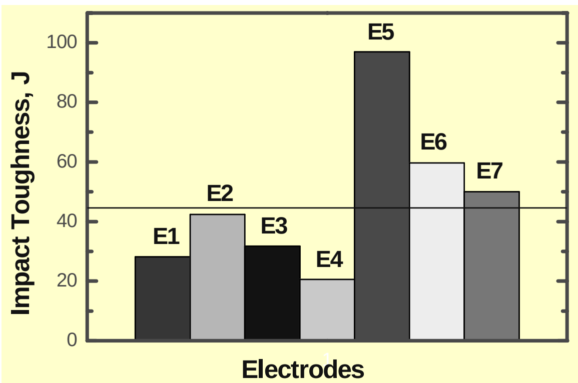
3. Welding of Modified 9Cr-Mo Steel

The major technological issues in weldability of modified 9Cr-Mo (grade 91) steel are the determination of the critical preheat-temperature to avoid hydrogen assisted cracking (HAC) and achievement of adequate toughness in the weld metal. Though Section IX of ASME code stipulates post-weld heat treatment (PWHT) at a minimum of 700°C for 1-2 hrs for grade 91 steel, it does not address the issue of preheat temperature. On the other hand, developers of this alloy recommended a mandatory minimum preheat temperature of 200°C. The job thickness, hydrogen content of the electrode, carbon equivalent, and weld heat input need to be considered together to determine the preheat temperature required to prevent cold cracking. International experience shows that the critical preheat temperature is a sensitive function of composition, but the results of various studies are not conclusive.

Achieving good toughness in the weld metal, especially in those produced by processes that involve fluxes (like SMAW, SAW and FCAW) has been an uphill task ever since the development of grade 91 steels. The high impact energy of GTA welds even in as-welded condition could be attributed to the clean GTAW process, low oxygen content (< 20 ppm) in the GTA weld metal compared to the SMA weld (400 ppm) and use of higher number of passes than SMAW. During the initial stages of development, it was found that achieving good toughness in the weld metal with a composition optimized for the plate or pipe materials is difficult. Systematic studies on effect of various alloying elements on weld metal toughness revealed that nickel is beneficial while niobium and silicon have deleterious effect on toughness. As this material is meant for high temperature application, many standards for these consumables do not specify toughness for these weld metal. Accordingly, nickel was added to the welding consumables, and niobium and silicon were reduced. Hence, when SMAW process was considered as one of the welding processes for fabrication of PFBR steam generator, a separate specification was drafted for welding electrodes so that the weld metal meets the desired toughness and RT_{NDT} (Reference Temperature – Nil Ductility Transition) requirements. Accordingly, it was specified that for production of electrodes core wire with composition similar to that of the base metal shall be used (non-synthetic electrodes). Also, an upper limit of 1.5% for Ni + Mn was specified so that the PWHT temperature would be lower than the transformation temperature for this steel, and impurity elements like sulphur and phosphorus were kept at lower limits while the composition range for the major alloying elements are kept in a narrow range. For steels with Cr > 9%, the microstructure of weld can contain a small volume fraction of delta-ferrite in both the HAZ and the weld metal. Toughness of both HAZ and weld metal is found to decrease with increase in volume fraction of delta ferrite. Delta-ferrite decreases the creep properties of grade 91 weld metal. Accordingly, compositions of both base metal and welding consumables are optimized to have no delta-ferrite in the weld metal or HAZ.

3.1 Development of SMAW electrodes

Electrodes based on the PFBR specification (AWS classification E9016-B9 of ASME Section II-C SFA-5.5 with modified/additional requirements), were developed with Indian electrode manufacturers. The composition of weld metals from these electrodes is given in Table 3 along with PFBR specification and composition of the weld metals from several other electrodes; and results of impact tests on the weld metals produced from these electrodes are given in Fig. 12. The weld metal of electrode E1 met the PFBR specification; but it was a synthetic electrode made from mild steel core wire. Electrode E2 is also synthetic. Only the electrodes that are developed as per the composition (E5, E6 and E7) possess minimum requirement of 45 J at 20°C after PWHT at 760°C for 3



<u>Fig. 12</u>: *Impact toughness of different welding electrodes*

hours. Most of the commercial electrodes do not meet the toughness requirement as per PFBR specification.

RT_{NDT} was determined for E1, E6 and E7 from a combination of drop weight test (ASTM E 208) and impact test. For the weld metals of E6 and E7 non-synthetic electrodes developed as per PFBR specification, this value was found to in range of –3°C and –5°C, respectively. The recommended temperature for hydro-testing of the components is 33°C above the RT_{NDT} determined for the material of construction for the component. This means, hydro-testing of the components fabricated using these consumable (in this case steam generator) can be conducted at ambient temperature (~30°C). It is interesting to note that the weld metal of a synthetic electrode had RT_{NDT} much above the room temperature and hydro-testing of a component made using such welding consumable would require use of hot water.

Table 3: *Chemical composition of weld metals from SMAW electrodes*

Elements	PFBR	SMAW weld metals						
		E1	E2	E3	E4	E5	E6	E7
C	0.08–0.12	0.09	0.06	0.062	0.1	0.085	0.10	0.1
Cr	8.0– 9.5	9.00	9.8	9.0	8.64	8.30	9.00	9.0
Mo	0.85–1.05	1.0	0.8	1.1	0.94	1.0	1.00	1.0
Mn	0.5 – 1.20	0.55	0.6	1.5	0.7	0.7	0.70	0.75
Si	0.15–0.30	0.20	0.35	0.3	0.25	0.28	0.24	0.32
S	0.01 max	0.007	0.015	0.01	0.01	0.015	0.012	0.008
P	0.01 max	0.015	0.015	< 0.007	0.006	0.015	0.009	0.01
Ni	0.4–1.0	0.6	0.1	0.9	0.6	0.5	0.70	0.52
Nb	0.04–0.07	0.06	–	0.03	0.05	0.069	0.06	0.065
V	0.15–0.22	0.07	0.012	0.012	0.19	0.004	0.17	0.21
N	0.03–0.07	0.033	0.025	0.03	0.046	0.025	0.055	0.06
O	NS	0.07	0.05	0.04	--	--	0.068	0.08
Cu	0.25 max	0.05	0.05	< 0.05	0.03	0.05	< 0.050	
Al	0.04 max	0.034	0.034	–	0.003	–	< 0.01	

3.2 Assessment of HAC susceptibility

Although grade 91 steel is highly weldable, one of the major concerns in its fabrication is HAC. Cracking is caused by the complex interaction of dissolved hydrogen atoms with the defects in the crystal lattice. In addition to hydrogen, a susceptible microstructure and sufficient restraint are also necessary for cracking to occur. Evaluation of HAC susceptibility of grade 91 steel was carried out using University of Tennessee (UT) – Modified Hydrogen Sensitivity Test during which the hydrogen content in the shielding gas was varied from 0.25 to 1.5 vol. % to obtain different levels of hydrogen content in the weld metal. The preheat temperature above which no specimen cracked for given hydrogen level and strain levels was chosen as the critical preheat temperature for that condition, and under identical testing conditions critical preheat temperature is always higher for grade 91 steel than for the plain 9Cr-1Mo steel.

Specimens of grade 91 steel tested without hydrogen in the shielding gas did not show any cracking at room temperature. However, those tested with 0.25% hydrogen in the shielding gas cracked without preheat. In the case of plain 9Cr-1Mo steel, no cracking was observed for the specimens prepared without preheat even with 0.5% hydrogen in the shielding gas. This established the higher susceptibility of grade 91 steel to HAC than plain 9Cr-1Mo steel. The reasons for the higher HAC susceptibility of grade 91 over 9Cr-1Mo steel are not very clear, although in general, the phenomenon is related to the degree of hydrogen trapping in the microstructure. The major difference between these steels is only in the micro-alloying elements niobium and vanadium in the modified version, which imparts superior creep properties. It has been reported that in Cr-Mo steel with 2–3%Cr, Nb and V do not significantly influence the cracking behaviour. However, there is a wide variation in the critical preheat temperature for 9Cr-1Mo steel due to minor variation in the composition. Increase in silicon content in the steel has been shown to increase the HAC susceptibility. Further, higher strength of grade 91 steel could also contribute to its increased susceptibility to cracking.

The lowest level of hydrogen, viz. 0.25 vol.%, that corresponds to about 1 ml hydrogen/100 g of weld metal, is much lower than the permissible hydrogen level of 4 ml/100 g of weld metal for low hydrogen electrodes (as per ASME Section II-C SFA 5.5). The fact that HAC is caused even with such a low level of hydrogen in the case of grade 91 steel clearly shows that sufficient preheating and post heating, baking of electrodes etc., should be properly employed during welding of this class of steel with SMAW process. Even while welding with GTAW process; it is advisable to ensure the quality of the gas so that moisture content is kept at a sufficiently low level. It must however, be noted that behaviour of weld metal deposited by SMAW will be influenced in addition by the inclusion content, and other compositional variations. The variation of hardness with tempering time at various temperatures reflects the complex microstructural changes that are responsible for the hardness variation, particularly when the weld metal contains high austenite stabilising elements. PWHT temperature and time must therefore be carefully selected depending on composition and deposition process.

3.3 Fabrication of Steam Generators

Steam generators are one of the most critical components of PFBR because in this component high temperature sodium flows in the shell side and water/steam in the tube side and the boundary separating them is the tube wall of thickness of 2.3 mm. Any leak in the tube or in the tube-to-tubesheet joint can result in direct sodium-water reaction with dangerous consequences. Figure 13 shows the schematic of SG and that of the tube-to-tubesheet joint in SG, one of the most critical joints in PFBR. As the SGs are made of grade 91 steel, this necessitates a dissimilar joint between stainless steel piping headers of grade 91 steel. Unlike austenitic stainless steels, PWHT after welding is mandatory for welds of this steel and this is another challenge that needs to be overcome during fabrication of SGs. As the steam generators to be subjected to hydro-testing, minimum toughness requirement has been specified for both the weld metal and base metal. Hence choice of welding process and consumable that would ensure good toughness for the weld metal was also a challenge to be overcome for SG fabrication.

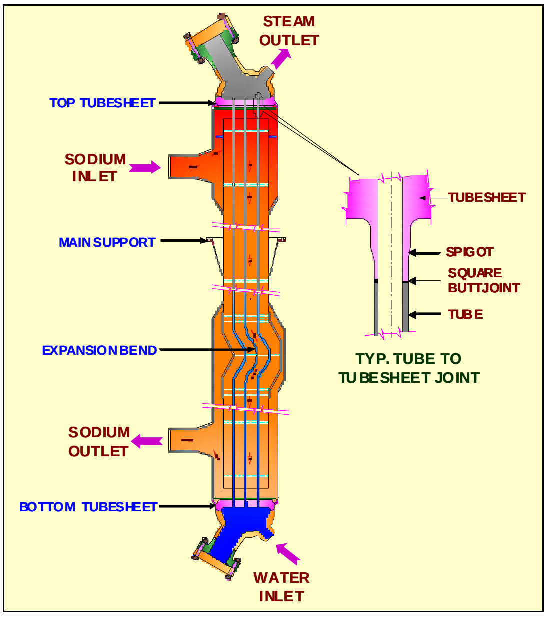


Fig. 13: *Schematic of steam generator of PFBR and its tube-to-tubesheet joint configuration*

3.3.1 *Thick section welding by narrow-gap GTAW*

Even though the natural choice of welding procedure for thick section welding of the SG shell, tubesheet and headers would have been a combination of GTAW (for root pass) and SMAW (for remaining pass), the all GTAW process using hot-wire Narrow Gap GTAW (NG-GTAW) process was chosen for the SGs of PFBR. This eliminated the uncertainty over toughness of the weld metal and the requirement of subzero RT_{NDT} could be easily met. The impact toughness obtained for the all GTA weld metal was ~75 J in contrast to ~43 J obtained for weld metal produced by GTAW+SMAW process, which also had high scatter. In addition, the risk of cold-cracking could also be reduced considerably by adopting the NG-GTAW process. This is also important considering the considerably time gap that would exist between the welding and PWHT during fabrication of such huge components and difficulty in conducting localized PWHT around the welds. In fact, the hot-wire NG-GTAW process was employed first time in India for fabrication of PFBR steam generators.

3.3.2 *Dissimilar metal weld (DMW) between austenitic SS and modified 9Cr-1Mo steel*

The austenitic SS/Cr-Mo steel DMWs have long been recognised to pose a potential problem, because of large thermal stresses generated due to difference in thermal expansion characteristics of the two steels. Thermal cycling during power plant operation plays a major role in premature service failure of this joint. Although similar failures are reported in creep-rupture tests, there is general agreement that in operating plants, stresses responsible for failure of this DMW are due to thermal cycling that occurs during plant start-ups and shut-downs. Laboratory test results and service experience have shown that a significant improvement in service life of this DMW can be achieved by using nickel-base welds instead of austenitic SS welds. However, service failures of DMWs with nickel-base welds have also been reported. Indeed, nickel-base welds only buy more time, but eventually fail before the plant's design life. Among various approaches attempted for development of improved DMWs, one approach is a trimetallic DMW with transition piece having coefficient of thermal expansion (CTE) intermediate to the ferritic and austenitic steels for obtaining a more gradual change in CTE and consequent decrease in magnitude of stresses from thermal cycling. Alloy 800, the most attractive choice for the transition piece, reduces hoop stress near the root of the ferritic steel by 37%, besides providing excellent resistance to oxidation and creep at elevated temperatures.

Numerous reports available on premature failures of these DMWs in fossil power plants worldwide encouraged us to carry out a detailed systematic study on the performance of the DMW between 316LN SS and grade 91 steel much before actual SG fabrication was taken up. A new trimetallic DMW configuration, which would last for entire life of the plant, was developed at IGCAR using a transition piece of Alloy 800. Comprehensive work was carried out on choice of welding consumables, evaluation of hot cracking susceptibility, high temperature stability of weld interface, and service performance using thermal cycling tests [11]. Based on these investigations, the trimetallic DMW joint configuration was evolved for the SG circuit (Fig. 14), in which Inconel 82/182 is used for the grade 91/ Alloy 800 joint, and ER16-8-2 for welding the Alloy 800/316LN SS joint. Performance evaluation by thermal cycling tests indicated a four-fold increase in the life of this joint with the trimetallic configuration as compared to bimetallic configuration. Accordingly, for PFBR, the trimetallic joint configuration, as shown in Fig. 13 (Detail-A) has been adopted.

In spite of extensive studies conducted and experienced gained on this trimetallic joint, this dissimilar weld did give some surprises during actual fabrication of SG. The intermediate pipe piece of Alloy 800 was produced by rolling Alloy 800 plate and L-seam welding it with Inconel 82 into a pipe. However, during C-seam welding of 316LN SS and Alloy 800 pipes using 16-8-2 welding consumable, hot cracks developed at the L-seam/C-seam junction. Consequently, the welding procedure for this location was modified to include buttering of the Inconel weld area with 16-8-2 weld metal prior to C-seam welding (Fig. 15).

Fig. 14: *Schematic of trimetallic transition joint developed adopted for joining SG header with SS piping in PFBR [number below each material denotes mean CTE, in μm/m/K, upto 600 °C]*

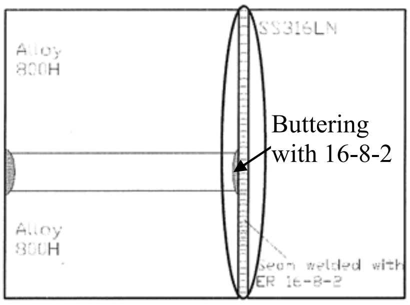


Fig. 15: *Modified procedure adopted to avoid hot cracking at L-seam/C-seam junction*

4. Welding of the Carbon Steel Roof Slab

A box-type structure, made of A48P2 carbon Steel (CS) (similar of ASTM A516 Grade 70 with lower limits for S) specified in the French Nuclear Code for FBRs RCC-MR, consists of a bottom plate and a top plate with the space between them being partially filled with concrete. This box-type structure is a massive structure of 12.9 m diameter, 1.8 m height and weighs about 650 tonnes. The thickness of the plate was chosen to be 30 mm from the consideration that stress relieving heat treatment is not mandatory for this thickness as per various fabrication codes. The fabrication of the box-type structure involves dissimilar metal weld (DMW) joint between A48P2 CS and 316LN SS plates at the bottom of the structure. Detailed studies were carried out to assess the soundness and life of the DMW joint that included studies on: (i) susceptibility of the joint to hot cracking; (ii) effect of partially mixed zone (PMZ) and unmixed zone (UMZ) on joint properties; (iii) impact properties of the weld metal, weld/base metal interfaces and CS-HAZ; and (iv) residual stress distribution in as-welded condition and after exposure to 180°C for a cumulative time of 120 hours that the joint is expected to experience in its operating life of 40 years. The welding procedure for this component were finalised based on the results of these studies.

4.1 Avoiding lamellar tearing in Roof Slab weld

Lamellar tearing is one of the defects that are expected during welding in fabrication of structures using thick section welding. These plates met through-thickness ductility of 25% and ultrasonic inspection requirements. However, during fabrication of the roof slab, lamellar tearing was observed in one heat of this steel, though this heat had met all the specification requirements. This was overcome by buttering the plate surface by welding, as permitted in ASME, and by changing the joint design. Figure 16 gives the details of the cracking observed, and buttering and modification of joint design to overcome lamellar tearing.

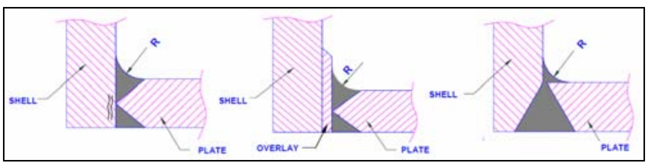


Fig. 16: *Avoiding lamellar tearing my buttering and modification of the joint configuration*

4.2 Dissimilar metal weld joint between A48P2 carbon steel and 316LN SS

Austenitic SS fillers are commonly used for this DMW when operating temperatures do not exceed 648 K. The commonly used welding consumable E309, containing 12-14%Ni and 22-25%Cr, was chosen for this A48P2/316LN SS joint. This high alloy content in E309 consumable is sufficient to prevent the formation of martensite or bainite in the weld even after dilution by the base metal, and also to retain some residual amount of delta-ferrite for minimising the possibility of hot cracking during welding under severe restraints. During the fabrication of a similar structure, a stress relieving heat treatment was given to all the shop-fabricated parts to ensure dimensional stability of the components, even though the plate thickness involved in most of the weld joints was only 35 mm, thus exempting the component from stress relieving heat treatment as per the applicable codes. In the present case, only the site-integration weld joints are not subjected to stress relieving heat treatment.

5. Hardfacing of Reactor Components

Many challenges tasks were undertaken at IGCAR to evolve a robust hardfacing strategy for the components of PFBR. At first, based on radiation dose rate and shielding considerations during maintenance, handling and decommissioning, nickel-base Colmonoy hardfacing alloy was chosen to replace the traditionally used cobalt-base Stellite alloys [6]. The next challenge was to adequately qualify and characterise this nickel-base alloy having poorer weldability and high-temperature stability than the cobalt-base alloys. Another challenge was to choose an appropriate deposition process. Metallurgical studies revealed that the hardness and microstructure of the GTA deposit of the nickel-base hardfacing alloy is significantly affected by dilution from the base metal with the width of the softer dilution zone (of up to 2 mm) often exceeding the recommended final hardface deposit thickness [12]. Also, certain components, like Grid Plate sleeves of about 80 mm inner diameter, which required hardfacing deep inside the inner surface of the sleeve, were not amenable for hardfacing by conventional processes like GTAW unless major design concessions were permitted. Hence, the more versatile PTAW process was chosen to ensure that the width of the dilution zone could be controlled to as low as 0.2 mm (Fig. 17) by optimising the deposition parameters [13]. An Indian fabricator, who has since been entrusted with the hardfacing of components for the project, designed and developed a suitable miniature PTAW torch (Fig. 18) for hardfacing the inner surface of Grid Plate sleeves. Now, the PTA process has been qualified and is being used for hardfacing of the necessary components of PFBR.

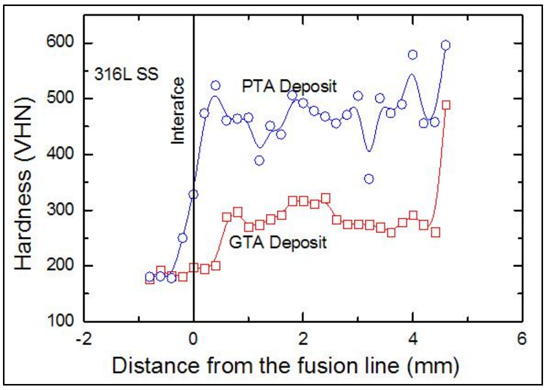


Fig. 17: *Hardness profiles for Colmonoy hardface deposits made by GTAW and PTAW processes*

Fig. 18: *Hardfacing of grid plate sleeve (inner diameter about 80 mm) using an indigenously designed PTAW torch*

5.1 Hardfacing of Grid Plate Assembly

The Grid Plate assembly of PFBR is a massive structure consisting of a two plates (top and bottom) about 6.5 m in diameter and comprises large number of sleeves in which the foot of fuel sub assemblies rest. The Grid Plate rests on the Core Support Structure that also acts as boundary between the cold and hot sodium in the reactor. Both the Grid Plate and the Core Support Structure are made of 316LN SS and are immersed in flowing sodium and remain in contact throughout the reactor life (at least 40 years). Hence, there should not be any self-welding between these components at their contact locations. Therefore, the design requires hardfacing on two annular grooves machined on the bottom plate of the Grid Plate. These grooves are located near the periphery of the bottom plate and hence, the diameters of these grooves are similar to that of the Grid Plate itself, with the total circumferential length of each hardfaced deposit being about 21 m. These components are designed to ensure that area of contact between Grid Plate and the Core Support Structure is confined to these hardfaced grooves on the bottom plate.

During technology development of the Grid Plate (using plates of similar dimensions as for the actual PFBR Grid Plate), extensive cracking of the deposit was observed when deposition was carried out as per the procedure finalised initially based on trails carried out on a 1000 mm diameter plate of 80 mm thickness. Subsequently a detailed review of the groove design, welding process, procedure, heat treatment etc. was undertaken. The groove width was reduced from 45 to 20 mm and the groove angle increased from 30 to 60°. This enabled to carry out hardfacing in single layer and single pass of deposition. Preheat temperature for deposition was increased from 500 to 650°C, and furnace for preheating and stress-relieving heat treatment was modified to ensure that temperature variation across the component during heating or cooling is reduced considerably. Insulation was also improved to reduce heat losses. It was also decided to carry out hardfacing continuously using four PTAW machines positioned on a circular track, which is concentric to the bottom plate. Machine controls were suitably modified to have smooth deposition between starting and ending locations of the deposits, which were found to be more prone to cracking than the other locations of the deposit. New trials were taken up during technology development for hardfacing of the Grid Plate and cracking of the deposits reduced considerably in these attempts. The process was further refined and it was demonstrated on the Grid Plate for technology development that crack-free hardface deposit meeting all design requirements could be made using this improved procedure.

After successfully demonstrating the procedure on the technology development Grid Plate, hardfacing of the bottom plate of the PFBR Grid Plate was taken up. Due to the above prior experience, it was possible to achieve much better control over temperature during heating and the heat treatment stages. Deposition was carried out simultaneously using four PTAW machines mounted on the track, 90° apart. After the bottom plate reached preheat-temperature the entire operation of hardfacing the two grooves of about 6.5 m diameter took only a few hours.

Fig. 19: *The bottom plate of PFBR Grid Plate mounted on the preheating furnace with hardfacing in progress*

Figure 19 shows the bottom plate of the Grid Plate mounted on the furnace with hardfacing operation in progress. Neither cracks nor debonding nor surface porosities were observed on the deposits. There was no need to carry out any repair though a procedure for repair had also been finalised. The deposits made on the bottom plate of the PFBR Grid Plate were found to be better than the deposits made during technology development. This was possible only because of the dedicated efforts of designers, engineers, hardfacing agency and the manufacturer of the component.

6. Concluding Remarks

Construction of India's 500 MWe PFBR is in an advanced stage of completion. Prior to the start of construction, extensive research-backed technology development was planned and implemented for materials, welding consumables, fabrication of stringent-specification components and finalisation of inspection and testing procedures of fabricated components. With close interaction amongst design, materials engineers, materials and welding consumable manufactures, and fabrication industries, it has been possible to overcome the challenges during fabrication of all the structural welds. Valuable experience gained from these technology developments were inputs to design engineers in finalizing the specification of material, freezing the design drawing and charting out the quality assurance plan for each components. The synergy between designers, welding and inspection engineers and fabricators has contributed significantly to the progress with respect to construction of PFBR.

Right from the preliminary design of the PFBR, IGCAR had realized the importance of welding both during fabrication and in service. Hence, a systematic programme was undertaken to integrate welding and fabrication and inspection aspects in design and selection of materials. This approach has enabled us to overcome the challenges faced during fabrication of the components with stringent specifications. A few examples of manufacturing technologies completed in time, and exceeding the specifications in most of the cases have been presented.

The experience gained in construction of PFBR is vital in the design and construction of the future Commercial Fast Breeder Reactors (CFBR). It is envisaged that selected modifications in the design, material selection, fabrication processes etc. will continue to be achieved to reduce cost of construction, have improved safety and thermal efficiency of the reactor. For example, use of activated GTAW for stainless steel pipes, flux-cored arc welding for fabrication of reactor vessels, etc are being pursued for such a realization of success. This continuing endeavour of learning from challenges and adapting R&D to the future fast spectrum reactors would ensure that India becomes a leader in sodium-cooled fast reactor technology.

Acknowledgement

This paper incorporates the results of more than a decade's efforts carried out with a large number of scientists and engineers primarily from the Reactor Engineering and Metallurgy & Materials Groups of IGCAR Kalpakkam. I would like to acknowledge the contributions of each and every member of these Groups.

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