A Comprehensive Analysis by PAUT of Stress Corrosion Cracking (SCC) in Austenitic Stainless Steel Super 304H & 347H Grade Tubes in Super critical thermal power plant

BY

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Outline of Presentation

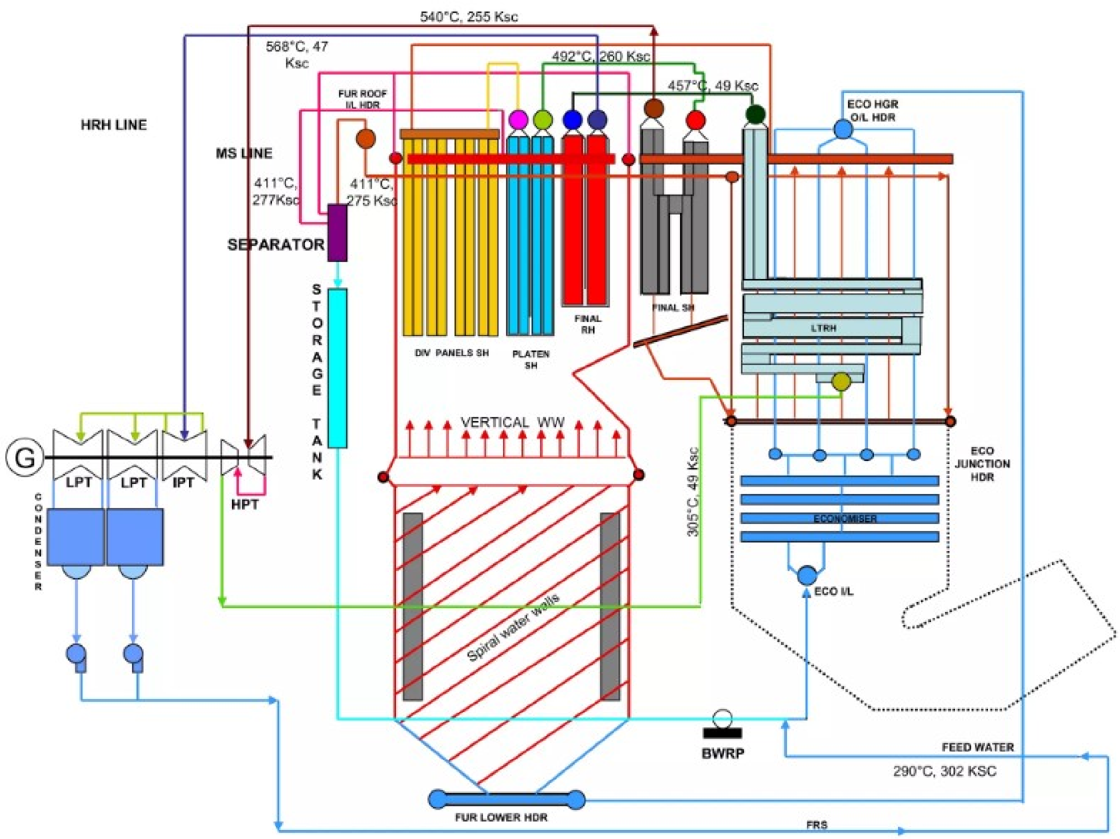
Super Critical (SC) & Ultra super critical (USC) boilers in NTPC- A Brief overview

एनटीपीसी NTPC

- NTPC had commissioned more than 25 SC units (each of 660MW /800MW) with a total capacity of 19000 MW & 3 USC units (each of 660MW).
- Higher Thermal Efficiency (of the order of 39%-42%) and lower emissions are ensured in the Coal based Thermal Power Projects working on SC /USC steam parameters.

S.No.	Type of Boiler	Feed Water Pressure (Kg/cm^2)	Temperature (SH/ RH), °C	Efficiency (%)	Material grade used in Superheater	Material grade used in Reheater
1	Sub-Critical	180	545/ 545	34	SA213 T91	SA213 T91
2	**Super Critical**	**256**	**545/ 565**	**39**	**Super 304H & 347H**	**Super 304H & 347H**
3	**Ultra Super Critical**	**270**	**600/ 600**	**41.5**	**Super 304H & 347H**	**Super 304H & 347H**

Typical Material selection for 660MW/ 800MW

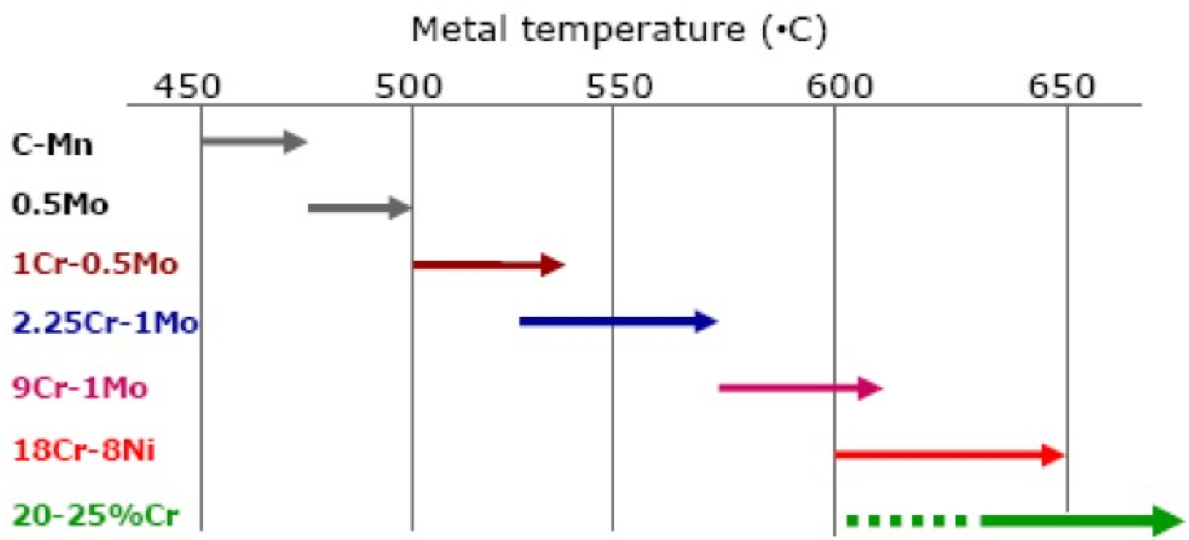


S.No.	Boiler Tube Material	Upto Temperature (°C)
1	SA 210 Gr.C / SA 106	400°C
2	SA 213 T11 / SA 335 P11	500°C
3	SA 213 T12 / SA 335 12	550°C
4	SA 213 T22 / SA 335 P22	550°C
5	SA 213 T23	550°C
6	SA 213 T91 / SA 335 P91	601°C
7	SA 213 T92 / SA 335 P92	610°C
8	SA 213 TP 347H	610-630°C
9	SA 213 UNS S3042	610- 700°C

Typical Material selection for Boiler tubes

Criteria for reliable operation at elevated temperature:

- Creep strength
- Steam side oxidation resistance
- Flue gas side corrosion resistance



Properties of 347H & Super 304H material

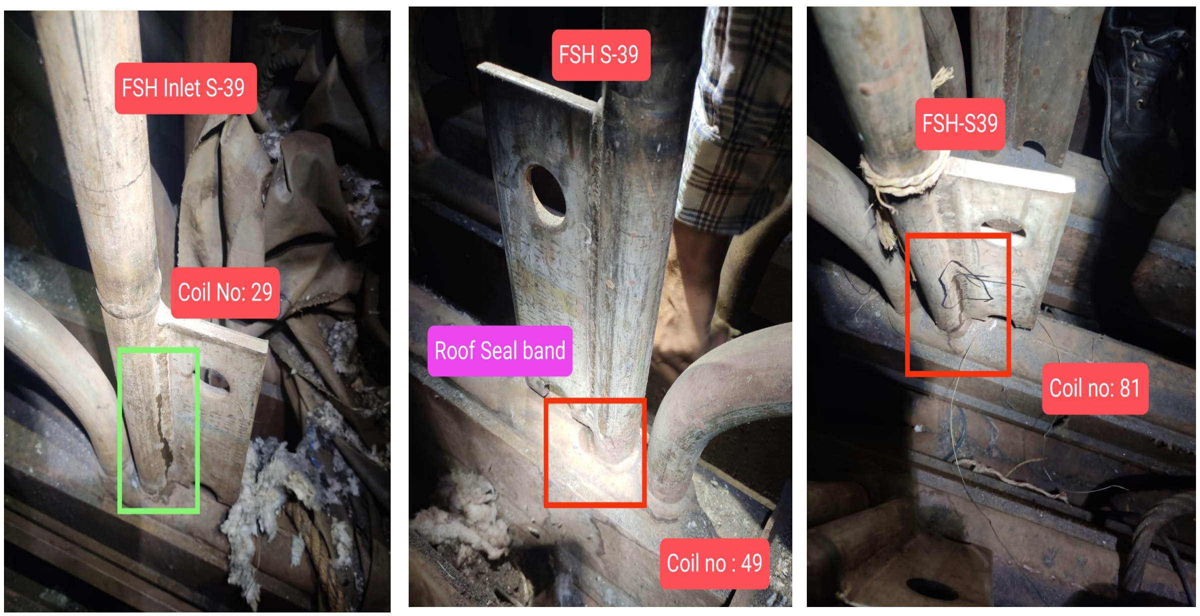
P No	Material Specification	C	Mn	P, max.	S, max.	Si	Ni	Cr	Cu	Nb+Ti	N	Tensile Strength (M Pa)	Remarks
P 8 /1	SA 213 TP 304 H	0.04-0.10	2	0.045	0.03	1	8.00-11	18.00-20	0	0	0.1	515	(1) **Copper** is added to super 304H to improve high strength and creep strength at elevated temperature
P 8 /2	SA 213 TP 347 H	0.04-0.11	2	0.045	0.03	1	9.00-12	17.00-19	0	1(Nb)	0.1	515	
P 8 /1	SA 213 UNS S30432 (Super 304H)	0.07-0.13	1	0.045	0.01	0.3	7.5-10.5	17.00-20	2.5-3.5	0.55 (Nb)	0.12	590	(2)**Niobium(Nb) + Titanium(Ti)** are added to reduce the sensitization

Benefits of using Super 304H Stainless Steel

- **Higher carbon content gives the material greater heat resistant qualities**
- **Higher tensile yield strength**
- **Greater creep strength**
- **High corrosion resistance**
- **Low oxidation rate**

Challenges faced in SC & USC Boilers with Super 304H & 347H material

- These Austenitic Stainless-Steel material poses serious quality challenges during erection / commissioning / operation of units, mainly due to the **phenomenon of Stress Corrosion Cracking.**



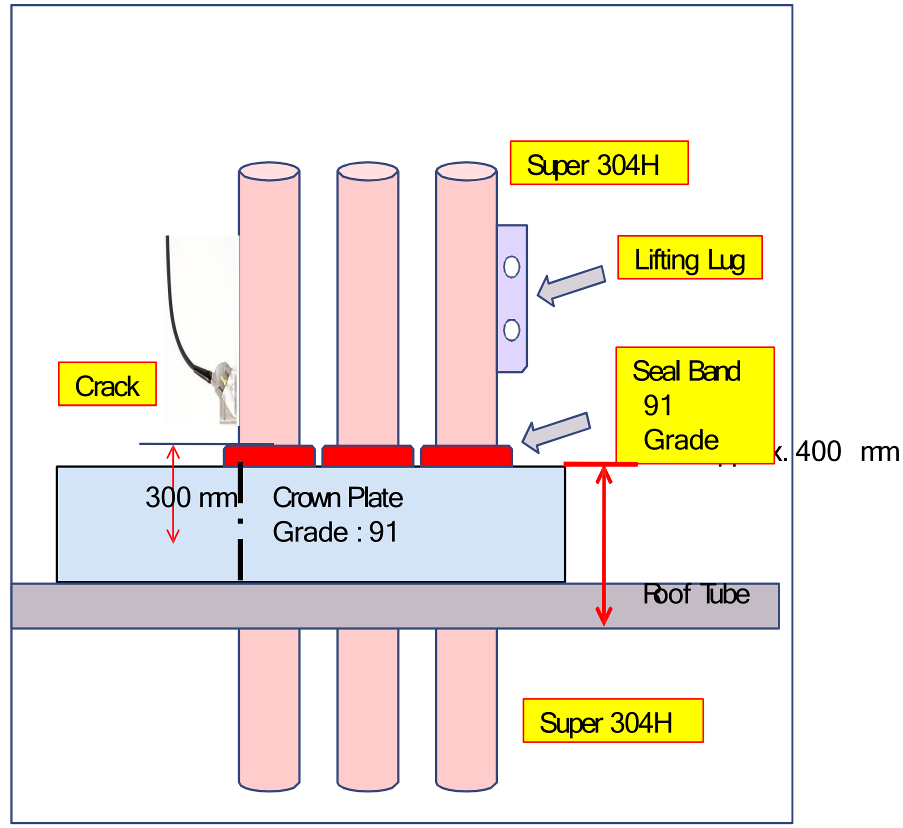
Seepages observed in Shop welded attachment lifting lug joints & Roof Seal band area in Finish Superheat (FSH) inlet Super 304H coils (S-39) of during 1st Hydrotest

Observed seepages in 29 tubes near SHOP WELDED Seal band joints of Finish Reheater (FRH) coils during 1st hydrotest

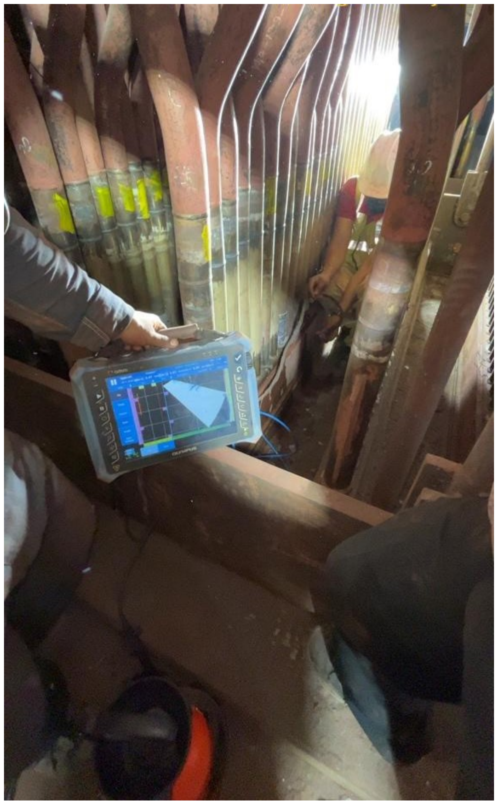
FINISH RE-HEATER (FRH)- TYPICAL ARRANGEMENT IN SC/ USC BOILERS:

Shop Welded Joints

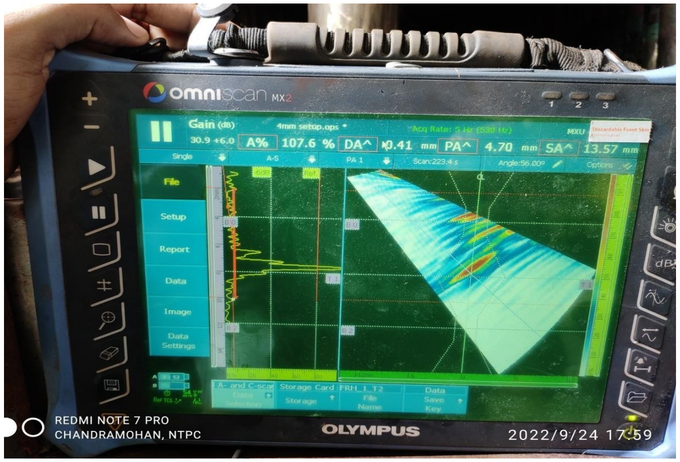
FRH coil tubes near Seal band weld lost it's ductility!



Visual examination & PAUT of FRH seal band area:



The weld joints and adjoining Heat Affected Zone (HAZ) were examined by Advanced NDE technique like Phased Array Ultrasonic Testing (PAUT) for detection of cracks on ID/OD of Super 304H tubes of FRH coils.



FRH outlet coils defects mapping:

FRH COIL

Coil	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	PAUT	LEAK	Remark
C1		PAUT													1	0	
C2			PAUT											PAUT	2	0	
C3		PAUT	LEAK	LEAK		PAUT					PAUT	PAUT			4	2	
C4				PAUT											1	0	
C5		PAUT												PAUT	2	0	
C6															0	0	
C7															0	0	
C8	PAUT														1	0	
C9		PAUT													1	0	
C10				PAUT											1	0	
C11		LEAK		PAUT						PAUT					2	1	NETRA T4
C12															0	0	
C13												PAUT			1	0	
C14				PAUT						PAUT					2	0	
C15		PAUT													1	0	
C16					PAUT		LEAK	LEAK							1	2	
C17		PAUT					PAUT								2	0	
C18		PAUT													1	0	
C19								PAUT	PAUT						2	0	
C20		PAUT													1	0	NETRA - T2
C21		PAUT									PAUT				2	0	
C22															0	0	
C23			PAUT												1	0	
C24	LEAK	LEAK	LEAK	LEAK											0	4	
C25			PAUT												1	0	
C26												PAUT			1	0	
C27											PAUT		PAUT	PAUT	3	0	
C28															0	0	
C29		PAUT													1	0	
C30			PAUT									PAUT			2	0	
C31						PAUT									1	0	
C32					LEAK			LEAK	PAUT						1	2	
C33							LEAK				PAUT				1	1	
C34		PAUT		PAUT											2	0	
C35		PAUT	PAUT	PAUT	PAUT	PAUT									5	0	
C36															0	0	
C37								PAUT	PAUT	PAUT		PAUT			4	0	
C38	PAUT	LEAK	LEAK	LEAK	LEAK	LEAK	PAUT	LEAK	LEAK	PAUT					3	7	
C39								LEAK	PAUT				PAUT		2	1	
C40					PAUT	PAUT		PAUT	PAUT			PAUT		PAUT	6	0	
C41		PAUT			PAUT	PAUT		PAUT		LEAK	LEAK	LEAK	LEAK	LEAK	4	5	
C42		PAUT	PAUT	PAUT	PAUT	LEAK	PAUT		PAUT	PAUT		PAUT	PAUT		9	1	
C43		PAUT	PAUT	LEAK				PAUT					PAUT		4	1	
C44			PAUT												1	0	
C45						LEAK	LEAK	PAUT						PAUT	2	2	
C46		PAUT											PAUT		2	0	
C47				PAUT			PAUT						PAUT		3	0	
C48		PAUT				PAUT		PAUT	PAUT	PAUT					5	0	
C49		PAUT	PAUT	PAUT	PAUT		PAUT				PAUT				6	0	
C50		PAUT						PAUT							2	0	
C51		PAUT	PAUT	PAUT	PAUT	PAUT	PAUT	PAUT	PAUT						8	0	
Total															108	29	137

(Red) : **1st time Hydrotest Seepages (in 29 tubes near Seal weld)**

(Blue) : **Defects in PAUT (108 tubes near seal weld)**

After replacing above 141 tubes, hydrotest was again carried and again 42 fresh seepages were observed.

Hence it was decided that remaining 581 FRH outlet tubes shall be replaced.

No.of FRH outlet coils	No.of tubes/ coil	Total no.of tubes to be replaced	No.of joints for total replacement of FRH outlet coils
51	14	714	1428 (Butt) + 714 (Fillet-seal welds)

Failure Analysis of FRH samples at NTPC-NETRA lab

Table 1: Details of the sample

Sl No	R&D Ref	Sample details	Dimensions, mm (measured) OD x Thickness
1	6588	FRH tube – Coil No 11 tube no 2	63.5 X 4.5
2	6589	FRH tube – Coil No 11 tube no 3	63.5 X 4.5
3	6590	FRH tube – Coil No 3 tube no 3	63.5 X 4.5
4	6591	FRH tube – Coil No 38 tube no 1	76.0 X 5.5

Seepage & pin hole leakage

No seepage & no defect in PAUT

Seepage in Hydrotest

Defect in PAUT in Lifting lug tube

Failure Analysis of FRH samples at NTPC-NETRA lab

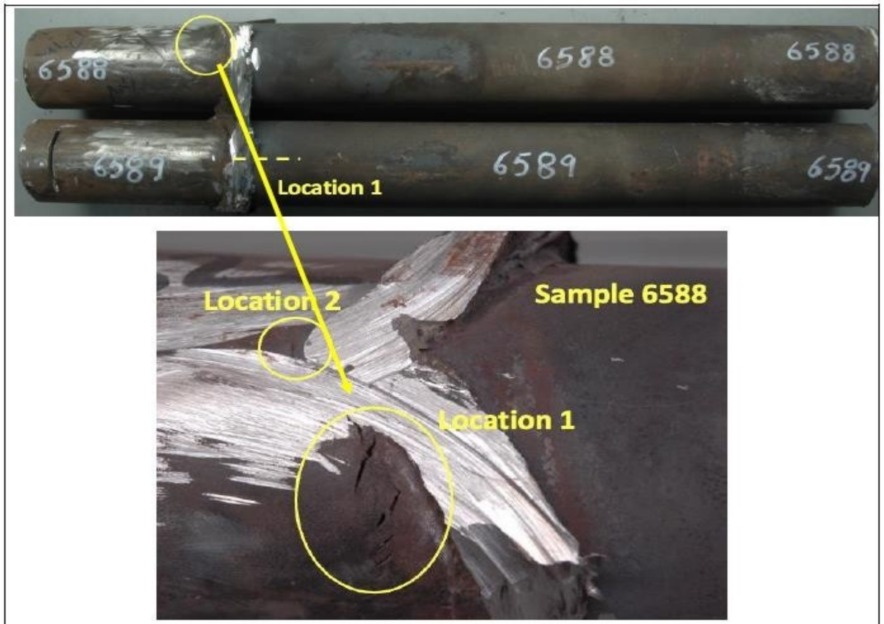


Figure –2
Photograph of as received final reheater tube (sample no **6588**) showed cracking close to fillet seal weld (Location 1).
Cracks also observed in the inaccessible zone between the tubes (Location 2).

Sample **6589** showed no visible cracks.

*Samples were sectioned at indicated locations for microscopy.

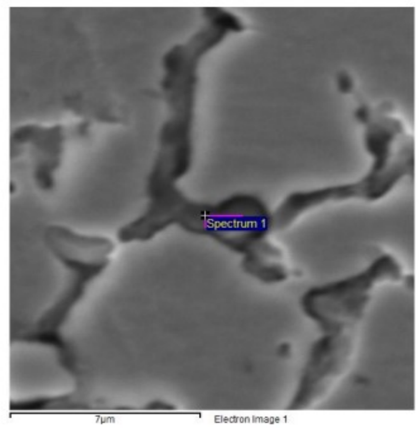
Figure – 5

SEM micrograph of the external surface showed cracks close to seal weld.

Failure Analysis of FRH samples at NTPC-NETRA lab

Table 2: Summary of Microstructure & Hardness

Microstructure	Hardness, HV10	Remarks
- Cracking on external surface close to fillet weld and at fusion line - Multiple cracks on external surface - Intergranular nature cracking - Presence of Chloride in the cracks - Minor cracks observed on internal surface	Base metal: 185-225 HV10 (sensitized)	**Intergranular stress corrosion cracking**



Element	Weight%
C K	8.60
O K	32.72
Si K	0.20
Cl K	1.05
Cr K	12.39
Fe K	30.12
Ni K	3.34
Cu K	3.40
Nb L	8.18

Figure – 27 **Internal surface cracks**

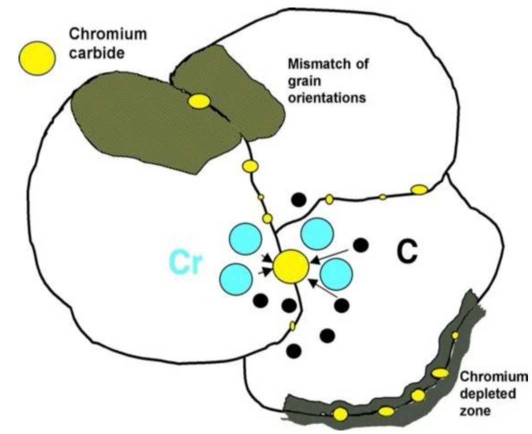
EDAX analysis at one of the *internal* surface crack locations showed presence of Cl.

Intergranular cracking up to a depth of 3mm (tube thickness of 4mm), high hardness, sensitization upto 300mm and presence of Chloride deposit confirmed that the tubes failed due to **intergranular stress corrosion cracking**.

Stress corrosion cracking also observed in the tube having **neither seepage & nor defect in PAUT**

Stress Corrosion Cracking in Austenitic Stainless steels ?

- **Sensitisation** is the phenomenon in which precipitation of Chromium carbides (Cr_3C_2) takes place at the grain boundaries when the SS tube is subjected to temperature of 450-800°C. Thereby the concentration of "Cr" at grain boundaries is reduced and hence corrosion resistance is deteriorated.



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- At this stage, **If "Chloride" enters the grain boundaries** from inside or from outside environment say water/ moisture, it will lead to localized corrosion at the grain boundaries.

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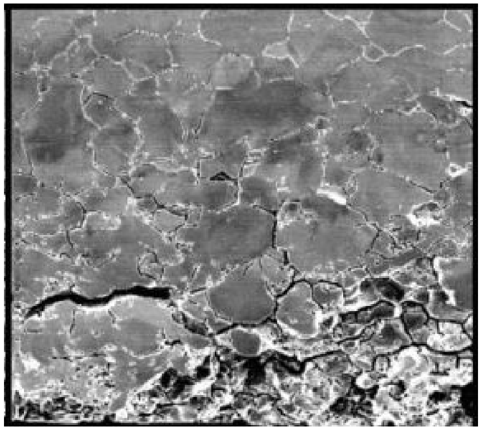
- **Residual stresses** due to (dissimilar/ attachment fillet) welding.



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Stress Corrosion Cracking (SCC)

Stress Corrosion Cracking?

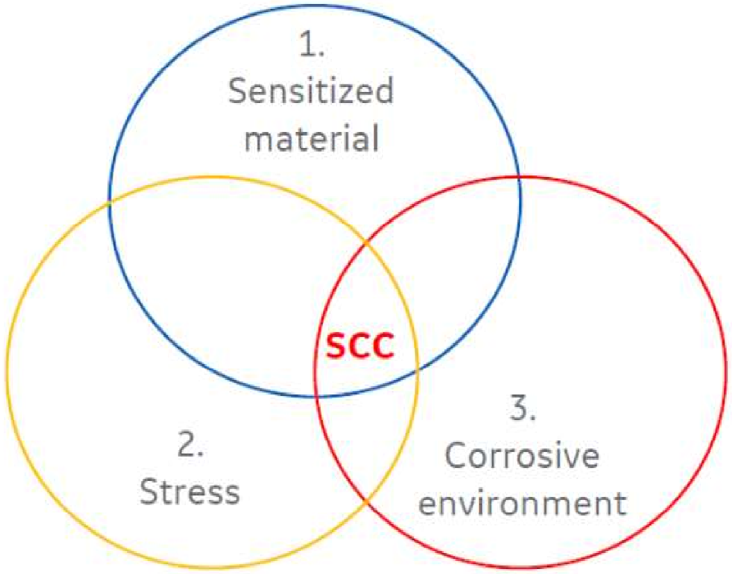
Stress Corrosion Cracking (SCC) is due to co-exist of

1) **Susceptible material** -Sensitized microstructure during
   Welding, PWHT & operation if the temp: 425° C to 800° C
1) **Stresses** – Residual stresses
3) **Corrosive environment** - Presence of Chloride

- **SCC in FRH & FSH coils** occurred due to presence of **Chloride deposits, Sensitized material & Residual stresses**
- **Sensitization and residual stresses cannot be avoided completely**

- **Chloride ingress may occur**

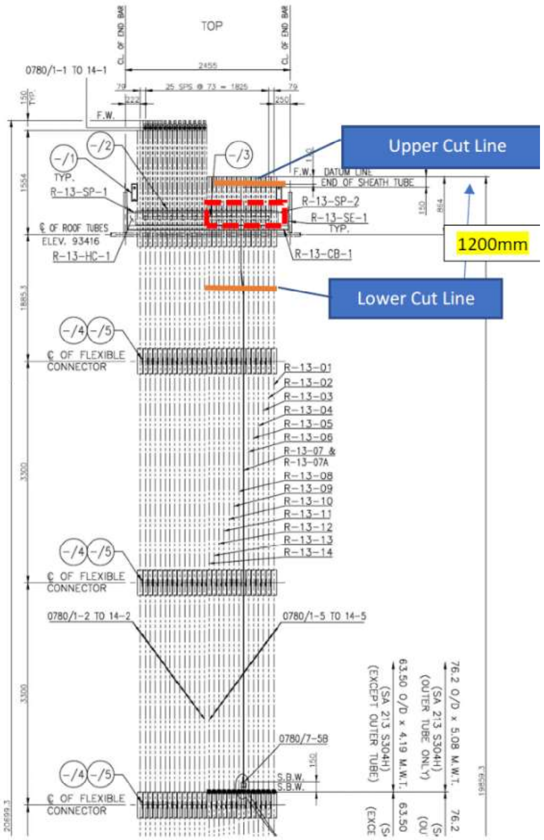
a) During Transport
b) During Hydro Test
c) At site during storage and erection
d) During Storage at manufacturer

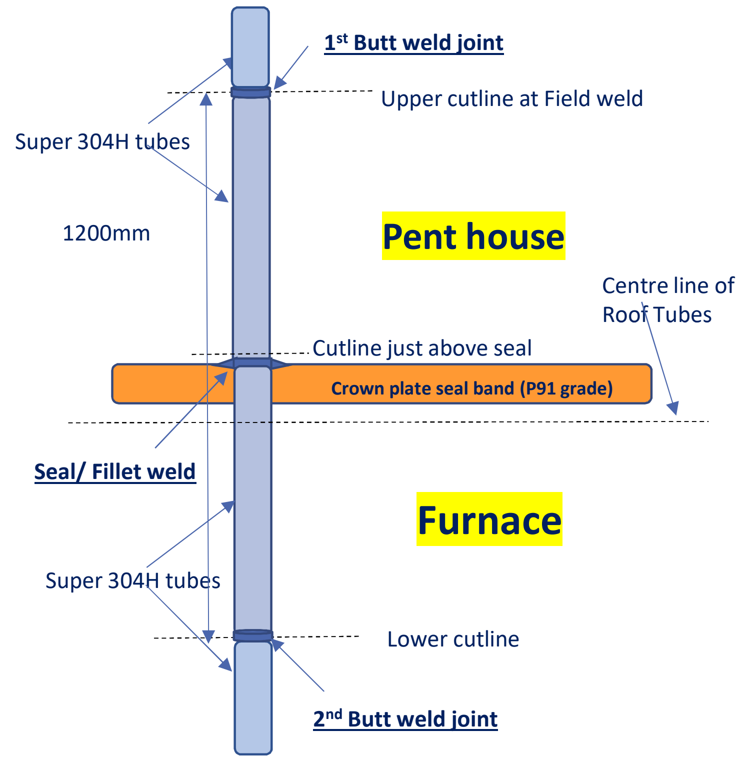


SCC failure mechanism

Solution is to restrict exposure to chloride content

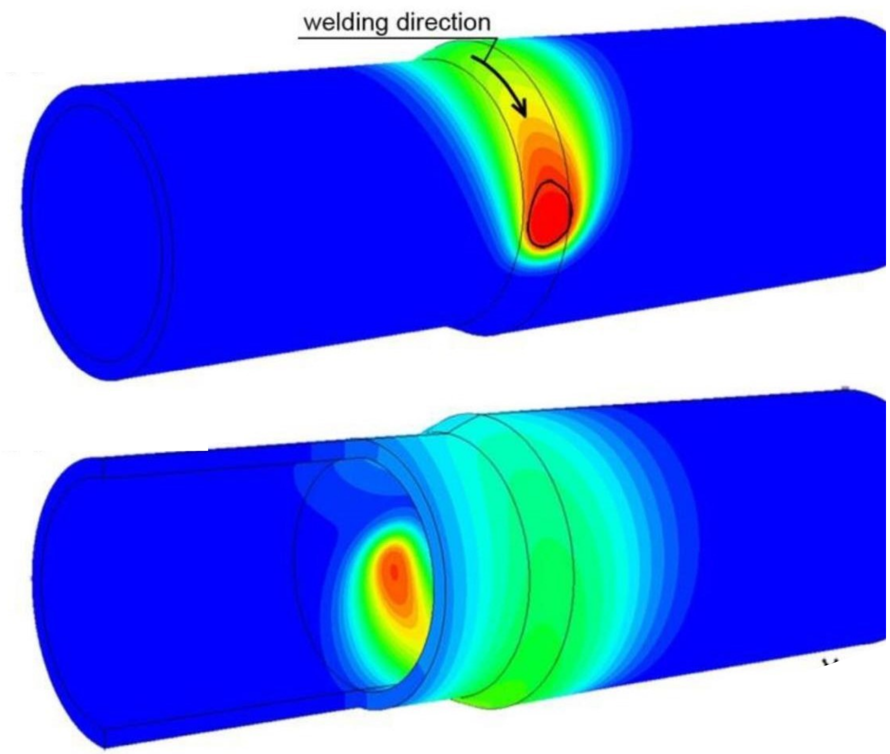
Rectification of FRH coils (affected by Stress corrosion cracking)

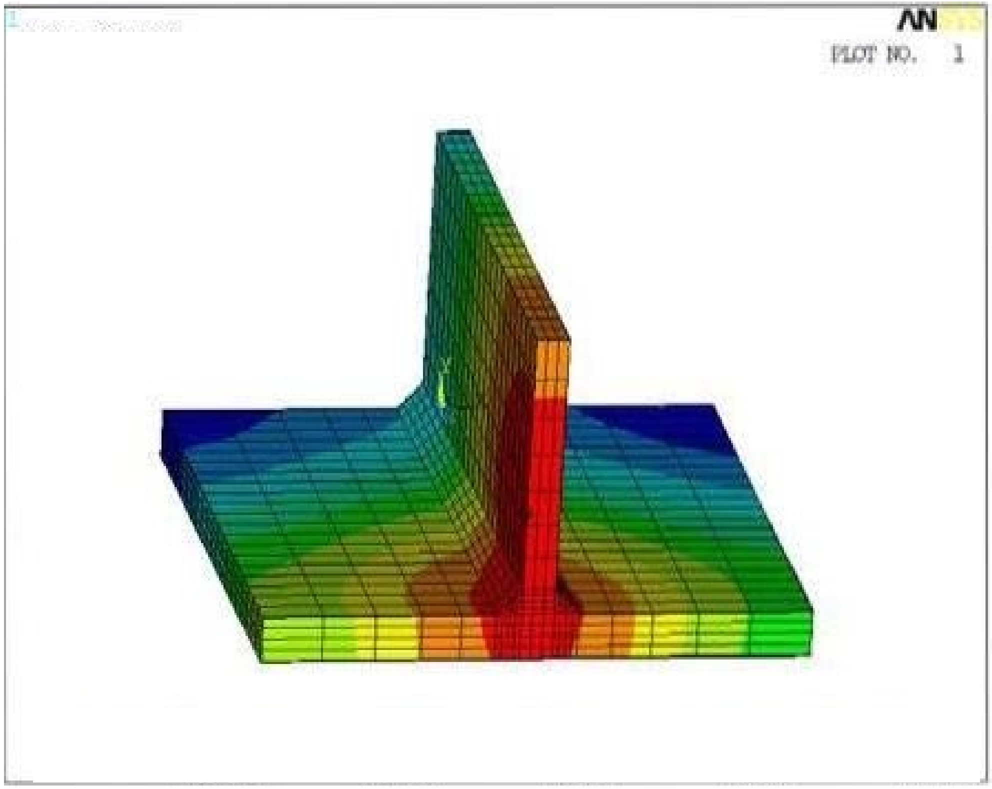




No.of FRH outlet tubes replaced: 581 Nos

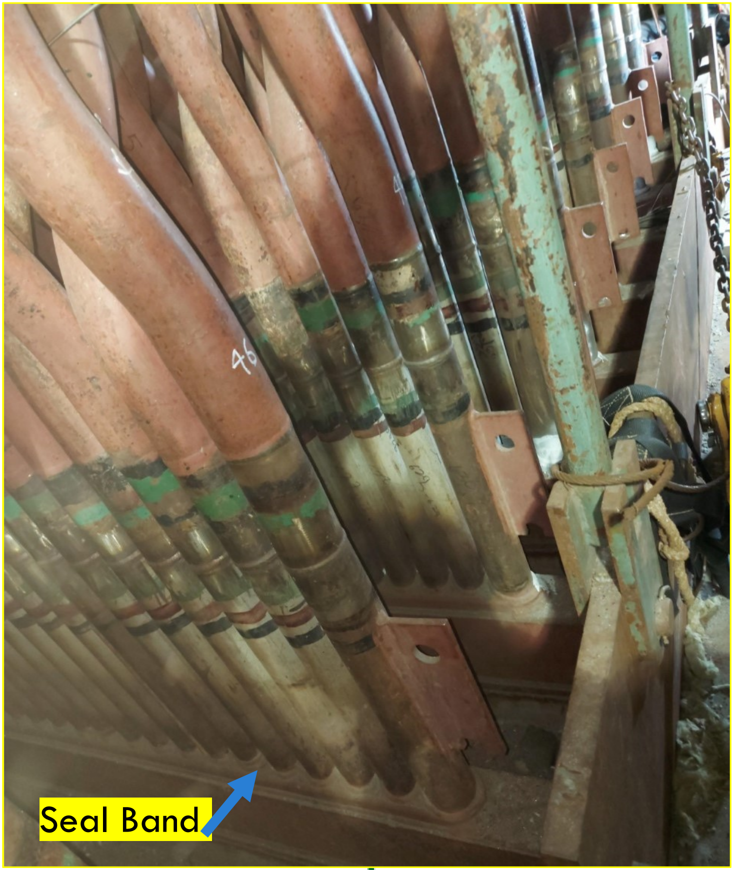
Stress Analysis of Weld joints



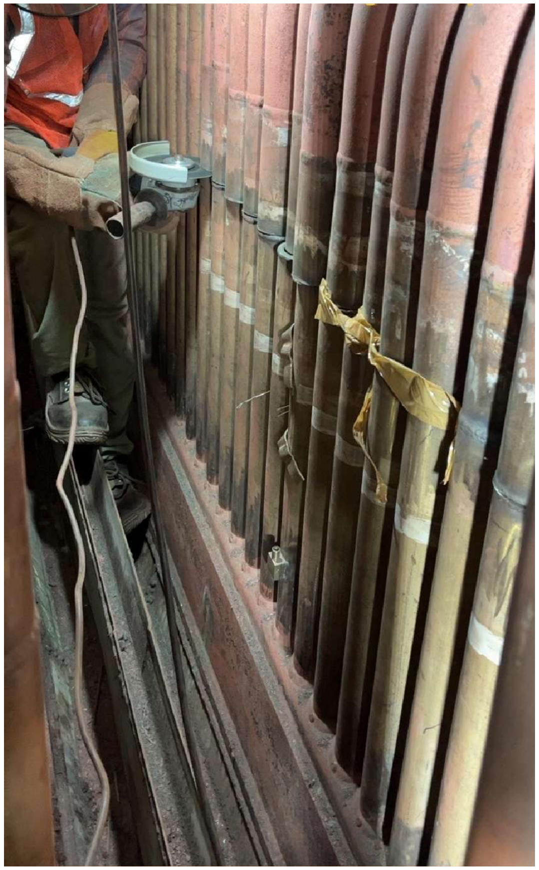


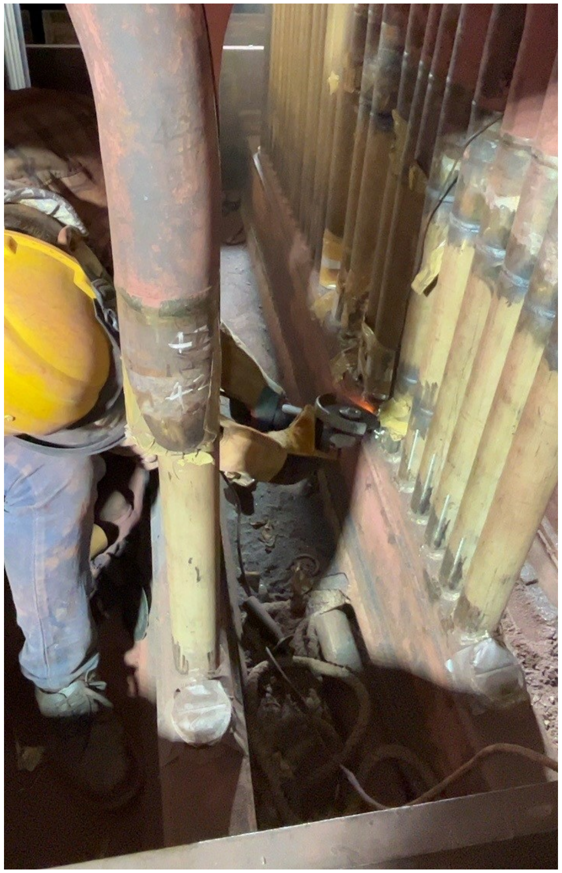
Stresses in Fillet joint is higher than in Butt weld joint

Finish Reheater (FRH) coils



Cutting & gauging of tubes to be replaced

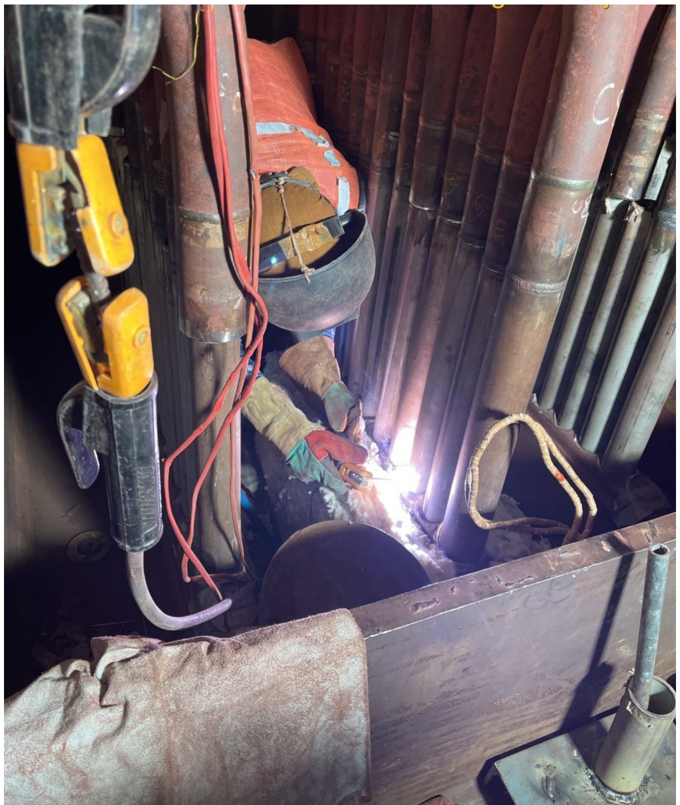




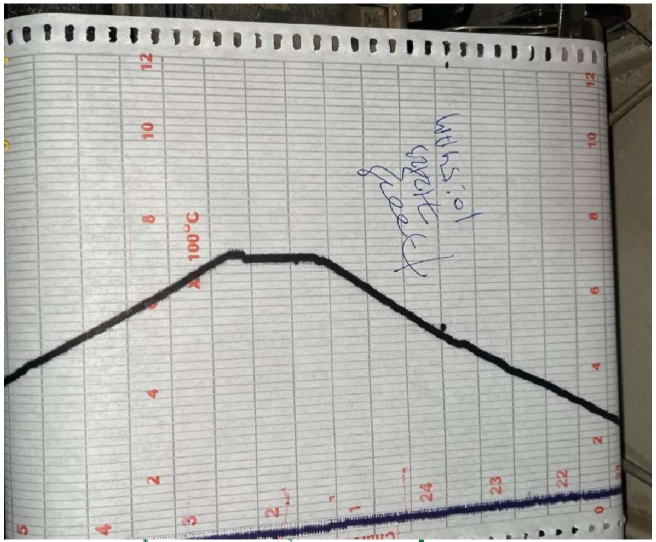
Welding of bottom &Top joints of FRH outlet coils

Welding of bottom &Top joints of FRH outlet coils

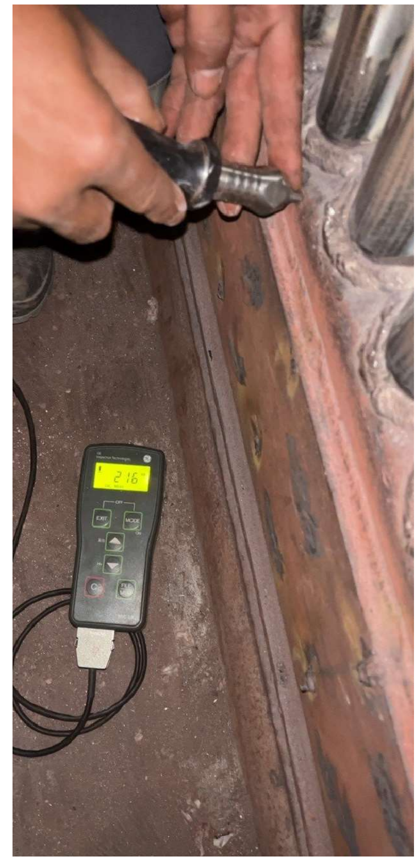
Pre-heating, welding & Stress Relieving of FRH Seal weld joints



Preheating, welding, cooling to 80°C & PWHT



DPT & hardness measurement of seal weld



Challenges faced during rectification FRH coils:

Cut-marks on the adjacent tubes

IBR welders are not giving desired quality at FRH location though Qualified in welder test

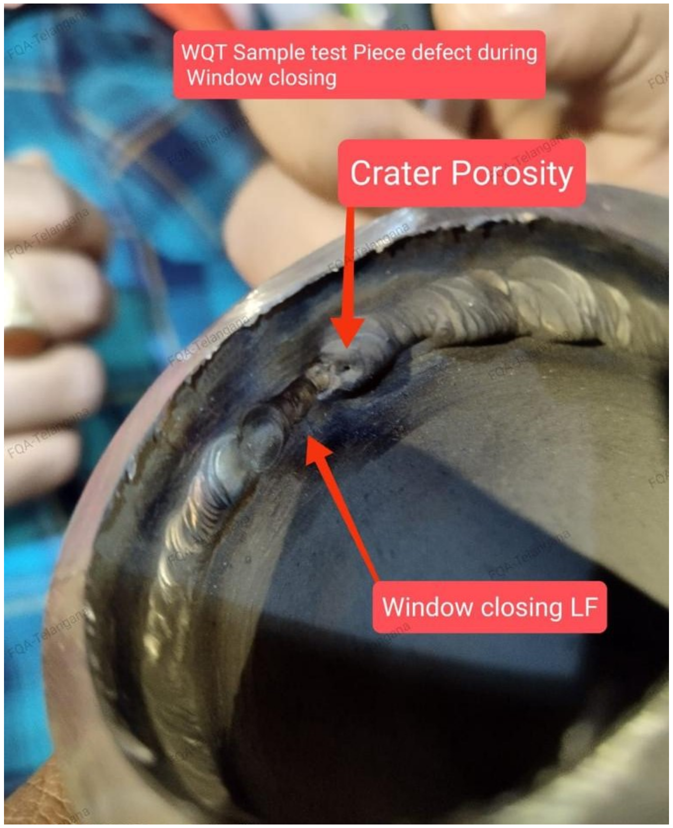
Vs.

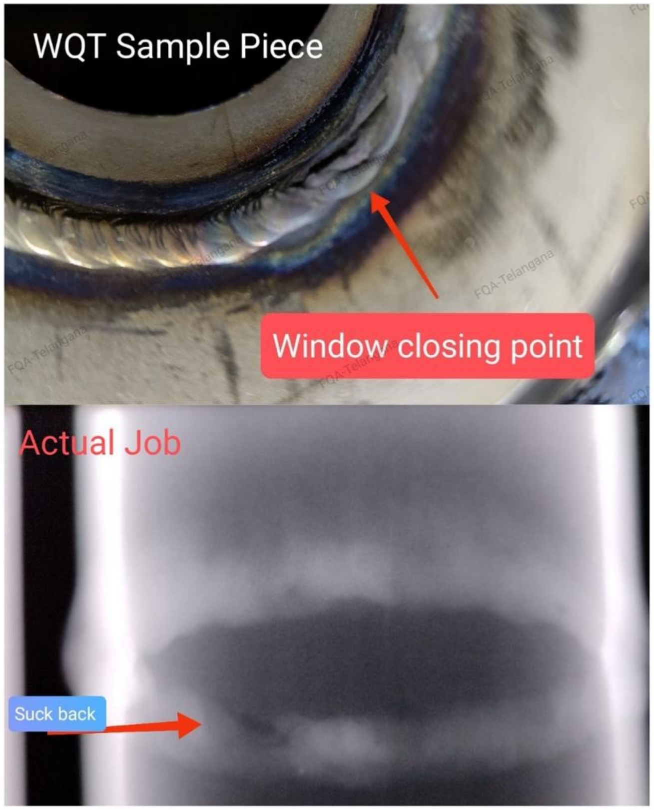
Welder Qualification in simulated condition

The extremely difficult approach to actual location of the weld joint imposes immense challenge to the welders to give defect free weld joint.

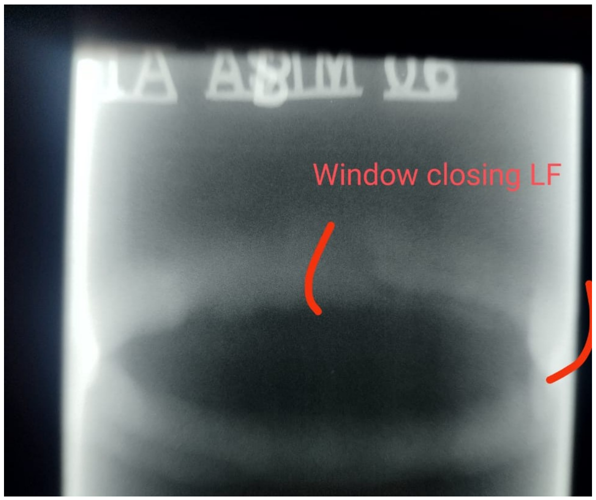
To minimise defect rate welders were trained on weld booth by simulating actual constraint conditions.

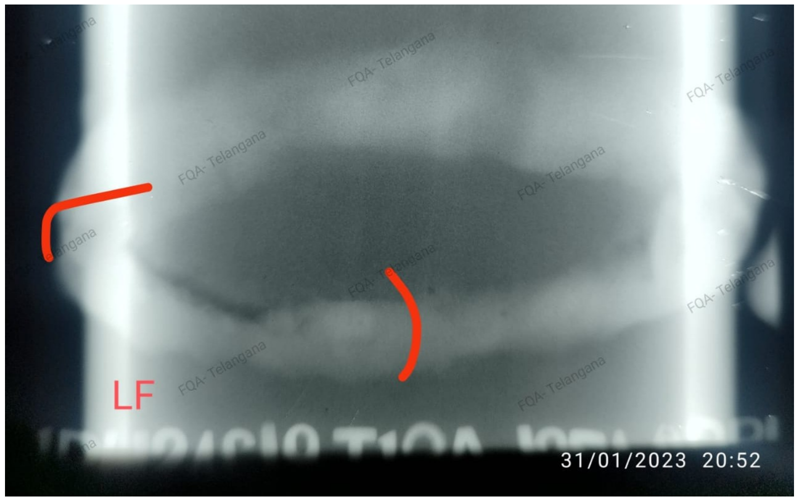
High % Repairs while closing the window of the Root welding





Radiograph images of defect joints





Action taken to mitigate the defects while closing window

1. Using Full purge
2. Welder Qualification in simulated condition
3. Using sloping in hot pass near the root window & grinding before window closing
4. Creating the opening in purge dam at the end
5. Welding with medium speed to ensure the full penetration
6. Daily monitoring of Welder performance & feedback to IBR welder by showing RT images

Full purging

While doing the bottom joint of the spool tube (inside the furnace, Purging gas is being given from top of spool tube @ penthouse & provided with dam (Fig-1). And purge paper is put below 100mm of bottom welding joint being done(Fig-3). While closing the window, make a hole in the dam at the top of the joint (Fig-2).

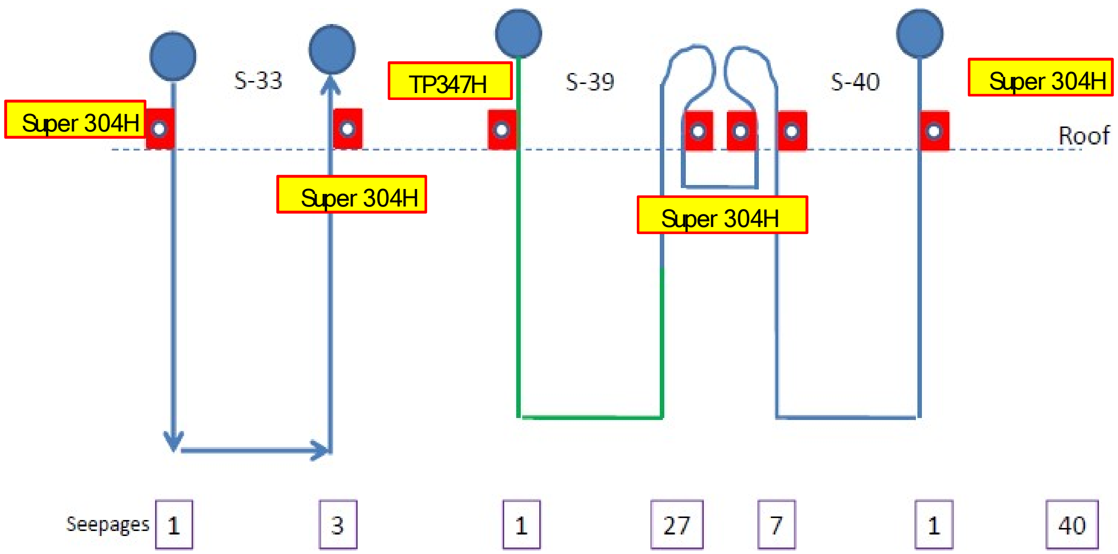
Sloping in hot pass near the root window & grinding before window closing

Sloping in hot pass near the root window

Grinding before window closing

Seepages in Seal band & Lug plate in PSH & FSH coils

Seepage Observed in Superheater in Hydrotest done after Steam Blowing



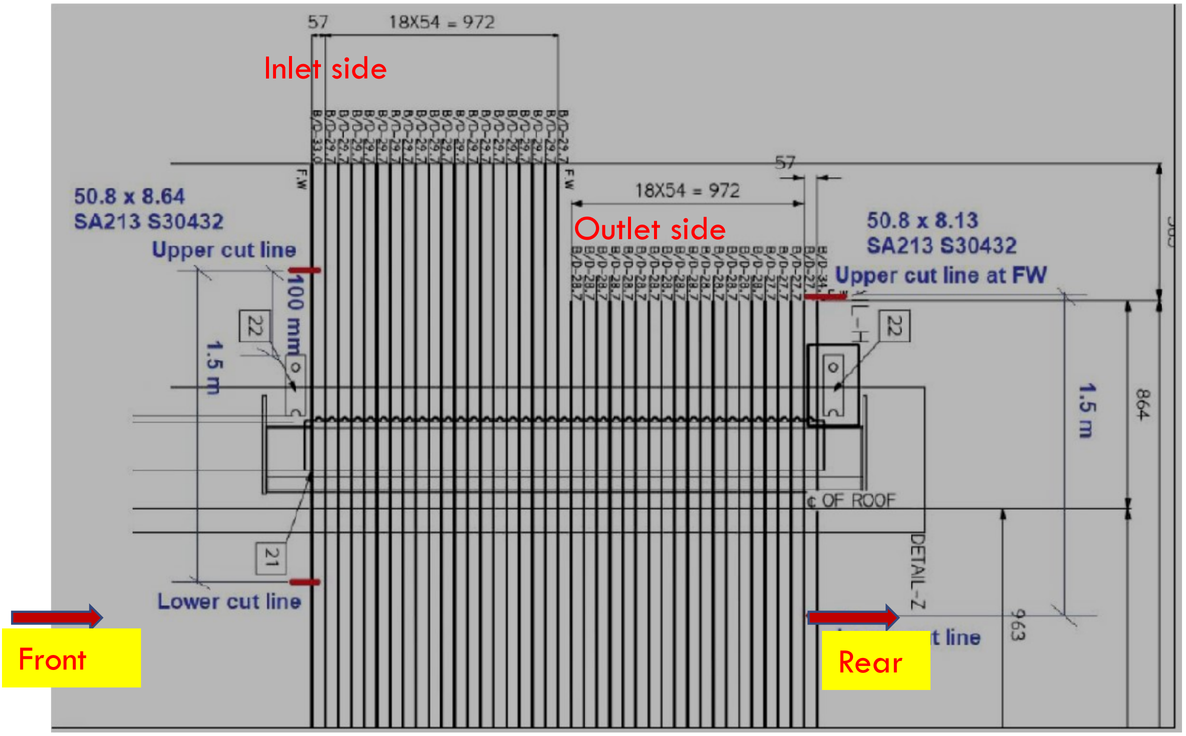
Summary of Lug plate tubes replacement

Sl	Description	Materials	No of Tubes	Total Length (Mtr) required
1	**S-33 Coils**		-	-
	Inlet tubes 50.8 × 8.64	SS304H	34	51
	Outlet tubes 50.8 × 8.13	SS304H	34	51
2	**S-39 Coils**		-	-
	Inlet tubes-44.45 × 8.13	TP347H	104	156
3	**S-39 Coils**			
	Outlet tubes-44.45 × 7.11	SS304H	104	156
4	**S-40 Coils**			
	Inlet tubes-44.45 × 7.11	SS304H	104	156
5	**S-40 Coils**			
	Outlet tubes-44.45 × 8.1	SS304H	104	156

Total no.of lug plate tubes to be replaced: **484 nos.**

Total no.of joints to be welded: 968 Butt joints + 484 fillet joints (Seal welds)

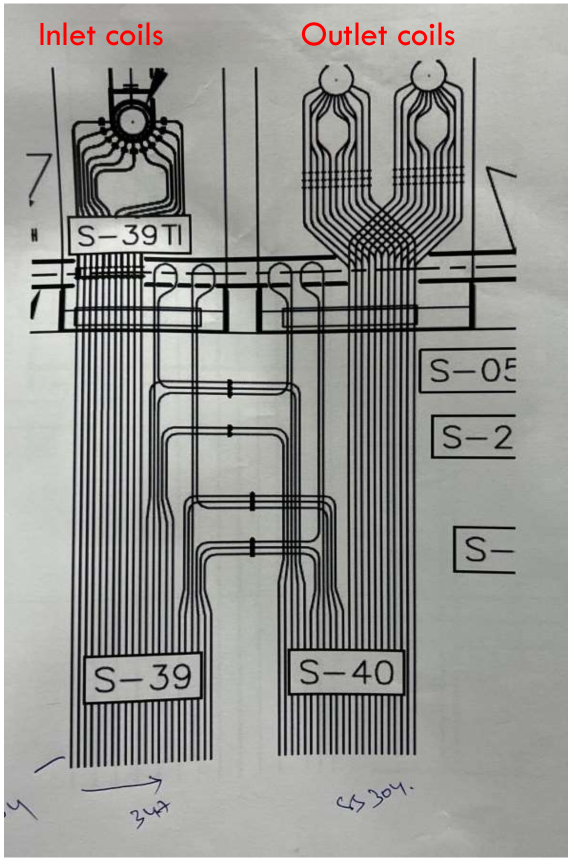
Replacement of leading tubes of PSH &FSH tubes having lifting lugs

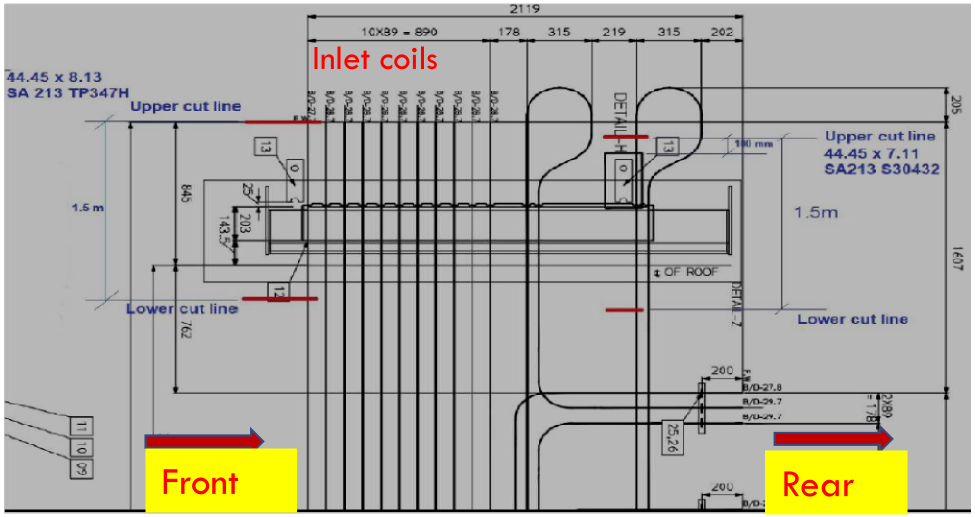


Platen SH coils (S-33)

PSH (S-33) FRONT

FSH inlet coil (S-39)

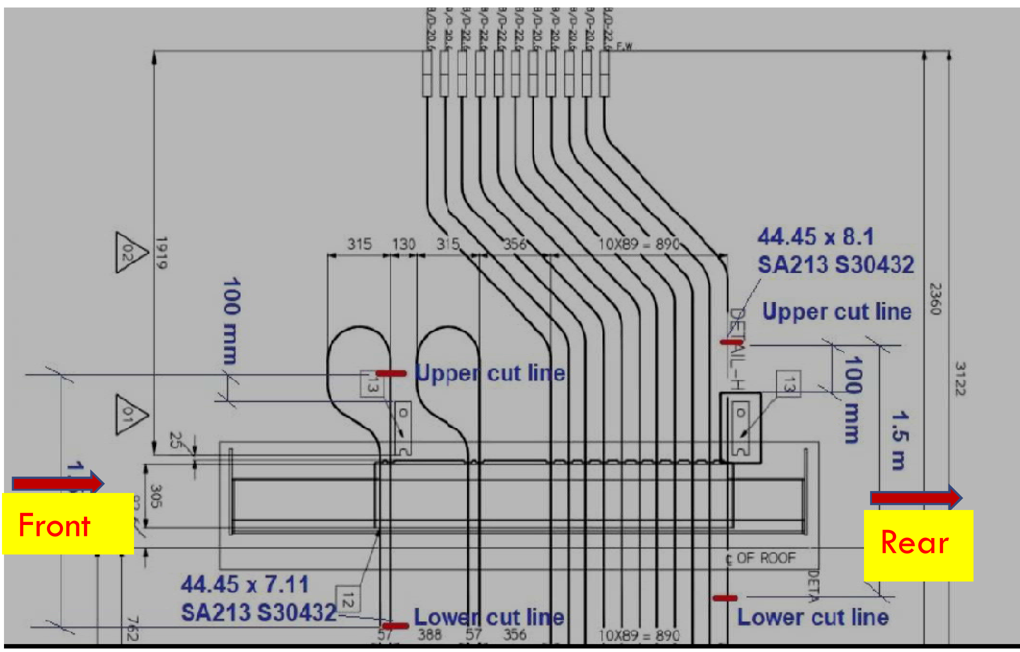




FSH INLET COILS (S-39) REAR

Finish SH outlet coils(S-40)

Outlet coils



Front

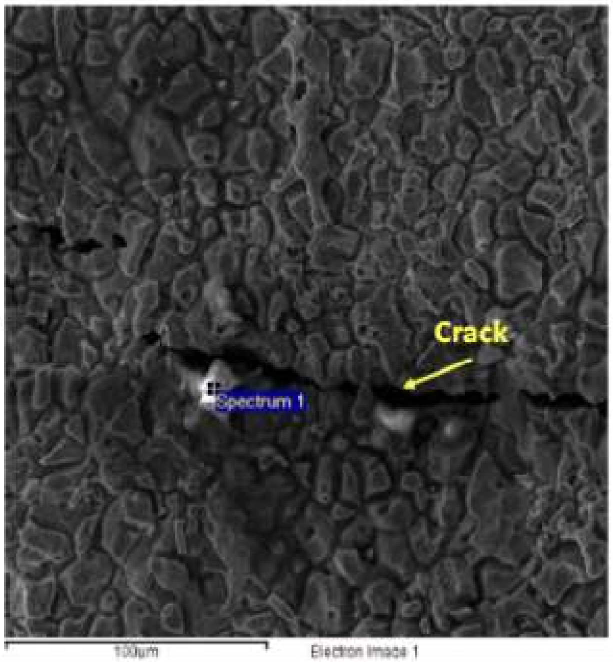
Rear

Failure Analysis of FSH sample at NTPC R&D lab

- Tube size: OD- 44.5 mm, thickness 8.1 mm
- Tube material: SA213 TP S30432 (Super 304H)
- One of the tube sample has been cut from the seal band crown plate weld location where seepage was observed in hydrotest
- Total FSH coils: 104 Nos.

Failure Analysis of FSH sample at NTPC R&D lab

FSH TUBE – TELANGANA UNIT #1 - SAMPLE # 6580



Element	Weight% Spectrum 1
O	16.84
Al	0.36
Si	0.58
P	0.38
S	0.37
Cl	2.16
K	1.22
Ca	2.72
Cr	13.03
Mn	0.54
Fe	55.37
Ni	5.65
Cu	0.78

Figure – 11 **At Failure**

EDAX analysis at internal surface showed white colored deposit rich in Cl content at the crack.

- **Trans-granular cracking** (on internal surface below the weld of tube with lifting lug) and high hardness at failure indicate high residual stresses at the tube below the fillet weld.
- **Presence of Chloride in deposits at failure location confirmed that the tube failed due to stress corrosion cracking (SCC).**

SS tubes were chemically cleaned, passivated & examined for Chloride content by EDAX analysis before use

Procedure for cleaning chlorides from Stainless steel tube surface as per ASTM A380:

1. A bath of diluted nitric acid is to be prepared for achieving the passivation of tube surface by dipping. Alternatively, clean cloth swab can also be used for passivating the surface.

2. The nitric acid solution/bath shall be prepared as indicated below:
   a. Nitric acid: 20% by volume
   b. Water: Remainder
   c. Temperature: Ambient

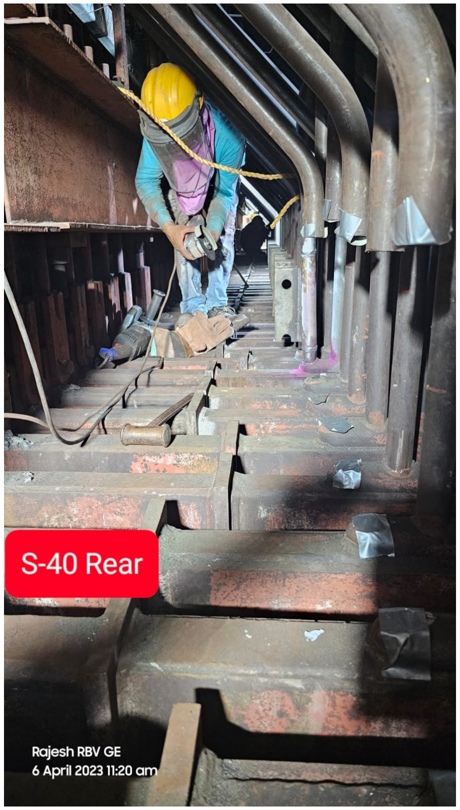
3. The tubes shall be soaked for 30 minutes in the bath as prepared above.

4. After chemical cleaning, rinse the surface with DM water.

5. The water shall be completely drained, and the surfaces shall be dried

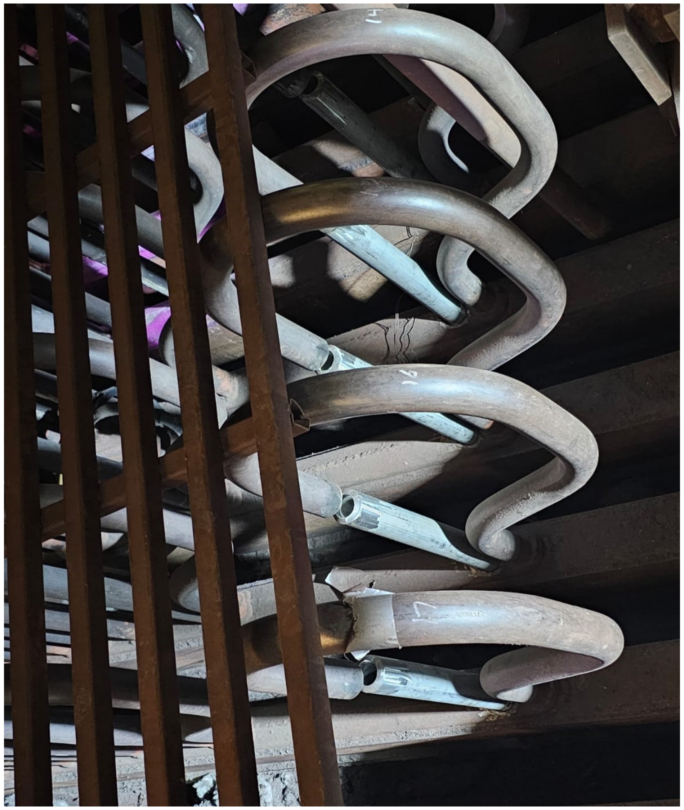
6. Complete packing with end caps & covering with Polythene cover

Rectification of PSH & FSH Coils



Cutting for removal of 1st tube

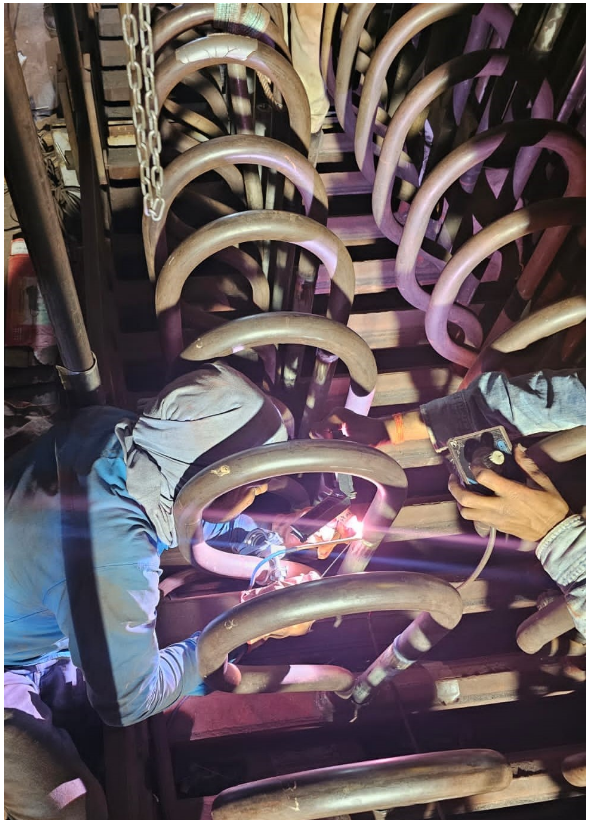
Covering of cut tubes with tapes to prevent ingress of foreign material



Inserted new spool tube

Rectification of PSH & FSH Coils

Cutting for removal of 1st tube

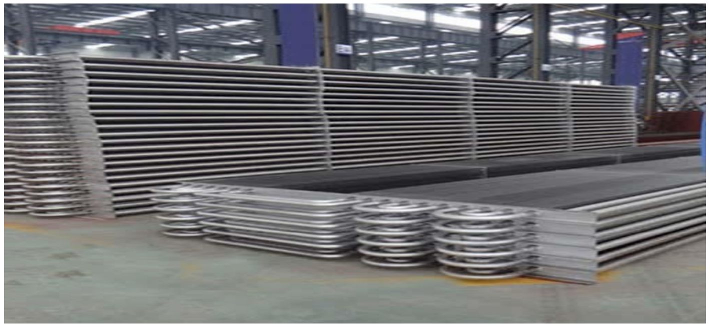


Welding of after inserting Spool

Below Roof Spool welding in progress

Preventive measures for avoiding Stress Corrosion Cracking

1. Proper Storage & preservation at manufacturer end, during transportation, at site during storage and erection. **It is recommended to stack the coils on RCC floor in closed storage SS Panels in shop and site.**



2. Proper packing & covering of tubes

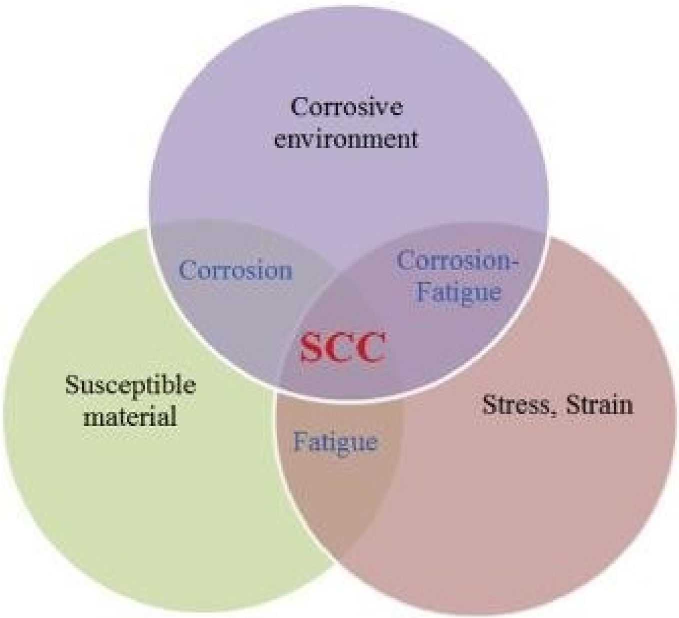
Reference Photo from Tube Manufacture - China

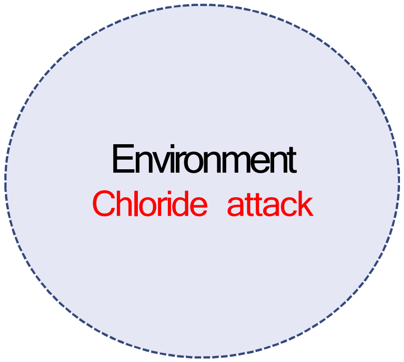
3. End caps (Non-metallic) to be ensured at all stages from manufacturing to erection.

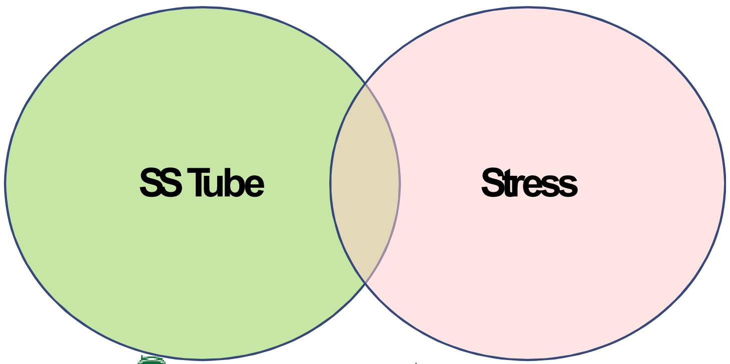
Preventive measures for avoiding Stress Corrosion Cracking (contd..):

4. Use of DM water for various stages of manufacturing
5. Cleaning and Passivation before welding/ Fabrication
6. Solution Annealing/ Heat treatment to be carried for the leading tubes having lug plate welding
7. The WPS was revised with PWHT soaking temperature maintaining on lower side (withing the code requirement). Filet size also to be maintained as per drawing to control the heat input.
8. Site clearance certificate before issue of Material Dispatch Clearance Certificate (MDCC) to be taken for site readiness for proper storage & Erection.
9. Metallurgy tests/ EDAX analysis of Super 304H/ 347H tube samples to be carried out for presence of any Chloride & microstructure in the following stages
   a) Before dispatch of material from tube manufacturer end
   b) At Main contractor's premises before start of fabrication and after hydrotest
   c) After receipt of coils at site and before start of erection i.e., before lifting of PSH, FSH & FRH coils
10. Additionally, painting of finished coils is suggested to protect from corrosive environment. Review and revise of painting schedule accordingly

Preventive measures for avoiding stress corrosion cracking







Conclusion

- NTPC has adopted Supercritical (SC) & Ultra-Supercritical (USC) technology having thermal efficiency goes up to 42% and less % emissions.

- The higher efficiency power plants demands advance metallurgy like Super 304H & 347H for better Creep strength properties & to withstand higher temperature ~600℃ & pressure ~ 280 Kg/cm^2.

- However, these Austenitic Stainless-Steel material posed serious quality challenges during erection / commissioning / operation of units, mainly due to the phenomenon of **Stress Corrosion Cracking (SCC).**

- SCC in FRH & FSH coils occurred due to *co-exist of* <u>presence of Chloride deposits</u>, <u>Sensitized material</u> & <u>Residual stresses</u>. We need to ***handle with care*** these materials which are prone for SCC.

- Though Sensitization and residual stresses cannot be avoided but needs to be controlled.

- Main solution to mitigate the problem of SCC is by avoiding exposure these materials to chloride environment.

- Preventive measures shall be followed meticulously for avoiding stress corrosion cracking for enhancing Availability and Reliability of the SC/ USC units after commissioning.


Migratory Birds at NTPC Dadri

Thank You

NTPC Ramagundam

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