Tube-to-Tubesheet Joints in Shell and Tube Heat Exchangers

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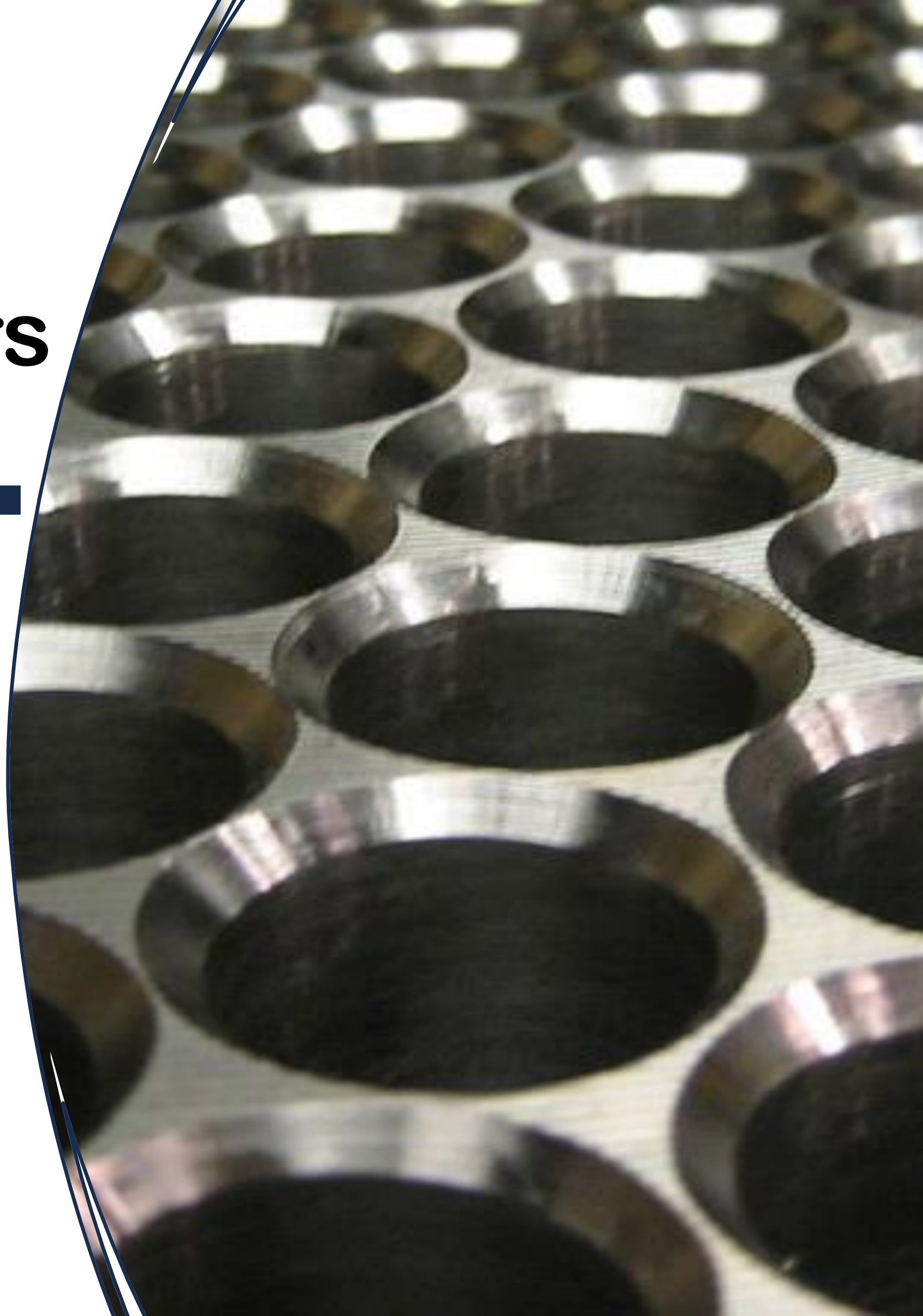
Free Webinar – 10 September 2022



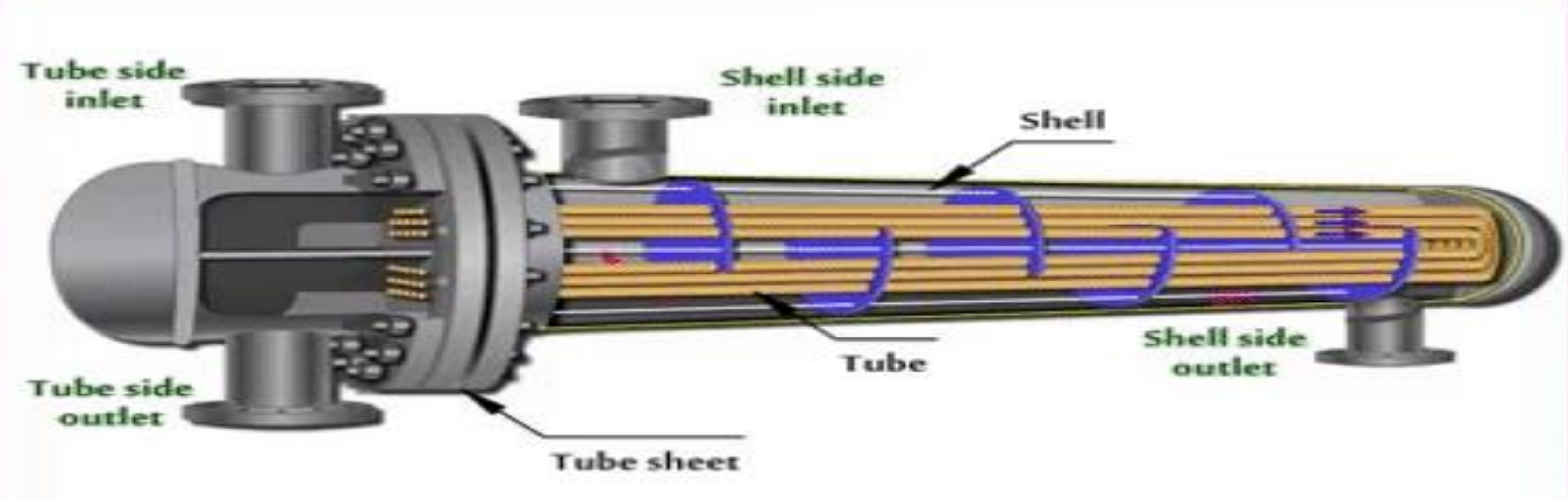
Tube-to-Tubesheet Joints in Shell and Tube Heat Exchangers

Webinar Outlines

- Introduction to shell and tube heat exchangers
- Types and features of tube-to-tubesheet joints
- Application requirements of expanded and welded tube-to-tubesheet joints
- Common defects of tube-to-tubesheet joints
- Inspection and Repair of tube-to-tubesheet joints
- Case Histories

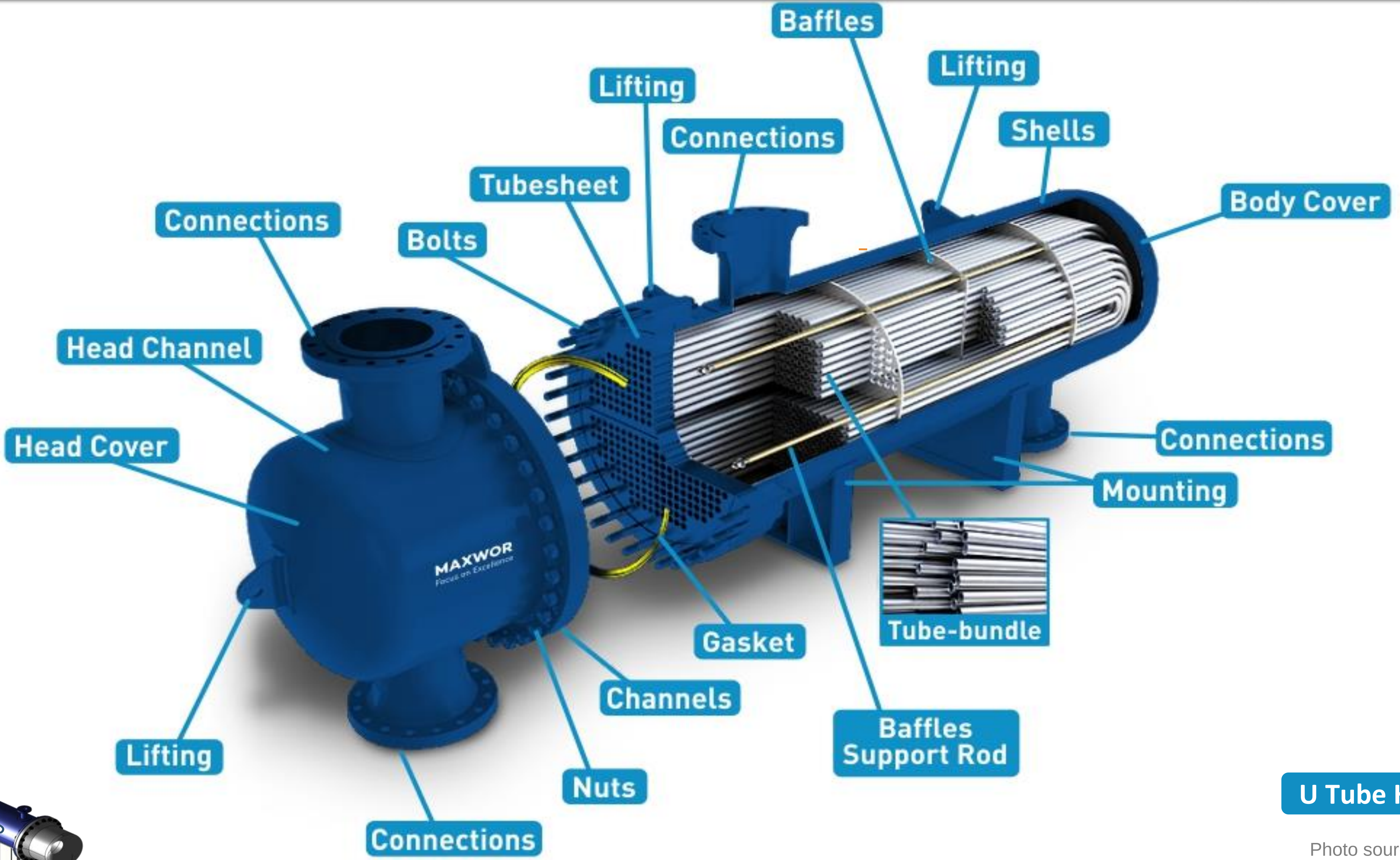
Shell and Tube Heat Exchanger is a type of exchangers used to transfer thermal energy between two fluids. The two fluids are not indirect contact; one pass in the tubes and the other in the shell.

Shell and Tube Heat exchangers are one of the most common equipment used in all oil and gas plants, petrochemical and power plants.



Animation from: gfycat.com

Components of Shell and Tube Heat Exchangers



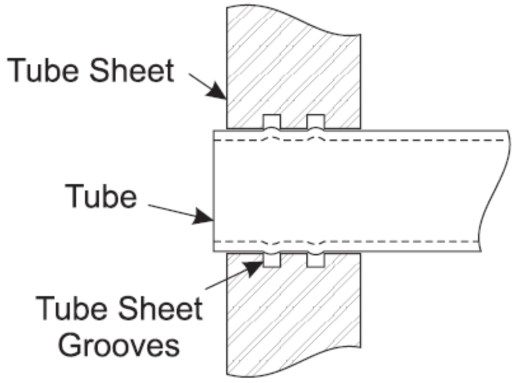
U Tube Heat Exchangers

Photo source: www.Maxwor.com

Tube-To-Tubesheet Joints (TTS)

Expanded

Process of expanding a tube to a fully plastic state into contact with tube hole that creates residual interface pressure between the tube and tubesheet

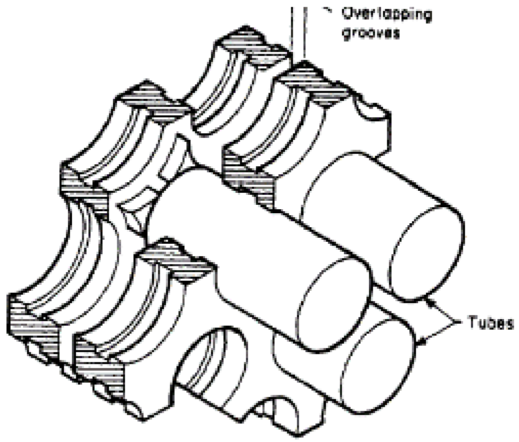


Strength Welded

Weld design strength is equal to or greater than the axial tube strength
Can be Full strength Weld or Partial Strength Weld

Full Strength Weld: in which the design strength is equal to or greater than the axial tube strength

Partial Strength Weld: in which the design strength is based on the mechanical and thermal axial tube loads that are determined from the actual design conditions



Seal Welded

Weld is used to supplement an expanded tube to tubesheet joint to ensure leak tightness

Heat Exchanger Data Sheet

Type of Tube-to-Tubesheet Joint is specified in the data sheet during thermal design of the exchanger

Care shall be taken by mechanical engineer in the review of the specified joint type

Company | SHELL AND TUBE HEAT EXCHANGER | Engineering contractor

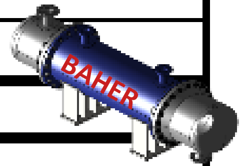
P.O. No.:

1 Client:
2 Process unit:
3 Job No.:
4 Service of unit:
5 Size:
6 Effective surface per unit (plain/finned)
7 PERFORMANCE OF ONE UNIT
8
9 Fluid name:
10 Fluid quantity, total:
11 Vapor (relative molecular mass)
12 Liquid:
13 Steam:
14 Water:
15 Non-condensable / relative mol
16 Temperature:
17 Density (vapor/liquid):
18 Viscosity (vapor/liquid):
19 Specific heat (vapor/liquid):
20 Thermal conductivity (vapor/liquid):
21 Specific latent heat:
22 Inlet pressure:
23 Velocity:
24 Pressure drop (allowable/calculated):
25 Fouling resistance:
26 Average film coefficient:

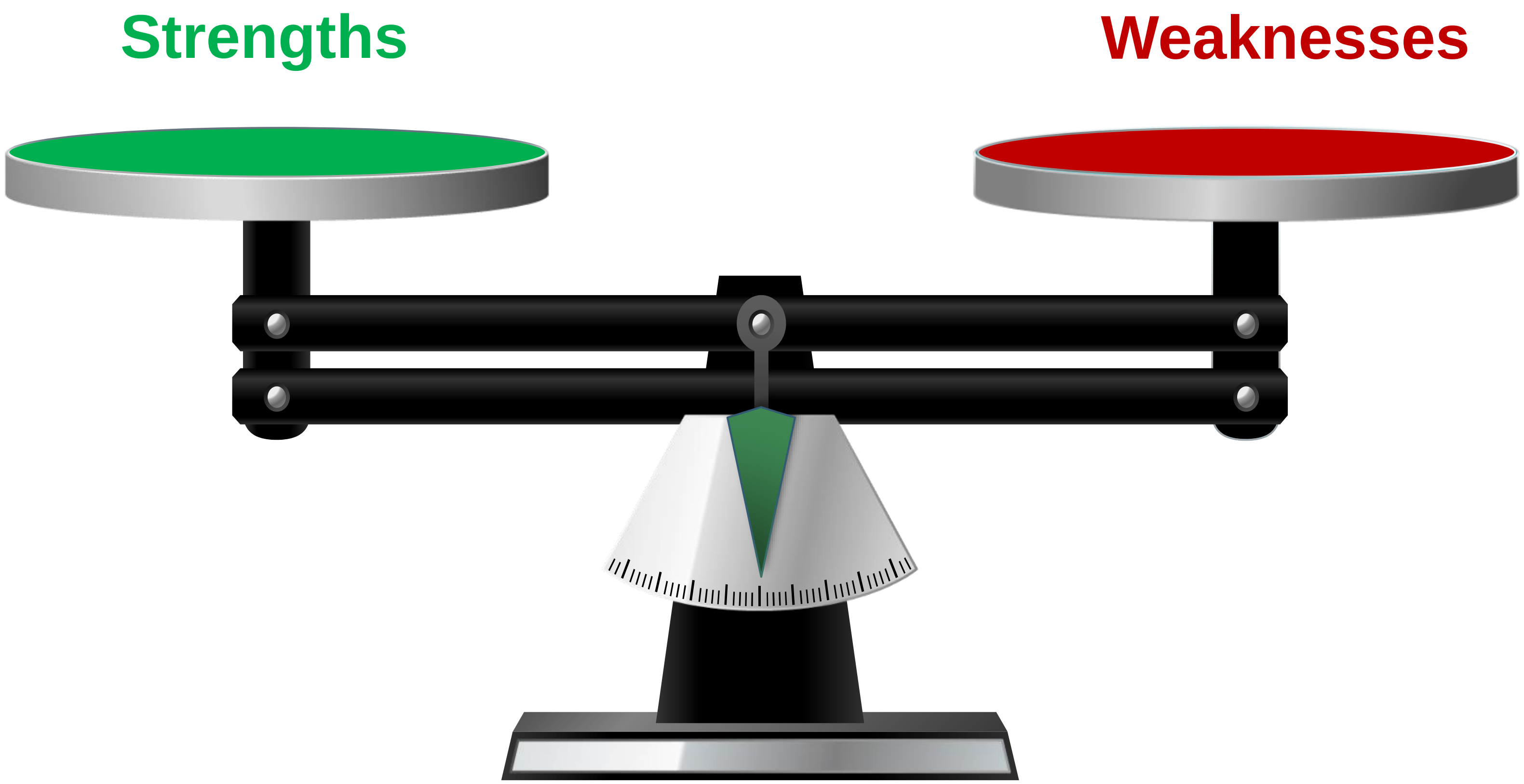
27	Heat exchanged: Btu/h	Mean temperature difference (MTD): °F corrected/weighted		
28	Heat transfer rate: Btu/(h·ft²·°F) Required:	Fouled:	Clean:	
29	ρV²:			
30	Hydrogen Service:	Tube Side		
31	CONSTRUCTION PER SHELL			
32	Tube Number:			
33	Tube Wall Thickness: in		TUBE SIDE	
34	Tube Pitch: in			
35	Tube Length: ft	Tube type: plain/finned/other	Outlet:	
36	**Tube to tubesheet joint:**		Intermediate:	
37	Shell diameter: in	(ID/OD) /	Vent:	
38	Cross-baffle type:		Drain:	
39	Baffle Spacing: c/c in	No. of cross passes:	Pressure relief:	
40	Baffle Cut: %	vertical/horizontal	Design pressure: psig	
41	Tube support type:		Vacuum: psia	
42	Longitudinal baffle seal type:		Design temp. (Max/MDMT): °F	/ /
43	Bypass seal type:		Number of passes per shell:	
44	Impingement protection: (Y/N) Type:		Corrosion allowance: in	
45	MATERIALS OF CONSTRUCTION			
46	Shell:	Tubes:	GASKETS	

47 Shell cover:
48 Channel or bonnet:
49 Channel cover:
50 Floating head cover/bolts:
51 Tubesheet: Stationary:
52 Baffles: Cross:
53 Tube support material:
54 Expansion joint type:
55 Pressure design code:
56 REMARKS:
57
58

Rev. No. | Revision | Date | Prepared by | Reviewed by



Balance your choice



Each Configuration of Tube-to-Tubesheet Joints has its features, strengths and weakness

Correct selection of the proper joint type and quality applications and testing are key features to obtain leak free long lasting joint

Features of Different TTS Types

Expanded Only

Strengths

- ✓ Economical and easy to apply compared to welding
- ✓ Easiest to re-tube
- ✓ Future plugging can be by simple tapper plug
- ✓ No tube sheet beveling required

Weaknesses

- ➢ Joint can loosen overtime and leak
- ➢ Potential to SCC of some materials
- ➢ Misunderstanding of proper parameters to maintain during application is frequently reported
- ➢ Highly sensible to axial scratches / imperfections in tube holes crating leading passes

Expanded and Seal Welded

Strengths

- ✓ Higher leak resistance compared to non welded expanded joints
- ✓ Less expensive than strength welds

Weaknesses

- ➢ Smaller weld size can still leak in severe service
- ➢ Re-tubing will require weld removal
- ➢ PWHT might be required and it is challenging activity specially during future repair, plugging or re-tubing
- ➢ Limitations in inspection techniques to ensure weld quality

Strength Welded, Not Expanded

Strengths

- ✓ Weld size calculated to be as strong as tube material
- ✓ No expansion grooves need to be machined in the tubesheet holes

Weaknesses

- ➢ Potential crevice corrosion from shell-side over time
- ➢ Limitations in inspection techniques to ensure weld quality
- ➢ Re-tubing will require weld removal
- ➢ PWHT if required is a challenging application
- ➢ Future plugging either by wedded plugs or advanced mechanical plugs
- ➢ Cyclic loading or vibration might cause weld cracking

Strength Welded and Expanded

Strengths

- ✓ The most leak resistant make it proper selection for critical severe application
- ✓ Only light expansion can be applied (expansion grooves are not necessary)

Weaknesses

- ➢ Most expensive technique
- ➢ Limitations in inspection techniques to ensure weld quality
- ➢ Re-tubing will require weld removal
- ➢ PWHT if required is a challenging application
- ➢ Future plugging either by wedded plugs or advanced mechanical plugs

In high temperature or pressure services or with aggressive fluids, welding should be considered

Expanded Tube-To-Tubesheet Joints (TTS)

- Tubes to be expanded with sufficient length. Tubes shall be expanded into the tubesheet for a length no less than 2" (50 mm) or the tubesheet thickness minus 1/8" (3.2 mm), whichever is smaller.
- In no case shall the expanded portion extend beyond the shell side face of the tubesheet.
- Expanding shall be uniform throughout without a sharp transition to the unexpanded portion.
- For welded-and-expanded tube-to-tubesheet joints requiring PWHT, the tubes shall be expanded after PWHT.

Suggested Amounts of Wall Reduction by Tubing Material

Tubing Material	Target Percent Wall Reduction (TEMA)	Max Percent Wall Reduction (API 660)
Carbon steel and low alloy steel	5 to 8 %	8 %
Austenitic Stainless Steel	5 to 8 %	6 %
Duplex stainless steel	4 to 6 %	Per API 983C *
Titanium and work hardening non-ferrous	4 to 6 %	5 %
Admiralty and non work hardening non-ferrous	6 to 9 %	8 %
Copper and copper alloys	7 to 10 %	8 %

The harder the tube material, the less wall reduction is recommended

* For DSS: Light expansion with wall reduction of 2% + strength weld. Higher expansion might be applied and mock-up shall include hardness test

Tube Holes in Tubesheet

TEMA RCB-7.2

To minimize work hardening, a closer fit between tube OD and tube ID as shown in column (b) may be provided when specified by the purchaser.

As a general rule the smaller the clearance the better, from the expanding point of view, no matter what expanding method is used.

For Austenitic SS, Duplex SS, Titanium, Cupronickel, or Nickel alloy tubes are specified, the tube holes shall be machined in accordance Special Close Fit.

Clearances are required to facilitate tube insertion and stuffing in the bundle Skelton

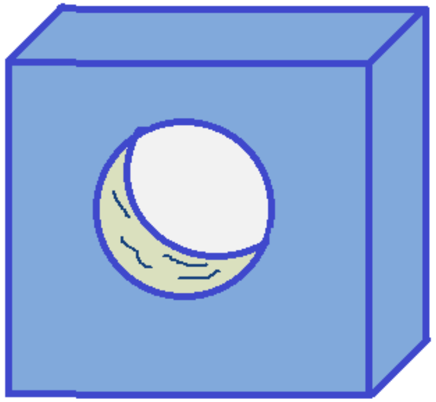
TUBE HOLE DIAMETERS AND TOLERANCES
(All Dimensions in mm)

	Nominal Tube Hole Diameter and Under Tolerance				Over Tolerance; 96% of tube holes must meet value in column (c). Remainder may not exceed value in column (d)	
	Standard Fit (a)		Special Close Fit (b)			
Nominal Tube OD	Nominal Diameter	Under Tolerance	Nominal Diameter	Under Tolerance	(c)	(d)
6.4	6.58	0.10	6.53	0.05	0.05	0.18
9.5	9.75	0.10	9.70	0.05	0.05	0.18
12.7	12.95	0.10	12.90	0.05	0.05	0.20
15.9	16.13	0.10	16.08	0.05	0.05	0.25
19.1	19.30	0.10	19.25	0.05	0.05	0.25
22.2	22.48	0.10	22.43	0.05	0.05	0.25
25.4	25.70	0.10	25.65	0.05	0.05	0.25
31.8	32.11	0.15	32.03	0.08	0.08	0.25
38.1	38.56	0.18	38.46	0.08	0.08	0.25
50.8	51.36	0.18	51.26	0.08	0.08	0.25
63.5	64.20	0.25	64.07	0.10	0.10	0.25
76.2	77.04	0.30	76.89	0.11	0.10	0.25

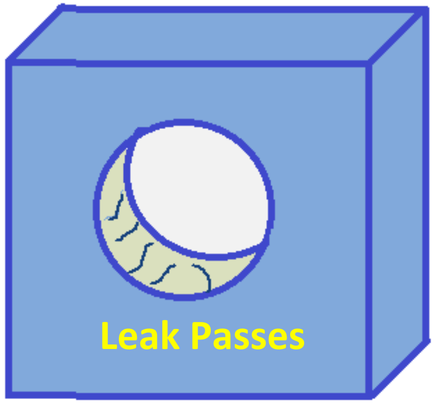
Tubesheet Hole Preparation

- Holes shall be free from radial or longitudinal scratches or imperfections
- Hole surface to be in as machined conditions (no need for polishing)
- Tube holes and tube external surfaces shall be cleaned
- Longitudinal scratches are of **higher risk** as it would create leak pass across the joint
- Tube outer surface at the interface with hole shall be also free from scratches or imperfections
- In hydraulic expansion the applied pressure caused the tube to take exactly the shape of the hole including the grooves and the imperfections or scratches (if exist)
- Mechanical roller shall be clean as well and free from scratches or imperfections. Its lubrications, temperature and performance shall be monitored during application

Tubesheet Hole Drilling



Radial Imperfection



Longitudinal Imperfection

Expanded Tube-To-Tubesheet Joints (TTS)

- Different methods techniques used to expand the tubes to tubesheet holes **(Roller expander, Hydraulic, Explosive)**
- Expanded joints should be machined with annular ring grooves (one or two grooves based on tubesheet thickness) for additional longitudinal load resistance

Roller Expander

For roller expanded tube joints, when tubesheet thickness exceeds 1" (25.4 mm) at least two grooves shall be used, each approximately 1/8" (3.2 mm) wide by 1/64" (0.4 mm) deep.

Tubesheet with thickness less than or equal to 1" (25.4 mm) may be provided with one groove.

Hydraulic Expander

For hydraulic or explosive expanded tube joints, at least one groove shall be used. Minimum groove width shall be calculated as $w = \mathbf{1.56}\sqrt{(\boldsymbol{R}\ \boldsymbol{t})}$

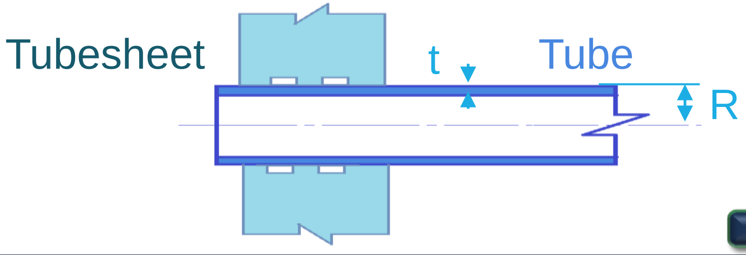
R = mean tube radius & t = tube wall thickness,

Max. groove width required 1/2" (12.7 mm).
Groove depth shall be at least 1/64" (0.4 mm).

For Cladded Tubesheets, grooves should be in the base metal

Examples for Required Groove Width for Hydraulic and Mechanical Rolling Expansion

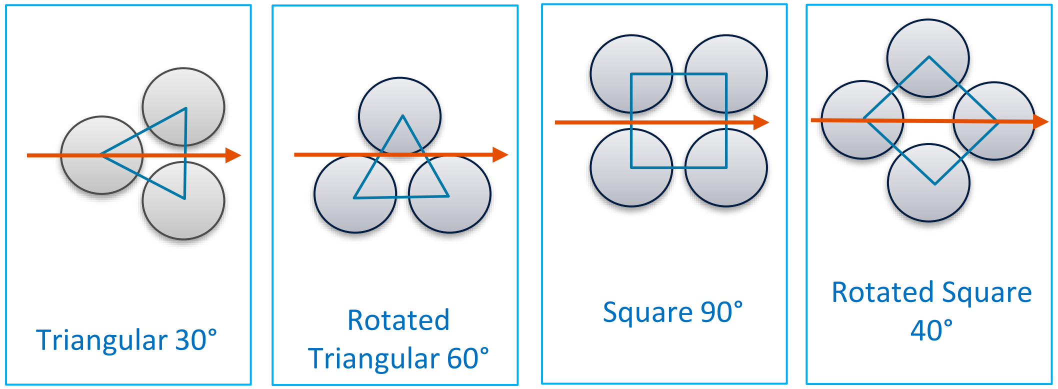
Tube OD (mm)	R mm	Tube (BWG)	t mm	*w* for Mechanical Roller (mm)	*w* for hydraulic expansion (mm)
15.88	7.94	12	2.769	3.2	7.31
15.88	7.94	14	2.108	3.2	6.38
15.88	7.94	16	1.65	3.2	5.65
15.88	7.94	18	1.245	3.2	4.90
19.05	9.525	12	2.769	3.2	8.01
19.05	9.525	14	2.108	3.2	6.99
19.05	9.525	16	1.65	3.2	6.18
19.05	9.525	18	1.245	3.2	5.37
25.4	12.70	12	2.769	3.2	9.25
25.4	12.70	14	2.108	3.2	8.07
25.4	12.70	16	1.65	3.2	7.14
25.4	12.70	18	1.245	3.2	6.20



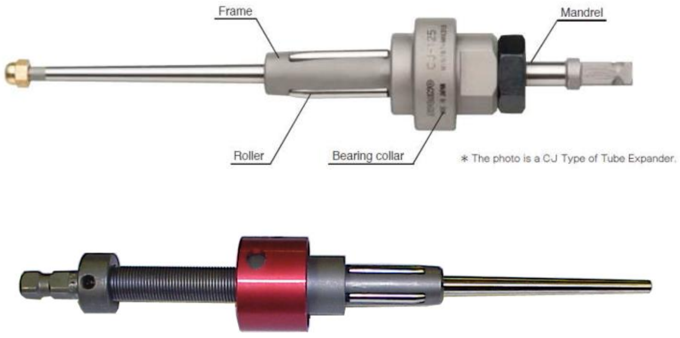
TEMA RCB-7.2.4

Mechanical Rolling Expander

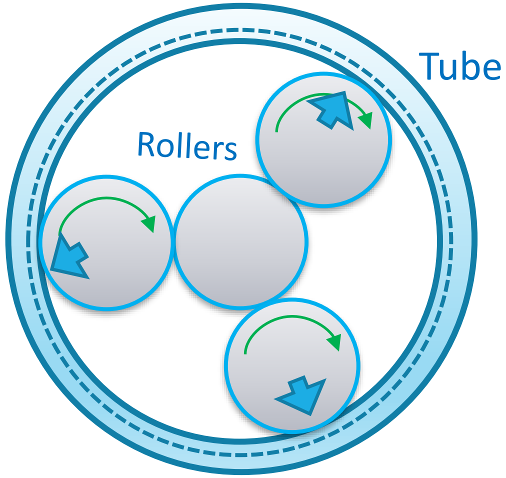
- Mechanical roller compress the tube wall against the tubesheet hole
- Tube material should be plastically formed (will not return to its original dimensions after removing the roller)
- Tubesheet at the ligament area should remain in the elastic zone. Applied force shall not be high to the level which could a misplace tube holes
- Generally triangular tube pitch is more sensitive due to the less relative ligaments thickness
- Under rolling result in less wall reduction and less joint strength residual
- Over rolling result in higher plastic deformations of the tubes, potential tube cracking and /or shifting of tube holes in the tube sheet
- Five rolls are recommended for thin wall tubes (~OD/T > 25). Typical examples are thin Ti tubes.



Tube Patterns



Tube Expander

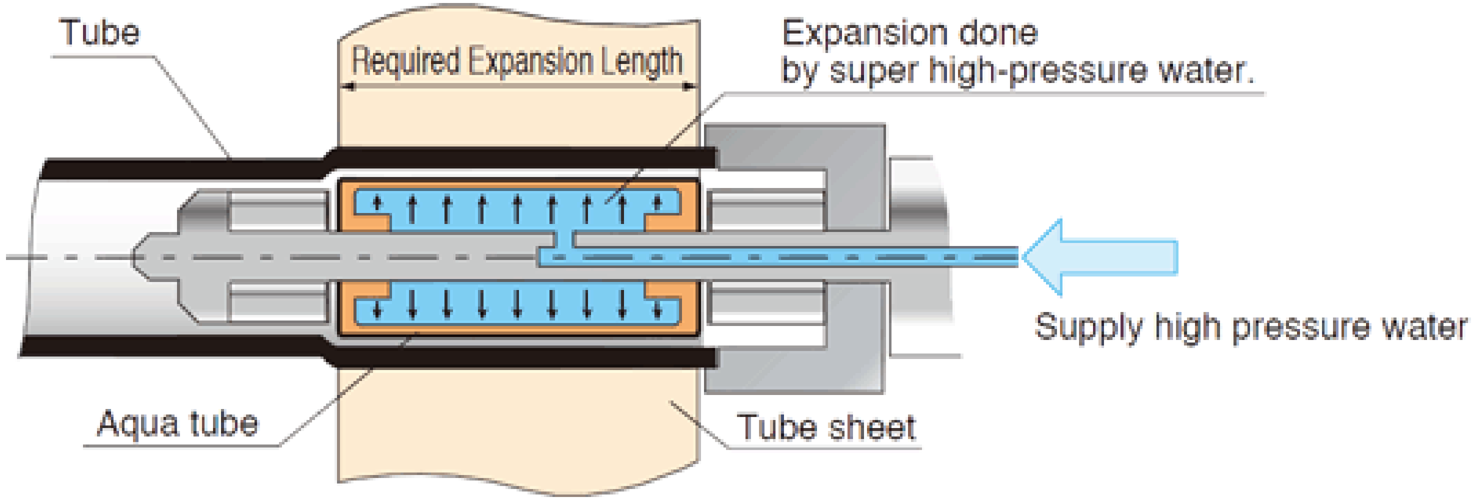


Three Roller Expander

(Courtesy of Elliott Tool Technologies Ltd)

Hydraulic Expander

- The tube is physically deformed simply by means of pressurized liquid.
- The amount of pressurized liquid introduced is a function of the proportion of elastic and plastic expansion occurring in the tube and tube sheet.
- In this a mandrel with two ‘O’ rings at appropriate location is inserted into the tube sheet. Hydraulic pressure applied between two ‘O’ rings causes the tube in that region to expand
- The applied pressure caused the tube to take exactly the shape of the hole including the grooves and the imperfections or scratches (if exist)



(Courtesy of Sugino Machine)

Cross secretion in expanded tube

Welded Tube-To-Tubesheet Joints (TTS)

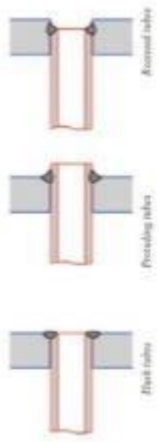
- Welding can be manual or automatic (Orbital welding)
- Strength-welded tube-to-tubesheet welds shall have a minimum of two weld passes and usually produced by gas tungsten arc welding (GTAW).
- TTS is a relative small size (deposited weld metal) in a high tubesheet thickness causing high heat sink and possible non uniform HAZ structure

Manual Welding

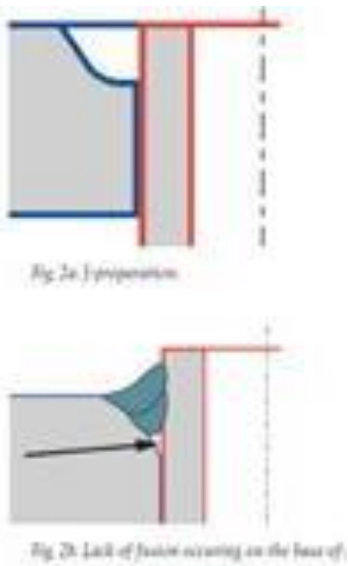
Orbital Welding

Welded Joints

Welded Tube-To-Tubesheet Joints (TTS) Configurations

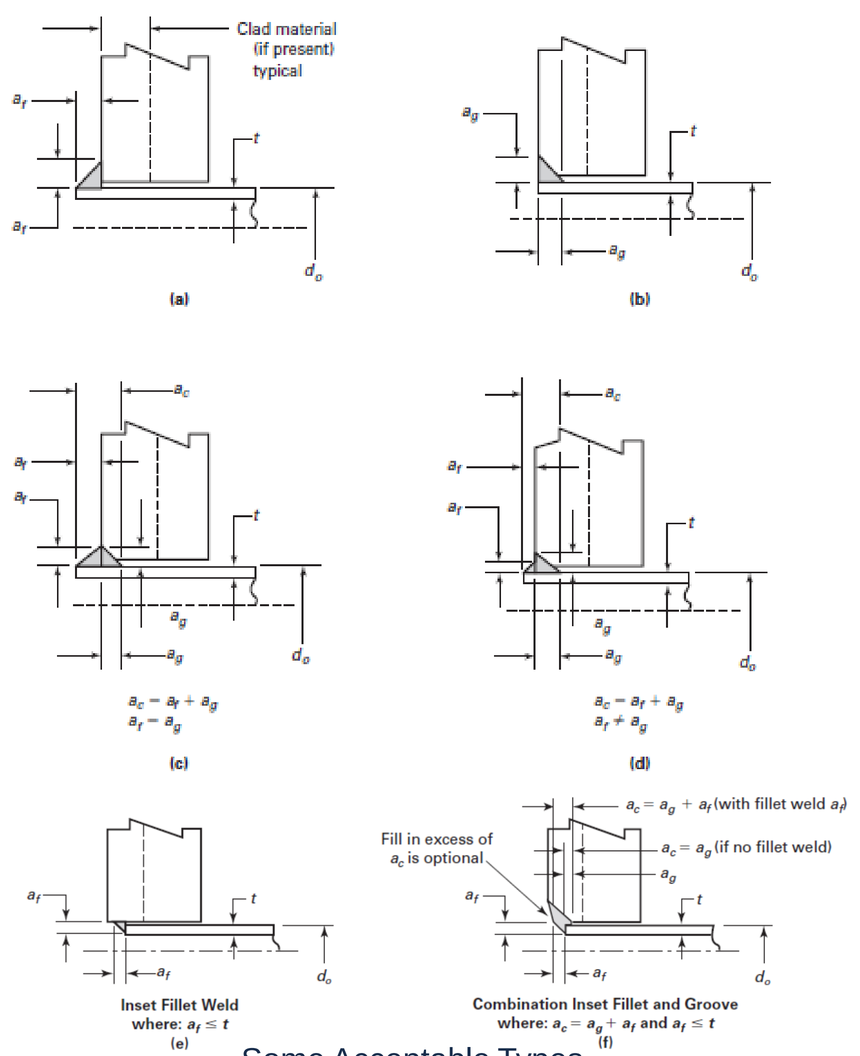


Other welding configurations can be used other than the listed in ASME

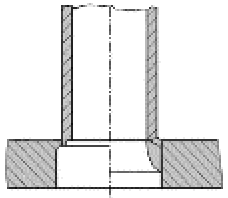


J groove is adopted in many specifications to enhance the penetration at the root pass

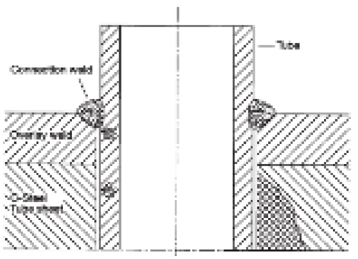
Figure UW-20.1
Some Acceptable Types of Tube-to-Tubesheet Strength Welds

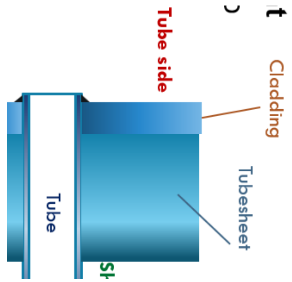


Some Acceptable Types
ASME Sec. VIII div.1 – UW-20.1



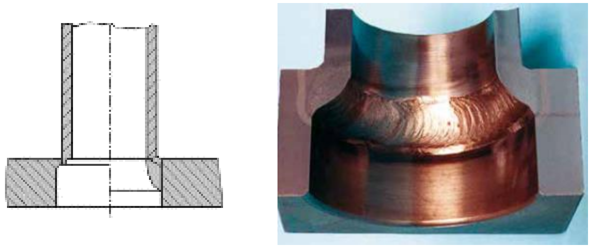
Special set back weld configuration used to prevent crevice corrosion at the shell side





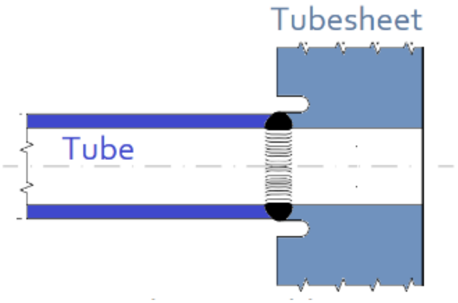
Welding to cladded / Weld overlay surface of tubesheet

Special TTS Welding Configurations



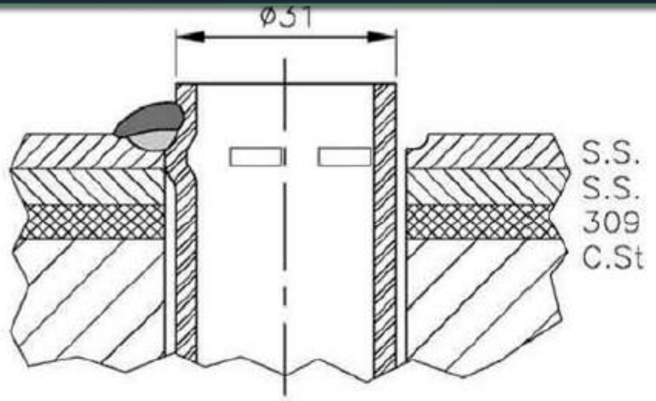
Special Set Back

- The tubes are connected to the tubesheet by a full penetration weld
- Root pass of tube to tubesheet weld is obtained by fusing edge of tube to edge of tubesheet with filler wire with shield gas to avoid any crevice on water side. Then multi-weld layers are applied
- No crevice corrosion can occur as there is no gap between tube and tubesheet.
- Typical example is reformed gas WHB in reformed section of Hydrogen, methanol and ammonia plants



Internal Bore Weld

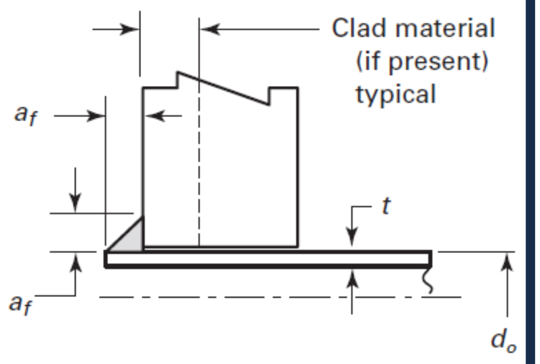
- Joint welded is in single pass without addition of filler wire and hence the thickness of tube is limited to 4.5mm.
- Welding is carried out by Internal Bore Welding technique from ID of the tube.
- The task becomes further critical due its non-accessibility since the welding has to be done at a depth of 300 - 500 mm from the Tube sheet face.
- Digital RT can be applied for inspection of this joint
- No crevice corrosion anticipated



Welded and Unexpanded joints

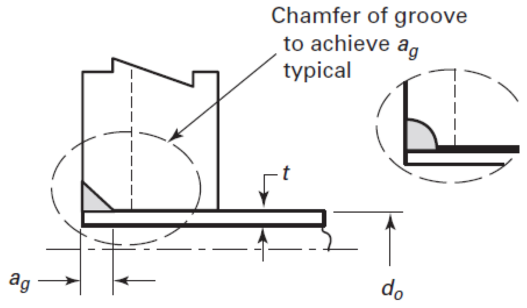
- Welding of corrosion resistance tubes to a cladded (Weld overlay face) of a carbon stell tubehseet where the tubeside fluid is highly corrosive
- Typical example of Urea stripper(ammonium Carbamate in tubeside and steam in shell side)
- In case of small leak, carbon steel can will be greatly corroded in short time
- In such applications, tubes should NOT be expanded in the carbon steel portion, so that leak will pass to steam side causing conductivity increase and early detection of the leak before tubesheet damage

Weld joint Calculations - ASME BPVC Sec VIII Div. 1



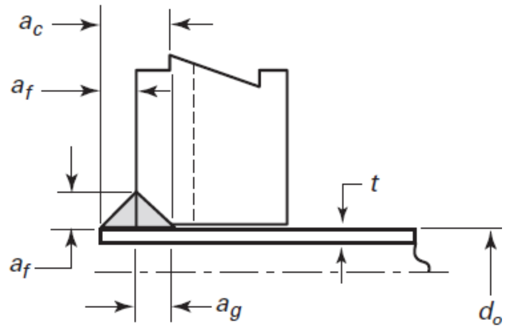
Fillet Weld

$$a_r = \sqrt{(0.75d_o)^2 + 2.73t(d_o - t)f_w f_d} - 0.75d_o$$



Groove Weld

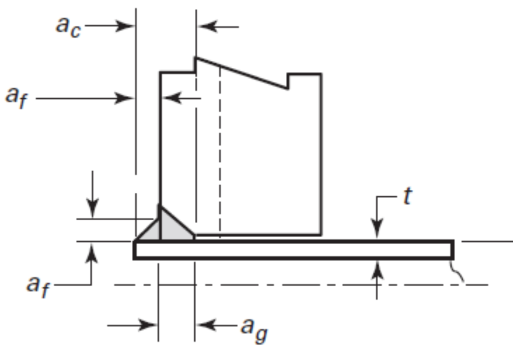
$$a_r = \sqrt{(0.75d_o)^2 + 1.76t(d_o - t)f_w f_d} - 0.75d_o$$



Combined Groove + Fillet Weld

$a_f = a_g$

$$a_r = 2\left[\sqrt{(0.75d_o)^2 + 1.07t(d_o - t)f_w f_d} - 0.75d_o\right]$$



Combined Groove + Fillet Weld

$a_f \neq a_g$

$$a_r = \sqrt{(0.75d_o)^2 + 2.73t(d_o - t)f_w f_d f_f} - 0.75d_o$$

Choose a_g and calculate a_r

	Fillet Weld	Groove Weld	Combined Groove + Fillet Weld ($a_f = a_g$)	Combined Groove + Fillet Weld ($a_f \neq a_g$)
Full strength Weld	$a_f >= a_r$ or 1.4 t	$a_g >= a_r$ or t	$a_c >= a_r$ or 1.2 t	$a_c >= a_r$ or (1.4 t-0.4 a_g)
Partial strength Weld	$a_f >= a_r$	$a_g >= a_r$	$a_c >= a_r$ $a_f = a_g = a_c/2$	$a_c >= (a_r+a_g)$

Welded and Expanded TTS – Sequence of Application

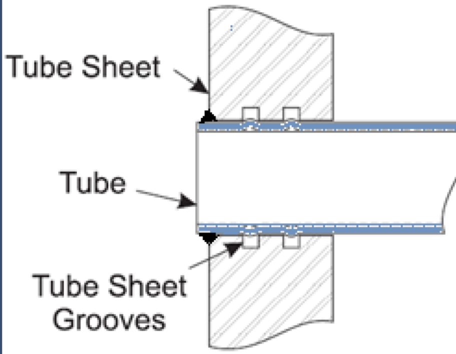
- Expansion is required for welded joints to close the cervices and to protect the weld form the effect of cyclic services and / vibrations of the tubes which can lead to fatigue cracks in the welded joints
- Expansion can be done before or after welding, each has its characteristics, pros and cons

Expansion then welding

- Expansion would close the gap at the backside of the root and might result in weld porosity
- Welding heat can loose / relax the expansion. Re-expansion would be required after welding or heat treatment (if applicable)
- Expansion can be tested before welding to confirm its tightness / sealing

Welding then expansion

- Welding might be affected /cracked during the expansion. Clearance of unexpanded portion usually recommended from the weld
- There will be no chance to check the tightness of the expansion



In expanded +seal weld: expansion will be the main sealing and seal weld is supplement. In this case proper expansion quality is favoured over welding quality

In Strength weld + light expansion: strength weld is the main sealing and its quality control is favoured over quality control of expansion

Tube-To-Tubesheet Joints (TTS)- Cladding Thk. of Tubesheet

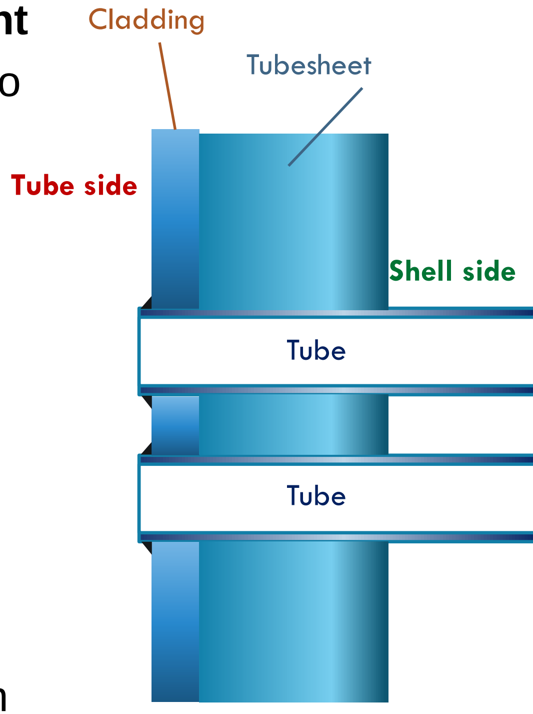
Cladding the tubesheet at tube side is beneficial in many situations:

- Corrosion resistance of the tube side fluid in lower cost instead of having solid thick corrosion resistance tubesheet
- Avoid dissimilar weld between tubes and tubesheet
- Avoid the need of PWHT in future plugging of tubes when required

---

Cladding / weld overlay thickness of the tubesheet depends on the type of tube to tubesheet joint

When the tubes are expanded only to the tubesheet the required clad thickness is HIGHER compared to the case when the tubes are welded to the tubesheet. This is to provide proper distance to expand the tube to the cladding materiel and prevent the ingress of the corrosive media to the base metal of the tubesheet.



[API 660]:

At the tube side face of a tubesheet shall not be less than 10 mm when tubes are expanded only, and 5 mm when tubes are welded to the tubesheet.

In shell side face of a tubesheet shall not be less than 10 mm

[TEMA]: RB-7.6

The nominal cladding thickness at the tube side face of a tubesheet shall not be less than 7.8 mm when tubes are expanded only, and 3.2 mm when tubes are welded to the tubesheet.

The nominal cladding thickness on the shell side face shall not be less than 9.5 mm

Cladding and Weld Overlay

Clad material is the typical choice for aggressive environments as an economical alternative to solid alloy steel. The corrosion resistant alloy is selected specifically for its performance in the process.

There are three typical choices

Explosion Welding

Explosive bonding uses the very-short-duration, high-energy impulse of an explosion to drive two surfaces of metal together, simultaneously cleaning away surface oxide films and creating a metallic bond.

Resist the most aggressive hydrogen charging scenarios

Hot Roll Bond

Produced when a steel mill heats the steel and corrosion resistant alloy together and rolls them as one package.

The rolling, under high temperature and pressure, causes the two metals to clad together.

It is generally accepted that a roll bond clad plate has the lowest bond shear strength of the three techniques described here.

Weld Overlay

Weld overlay is a fusion deposition of corrosion resistant alloy onto a steel or alloy steel substrate.

Usually, weld overlay is done in place, after the pressure vessel has been through many of the fabrication steps, but not always.

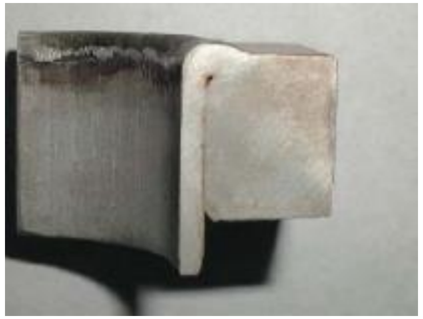
In many cases, dilution concerns necessitate the use of 'butter passes' and over alloying in an attempt to overcome the issues of dilution

Cladding and Weld overlay

Characteristics	Explosion Welding	Hot Roll Bond	Weld Overlay
Full Chemistry of Corrosion Resistance Alloy	YES	YES	NO
Unaltered Corrosion Resistance	YES	NO	NO
Easy to Inspect	YES	NO	NO
Resists Hydrogen Induced Dis-bonding	YES	NO	YES

Mock-UP of the tube-to-tubesheet welding

- ASME BPVC Sec. IX QW-193 to be followed with additional requirements based on case by case
- Mock-up required for EACH Welding / procedure qualification
- The mockup assembly shall essentially duplicate the tube-to-tubesheet weld joint design to be used in production
- For tube-to-tubesheet welds to clad tubesheet, the cladding or overlay may be represented by a base material with a chemical composition that is essentially equivalent to the cladding composition
- The mock-up shall consist of minimum **10 tubes** for procedure qualifications and minimum **5 tubes** for EACH welder qualifications.
- Hardness testing to be considered for work hardening materials (ex. DSS and Ti) or for service requirements (e.g sour service)
- It is advised that dummy tubehsheet to be from the same material of the production tubesheet, to ensure that HAZ in the mockup (dummy) tubesheet will give representative results



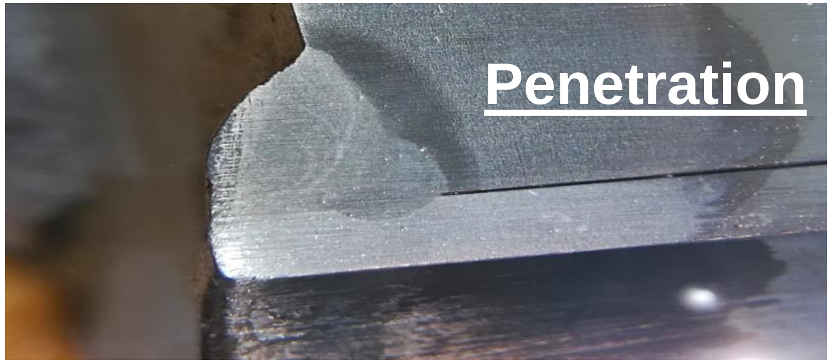
Mock-up is required for procedure qualifications and for welder qualifications as well each time WPS should be applied

Mock-Up Procedure

Detailed mock-up procedure shall be prepared including the sequence of application, sketch and dimensions of the used material, acceptance criteria, template for the output results report

All Mock-UP shall be subjected to:

1. Check the conditions of the tubesheet holes and tube surface
2. Measure and record the actual holes diameters, Tubes' inner diameter, tube thickness for all tubes
3. Follow the same sequence of expansion and welding as agreed for the production
4. Visual Examination: complete fusion, free of visual cracks, porosity indications, no evidence for tube burn through
5. Liquid penetrant for root pass and final pass
6. Measure and record the actual tube ID after expansion and calculate wall reduction ratio for all tubes
7. Macro examination: section the mockup through center and the 4 exposed surfaces to smoothed, etched. Use magnifications 10X to 20 X (preferred 20 X for better visibility)
   - ✓ Minimum Leak Path (MLP)
   - ✓ No cracking
   - ✓ Complete fusion



Target wall Reduction Measurements and Calculations

$$R = \frac{(di\ - do) - (H\ - D)}{D - do} * 100\ \%$$

R = Expansion Ratio (%)

di = Inside diameter of tube after expansion

do = Inside diameter of tube before expansion ‘

H = Diameter of tubesheet hole

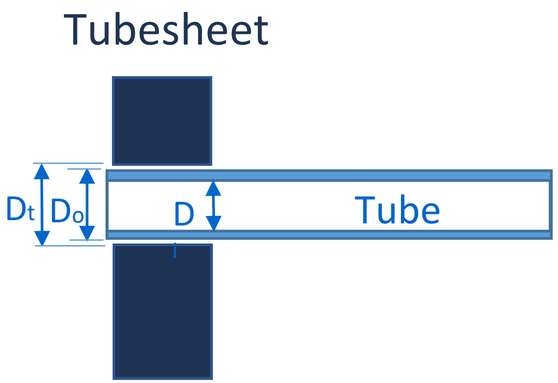
D = Outside diameter of the tube before expansion

internal measuring gauge

Internal three point expanding dial calliper for measurement of tube ID before and after expansion and

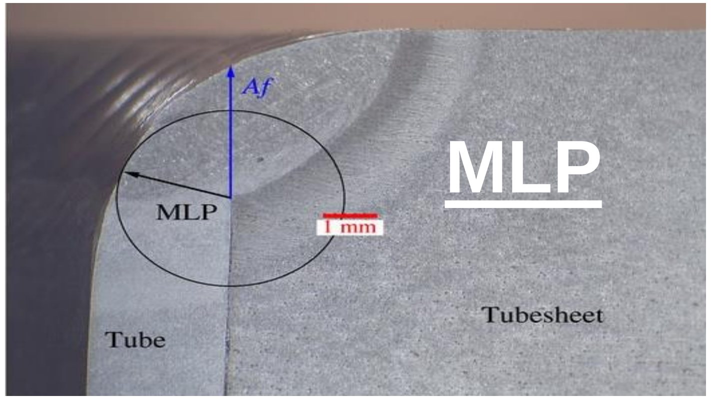
Sample Calculations of Tube Wall Reduction %

#	Tubesheet Hole Dia.	Tube OD	Tube ID before expand.	Tube Thickness	Final Tube ID after expansion	Expansion Ration %
1	25.26	25.17	23.592	0.789	23.784	6.46%
2	25.26	25.11	23.529	0.7905	23.767	5.57%
3	25.263	25.11	23.571	0.7695	23.795	4.61%
4	25.265	25.09	23.512	0.789	23.777	5.70%
5	25.265	25.13	23.532	0.799	23.804	8.57%

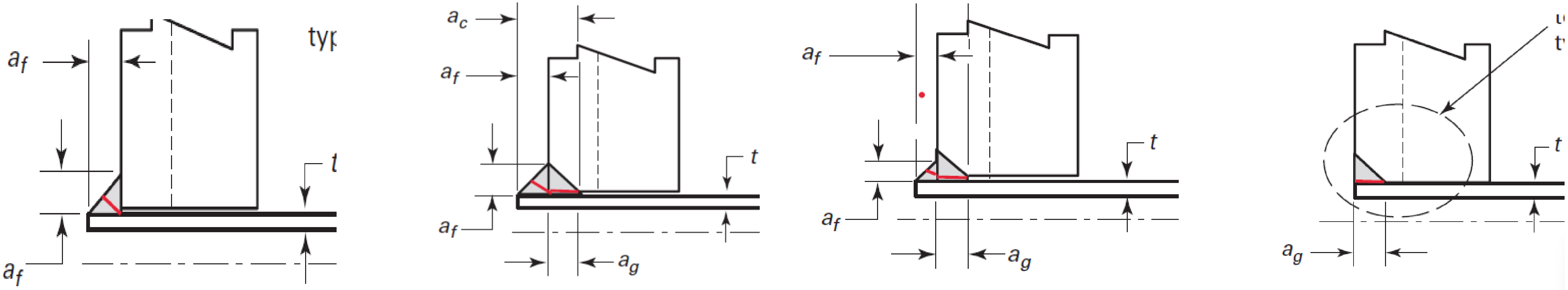


Minimum Leak Path (MLP)

- **Minimum Leak Path (MLP):** is the minimum path where the media can leak and can be defined as the minimum distance in any direction from the root of the TTS weld to the nearest surface
- **MLP** will depend on the type of the joint (fillet / groove / Fillet + groove / … etc.) and the actual shape of the applications (concave / convex / actual geometry / …etc.)
- In **API 660** it is required to be **>=** 2/3 nominal tube thickness
- In **ASME sec. IX** it is required to meet the design, but there is no specific requirements for how to be identified



MLP = the radius of the largest circle **totally** inscribed in the weld whose centre is situated at the root of weld



MLP for different ASME joints

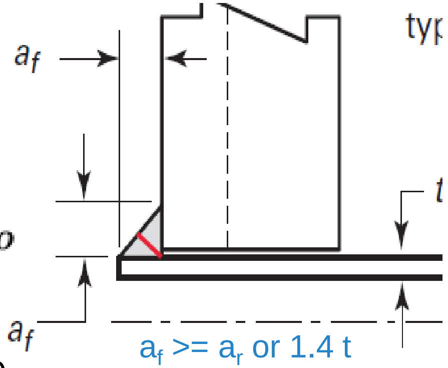
Minimum Leak Path (MLP)

Demonstrative Examples:

CS tube SA 179 to CS Tubesheet SA 266 Gr.2: Do= 19.05 mm, BWG 14 (2.108 mm thickness) – Td= 200 ºC

Fillet Weld – Full Strength Weld

$$a_r = \sqrt{(0.75d_o)^2 + 2.73t(d_o - t)f_w f_d} - 0.75d_o$$



Sa = 92.4 Mpa ….. Tube all. stress ASEM sec. II part D
St= 138 Mpa….. Tubesheet all. stress ASEM sec. II part D
Fw= Sa/Sw = 1 (Sw is smaller of Sa and St)
Fd = 1 for full strength weld

ar= $\sqrt{[(0.75X19.05)^2 + 2.73X2.018X(19.05 - 2.018)X1X1]} - 0.75X19.05$

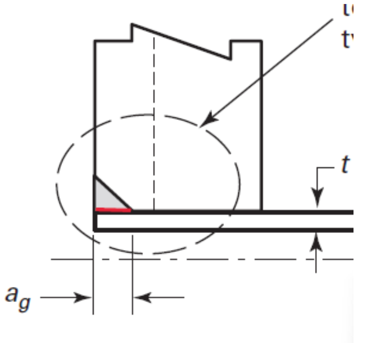
ar = 2.93 mm ……. 1,4t = 1.4X2.018 = 2.825 mm
af >= greater of ar or 1.4t …….. af = 2.93 mm
MLP Throught distance = af / $\sqrt{2}$ = 2.93 / $\sqrt{2}$ = 2.07 mm

Calculated MLP = 2.07 mm

MLP as 2/3 t= 1.405 mm …… per API 660

Groove Weld – Full Strength Weld

$$a_r = \sqrt{(0.75d_o)^2 + 1.76t(d_o - t)f_w f_d} - 0.75d_o$$



Sa = 92.4 Mpa ….. Tube all. stress ASEM sec. II part D
St= 138 Mpa….. Tubesheet all. stress ASEM sec. II part D
Fw= Sa/Sw = 1 (Sw is smaller of Sa and St)
Fd = 1 for full strength weld

ar= $\sqrt{[(0.75X19.05)^2 + 2.73X2.018X(19.05 - 2.018)X1X1]} - 0.75X19.05$

ar = 2.93 mm …….
ag >= greater of ar or t …….. ag = 2.93 mm
MLP = depth of groove = ag = 2.93

Calculated MLP = 2.93 mm

MLP as 2/3 t= 1.405 mm …… per API 660

Common Defects

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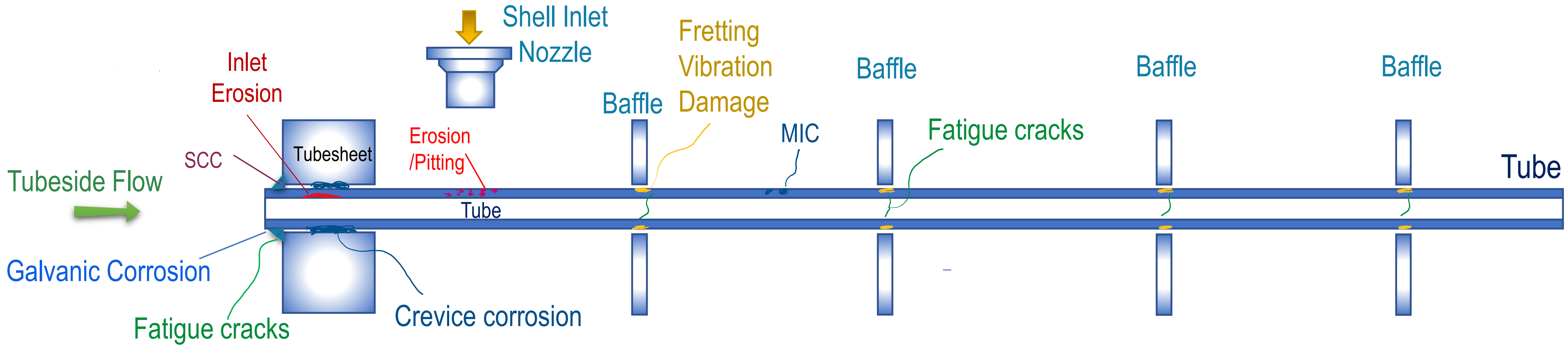
Common Defects in Heat Exchanger Tubes



Erosion-Corrosion	Pitting	Galvanic Corrosion	MIC
Crevice Corrosion	Fatigue Cracking	Fretting Corrosion	SCC

This is not inclusive list, only most common defects

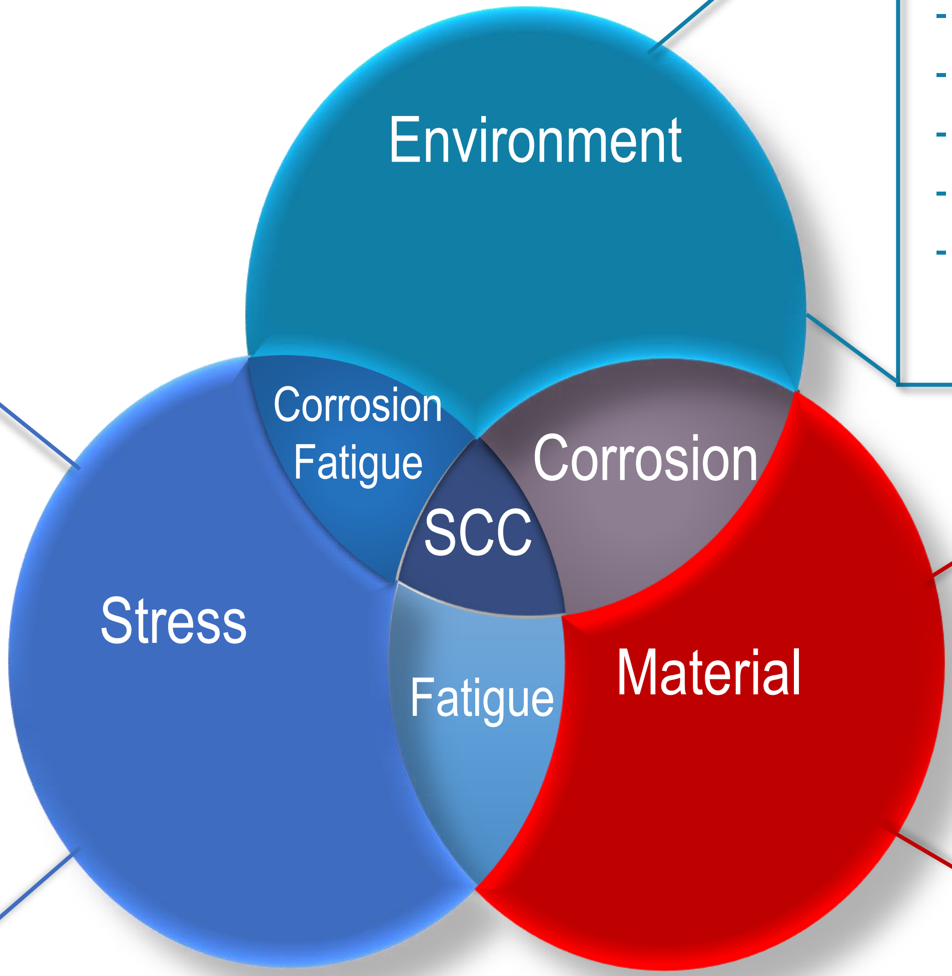
Factors Influencing Corrosion

Environment Factors

- Degree of aeration
- Flow Velocity
- Impurities
- pH
- Temperature
- concentration of corrodents

Stress

- Design Factors (crevice; U bends, stagnant areas, geometry of TTS)
- Fabrication
- Metallurgical factors

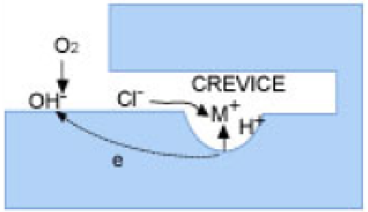


Material Factors

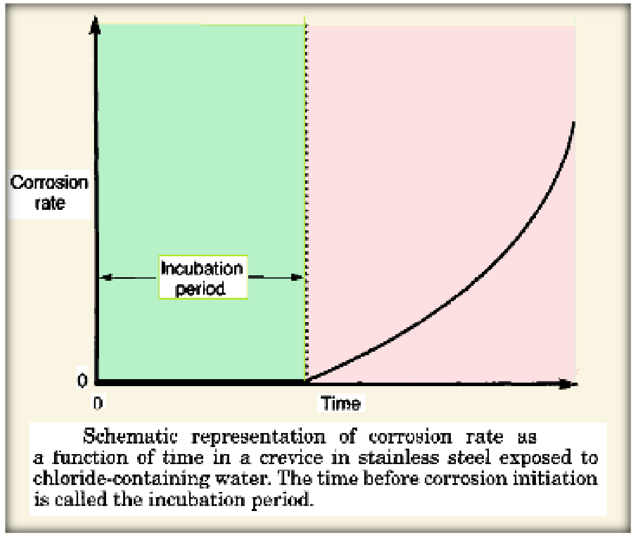
- Composition
- Microstructure
- Surface conditions
- Cold / hot hardening

Crevice Corrosion

Crevice Corrosion is an intense localized corrosion frequently occurs within crevices and other shielded areas on metal surfaces exposed to corrosives. This type of attack is usually associated with small volumes of stagnant solution caused by holes, gasket surfaces, lap joints, surface deposits, and crevices under bolt and rivet heads



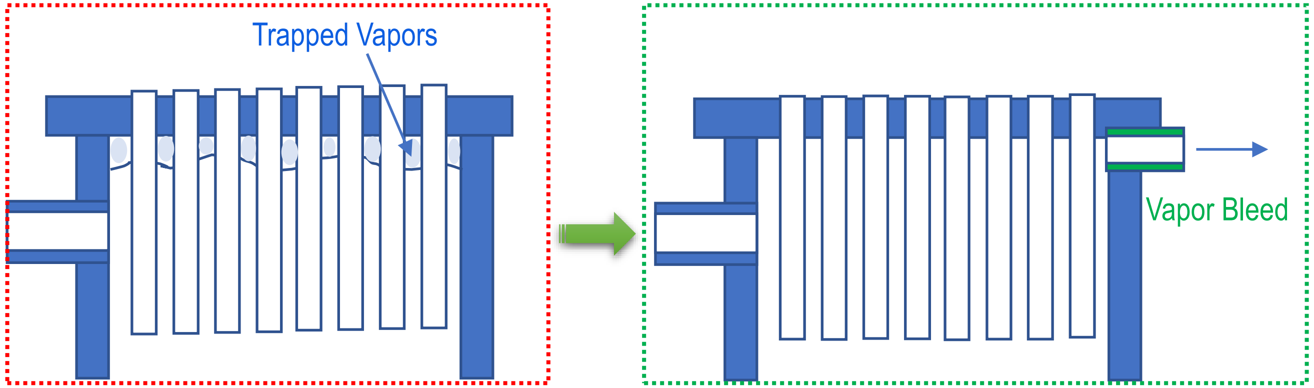
Crevice Corrosion



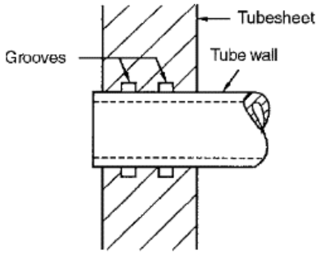
Reference: NALCO Guide to Cooling Water System Failure Analysis

Control

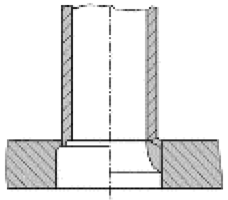
- Redesign of Tube-To-Tubesheet joint to eliminate crevices.
  - ✓ Proper expansion of tube to tubesheet
  - ✓ Use setback weld or internal bore weld
- Select more corrosion resistant or inert alloys
- Fluid of tendency to cause concentration cell to be allocated in tubeside
- Vent / blead trapped or stagnant media
- Ensure full penetration of welded TTS



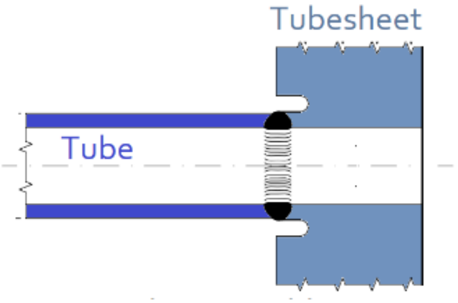
Crevice corrosion due to concentration of vapor phase and remedial measure.



Tube Expansion



Set back weld



Internal Bore Weld

Pitting and Erosion

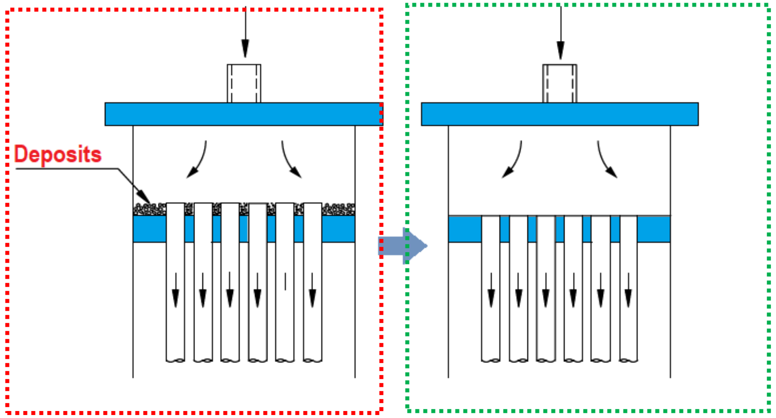
Pitting is a form of extremely localized attack that results in holes in the metal. These holes may be small or large in diameter, but in most cases they are relatively small. Pits are sometimes isolated or so close together that they look like a rough surface.

For stainless steels, pitting resistance equivalent number (PREN) :

$$PREN = Cr + 3.3 (Mo + 0.5 W) + 16N$$

Control

- Choose the material most appropriate for the service conditions
- Avoid stagnant zones and deposits
- Reduce the aggressivity of the medium (using inhibitors)
- Maintain the protective film of the material
- Avoid condensate corrosion (ex. CO_2 cooled below dew point)



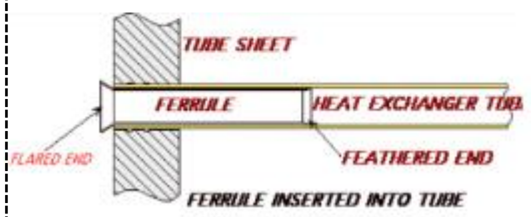
Avoid projection of tubes in top tubesheet of vertical heat exchangers

Erosion-corrosion is a description for the damage that occurs when particle erosion and/or high flow velocity contributes to corrosion by removing protective films or scales or otherwise accelerating the corrosion rate.

Control

- Changes in shape, geometry, and materials can help mitigate erosion and erosion-corrosion.
- Heat exchangers utilize impingement protection (plates, rods,..) for shell inlet erosion and occasionally tube ferrules for tube inlet portion
- Improved resistance to mechanical erosion is usually achieved by increasing component hardness
- Ensure proper operation to avoid water droplets in the steam system.

Tube Ferrules



Inlet tube erosion

Stress Corrosion Cracking

SCC is Cracking caused by the simultaneous presence of tensile stress and a specific corrosive medium. Usually lead to unexpected sudden failure.

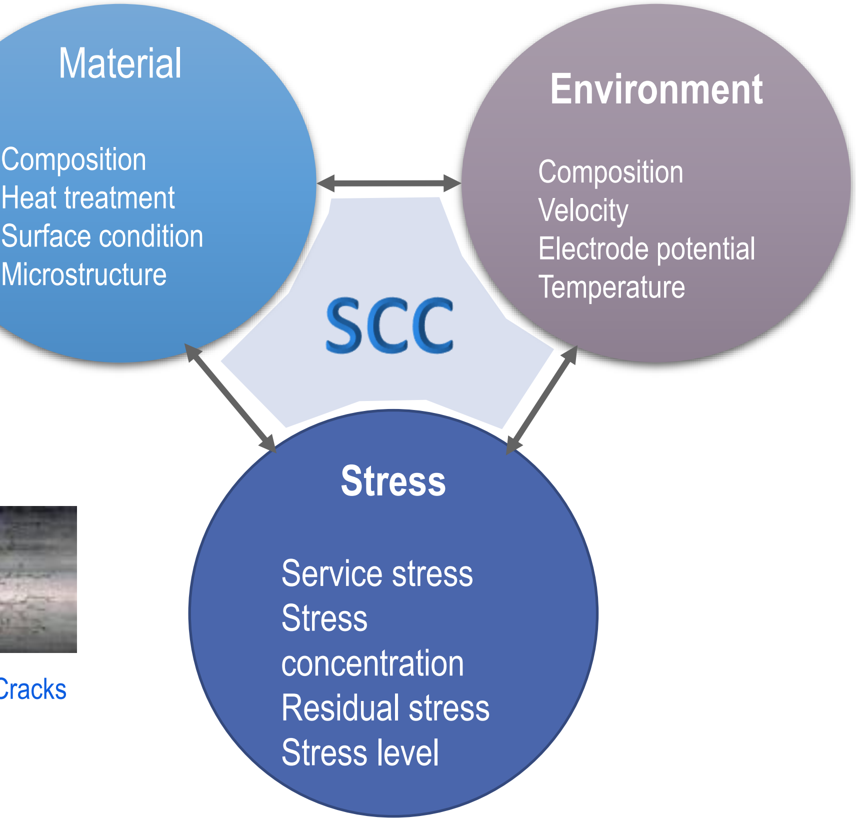
SCC is believed to be nucleated at pitting damage sites and develops under local tensile stresses as a highly branched network of fine cracks.

Can be expected at TTS, baffle area, U bends

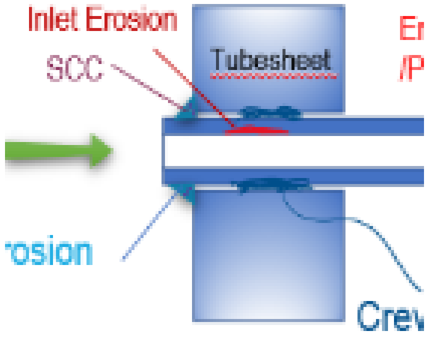
Examples: (Chloride SCC, Carbonate SCC, Caustic SCC, Ethanol SCC, HF SCC and Polythionic acid SCC)

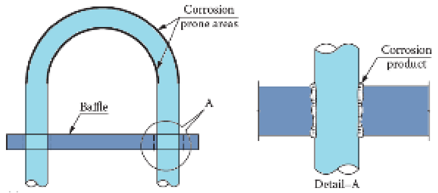
Control

- Use resistant material
- Residual stress release application when applicable (for TTS and U bends as applicable)
- Design to avoid stagnant conditions of species causing SCC (eliminate crevice).
- Proper tub expansion to tube sheet
- Full weld penetration
- PWHT application based on materials and service
- Reduce bundle vibration




SCC Branched Cracks





Other Locations in the tube can suffer SCC

Stress Corrosion Cracking

Alloy	Environment
Austenitic stainless steel	Chlorides Hot concentrated caustic Sulphurous and polythionic acids Hydrogen sulfide
Carbon steel	Concentrated caustic Concentrated nitrate solutions Anhydrous ammonia Carbonate and bicarbonate
Copper-based alloys	Ammonia (vapors and solutions) Amines Sulfur dioxide Nitrates, nitrites
Titanium	Ethanol Methanol Hydrochloric acid

Reference: NALCO Guide to Cooling Water System Failure Analysis

Galvanic Corrosion

Galvanic Corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path.

It occurs when dissimilar metals are in contact.

It can be expected at the tube-to-tubesheet joint or interface between tubes and baffles in case of using dissimilar material

Control

- Use of galvanically compatible materials
- Avoid unfavorable area effects of a small anode and large cathode
- Apply cladding / weld overlay of tubesheet to match the tube material at the TTS
- Apply coating to tubesheet after assembly to isolate from the electrolyte

Galvanic Series Chart

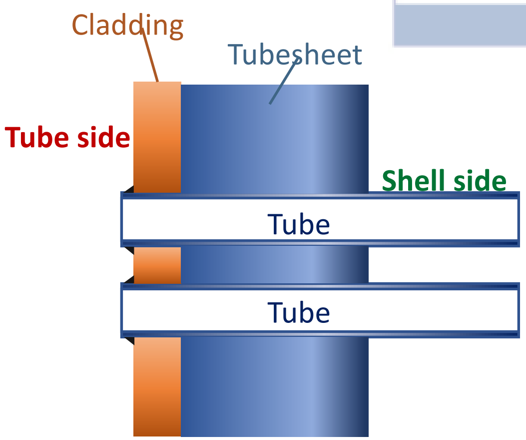
	Active	Magnesium
Anode (-)	(most susceptible to	Zinc
	corrosive attack)	Galvanized Steel
		Aluminum
		Mild Steel
		Cast Iron
		Lead
		Brass
		Copper
		Bronze
		Monel
		Nickel
		Stainless Steel 304
		Stainless Steel 316
		Silver
		Titanium
	Noble	Gold
Cathode (+)	(least susceptible to	Graphite
	corrosive attack)	Platinum

Electrical current/movement of ions

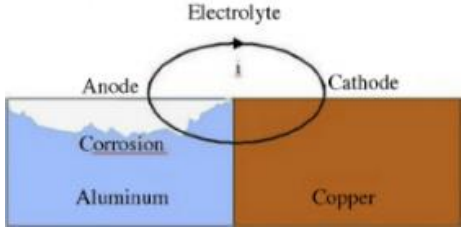
Direction of attack

Galvanic Attack – Stainless Tubes with Carbon Steel Tubesheet

Epoxy Coated Tubehseet



Tubehseet Cladding



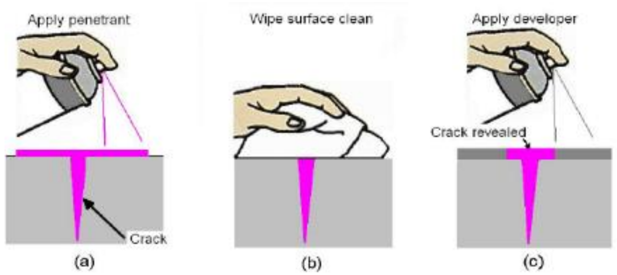
Galvanic Cell

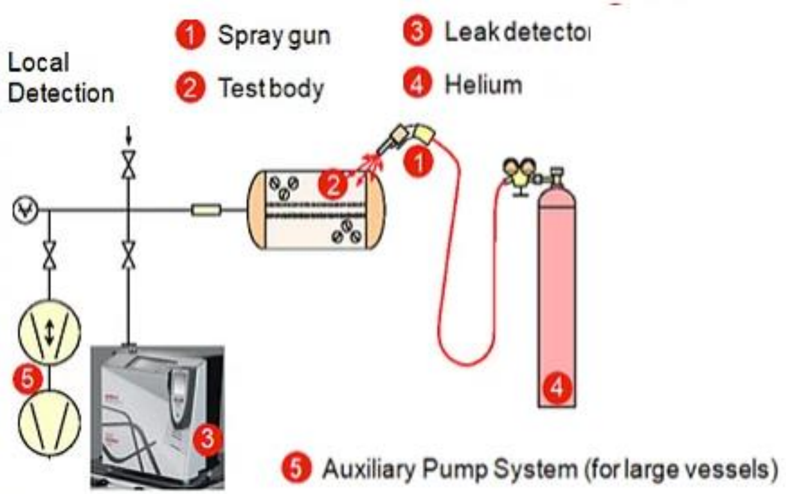
Common Defects in TTS Welds

Defect	Possible Cause(s)	Remedial Actions
Porosity	• In sufficient shielding & purging gas, unclean base material, unclean filler, etc.	• Sufficient flow of shielding and purging gas, proper cleaning of base metal and filler wire, etc
Lack of fusion	• Improper welding parameters like low current, high speed, unclean surface, etc.	• Use of proper welding parameters, clean surface
Incomplete penetration	• Low amperage, tight root opening, high travel speed, short arc length, etc. • Improper groove size, large size of filler wire	• Use of proper welding technique and welding parameters • Use J or U groove for better penetration
Burn through	• Excessive heat input • Very thin tubes	• Reduce heat input by reducing current, increasing speed, use of heat sink, etc • Consider the weldability while selecting tube thickness
Undercut	• Improper welding parameters like high current, long arc length, high travel speed, etc	• Use of proper welding technique and welding parameters
Crack	• Improper preheat temperature, high restraint, unclean surface, base material impurity, etc.	• Follow recommended preheat, ensure proper cleaning, etc. • Apply global heating instead of local preheat for thick tubesheet

Inspection of Tube-To-Tubesheet Joints (TTS)

- Visual Examination
- Surface examination by PT
- Volumetric examination by UT
- In situ replica examination
- Helium leak test
- Hydrostatic test
- Tube end Callipers for internal tube ID and expansion percentage
- Radiographic Examination, RT (recent techniques, not common application)





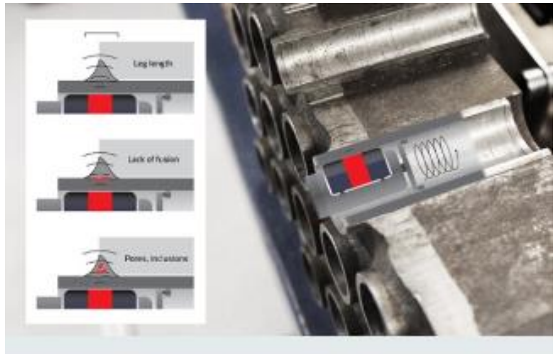
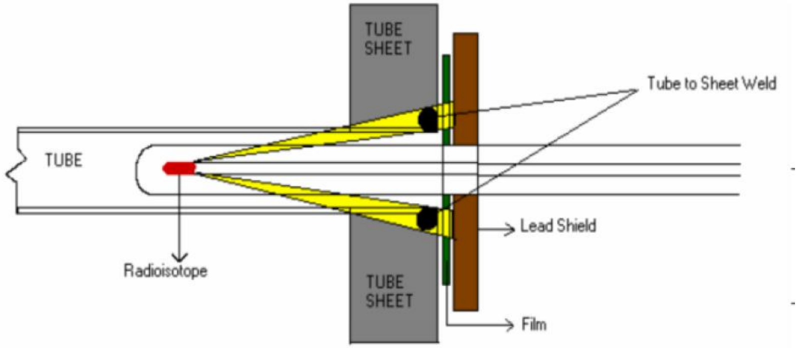


Image showing the typical failures in tube-to-tube sheet welds.



TUBE-TO-TUBESHEET JOINTS

LEAK REPAIR

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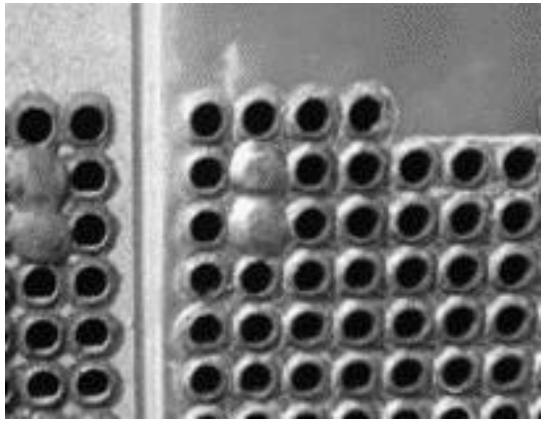
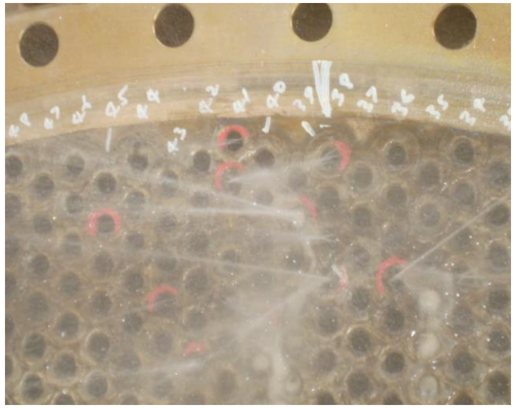
Repair Options

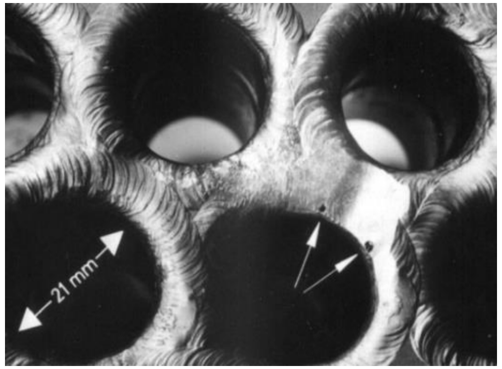
- TTS weld repair
- Re-expansion
- Retubing
- Plugging (taper plug, mechanical plug, welded plug)
- Internal sleeve / Ferrule



Suggested Weld Repair Procedure

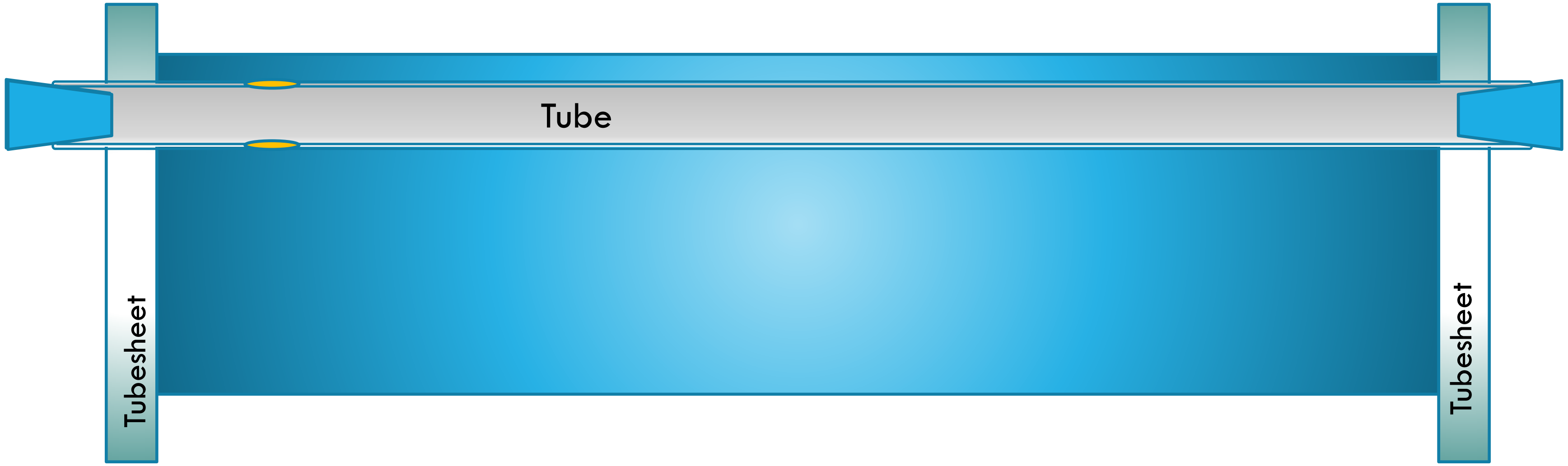
- Grind out the defected weld carefully to avoid propagation of defect (especially in cracked welds). Pencil grinder is preferred for small repairs and crack excavations (but time consuming)
- Step wise DPT application until confirming the full removal of the defect
- Welding first pass
- DPT for the first pass
- Pre-leak test (pneumatic / hydrostatic) to be applied for the root pass (optional step based on the practicality of application)
- Second / filling passes
- DPT for the last pass
- PWHT if applicable
- Re-expansion of the tube to tubesheet to compensate the relaxation form the PWHT heat (if no PWHT, this step can be omitted)
- Hardness check for the weld and HAZ
- Ferrite content measurement for DSS welds
- Hydrostatic test
- Helium leak test for critical applications
- Mock up can be prepared to simulate the repair situations

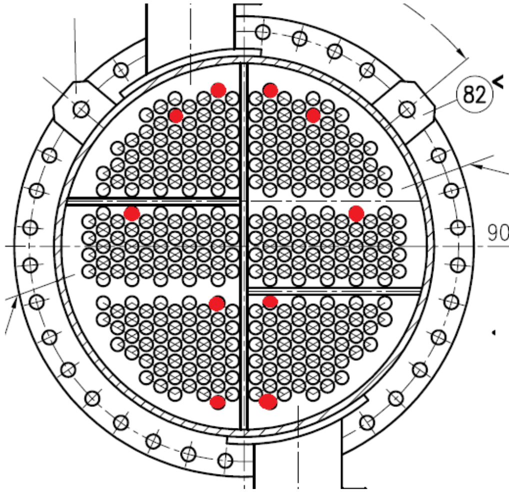




Tube Plugging – Tapper Plug

All tubes that are plugged **should be pierced** to provide venting and draining to prevent possible plug blowout. Always puncture the tube before plugging





Plug Map

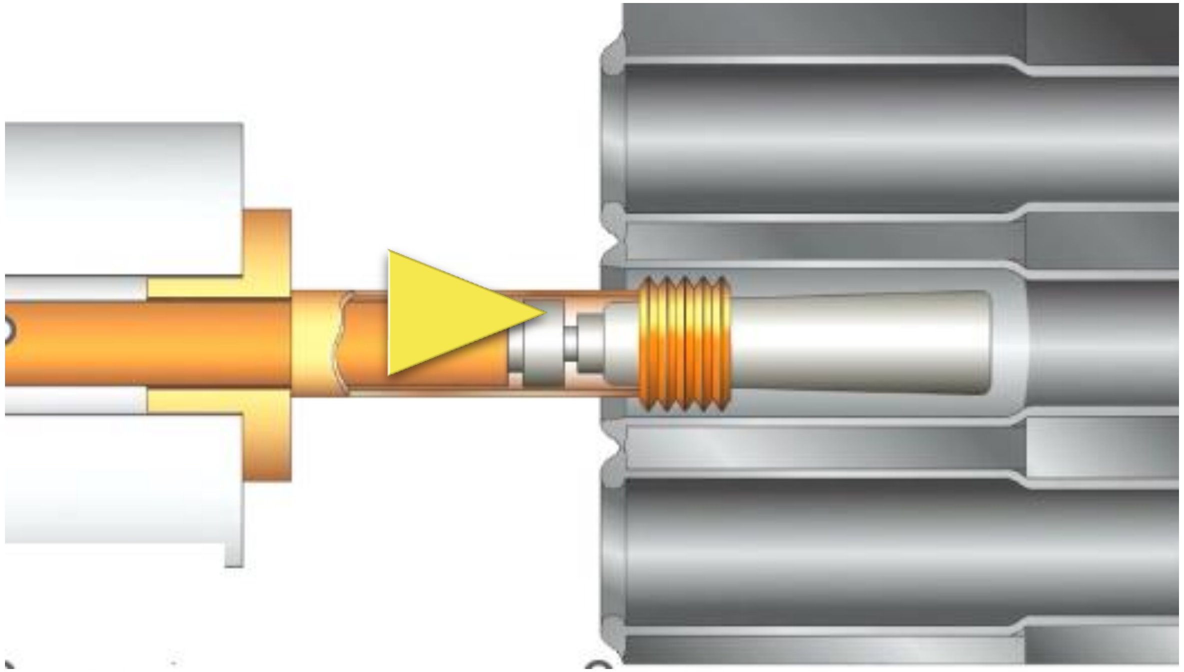
Friction Taper Plug to be used only when (per ASME PCC2)

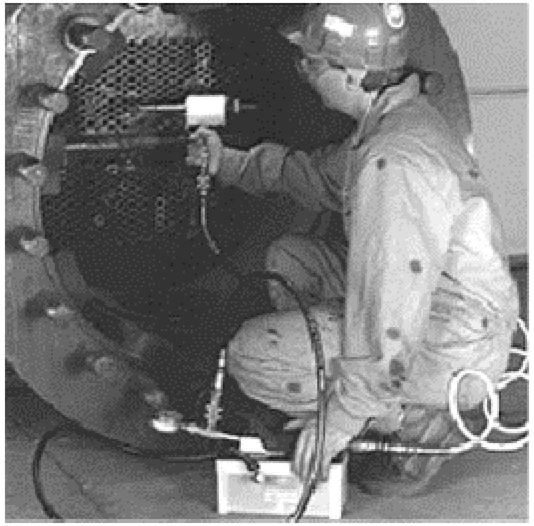
- Shell side operating pressure <=1.5 Mpa
- Shell side operating temperature <=205 ^{o}C
- Tube to tubesheet are expanded not welded

Excessive tube plugging may result in reduced thermal performance, higher pressure drop, and/or mechanical damage

Tube Plugging – Mechanical Plug

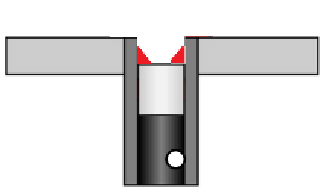
- Mechanical plugs should be considered in situations where friction fit tapered plugs are not appropriate for the pressure and/or temperature of service or other technical / environmental conditions.
- Mechanical plugs are typically installed by a pneumatic or hydraulic system. Other styles of plugs may be considered for higher pressures.

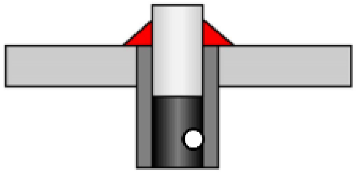


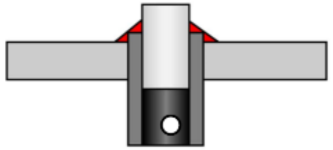


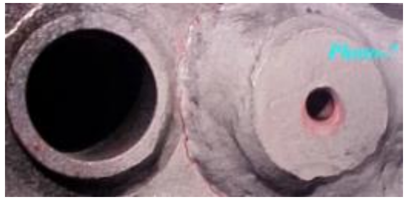
Tube Plugging – Welded Plug

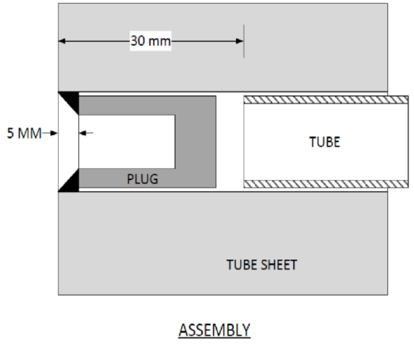
- Plugs with different shapes can be installed by welding to the tubesheet or to the inner surface of the tube
- Sometimes the plug is welded to ensure it doesn’t leak or blow out and turn into a projectile.
- When it is welded, the plug should have a material test report.
- The welding must be done in accordance with approved WPS, with care of requirements of Dehydrogenration (if applicable) PWHT … etc.
- Mock-up to be prepared to ensure proper application and qualifications of the welders
- Plug map shall be prepared to record number of location of plugged tubes

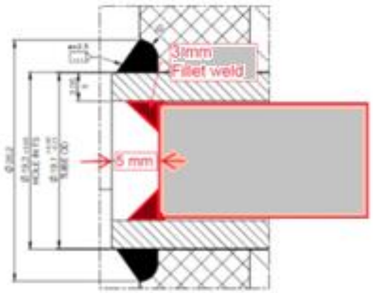


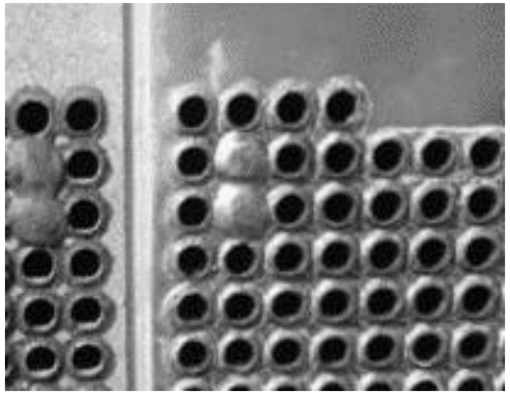












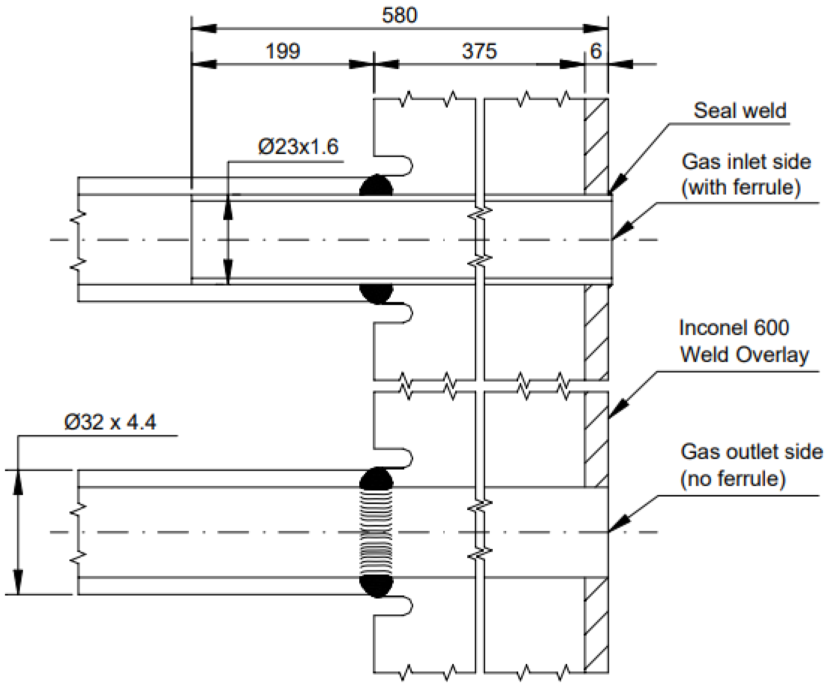
TUBE-TO-TUBESHEET JOINTS

CASE HISTORIES

Baher Elsheikh

CASE-1: Repair of Internal Bore Weld Joints

- **Equipment:** Synthesis Loop Waste Heat Boilers in Ammonia Plant
- **Service:** synthesis gas in tube side and BFW in shell side (H2 service)
- **Tubesheet material:** SA333 F22 Cl3
- **Tube material:** SA213 Gr.T22
- **Tube-to-tubesheet joint:** Internal Bore Weld IBW (Butt weld) – no filler used
- **Ferrules material:** Inconel 601
- **Lifetime of the equipment up to the leak:** 9 months



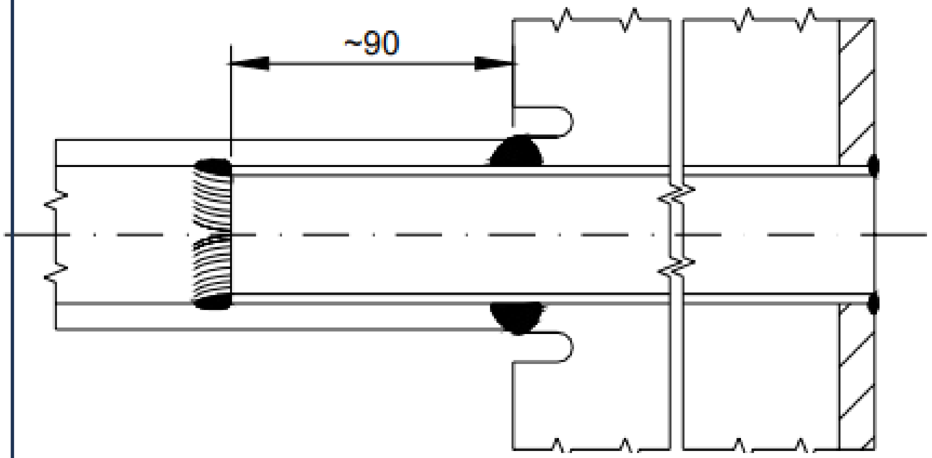
Original Configuration of TTS at inlet and outlet side

Leaking tube-to-tubesheet joint at the inlet (hot) side

CASE-1: On site Repair of IBW Joints – Cont'

Repair Methodology

- Inconel ferrule inserted inside the tubesheet extended beyond the IBW
- Ferrule welded to the inner tube surface and the tubesheet face
- Mock-up done with all details including simulation of the actual tubesheet and tube hardness
- Thorough clean applied for the inner surface of the tube
- Visual inspection, hardness, Borescope examination, DPT, and hydrostatic testing



Joint Restoring Scheme

Investigation results for the cause of immature failure

- Sample taken showed High hardness coarse grain
- Comparing the mock-up results during equipment fabrication, it was concluded that impurities in the used material is the cause of the failure.
- Although same material use for the mock up but from different heat number which did not have the same impurities issue

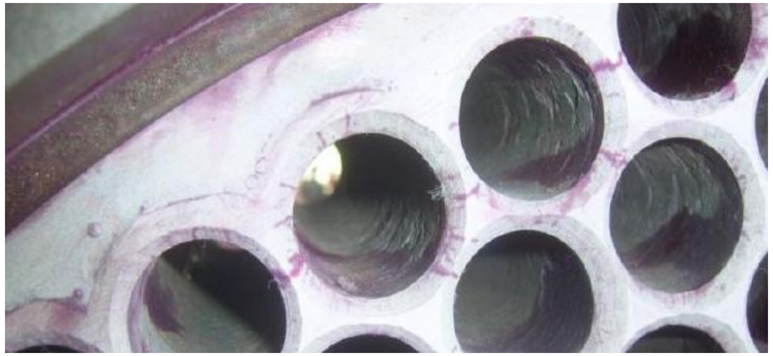
Highly advised to use in the mock-up material from the same heat number of the production in order to have representative results

Source: FBM Hudson Italiana SPA – Ammonia technical manual, 2003

CASE-2: SCC and Crevice Corrosion Attack

Equipment: Waste heat boiler in ammonia plant.

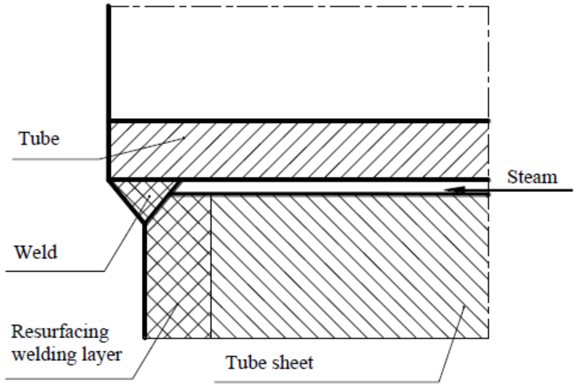
- Many cracks were found in U-tubes and in resurfacing welding layer of tube sheets.
- The design pressure and temperature of shell side is 2.8MPa and 340°C.
- The design pressure and temperature of tube side is 31.4MPa and 380°C.
- The hot flow in tube side is mixed gases. They are H_2, N_2, CH_4, Ar, and NH_3.
- Tube size is Φ35×6.5mm
- Tube material: SS 304



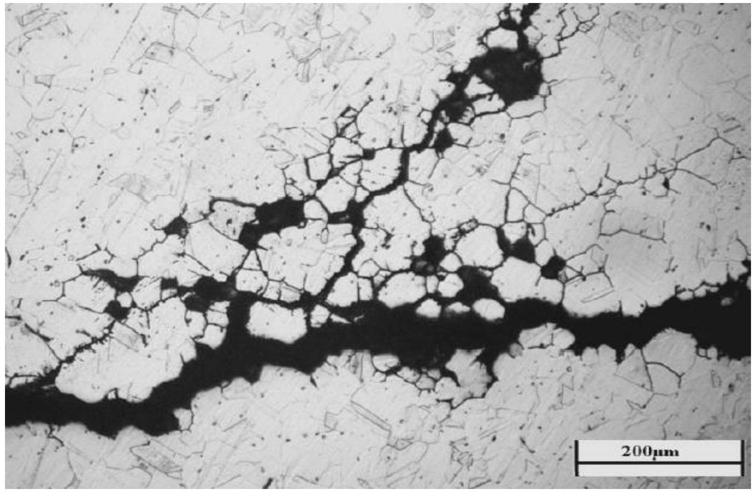
Multiple Cracks in TTS as detected by DPT

Investigation :

- Cracks are SCC from the BFW side due to improper expansion of the tube to tubesheet



Leak caused by crevice corrosion at the gap between tube and tubesheet



Cracks optical micrograph

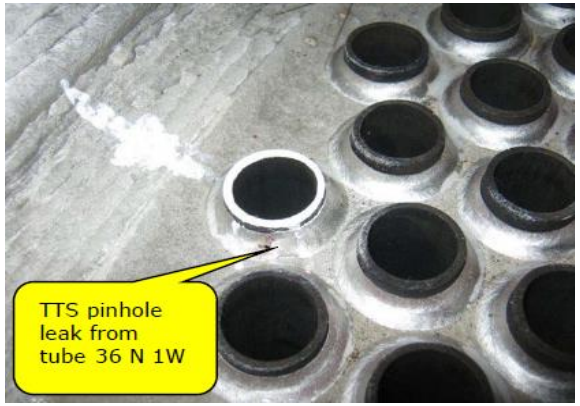
- Proper expansion is crucial to the integrity of the exchangers in potential crevice corrosion attack service
- Austenitic stainless steels are highly sensitive to chloride SCC even with very low Cl content especially at high temperature applications

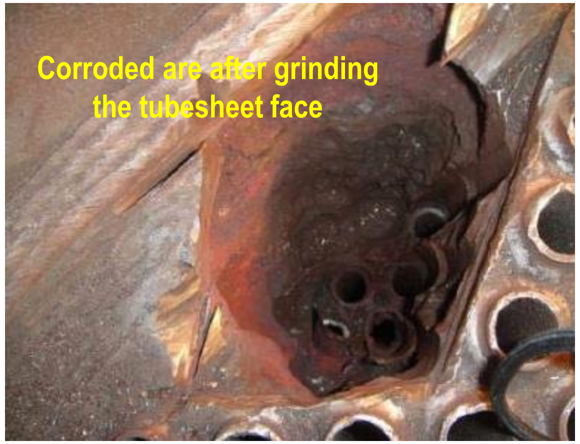
Source:The Stress Corrosion Cracking of Austenitic Stainless Steel Heat Exchange Tubes:, Shugen Xu and W. Wang, ASME PVP 2010

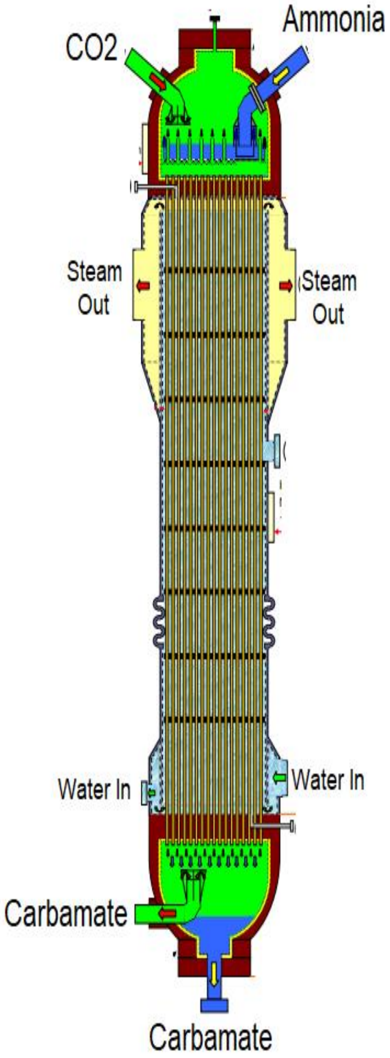
CASE-3: Carbamate Condenser TTS Leak

Equipment: HP carbamate condenser (HPCC)

- Shell side: water / steam, P 0.8 Mpa and T 165 C – Tube side Carbamate, P 16.1 Mpa, T 220 C
- Tubes are SS 316 L urea grade , tubesheet Carbon steel cladded with SS 316 L Urea grade







Investigation :

- Leak occurred from a small pin hole in the tubesheet, passed the aggressive carbamate to the carbon steel base material of the tubesheet
- A huge cavity in the tubesheet at the backside of the SS cladding
- Leal usually detected by monitoring the chemistry of the water / steam chemistry (conductivity, Ammonia content)
- If tubes are expanded to the tubehsheet causing a restriction to pass the carbamate to the water side, more corrosion will occur to the carbon steel tubesheet
- Tubes shall not be expanded to the tubesheet for the HPCC equipment

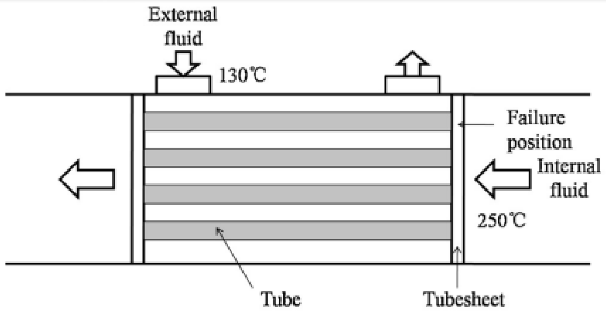
- There is no one joint type suits all applications, usually expansion of the tubes are recommended, but for this case it is prohibited to allow for early leak detection before sever impact on the tubesheet.
- *There is no one size fits all ! Balance your Choice*

Source:High Pressure Carbamate Condenser Leak Detection and Control,- Ammonia Manual-2013

CASE-4: SCC and Crevice Corrosion Attack

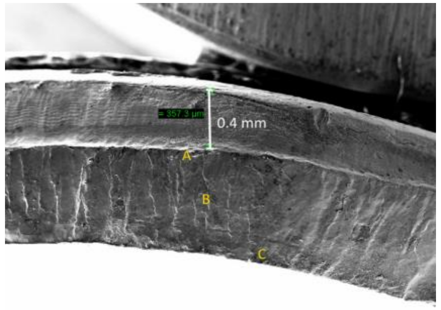
Equipment: HE process gas in tubeside (250ºC/0.25 Mpa and water in shell side 130ºC/0.8 Mpa)

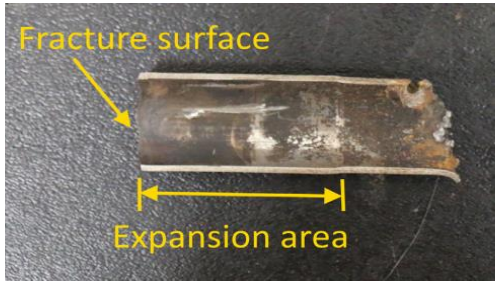
- Tubesheet and tubes are carbon steel
- TTS is strength weld + expansion (no grooves)
- Exchanger failed by multiple cracks / leaks at inlet side TTS after 30 days in service

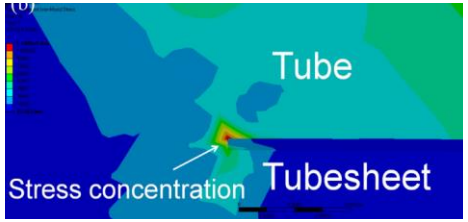


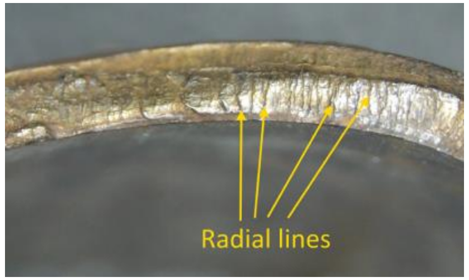
Investigation :

- Cracks at the weld without any corrosion signs
- Failure mechanism is fatigue exited by tube vibrations / cyclic service and cracked at a lack of fusion at the TTS
- Expansion was extended to nearby the weld joint causing high stress concentration at this area









- Weld quality is crucial, considering the inspection limitation, Mock up is of high value
- Enough clearance / gap shall be maintained between end of expansion distance and the weld (min 6 mm as per API 660)
- Service conditions (e.g. vibration, corrosion,..) might have no tolerance for lack of quality of the TTS

Source:Failure analysis of tube-to-tubesheet welded joints in shell and Tube heat exchanger, Long Liu, Ning Ding,- Elsevier

Recommended Readings

- TEMA, Tubular Exchanger Manufacturer Association
- API Std 660, Shell and Tube Heat Exchangers
- ASME BPVC: Sections VIII div.1 , Sec. V and Sec. IX
- NALCO Guide to Cooling Water System Failure Analysis
- ASME PCC2, Repair of pressure equipment and piping
- API TR 938 C, Use of Duplex Stainless Steels in the Oil Refining Industry

Tube to Tubesheet Joints
In Shell and Tube Heat Exchangers

Thank you for Attending

Baher Elsheikh

THE INDIAN INSTITUTE OF WELDING
(A Member Society of the International Institute of Welding)

Contact me @

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