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FEATURING

ABNORMAL CRACKS LED TO PREMATURE DECOMMISSIONING OF BOILER FEED WATER EXCHANGER – WHAT HAPPENED AND WHY?

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ABNORMAL CRACKS LED TO PREMATURE DECOMMISSIONING OF BOILER FEED WATER EXCHANGER – WHAT HAPPENED AND WHY?

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INTRODUCTION

A small leak from top tubesheet-to-tube welds prompted further inspection of the 1¼Cr- ½Mo Ammonia Converter Boiler Feed Water (BFW) Exchanger during a planned shutdown. Further cracks were identified in the top channel to tubesheet butt weld that operated at 700 °F. After grinding halfway through thickness with these cracks still being present, excavations of the 2 1/8” thick shell were stopped. As well, attempts to repair the top tubesheet-to-tube welds resulted in further cracks developing. The BFW exchanger was scrapped after being in service for 7 years. In contrast, previous exchangers in this service had operated without known cracks for more than 15 years. The findings as to the causes and potential measures to obtain a better service life are presented below.

VESSEL BACKGROUND INFORMATION

The Ammonia Converter BFW Exchanger:

- Has a process pressure of 2075 psig. [Design pressure 2200 psig] [Design temperature 8000F]
- Carries boiler feed water on the shell side. [Design pressure 1750 psig] [Design Temperature 6250F]
- Is welded with a double submerged arc welding (DSAW) procedure.
- The DSAW Weld metal is ASME Section II Part C SFA 5.23, Grade EB2.
- Top channel has a wall thickness of 2 1/8” and an ID of 35 ½ inches.
- Has channels made of ASME SA387 Grade 11 Class 2 plate.
- Has its butt welds Post Weld Heat Treated (PWHT) at the time of manufacture as per ASME Section VIII, Division 1 requirements.
- Is installed in the vertical position. The Top Tubesheet is hotter than the Bottom one.
- Has a H₂ content of approximately 55-60%.
- The hydrogen partial pressure is approximately 1150 – 1254 psia.
- Operates below the Nelson curve for 1¼Cr- ½Mo in API 941.¹

LESSONS LEARNED

- Rigorous control of the post weld heat treatment is fundamental.
- Verification of the hardness of the process side heat affected zones is important. Meticulous surface preparation is required to obtain meaningful field hardness measurements.

PART A: TOP CHANNEL TO TUBE SHEET WELD 1. Visual and Magnetic Particle Inspections (MPI)



Figure 1(a) and (b). Vessel Images

The type of vessel is illustrated in **Figures 1(a) and 1(b)**. The photographs show the vessel's Inside Diameter (ID) surfaces after attempting to excavate the cracks on the top channel to tubesheet weld. Magnetic particle inspections showed cracks mainly transverse to the welding direction. The cracks are mainly confined to the deposited weld metal (DWM). See **Figures 2-4**.

Prior to being received for examination, most of the cracks were excavated. The DWM was flame cut and mainly removed when attempts were made to join a new channel to the tubesheet. In other words, most of the cracked zones had been eliminated or subjected to localized heat. The remnants had mainly channel Parent Metal (PM) with some flame cut formerly welded surfaces. See **Figure 5**.

¹ API 941 “Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants.”



Figure 2. Cracks in the vessel after partial excavation.



Figure 3. Cracks in the vessel after partial excavation.



Figure 4. Close-up of cracks in the vessel after partial excavation.

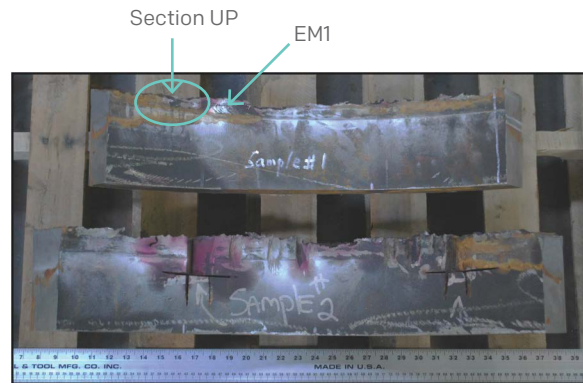


Figure 5. Top Channel sections, ID.

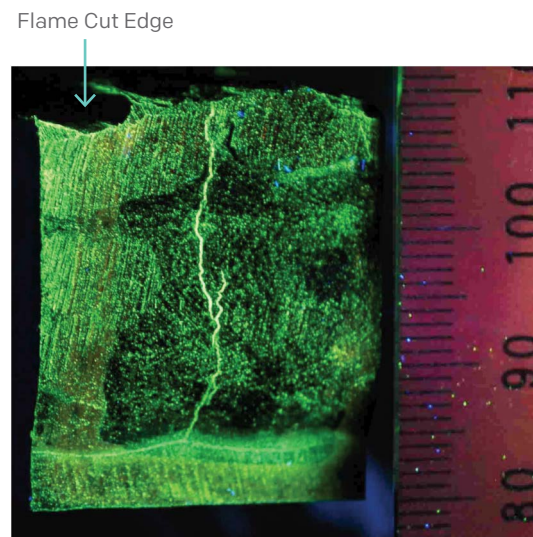


Figure 6. Magnetic particle inspection of ID, Section UP mainly DWM is shown.

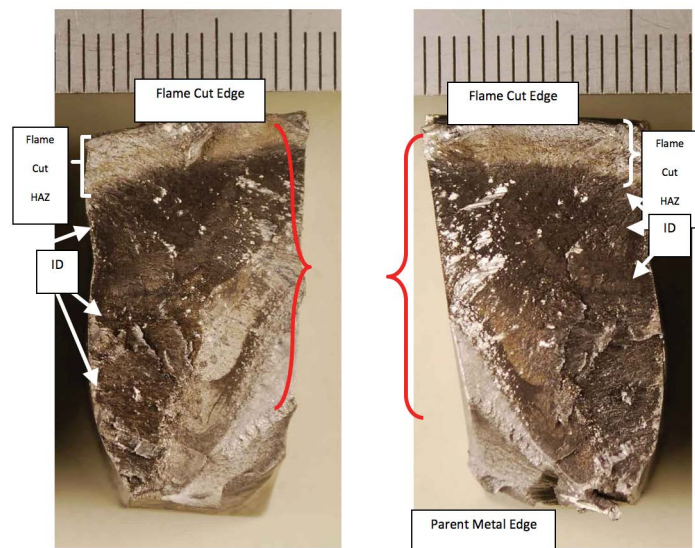


Figure 7. Fracture Surface Overview, Section UP. Matching sides of the fracture surface are shown side by side. The red brackets frame the portion of the fracture that propagated through deposited weld metal.

Wet fluorescent magnetic particle inspection (MPI) showed a crack running perpendicular to the DWM in Section UP identified in **Figures 5 and 6**. The crack was opened and the fracture surfaces are shown in **Figure 7**. The fracture fans out from the ID (the process side). Next to the flame cut end, it is whiter. Away from the flame cut end and next to the inside surface, the fracture has a brittle and rough interdendritic appearance.

Matching sides of the fracture surface are shown side by side. The red brackets frame the portion of the fracture that propagated through deposited weld metal.

2. Fracture Surface Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) Analysis

Prior to receiving the parts shown in **Figures 5 - 7**, a boat sample was extracted from the top channel to tubesheet butt weld crack. The crack was examined with the SEM. Without cleaning, the fracture faces appeared to have an intergranular appearance, and an adherent scale (See **Figure 8**). The scale mainly contained large amounts of Fe, and O with smaller amounts of Cr, Mn, and Si (See **Figure 9**). It mainly contained iron oxides.

The fracture surface is shown after cleaning with Alcanox detergent in an ultrasound cleaner. It is intergranular (See **Figures 10 and 11**). EDX analysis of the surface indicates the surface had large amounts of Fe, with smaller amounts of, Mn, Cr, Mo, and Si (See **Figure 12**). These are all constituents of the 1.25 Cr + 0.5 Mo steel Deposited Weld Metal (DWM).

3. Metallographic Examination

Several metallographic samples were prepared for examination:

- Sample EM1 [See **Figure 5** for location] from the top channel to tube sheet weld contains a ground section of DWM, some of its HAZ and some of the PM beneath it. This cross-section is parallel to the welding orientation (See **Figure 13**).

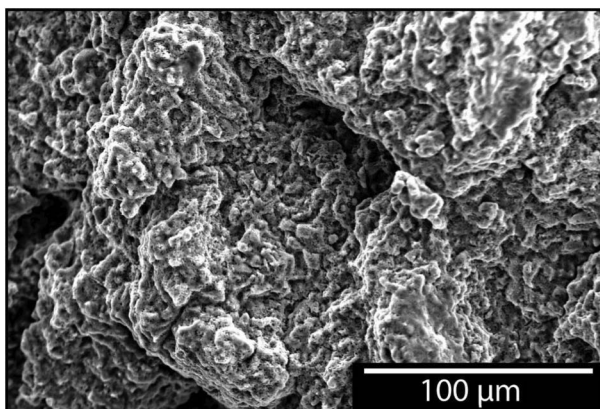


Figure 8. Fracture surface Secondary Electron Microscopy (SEM) image.

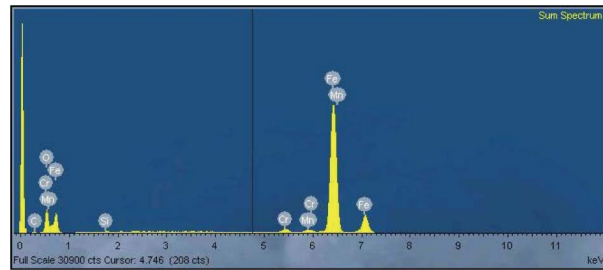


Figure 9. EDX Spectrum of the surface in **Figure 8**. image.

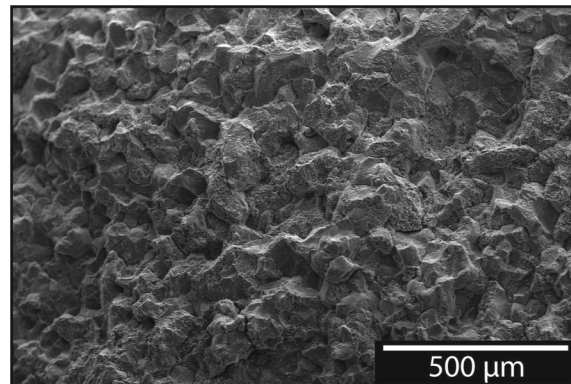


Figure 10. Sample A2 SEM image of the cleaned face.

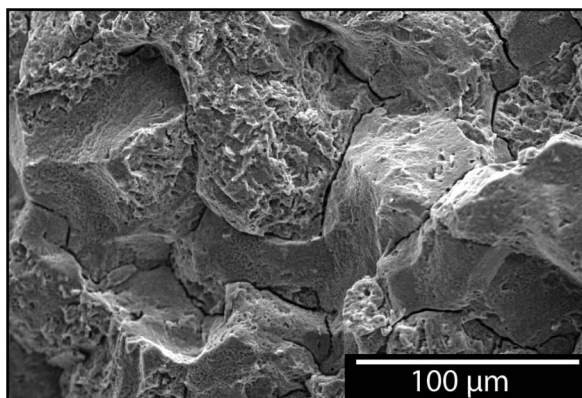


Figure 11. Sample A2 SEM image of the cleaned face at higher magnification.

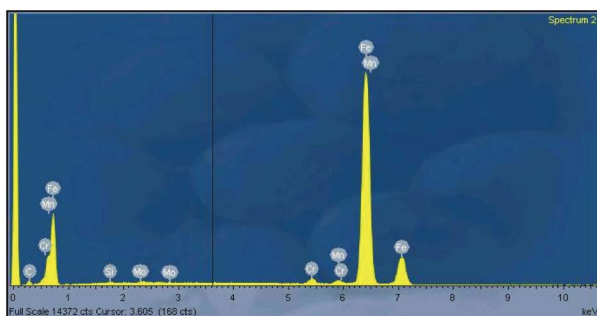


Figure 12. EDX Spectrum of the fracture surfaces shown in **Figures 10 and 11**.

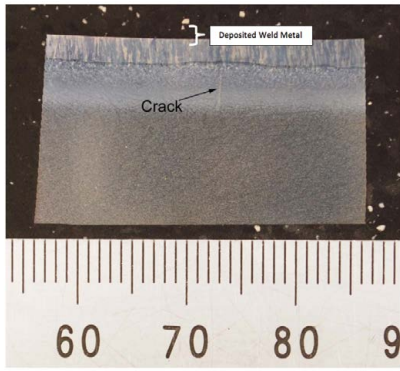


Figure 13. Metallographic Cross-Section EM1 Overview.

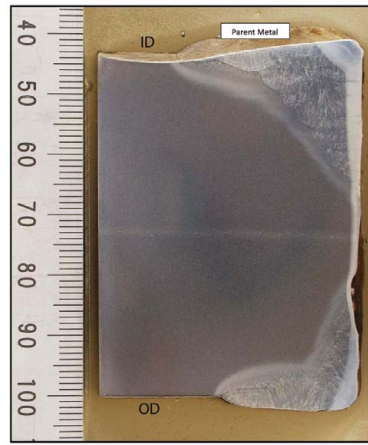


Figure 14. Overview of Top Channel to Top Tubesheet Sample TC1.

Figure 16. Metallographic Cross-Section EM1 Overview. The Figure on the right is the continuation of the figure on the left.

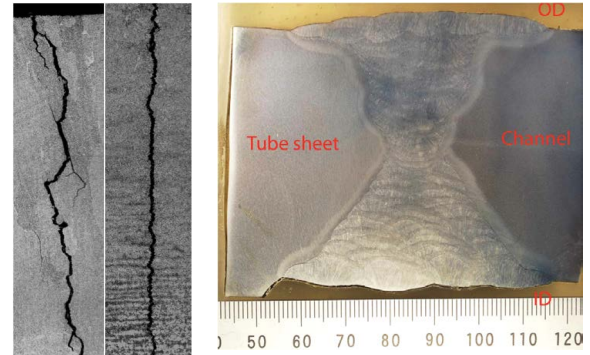


Figure 15. BC1 Bottom Channel to Tube Sheet Weld.

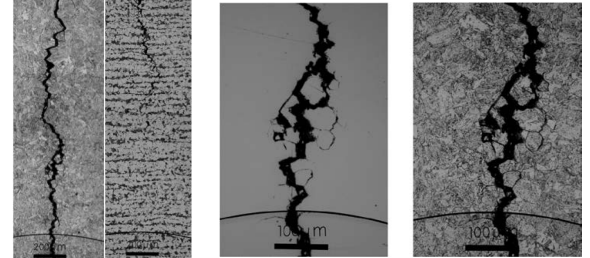


Figure 17. EM1 Crack along the HAZ, 4% Nital Etch on the right.

- Sample TC1 from the top channel to tube sheet weld contains some PM, some DWM and some Heat Affected Zone (HAZ) associated with the flame cutting. This cross-section is perpendicular to the welding orientation (See **Figure 14**).
- Sample BC1 from the bottom channel to tube sheet weld contains some Bottom Channel PM, some Bottom Channel Heat Affected Zone (HAZ), some DWM, some Tube Sheet HAZ and some Tube Sheet PM. This cross-section is perpendicular to the welding orientation (See **Figure 15**).
- Metallographic Sample EM1 has a crack running from the ID through the HAZ and into the PM (See **Figure 16**). Through the DWM, the crack is interdendritic. Through the HAZ and the PM the crack is intergranular (See **Figure 17**). The crack has minimal branching from the ID toward the OD. The crack surface has minimal to nil deposits.

4. Chemical Analyses

Chemical analysis of the top and bottom channel materials were completed with a combination of Inductively Coupled Plasma Mass Spectrometry (ICP MS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES) and Leco examinations. The results are shown below in **Tables 1 - 3**.

In summary, both the bottom and top channel to tubesheet DWM meet the requirements listed in API TR 934-D, API RP 934-C, and in the SA 387 Additional Supplementary Requirements. The bottom tubesheet and channels do not. Therefore, these components are more susceptible to temper embrittlement.

Table 1 - Top and Bottom Tubesheet Chemical Analysis Results

Element	Top Tubesheet (wt%)	Bottom Tubesheet (wt%)	SA 182 F11 Class 2 (wt%)	API RP934-C ² (wt%)
Al	0.0194 ^A	0.0194 ^A	NS	NS
Sb	0.0011 ^A	0.0011 ^A	NS	NS
As	0.00408 ^A	0.00412 ^A	NS	NS
B	0.0004 ^A	0.0004 ^A	NS	NS
Ni	0.0953 ^A	0.0959 ^A	NS	0.30
Nb	0.0002 ^A	0.0002 ^A	NS	NS
Sn	0.0126 ^A	0.0127 ^A	NS	NS
Ti	0.0155 ^A	0.0161 ^A	NS	NS
V	0.00449 ^A	0.00452 ^A	NS	NS
Cu	0.0667 ^A	0.0663 ^A	NS	0.20
Mn	0.484 ^B	0.49 ^B	0.30 - 0.80	NS ^D
P	0.008 ^B	0.01 ^B	0.04	0.007
Si	0.636 ^B	0.636 ^B	0.50 - 1.00	NS
C	0.148 ^C	0.145 ^C	0.10 - 0.20	0.15
Cr	1.16 ^B	1.16 ^B	1.00 - 1.50	NS
Mo	0.521 ^B	0.519 ^B	0.44 - 0.65	NS
S	0.0072 ^C	0.0081 ^C	0.04	0.007
X-Bar	14.0	16.0		< 15

^A ICP MS measurement; ^B ICP OES measurement; ^C Leco measurement;

^D NS: Not Specified in API RP934-C, but in the applicable ASME specification.

² API RP 934-C "Materials and Fabrication of 1 1/4Cr-1/2Mo Steel Heavy Wall Pressure Vessels for High-pressure Hydrogen Service Operating at or below 825 degrees F (441 degrees C)."

Table 2 – Top and Bottom Channel Chemical Analysis Results

Element	Top Channel (wt%)	Bottom Channel (wt%)	SA 387 Grade 11 Class 2 (wt%)	API RP934-C (wt%)	API TR 934-D ³ and SA 387 Additional Supplementary Requirements
Al	0.0192 ^A	0.018 ^A		NS ^D	
Sb	0.00423 ^A	0.0039 ^A		NS	
As	0.0099 ^A	0.00953 ^A		NS	
B	0.0005 ^A	0.0004 ^A		NS	
Ni	0.101 ^A	0.0914 ^A		0.30	≤0.30
Nb	0.0002 ^A	0.0002 ^A		NS	
Sn	0.0141 ^A	0.0135 ^A		NS	
Ti	0.00229 ^A	0.002 ^A		NS	
V	0.00223 ^A	0.0019 ^A		NS	
Cu	0.15 ^A	0.157 ^A		0.20	≤0.20
Mn	0.564 ^B	0.569 ^B	0.35 – 0.73	NS	
P	0.007 ^B	0.008 ^B	0.035	0.007	
Si	0.47 ^B	0.483 ^B	0.44 -0.86	NS	
C	0.14 ^C	0.158 ^C	0.04 – 0.17	0.15	
Cr	Note E	1.08 ^B	0.94 – 1.56	NS	
Mo	Note E	0.488 ^B	0.40 – 0.70	NS	
S	Note F	0.0037 ^C	0.035	0.007	
X-Bar	15.8	16.3			< 15

^A ICP MS measurement; ^B ICP OES measurement; ^C Leco measurement; ^D NS: Not Specified in API RP934-C, but in the applicable ASME specification.

Table 3 – Top and Bottom Channel to Tubesheet DWM Chemical Analysis Results

Element	Bottom Channel to Tubesheet DWM (wt%)	Top Channel to Tubesheet DWM (wt%)	ASME Section II Part C SFA 5.23, Grade EB2	API RP934-C (wt%)	API TR 934-D and SA 387 Additional Supplementary Requirements
Al	0.0131 ^A	0.0122 ^A		NS ^D	
Sb	0.0007 ^A	0.0012 ^A		NS	
As	0.0028 ^A	0.0036 ^A		NS	
B	0.0004 ^A	0.0009 ^A		NS	
Ni	0.0415 ^A	0.0478 ^A		0.30	≤0.30
Nb	0.0002 ^A	0.0002 ^A		NS	
Sn	0.0026 ^A	0.00349 ^A		NS	
Ti	0.00567 ^A	0.00535 ^A		NS	
V	0.0037 ^A	0.00401 ^A		NS	
Cu	0.111 ^A	0.11 ^A	0.35, max.	0.20	≤0.20
Mn	1.02 ^B	1.02 ^B	0.45 – 1.00	NS	
P	0.01 ^B	0.01 ^B	0.025, max.	0.007	
Si	0.272 ^B	0.296 ^B	0.05 – 0.30	NS	
C	0.085 ^C	0.084 ^C	0.07 – 0.15	0.15	
Cr	1.17 ^B	1.13 ^B	1.00 – 1.75	NS	
Mo	0.512 ^B	0.52 ^B	0.45 – 0.65	NS	
S	0.0042 ^C	0.01 ^C	0.025, max.	0.007	
X-Bar	11.7	12.4			< 15

^A ICP MS measurement; ^B ICP OES measurement; ^C Leco measurement; ^D NS: Not Specified in API RP934-C, but in the applicable ASME specification.

³ API TR 934-D “Technical Report on the Materials and Fabrication Issues of the 11/4CR-1/2Mo and 1Cr-1/2Mo Steel Pressure Vessels.”

Table 4 – Charpy Impact Values

Sample	Location	Results ft-lbf (average)	Fracture Surface Appearance
TW1	DWM next to Top Channel, ID	42, 86, 105 (78)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is very large. • The fracture is not flat.
TC2	Top Channel ID	64, 27, 62 (51)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is large. • The fracture is not flat.
TC3	Top Channel Midwall	64, 23, 41 (43)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is large. • The fracture is not flat.
TT4	Top Tubesheet ID	5, 4, 8 (6)	<ul style="list-style-type: none"> • The fractured area has mostly shiny brittle areas. • Lateral expansion is nil. • The fracture is flat.
TT5	Top Tubesheet Midwall	10, 8, 5 (8)	<ul style="list-style-type: none"> • The fractured area has mostly shiny brittle areas. • Lateral expansion is nil. • The fracture is flat.
BC6	DWM next to Bottom Channel, ID	55, 75, 91 (74)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is very large. • The fracture is not flat.
BW7	DWM Bottom Tubesheet Midwall	32, 28, 107 (56)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is very large. • The fracture is not flat.
BC8	Bottom Channel Midwall	78, 46, 29 (51)	<ul style="list-style-type: none"> • The fractured area has many dull grey colored areas and some shiny brittle areas. • Lateral expansion is large. • The fracture is not flat.
BT9	Bottom Tubesheet ID	6, 7, 5 (6)	<ul style="list-style-type: none"> • The fractured area is mostly shiny brittle areas. • Lateral expansion is nil. • The fracture is flat.
BT10	Bottom Tubesheet Midwall	7, 5, 5 (6)	<ul style="list-style-type: none"> • The fractured area is mostly shiny brittle areas. • Lateral expansion is nil. • The fracture is flat.

API RP934-C recommends:

- A minimum CVN impact average at 0 °F for three specimens of 40 ft-lbs.
- A 20 ft-lbs minimum for a single specimen.
- Percentage shear fractures that should meet 25 % minimum.

8. Top Channel to Tubesheet Butt Weld Failure Summary

The transverse cracks in the top channel to tubesheet butt weld are likely associated with creep and temper embrittlement. This conclusion was drawn because the cracks are:

- Interdendritic through the DWM and intergranular through the Heat Affected Zone (HAZ) and Parent Metal (PM) as described in API TR 934-D.
- Located on the top channel side of the weld where the top channel has a composition that makes it susceptible to embrittlement. The top and bottom channels do not meet the API TR 934-D recommended chemical composition range for the X-bar.
- Located only in the top channel Inside Diameter (ID) HAZ

surfaces which had higher localized hardness values than the bottom channel ID surfaces.

Excessive hardness values contributed to the development of these cracks. This is concluded since:

- The cracks are always located in hardened zones. The hardened zones have hardness values that exceed the 235 HV10 maximum recommended by API RP 934-C.
- 1¼Cr-½Mo steel is prone to developing cracks in this type of service when it has areas of high stress concentration.⁴ The localized hard zones are areas of high stress concentration.
- The bottom channel to tubesheet butt weld hardness values are all below the API RP 934-C maximum recommended value and this weld did not crack.

⁴ James Brennan, Ben Pletcher, Techniques for Joining 1¼Cr-½Mo Steels, Welding Journal, April 2010, p. 46

Table 5 – Vickers HV10/15 Hardness Values

Sample	Top Tubesheet	Top Tubesheet HAZ	Top Tubesheet to Channel DWM	Top Channel HAZ	Top Channel
EM1 immediately next to crack	N/A	N/A	253, 257	268, 267, 241, 240, 214, 208	181, 183
EM1 0.5" away from crack	N/A	N/A	240, 244	236, 232	175, 177
Sample	Top Tubesheet	Top Tubesheet HAZ	Top Tubesheet to Channel DWM	Top Channel HAZ	Top Channel
TC1	N/A	N/A	243, 246, 254, 246, 236, 249, 251, 260, 231 (OD) 228, 224, 221, 225, 230, 259, 241, 233, 274, 241 (ID)	205, 224, 234 (OD) 234, 224, 254 (ID)	177 (OD) 165, 168, 173 212, 183, 192 (midwall) 168, 168 177 (ID)
Sample	Bottom Tubesheet	Bottom Tubesheet HAZ	Bottom Tubesheet to Channel DWM	Bottom Channel HAZ	Bottom Channel
BC1	171, 167 (OD) 173 162, 161, 164 (midwall) 158 177 173 184, 190 (ID)	183 (OD) 188, 212, 194, 198, 197, 201 (midwall) 201 229 223 (ID)	202, 224 218 218, 230, 211, 201 227 223, 226	206 (OD) 201, 210 219, 220, 221, 217 (midwall) 225 209 210 (ID)	163, 166 (OD) 164 167, 157, 161 (midwall) 161 158 163 (ID)
SA 387 Grade 11 Class 2 (Channel Specification): Hardness 150 – 210 HV (by conversion from specified tensile strength requirements)					
SA 182 F11 Class 2 (Tubesheet Specification): 143 – 207 HV					
API RP 934-C recommends:					
<ul style="list-style-type: none"> • The hardness should not exceed 235 HV10 in tested weld coupons. • Hardness values should not exceed 225 HBW in production welds. 					



Figure 23. Top channel quarter section, top view

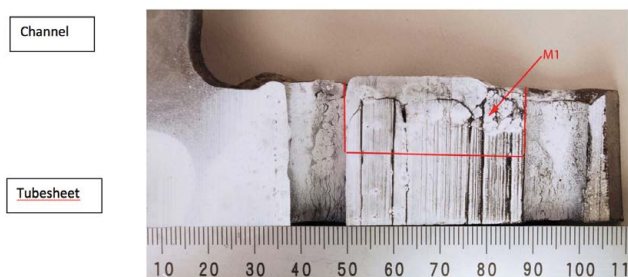


Figure 24. CM1 – Location, Top Tube Sheet (Near Top Channel).

Table 6 – Micro Hardness Values – Top and Bottom Channel HAZ

Portion	Top Channel HAZ ID HV	Top Channel HAZ OD HV
Top Channel Portion 1	295, 218, 230, 287, 244, 225, 255	183, 156, 154, 160, 156, 148, 156
Top Channel Portion 2	257, 273, 248, 278, 258, 241, 235, 230	200, 208, 207, 211, 213, 204, 206
Top Channel Portion 3	253, 267, 253, 270, 247, 250, 260	192, 185, 208, 196, 199, 181, 208
Bottom Channel Portion 1	211, 206, 205, 201	191, 192, 196, 199, 206, 204
Bottom Channel Portion 2	192, 189, 194, 185, 192	189, 199, 206, 217, 190, 202

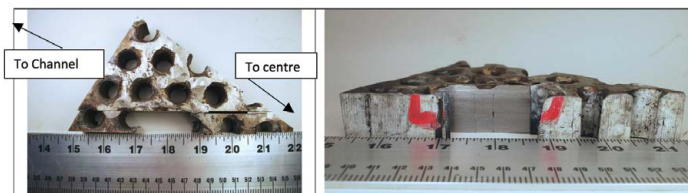


Figure 25. CM2 Location, Top Tubesheet (Near Center), after sample removal.

Some anomalies occurred during the PWHT of the top channel to top tubesheet butt weld. This conclusion was made since only the top channel ID side HAZ has portable test hardness values exceeding 235 HV. The bottom channel HAZ ID and OD do not have hardness values exceeding 235 HV. The top channel HAZ OD does not have hardness values exceeding 235 HV.

The excessive hardness values are not a consequence of prolonged exposure to high temperature service. This type of exposure would tend to soften the material.

PART B: CRACKS BETWEEN THE TOP TUBESHEET AND THE TUBES

1. Visual and Magnetic Particle Inspections (MPI)

The surfaces exposed by longitudinal cuts on the top channel tubesheet were inspected with color contrast MPI. Some of the welds between the tubes and the top tubesheet had MPI crack-like indications (See **Figures 23 and 24**).

2. Metallographic Examination

Two metallographic samples were prepared:

- Sample CM1 from a top tubesheet to tube weld, near the channel ID (See **Figure 24**).
- Sample CM2 from a top tubesheet to tube weld near the tubesheet center (See **Figure 25**).

Sample CM1 has DWM from original fabrication referred to as “Old DWM.” The samples also have “New DWM” deposited in 2012 during attempts to repair the tube to tubesheet leaks (See **Figure 26**). The Old DWM has multiple mainly parallel intergranular/interdendritic cracks (See **Figures 27 and 28**). The cracks are typically parallel to the intersection between the tube and the tubesheet. The cracks arrest at the fusion line between the Old DWM and the New DWM.

The Old DWM microstructure comprises ferrite and tempered martensite and/or bainite. The New DWM was not etched by 2% Nital. Reportedly, it was a high nickel electrode consistent with the metallographic appearance of the deposited weld metal. Sample CM2 has multiple mainly parallel intergranular/interdendritic cracks in the Old DWM. The cracks are typically parallel to the intersection between the tube and the tubesheet. They arrest at the fusion line between the Old DWM and the New DWM.

The Old DWM microstructure comprises ferrite and tempered martensite and/or bainite. The New DWM was not etched by 2% Nital. Reportedly, it was a high nickel electrode consistent with the metallographic appearance of the deposited weld metal (See **Figures 29 – 32**).

3. Laboratory Hardness Measurements

The HV_{1/15} hardness values were measured:

- Sample CM1 had the following values: 242, 260, 258, 258, 254 and 278.
- Sample CM2 had the following values: 269, 308, 289, 269, 271, 269, 313, 301, 301, 314, 300.

All the values exceed the API RP 934-C recommended maximum hardness.

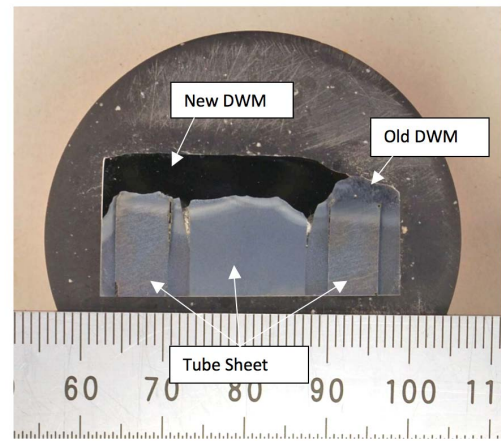


Figure 26. CM1 Top Tube sheet (Near Channel) Overview.

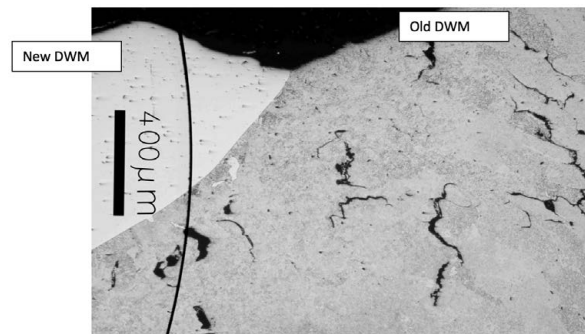


Figure 27. CM1 Top Tube Sheet (Near Channel) Cracking in Old DWM, 2% Nital Etch.

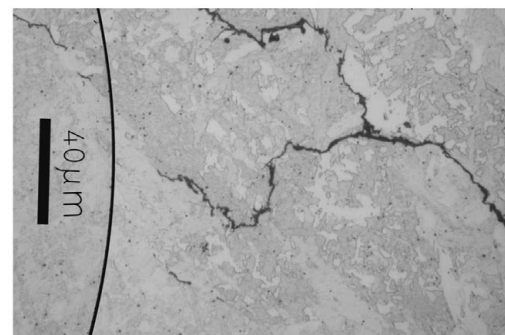


Figure 28. CM1 Top Tube Sheet (Near Channel) Cracking in Old DWM, 2% Nital Etch.

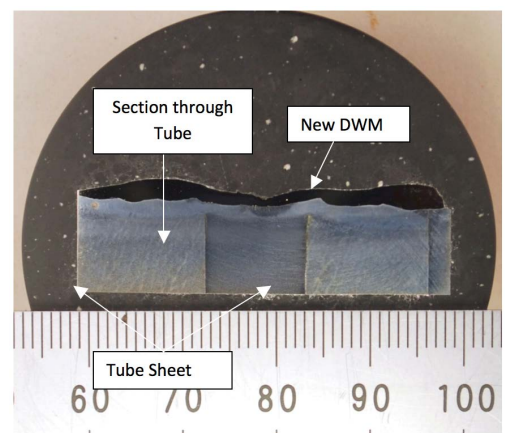


Figure 29. CM2 Top Tube Sheet (Near Centre) Overview.

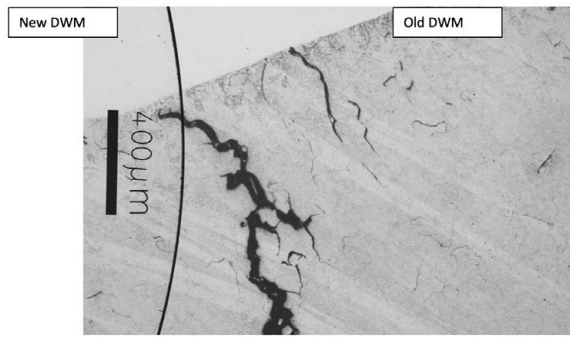


Figure 30. CM2 Top Tube Sheet (Near Centre) Cracking in Old DWM, 2% Nital Etch.

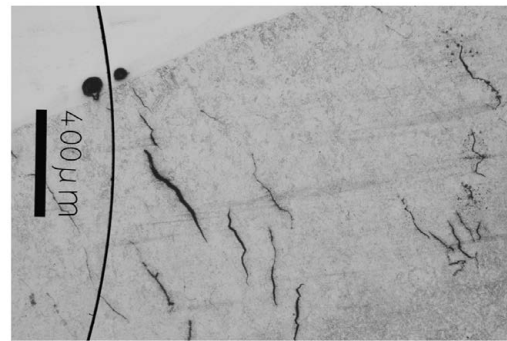


Figure 31. CM2 Top Tube Sheet (Near Centre) Cracking in Old DWM, Porosity in New DWM, 2% Nital Etch.

4. Failure Summary of Cracks between the Top Tubesheet and the Tubes

These cracks are likely associated with creep and temper embrittlement since they are:

- Interdendritic/intergranular as reported for creep cracks.⁵
- Typically parallel to the intersection between the tube and the tubesheet. This is an area subjected to high welding related stresses where creep damage can develop.
- Only present on the top tubesheet welds. They are not present on the bottom tubesheet to tube welds which operated at temperatures lower than the top sections.

According to API TR 934-D, “creep embrittlement is meant to describe cracking that has usually occurred after long term service at the weld HAZ after the weld HAZ has lost ductility and creep strain tolerance... The actual property change probably occurs during fabrication ...and creep crack propagation is occurring during service.”

5. Recommendations

- The PWHT of replacement vessels should be monitored rigorously. The ID PWHT temperatures require monitoring.
- The PWHT of the shell joints and the tubesheet to tube welds require monitoring.
- Verify that the process side heat affected zones meet the hardness requirements specified in API RP 934-C.

*This article is an adaptation of a technical presentation given at the 18th Annual IPEIA Conference. ■



Figure 32. CM2 Top Tube Sheet (Near Channel) Cracking in Old DWM, 2% Nital Etch.

⁵ W. T. Becker (Author), R. J. Shipley, ASM Handbook: Volume 11: Failure Analysis and Prevention, Copyright 1986