MSi Investigative Summary

BACKGROUND

Two (2) welded stainless steel tube samples removed from a Bottom Circulation (BC) Heater #1 and identified as "failed" and "intact" were submitted to our laboratory for a metallurgical investigation. Reportedly, the failed tube developed cracking after being in service for ~6 months. The intact tube was supplied as a reference. During normal operation the OD surfaces of the tubes had been exposed to saturated steam at ~377°F/190 psia, while the ID surfaces were exposed to a mixture of white and black liquor at ~290°F/280 psia. It was also reported that the BC Heater #1 experienced multiple tube failures, which had occurred roughly at the same location.

The material processing of the welded tubes included bright solution anneal at 1900° F min., followed by quenching in an inert gas atmosphere. No further background information was available. We were requested to determine the failure mechanism responsible for the cracking of the affected tube and identify any detrimental material processing or welding-related conditions that could have contributed to the failure. ***Note:*** *The unaffected, intact tube was provided for mechanical testing.*

SAMPLE IDENTIFICATION

Part Description	Size	Specified Grade	No. of Samples
Welded Tube	1.5" OD x .065 wall	ASTM A249/A (SA249/A) TP304/304L	2

PERFORMED TESTING

Visual and Stereoscopic Examination
Metallographic (Microstructural) Examination
Hardness Testing
Tensile Testing
Chemical Analysis

CONCLUSIONS

1. Based upon the performed tests and examinations, it is our opinion that the tube failure in the BC Heater #1 was caused by a transgranular stress-corrosion cracking (SCC) attack. The reported localized nature of the cracking was attributed to exposure of the tube metal to localized impingement by steam and to corrosive species present in the steam.

2. The SCC attack originated on the steam side of the tube (the OD surface) and propagated inwards. No detectable SCC was observed on the liquor side of the tube (the ID surface).

3. The phenomenon of stress-corrosion cracking (SCC) occurs in metals when three conditions are met simultaneously. These conditions are: (1) corrosive environment, (2) presence of residual, or service-applied tensile stresses in the material, and (3) susceptible material. Removal of one of these conditions will prevent SCC from occurring.

4. Chemical testing confirmed that the failed tube met the composition requirements of ASTM A249/A (SA249/A) for TP304/304L austenitic stainless steel. This type of material is known to be susceptible to SCC failures when exposed to chlorides, bleach or hydrated liquor salts. Identification of the corrosive species directly responsible for the attack could not be performed, since the OD surface of the affected tube had been mechanically polished by maintenance personnel.

5. Localized impingement of the tube surfaces by the steam flow added to the stress level in one area on the tube bundle and accelerated the SCC attack within the affected site. Such localized condition could have been created by insufficient baffling or by damage to the baffle plate.

6. Metallographic examination of the tubing material revealed a normal microstructure with no evidence of sensitization, pre-existing steel defects, excessive nonmetallic inclusions, or any other detrimental material conditions that could have contributed to the failure.

7. Hardness and tensile testing confirmed that the tubing material met the requirements of ASTM A249/A (SA249/A) for TP304/304L austenitic stainless steel.

8. To prevent similar future BC heater tubing failures, we respectfully recommend that service exposure of the 300-series stainless steel tubes to chlorides, bleach or hydrated liquor salts be avoided. Another alternative is to review and improve the baffling of the tube bundle. If service conditions would require continual or intermittent exposure of the tubing to a corrodent-bearing environment, then an upgrade to a more SCC-resistant material may be warranted. The examples include, but are not limited to, ferritic stainless steels 29-4C and Sea-Cure. Duplex stainless steels with 10-28% Cr and 4-8% Ni can also be taken into consideration as alternative materials. Although duplex stainless steels are susceptible to chloride-induced SCC, the stress level that triggers the attack in duplex steels is generally much higher than that for austenitic stainless steels. ***Note****: any design changes (including material upgrades) must be approved by the original equipment manufacturer.*

SUMMARY of TEST RESULTS

Visual and Stereoscopic Examination

1. Visual and stereoscopic examination of the tubing samples from the BC Heater #1 revealed dark-gray discoloration on the intact tube and evidence of surface polishing on the failed tube (see Photo 1).

2. When viewed at a higher magnification, the OD surface on the failed tube exhibited a network of transverse and oblique cracking (see Photo 2).

3. The failed tube sample was used for metallographic examination, chemical analysis and hardness testing, described in the following sections of this report.

4. The intact tube sample was reserved for mechanical testing described in the following sections of this report.

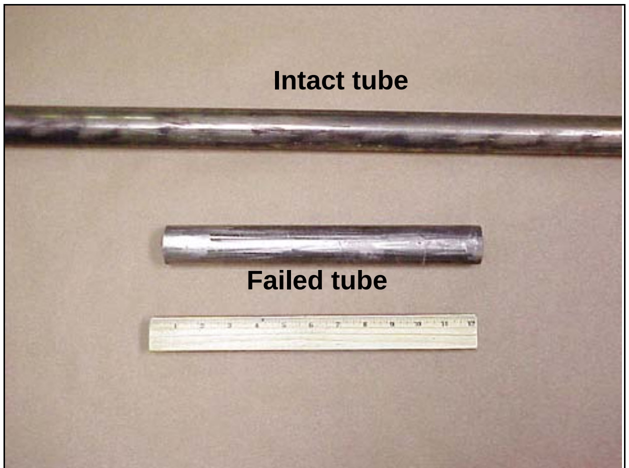

Photo 1: Tube samples from the BC Heater #1, as received.

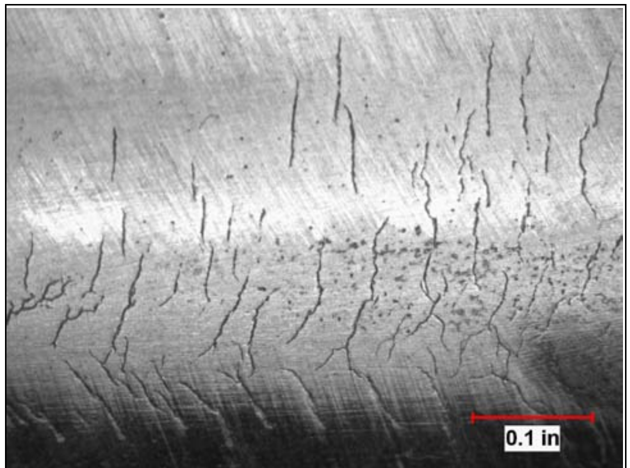

Photo 2: A network of fine cracking on the OD surface of the failed tube (a close-up view).

Metallographic Examination

1. Transverse and longitudinal sections removed from the failed tube revealed multiple branching cracks propagating from the OD surface (see Photos 3 – 6 on the following page). Through-wall crack propagation in the examined areas was estimated at ~85%.

2. The mode of cracking was identified primarily as transgranular with occasional evidence of intergranular propagation. The cracks appeared to be uniformly distributed throughout the welded areas and the areas away from the weld. The observed cracking morphology is characteristic of a stress-corrosion cracking (SCC) attack in 300-series stainless steel.

3. SCC failures in 300-series stainless steels occur under exposure to chlorides, bleach or hydrated liquor salts. Identification of the corrosive species directly responsible for the attack could not be performed, since the OD surface of the affected tube had been

mechanically polished by maintenance personnel.

Metallographic Examination (cont.)

4. The tubing material revealed a normal equiaxed austenitic microstructure typical of Type 304/304L stainless steel in an annealed condition. The metal showed no evidence of sensitization, pre-existing steel defects, excessive nonmetallic inclusions, or any other detrimental material conditions that could have contributed to the failure.

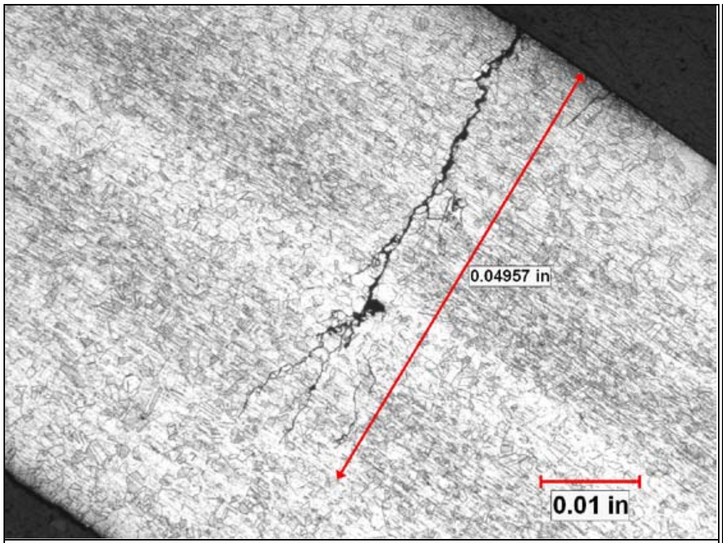

Photo 3: Mag: 100X Etchant: 10% oxalic acid (electrolytical). Transverse tube section, SCC cracking away from the weld.

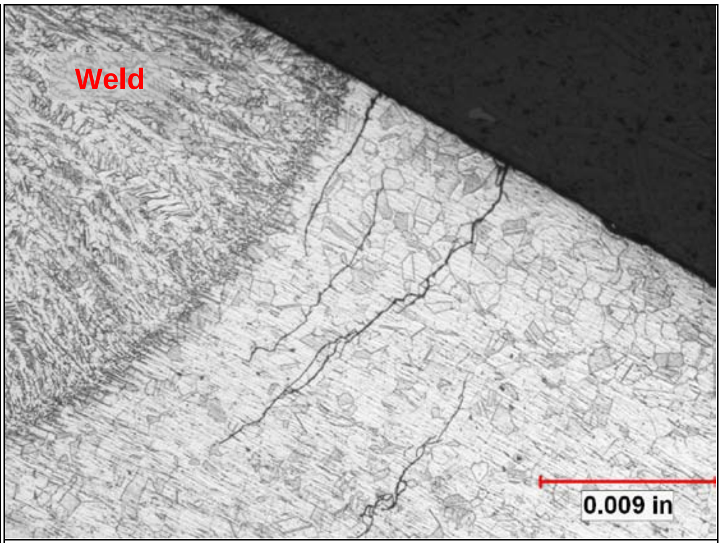

Photo 4: Mag: 100X Etchant: 10% oxalic acid (electrolytical). Transverse tube section, SCC cracking near the weld.

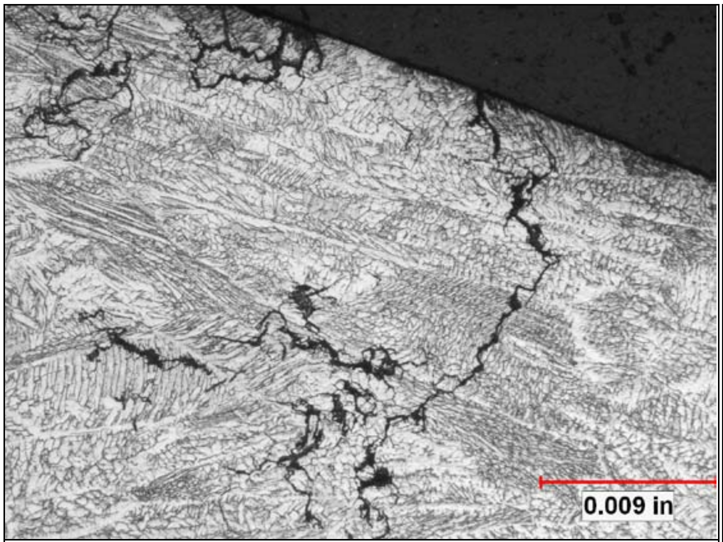

Photo 5: Mag: 100X Etchant: 10% oxalic acid (electrolytical). Transverse tube section, SCC cracking in the weld.

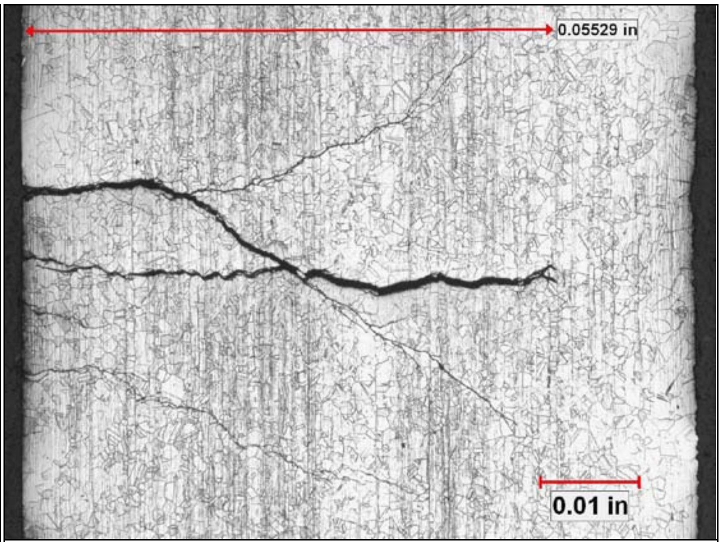

Photo 6: Mag: 100X Etchant: 10% oxalic acid (electrolytical). Longitudinal tube section, SCC cracking away from the weld.

Hardness Testing

1. Hardness testing results confirmed that the tubing material met the requirements of ASTM A249/A (SA249/A) for TP304/304L austenitic stainless steel. The obtained value of 84 HRBW is typical of an annealed condition.

2. The results are shown in Table 1 attached.

Tensile Testing

1. Tensile testing confirmed that the tubing material met the tensile requirements of ASTM A249/A (SA249/A) for TP304/304L austenitic stainless steel.

2. The results are shown in Table 2 attached.

Chemical Testing

1. Chemical testing confirmed that the tubing material met the composition requirements of ASTM A249/A (SA249/A) for TP304/304L austenitic stainless steel.

2. The results are shown in Table 3 attached.

Respectfully submitted,
MSi ***Testing & Engineering, Inc.***

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Table 1 – Hardness Testing*

Hardness, HRBW		
84	84	84

* Testing performed in accordance with ASTM E18.

Table 2 – Tensile Testing*

	Intact Tube	A249/A limits for TP304/304L (min.)
Tensile Strength, psi	90,700	75,000/70,000
Yield Strength, psi (.2% offset)	46,900	30,000/25,000
% Elongation in 2”	56	35/35

* Testing performed in accordance with ASTM E8-04.

Table 3 – Chemical Testing*

Element	Failed Tube
Carbon	.025%
Manganese	1.53
Phosphorus	.032
Sulfur	.014
Silicon	.46
Nickel	8.18
Chromium	18.19
Molybdenum	.37
Copper	.40
Nitrogen	.07

* Testing performed in accordance with ASTM E1086.