Appendix E

Lab Analysis Report

Fernie Curling Rink Refrigeration

System Component Failure Evaluation

Acuren Group Inc.

Acuren Group Inc.
12271 Horseshoe Way
Richmond, BC, Canada V7A 4V4
www.acuren.com

Phone: 604.275.3800
Fax: 604.274.7235

A Higher Level of Reliability

FERNIE CURLING RINK REFRIGERATION SYSTEM COMPONENT FAILURE EVALUATION

Prepared for:

WorkSafeBC
PO Box 5350 Stn. Terminal
Vancouver, B.C.
V6B 5L5

Attention: Mr. Steven Liu

Technical Safety BC
Suite 600-2889 East 12th Avenue
Vancouver, B.C.
V5M 4T5

Attention: Mr. David Clancy

File Number: A18605-14011
Date: July 19, 2018

Robert Milne, P.Eng.
Email: bmile@acuren.com
Direct: 604-448-3856

TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY

An ammonia release occurred at the Fernie Memorial Arena. Components of the refrigeration system, including the curling rink brine chiller, brine pipe couplings and pipe segments, brine and ammonia system valves, and pressure relief valves were brought to Acuren for testing and analysis to determine aspects of their condition and potential failure modes.

Examination of the chiller unit determined that a hole was present in a steel chiller tube at row 2 - tube 3. In the same longitudinal line additional penetrations were also noted which appear to be through wall and may have allowed product leaking. This was the only location where a leaking defect was found in the chiller tube bundle. The hole was caused by pitting corrosion originating at a fusion defect in the ERW welded carbon steel chiller tube (ASTM A214 - Standard Specification for Electric-Resistance-Welded Carbon Steel Heat-Exchanger and Condenser Tubes). A line of similar fusion defects was found adjacent to the leaking defect that indicated that the tube was manufactured using a low frequency ERW welding system (or a defective welding unit producing similar results). The fusion defects caused accelerated pitting in the brine environment and led to the observed through-wall defect. No evidence of stress corrosion cracking or microbiological corrosion was found with the steel chiller tubes.

Chiller tube testing by eddy current testing (RFT) proved to be ineffective due to the deteriorated condition of the tubes. Ultrasonic testing of the ammonia vessel walls did not discover any significant metal loss due to corrosion.

Examination of the selected tube samples that were removed from the bundle and cross-sectioned revealed considerable pitting corrosion and fusion line defects with all of the tubes. There was a general trend toward increased amounts of both shallow and deep pitting near the top of the bundle. Some amount of the observed corrosion likely occurred after the refrigeration system failure event took place and the bundle was exposed to the atmosphere.

Dye penetrant testing of the tube – tubesheet rolled joints in the chiller did not reveal any leaking defects. Tubesheet to ammonia vessel welds were also found to be free of leaks. Examination of supplied brine reports indicate that an internal ammonia leak to the brine side of the chiller first occurred prior to May 11, 2017.

Testing of valves and couplers removed from the site revealed extensive corrosion damage, plugging and partial plugging of pipe nipples with iron oxide, calcium chloride, and zinc chloride. Much of the corrosion deposits and brine salts observed in the valves and fittings likely occurred after the failure event when the system was exposed to the atmosphere. The position of the submitted valves was determined through radiographic examination.

The Pressure Relief Valve (PRV) mounted in parallel to the PRV in operation at the time of the event was found to be working correctly. No evidence of brine salts was found in the dismantled PRV operating at the time of the event.

Testing of an exemplar [redacted] coupling determined that it could sustain a pressure of between 30 psi and 24 psi without slipping apart in the axial direction. The application of oil to the bolts had a detrimental effect on the installation of the coupling, since the rubber gasket was deformed by the excessive bolt tension generated.

2.0 INTRODUCTION

An ammonia release occurred at the Fernie Memorial Arena. Components of the refrigeration system, including the curling rink brine chiller, brine pipe couplings and pipe segments, brine and ammonia system valves, and pressure relief valves were brought to the

Acuren Laboratory Facility for testing and analysis to determine aspects of their condition and potential failure modes.

A comprehensive study of the Fernie Curling Rink refrigeration system failure has been undertaken by WorkSafeBC and Technical Safety BC under the direction of their lead investigators, Mr. Nigel Corduff and Mr. Jeff Coleman. Acuren Group Inc. was asked to assist the investigators with respect to laboratory analysis of refrigeration system components involved in the incident.

3.0 COMPONENT DELIVERY TO THE ACUREN FACILITY

The failure investigations were initiated by WorkSafeBC and Technical Safety BC at the Fernie Site immediately after the event took place (October 17, 2017). The refrigeration equipment of interest was documented at the site and placed in two wooden crates several weeks later for shipment to the Acuren Richmond laboratory facility.

The chiller assembly was purged with nitrogen and placed under an internal pressure of 3 psi (nitrogen) after site examination was complete. The two crates were shipped by Badger Delivery (Calgary) and arrived at the Acuren Facility on the evening of 27 January, 2018. The crates were placed in a fenced and locked yard at the Acuren Facility. The transfer of materials was witnessed by WorkSafeBC investigator Mr. Mike Stewart. A chain of custody procedure was followed thereafter.

The larger crate contained the chiller and surge tank. Pressure gauges on the shell side and tube side of the chiller indicated that the nitrogen pressure had dropped during shipping and storage; however, a small amount of positive pressure still existed on both sides of the chiller (< 2 psi).

The second crate contained valve and piping components that were placed in individual plastic containers sealed with "evidence" tape. The "evidence" tape was intact with all of the sample component boxes. The sealed boxes were moved inside the Acuren facility and stored in a fenced and locked compound within the building. The components were only removed from the compound during times of inspection at which point the evidence tape was cut from the boxes and the components inside were removed for inspection on a controlled bench. The components within each box were at all times stored (at times of no inspection) within their labelled plastic container and inside the compound.

4.0 LABORATORY EXAMINATION PROTOCOL

4.1 Qualifications of the Author

Acuren operates a full service Metallurgical Laboratory in Richmond, British Columbia. The laboratory is qualified to ISO 9001 and ISO 17025 (Failure Analysis) quality programs. The laboratory utilizes state-of-the-art equipment to perform metallurgical analysis. Some of the methods utilized in the chiller analysis work included Scanning Electron Microscopy (SEM) with attached energy dispersive X-ray analysis capability (EDXA), optical emission spectroscopy (OES), metallography, hardness testing, pressure testing, and radiography. All of these techniques are performed in-house on a routine basis.

The chiller analysis was performed under the direct supervision of Robert Milne, P.Eng. (CV attached; Appendix C). The author has 40 years of experience in failure analysis work and has managed the Acuren Failure Analysis Laboratory for the past 15 years. Approximately 1400 failure analyses of varying complexity are performed by the Acuren Laboratory each year. Many of the projects completed have involved pressure vessels, heat exchangers, and corrosion of all types.

4.2 Personnel Attending Examinations

Initial examination of the refrigeration system components was performed in the presence of interested parties. The following personnel attended laboratory examinations and testing during the week of 23 - 27 April, 2018:

1. Nigel Corduff – WorkSafeBC Lead Investigator
2. Dean Albrecht, P.Eng. – WorkSafeBC Senior Engineer
3. Tom Ng, P. Eng. – Technical Safety BC Senior Engineer
4. Jeff Coleman, P.Eng. – Technical Safety B.C. Director of Risk and Safety
5. Jarrod Babiuk – Charles Taylor Adjusting
6. Ryan Hazlett, P.Eng. – CEP-Sintra
7. Ron Strong, P. Eng. – Strong Refrigeration Consultants Inc.
8. Wendall Marshal – Strong Refrigeration Consultants Inc.
9. Dan Welsh – Barantas Inc.
10. Dan Blosdale, P.Eng. – HT Industrial
11. Michael Stewart – WorkSafeBC Investigation Officer
12. John Toplis – Refrigeration Components Canada Ltd.
13. Serge Gosselin – Fernie Ice Rink Operator
14. Gilles Amirault – Envista Forensic Engineering) Calgary
15. Mathew Powell – Cyrus Shank
16. John Ryan – Parker Hannifin
17. Ali Fayazbakhsh – Envista Forensic Engineering Richmond
18. Steve M. Mesner – Parker Hannifin –
19. Adam Howden-Duke – Guild Yule LLP
20. Adam Farnham – Unified Investigation & Sciences, Inc.
21. Jonathan Reinheimer – Robar

4.3 Requested Examinations and Tests

The requested examinations and tests were performed under the direction of WorkSafeBC lead investigator Mr. Nigel Corduff, WorkSafeBC Senior Engineer Mr. Dean Albrecht, P.Eng. and Technical Safety BC Senior Engineer Mr. Tom Ng, P.Eng. The examinations and tests required were requested in writing by Mr. Steven Liu (WorkSafeBC Council).

4.4 Testing Process and Responsibilities

The testing schedule that was initially proposed and the results presented in Section 5.0 do not necessarily follow the sequence of inspections. Evaluations of each component and the inspection techniques performed were conducted to optimize lab time efficiency.

All testing and reporting were done under the direct supervision of Robert Milne, P.Eng.

5.0 TEST RESULTS

5.1 Quarter Turn Ball Valves; WorkSafeBC Items X, A3, A6, A2 and Z

5.1.1 Valve X

An overall view of Valve X is shown in Figure 1. The valve is connected to galvanized steel nipples on each end. The two ends of the valve piping are plugged or partially plugged with corrosion deposits and salts. The nipple marked "top" is completely plugged at the end as shown in Figure 2. The end marked "bot" is severely corroded and is partially plugged with debris as shown in Figure 3.

Radiographs of Valve X and attached nipples are shown in Figure 4. The two views are shot 90° apart. The radiographs show that Valve X is in the fully closed position. The light areas on the right-side nipple ("top") show that the pipe is mostly plugged along the length of the nipple. The small areas (dark) within the nipple are void areas that are not plugged. The left side nipple ("bot") is only partially plugged along its entire length.

The material plugged in the valve was analysed using an energy dispersive x-ray system attached to a Hitachi S3500 Scanning Electron Microscope (SEM). The material plugging the "top" nipple is a mixture of calcium chloride, zinc chloride, and iron oxide (Figure 5).

Some or all of the material plugging the valve may have formed after the system failure occurred and brine remained in the piping. Exposure to the atmosphere and drying action would have allowed compounds to precipitate from the residual brine solution in the pipes.

5.1.2 Valve A3

An overall view of Valve A3 is shown in Figure 6. The valve handle is in the fully closed position. The valve is connected to galvanized nipples on both ends. The nipples are relatively free of salt precipitates, but corrosion products coat the inside of the pipe nipples (Figure 7).

Radiographs of Valve A3 in two different views 90° apart show that the valve is completely closed as indicated by the handle position (Figure 8). Plugging is not evident in this valve and the associated nipples.

Some or all of the corrosion observed in the nipple interiors may have occurred after the system failure took place. It is expected that this valve would operate with full flow capability in the open position.

5.1.3 Valve A6

An overall view of Valve A6 is shown in Figure 9. The valve handle is in the fully open position. The valve is connected to galvanized nipples on both ends. The nipples are relatively free of salt precipitates, but corrosion products coat the inside of the pipe nipples (Figure 10).

Radiographs of Valve A6 in two different views 90° apart are shown in Figure 11. The valve is completely open as indicated by the handle position. Plugging is not evident in this valve and the associated nipples.

Some or all of the corrosion observed in the nipple interiors may have occurred after the system failure took place. It is expected that this valve would operate with full flow capability in the open position.

5.1.4 Valve A2

Overall views of Valve A2 and associated piping are shown in Figures 12 – 15. The valve handle is in the fully open position. The valve is connected to galvanized nipples and a "tee" fitting. Corrosion products are present all along the piping, but very little evidence of brine salts is present.

Radiographs of Valve A2 as received in two different views are shown in Figure 16. The valve is in the fully open position which matches the valve handle position. Corrosion products are more prevalent on the nipple which does not contain the "tee", but full flow would be expected with the valve in the open position.

The valve handle was moved to the fully closed position and re-radiographed in this position. The valve operated normally.

Some or all of the corrosion products observed in the valve A2 piping may have occurred after the system failure took place.

5.1.5 Valve Z

An overall view of Valve Z is shown in Figure 18. The valve handle is mostly in the closed position but is cocked by approximately 10° toward the open position. The nipples on each end of the valve contained large volumes of white precipitates and smaller amounts of red-brown iron oxide (Figures 19 and 20). The nipples appeared to be partially plugged along their entire lengths.

Radiographic images of Valve Z taken 90°apart are shown in Figure 21. Debris can be seen along the length of both nipples.

The valve with attached nipples was mounted in the vertical position (N side up) and filled with water. The water was left for a period of 15 minutes and checked for leakage (Figure 22). No leakage was found. The valve was then dismantled and found to be completely plugged with salt and corrosion products (Figure 23).

It is probable that the white material found in and around the valve components precipitated from residual brine remaining when the pipes where drained. The operating condition of the valve with the handle cocked 10° could not be determined, since the amount of debris present in the valve and piping prior to the event is not known.

5.2 Quarter Turn Ball Valve; WorkSafeBC Label A10

The quarter turn ball valve was installed into a steel elbow. The elbow was severely corroded both internally and externally (Figure 24). The exposed ball surface contained corrosion products as shown in Figures 25 and 26. The valve handle was missing and had likely broken off at some earlier time.

The surface of the valve body was cleaned with a wire brush to reveal the manufacturer's markings. The markings are shown in Figures 27 and 28:

TOYO ½
600 WOG

Radiographs of the valve taken 90° apart are shown in Figure 29. The valve is in the closed position and appears fully functional. The normal operating position of the valve appears to be the closed position as found, since the lack of a handle and corrosion markings on the ball surface indicated it had not been operated recently.

5.3 Gate Valve; WorkSafeBC Label Y

An overall view of gate valve Y is shown in Figures 30. The valve is attached to galvanized nipples with a reducer on one of the nipple ends. Severe corrosion damage on the nipple end without a reducer had consumed the nipple threads (Figure 31).

A radiograph of Valve Y (Figure 32) revealed that the valve gate is in the fully open position. Attempts to move the gate were unsuccessful. The valve was taken apart to determine why it would not move. The gate stem area contained greenish blue corrosion products and had fractured (Figure 33).

The corroded nipple was removed from the valve to reveal the valve interior. Both blue and red-brown corrosion products are present in the gate cavity (Figure 34). Flow would have been impeded through both the gate valve body and nipples due to the presence of corrosion products.

5.4 Solenoid Valve, Arena Chiller Ammonia Feed Valve; WorkSafeBC Label B26

An overall view of the B-26 solenoid valve is shown in Figure 35. The valve is a Parker unit (Model S4A, Serial No. 11-2016). The stem position indicated that the valve was in the manually opened position. The unit was attached to 90 psi air for leak testing but would not operate electrically (Figure 36). The unit was radiographed to determine the position of the valve gate. The valve stem was determined to be mechanically adjusted to the open position (Figure 37), but the valve was actually closed. The stem was turned mechanically to the closed position but the valve position did not change (Figure 38). The unit was dismantled and the piston was found to be corroded and seized in place (Figure 39). WD 40 penetrating oil was applied and eventually the piston was freed. The observed corrosion was relatively light and it is possible that the observed corrosion occurred after the valve was exposed to the atmosphere.

With the piston free and corrosion products removed from the area of the piston, the valve was operated successfully and held 90 psi air pressure.

5.5 Solenoid Valve, Curling Rink Chiller Ammonia Feed Valve; WorkSafeBC Label B-35

An overall view of the B-35 solenoid valve is shown in Figure 40. The unit is identical to the B-26 unit (Model S4A) with the same serial number (11-2016). The stem position indicated the valve was in the manually opened position.

Radiography confirmed that the valve was in the open position (Figure 41). The unit was connected to 90 psi air and operated electrically. No movement in the valve was noted and air passed freely.

The stem was turned mechanically to the fully automatic and normally closed position and the unit was re-radiographed (Figure 42). No valve movement was noted. The unit was dismantled and relatively severe corrosion was found on the piston (Figure 43). As with solenoid valve B-26, it is possible that the observed corrosion occurred after the event when the valve was exposed to the atmosphere. Attempts to free the piston by soaking in penetrating oil were unsuccessful and further testing was stopped.

5.6 Pressure Relief Valve Assembly for the Curling Rink Chiller; WorkSafeBC Label R8

An overall view of the pressure relief valve assembly labelled R8 is shown in Figure 44. The two PRVs are were not distinctly labelled and were arbitrarily labelled "1" and "2". The valves are connected through nipples and a central gate valve. The gate valve allows either PRV to operate while one valve is being serviced. The "1" valve was operating at the time of the event. The gate valve was checked for leakage with oil and found to be completely closed off to the "2" PVR side.

The PRVs are properly tagged with wire and crimps intact on both units. The valves appear identical but have slightly different CRN numbers (OG9760.5C vs OG9760.5). The following information is present with the valves:

Table 1: Cyrus Shank Valve Identification

ID ITEM	SIDE "1"	SIDE "2"
Type	803	803
Serial number	48008	
Size	½ inch	½ inch
Set Pressure (psi)	150	150
CRN	OG9760.5 C	OG9760.5
Date	03/13/10	12/05/5
Capacity (air)	355 SCF	355 SCF
Capacity (ammonia)	Blank	Blank
Tag dates	Replace by Aug. 2020	Installed Aug. 2015

The valves were radiographed as shown in Figure 45. Both valves appear to be fully intact and in good condition internally. The "1" PVR (operating valve) was dismantled to determine if any dirt or corrosion products might have affected its performance. All of the components appeared very clean and in a serviceable condition. No evidence of calcium chloride (brine deposits) were found within the PRV. The internal components, including springs, seats, and guides, are shown in Figures 46 – 51.

The valve seats were examined with a stereo microscope for evidence of debris on the seats. A small amount of fine debris was found as shown in Figures 52 and 53. The compressed debris indicates that the valve was activated at some time in its life. It is probable that the valve was bench tested when it was first set and debris may have been embedded at that time. It could not be determined if the PRV operated at the time of the event.

The "2" side valve was pop tested with compressed argon as shown in Figure 54. Three separate tests were done with the following results:

1	160 psi
2	155 psi
3	155 psi

The valve appeared to operate as intended with respect to the opening pressure stated on the valve. The valve flow capacity was not checked.

5.7 Two Pieces of Metal Identified as Items 28A and 28B

5.7.1 Piece 28A

Item 28A was found on the inlet side of the chiller between the end dome and the tube sheet with one end sitting within a tube. An overall view of the metal piece is shown in Figure 55. The piece is curved with a radius of approximately 179 mm (7 in) as shown in Figure 56. The surface looks like it was cut from a piece of pipe to fit or shim a joint (or something similar). The material was analysed using Energy-Dispersive X-ray Spectroscopy (EDXA) and found to be a plain carbon steel with a manganese content typical of ASTM A53 grade B pipe. The hardness of the material was HB 110, which corresponds to a tensile strength of approximately 65,000 psi. A wide variety of piping or structural steel materials could meet the chemical and strength values found with the steel piece.

The origin of item 28A could not be identified. The curved shape of the piece creates a projected area greater than that what could fit through a ¾" chiller tube. This means that the piece must have come through a 4" outlet/inlet pipe in order to reach this position within the chiller, or it was inadvertently left in the space during bolt-up of the head.

5.7.2 Piece 28B

Item 28B is a piece of bent wire approximately 8 cm in length (Figure 57). The piece is magnetic and badly corroded. EDXA revealed a chemistry typical of a mild steel with relatively low manganese. The wire may have been a welding consumable from a MIG type welding process.

The wire likely originated outside of the chiller and entered through the 4" inlet or outlet pipe. In its curved condition, it could not have fit through a ¾" chiller tube.

5.8 Ammonia Liquid Level Controls, WorkSafeBC Labels LC-1, LC-2, LC-3 and LC-4

5.8.1 Switch LC-1

An overall view of LC – 1 is shown in Figure 58. The unit was mounted vertically in a vice and activated with olive oil. Olive oil was chosen as the activation liquid since it was safe to use in an open lab and had a specific gravity close to that of ammonia (0.62 liquid NH_3 vs 0.70 olive oil). The switch is labelled type LL. A measurement of 21.5" was made from the bottom of the tank to the top of the switch.

A radiograph of the switch is shown in two views in Figure 59. No anomalies were found within the tank.

The switch was connected to an electrical continuity checker and filled with oil until the switch activated. The switch appeared to operate normally. No leaks or perforations were observed.

5.8.2 Switch LC-2

An overall view of LC – 2 is shown in Figure 60. The switch is labelled type LLSS, which is similar to LC-1 with a different float and a stainless steel tank. A measurement of 22.75" was made from the bottom of the tank to the top of the switch.

Radiographic images of the switch are shown in two views in Figure 61. No anomalies were found within the tank.

The switch contained an anomaly that was not found with other switches. A black zip-tie was found on the bottom shaft, the exact purpose of which is unknown (Figure 62). The position of the zip-tie would have increased the height of the switch assembly. This may have resulted in the switch activating at a higher level than intended by the manufacturer.

The switch was connected to an electrical continuity checker and filled with oil to a level that should have activated the switch. The switch did not activate. No leaks or perforations were observed.

5.8.3 Switch LC-3

An overall view of LC – 3 is shown in Figure 63. The switch is labelled type LL, which is identical to LC-1. A measurement of 21 ⅛" was made from the bottom of the tank to the top of the switch.

A radiograph of the switch is shown in two views in Figure 64. No anomalies were found within the tank.

The switch was connected to an electrical continuity checker and filled with oil. The switch appeared to activate normally. No leaks or perforations were observed.

5.8.4 Switch LC-4

An overall view of LC – 4 is shown in Figure 65. The switch is labelled type LLSS, which is identical to LC-2. A measurement of 22.25" was made from the bottom of the tank to the top of the switch. Although no zip-tie was used to position the switch, the set screw that is normally used to position the switch at a "factory" setting was set to a higher than normal position. The switch would therefore activate at a higher than intended level.

Radiographic images of the switch are shown in two views in Figure 66. No anomalies were found within the tank.

The switch was connected to an electrical continuity checker and filled with oil. The switch appeared to activate normally. No leaks or perforations were observed.

5.9 Horizontal [redacted] Coupling and Associated Outlet Brine Pipe

The [redacted] coupling installed in the 4" brine outlet line separated suddenly on the down – stream side in service. This type of coupling is normally restrained to prevent axial movement caused by internal pressure. It is understood that only one side of the coupling was adequately restrained in service.

5.9.1 Exemplar [redacted] Coupling Tests

An exemplar [redacted] coupling was obtained for pressure testing with new nominal 4" pipe supplied by Technical Safety BC. The [redacted] installation guide specifies an installation torque of 80 ft-lb while maintaining equal bolt extensions at each corner. The [redacted] engineer present during testing stated that installation torque should be 70 ft-lb – 80 ft-lb. Bolt lubrication is not specified. The [redacted] representative present did not think that lubrication would normally be used.

The measured pipe size was 4.52" OD. The rubber gaskets had a hardness of Shore A 45. A calibrated torque wrench was used for the tightening of the bolts dry. The initial test was done without any lubricant on the rubber gasket.

The fitting was installed with the two pipe ends evenly inserted into opposite ends of the coupler. Separation between the two sides was maintained in accordance with AWWA C219 (*Bolted Sleeve-Type Couplings for Plain -End Pipe*). The bolts were torqued to 70 ft-lb with type 403 cast steel retainers maintained perpendicular to the pipe axis. The pipe exit point was marked with green tape (Figure 67). Water pressure was gradually applied with a hand pump until slippage was noted on one end at a pressure of 30.0 psi (Figure 68). The pressure was released suddenly and the pipe was sucked back into its starting position.

The coupling was reassembled using light lubrication (SLIKSTYX) on the bolts and rubber gasket sealing surface. Severe deformation of the rubber gaskets was noted during tightening of the lubricated bolts. It was apparent that bolt lubrication removed a large amount of friction from the bolt threads. The bolt extensions far exceeded the bolt extensions developed during dry bolt tightening. Water pressure was applied to the coupler and slipping began at 25.0 psi but the coupler held at that pressure. The pressure was brought back up to 30 psi and the unit began to pop apart (Figure 69). Pressure dropped back to 24 psi, then the pipe suddenly separated from the coupler.

5.9.2 Separated Horizontal [redacted] Coupler from Curling Rink

An overall view of the horizontal [redacted] coupling after removing the shipping splint holding the assembly in its as-found orientation is shown in Figure 70. The coupler is in relatively good condition externally. The coupling had been painted at some time after the bolts had been tightened.

Radiographs were taken showing two different views of the coupling (Figures 71 and 72). The remaining pipe is inserted past the midpoint by approximately 10 mm. The pipe has been pulled sideways, likely by separation forces, and remains pinned to the side of the coupling body.

The nuts were seized and were cut from the coupling with a zip disc. The unit was pulled apart as shown in Figure 73. The white material found within in the coupling and associated piping was analysed and found to contain calcium chloride with smaller amounts of iron oxide present (Figure 74).

The rubber gaskets appeared to have set and were relatively hard (Shore A 52). Little deformation remained with these gaskets when compared with the deformation produced during tightening of the exemplar gaskets. The gasket ends were relatively flat and had lost some of their resilience (Figures 75 and 76). The fact that the bolts were relatively loose may indicate that the gaskets were never properly compressed.

5.9.3 Outlet Brine Pipe Segment; WorkSafeBC Label 24B

The brine pipe segment which separated from the coupling is shown in Figure 77. The pipe is severely corroded where it entered the coupling. The area beneath the rubber gasket is less corroded where it was inserted into the coupling (Figure 78). The inside surface of the coupling was severely corroded as shown in Figure 79.

The brine pipe was sectioned longitudinally to reveal internal corrosion (Figures 80 and 81). The area containing the worst corrosion was sand blast cleaned to reveal the true nature of the corrosion. Relatively deep pits were found in some areas (Figure 82). The location of the pits in longitudinal strips around the apex of the weld flash area indicates that pitting may have occurred in residual salt solutions after the event took place. Pits up to 0.055" in depth were found in these areas.

The horizontal [redacted] coupling could not be reassembled and pressure tested as requested. The coupling components, including the gaskets and bolts, were in poor condition and would not yield useful results.

5.10 Vertical [redacted] Coupling and Associated Piping

The vertical [redacted] coupling arrived in a foam filled bucket as shown in Figure 83. The piece was radiographed in two directions 90° apart before the foam was removed. The radiographic images are shown in Figures 84and 85. The coupling assembled with the two pipes equally inserted into the coupling body. The centerlines of the two compression ends are roughly parallel to the longitudinal axis of the pipes. The centerline gap is between ½" and ¾", which meets the specification requirements of AWWA C219 (maximum centerline gap 1½").

An overall view of the vertical [redacted] coupling after foam removal is shown in Figure 86. Light external corrosion damage is present on the coupling body. A slight misalignment of one pipe due to mechanical loading is shown in Figure 87. General corrosion is present throughout the vertical piping (Figure 88). The piping had been coated at some time in its life and more severe external corrosion was visible under the rubber gaskets (Figure 89).

Attempts were made to remove the bolts using a calibrated torque wrench. Three of the nuts were relatively loose and turned at less than 30 ft-lb (nuts spun forward below the minimum 30 ft-lb setting on calibrated torque wrench). One nut was frozen in place by paint and corrosion products and was cut from the coupling with a zip disc (Figure 90). The rubber gaskets were in a similar condition as was found with the horizontal coupling. The rubber appeared to have lost some of is resilience and had a measured hardness of Shore A 52.

Due to the relatively poor condition of the rubber gaskets and the piping surfaces, reassembly and pressure testing of the Vertical [redacted] coupling was not done.

5.11 Curling Rink Chiller and Associated Surge Tank; WorkSafeBC Label HX-2

At the incident site, chiller heads were removed to access the steel tubes. The shell side was pressurized with 2 psi nitrogen and ultrasonic listening devices were used to identify tube leaks. This technique is minimally invasive as it avoids any destructive testing and limits compromising the metallurgical evidence (i.e. corrosion deposits and product remnants). At least one tube leak was identified by this method.

5.11.1 Chiller As-Received

The chiller with attached surge tank is shown as - received in Figure 91. The unit name plate is shown in Figure 92. The unit is a Chil-Con product built in Brantford Ontario. The chiller has model number FA-12120-200 C-19963 and was built in 1986. The CRN number is F2043.524031. Positive nitrogen pressure (Figures 93 and 94)) was observed on both the brine side and the ammonia side of the unit. A strong smell of ammonia was present when vent valves were initially opened.

5.11.2 Surge Tank

The surge tank was cut from the ammonia tank with a zip disc cutter. A strong smell of ammonia was noted in the area of the cut. The interior of the tank was coated with light corrosion products as observed through a video probe. No evidence of brine salts was found within the surge tank. No significant external or internal corrosion was observed with the surge tank.

5.11.3 NDT Inspection of Ammonia Tank

The ammonia tank was given a comprehensive Ultrasonic Thickness (UT) survey[SN9]. The attached UT report (Appendix B) shows that very little corrosion loss is present within the ammonia tank. No significant pitting of any kind was observed with the ammonia tank shell by UT testing. This was confirmed by visual inspection after the bundle was removed from the vessel.

An attempt was made to inspect the chiller tubes using remote field eddy current techniques (RFT). This technique utilizes a probe which is pushed through the tube from one end to the other. The system detects wall thickness loss and cracks but must have a relatively clean tube surface to be effective. The tubes contained significant amounts of brine residue and corrosion debris. The tubes were cleaned with a 4000 psi pressure washer and swept with a rotating soft brush. The results of trial inspections were inconclusive due to the large amounts of background noise produced by the internal surface condition of the tubes. This method of inspecting the chiller tubes did not yield any meaningful results and was stopped. [SN10]

5.11.4 Head Removal

The heads of the chiller had previously been removed and the installation bolts were relatively loose. The heads were removed to reveal the tubesheets and steel brine tubes within the vessel. The chiller construction consists of carbon steel tubesheets welded to the ammonia tank shell and rolled-in steel tubes. The tubes were supplied in accordance with ASTM A214 (Standard Specification for Electric-Resistance-Welded Carbon Steel Heat-Exchanger and Condenser Tubes).

The tubesheet on the inlet/outlet side of the chiller is shown in Figure 95. A total of 132 tubes are present. No welding was observed on the tube to tubesheet joints. Significant amounts of reddish brown corrosion products are present with most of the lower tubes. The lowest tubes contain a black oily residue which coats the underlying corrosion products. The upper tubes contain only minor amounts of reddish-brown corrosion products. The inlet/outlet head is shown in Figure 96. Both sides of the head contain a dark, oily scale.

The tubesheet from the return side of the chiller is shown in Figure 97. Both white and reddish-brown corrosion products are present on the tubes. The lower tubes contain a black oily substance as with the opposite side tubesheet. The return head interior is shown in Figure 98. The head interior surface is relatively clean and contains a blue-black scale.

5.11.5 Tube Pressure Testing

Each tube in the heat exchanger was pressure tested with argon (<10 psi) and a hand-held rubber bung. The test technician held the bung in place for a few seconds and released the pressure if no pressure drop was felt. Using this technique, a leak was detected at row 2 – tube 3. Following this procedure, a pressure gauge was adapted to the test system to quantify any pressure drop during the test. The test set-up is shown in Figure 99. The pressure seal was not perfect due to corrosion around the edges of the tubes. A pressure of 8 psi (gauge) was introduced to each tube and a pressure drop of 0.1 psi typically occurred every 5 – 10 seconds. This was indicative of a tube with no leaks. An instant pressure drop to atmosphere was observed if a small hole was present in the tube. A tube with a small mechanically induced hole was used as a calibration tool. Testing using the measured pressure drop technique found only the single leaking tube at row 2 – tube 3. No other leaking defects of any kind were discovered.

5.11.6 Tube Examination and Leaking Defect Removal

The chiller shell was cut away from the area where a tube leak was suspected (Tube 2 – 3). Cuts were made with a zip disc to allow a section of the shell to be lifted off without damaging the underlying tubes. Low pressure argon was blown through row 2 – tube 3 to identify the exact location of the leak. The leak in row 2 – tube 3 was found at the general location shown by the arrow in Figure 100. Large amounts of white deposits were found in the immediate area of row 2 – tube 3 near the turnaround end of the chiller. A closer view of the white deposits is shown in Figure [SN1]101. The material is deposited in thick layers at this location. Samples of the white material were analysed using EDXA and found to be almost pure calcium chloride (Figures 102 and 103).

The white calcium chloride material appeared to disappear as time passed during the tube examinations. This is because anhydrous calcium chloride is deliquescent. If exposed to moist air, it will absorb sufficient water from the air to allow it to dissolve into a clear liquid.

The top row of tubes (1-1, 1-2 and 1-3) were removed from the tube bundle to allow access to row 2 – tube 3 (Figure 104). A closer view of the leak area is shown in Figure 105. The leak was found at roughly the 4 o' clock position on the side of row 2 – tube 3 as indicated with the arrow in Figure 105.

White debris was found sprayed over large areas within the chiller tank. In particular, a large spray was found at the location shown in Figure 106. The shell was removed in this area and the white material quickly disappeared. No evidence of leaks was found in this area.

The leak in row 2 - tube 3 is shown in Figure 107. The leak consists of an elliptical opening approximately 2.2 mm x 0.2 mm in size and a line of smaller defects to the left of the main defects (the size of the hole varies between the exterior and interior surfaces of the tube). Some of the smaller line defects appear to have penetrated, or nearly penetrated, the tube wall thickness and may have been weeping or leaking a small amount in service. This was the only leaking tube found in the chiller tube bundle.

5.11.7 Tubesheet – Tube Rolled Joint Examination

The tubesheets were cut from the tube bundle to further evaluate the condition of the tubesheet joints. A dye penetrant examination was performed on each tubesheet by coating the head – side surface of the tubesheet with white developer and filling the shell side of the tubesheet with red dye (Figure 108). A dwell time of 18 hours was used to allow any joint leaks to occur and show as a red line on the white developer. No rolling defects or leaking joints were detected by this method (Figure 109).

The tube bundle was removed from the tank at this time for a thorough visual examination. Oily liquid containing white products were found at the bottom of the bundle. (Figures 110 and 111). No evidence of any further leaks was found at any location in the removed bundle.

A section of the tubesheet at row 2 - tube 1 was cut from the tubesheet and mounted for examination in a metallurgical microscope. A macro view of a typical joint is shown in Figure 112. Two roll grooves are present with each tube. The grooves are not completely filled with tube material, which is common with this type of joint. However, the corners of the joint are very tight as shown in Figure 113. It is the corner tightness that ensures that leaks do not occur. Each joint has 4 corners to make a tight seal.

Corrosion was observed at the rolled interface at each joint as it exited the tubesheet (Figure 114). The amount of corrosion found was relatively small and may have partially occurred after the tubesheets were exposed to the atmosphere during the chiller evaluation.

5.11.8 Metallurgical Evaluation of Leaking Defect in Tube 2-3

A close-up view of the leaking defect in row 2 - tube 3 is shown in Figure 115. The area around the leaking defect is surrounded by a mixture of white calcium chloride and iron oxide products. The tube was sectioned to reveal corrosion damage on the interior surface of the tube. The leaking defect is shown at the arrow in Figure 116. A closer view of the defect is shown in Figure 117. The leaking defect is one of a series of pits that follow a relatively straight line. A transverse gouge is present at the leaking defect which appears to be caused by a jetting action from ammonia entering the hole. A series of shallow irregular pits surround the linear line of deep regular pits which include the leaking defect.

The leaking tube was sectioned along its length adjacent to the leak. Severe pitting is evident all along the tube internal surface (Figure 118). A closer view of the internal surface shows a linear line of pits similar to the pits which caused the leak (Figure 119).

Cross sections were cut through typical linear pits to determine the nature of the pitting. A typical pit cross section is shown in Figure 120. In this figure, it can be seen that the tube microstructure is normalized as required by the ASTM A214 specification. The observed pit is directly on an ERW weld line. The upset caused by the ERW weld can be seen in Figures 121 and 122 by the curved lines of inclusions which are not altered by normalizing (arrow). The pit shown in Figure 121 pit is not corroded out and represents an unfused area along the ERW fusion line. A similar unfused area is shown in Figure 122. Note the upset lines shown at the arrows in Figures 122 and corrosion products at the bottom of the unfused area.

Further examination of the leaking defect was performed at higher magnification using a Keyence Metallurgical microscope. The leaking defect is shown at a higher magnification in Figure 123. The "zipper-like" effect of the line of unfused material is typical of a low frequency ERW weld.[4] The same effect can be found where high frequency ERW tube welding system systems are operated at too high a speed. The welding process has produced a partially fused joint with uniformly spaced lack of fusion defects on the interior of the tube. The tube would likely have passed a hydrostatic test and would therefore have met the ASTM A214 specification requirements.

The unfused zone in a weld of this type contains oxide and other materials expelled by the welding process. The unfused area acts like a pit and attracts chloride ions available in the brine solutions. This is a place where high pitting frequency and pitting rates can occur since the unfused area is a natural initiation site for pits to form and propagate.

Oblique views of the leaking defect are shown in Figures 124 and 125. Corrosion has driven through the pipe wall thickness in pits started in unfused areas on the fusion line of the ERW weld. The leaking pit and the adjacent pit profiles are shown in Figure 126. The profile indicates the steep pit profile at the location of the leak.

5.11.9 Chiller Tube Condition at Selected [SN12]Locations around the Chiller Tube Bundle

Selected chiller tubes were removed from the bundle at the locations shown in Figure 127. The tubes were selected from locations which represented the overall condition of the tubes with respect to upper, lower, middle, and side to side locations within the bundle. In every case, the tube external condition was good with only minor corrosion damage which most likely occurred after the bundle was exposed to the atmosphere in the Acuren yard. The following tubes were removed and examined in detail:

- 4 -1 (return end side)
- 4 -10 (return end side)
- 7-1 (return end side)
- 7-13 (return end side)
- 11-1 (return end side)
- 11-10 (return end side)
- 14 -2 (return end side)

Each tube was sectioned longitudinally to reveal the internal condition of the tube. The orientation of the tubes was marked on each tube. "Top" indicates the 12 o'clock position, and "Bot" indicates the 6:00 o'clock position, with respect to their relative position in the chiller bundle. The corroded condition of each tube was documented and the internal surfaces were then blasted with plastic beads to remove loose scale. Tightly adhering scales remained after plastic bead blasting and a final blast with aluminum oxide was performed.

Photographic images of each tube are shown in Figures 128 - 158. The images show common features with each tube:

1. The ERW weld line has a "stitch – like" lack of fusion defect at regular intervals along the entire length of the piece. There is no correlation between the position of the tube (top or bottom in the bundle) and the ERW weld line. It is apparent that the chiller manufacturer did not feel it was necessary to orientate the ERW weld lines within the bundle.

2. Pitting was found with every tube examined. The depth and frequency of pitting trended less toward the bottom of the bundle.

3. The maximum depth of pitting, measured with a pit gauge, was 0.045 inches (1145 microns) on tube 4-1. The maximum depth of pitting found with 14-2 was approximately 0.025 inches (630 microns). The other tubes had pit depths within this range.

4. It is likely that some of the corrosion found within the tubes occurred after the failure event took place since residual brine sat in the tubes for several weeks.

5.11.10 Scanning Electron Microscope Evaluation of ERW Fusion Defects

Typical fusion line "stitch-like" defects are shown at low and high magnification in Figures 159 and 160 respectively. Chemical analysis of the material in these defects using energy dispersive x-ray analysis (EDXA) show that the material filling the cavities is comprised mostly of iron oxide (Figure 161). This is the material expelled from the weld during the ERW process.

The area of the leaking defect is shown at low magnification in Figures 162a -162e. Traces of chromium were found in the scale, indicating that a chromate-based inhibitor may have been used at some time with the chiller. Calcium chloride mixed with iron oxide comprised the majority of the scale materials. Small amounts of silicates were also found at random locations.

Sample Tube 7 – 1 was chosen for detailed examination of typical corrosion pits found in the tubes. A cross section was prepared through typical pits using dry polishing techniques to prevent chloride contamination. Typical pits are shown in Figures 163 and 164a. EDXA spectra in Figures 164b – 164f show that each layer of scale has progressively more chlorine toward the steel interface. This is typical of corrosion pitting driven by chloride ions[1].

5.11.11 Opinion of Chiller Corrosion Mechanism

A single steel chiller tube failed by corrosion penetration in service allowing ammonia to enter the tube and mix with the brine. It is also probable that pressure conditions existed in service that allowed brine to enter and mix with ammonia. The evidence shows that the tube was ERW welded and normalized in accordance with ASTM A214 (Standard Specification for Electric-Resistance-Welded Carbon Steel Heat-Exchanger and Condenser Tubes). The tube chemistry, hardness (R_B 72 maximum) and heat treatment condition meet the ASTM A214 specification requirements.

Corrosion in various forms can occur in chiller brine tubes due to oxygen present in the brine (oxygen content of the brine will change due to additions of inhibitors, sample taking, and periodic addition of brine). Inhibitors are added to reduce the amount of corrosion possible. The level of corrosion inhibitor must be monitored to ensure that corrosion is not occurring. The evidence shows that chromate inhibitors may have been used early in the life of the chiller. It is understood that organic inhibitors are currently used with the Fernie Ice Rink chillers[2].

All of the tubes examined contained ERW fusion defects on the weld line. The leaking through-wall corrosion pit was found on the weld fusion line of row 2 – tube 3 initiating at a lack of fusion defect. These types of fusion defects are caused by an improper ERW welding process. Either the welder frequency was too low, or the speed of welding was too high, or both. In any case, each tube has a "stitch-like" fusion defect on the weld line interior surface that accelerated the pitting process at that location. Fusion defects of the type noted are essentially surface holes in which corrosion can occur more readily due to stagnant conditions within the hole. Once started, the dissolution of iron in the hole creates an excess of positive charge ions to which negative chloride ions are attracted. The high concentration of iron chloride within the pit leads to hydrolysis and formation of both hydrogen and chlorine ions which leads to further iron dissolution. The whole process is autocatalytic[3], in that the pitting rate gets higher and higher as time passes. Inhibitors can slow the rate of pitting but cannot stop it completely. Any time the inhibitor level becomes weak, rapid pitting rates would be expected in the brine environment.

The overall condition of the chiller was relatively good with no evidence of tube – tubesheet leaks and no evidence of any significant corrosion on the ammonia pressure vessel. The condition of the steel brine tubes would be difficult to ascertain with the unit in service. Eddy current testing of the brine tubes requires removal of the brine, removal of the heads, and cleaning of the tubes. Defective tubes cannot be replaced easily in this type of heat exchanger. The condition of the steel chiller tubes should be checked by visual inspection and trending the iron content in the brine. High iron content would indicate significant corrosion occurring within the chiller tubes.

6.0 REFERENCES

1. Bradford, Samuel, Corrosion Control, Section 5.6, Pitting, Van Nostrand, Reinhold, 1993

2. Brine Analysis Reports; RMC Canada Ltd., January 18, 2016, May 11, 2017, August 4, 2017

3. Fontana, Mars, Corrosion Engineering, Section 3, Pitting, McGraw Hill, 1986

4. Kiefner, John F., *Dealing with Low Frequency Welded ERW Pipe and Flash-Welded Pipe with Respect to HCA – Related Integrity Assessments*, ASME Engineering Technology Conference on Energy, February 4 – 6 2002, Houston Texas

Robert Milne, P.Eng.

ACUREN

APPENDIX A

FIGURES 1 - 164

ACUREN

Figure 1 Overall view of Valve X. Handle is in closed position.

Figure 2 Plugged end fitting on top end of Valve X.

Figure 3 Partially plugged nipple on bottom end of Valve X.

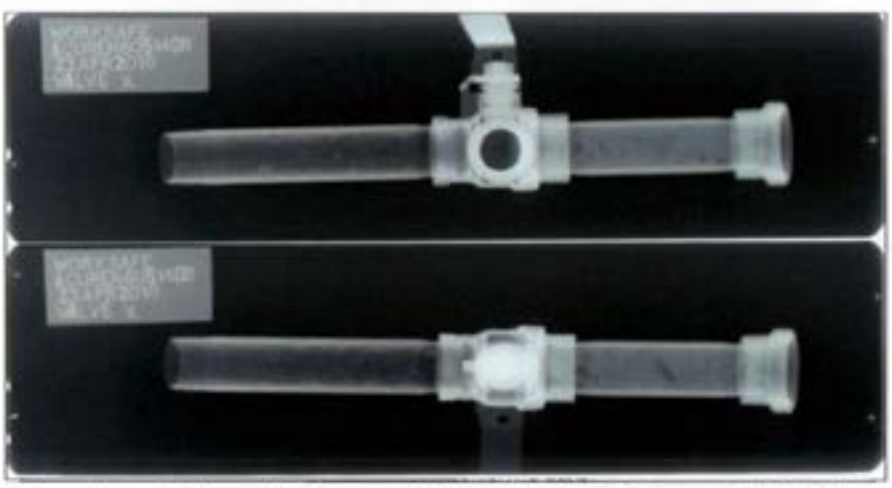

Figure 4 Radiographic images of Valve X in views 90° apart. Ball is fully closed.

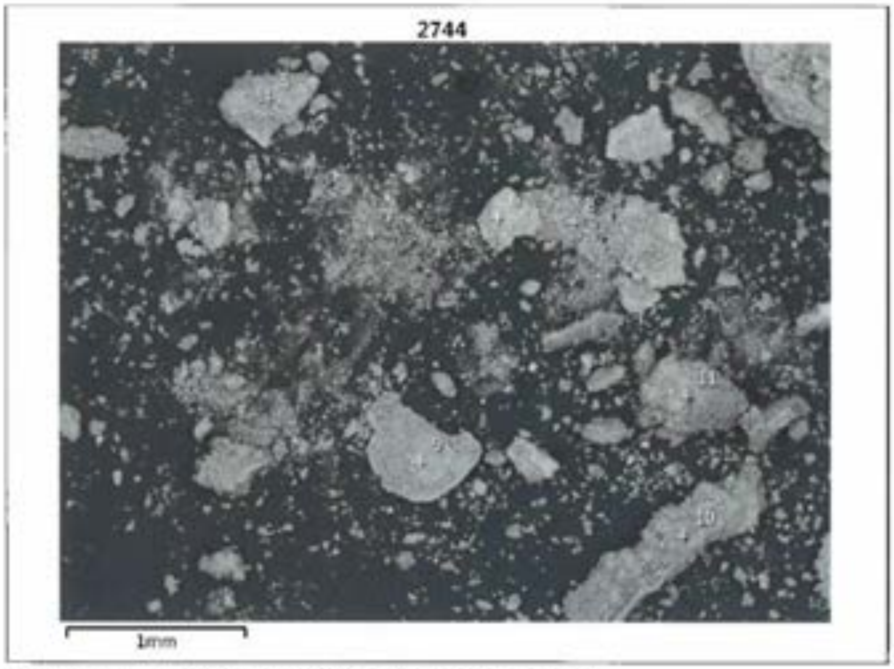

Figure 5a SEM view of debris from Valve X plug.

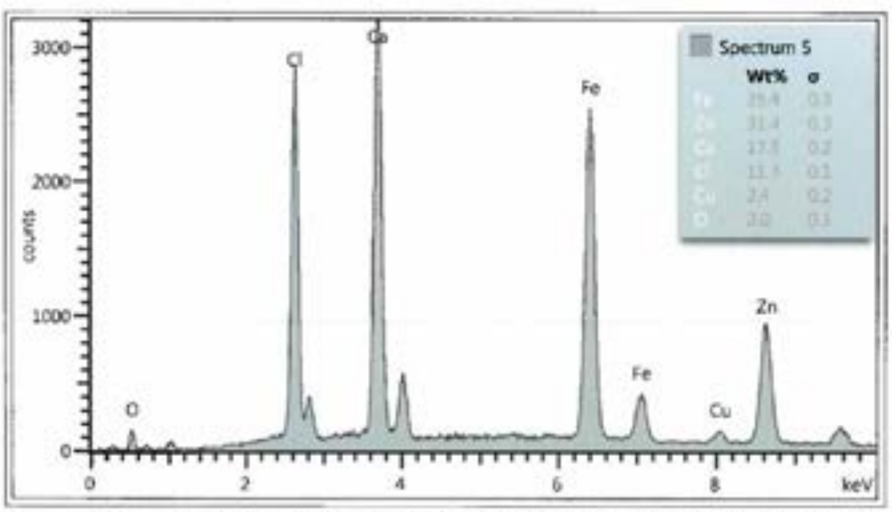

Figure 5b Analysis of debris in Valve X plug. Material is a mixture calcium chloride, zinc chloride, and iron oxide.

Figure 6 Overall view of Valve A-3.

Figure 7 Corrosion products on nipple end of Valve A-3.

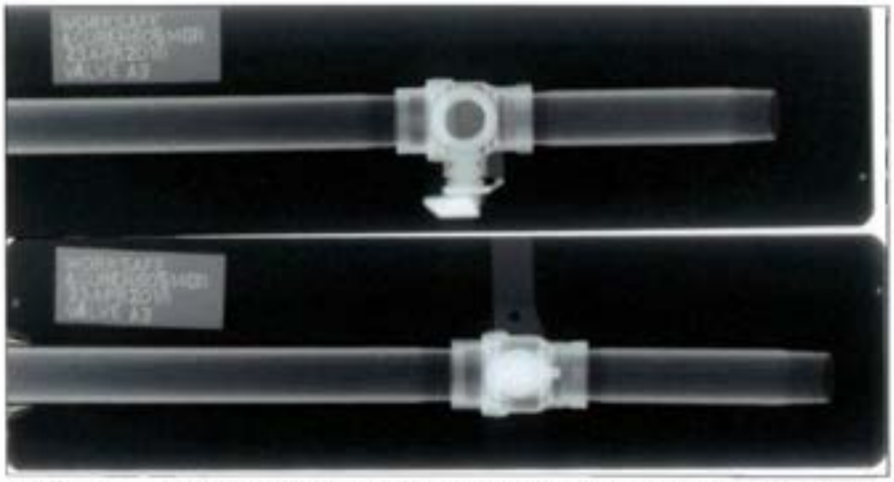

Figure 8 Radiographic images of Valve A-3 in views 90° apart. Ball is fully closed.

Figure 9 Overall view of Valve A-6. Handle is in open position.

Figure 10 Nipple end of Valve A-6 piping showing internal deposits.

Figure 11 Radiographic images of Valve A-6 showing 2 views 90° apart. Ball is fully open.

Figure 12 Overall view of Valve A-2. Handle is in open position.

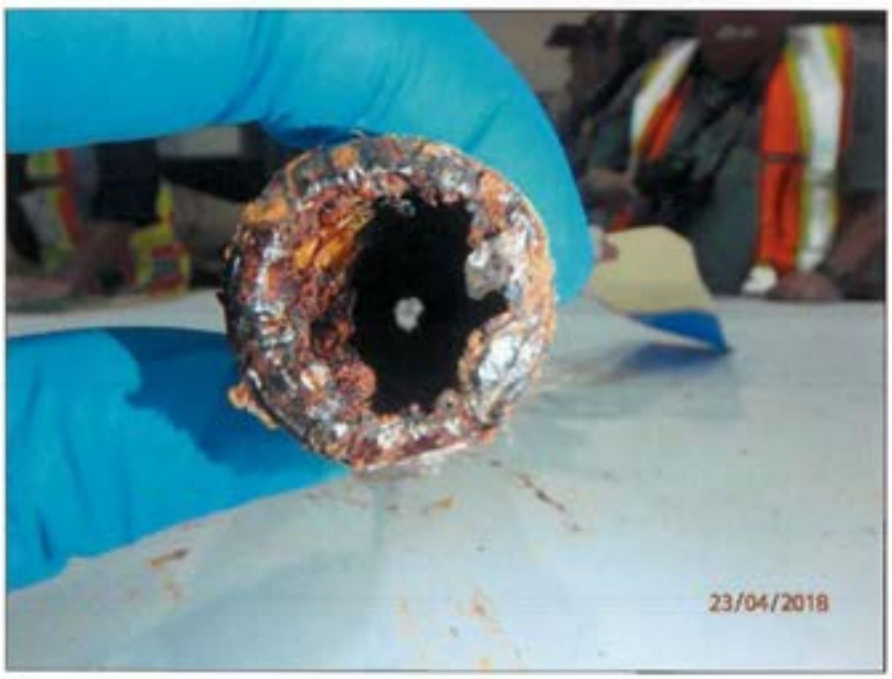

Figure 13 Corrosion damage and partial plugging of nipple end of A-2.

Figure 14 Relatively minor corrosion debris in Tee end of Valve A-2.

Figure 15 Relatively minor corrosion debris in second Tee end of Valve A-2.

Figure 16 Radiographic image of Valve A-2 in open position.

Figure 17 Radiographic image of valve A-2 in closed position.

Figure 18 Overall view of Valve Z. Handle is cocked by approximately 10°.

Figure 19 White deposit partially plugging Valve Z. White material is calcium chloride.

Figure 20 Opposite end of Valve Z showing partial plugging.

Figure 21 Radiographic images of Valve Z. Views are taken 90° apart.

Figure 22 Water remaining at steady level in valve Z leak test.

Figure 23 Corrosion debris surrounding ball in partially cocked valve Z.

Figure 24 Inside of Elbow A-10 showing severe corrosion damage.

Figure 25 Valve A-10 on rusty elbow. Ball appears corroded and slightly worn.

Figure 26 Closer view of ball on Valve A-10 showing light corrosion.

Figure 27 Markings on Valve A-10.

Figure 28 Markings on Valve A10.

Figure 29 Radiographic images of Valve A-10.

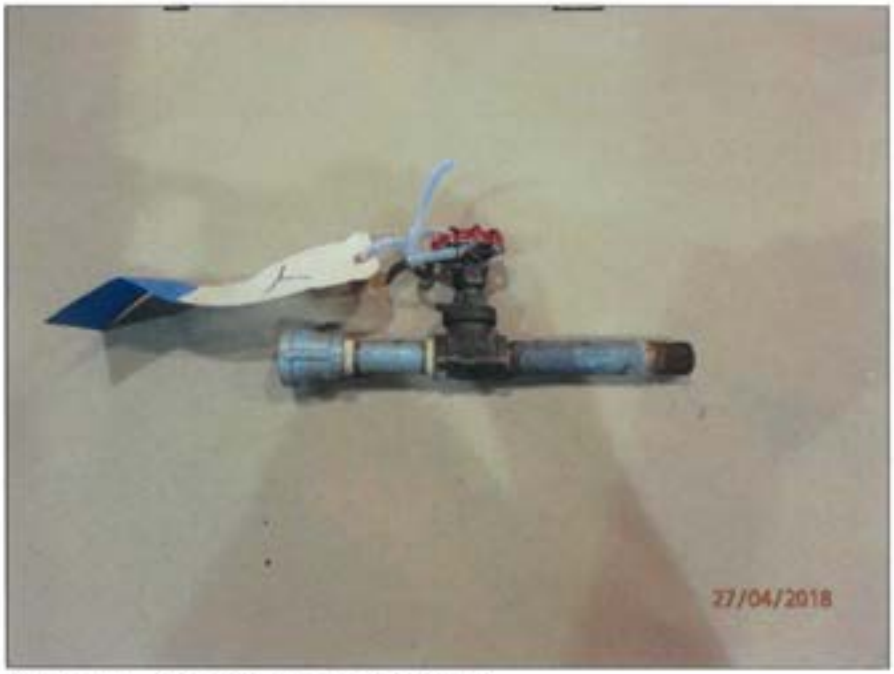

Figure 30 Overall view of gate Valve Y.

Figure 31 Corroded nipple threads on Valve Y nipple.

ACUREN

Figure 32 Radiographic view of Valve Y. Gate is fully open.

Figure 33 Gate Valve Y internal components. Stem would not engage and appeared fractured.

Figure 34 Blue corrosion product in Valve Y body. Body is partially plugged.

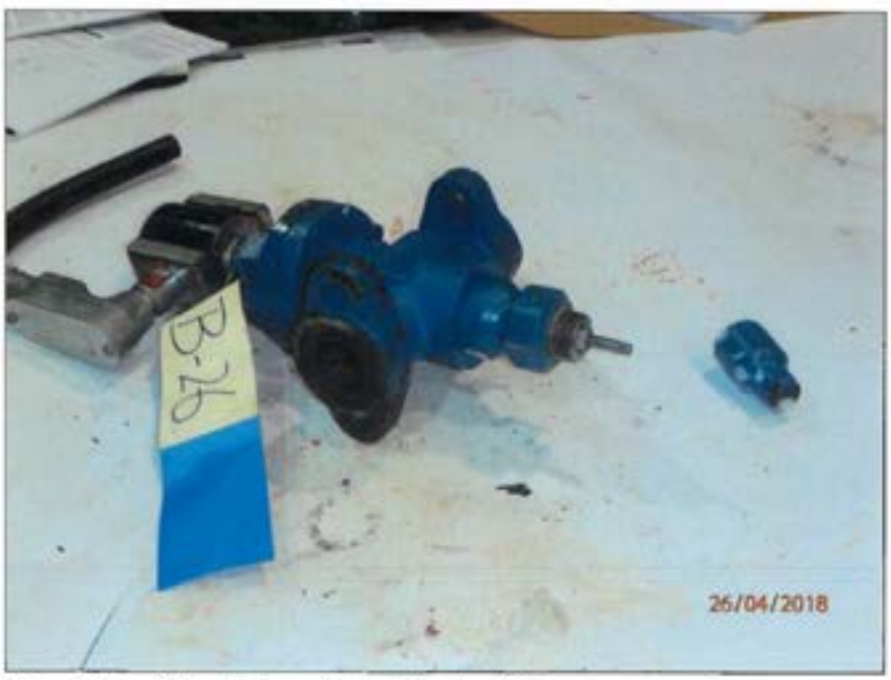

Figure 35 Overall view of solenoid valve B26.

Figure 36 Solenoid valve test set-up.

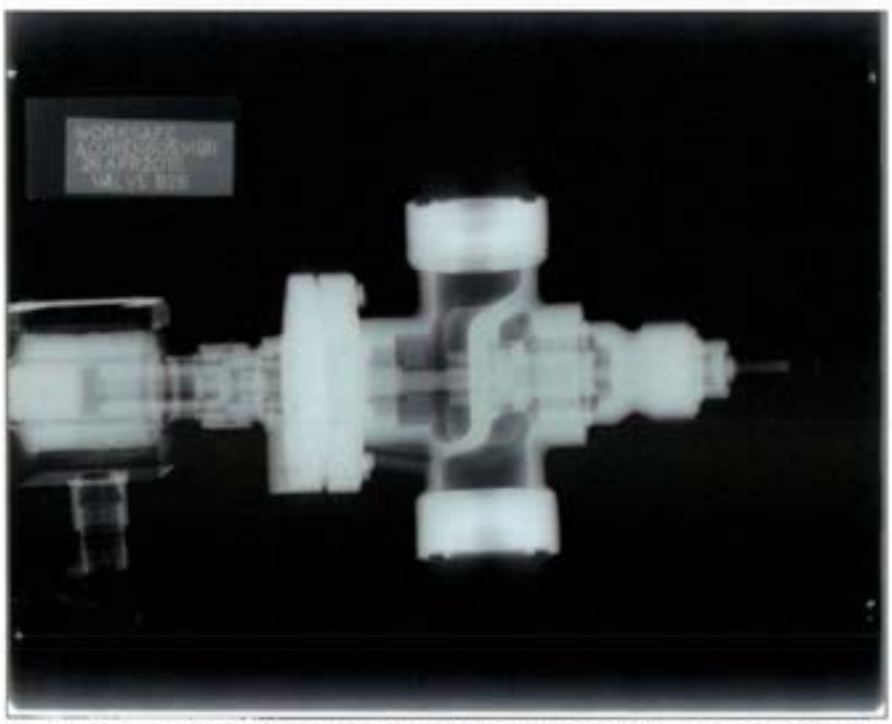

Figure 37 Radiographic view of solenoid valve B-26 showing closed position with stem backed out.

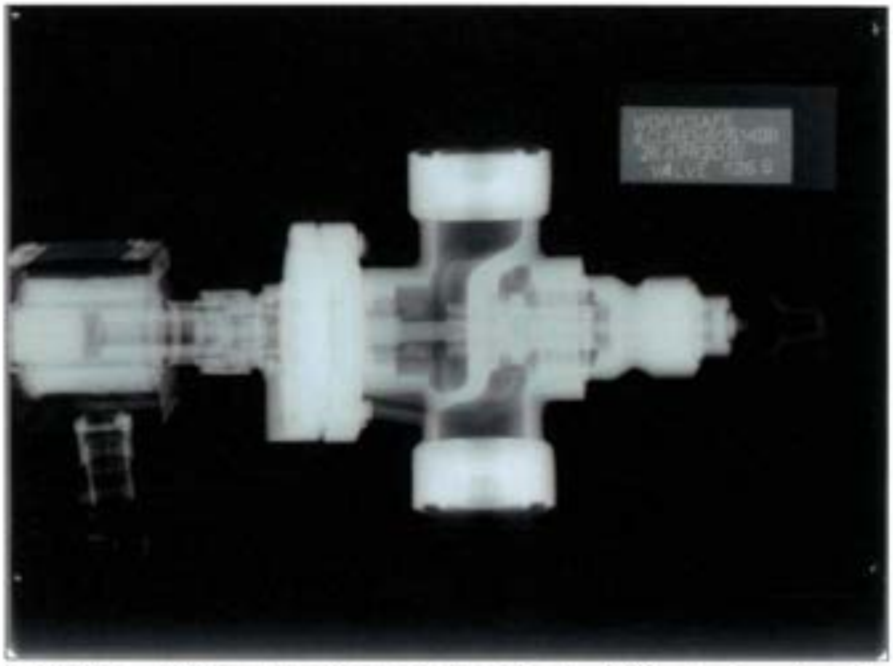

Figure 38 Radiographic view of solenoid valve B-26 showing closed position with stem turned in.

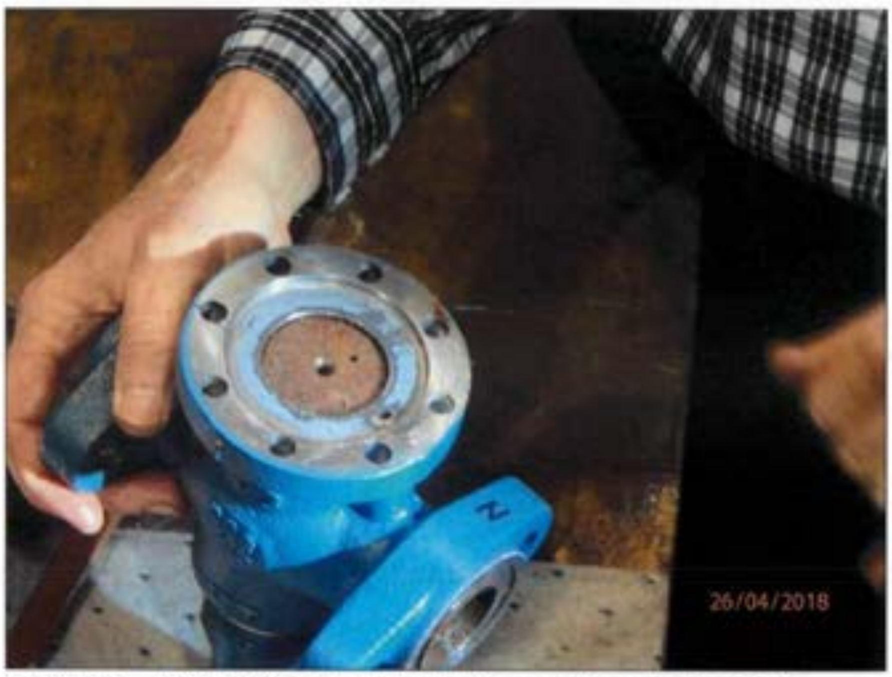

Figure 39 Valve B-26 dismantled showing corrosion and seized piston.

Figure 40 Overall view of solenoid valve B-35.

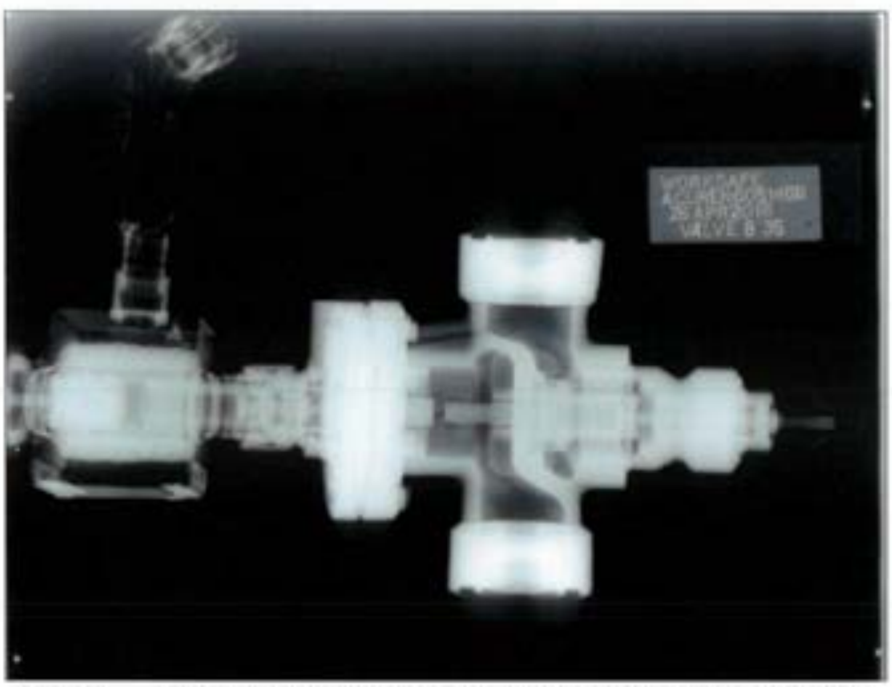

Figure 41 Radiographic image of solenoid valve B-35 with stem out and partially open.

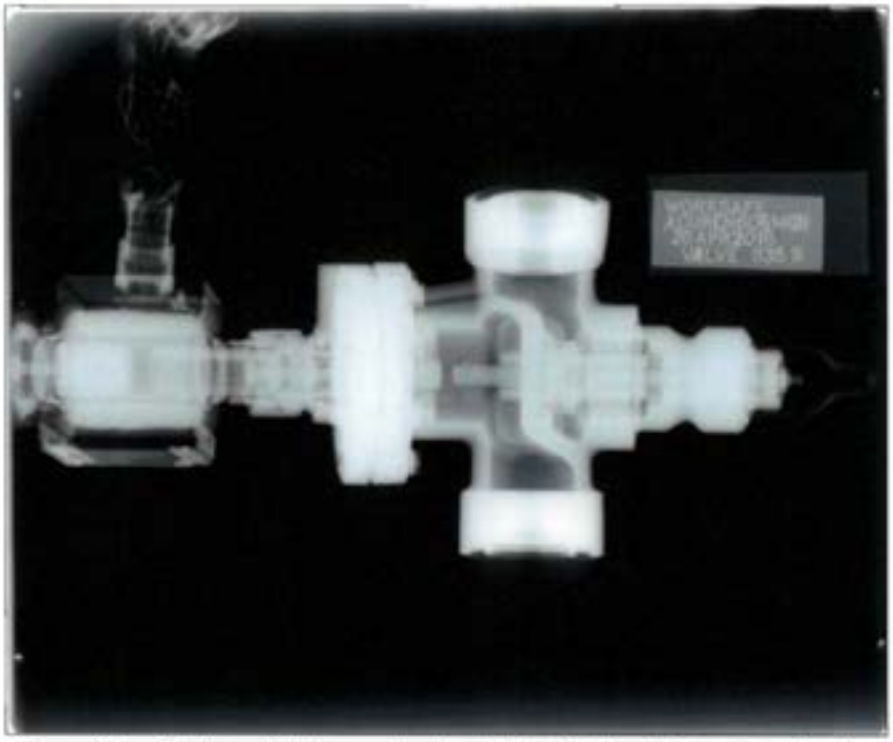

Figure 42 Radiographic image of solenoid valve B-35 with stem completely in and still partially open.

Figure 43 Severe corrosion on B-35 piston. Piston could not be freed.

Figure 44 Overall view of pressure relief valve "Y" connection labelled R8.

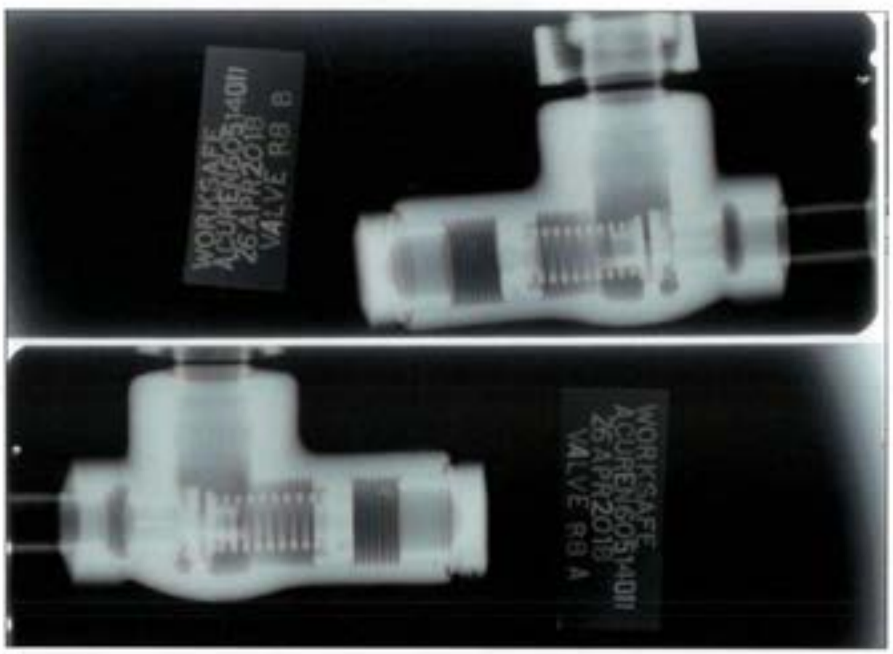

Figure 45 Radiographic images of pressure relief valves "1" (A) and "2" (B). The "1" valve was in service at the time of the event. Both units appear to be in good condition with no blockages.

ACUREN

Figure 46 PRV "1" spring. No evidence of calcium chloride is present.

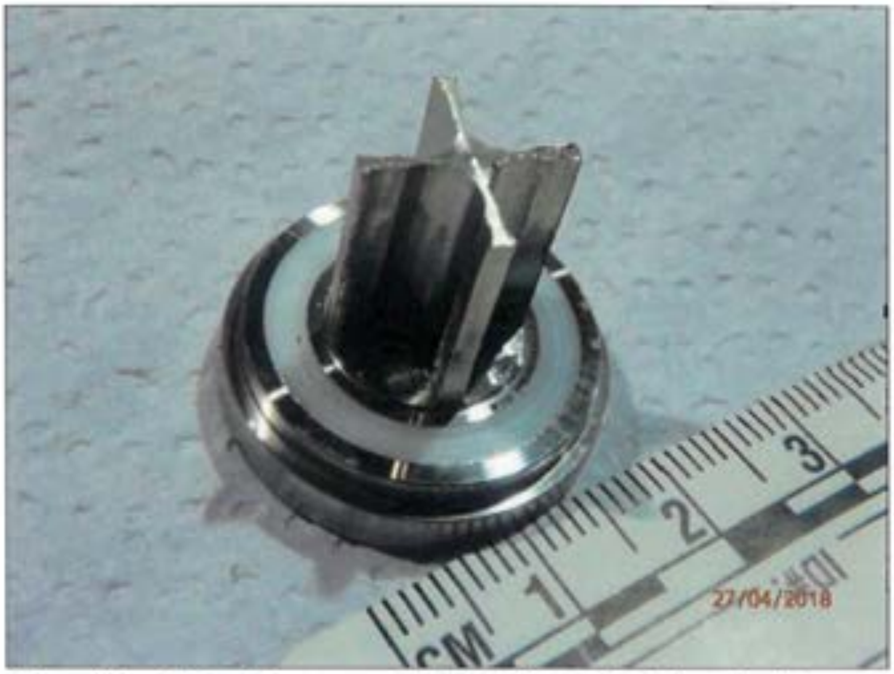

Figure 47 Valve "1" pressure seal. No evidence of calcium chloride was found. The seat contains minor amounts of debris.

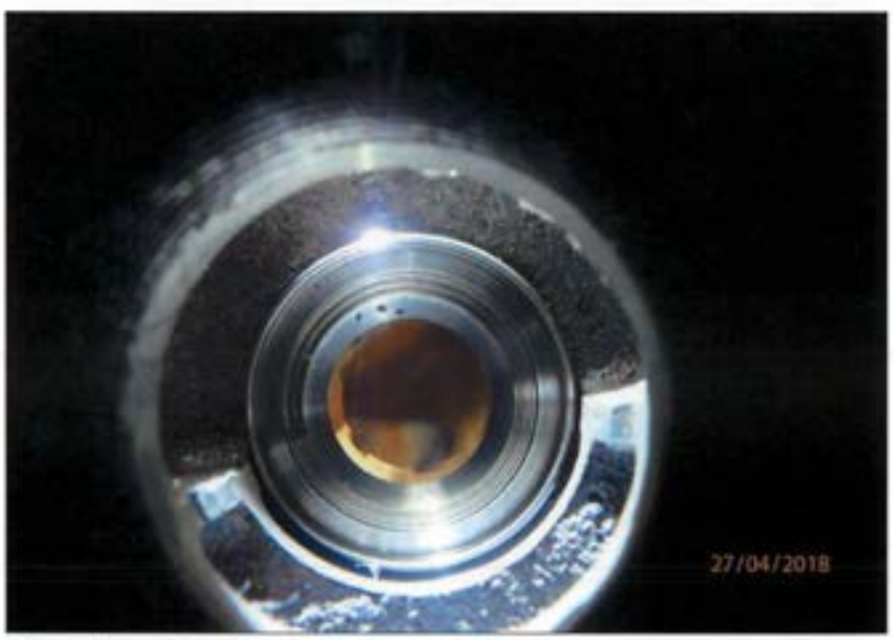

Figure 48 PRV Valve "1" internal bore. No evidence of calcium chloride is present.

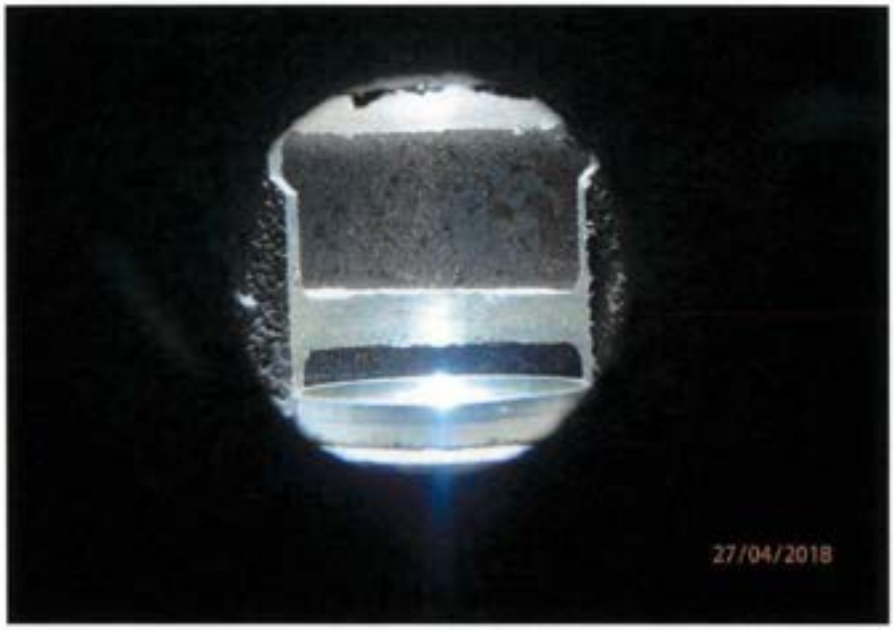

Figure 49 PRV Valve "1" internal bore. No evidence of calcium chloride is present.

Figure 50 PRV Valve "1" spring seat. No evidence of calcium chloride is present.

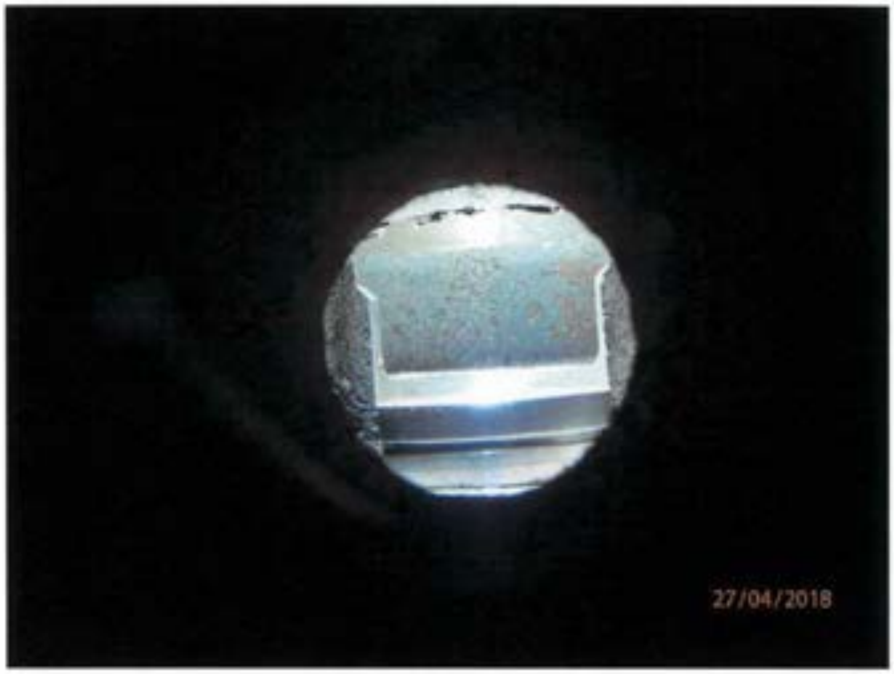

Figure 51 PRV Valve "1" bore. No evidence of calcium chloride is present.

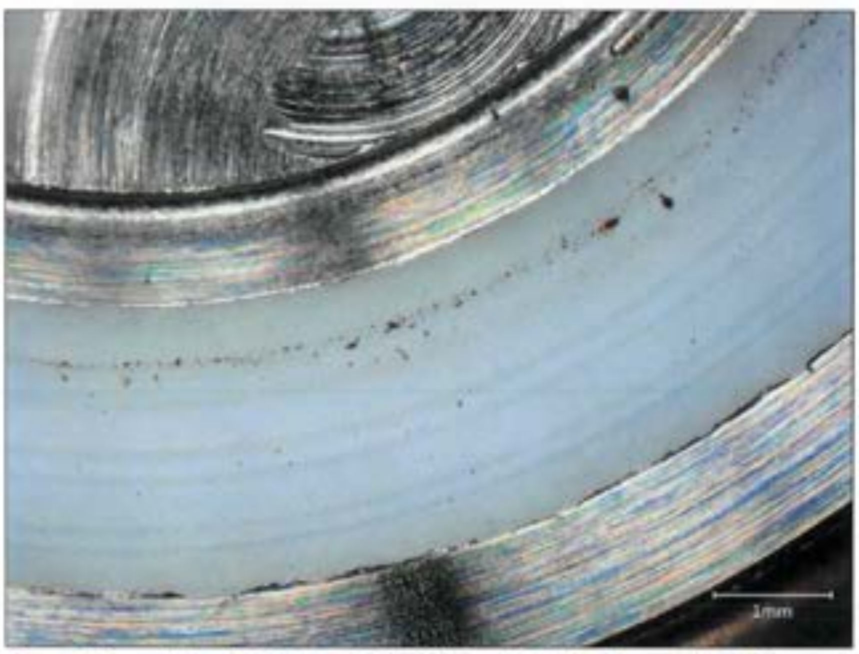

Figure 52 Magnified view of debris imbedded in valve seal. PRV was likely operated during setting.

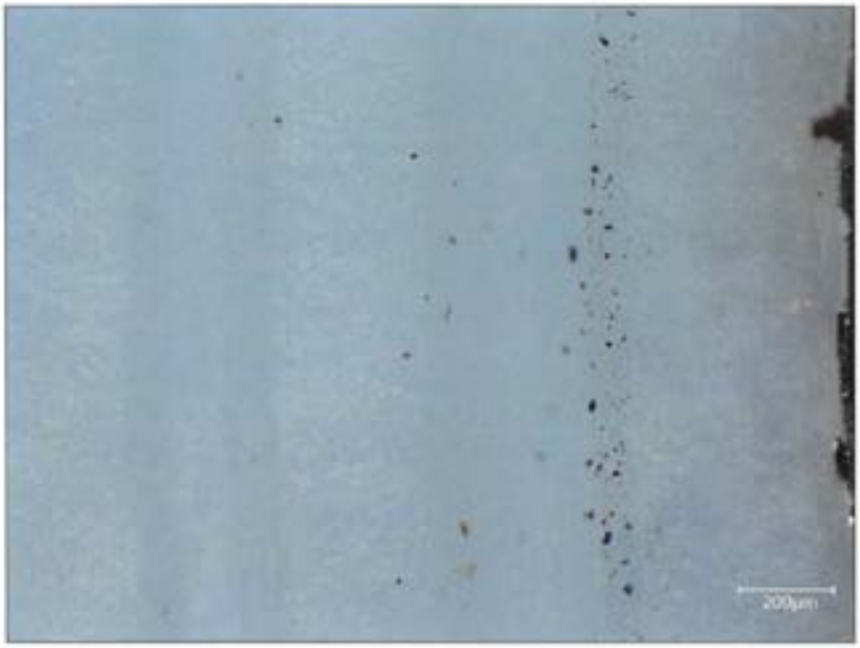

Figure 53 High magnification view of debris in seal surface. Debris is up to 20 microns in overall dimensions.

Figure 54 PRV test set-up. Argon was used to operate PRV Valve "2".

Figure 55 Piece of metal debris 28A found between head and tubesheet on inlet/outlet side of chiller.

Figure 56 Estimated diameter of curved metal piece found between head and tubesheet on inlet/outlet side of chiller (179 mm or 7 inches).

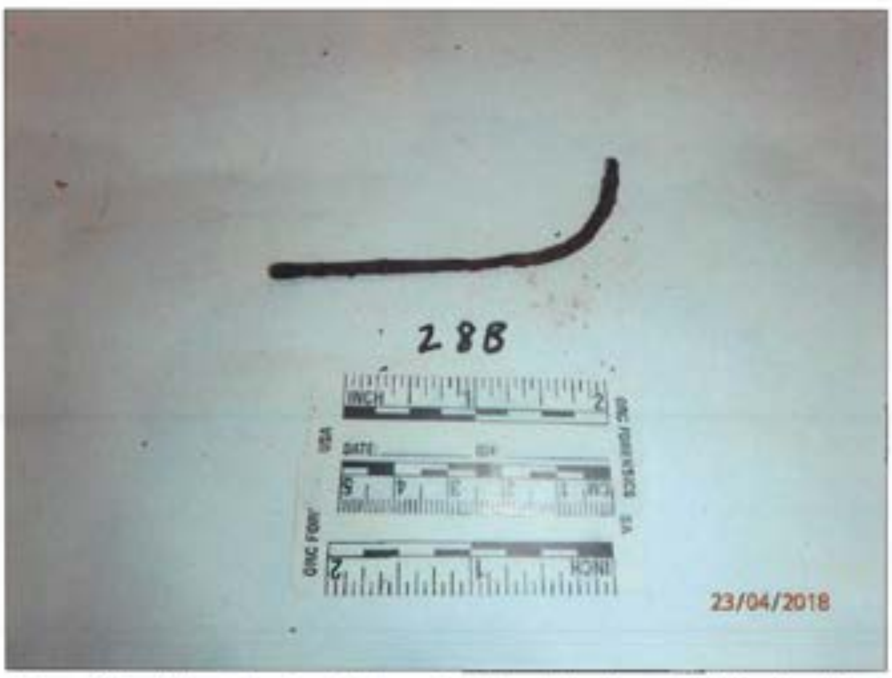

Figure 57 Wire piece found between head and tubesheet on inlet/outlet side of chiller.

ACUREN

Figure 58 Test set-up for actuation of LC1. Olive oil was used to simulate ammonia.

Figure 59 Radiographic images of LC1 tank and switch taken 90° apart.

ACUREN

Figure 60 Test in progress on LC2. Switch would not engage.

Figure 61 Radiographic images of LC2 tank and switch taken 90° apart. All components appear intact.

Figure 62 Zap strap found on LC2. Operation was restricted by this strap.

Figure 63 Overall view of LC3 prior to test.

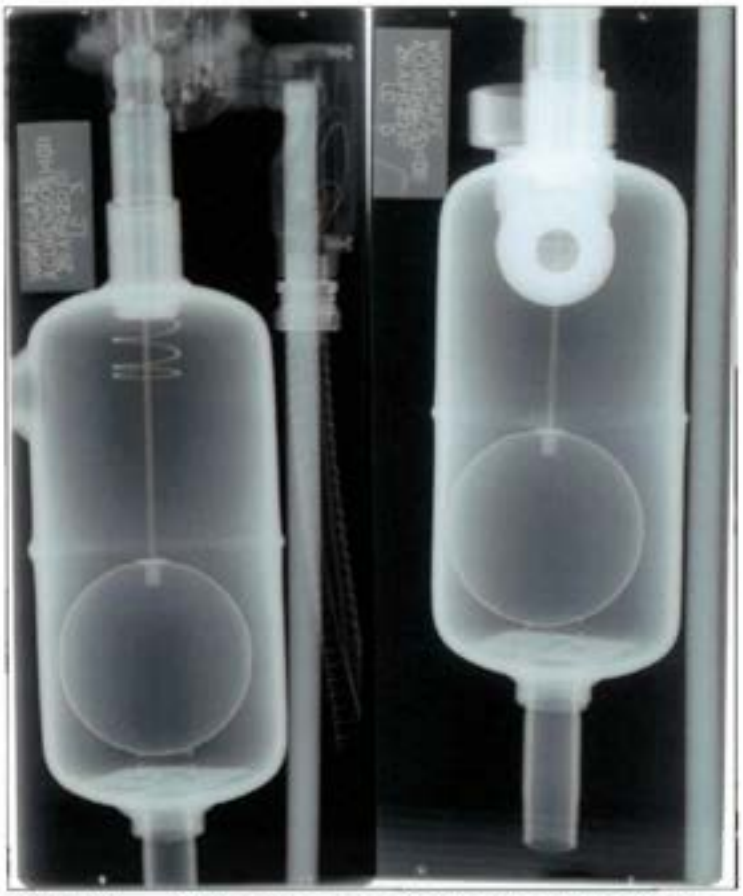

Figure 64 Radiographic images of LC3 tank and switch taken 90° apart. All components appeared intact with no blockages.

Figure 65 Overall view of LC4 prior to test.

Figure 66 Radiographic images of LC4 tank and switch taken 90° apart. All components appear intact.

Figure 67 Exemplar [redacted] coupling prior to test.

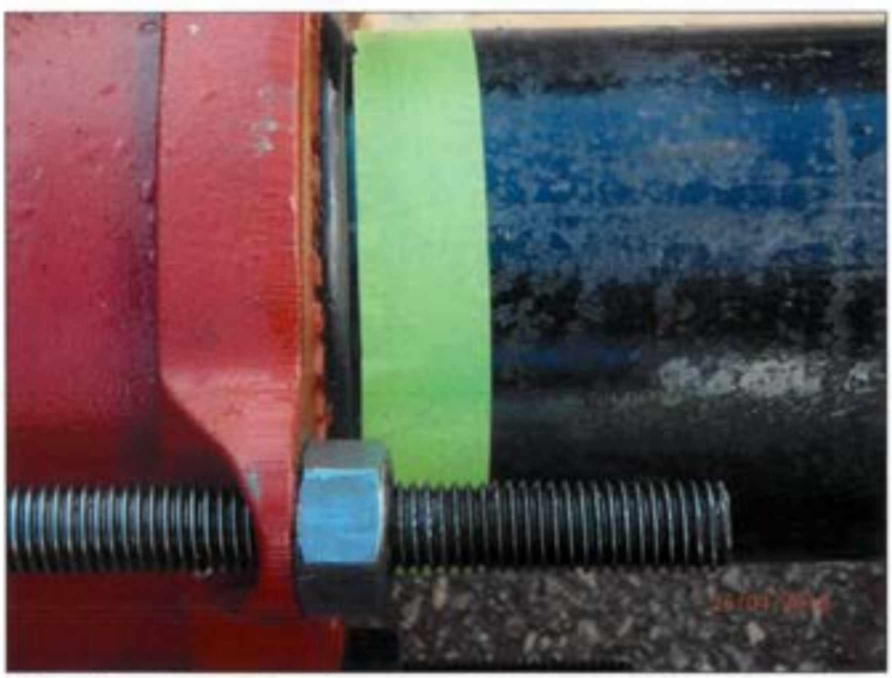

Figure 68 Exemplar [redacted] coupling; Initial slip at 30 psi.

Figure 69 Slipped exemplar [redacted] coupling at 24 psi.

Figure 70 Overall view of separated horizontal [redacted] coupling.

ACUREN

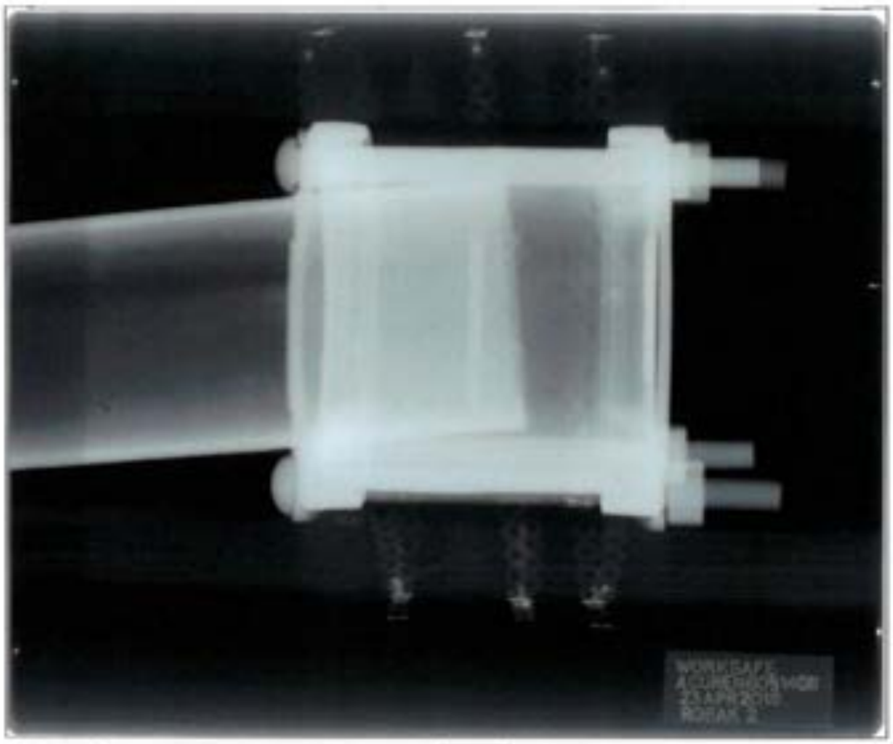

Figure 71 Radiograph of horizontal [redacted] coupling showing misalignment and pipe location past the midpoint of the coupling body.

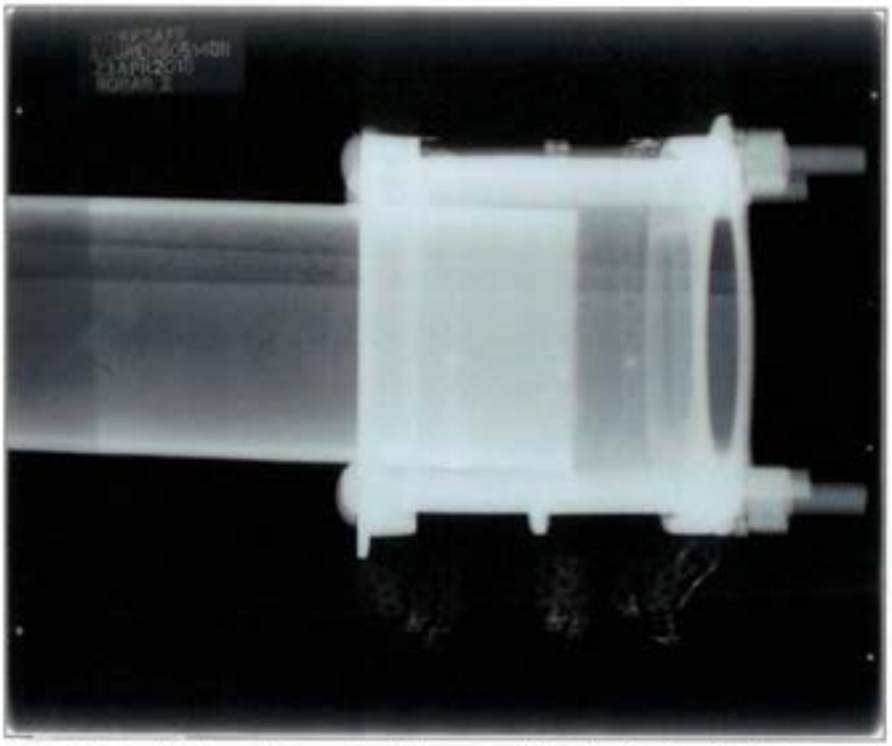

Figure 72 Horizontal [redacted] coupling rotated 90° showing installed pipe past the mid-point of the coupling body.

Figure 73 Horizontal [redacted] coupling that separated in service, disassembled for examination. White debris in pipe is a mixture of calcium chloride and iron oxide.

Figure 74 Typical white salts found within the pipe attached to horizontal [redacted] coupling.

Figure 75 Rubber gasket on sleeve end of horizontal coupler showing imprint of end plate casting surface. Hardness was Shore A52.

Figure 76 Rubber gasket on sleeve end where horizontal pipe separated.

Figure 77 Horizontal brine pipe that detached from coupling.

Figure 78 Corrosion found in unpainted area of separated pipe mounted within horizontal coupling.

ACUREN

Figure 79 Severe corrosion in horizontal brine pipe that detached from coupling.

Figure 80 Corrosion found in horizontal brine pipe separated from coupling.

Figure 81 Corrosion found in horizontal brine pipe separated from coupling (opposite side of Figure 80 piece).

Figure 82 Sand blasted internal surface of separated horizontal brine pipe showing pitting around weld seam.

Figure 83 Vertical [redacted] coupling packed in foam for transport.

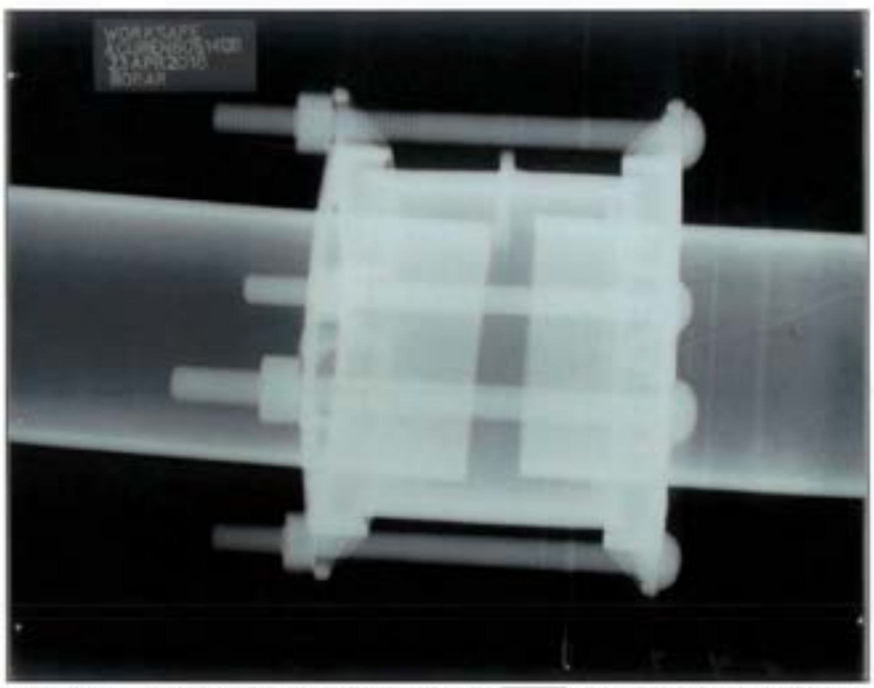

Figure 84 Radiographic image of vertical [redacted] coupling showing proper installation and misalignment caused by event forces.

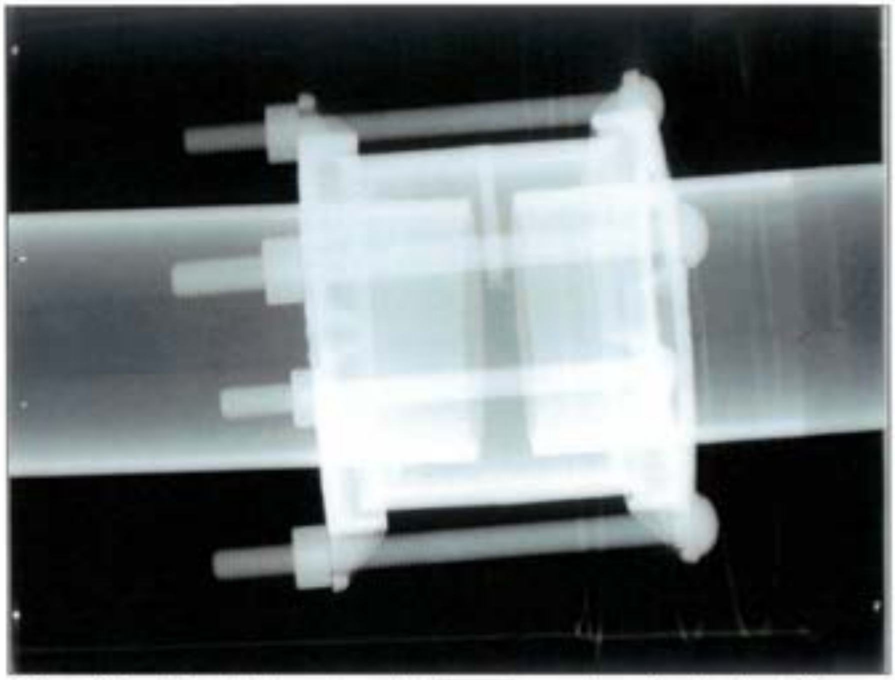

Figure 85 Second view of vertical [redacted] coupling showing installation location and misalignment caused by event forces.

Figure 86 Vertical [redacted] coupling after removal from foam.

Figure 87 Misalignment with coupling after event. Bolt extensions are roughly equal.

Figure 88 Severe corrosion damage on interior surface of vertical [redacted]-coupling.

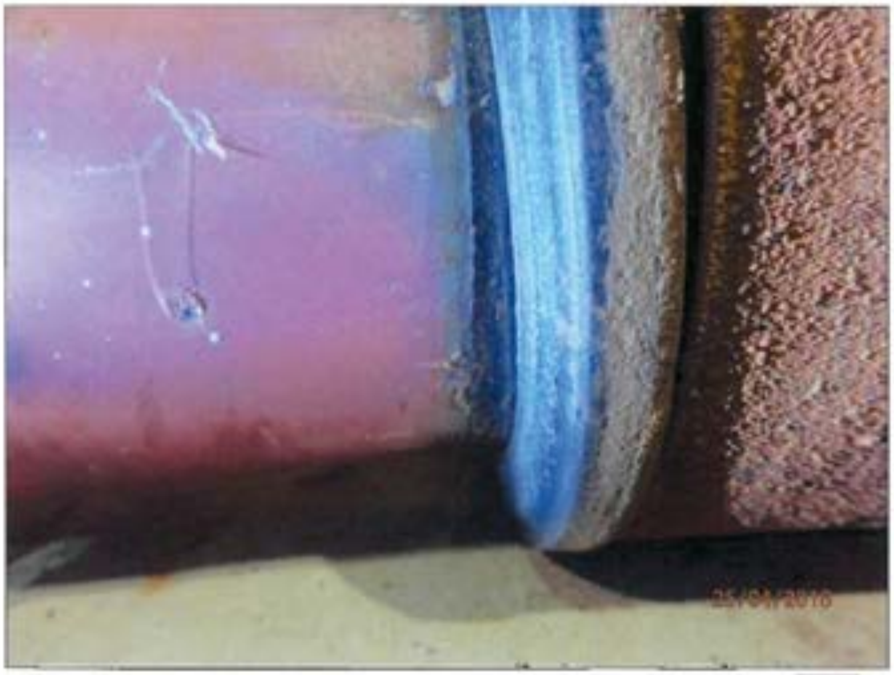

Figure 89 Corrosion damage beneath rubber gasket on vertical [redacted] coupling.

Figure 90 Overall view of vertical [redacted] coupling after removal from foam constraints.

Figure 91 Overall view of chiller as received at Acuren facility (sides and top of shipping box removed).

Figure 92 Chiller name plate with CRN number and manufacturing data.

Figure 93 Positive pressure on ammonia side of chiller.

Figure 94 Positive pressure on brine side of chiller.

Figure 95 Inlet/outlet tubesheet on return side of chiller.

Figure 96 Inlet/outlet head removed from chiller.

ACUREN

Figure 97 Return tubesheet side of chiller. Tubes are corroded and partially filled with debris.

Figure 98 Return side head showing a blue-black scale and very little corrosion damage.

ACUREN

Figure 99 Pressure-test set up for steel chiller tubes.

Figure 100 General area of leak found by pressurized argon testing.

ACUREN

Figure 101 Closer view of leak area on row 2 – tube 3. Note relatively large amounts of white material deposited on surfaces.

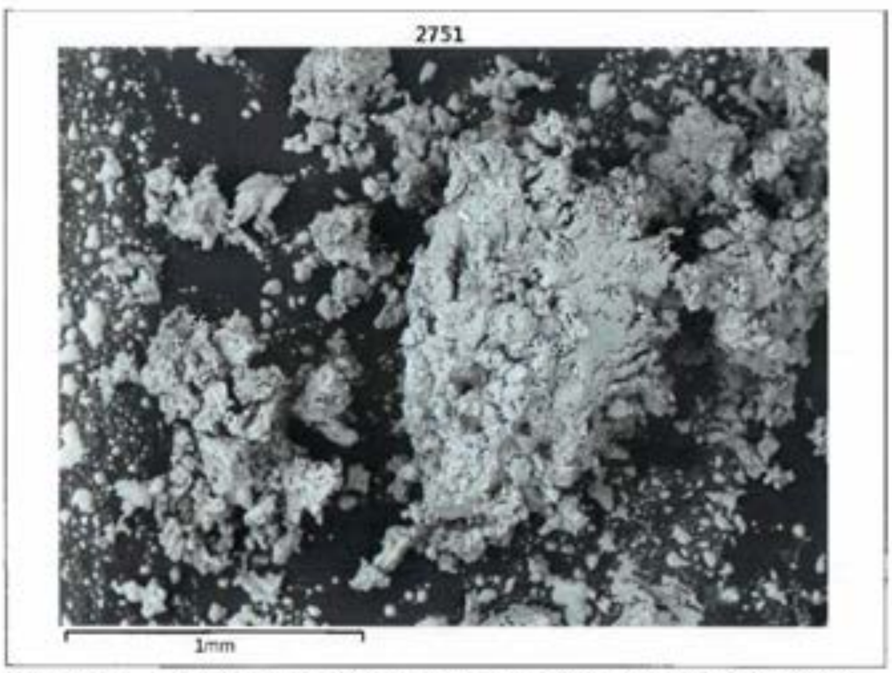

Figure 102 SEM image of white material in area of leak removed for analysis.

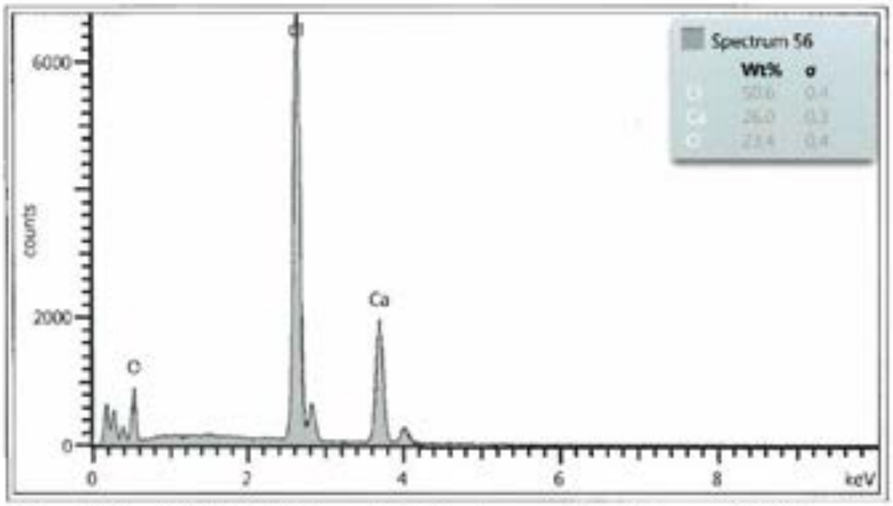

Figure 103 EDXA of white material showing mainly calcium and chlorine.

Figure 104 Row 1 tubes removed for access to leak area. Note white material has begun to be dissolved by a process of deliquescence.

Figure 105 Location of leaking defect on Row 2 – Tube 3.

Figure 106 Area where white material was sprayed onto the tank wall and tubes (orange paint).

Figure 107 Main leaking defect on row 2 – tube 3 removed from bundle. Several smaller defects were found along the ERW weld.

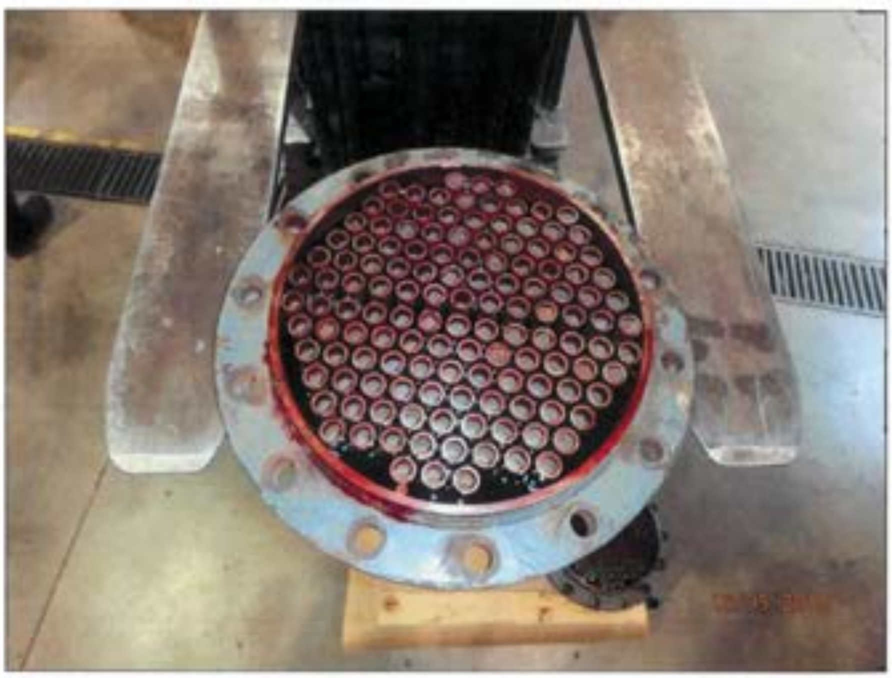

Figure 108 Testing for tubesheet leaks with dye penetrant.

Figure 109 No sign of leaks after 18 hours of dwell time.

Figure 110 White material found in ammonia tank bottom after bundle removal. EDXA determine white material was calcium chloride.

ACUREN

Figure 111 Tube bundle after removal from tank. An oil residue mixed with white deposits (calcium chloride) was present on tubes at the bottom of the tank.

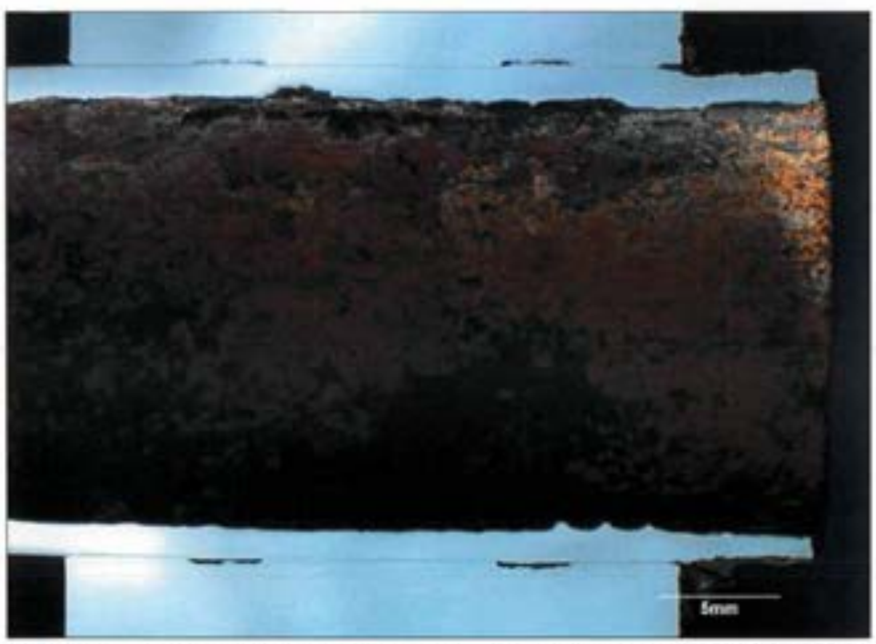

Figure 112 Cross section of typical tube – tubesheet interface. Two grooves are present at each joint.

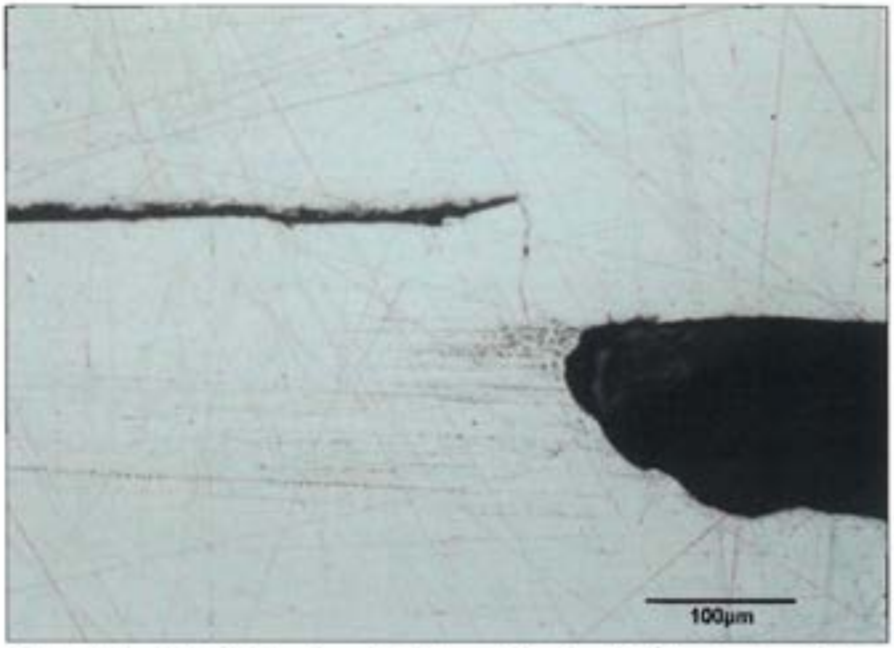

Figure 113 Magnified view of tube – tubesheet joint showing tight connection at corner of groove.

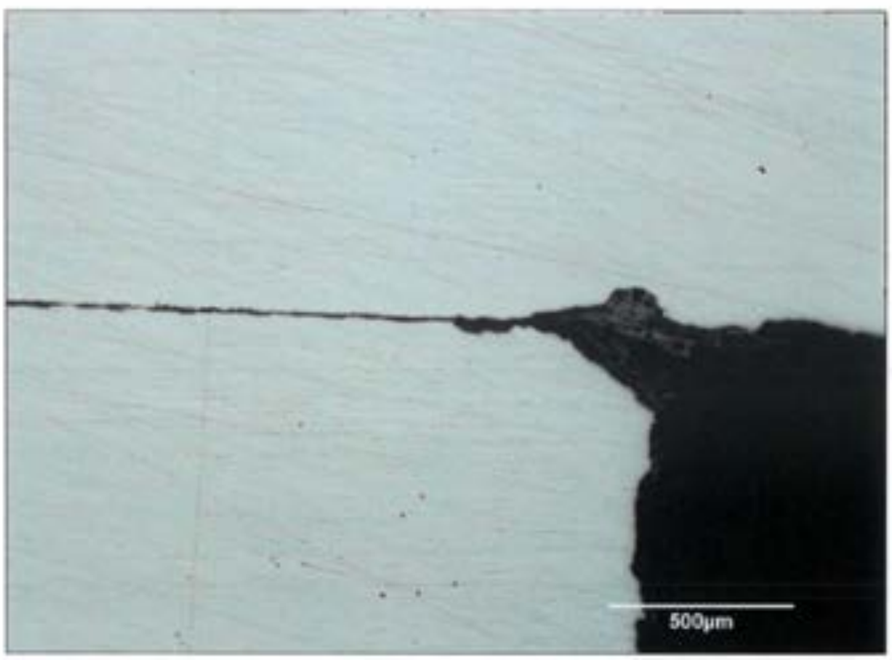

Figure 114 Corrosion beginning to attack tube – tubesheet joint.

Figure 115 Close-up view of leaking defect on row 2 – tube 3 showing white deposits.

Figure 116 Row 2 – tube 3 split to reveal interior surface. Leaking defect is at arrow.

Figure 117 Closer view of leaking defect showing a line of "stitch-like" defects adjacent to the leaking defect. Nozzling effect has removed material above the leak.

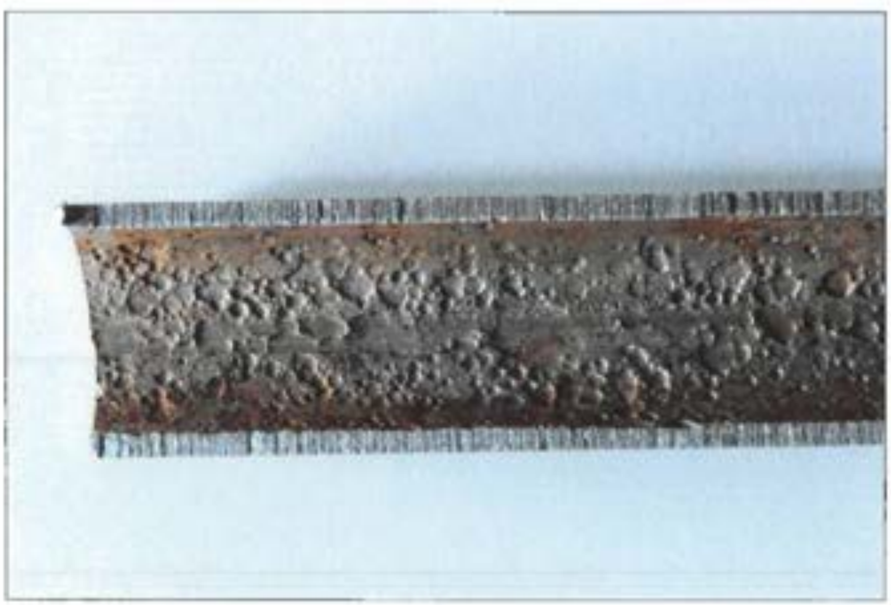

Figure 118 Typical corrosion damage found along row 2 – tube 3 approximately 12" from the leaking defect.

Figure 119 Closer view of corrosion damage showing a line of small, deep pits (arrows).

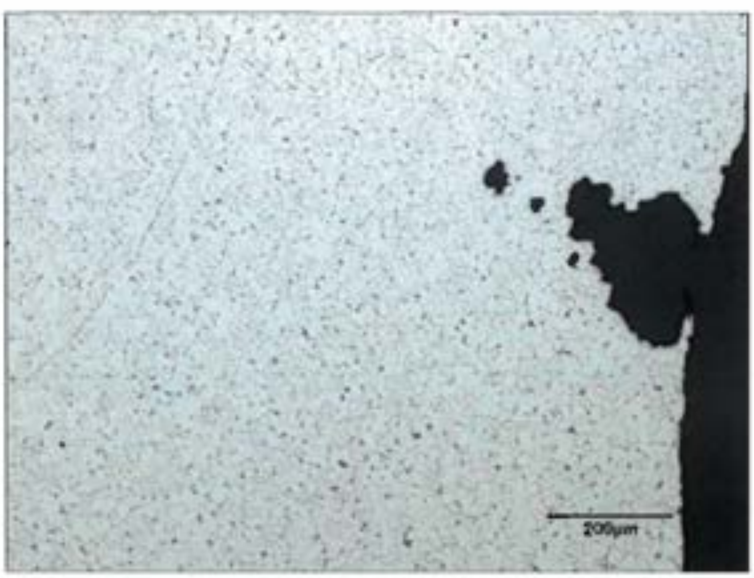

Figure 120 Cross section through typical "stitch" defect showing a corrosion depth of approximately 270 microns.

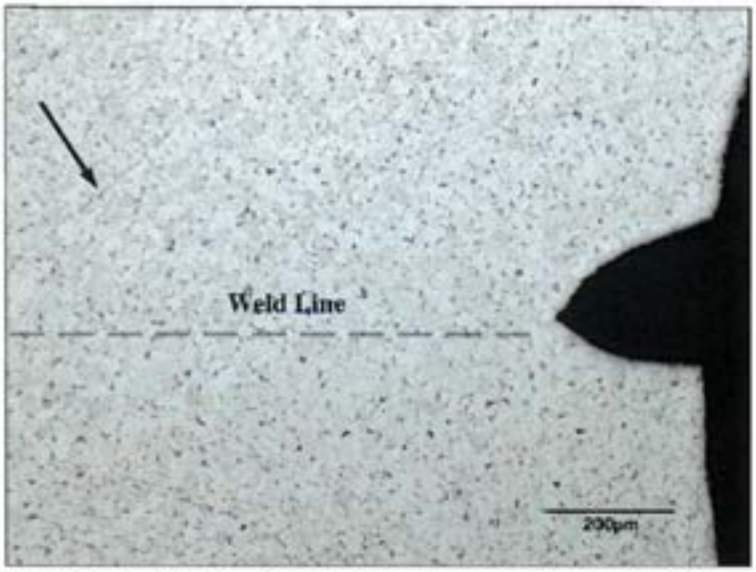

Figure 121 "Stitch -like" defect found along ERW weld line. Note inclusion upset at arrow indicating weld line.

Figure 122 Linear "stitch-like" defect found on row 2 - tube 3 ERW weld line. Microstructure is fully normalized. Arrows show curved upset lines around joint (inclusions).

ACUREN

Figure 123 Closer view of pit line in row 2 – tube 3 at leak.

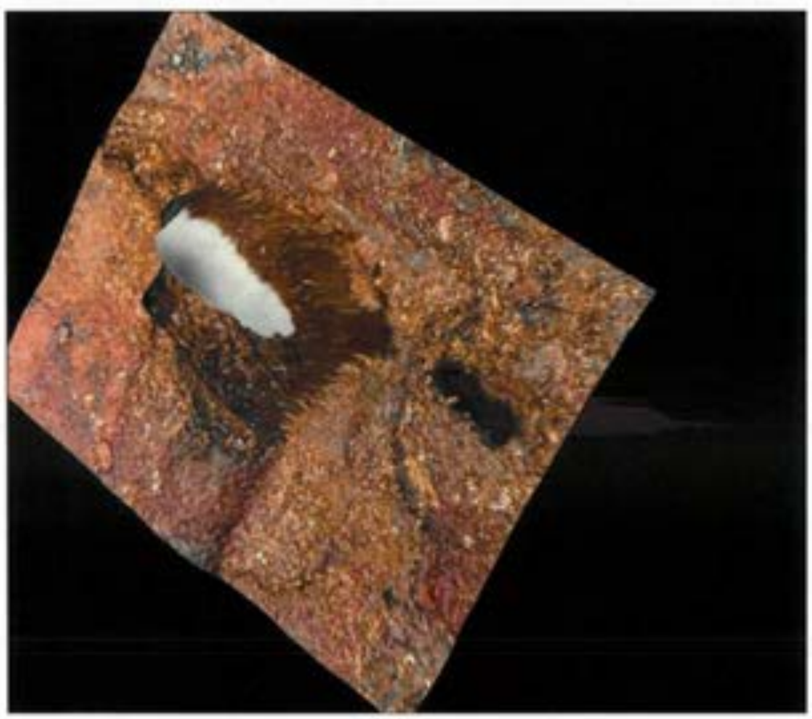

Figure 124 Oblique view of leaking pit showing corrosion attack through cross section.

ACUREN

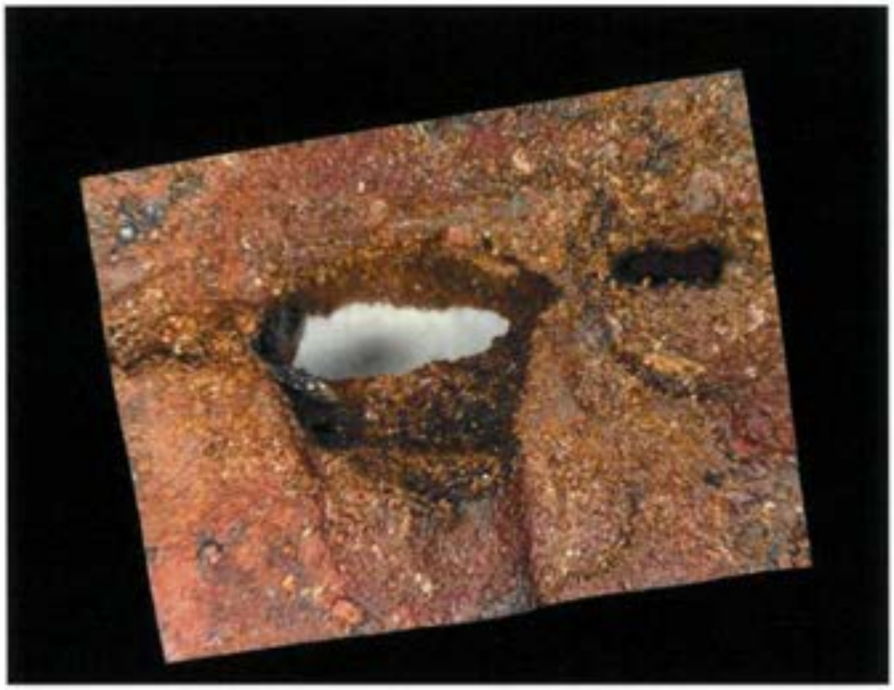

Figure 125 Oblique view of leaking pit showing corrosion attack through cross section.

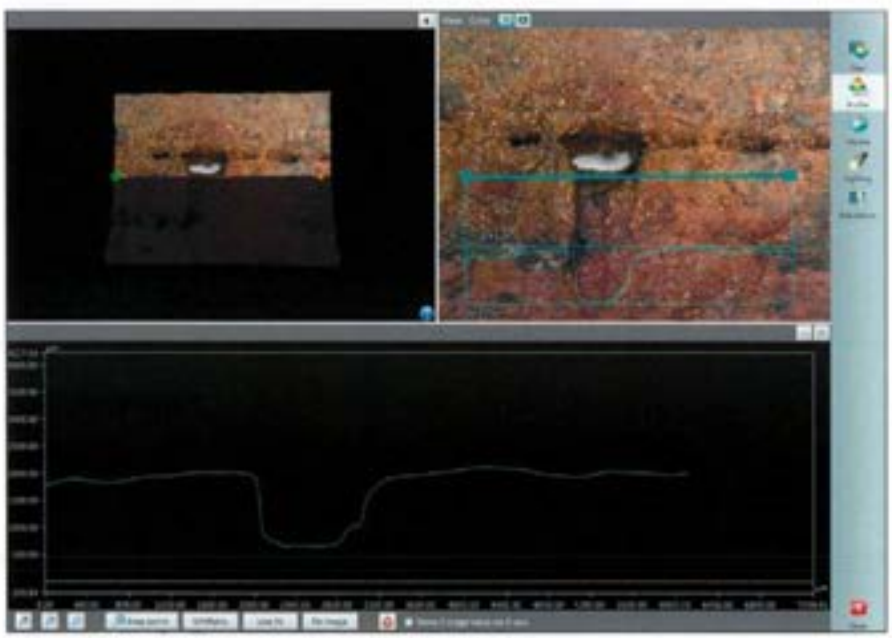

Figure 126 Pit profile showing steep walls of pit.

Page 1?? of 132

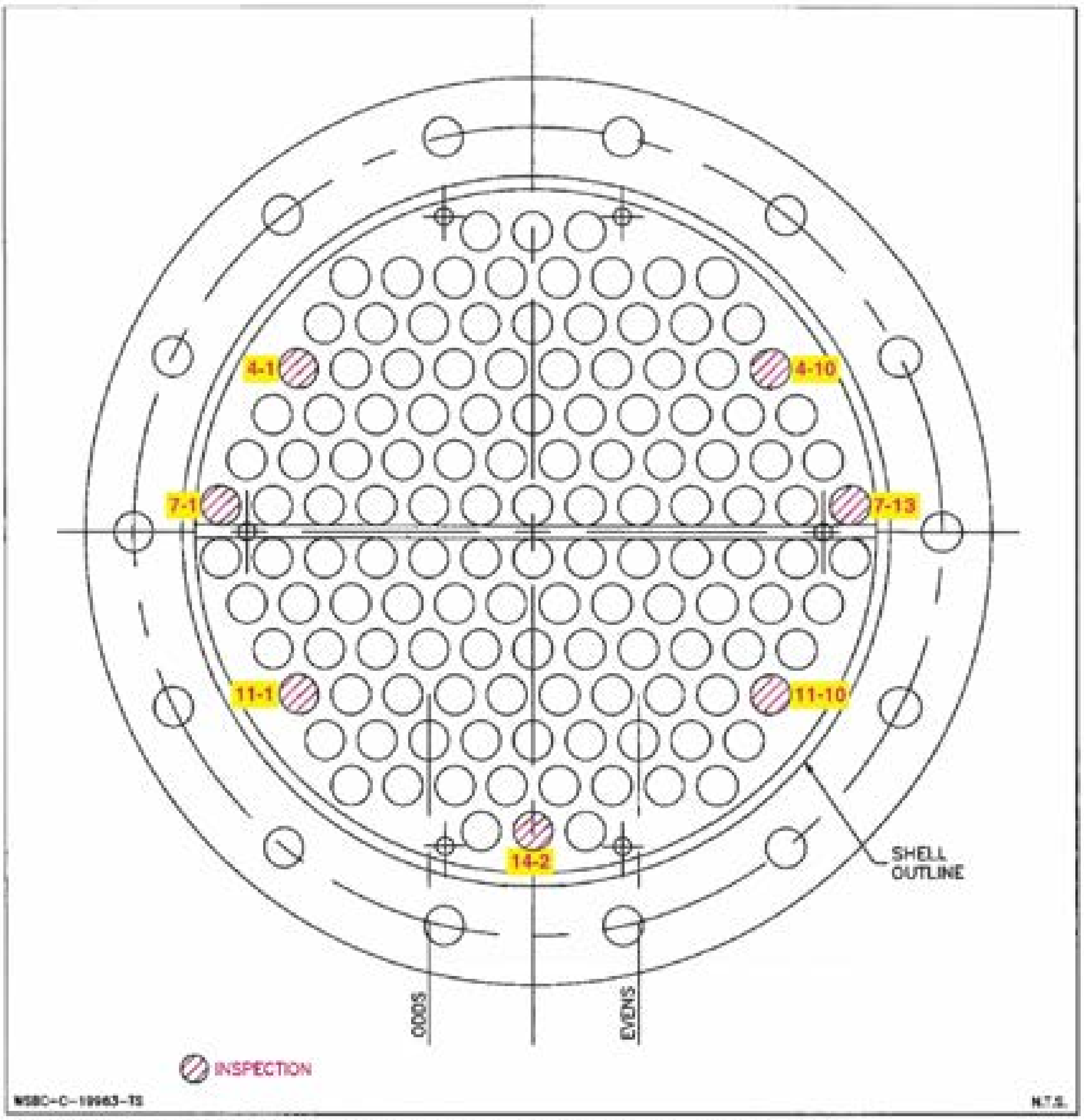

Figure 127 Location of tubes removed from chiller for cross section evaluation.

Figure 128 Corrosion damage on row 4 – tube 1 (bottom) after plastic bead blasting.

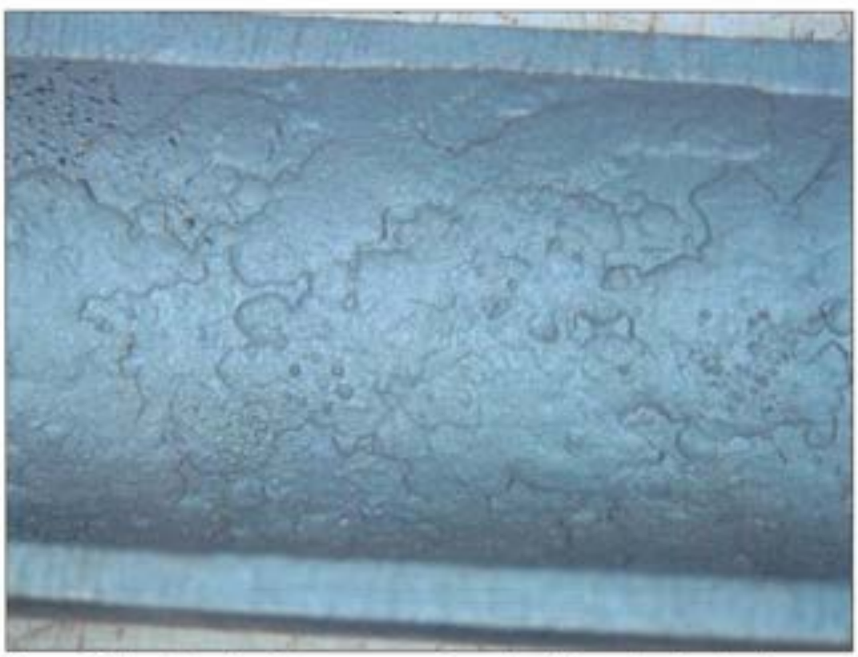

Figure 129 Corrosion damage on row 4 – tube 1 (bottom) after aluminum oxide blasting.

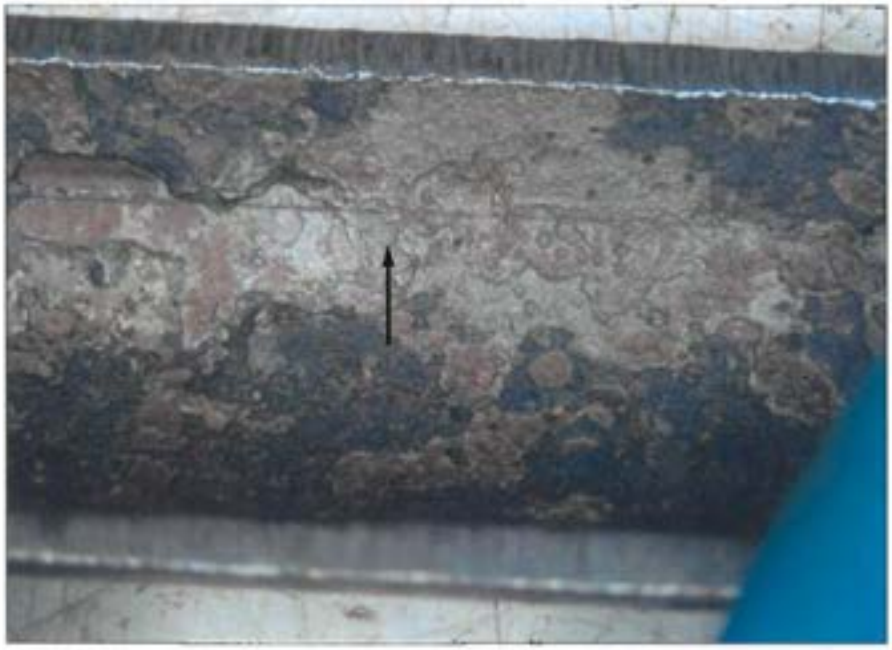

Figure 130 Corrosion damage on row 4 – tube 1 (top) after plastic bead blasting. Note ERW fusion line (arrow).

Figure 131 Corrosion damage on row 4 - tube 1 (top) after aluminum oxide blasting. Note "stitch-like" defects along fusion line.

Figure 132 Corrosion damage on row 4 - tube 10 (bottom) after plastic bead blasting.

Figure 133 Corrosion damage on row 4 - tube 10 (bottom) after aluminum oxide blasting. Note "stitch-like" defect along fusion line of ERW weld.

Figure 134 Corrosion damage on row 4 - tube 10 (top) after plastic bead blasting.

Figure 135 Corrosion damage on row 4 - tube 10 (top) after aluminum oxide blasting.

Figure 136 Corrosion damage on row 7 - tube 1 (bottom) after plastic bead blasting.

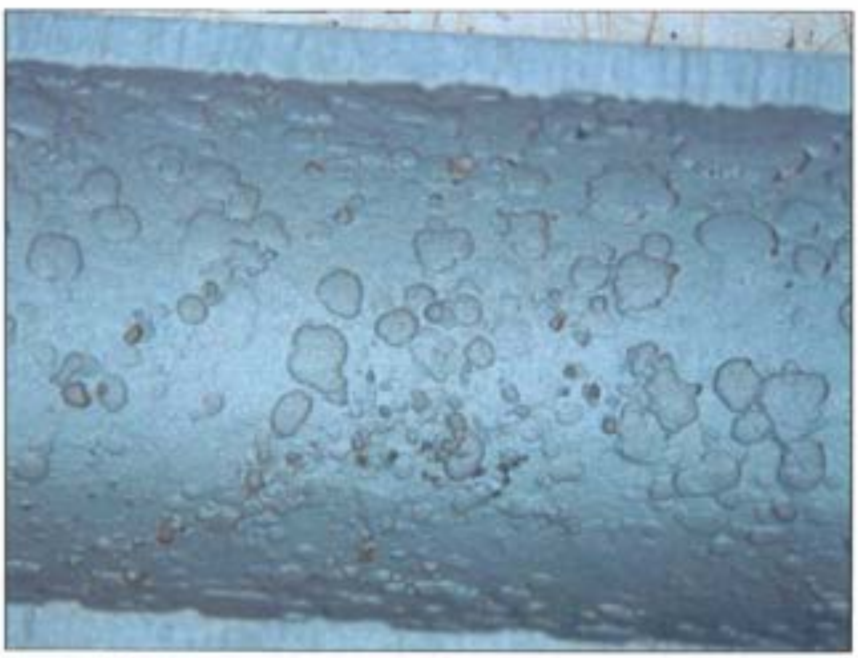

Figure 137 Corrosion damage on row 7 - tube 1 (bottom) after aluminum oxide blasting.

Figure 138 Corrosion damage on row 7 - tube 1 (top) after plastic bead blasting.

Figure 139 Corrosion damage on row 7 - tube 1 (top) after aluminum oxide blasting.

Figure 140 Corrosion damage on row 7 - tube 13 (bottom) after plastic bead blasting.

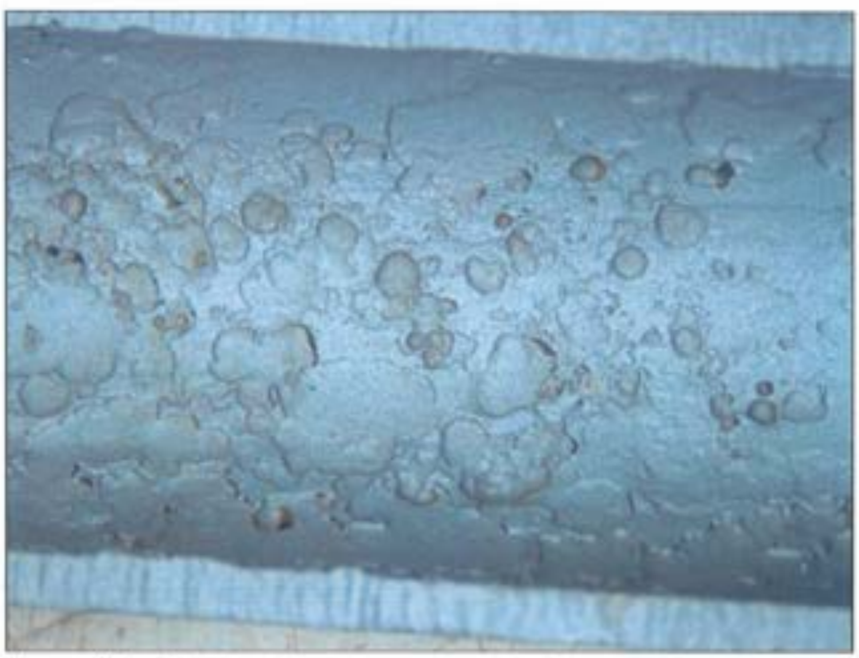

Figure 141 Corrosion damage on row 7 - tube 13 (bottom) after aluminum oxide blasting.

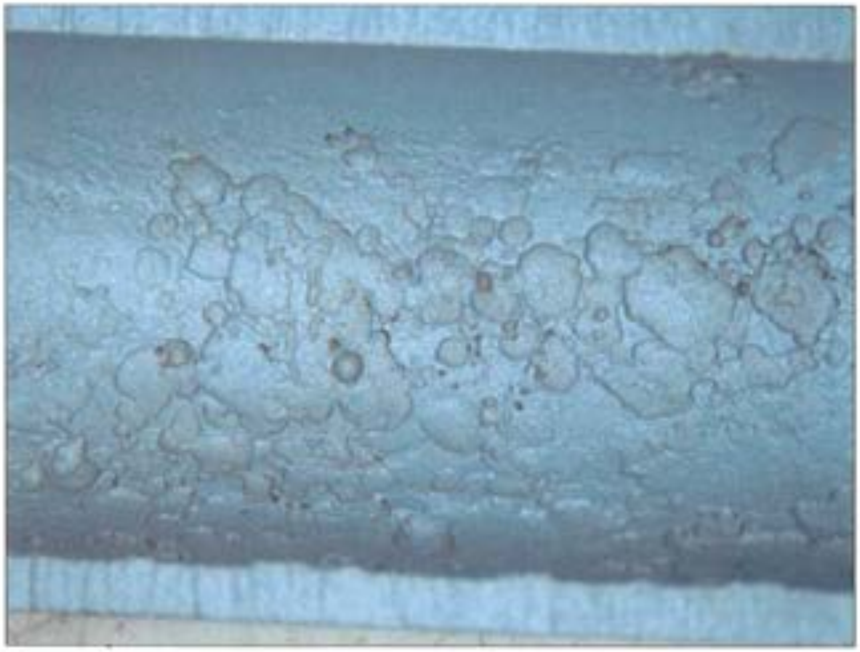

Figure 142 Second area of corrosion damage on row 7- tube 13 (bottom) after aluminum oxide blasting.

Figure 143 Corrosion damage on row 7 - tube 13 (top) after plastic bead blasting.

Figure 144 Corrosion damage on row 7 - tube 13 (top) after aluminum oxide blasting.

Figure 145 Corrosion damage on row 11 - tube 1 (bottom) after plastic bead blasting.

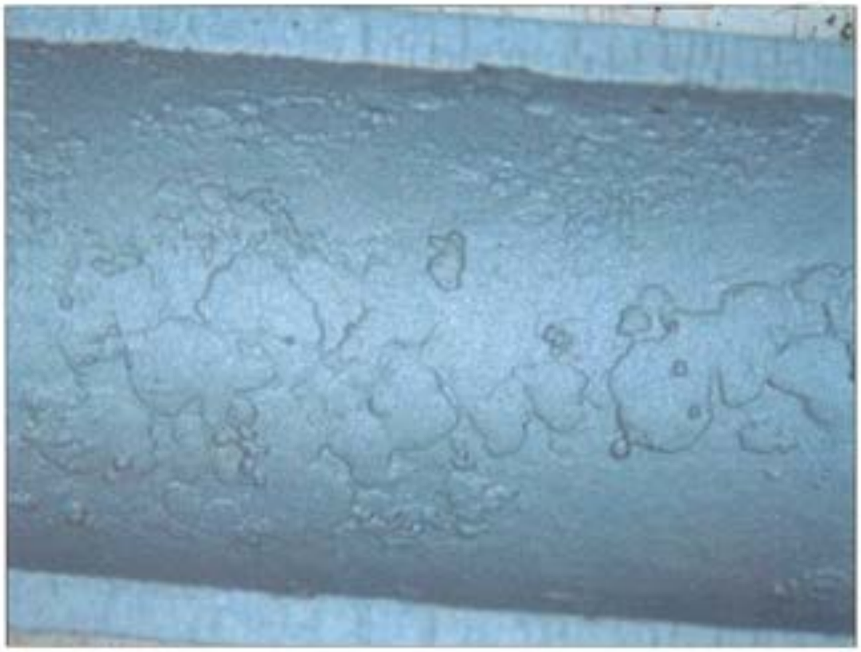

Figure 146 Corrosion damage on row 11 - tube 1 (bottom) after aluminum oxide blasting.

Figure 147 Corrosion damage on row 11 - tube 1 (top) after plastic bead blasting.

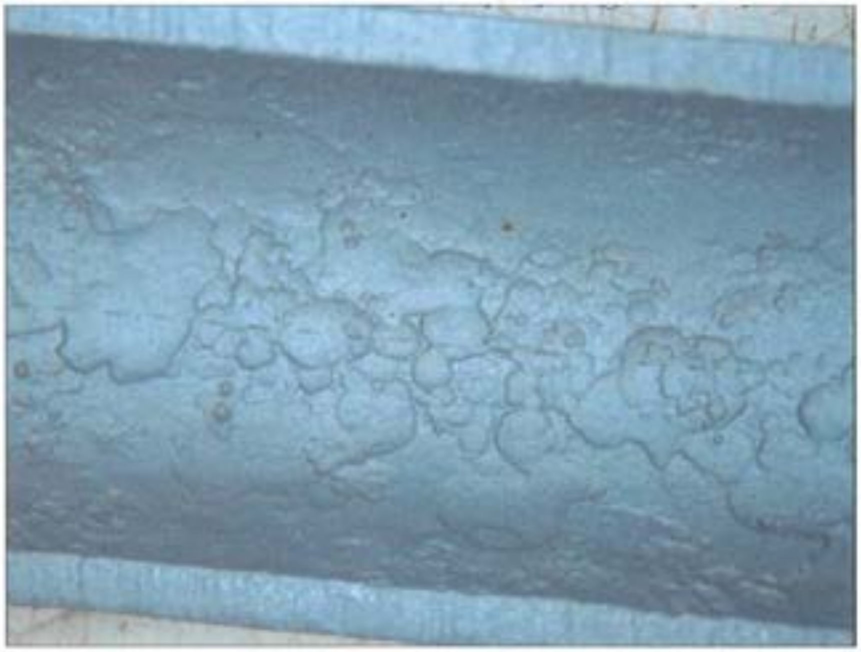

Figure 148 Corrosion damage on row 11 - tube 1 (top) after aluminum oxide blasting. Note "stitching" along fusion line of ERW joint.

Figure 149 Corrosion damage on row 11 - tube 10 (bottom) after plastic bead blasting.

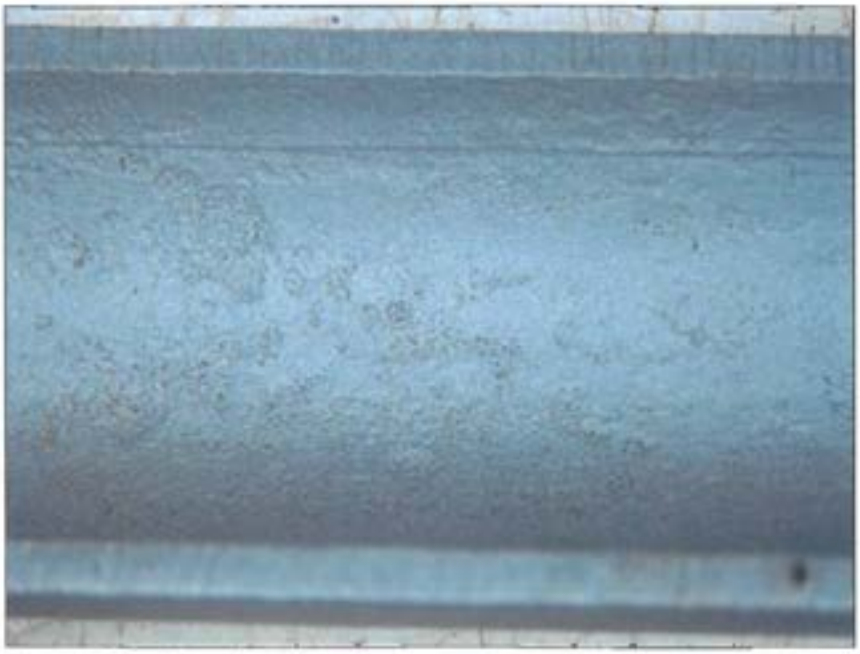

Figure 150 Corrosion damage on row 11 - tube 10 (bottom) after aluminum oxide blasting.

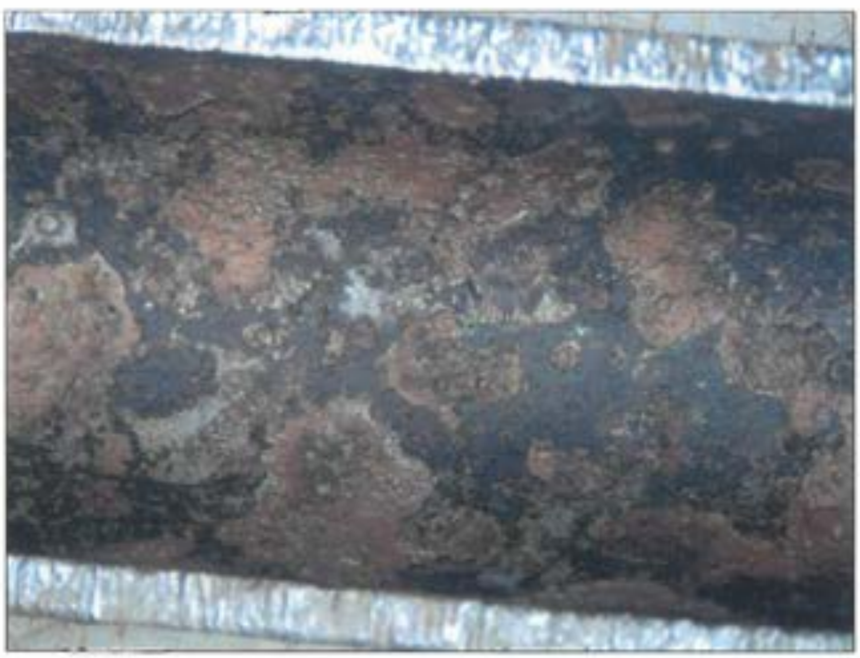

Figure 151 Corrosion damage on row 11 - tube 10 (top) after plastic bead blasting.

ACUREN

Figure 152 Corrosion damage on row 11 - tube 10 (top) after aluminum oxide blasting.

Figure 153 Corrosion damage on row 14 - tube 2 (bottom) after plastic bead blasting.

Figure 154 Corrosion damage on row 14 - tube 2 (bottom) after aluminum oxide blasting.

Figure 155 Corrosion damage on row 14 - tube 2 (top) after plastic bead blasting.

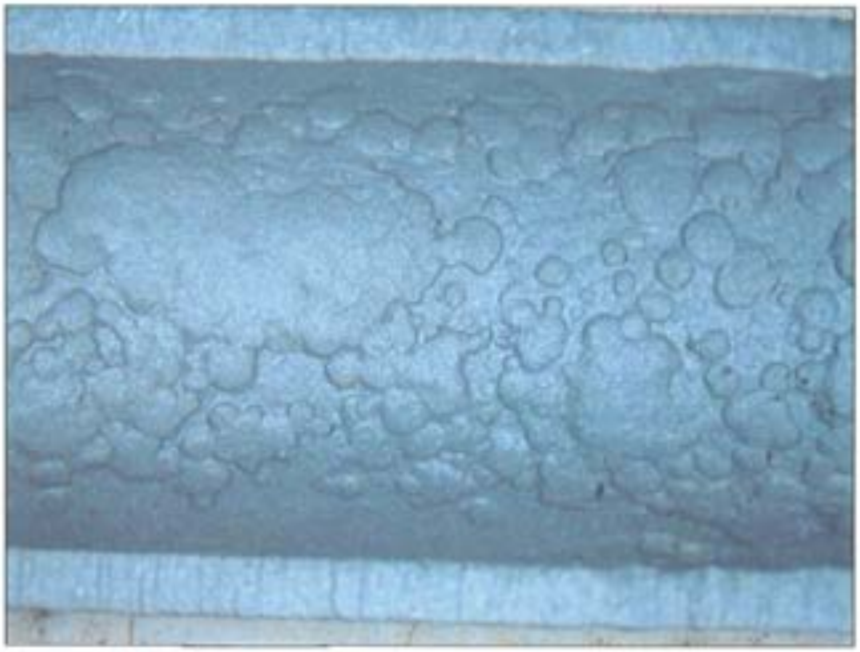

Figure 156 Corrosion damage on row 14 - tube 2 (top) after aluminum oxide blasting.

Figure 157 Second area of corrosion damage on row 14 - tube 2 (bottom) after plastic bead blasting.

ACUREN

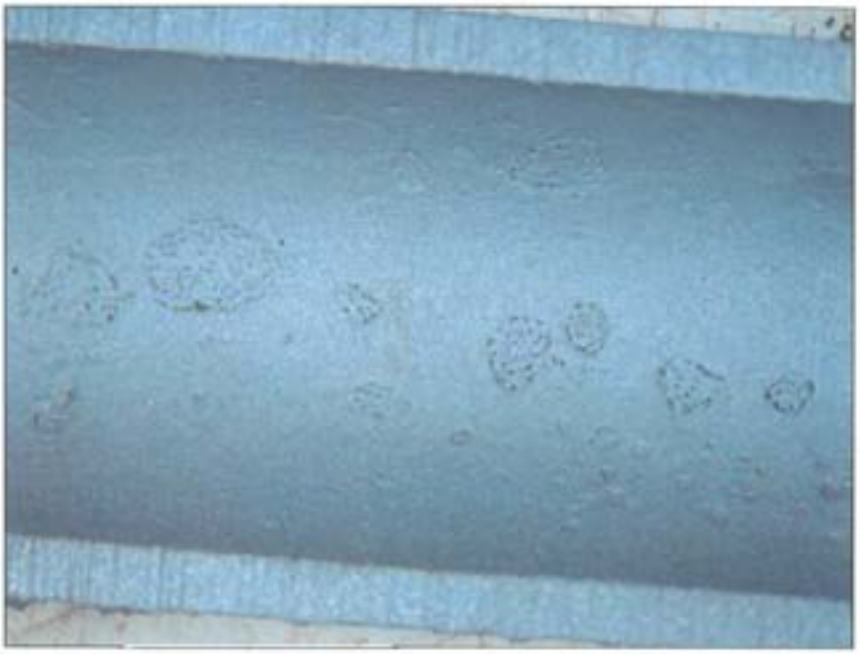

Figure 158 Second area of corrosion damage on row 14 - tube 2 (bottom) after aluminum oxide blasting.

Figure 159 Higher magnification view of typical "stitching" along ERW fusion line.

ACUREN

Figure 160 High magnification SEM view of "stitch" defect EDXA determined that stitch defect is mostly iron oxide.

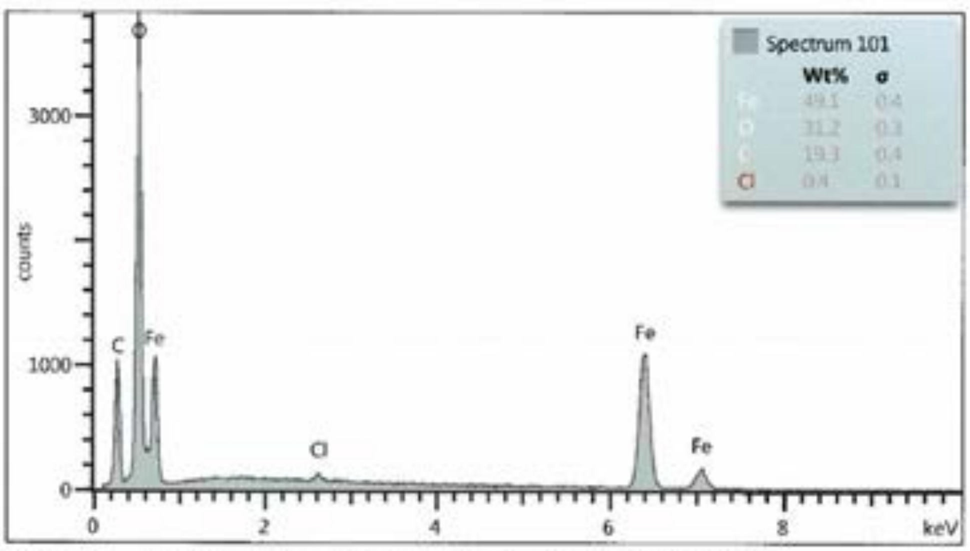

Figure 161 EDXA analysis of material in typical fusion line "stitch" area.

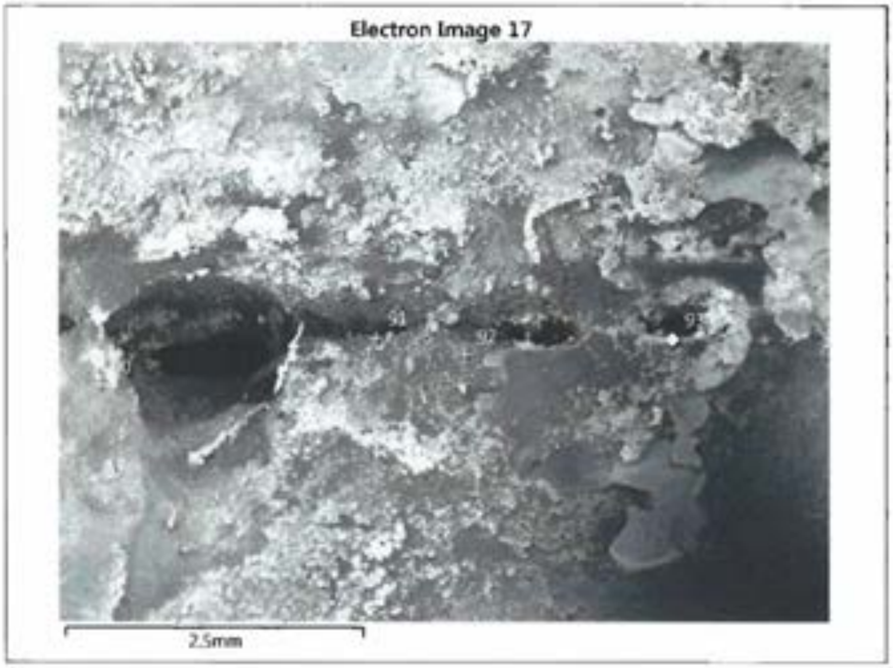

Figure 162a SEM view of scale surrounding leaking defect.

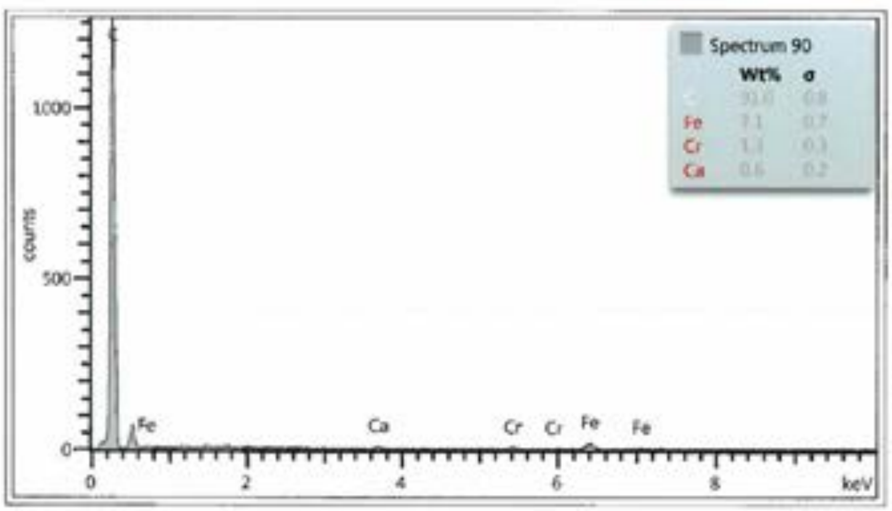

Figure 162b Area 90 containing mostly organic material.

ACUREN

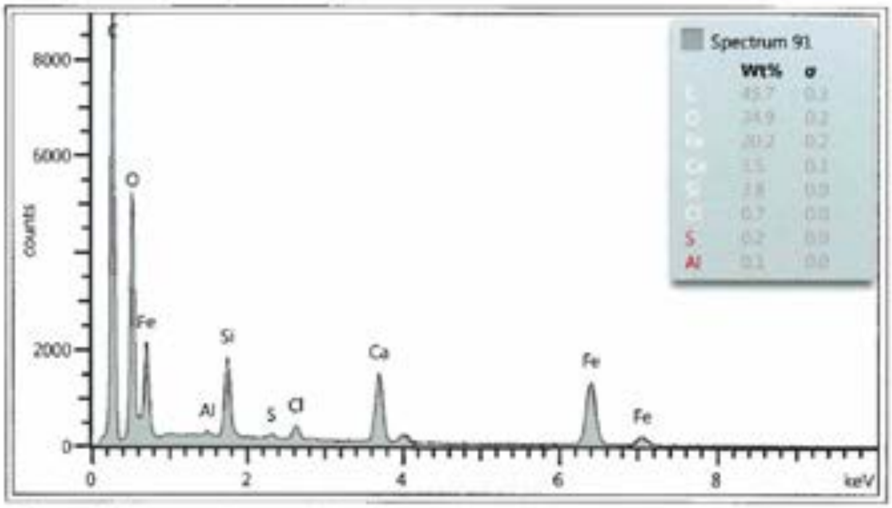

Figure 162c Area 91 containing iron oxide, calcium chloride and silica.

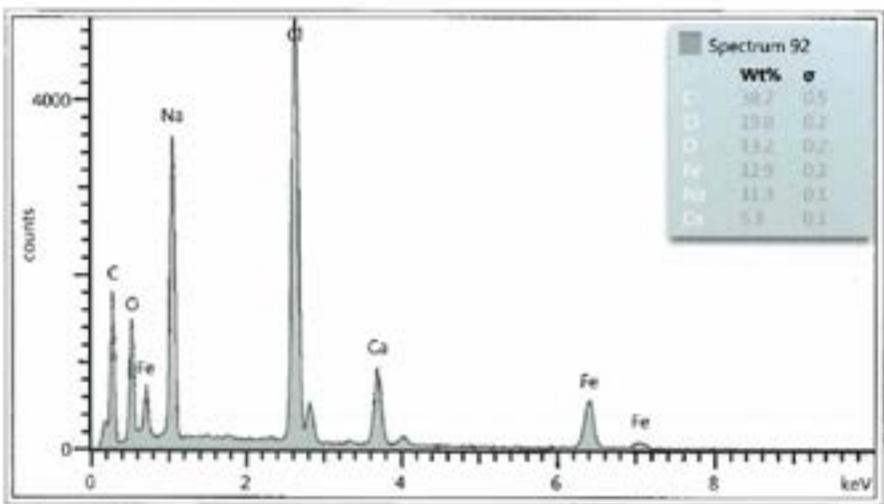

Figure 162d Area 92 containing large chlorine, calcium and iron peaks. Sodium chloride appears to have been present in the brine as a contaminant.

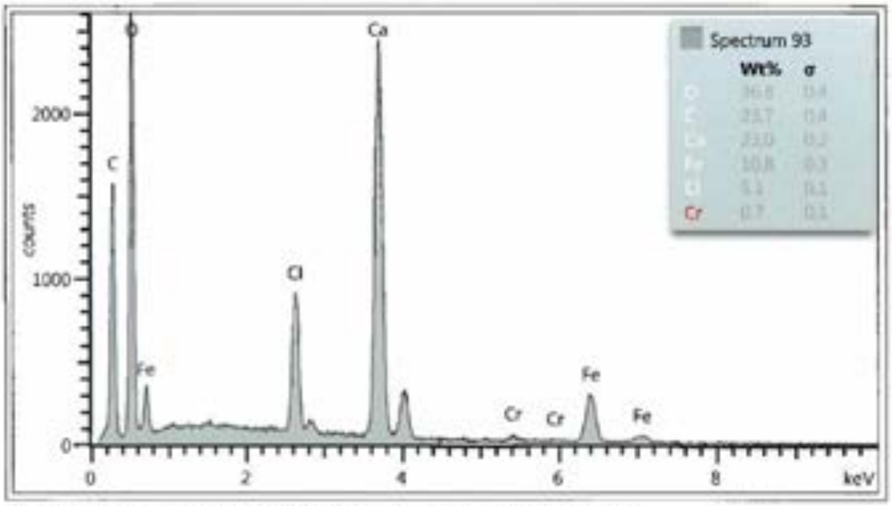

Figure 162e Area 93 containing mostly calcium chloride.

Figure 163 Cross section through typical pit in row 7 – tube 1.

ACUREN

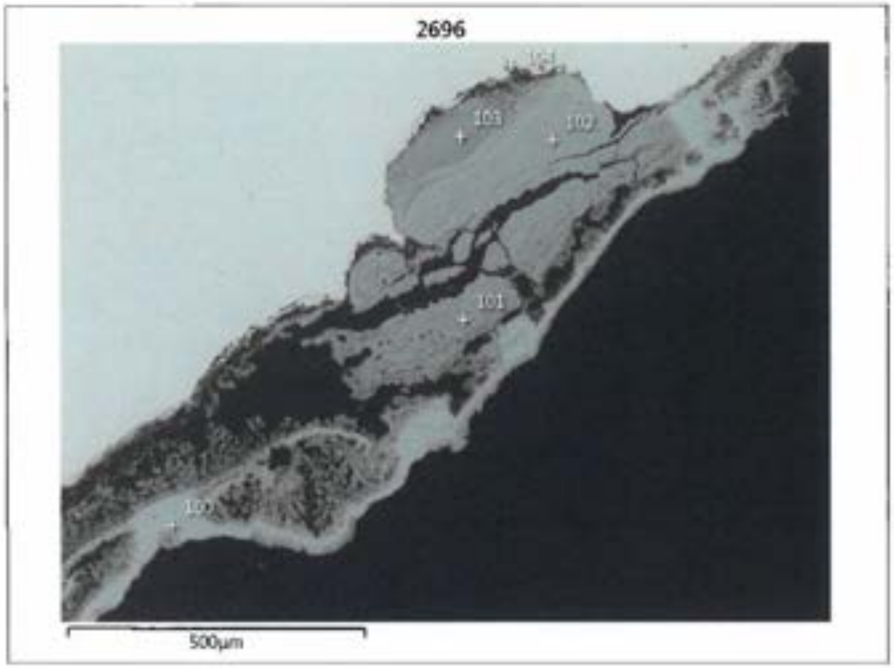

Figure 164a Typical pit in row 7 – tube 1 showing different layers Corrosion mechanism is chloride induced pitting as indicated at area 104.

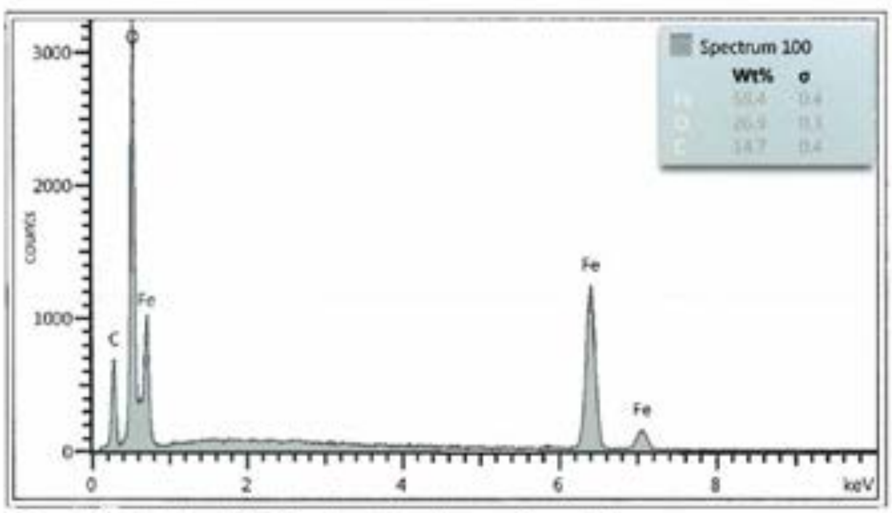

Figure 164b Area 100 showing relatedly pure iron oxide.

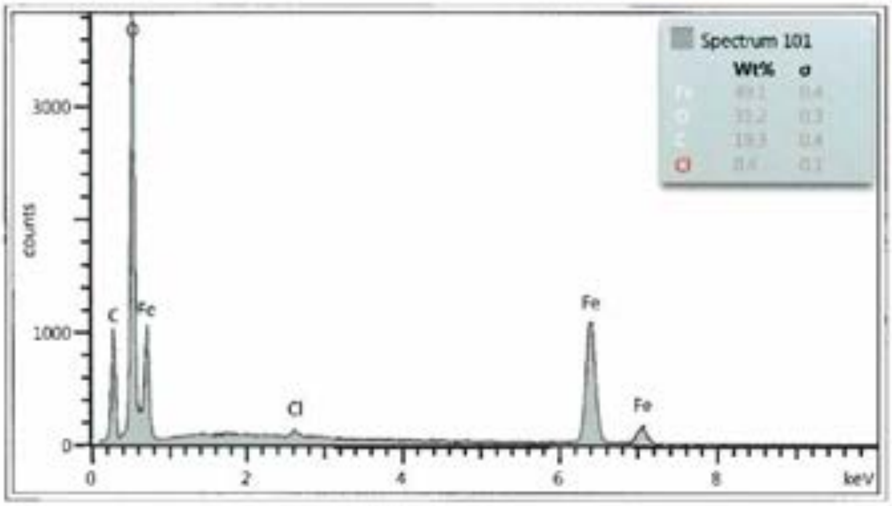

Figure 164c Area 101 with iron oxide and small amounts of chlorine.

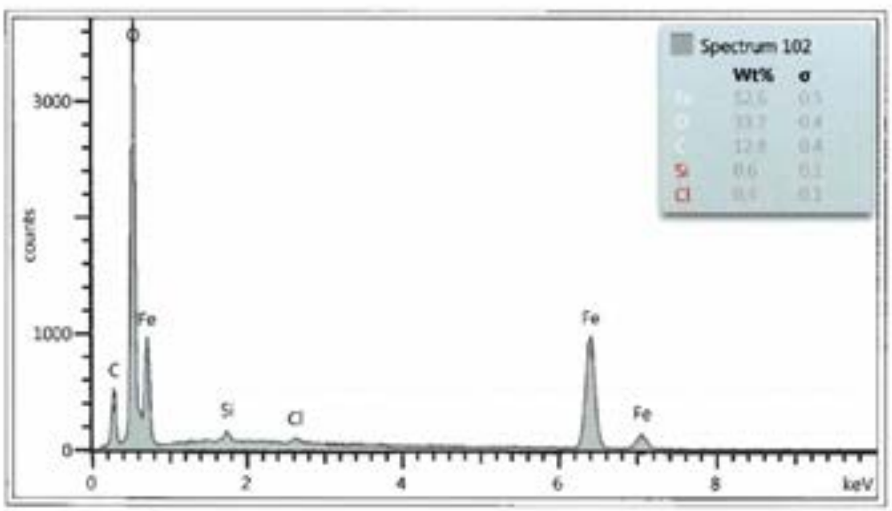

Figure 164d Area 102 with iron oxide and small amounts of silica and chlorine.

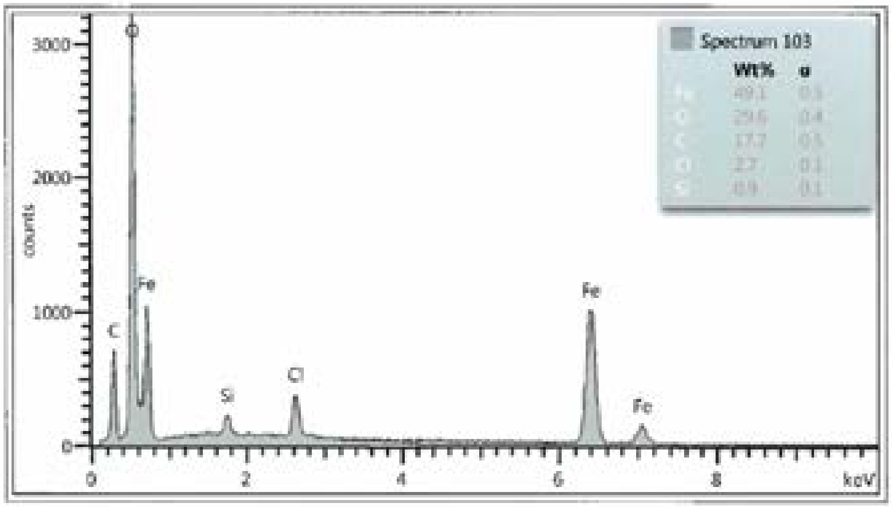

Figure 164e Area 103 in layer area immediately above steel interface showing relatively high chlorine content.

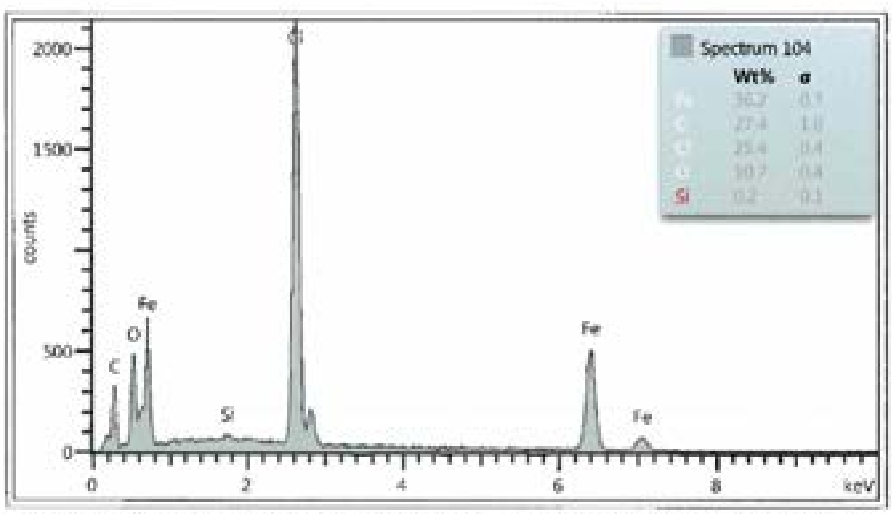

Figure 164f Area 104 in direct contact with steel interface showing very high chlorine content. Material at the interface is iron chloride ($FeCl_3$, black colour).

ACUREN

APPENDIX B

NDT REPORT

Acuren Group Inc.
12271 Horseshoe Way
Richmond, BC, Canada V7A 4V4
www.acuren.com

Phone: 604.275.3800
Fax: 604.274.7235

NDT, Inspection and Engineering

NONDESTRUCTIVE EXAMINATION

TO: WORKSAFE BC
8100 GRANVILLE AVENUE
RICHMOND, B.C.
V6T 3T6

APPENDIX: B

PAGE: 128 of 132

DATE: April 24, 2018
ACUREN JOB #: 60514011
REPORT #: N/A
PO: Pending

ATTENTION: **STEPHEN LIU**

WORK LOCATION: Acuren shop, Richmond, BC

PROJECT: Ammonia Chiller

ITEM(S) EXAMINED: Ammonia Chiller

PART #: N/A MATERIAL: Carbon steel THICKNESS: See below

SCOPE: To conduct ultrasonic thickness measurements on the shell of ammonia chiller.

TYPE OF INSPECTION: Ultrasonic

TEST DETAILS:

ACCEPTANCE STANDARD: Client's information REVISION: N/A
PROCEDURE/TECHNIQUE: CAN-UT-14T001 REVISION: 7

TYPE: Flaw Detection METHOD: Contact

INSTRUMENT: Olympus MODEL: Epoch 650 S/N: 150015301 CAL DUE: April 04, 2019

CAL BLOCK: Step Block S/N: 172714 CABLE-TYPE: Coaxial LENGTH: 1.8m
CAL BLOCK: N/A S/N: N/A COUPLANT: Sonotech - UT-X

Probe & Technique Details:

	TEST ANGLE (°)	PROBE TYPE	CRYSTAL SIZE	FREQ. (MHZ)	SERIAL NUMBER	DAMPING Ω	TEST FROM	REFERENCE REFLECTOR	TRANSFER VALUE	REFERENCE dB	REFERENCE % FSH	SCAN dB	RANGE
1	0	Single	¼"	5	871653	50	OD	Back wall	N/A	64	100	+6	0.750"

TEST SURFACE CONDITION: As coated TEST SURFACE TEMPERATURE: 0°C to 50°C

RESULTS:

As requested, ultrasonic thickness measurements were taken on the shell of ammonia chiller and measurements were taken at four quadrants and every 6" apart.

- Shell thickness ranged from 0.238" to 0.250" and see below Table 1 for details.

CLIENT REPRESENTATIVE:
TECHNICIAN: (Signature on Original)

2nd Technician

REVIEWER:

TOTAL HOURS S.T. O.T. SHIFT
1ST TECHNICIAN: Day ☐
2ND TECHNICIAN: PM ☐
KILOMETRES: N/A OTHER CHARGES: YES ☐ NO ☐
(IF YES, SEE DAILY OR PROJECT TIME REPORT)
(Generated Using: CAN-QUA-02F007 R02 - 12/15/2015)

FIGURE B1: AMMONIA CHILLER

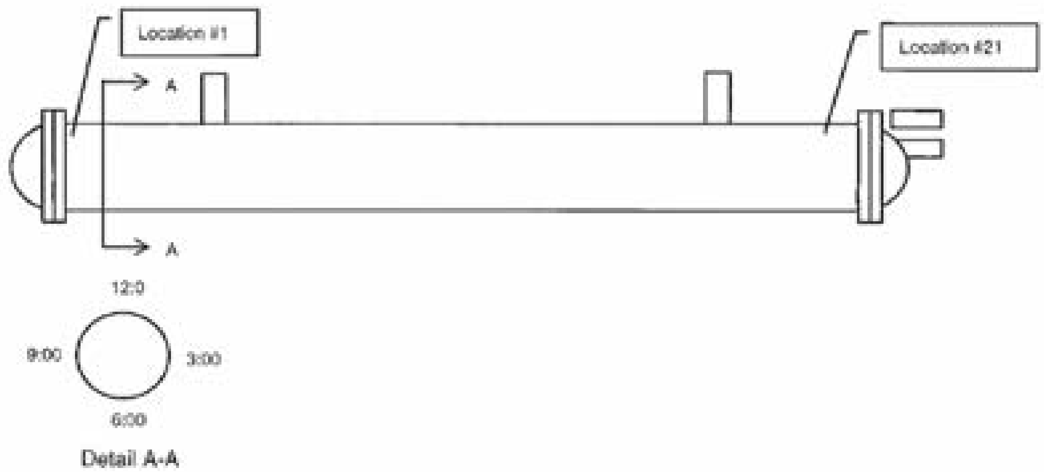

TABLE 2: ULTRASONIC THICKNESS MEASUREMENTS

LOCATION	@12:00	@3:00	@6:00	@9:00
1	250	245	245	249
2	246	246	243	245
3	246	245	243	245
4	248	246	242	244
5	246	247	243	243
6	247	248	243	244
7	248	249	243	244
8	248	245	243	245
9	248	246	247	245
10	248	244	243	246
11	248	247	245	247
12	244	247	243	245
13	246	244	244	246
14	244	242	243	245
15	244	242	241	243
16	243	243	240	244
17	245	248	242	243
18	246	245	240	243
19	243	246	238	248
20	244	243	242	243
21	250	242	240	246

Note: Measurement is in thousandth of an inch, otherwise specified.

ACUREN

APPENDIX C

CURRICULUM VITAE; R.W. MILNE, P.ENG.

BOB MILNE
P.Eng.

Manager –Engineering Group
Pacific Region

EDUCATION

1977 Bachelor of Applied Science (Metallurgy), University of British Columbia

PROFESSIONAL MEMBERSHIPS

Association of Professional Engineers and Geoscientists of British Columbia

American Society for Metals (ASM)

National Association of Corrosion Engineers (NACE)

EXPERIENCE

Bob Milne joined Acuren as a senior metallurgical engineer in 1989. Prior to that, he spent 13 years with B.C. Hydro and Powertech Labs performing failure analysis, materials engineering and maintenance engineering.

Bob manages our staff of engineers, laboratory technicians, and visual inspection technicians. The engineering department provides services to industrial, aerospace, construction, insurance, and legal clients. Approximately 2000 separate projects are performed within his supervision each year. The staff provides consulting and testing in failure analysis, materials selection and testing, specification preparation, quality assurance, welding engineering, corrosion engineering, and scanning electron microscopy.

Bob is active in the field, as well as in the laboratory, performing fitness for purpose evaluations using fracture mechanics, strain gauging, and FEA techniques. He is often called upon to act as an expert witness in legal and insurance matters, and has a particularly valuable understanding of the power generation, pipeline and aerospace industries.

ACUREN
NDT, Inspection and Materials Engineering
a Rockwood Company