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METALLURGICAL INVESTIGATION OF A FRACTURED SECTION OF THE 20" O.D. PIPELINE AT MILEPOST 314.77 IN THE CONWAY TO CORSICANA SEGMENT OF THE PEGASUS CRUDE OIL PIPELINE

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REPORT NO. 64961

Prepared for ExxonMobil Pipeline Company and
the Pipeline and Hazardous Materials Safety Administration
pursuant to Corrective Action Order CPF 4-2013-5006H

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METALLURGICAL INVESTIGATION OF A FRACTURED SECTION OF THE 20" O.D. PIPELINE AT MILEPOST 314.77 IN THE CONWAY TO CORSICANA SEGMENT OF THE PEGASUS CRUDE OIL PIPELINE

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1.0 INTRODUCTION

1.1 Brief Narrative of the Incident

On March 29, 2013 at 2:37 pm CST, a drop in pressure was detected within the Pegasus Pipeline of the Conway to Corsicana line segment by ExxonMobil Pipeline Company (EMPCo) at their Operations Control Center in Houston, Texas. The cause of the pressure drop was the rupture of a section of the pipeline at Milepost 314.77 in Mayflower, Arkansas. The operating pressure at the time of failure was estimated to be between 702 psig and 708 psig.

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1.2 Scope of the Investigation

Hurst Metallurgical Research Laboratory, Inc. (HurstLab) was retained by EMPCo with approval by the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA), to provide technical support in the investigation of the failed section of the pipeline, as well as conduct and direct the required metallurgical tests to determine, if possible, the root cause of the failure pursuant to Corrective Action Order CPF 4-2013-5006H.

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The investigation of the cracked section of the pipeline conducted by HurstLab is a joint effort by various staff members of the Laboratory, which includes some of the report writing and analysis conducted by Susan Dalrymple-Ely, Materials Analyst and metallurgical tests conducted by Clint Myers, Staff Metallurgist of the Laboratory. The investigative effort made by this Laboratory also includes a review of the UT data and SEM fractographs provided by approved vendors.

The investigation conducted by this Laboratory is primarily based on the tests and analyses performed in accordance with the approved test protocol, review of the available information and research conducted by this Laboratory. We reserve the right to change, amend, or omit our opinions, as warranted, based upon any additional information or further test results that may be obtained or made available to this Laboratory.

1.3 Development of Test Protocol

On April 13, 2013, a preliminary metallurgical test protocol was development by HurstLab following the general guideline entitled "Metallurgical Laboratory Examination Protocol" dated 05/08/2007 for metallurgical failure investigation of pipeline prepared by PHMSA. Following various revisions that were made to incorporate the changes requested by PHMSA, a protocol entitled "Pegasus Line - Conway to Corsicana M.P. 314.77, Mechanical and Metallurgical Testing and Failure Analysis Protocol", referenced as Test Protocol Rev. 4, CPF No. 4-2013-5006H, Amended 4/18/13, was developed and approved by PHMSA. A copy of the final approved protocol is presented in Appendix I.

2.0 BACKGROUND INFORMATION

2.1 Pipe Manufacturing and Coating

2.1.1 The subject section of the 20" Patoka to Corsicana #1-20" North Pipeline, the segment from Conway to Corsicana, consisted of approximately 50' long sections of 20" O.D. x 0.312" thick wall DC Electric Resistance Welded (ERW) pipe that was manufactured in 1947 and 1948 by Youngstown Sheet and Tube Company in Youngstown, Ohio. The welded pipe was manufactured from Open Hearth Steel meeting Grade B mechanical requirements.

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2.1.2 The O.D. surface of the pipeline was coated with some type of a viscous bitumen or coal-tar coating, on top of which was a layer of somewhat harder but more brittle fibrous coating. No details concerning the coating type or process were available. The pipeline had reportedly been impressed current cathodically protected since installation, with possible anodes as well. The weight of the coated pipe was reported to be 65.71 lb/ft.

2.2 Inspection and Service History

2.2.1 The subject section of pipeline was placed in service in 1948, and was buried approximately 3' below ground in native sandy clay soil. The pipeline carried crude oil from west Texas to Patoka, Illinois between 1948 and 1995. From 1995 to 2002, the line carried both west Texas crude oil and foreign crude oil (via the Gulf of Mexico) northward. In December 2002, the line was purged and idled with nitrogen. The pipeline containing the subject section of the pipe was successfully hydrostatic tested on January 24, 2006 at 1082 psig, which established a calculated MAOP of 866 psig at the failure location (based upon the Arkansas River ROV test site pressure at 1091 psig adjusted for elevation difference to the failure location). The line was then placed back in service transporting crude oil south towards the Gulf of Mexico, and remained in service up until the time of the failure.

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2.2.2 Prior to failure, the pipeline was reported to typically operate between 47°F and 78° at pressures ranging between 240 psig and 820 psig. The pressure at the time of the failure was estimated to be between 702 psig and 708 psig. The fractured segment of the pipeline was located in a cleared right-of-way at the edge of a subdivision. No trees, roads, or buildings were located directly above the pipeline at the fractured segment. As noted in Figure 1, two homes were built in close proximity to the pipeline, with driveways crossing over the pipeline at two points downstream of the fractured segment. During construction of the homes, the pipeline may have experienced vehicle loadings caused by construction equipment and/or vehicles crossing the pipeline at multiple locations, including over the fractured segment. There was no indication of construction, digging, localized flooding, or other ground movements in the area of the fractured segment occurring at or immediately prior to the pipeline rupture.

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2.3 Specifications

2.3.1 At the request of EMPCo, the subject pipe was compared to two (2) versions of the API 5L specification throughout this report, both the edition that was in effect at the time the pipe was manufactured, and the current edition of said specification, both of which are detailed below.

2.3.1.1 At the time the pipe was manufactured in 1947 and 1948, the specification in effect was API STD. 5-L, 10th Edition, August 1945. Per this specification, the smelting type of steel was reportedly Open Hearth Steel, the pipe was classified as an Electric Welded Pipe, and the strength was specified to meet Grade B requirements. This edition will be referred to as API 5-L, 10th Edition throughout the report and the accompanying tables.

2.3.1.2 The currently applicable edition of the specification is ANSI/API 5L, 44th Edition, Effective October 1, 2007, with Errata dated January 2009, Addendum 1 dated February 2009, Addendum 2 dated April 2010, and Addendum 3 dated July 2011. The requirements for PSL 1 Welded Pipe, Grade X42 will be used for comparison, with the exception of the Charpy V-Notch (CVN) impact tests. For the CVN impact tests, there are no requirements for PSL 1 Welded Pipe, so the requirements for PSL 2 Welded Pipe will be referenced instead. This edition of the specification will be referred to as API 5L, 44th Edition throughout the report and accompanying tables.

2.4 Items Received for Testing

2.4.1 On April 16, 2013 at approximately 1:50 pm CST, HurstLab received two (2) cut sections of pipe, and various other items from the failure location in Mayflower, Arkansas, which were transported on a flatbed. The two (2) sections of pipe were each wrapped in protective plastic with the open ends of the pipe sealed, with the entire surface covered with plastic padding to protect from damage during loading/unloading and transportation. A 55 gallon steel drum, containing the coating that was removed in the field where the pipe was sectioned transversely, as well as a small bag containing possible calcareous deposits, were also received. The two (2) sections of pipe are described below in the same manner they are referenced throughout the report.

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1:50 pm CST

1) 33' 11-1/2" Long Fractured Section of a 20" O.D. x 0.312" wall Pipe; Removed from Milepost 314.77 in the Conway to Corsicana Pegasus Crude Oil Pipeline after it failed in service in Mayflower, Arkansas;

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2) 19' 10" Long Intact Section of a 20" O.D. x 0.312" wall Pipe; Removed from Milepost 314.77 in the Conway to Corsicana Pegasus Crude Oil Pipeline after it failed in service in Mayflower, Arkansas;

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1947 to 1948

The Chain of Custody documents for the sections of pipe, as well as the steel drum of coating material and the possible calcareous deposits as well as the photographs documenting the evidence in the as-received condition are presented in Appendix II of this report.

3.0 METALLURGICAL EXAMINATION, TESTING AND ANALYSIS

3.1 Visual and Macroscopic Observations

3.1.1 A 49' 9-1/2" long section of the Pegasus Pipeline, which fractured over a length of 22' along the ERW seam and 3" into the base metal at Milepost 314.77 in Mayflower, Arkansas, as shown in Photographs No. 1 through No. 3, was removed from the ground by sectioning through three (3) locations of the pipeline following removal of the coating at those areas on the O.D. surface. The pipeline was transversely sectioned 3' upstream from the north girth weld through the adjoining intact pipe, 33' 11-1/2" from the north cut end, and 1' downstream from the south girth weld through the adjoining intact pipe.

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3.1.2 The sections of pipe were received at HurstLab on April 16, 2013. The protective plastic, wrapping, and end plugs from both 33' 11-1/2" and 19' 10" long sections of the pipeline were carefully removed following receipt for examination, documentation of the evidence in the as-received condition, and to allow examination of the general condition of the pipe sections, such as fracture, ERW seam and girth weld conditions, coating condition, evidence of any corrosion, mechanical damage, etc. Photographs No. 4 through No. 7 display the pipe sections in the as-received condition, and following removal of the plastic and wrapping.

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Examination of the 33' 11-1/2" long section of the pipe revealed a 22' long fracture along the ERW weld seam, which traversed diagonally, approximately 3" in length, into the base metal near the south end of the fracture. The fracture faces had been coated with a protective white grease in the field following the pipeline rupture to help preserve the fracture faces for subsequent analysis. All four (4) cut ends of the pipe sections were marked in the field denoting the location of the ERW seam, the relative position in ground, direction of the crude oil flow, station number and field cut match line in each section of the pipe. Photographs No. 8 and No. 9 display the as-received condition of the pipe and field markings on the pipe sections.

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3.2 As-Received Condition of the Pipe and Coating

3.2.1 Following unloading of the pipe from the transport truck and unwrapping of the protective material, the pipe was closely inspected to ascertain and document the as-received condition of the pipe and the coating. The 3' 11-1/2" long section of pipe contained a circumferential girth weld at the north end, and an approximately 3' long section of the adjoining intact pipe. The fracture, which followed the ERW seam at the 12:00 o'clock position of the pipe, extended 22' 3" in length, with one crack tip terminating in the north girth weld and the other in the base metal adjacent to the ERW seam. The maximum separation of the open fracture was approximately 1-3/8" wide near the center of the crack, 12' from the north girth weld.

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3.2.2 Examination of the coating noted a number of areas where the coating was damaged or split adjacent to the ERW seam. The maximum width and depth of the various splits in the coating on the O.D. surface of the pipe adjacent to the ERW seam, between the

10:30 and 1:30 positions, were measured and photographically documented. Photographs No. 10 through No. 23 show the condition of the coating from 3' north of the north girth weld, referenced to as -3' from the north girth weld, to the girth weld at 0', and all the way to 50' 9-1/2" south of the north girth weld. As previously mentioned, the coating had been removed in the field from the areas where the pipe had been transversely sectioned.

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Distance from North Girth Weld		Max. Coating Split Width	Max. Coating Split Depth	Notes
-3'	0'	1"	**	Some coating had been removed during sectioning in the field
0'	4'	2"	0.10"	Longitudinal fracture or rupture extended from the north girth weld at 0' to 22'
4'	8'	0.5"	0.14"	
8'	12'	0.5"	**	
12'	16'	**	0.07"	
16'	20'	0.25"	0.09"	
20'	24'	0.5"	0.10"	
24'	28'	1.5"	0.10"	
28'	30' 11-1/2"	1"	0.05"	Some coating had been removed during sectioning in the field
30' 11-1/2"	35'	1"	0.15"	

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Distance from North Girth Weld		Max. Coating Split Width	Max. Coating Split Depth	Notes
35'	39'	1"	0.10"	
39'	43'	0.75"	0.11"	
43'	47'	0.5"	0.11"	
47'	50' 9-1/2"	1"	**	Some coating had been removed during sectioning in the field

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**Not measurable at location.

The total thickness of the coating was estimated to be approximately 0.15" based on relatively intact areas of the coating, so some of the splits in the coating noted in the table above had likely penetrated to the base metal of the pipe.

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In addition to the splits noted above, the coating at the bottom, or 6 o'clock position of the pipe was wrinkled, with the coating appearing to have sagged downward during the years the pipe lay buried. Although the coating did not appear stretched over the top and sides of the pipe, excess coating was folded over at the bottom of the pipe. Several places had small areas of coating missing, although it is not known at what point the coating loss had occurred during service. Additional photographs of the pipe and coating in the as-received condition are displayed in Photographs No. 24 through No. 64.

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3.3 Coating Removal Process

A procedure for a safe removal of the coating from the O.D. surface of the pipe was developed and approved by EMPCo and PHSMA, and is listed in Section A4 of the Test Protocol in Appendix I.

The coating on the O.D. surface of the pipe was carefully removed on April 22, 2013 by Watkins Construction Company, LLC. (Watkins), a vendor contracted directly with EMPCo. Prior to proceeding, the contracted workers were briefed by HurstLab personnel as to the importance of preserving the fracture surface and integrity of the pipe; HurstLab personnel supervised the removal of the coating to ensure the safe removal of the coating.

The coating on both pipe sections was first wet down with water, and each pipe section was then tightly wrapped in plastic wrap to securely collect all the coating. To remove the coating it was first cracked by tapping, and was then gently peeled off. First striking the coating with a resin hammer was tried; when the resin hammer did not crack the coating a steel mallet was used. The steel mallet was tapped against the coating, cracking the coating but not damaging the pipe underneath. The pipe sections were then cleaned using mineral spirits. Extreme care was taken to prevent any damage to the pipe or the fracture surface that could have affected the metallurgical investigation.

All of the coating removed from the pipe sections at HurstLab, as well as the steel drum containing the coating that was removed in the field by EMPCo personnel, was collected and retained at EMPCo's facility in Corsicana, Texas. Appendix III shows several representative photographs of the coating removal process and contains the document signed by the employees of Watkins who removed the coating following the briefing by HurstLab personnel.

3.4 Condition of the Pipe Following Coating Removal

3.4.1 Following removal of the O.D. coating in accordance with the specified guidelines, the pipe sections were re-examined to ascertain and photographically document the conditions of the pipe. The bottom of the pipe sections between approximately 4 and 8 o'clock, at the locations where the coating had wrinkled and sagged, was covered with a reddish-orange substance, likely a mixture of the surrounding native sandy soil that the pipe had been buried in and various corrosion products resulting from contact between the pipeline and moisture. Some light corrosion pitting was visible within this area, as well as at various locations along the O.D. surface where the coating had previously split and allowed moisture to contact the surface of the pipe. No preferential or knife-like corrosion was present along the ERW seam at 12 o'clock.

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3.4.2 The depth of the corrosion pitting at the various locations around the O.D. surface of the fractured pipe section was measured using a certified and calibrated caliper, and the results are summarized in the following table.

Distance from North Girth Weld	Circumferential Location (o'clock position)	Depth of Corrosion Pitting		
		Minimum	Average	Maximum
-3' to 0'	All	No Corrosion Pitting Visible		
0' to 4'	7:30 to 10:00	0.006"	0.017"	0.029"
4' to 8'	1:30 to 3:00	0.008"	0.013"	0.026"
	6:45 to 10:00	0.002"	0.013"	0.037"
8' to 12'	3:45 to 5:00	0.004"	0.011"	0.022"
	7:30 to 11:15	0.002"	0.011"	0.026"
12' to 16'	3:00 to 5:00	0.003"	0.013"	0.033"
	6:30 to 10:00	0.003"	0.017"	0.031"
16' to 20'	2:45 to 5:15	0.005"	0.015"	0.031"
	7:00 to 10:00	0.006"	0.012"	0.021
20' to 24'	2:45 to 5:00	0.004"	0.020"	0.033
	7:15 to 10:00	0.005"	0.010"	0.021
24' to 28'	All	No Corrosion Pitting Visible		
28' to 31'	All	No Corrosion Pitting Visible		

As shown, all of the corrosion pitting occurred between 1:30 and 11:15 o'clock positions on the fractured section of pipeline; no pitting corrosion was observed at the 12 o'clock position where the ERW seam was positioned in the pipe. The average pitting depth over the entire section of the pipe was determined to be 0.014", and the maximum depth at any location was 0.037", which are approximately 4.5% and 12%, respectively, of the total wall thickness of the pipe. No corrosion pitting was present at either cut end of the fractured pipe section. Photographs showing the corrosion pitting on the east and west sides of the pipe following removal of the coating are displayed in Photographs No. 65 through No. 82.

3.4.3 The I.D. surface of both pipe sections was examined using oblique lighting and pivoting mirrors and magnifying glasses prior to sectioning. No corrosion pitting was visible on the I.D. surface of either the fractured or intact sections of pipe. However some shallow bottomed depressions were observed at random locations.

Following sectioning of the 33' 11-1/2" long and the 19' 10" long pipe lengths, the I.D. surfaces at several areas were more closely examined. Multiple shallow depressions (including those noted above) were visible around the entire circumference of the I.D. surface. The depressions were very smooth in appearance and contained no visible corrosion products, suggestive of mechanical deformation as opposed to corrosion pitting. No evidence of any significant corrosion pits was visible on the I.D. surface. Photographs No. 83 and No. 84 show representative areas of the I.D. surface.

3.5 Dimensional Measurements

3.5.1 The out-of-roundness at intact locations at either end of the fracture, as well as at the south cut end of the 33' 11-1/2" long fractured section of pipe was determined as specified in Section 10.2.8.3 of API 5L, 44th Edition. At each of the three (3) locations, four (4) measurements of the I.D. were taken, spanning between 12:00 and 6:00 o'clock, 1:30 and 7:30 o'clock, 3:00 and 9:00 o'clock, and 4:30 and 10:30 o'clock using a certified and calibrated I.D. micrometer. In accordance with the method specified in the aforementioned section of API 5L, 44th Edition, the out-of-roundness at each location was then determined to be the difference between the largest and smallest I.D. measurement. The calculated out-of-roundness at each location is displayed in the following table, along with the API requirements.

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Circumferential Location of Measurement		I.D. Measurement		
		Distance from North Girth Weld		
Begins	Ends	-6"	271"	371"
12:00	6:00	19.3652"	19.363"	19.392"
1:30	7:30	19.463"	19.375"	19.457"
3:00	9:00	19.353"	19.390"	19.357"
4:30	10:30	19.350"	19.354"	19.437"
Calculated Out-of-Roundness		0.111"	0.036"	0.100"
API 5L, 44th Edition, Table 10, Pipe Except End Out-of-Roundness tolerance for D = 20"				0.400"

As shown, at each of the locations tested the calculated out-of-roundness was determined to be within the allowable tolerance specified in API 5L, 44th Edition, Table 10 for welded pipe with a nominal O.D. between 6.625" and 24". The results of the multiple I.D. measurements and the out-of-roundness calculations are recorded in Table 1.

3.5.2 Wall thickness measurements of the failed pipe were made at 2" intervals along the fracture adjacent to each mating fracture surface, using a certified and calibrated micrometer. The measurements were taken beginning at a location 40" south of the north girth weld and terminating at the fracture tip, located 267"(22' 3") from the north girth weld. Although the other fracture tip was located at the north girth weld, the distance between the mating fracture surfaces was too small to allow for accurate wall thickness measurements at or directly adjacent to the north girth weld.

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The smallest wall thickness was measured to be 0.310" and the largest was 0.321". The average wall thickness was calculated to be 0.315", while the nominal specified wall thickness for the 20" O.D. pipe was 0.312". The complete results of the wall thickness measurements taken on either side of the crack using a certified and calibrated digital micrometer are recorded in Table 2.

3.5.3 The wall thickness of the fractured pipe was measured at numerous locations both at and away from the fracture by SGS-PfiNDE, Inc. (PfiNDE), an approved third party vendor using the non-destructive ultrasonic test method.

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3.5.3.1 A grid or 'map' of ultrasonic wall thickness measurements, covering from 12" upstream to 12" downstream of the fracture and around the entire 360° circumference of the pipe, were taken at 2" intervals over a total pipe length of 24.67'. The wall thickness was determined to range between 0.288" and 0.316" along the evaluated length. No internal corrosion areas were noted, although a linear inclusion in the mid-wall area of the pipe was noted on the CMAPPs (AUT) inspection. The complete results of the ultrasonic wall thickness measurements of the fractured pipe are recorded in Appendix IV.

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3.6 Residual Stresses

3.6.1 As the pipe containing the fracture was being sectioned for fractographic examination, a significant amount of displacement of the sectioned portion of pipe was observed near the fracture tip adjacent to the north girth weld, as shown in Photograph No. 85, indicating the pipe was placed under a considerable amount of constraint since it was manufactured, placing the ERW seam under

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sustained tension forces,

which contributed to the increase in stresses at the ERW seam joint. Specifically, Photograph No. 85 shows elastic spring back along the axial direction of the pipe, confirming the presence of axial residual stress. In addition, the separation of the fracture faces confirms elastic spring back in the circumferential direction indicating the presence of circumferential residual stress likely associated with the pipe's original forming and seam welding. However, the extent to which these residual stresses may have contributed to the initiation of hook cracks or final fracture is unknown at this time.

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3.7 Fractographic Examination

3.7.1 The mating fracture faces of the entire 22' 3" long fracture were visually examined using the oblique lighting prior to removal of the coal-tar coating, but following removal of the protective grease with mineral spirits, acetone, and a nylon brush. A thorough, careful examination of both mating fracture faces of the fracture revealed fine chevrons or radial lines emanating from the fracture zone at a distance between 19' 10" and
21' 6-1/4" from the north girth weld, indicating that the final fracture which resulted in the leakage of the crude oil originated from this zone. Visual examination of the mating fracture faces from the distance between 1/4" and 26" south of the north girth weld revealed evidence of upturned grain flow lines, or bands, and/or inclusions near the outer wall. However there was no evidence of any chevron marks pointing to this fracture zone, indicating that the fracture did not initiate from this zone, but rather propagated through the surface imperfections. Photograph No. 86 displays overall and close-up views of the fracture origin and the tip areas, as well as field markings on the pipe.

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The fracture zone from a distance between 19' 10" and 20' from the north girth weld was further examined to characterize the fracture morphologies. Fractographic examination revealed flat, highly oxidized, flaw zones predominantly in the upper half (adjacent to the O.D. surface) of the fracture surface along the ERW seam, which are characteristic of hook crack defects. Examination further revealed radial lines emanating from the tips of the hook cracks, indicating that the final rupture originated from the roots or tips of initial hook cracks, which had reduced the effective cross-sectional area of the wall at the ERW seam location. A hook crack is defined in API Bulletin 5TL as "Metal separations resulting from imperfections at the edge of the plate of

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skelp, parallel to the surface, which turn toward the inside diameter or outside diameter pipe surface when edges are upset during welding." Photograph No. 87 displays the fracture initiation sites with insert photographs, revealing the hook cracks, fracture zones, and the direction of the

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fracture propagation. The secondary fracture zone, found from a distance between 1/4" and 26" from the north girth weld, also, contained ERW seam manufacturing imperfections in the upset/HAZ area. That area (displayed in Photographs No. 88 through No. 94), however, most likely failed as a result of the fracture propagation during the rupture event.

3.7.2 A sample of the pipe (approximately 3-1/2" to 4" in width and approximately 40" in length) containing the hook cracks, was cut and removed from the pipe for closer examination of the O.D. and I.D. surfaces, and characterization of the fracture morphology. Photographs No. 95 and No. 96 display the cut sections. Close-up examination of the fracture face from a distance between 18' 10" and 19' 10-1/4" from the north girth weld revealed fine chevrons pointing to the hook cracks, indicating that the final fracture/rupture originated from the hook cracks and propagated upstream toward the north girth weld through the HAZ of the ERW seam. Photographs No. 97 through No. 100 display the evidence of chevrons pointing to the hook cracks. Further examination of the fracture face from a distance between 19' 10" and 20' 8" from the north girth weld revealed continuation of the hook cracks and transitioning of the radial lines into vertical lines, indicating the primary fracture/rupture origins to be between 20' 2-3/8" and 20' 7-3/8", as displayed in Photographs No. 101 through No. 103. Examination of the remaining fracture surface of the selected fracture face revealed continuation of the hook cracks with intermittent termination and continuation up to a point approximately 20' 11" from the north girth weld and occasional hook cracks near the lower half of the pipe wall with chevrons pointing in the opposite direction, indicating that the remaining final fracture propagated toward the south end and terminated in the base metal, as displayed in Photographs No. 104 through No. 110.

In addition to the total depth of the initial hook cracks, the length and depth below the O.D. surface of several various fracture zones on the fracture surface were measured as per the client's request. The darker smooth areas on the fracture surface, all beginning at the O.D. surface, indicated areas of the initial hook cracks that contained a tightly adhered layer of oxide scale suggesting long-term exposure to moisture; the length and maximum depth of each of these areas was measured. Several longitudinal ridges were also visible on the fracture surface within the initial fracture zone, formed as a result of the microstructural

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conditions of the upturned

grains within the ERW seam upset and primary HAZ through which the fracture occurred. The following table records the measurements, along with the distance from the north girth weld and reference to the photographs showing the various fractographic features.

Fracture Zone Number	Photograph Number	Distance from North Girth Weld	Feature Appearance	Total Length	Depth Below O.D. Surface
1	101	20' 3/8" to 20' 7/8"	Darker Smooth Area	1/2"	0.125"
2	102	20' 2-1/8" to 20' 2-5/8"	Darker Smooth Area	1/2"	0.063"
3	102 - 103	20' 3" to 20' 4-3/8"	Darker Smooth Area	1-3/8"	0.085"
4	102	20' 3" to 20' 3-3/4"	Ridge	3/4"	0.061"
5	102 - 103	20' 3-7/8" to 20' 4-1/8"	Ridge	1/4"	0.058"
6	103	20' 4-5/8" to 20' 7-5/8"	Darker Smooth Area	3"	0.150"
7	103	20' 4-5/8" to 20' 6-3/8"	Ridge	1-3/4"	0.113"
8	104	20' 7-7/8" to 20' 8-1/8"	Darker Smooth Area	1/4"	0.046"
9	104	20' 8-5/8" to 20' 9"	Darker Smooth Area	3/8"	0.063"
10	104 - 105	20' 9-1/8" to 20' 11-1/4"	Darker Smooth Area	2-1/8"	0.048"
11	105 - 106	21' 1/8" to 21' 1-1/2"	Darker Rough Area	1-3/8"	0.062"
12	106 - 107	21' 3" to 21' 4-3/8"	Darker Rough Area	1-3/8"	0.031"
13	107	21' 5" to 21' 5-1/2"	Darker Rough Area	1/2"	0.042"
14	107	21' 5-1/2" to 21' 5-7/8"	Darker Smooth Area	3/8"	0.020"

3.7.3 An approximately 5-1/2" long sample of the pipe containing the hook cracks between a distance of 20' 2-1/2" and 20' 8" from the north girth weld was removed, electrolytically descaled, cleaned using alkaline Endox® 214 solution, and examined at low magnifications to ascertain the general condition of the pipe surface at the O.D. and I.D. surfaces along the ERW seam near the fracture origins. The mating fractured segment was not cleaned to preserve the sample for the later evaluation of the condition of the scale or oxidation that was present on the fractured face.

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Close-up examination of the sample containing the cleaned fracture face with the hook cracks, associated areas of potential crack growth, the final fracture origins revealed that one of the hook cracks was at a location where the outer coal-tar coating had split diagonally during service. Some of the coal-tar had melted onto the fracture surface. The examination also revealed localized melting of the base metal caused by the copper electrode contacts that were apparently originally used to weld the skelp to form the ERW pipe. Photographs No. 111 through No. 116 display the O.D. surface condition of the pipe near the fracture origins.

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Close-up examination of the fracture face between a distance of 20' 2-1/2" and 20' 8" from the north girth weld revealed highly oxidized hook cracks and areas of potential crack growth and/or coalescence originating from the initial hook cracks, which were present to a maximum depth of 0.150". Photographs No. 117 through No. 122 display the hook cracks and areas of potential crack growth and/or coalescence from where the final fracture initiated and propagated north toward the north girth weld along the ERW seam and south into the base metal south of the fracture origins.

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3.7.4 The initial hook cracks and associated areas of potential crack growth and/or coalescence across the entire fracture face from the O.D. to the I.D. of the pipe at two (2) of the several fracture origins, located at 20' 5-5/16" and 20' 6-3/4" from the north girth weld (as shown in Photographs No. 117 through No. 122), were examined at higher magnifications using a Scanning Electron Microscope (SEM) to further characterize the fracture morphologies. The SEM examination of the hook cracks revealed fractures through the multiple planes across the weld upset, HAZ, and/or fusion line of the ERW seam, which were covered with tightly adhered scale or oxidation products obscuring the fracture morphology. However, the fractures through multiple planes in the weld upset, HAZ, and/or fusion line suggest that the cracks grew or propagated through the path of least resistance. There was some evidence of what appeared to be intergranular fracture in an extremely small area of the initial hook crack, which can be attributed to the prior grain structure of the material. The final rupture revealed essentially cleavage to quasi-cleavage fracture, indicative of brittle instantaneous failure. The fracture adjacent to the weld flash near the I.D. surface revealed evidence of ductile fracture. Photographs No. 123 through No. 150 document the fracture morphologies at the fracture origin locations.

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3.8 Crack Measurements

3.8.1 Fractographic examination of the fracture face between 19' 10" and 22' revealed the presence of the initial hook cracks along the multiple planes of the ERW seam between a distance of 19' 10-1/8" and 21' 9-1/2"; however, the hook cracks were predominantly between 19' 10-1/8" and 20' 11-3/8", and 21' 2" and 21' 9-1/4", as measured from the north girth weld. The maximum depth of the hook cracks plus any crack growth/coalescence, from where the final fracture initiated during service and lead to the rupture of the pipeline, was 0.150"; however, the depth of the hook cracks plus any growth/coalescence varied between 0.016" and 0.150", as recorded in Table 3.

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3.8.2 The mating fracture faces in the primary hook crack origins area from where the final fracture had initiated between a distance of 20' 2-1/2" and 20' 8" were reconstructed and sectioned transversely across the fractured ERW seam, more specifically at a distance of 20' 3-3/4", 20' 4-7/8", and 20' 5-1/2" from the north of the girth weld, and were prepared for metallographic examination as well as the crack width measurements. Additional cross-sections were also removed through the fractured ERW seam from a distance of 20' 6-13/16" and intact seam from a distance of 35' 8-1/2" and prepared for metallographic examination.

3.8.3 The maximum width and depth of the hook cracks was measured at several locations and was found to be 0.0038" and 0.150", respectively. It should be noted here that the hook crack width measurements were made following reconstruction of the two (2) mating fracture faces and, therefore, the values shall be considered as approximates only. Table 4 records the hook cracks' width measurements.

3.9 Metallographic Evaluation

3.9.1 Microstructural examination of the cross-sections removed transversely through the ERW seam at a distance of 20' 4-7/8" and 20' 6-13/16" from the north girth weld and prepared for metallographic examination was performed to characterize the microstructural conditions of the ERW seam at the fracture origin locations. Microstructural examination revealed hook cracks through the ERW upset/HAZ along the realigned inclusions and upturned bands of extremely brittle untempered martensite.

Both cross-sections removed through the final fracture origins and prepared for metallographic examination revealed the hook cracks through the excessive amount of manganese sulfide inclusions and bands, which were essentially parallel to the ERW fusion line, an undesirable condition that was apparently created during the skelp forming and ERW processes. The microstructure of the upturned bands consisted of very brittle, hard untempered martensite, while the ERW upset/HAZ area consisted of a mixed-microstructure with grain boundary ferrite, unresolved bainite, and some untempered martensite, which is undesirable since this microstructure possesses extremely low ductility. The secondary HAZ and the base metal consisted of grain boundary ferrite and pearlite.

Microstructural examination also revealed evidence of the localized melting and cracking to a shallow depth at the electrode contact areas at the O.D. locations parallel to the weld seam. Photographs No. 151 through No. 202 document the microstructural condition of the ERW seam at the locations of the hook cracks from where the final fracture had initiated and predominantly propagated upstream toward the north girth weld.

3.9.2 A cross-section was removed transversely through the intact portion of the ERW seam of the 49' 9-1/2" section of the pipeline at a distance of 35' 8-1/2" from the north girth weld and prepared for metallographic examination to characterize the microstructural condition of the ERW joint.

The microstructural examination revealed excessive amounts of predominantly manganese sulfide stringers and some oxide inclusions, several of them aligned parallel to the fusion line in the upset area of the ERW seam, which are characteristic precursors for hook cracks. The microstructural examination of the cross-section following etching in a 2% Nital solution revealed the presence of some upturned bands, however, not as severe as those found in the fractured seam. The microstructure of the upturned bands consisted of brittle untempered martensite, while the upset/HAZ away from the bands consisted of mix-microstructure of grain boundary ferrite, bainite, and some untempered martensite. Photographs No. 203 through No. 220 document the microstructural condition of the intact ERW seam.

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3.9.3 Longitudinal cross-sections were removed through the corrosion pitting at representative areas on the O.D. surface and through the shallow indentations on the I.D. surface, and were metallographically prepared and etched in a solution of 2% Nital. On the O.D. surface multiple pits filled with oxides and corrosion products were visible, extending to a maximum depth of 0.008" on the metallographically prepared cross-sections. Following etching, the non-uniform pits were confirmed to be the result of material loss due to corrosion, with no evidence of grain deformation or mechanical damage. As previously noted, all of the corrosion pitting was observed between the 1:30 and 11:15 positions on the fractured section of pipeline, and no pitting corrosion was observed at the 12:00 position where the ERW seam was positioned in the pipe. As a result, the minor amounts of corrosion observed on the O.D. surface had no impact on or contribution to the pipeline failure.

Examination of the I.D. surfaces on the metallographically prepared cross-sections revealed that the shallow depressions were smooth indentations, between 0.137" and 0.189" wide and up to 0.007" deep. The I.D. surface and the surfaces of the indentations were smooth, with no visible oxide scale, and in the etched condition some grain deformation was visible at the edges of the indentations, indicating mechanical damage. However, the thickness of the microstructural band containing partial decarburization on the I.D. surface remained constant, indicating that the impressions occurred most likely during the hot-rolling of the steel or manufacturing of the pipe and not during service. As a result, the I.D. surface indentations had no impact on or contribution to the pipeline failure. Photographs No. 221 through No. 226 display representative areas of the O.D. and I.D. surfaces on the metallographically prepared longitudinal cross-sections in both the as-polished condition and following etching in a solution of 2% Nital.

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3.10 Microhardness Surveys

3.10.1 Vickers microhardness surveys were performed on the metallographically prepared cross-sections at both the representative fractured and intact locations of the ERW seam on the pipe sections in accordance with the test method specified in ASTM E384-11^{E1}. The Vickers microhardness values were converted to equivalent Rockwell B or C scale values based on the conversions provided in ASTM A140-07, Tables 1 and 2. It should be emphasized that the hardness equivalents are approximates based on equations developed from empirical data, and are typically higher than the results obtained if testing using the larger Rockwell indenter and much higher load forces.

3.10.2 Vickers microhardness surveys were performed on the metallographically prepared cross-sections removed from representative fractured areas of the ERW seam at 20' 4-7/8" and 20' 6-13/16" from the north girth weld. Each cross-section was evaluated along the fracture surface, including along the initial hook crack, the hardened martensitic upturned grains, and the final fracture zone, as well as in the ERW seam at the fusion line, the HAZ and the base metal. The results of the Knoop microhardness surveys at fractured locations of the pipe are summarized in the following table.

Cross-section Location (from North Girth Weld)	Average Hardness, Rockwell Equivalent					
	Heat-Affected Zone	At Fracture Surface				ERW
		Initial Hook Crack	Hardened Upturned Grains	Final Fracture	Fusion Line	
20' 4-7/8"	96 HRB	100 HRB	29 HRC	52 HRC	28 HRC	42 HRC
20' 6-13/16"	100 HRB	21 HRC	29 HRC	49 HRC	29 HRC	32 HRC

As shown, the hardness varied extensively along the fracture surface of the initial hook crack within the upturned grains. The hardened, martensitic microstructure was 20 to 23 Rockwell C hardness points higher than the adjacent microstructure within the upturned grains and along the fusion line in the ERW seam. The hardness decreased the farther away from the ERW seam, resulting in approximately a 30 Rockwell C hardness point difference between the ERW seam and the softer base metal. The large difference in hardness can result in increased internal stresses, which can contribute to crack initiation and/or growth. The complete results of the Vickers microhardness surveys, including micrographs showing the locations of each indentation on the metallographically prepared cross-sections removed through the crack are displayed in Table 5 and Table 6.

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3.10.3 A Vickers microhardness survey was also performed on the metallographically prepared cross-section that was removed through the ERW seam at a representative intact area approximately 35' 8-1/2" from the north girth weld for comparison with the data from the fractured location. The results of the Vickers microhardness survey of the intact area are displayed in the following table.

Cross-section Location (from North Girth Weld	Hardness, Rockwell Equivalent			
	Base Metal	Heat-Affected Zone	Upturned Grain Flow Lines	ERW Fusion Line
35' 8-1/2"	100 HRB average	99 HRB average	Varied between 21 HRC and 54 HRC	Varied between 23 HRC and 54 HRC

As shown, the cross-section removed from an intact area of the pipe also contained a hardened martensitic microstructure within the upturned grain flow pattern of the ERW seam at the O.D. surface. The fusion line, HAZ, and base metal hardnesses of the intact cross-section were similar to those areas on the fractured cross-sections, including the large variation between the ERW seam and the base metal of the pipe. The complete results of the Vickers microhardness survey, including a micrograph of the metallographically prepared cross-section removed from the ERW seam in an intact area, are displayed in Table 7.

3.11 Tensile Tests

3.11.1 In order to determine the ultimate tensile stress, yield stress at a 0.5% offset, and percent elongation of the pipe, multiple tensile test specimen blanks were removed through the ERW seam, as well as in both the transverse and longitudinal directions away from the seam, on the intact 19' 10" long section of pipe as shown in Appendix V. All of the test specimens were machined to have a 2" long gauge length, a 1-1/2" wide reduced section, and represented essentially the entire wall thickness, with only slight sanding to remove minor surface imperfections or, as noted, the weld flash.

3.11.2 Six (6) transverse tensile test specimen blanks were removed through the ERW seam and were then flattened as specified in both the 10th Edition and the 44th Edition of API 5L. The tensile test specimens were then machined and tested in accordance with ASTM A370-12a and the applicable sections of each edition of the API 5L specification. The results of the transverse tensile tests through the ERW seam, along with the tensile requirements from both the 10th Edition of API 5-L that was in effect at the time the pipe was manufactured and the current API 5L, 44th Edition are shown in the following table.

Sample Identification	Ultimate Stress (psi)	Yield Stress (psi)	Elongation (%)	Fracture Location
Transverse, Through ERW Seam, Weld Flash Included, Sample 1	101,000	77,000	4	HAZ
Transverse, Through ERW Seam, Weld Flash Included, Sample 2	93,500	79,000	5	HAZ
Transverse, Through ERW Seam, Weld Flash Included, Sample 3	102,000	84,000	23	Base Metal
Transverse, Through ERW Seam, Weld Flash Removed, Sample 1	85,500	73,000	3	HAZ
Transverse, Through ERW Seam, Weld Flash Removed, Sample 2	85,500	75,000	3	HAZ
Transverse, Through ERW Seam, Weld Flash Removed, Sample 3	92,500	77,000	5	HAZ
API 5-L, 10th Edition, Electric Welded Pipe, Open Hearth Steel, Grade B	60,000 minimum	None Specified	None Specified	Not Applicable
API 5L, 44th Edition, PSL 1, Welded Pipe, Grade X42	60,200 minimum	None Specified	None Specified	Not Applicable

As shown, all of the tensile test specimens, regardless of whether the specimens contained the weld flash, met the minimum ultimate stress requirements specified in both API 5-L, 10th Edition and API 5L, 44th Edition. The complete results of the transverse tensile tests through the ERW seam are recorded in Table 8.

3.11.3 Multiple base metal transverse tensile test specimen blanks were removed from the pipe, at locations 90° from the ERW seam and 180° from the ERW seam, and were flattened prior to machining. Longitudinal base metal tensile test specimen blanks were also removed from the pipe at a location 90° from the ERW seam. All of the tensile test blanks were machined and tested in accordance with ASTM A370-12a and the applicable sections of sections of each edition of API 5L. The results of both the transverse and longitudinal base metal tensile tests, along with the tensile requirements from both the 10th Edition of API 5-L that was in effect at the time the pipe was manufactured and the current API 5L, 44th Edition are shown in the following table.

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Sample Identification	Ultimate Stress (psi)	Yield Stress (psi)	Elongation (%)
Transverse, 90° from ERW Seam, Sample 1	87,000	59,000	30
Transverse, 90° from ERW Seam, Sample 2	86,500	59,000	31
Transverse, 90° from ERW Seam, Sample 3	89,000	62,000	28
Transverse, 180° from ERW Seam, Sample 1	87,000	63,000	28
Transverse, 180° from ERW Seam, Sample 2	85,500	60,000	28
Transverse, 180° from ERW Seam, Sample 3	87,500	64,000	28
Longitudinal, 90° from ERW Seam, Sample 1	89,000	64,500	31
Longitudinal, 90° from ERW Seam, Sample 2	90,000	66,500	31
Longitudinal, 90° from ERW Seam, Sample 3	90,500	68,500	31
API 5-L, 10th Edition, Electric Welded Pipe, Open Hearth Steel, Grade B	60,000 minimum	35,000 minimum	Unknown[1]
API 5L, 44th Edition, PSL1, Welded Pipe, Grade X42	60,200 minimum	42,100 minimum	27% minimum

[1] The required minimum elongation specified on the tensile requirements table in the provided paper copy of API 5-L, 10th Edition is illegible.

As shown, all of the base metal tensile test specimens, in both the transverse and longitudinal directions, met the requirements specified in both API 5-L, 10th Edition and API 5L, 44th Edition. Although the measured yield stress typically exceeded the minimum ultimate stress requirement, it should be noted that there were not any maximum strength requirements. The complete results of the base metal transverse and longitudinal tensile tests are recorded in Tables 9 and 10.

3.11.4 Sub-sized round, non-flattened transverse tensile test specimen blanks were removed through the ERW seam, 90° from the ERW seam, and 180° from the ERW seam of the intact section of pipe, and were machined and tested in accordance with the applicable sections of API 5L and ASTM A370-12a. The results of the non-flattened transverse tensile tests are summarized in the following tables.

Sample Identification	Ultimate Stress (psi)	Yield Stress (psi)	Elongation (%)
Transverse, Through ERW Seam, Weld Flash Removed, Non-flattened	99,600	65,100	21
API 5-L, 10th Edition, Electric Welded Pipe, Open Hearth Steel, Grade B	60,000 minimum	None Specified	None Specified
API 5L, 44th Edition, PSL1, Welded Pipe, Grade X42	60,200 minimum	None Specified	None Specified

Sample Identification	Ultimate Stress (psi)	Yield Stress (psi)	Elongation (%)
Transverse, 90° from ERW Seam, None-flattened	86,100	56,700	27
Transverse, 180° from ERW Seam, None-flattened	83,600	57,900	22
API 5-L, 10th Edition, Electric Welded Pipe, Open Hearth Steel, Grade B	60,000 minimum	35,000 minimum	Unknown[1]
API 5L, 44th Edition, PSL1, Welded Pipe, Grade X42	60,200 minimum	42,100 minimum	27% minimum

[1] The required minimum elongation specified on the tensile requirements table in the provided paper copy of API 5-L, 10th Edition is illegible.

As shown, the sub-sized, non-flattened transverse tensile test specimens met the requirements specified in both API 5-L, 10th Edition and API 5L, 44th Edition. The complete results of the sub-sized, non-flattened transverse tensile tests are recorded in Table 11.

3.12 Charpy V-Notch Impact Tests

3.12.1 Test blanks for multiple sets of transverse Charpy V-Notch (CVN) impact test specimens were removed from the intact 19' 10" long section of pipe as shown in Appendix V. Sets of half-sized 10 mm x 5 mm test specimens were machined per Section 9.8 of API 5L, 44th Edition and ASTM A370-12a and were notched in the fusion line of the ERW seam, the primary HAZ of the ERW seam, and the base metal. Then for each notch location, one (1) set of three (3) specimens was tested per ASTM A370-12a at the selected test temperatures of plus 32°F, plus 65°F, plus 80°F, and plus 95°F. Base metal specimens were also tested at additional temperatures.

Comment [RJR1]: Report should define the primary HAZ Charpy location in terms of the distance from the ERW bond line, e.g., approx 1 mm off the bond line.

3.12.2 The results of the CVN impact tests for each location and each test temperature are recorded in the following tables.

V-Notch Location: ERW Fusion Line

Specimen Number	Test Temperature	Impact Value (ft-lbf)	Lateral Expansion (mils)	Percent Shear (%)
1	Plus 95°F	3	0	0
2		2	1	0
3		3	0	0
1	Plus 80°F	3	0	0
2		2	0	0
3		3	1	0
1	Plus 65°F	3	1	0
2		2	0	0
3		3	1	0
1	Plus 32°F	3	0	0
2		3	0	0
3		2	0	0

V-Notch Location: ERW Primary Heat-Affected Zone

Specimen Number	Test Temperature	Impact Value (ft-lbf)	Lateral Expansion (mils)	Percent Shear (%)
1	Plus 95°F	3	3	0
2		3	4	0
3		4	6	0
1	Plus 80°F	5	7	0
2		4	5	0
3		8	5	0
1	Plus 65°F	3	2	0
2		3	1	0
3		5	2	0
1	Plus 32°F	4	0	0
2		3	0	0
3		4	0	0

V-Notch Location: Base Metal

Specimen Number	Test Temperature	Impact Value (ft-lbf)	Lateral Expansion (mils)	Percent Shear (%)
1	Plus 95°F	10	16	15
2		10	12	10
3		10	14	10
1	Plus 80°F	9	9	5
2		9	10	5
3		9	13	5
1	Plus 65°F	10	13	5
2		10	14	5
3		10	13	5
1	Plus 32°F	8	8	5
2		9	12	5
3		9	10	5
1	Zero°F	5	1	0
2		4	2	0
1	Minus 32°F	2	0	0

As shown, the impact values at each notch location were essentially the same between plus 32°F and plus 95°F, while the base metal impact values at 0°F were half the values at 32°F and above, and continued to drop with lower temperatures. The fusion line of the ERW seam had the lowest impact values and the base metal, as expected, had the highest values. The lateral expansion and percent shear was essentially zero at the fusion line of the ERW seam, and the lateral expansion was only slightly higher in the HAZ. The base metal had the largest lateral expansion and percent shear values. The results of the CVN impact tests are recorded in Tables 12, 13, and 14.

At the time the pipe was manufactured, no CVN impact tests or requirements were specified in APL 5-L, 10th Edition. Likewise, there are no impact requirements for Type PSL 1 welded pipe in the current 44th Edition of API 5L. The only impact requirements for comparison are that in the 44th Edition of API 5L, for all notch locations on Type PSL 2 welded pipe, Grade ≤X60, half-size transverse test specimens are required to have a 10 ft-lbf minimum average for a set of three test specimens and 8 ft-lbf minimum for a single individual test specimen, when tested at a test temperature of 32°F.

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3.12.3 The CVN impact test results were then intended to be used to determine the lower shelf energy, upper shelf energy, the ductile-to-brittle transition temperature for the base metal, and if possible, the ERW seam, by plotting the results and developing an S-curve graph. The ductile-to-brittle transition temperature for the ERW fusion line and HAZ cannot be determined, because the results of the impact tests at these areas were essentially the same regardless of test temperature. All of the CVN impact test specimens notched in the ERW seam, whether at the fusion line or in the HAZ, failed in an essentially brittle manner, therefore the ductile-to-brittle transition temperature is above 95°F and is outside the scope of this investigation.

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However, additional tests at a temperatures below plus 32°F were performed on transverse CVN impact test specimens machined from the base metal because the base metal test specimens did fracture in a more ductile manner. The lower shelf would be considered to be around 2 ft-lbf for the size tested, or 4 ft-lbf for a full-size test specimen.

Comment [RJR2]: It is standard practice to define transition temperature as the temperature where a certain energy was achieved (e.g., 27 J) or the fracture face exhibited 50% shear (50% FATT). The Charpy results for the base material exhibit lower shelf behavior up to approx 80 deg F and at 95 deg F. EMPCo disagrees with the statement that the pipe material exhibits a ductile to brittle transition at 0 deg F given that at 95 deg F the fracture is still predominantly brittle.

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3.13 Chemical Analyses

3.13.1 An approximately 2" by 2" section was removed away from the ERW seam on the intact 19' 10" long section of pipe, as shown in Appendix V, and the surface was sanded smooth in preparation for determining the chemical composition of the pipe using the Optical Emission Spectroscopic (OES) test method in accordance with ASTM E415-08, with the percent carbon determined by an approved vendor using the combustion method specified in ASTM E1019-11. The results of the chemical composition analysis, as well as the compositional requirements for both the 10th Edition of API 5-L that was in affect at the time the pipe was manufactured and the current API 5L, 44th Edition are shown in the following table.

Element (wt%)	Sample Tested	API 5-L, 10th Edition, Electric Welded Pipe, Open Hearth Steel, Grade B Spec.	API 5L, 44th Edition, PSL 1, Welded Pipe, Grade X42 Specification
Carbon	0.30	0.30 max	0.26 max
Manganese	1.47	0.35 to 1.50	1.30 max
Phosphorus	0.017	0.045 max	0.030 max
Sulfur	0.031	0.06 max	0.030 max
Silicon	<0.01	[1]	[1]
Chromium	<0.01	[1]	0.50 max
Nickel	0.04	[1]	0.50 max
Molybdenum	<0.01	[1]	0.15 max
Copper	0.02	[1]	0.50 max
Aluminum	<0.01	[1]	[1]
Niobium	<0.01	[1]	[2]
Vanadium	<0.01	[1]	[2]
Titanium	<0.01	[1]	[2]
	Base	Base	Base

[1] Analytical range not specified for element.
[2] Sum of Niobium + Vanadium + Tantalum = 0.15% maximum

As shown, the pipe met the chemical composition that was specified in API 5-L, 10th Edition at the time of the pipe manufacture, but does not meet the compositional requirements specified in the current API 5L, 44th Edition for welded pipe. The complete results of the OES chemical analysis of the pipe are recorded in Table 15.

3.13.2 The foreign materials on the fracture surfaces, the O.D. surface, and the tightly adhered, very viscous black coating of the pipe was analyzed using the Energy Dispersive X-ray Spectroscopic (EDS) test method in accordance with ASTM E1508-12a in order to determine the elements present and the relative amounts of each. It should be noted that the fracture surface was protected with white grease prior to shipment to the laboratory, which was removed with the mineral spirit and acetone, and therefore the results of the EDS analysis may not be taken at the face value. Furthermore, it should be noted that EDS is a semi-quantitative test method, and that the results should be used as comparative or relative values only. It should also be noted that the EDS used was not capable of detecting light elements, those elements with atomic weights less than fluorine.

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The following table shows the results of the EDS analysis at three (3) different locations of the fracture surface.

Element (wt%)	Fracture Surface EDS-1	Fracture Surface EDS-2	Fracture Surface EDS-3
Magnesium	3.980	1.925	2.084
Aluminum	3.484	4.776	3.118
Silicon	12.974	12.032	8.578
Sulfur	4.081	2.144	3.006
Chlorine	2.794	2.377	1.864
Potassium	0.975	0.883	0.698
Calcium	1.162	0.874	1.198
Titanium	0.810	0.836	[1]
Manganese	1.603	1.056	1.541
Iron	68.137	73.097	77.912

[1] Element not detected.

As shown, in addition to iron and manganese from the base metal of the pipe, high levels of silicon, aluminum, and magnesium, were detected, most likely due to soil adhering to the fracture surface; similarly the calcium, potassium, and titanium were also likely from the surrounding soil. High levels of the corrosive elements chlorine and sulfur were also detected, although no pitting corrosion had yet occurred on the fracture surfaces. The complete results of the EDS analyses of the material on the fracture surfaces, including line spectra and SEM images of each location, are recorded in Tables 16, 17, and 18.

3.13.3 The chemical composition of the reddish-brown products on the O.D. surface of the pipe was also evaluated using the EDS test method. The results of the EDS analysis are displayed in the following table.

Element (wt%)	Reddish-Brown Product on O.D.
Magnesium	0.417
Aluminum	6.783
Silicon	33.882
Sulfur	0.391
Potassium	1.679
Titanium	0.949
Manganese	0.306
Iron	55.594

As shown, the products on the O.D. surface of the pipe were composed of primarily silicon with aluminum and potassium, in addition to the iron from the base metal of the pipe. The reddish-brown product on the O.D. surface of the pipe was likely soil that had migrated through the splits in the coating of the pipe. Some of the products may also have been from corrosion of the pipe, although it should be stressed that there was no evidence of significant localized or pitting corrosion on the received sections of pipe. The results of the EDS analysis of the products on the O.D. surface of the pipe are recorded in Table 19.

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3.13.4 The surface deposits on the viscous black bitumen, or coal-tar, coating that was on the O.D. surface of the pipe underneath the layer of fibrous coating was also analyzed using the EDS test method. The results of the test are displayed
in the following table.

Element (wt%)	Black Bitumen Coating

Magnesium	4.522
Aluminum	6.942
Silicon	42.773
Sulfur	65.763
Silver	0.000

No specific chemical composition of the coating was available for comparison. Bitumen is a highly viscous mixture composed primarily of highly condensed polycyclic aromatic hydrocarbons that is used as a waterproof coating for buried pipe, among other uses such as paving roads. The results of the EDS analysis of the surface deposits on the viscous black coating on the O.D. surface of the pipe are recorded in Table 20.

4.0 CONCLUSION

4.1 Technical Causes of Failure

Based on the inspection, testing, and evaluation performed in accordance with the approved metallurgical test protocol, review of the background information, and technical research, the following is HurstLab's opinion.

The failure of the pipeline at Milepost 314.77 in the Conway to Corsicana section of the Pegasus crude oil pipeline located in Mayflower, Arkansas, which occurred at 2:37 pm CST on March 29, 2013, resulted because of the reduction of the wall thickness in the upset zone of the Electric Resistance Weld (ERW) seam caused primarily by the presence of original manufacturing defects, namely hook cracks. Contributing factors to the pipeline failure include: localized stress concentrations at the tips of the prior hook cracks; low fracture toughness of the material in the upset/HAZ; significant residual stresses in the pipe from the initial forming and seam and girth welding processes; and the internal pressure hoop stresses.

The hook cracks with dimensions of 0.0038" in width, a maximum 0.150" in depth, and 13-1/4" in length were present in the ERW seam prior to the incident for an unknown period of time. The weak upturned fibers or bands of untempered brittle martensite, along which the hook cracks initiated, were created during the manufacturing of the pipe. The presence of the tightly adhered scale

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4.1 Manufacturing History of ERW Pipe¶
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First becoming commonly used in the 1920s, Electric Resistance Welded (ERW) pipe was manufactured by cold-forming typically hot-rolled sheets or strips and joining the longitudinal edges using heat and pressure in an autogenous welding process, a welding process that does¶
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not involve a separate filler metal. In the beginning, most ERW pipe was manufactured using low-frequency DC current from low carbon steel made using electric-arc or open hearth furnaces, although special war provisions were written into several API 5-L Specifications in the¶
1940s allowing the substitution of Bessemer steel.¶
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Prior to 1962, ERW pipe was manufactured using low-frequency DC current or sometimes low-frequency AC (up to 360 cycles); however by the end of the 1970s the use of low frequency DC current was essentially discontinued due to multiple quality issues. During the low-frequency DC resistance welding, continuous direct contact was required between the rolling electrodes and the steel, and any dirt or oxide scale present would interrupt the contact. Interrupted contact due to dirt, as well as power fluctuations or complete loss of current, would result in inadequate heating and isolated non-bonded areas, commonly referred to as cold welds. Advances in available technology allowed the use of high-frequency welding equipment (450,000 cycles) which resulted in m ... [1]

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or oxidation products on the hook crack faces would suggest that the hook cracks had been present for many years. It is unclear, however, whether the hook cracks themselves were present immediately after manufacturing or initiated later along the weak brittle grain flow lines/fibers that were created during the manufacturing of the pipe, due to effects of: the stresses induced by hydrostatic testing; thermal stresses; residual stresses; and/or pressure cycles.

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The hook cracks may not have occurred instantaneously, as suggested by variation in coloration of the scale or oxides on the fracture surface and the macroscopic features of the fracture, but rather coalesced and/or grew as the result of in-service stress conditions.

4.2 Failure Scenario

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Based on the preceding conclusion, the evidence of the prior hook cracks through multiple ductile and brittle zones, significant variance in hardness between the various zones of the ERW seam, the tightness and depth of the hook cracks along multiple planes through the upset heat-affected zones, and the extremely low impact toughness and elongation properties across the ERW seam, it is highly probable that some micro-cracking within the upset heat-affected zone might have occurred immediately following the pipe manufacturing. The micro-cracks then likely would have coalesced or propagated by further cracking through the adjacent areas in the localized upset/HAZ zones during service, forming a continuous hook crack in each localized areas to the critical depths, at which point the remaining wall thickness combined with the localized stress concentration, and the residual stresses could no longer support the internal hoop stresses and resulted in the final failure.

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Submitted by,

MMadhani

Mahesh J. Madhani
Chief Metallurgist

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PIPE MANUFACTURING PROCESS

4.1 Manufacturing History of ERW Pipe

First becoming commonly used in the 1920s, Electric Resistance Welded (ERW) pipe was manufactured by cold-forming typically hot-rolled sheets or strips and joining the longitudinal edges using heat and pressure in an autogenous welding process, a welding process that does

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not involve a separate filler metal. In the beginning, most ERW pipe was manufactured using low-frequency DC current from low carbon steel made using electric-arc or open hearth furnaces, although special war provisions were written into several API 5-L Specifications in the 1940s allowing the substitution of Bessemer steel.

Prior to 1962, ERW pipe was manufactured using low-frequency DC current or sometimes low-frequency AC (up to 360 cycles); however by the end of the 1970s the use of low frequency DC current was essentially discontinued due to multiple quality issues. During the low-frequency DC resistance welding, continuous direct contact was required between the rolling electrodes and the steel, and any dirt or oxide scale present would interrupt the contact. Interrupted contact due to dirt, as well as power fluctuations or complete loss of current, would result in inadequate heating and isolated non-bonded areas, commonly referred to as cold welds. Advances in available technology allowed the use of high-frequency welding equipment (450,000 cycles) which resulted in much higher quality welds with smaller heat-affected zones and higher weld toughness.

The use of early electric-arc and open hearth steels, that would typically be considered 'dirty steel' as compared to current standards, in the manufacturing of early ERW pipe also caused problems. High amounts of the element sulfur, which combined with the manganese present in the low carbon steel, resulted in an excessive amount of manganese sulfide stringer-type inclusions. These non-metallic inclusions are formed into elongated stringers during the hot rolling of the original steel plate. Excessively large complex oxide inclusions and brittle titanium carbonitrides were also commonly present in the low carbon steel. The conversion to basic oxygen steel making in the 1970s and 1980s, along with microalloying and thermomechanical processing, has greatly improved the quality of steel used in the ERW process.

4.2 Hook Cracks

Hook cracks, upturned fiber imperfections, are defined by API Bulletin 5TL as "metal separations resulting from imperfections at the edge of the plate or skelp, parallel to the surface, which turn toward the inside

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diameter or outside diameter pipe surface when the edges are upset during welding." The predominant cause of these J-shaped hook cracks in early ERW pipe was an excessive amount of non-metallic inclusions, most often manganese sulfide stringer-type inclusions, in the low carbon hot-rolled steel plates. In the steel plates, these stringers are longitudinally elongated and oriented in the original rolling direction of the plate, resulting in planes of weakness and a layered structure of the base metal. However, when formed into pipe, at the ERW fusion line these weak layers become reoriented; whereas in the base metal they are oriented parallel to the original plate surface, during the welding process they are curved around and become reoriented parallel to the ERW fusion line. This creates planes of weakness that subsequently experience tensile hoop stress when the pipeline is pressurized. Cracks then occur along these weak planes, resulting in J-shaped hook cracks that curve from parallel to the ERW fusion line at the O.D. or I.D. surface, to parallel to the rolling direction of the plate at some depth below the surface.