Non-Destructive Evaluation of Low-frequency Electric Resistance Welded (ERW) Pipe Utilizing Ultrasonic In-Line Inspection Technology

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Abstract: As a result of recent studies concerning low-frequency ERW pipe and its susceptibility to long seam failures, a Pipeline Company chose to incorporate ERW long seam assessment into their integrity management program. A 94 mile crude oil pipeline section constructed of 1948 vintage 10" low-frequency ERW pipe was recently inspected utilizing a LineExplorer UC in-line inspection (ILI) tool. This new generation of ultrasonic crack detection tool is a part of Tuboscope Pipeline Service's new fleet of ultrasonic in-line inspections tools which were built and developed by NDT Systems and Services AG. This paper will describe the logistics of the ILI survey and verification of ILI results.

Background

Electric Resistance Weld (ERW) pipe materials and a similar material called electric-flash-welded (EFW) pipe first appeared in the 1920s. Both processes involved making line pipe by cold forming previously hot-rolled plates or strips into round "cans" and joining the longitudinal edges of the cans by a combination of localized electrical resistance heating and mechanical pressure. The heat-softened edges were forced together extruding excess material to the outside and inside of the newly formed pipe. The excess material was immediately trimmed away leaving smooth surfaces or at most a small protrusion along the bondline.

Prior to 1962, all ERW materials and EFW pipe were made by means of DC or low frequency AC current (up to 360 Hz) using low-carbon steels made in open hearth or electric arc furnaces and cast into ingots. The DC or low-frequency AC currents used for resistance heating required intimate contact between the rolling electrodes and the "skelp" (i.e., the plate or strip used to form the cans). Dirt, grease, scale, or other oxide films on the skelp could, and often did, cause enough interference to prevent adequate heating at the bondline interface. Momentary reductions or loss of current could result in isolated or repeated areas of nonbonding called "cold welds" as well as other imperfections. [1] Lack of fusion due to insufficient heat and pressure is the principal defect, although hook cracks can also form due to realignment of non metallic inclusions at the weld interface.

A hook crack or upturned fiber imperfection is defined in 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 diameter or outside diameter pipe surface when the edges are upset during welding." The precursors for hook cracks are non- metallic inclusions, primarily manganese sulfide "stringers". These flattened, non-metallic inclusions are formed during hot rolling of plate or skelp. In general, they reduce the ductile toughness of the steel even in their normal position (i.e., layers interspersed between the rolling elongated grain structure of the steel). In this position, they can cause poor through-thickness properties that inherently reduce ductile fracture tearing resistance but not necessarily the yield or tensile strength of the material. Near an ERW bondline, however, these weak layers become reoriented such that they are subjected to tensile hoop stress when the pipe is pressurized. The layers may be of sufficient extent or so closely associated that the resulting planes of weakness separate, forming J-shaped (i.e., hook) cracks that curve from being parallel to the plate surfaces near mid-wall to being nearly parallel to the ERW bondline at the OD or ID surface. These cracks can be up to 50 percent of the wall thickness in depth and up to several inches in length. [1]

Figure 1 is a photomicrograph of a hook crack. It measures 0.186 inches (4.7 mm) deep with a part of that measurement being associated as a possible fatigue crack.

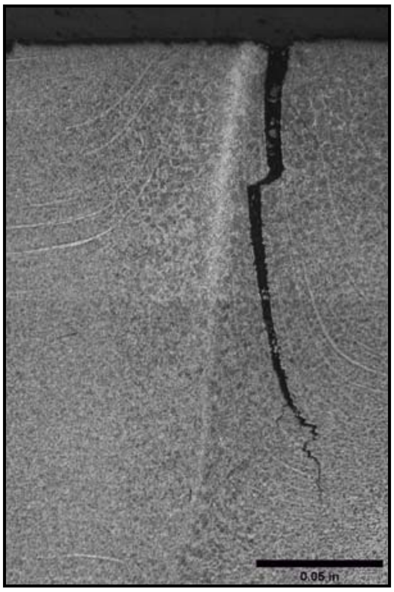

Figure 1 - Hook Crack

This is an excellent example of the formation of hook cracks and the reasons for concern. The ERW fusion bond is visible as a whitish line running from top to bottom. The white lines that appear to swirl upwards to the top or outside surface of the pipe are the original laminations in the plate. These would have been parallel to the plate surface until the edges of the plate were upset during the welding process thus reorienting the lamination to the shape shown. The hook crack formed as a result of the original lamination.

Grooving corrosion or selective seam weld corrosion is also a phenomenon that results from the sulfide-inclusion problem. The sulfide layers appear to make the material immediately adjacent to the bondline more susceptible to corrosion than the surrounding material. As a result, when corrosion (external or internal) occurs in an area that includes the bondline, the corrosion rate will be higher in the bondline region than in the parent material. The frequent result of such corrosion is the creation of a long, sharp V-notch along and centered on the bondline. In no case should such corrosion be treated or evaluated as one would treat or evaluate pitting corrosion in the parent pipe. The resulting anomaly is equivalent to a sharp crack in a relatively brittle material with a depth of penetration that is difficult, if not impossible, to accurately measure.

ERW Welds and Pipeline Integrity

A part of the integrity management requirements for pipelines in high consequence areas, as outlined in 49 CFR 195.452 [2] requires operators of pipelines containing low frequency ERW pipe susceptible to longitudinal seam failure to select integrity assessment methods capable of assessing seam integrity. The rule envisions three methods.

1. Internal inspection tools capable of detecting corrosion and deformation anomalies including dents, gouges and grooves. For ERW pipe or lap welded pipe susceptible to longitudinal seam failures, the Rule provides that the integrity assessment methods be capable of assessing seam integrity and of detecting corrosion and deformation anomalies. An operator's integrity program must address any risk factors associated with those types of pipe.
2. Pressure test in accordance with Part 195 subpart E; or
3. Use other technologies that provide an equivalent understanding of the condition of the pipe.[3]

The Inspection Program

A Pipeline Company owns and operates a 10-inch (254 mm) diameter pipeline. The pipe is comprised primarily of 0.344 inch (8.7 mm) wall thickness, grade B, low frequency electrical resistance welded (ERW) pipe and has a field applied tar coating.

As part of its ongoing integrity management program the Pipeline Company chose a section of this pipeline for longitudinal seam weld assessment.

While no hydrostatic test failures or in-service failures have occurred, the Pipeline Companies concern was that if anomalies did exist in the ERW seam they could possibly grow in-service through operational pressure cycling, ultimately failing through a fatigue mechanism. In addition to improving the integrity of the pipeline The Company viewed this seam weld assessment as a means to evaluate new ultrasonic inspection technology and determine the effectiveness of using advanced inspection technology in the ongoing integrity programs for their pipeline system.

The Inspection Technology

The prevailing method to deal with the issue of cracks and crack-like features in the ERW weld region is hydrostatic testing. This technique, while effective, requires the operator to remove the pipeline from service resulting in throughput losses and significant cost to associated end-users such as refineries.

Reliable detection of cracks and crack-like features in pipelines constitutes a challenge for the pipeline inspection industry. Depending on the type of pipeline, pipeline material and operating condition, different types of cracks or crack-like features can occur, including stress corrosion cracking (SCC), fatigue cracks, and cracks in the weld and heat affected zone of longitudinal or girth welds.

Tuboscope Pipeline Services, with its partner NDT Systems and Services AG, has introduced new In-Line-Inspection (ILI) technology that may be as effective as hydrostatic testing while being more economical and better suited to the long-term management of the pipeline asset. The inspection tool uses the well established methods of Ultrasonic Testing (UT), optimized to detect and size axial cracks or crack-like features.

The Ultrasonic Technology Crack Detection (UTCD) tool uses liquid-coupled ultrasonic transducers where each sensor is inclined at such an angle as to generate a refracted shear wave propagating through the pipe wall at an angle of 45 degrees. The tool can also be optimized to detect and measure general corrosion defects by using a different sensor configuration. Figure 2 shows a 10-inch crack detection tool in the launch tray and Figure 3 the crack detection sensor array.

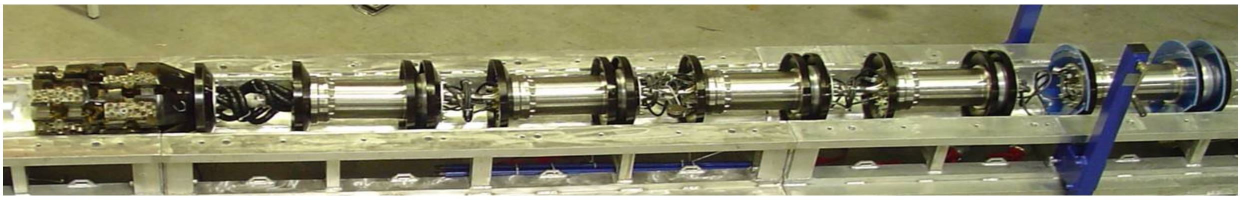

Figure 2 – 10-inch Crack Detection Tool

Figure 3 – Transducer Array

The 10 inch (254 mm) UTCD tool is 11.9 feet (3.6 m) long and weighs 240 pounds (110 kg). It can negotiate 1.5 D bends and inspect up to 100 miles (150 km) of pipe in a single run at velocities up to 4.9 feet/second (1.5 m/s).

For cracks and crack-like features exceeding 1.2 inches (30 mm) in length and 0.040 inches (1 mm) in depth the Probability of Detection (POD) is 90%. The length sizing accuracy is ± 0.040 inches (1 mm) for features less then 4.0 inches (100 mm) in length and ± 10% for features longer than 4.0 inches (100 mm). Features are graded into four depth classifications; > 0.040 in (1 mm), 0.040 to 0.080 inches (1 – 2 mm), 0.080 to 0.160 inches (2 – 4 mm) and > 0.160 inches (4 mm) with an accuracy of 1 class 90% of the time.

It is easy to underestimate the engineering challenge of designing an inspection tool capable of completing a full inspection of the pipe wall while moving through the pipeline at 4.9 feet per second (1.5 m/s). Those familiar with UT testing will appreciate that a skilled technician, in the ditch with an ultrasonic instrument, can take several hours to complete an inspection of a single longitudinal weld seam for crack-like features. The inspection tool must inspect not only the weld area but the entire pipe wall. For a standard 40-foot (12 m) joint of pipe it has less than 10 seconds to acquire the data. It is a remarkable feat of engineering and required radical improvements in electronic design, digital signal processing, mechanical design and software. In addition, it required new methods of analyzing and displaying the data. The overall result is a tool with enhanced detection and sizing capability and improved operational performance. The UTCD tool is not only the first of is kind; it is in a class by itself.

The Inspection

The Company executed a cleaning program to remove wax, tar, clay, sand and other debris. Tuboscope Pipeline Services then inspected the line using a Deformation/INS tool. The Deformation package measures the bore of the pipe to ensure that there are no obstructions that could restrict passage of the more advanced UTCD tool. The INS package is an inertial navigation system that provides accurate centerline positioning of the pipeline to allow GPS positioning for all pipeline features and can be used to coordinate all subsequent inspections.

Figure 4 shows the UTCD tool being prepared for the inspection. The tool ran for 34 hours at an average speed of 2.7 miles per hour (4.4 km/h). The tool was easy to handle during the launch and receive procedures.

Figure 4 - UTCD Tool Being Prepared for Launch

When the tool was received the data was downloaded and secured. Engineers immediately confirmed that the run was successful. Further analysis revealed that all components of the tool and all sensors worked perfectly, demonstrating the robustness and effectiveness of the new designs.

The Inspection Results

The data were reviewed in the Tuboscope's Houston office and verification dig-sites selected.

Tuboscope mobilized personnel from Marr Associates (a wholly owned subsidiary) to assist in field investigations. These technicians helped with feature location and investigation and performed an on-site analysis of the environmental conditions, including soils survey, cathodic protection system effectiveness and coating condition assessment. This information will be useful in understanding the mechanisms involved in the ERW weld issue and may also help refine the analysis processes for the UTCD tool. Twenty-four feet (7.3 m) of coating was removed at 3 locations and the pipe surface prepared for inspection. Twenty lack of fusion features were detected using black on white Magnetic Particle Inspection (MPI) and ultrasonic testing on the ERW long seam. All 20 of these features correlated correctly to the UTCD data. Feature detection and sizing were within the tolerance specified for the tool.

Subsequent to the verification digs, a preliminary report was issued and fourteen additional field excavations performed. A third party NDE provider was contracted to perform onsite NDE using MPI and UT techniques. Several joints of pipe were removed from the pipeline and subjected to more critical and comprehensive testing including full scale burst testing.

Final Results

The Final Report issued by Tuboscope in March of 2004 identified crack-like features with an estimated depth between 0.040 and 0.080 inches (1 – 2 mm), and other crack-like features with an estimated depth of between 0.080 and 0.160 inches (2 – 3 mm). It must be noted that features less than 0.040 inches (1 mm) in depth were below the established reporting threshold but may have been detected by the tool.

The Pipeline Company implemented a comprehensive data validation program to "prove up" the non-destructive test results provided by both the UTCD tool and the NDE field technicians. Destructive testing was performed for selected pipe joints in order to establish an effective maintenance and repair program and to provide the necessary feature detail to assist Tuboscope in improving UTCD tool performance. To date, 3 joints of pipe have been burst tested and several other joints destructively tested and analyzed.

Destructive evaluation of selected pipe joint:

Joint A
The UTCD tool detected 8 external crack-like weld features in this joint of pipe.

Feature ID	Feature Type	Distance (ft)	Length (in)	Depth (in)	Distance to US weld (ft)
24168	Crack-like	201597.92	5.5	<0.04	2.59
900450	Crack-like	201607.93	14.1	0.04 – 0.80	12.6
24174	Crack-like	201609.83	7.4	<0.04	14.49
24175	Crack-like	201612.36	4.3	<0.04	17.02
24177	Crack-like	201615.74	5.7	0.04 – 0.80	20.41
24181	Crack-like	201625.42	4.6	<0.04	30.08
24183	Crack-like	201632.23	12.5	0.04 – 0.80	36.89
24187	Crack-like	201639.26	5.8	<0.04	43.93

Table 1 - Features Detected by the UTCD Tool in Joint A

It should be noted that only three of the features detected exceed the 0.040 inch (1 mm) reporting threshold. The three reported features and the field NDE results are shown in Figure 5.

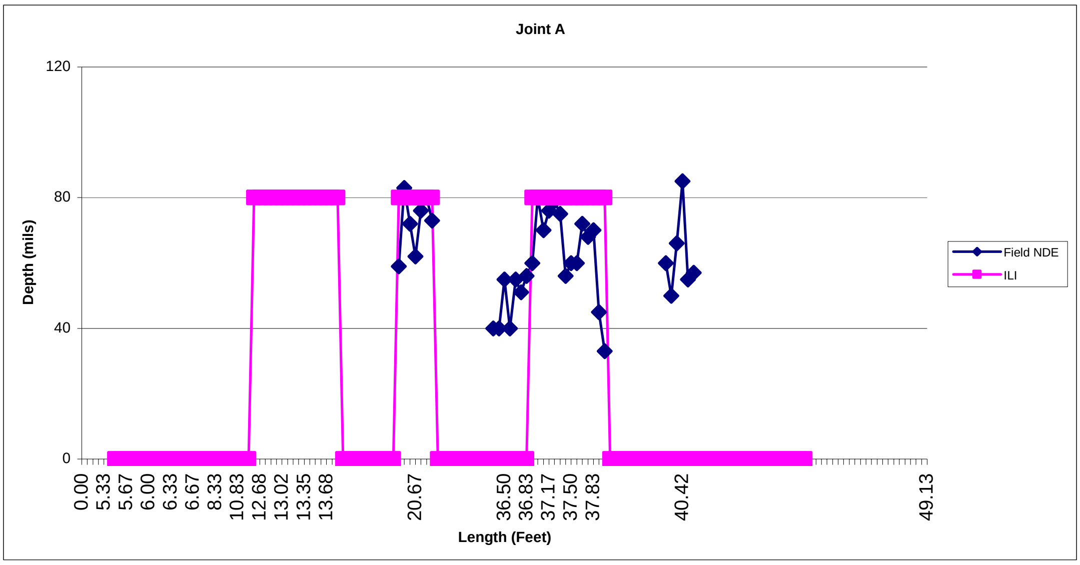

Figure 5 - UTCD Tool Results / Field NDE Results (Joint A)

The NDE field technicians confirmed two of the reported features but at the same time failed to confirm one UTCD predication and reported one feature that was not reported by the UTCD tool. This unreported feature was actually detected by the tool but the depth estimate was below the reporting threshold. (See Table 1.)

UTCD feature 24183 was targeted for additional analysis. A coupon was cut and sectioned for 3 types of destructive analysis: photomicrographs (the longs seam is left intact), Scanning Electron Microscope (SEM), and Brittle Fracture with liquid nitrogen.

Figure 6 shows a comparison of the UTCD tool prediction, the field measurements and the measurements obtained from destructive testing of this feature.

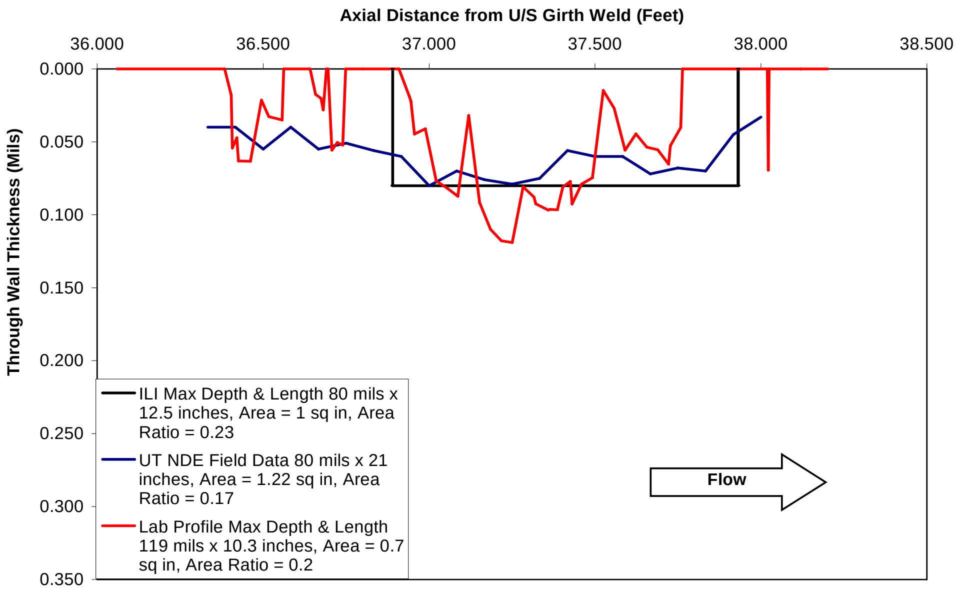

Figure 6 - UTCD, Field Data and Feature Measurements (Joint A)

There are several points of interest when reviewing Figure 6:

- The ILI depth prediction was under called when compared to the actual maximum crack penetration. Also, the actual maximum penetration is in the 2-3 mm grade band.

- Actual crack profiles will prove beneficial for establishing more accurate depth prediction algorithms, establishing future models that build a crack profile from ILI data, and aiding in the discrimination of the origin of a reflection. In this example hook cracks were identified.

Joint B

The UTCD tool identified 5 crack-like features in this joint, Figure 7. The field evaluation confirmed two of the features but could not locate the other three.

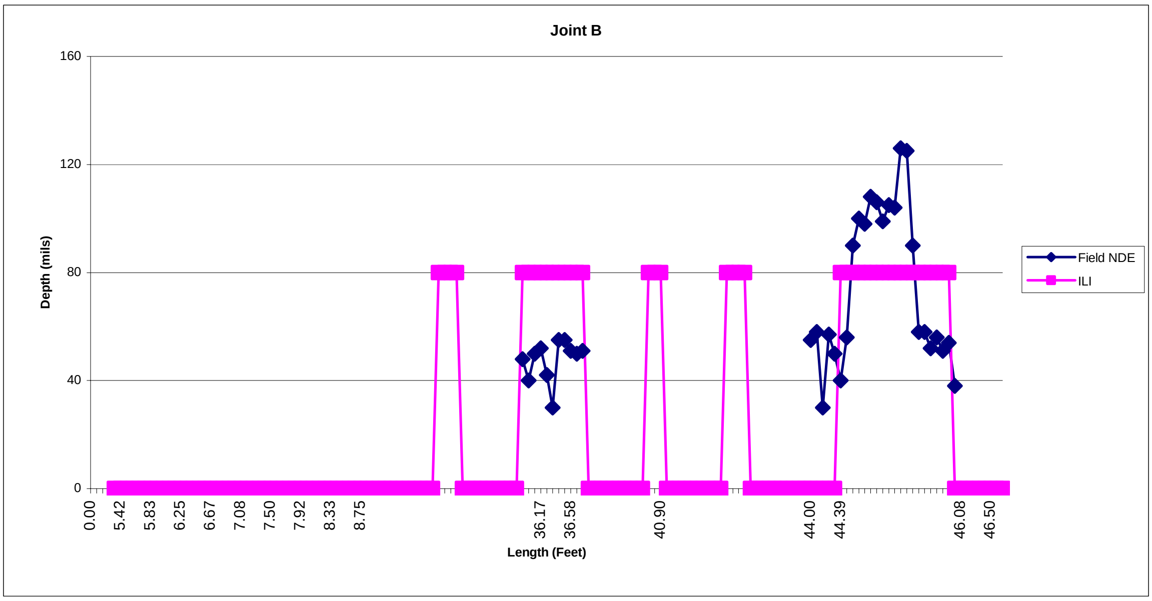

Figure 7 - UTCD Tool Results / Field NDE Results (Joint B)

Figure 8 shows a comparison of the UTCD tool prediction, the field measurements and the measurements obtained from destructive testing of the feature at 43 feet.

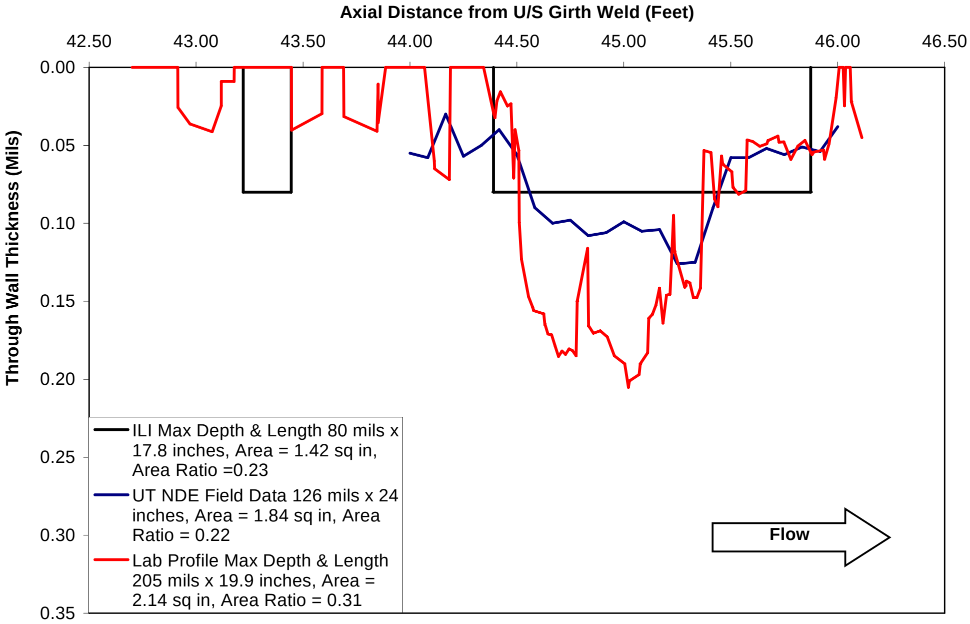

Figure 8 - UTCD, Field Data and Feature Measurements (Joint B)

This joint was analyzed using conventional destructive testing techniques. At this time it was determined that the ERW weld contained hook cracks. Although hook cracks are mill anomalies, they are potential initiators of fatigue cracks. Figure 9 is a photomicrograph of a hook crack found in this joint. It measures 0.186 inches (4.6 mm) in depth with a part of that measurement being associated with a possible fatigue crack. The UTCD tool estimated the depth of this crack as 0.040 – 0.080 inches (1 – 2 mm). It is likely that the sloping orientation toward the bottom of the crack did not allow for more accurate sizing.

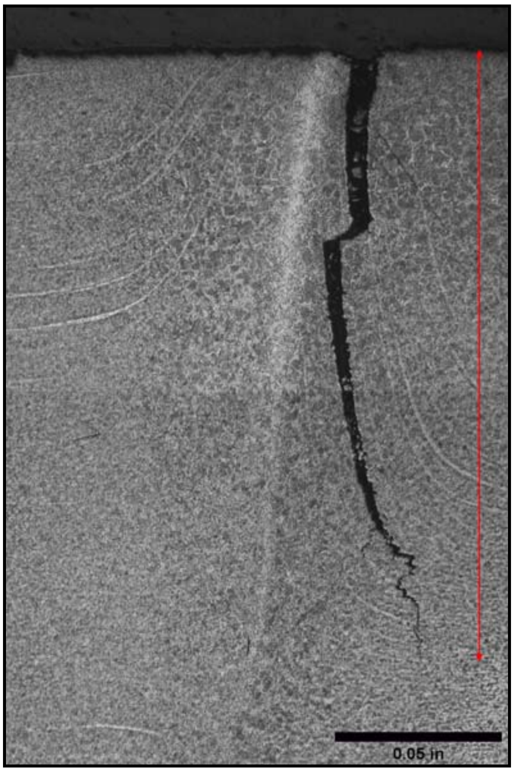

Figure 9 - Hook Crack

After discovering this crack the operator asked Tuboscope to review the data and determine if any other features exhibited similar characteristics. A review resulted in several locations being identified for field investigations. This is an important outcome of the integrity process. Cooperation between the Service Provider and the Operator is essential. Feedback from the Operator is the tool by which improvements can be made and ILI analysis algorithms advanced.

Joint C
ILI Results
The UTCD tool did not report any features in this pipe joint yet field evaluation indicated several crack-like features.

The initial assessment by field NDT is that the UTCD tool did not detect these features. In fact, the tool detected 7 such features but estimated the depth below the reporting threshold.

This joint was specifically chosen for destructive examination due to the apparent discrepancy between field measurements and the UTCD tool predictions.

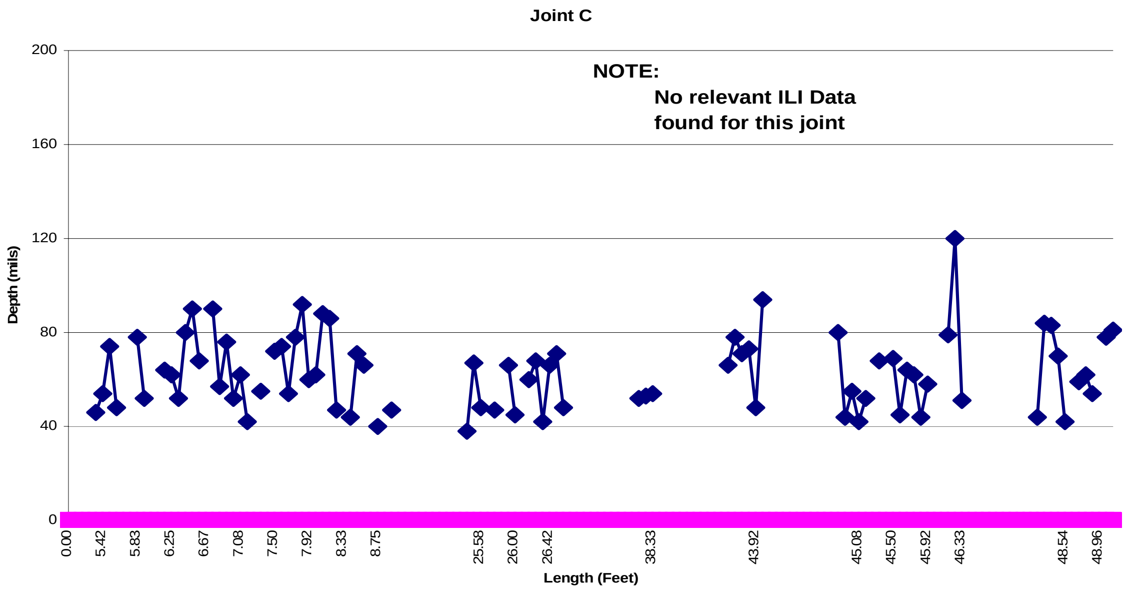

Figure 10 - UTCD Tool Results / Field NDE Results (Joint C)

Figure 11 is a screen shot of the C Scan UTCD data [4] with the actual analysis results tabulated in Table 2.

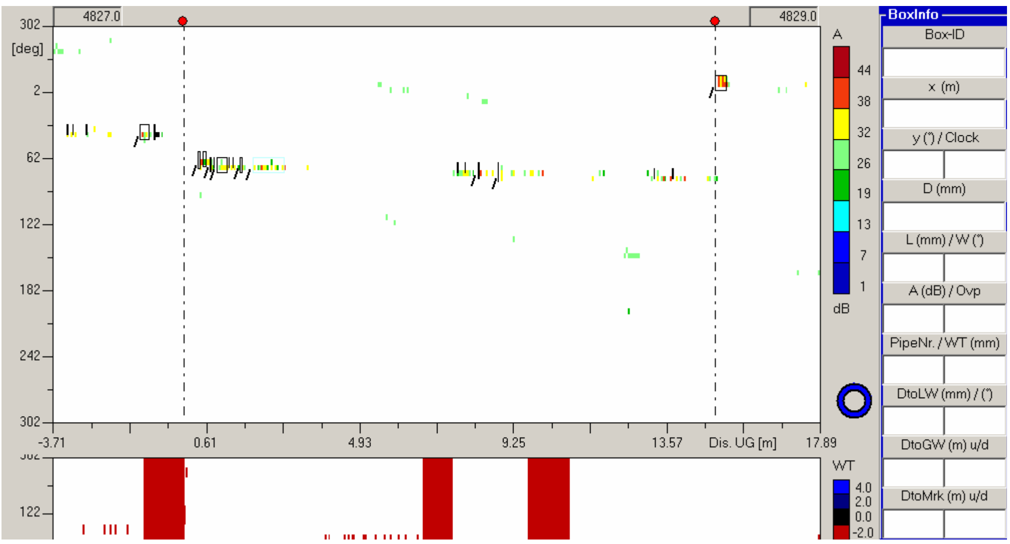

Figure 11 - Screen Shot of Joint C

Feature ID	Feature Type	Wall Loc.	Ref. Loc.	Absolute Distance (ft)	Circ. Pos. (o'clock)	Len. (in)	Depth (mils)	Dist. To UpGW (ft)	Dist. To DnGW (ft)
26924	Crack-like	ext	ilw	224501.35	2:22	3.5	<40	1.37	47.5
26926	Crack-like	ext	ilw	224502.44	2:26	2.5	<40	2.46	46.66
26928	Crack-like	ext	ilw	224503.05	2:28	11.9	<40	3.07	46.05
26931	Crack-like	ext	ilw	224505.20	2:28	3.4	<40	5.23	43.90
900469	Crack-like	ext	ilw	224506.35	2:30	35.4	<40	6.38	42.75
26941	Crack-like	ext	ilw	224527.18	2:40	2.0	<40	27.20	21.92
26942	Crack-like	ext	ilw	224529.11	2:46	1.7	<40	29.13	19.99

Table 2 - Analysis Results of Joint C

This joint of pipe was burst tested. Both water volume and pressure were measured in order to establish a stress/strain curve.

This joint failed at 3964 psi (270 bar). This was a much higher failure pressure than expected when using the feature profiles from the field NDE in the failure prediction model. A review shows the failure initiation point is between 4.5 feet (1.35 m) and 5.5 feet (1.68 m) from the upstream girth weld and can be correlated to one of the UTCD feature locations (26931).

Figure 12 shows a comparison of the field measurements and the measurements obtained from destructive testing of the first 9 feet (3 m) of the pipe joint.

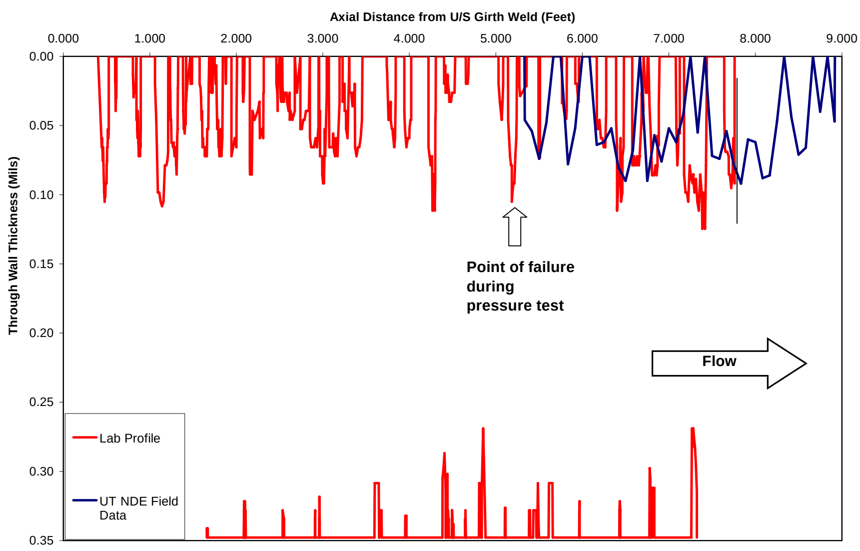

Figure 12 - Field Data and Feature Measurements (Joint C)

It appears that the UTCD depth predictions are under called. In particular, at 5.4 feet there is an approximate 0.100 inch (2.5 mm) external crack. The ILI results identify this crack as < 0.040 inches (1 mm).

Joint D

This joint of pipe was selected for testing because The UTCD tool did not detect any anomalies in the long seam weld nor did field NDE report any defects features.

This joint of pipe failed at 4255 psi (289 bar) after considerable yielding. It did not fail in the long seam but in the body of the pipe.

Joint E
Figure 13 is a graphical output of field NDE and UTCD results. This joint of pipe was selected for burst testing due to the correlation between the UTCD predictions and the field measurements. The features found in this joint of pipe are also hook cracks.

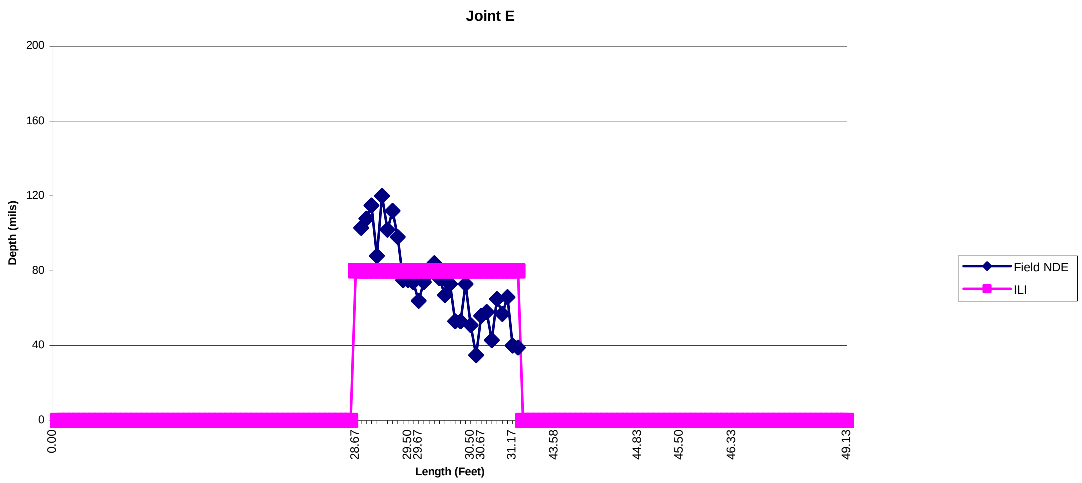

Figure 13 - UTCD Tool Results / Field NDE Results (Joint E)

Figure 14 shows a comparison of the UTCD tool prediction, the field measurements and the measurements obtained from destructive testing of this feature.

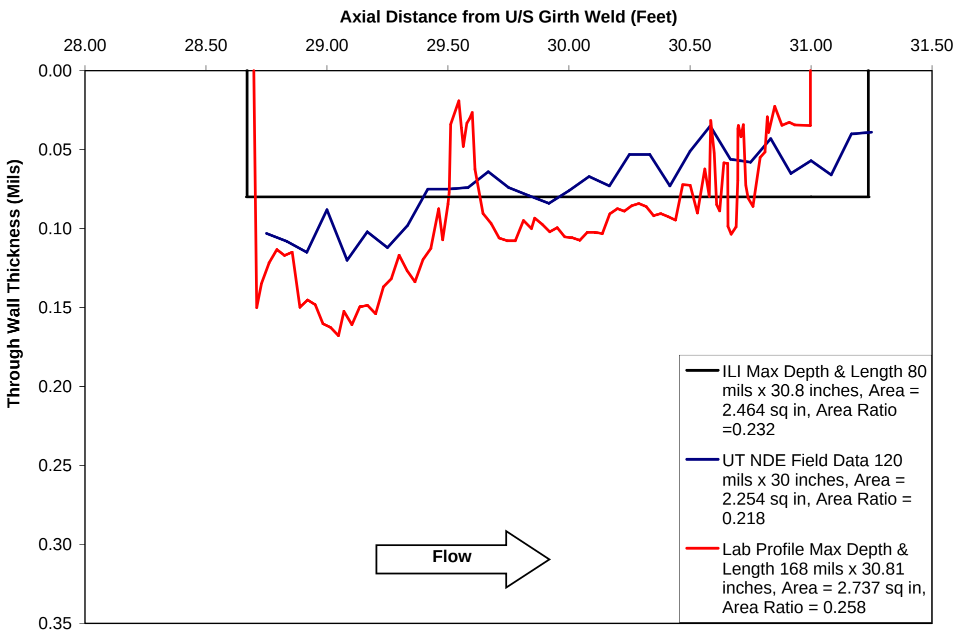

Figure 14 - Field Data and Feature Measurements (Joint D)

This joint failed at 2900 psi (197 bar). This was a higher failure pressure than expected. The initiation of the rupture correlated with both field NDE and the ILI results.

Conclusions

Tuboscope Pipeline Services crack detection In-Line-Inspection technology was selected to assess the integrity of this pipeline. Tuboscope’s tool uses ultrasonic technology optimized for detecting cracks and crack-like feature and was developed by its partner NDT Systems and Services AG. The inspection detected several crack-like features that exceeded the reporting threshold of 0.040 inches (1 mm) in depth and 1.2 inches (30 mm) in length.

Initial verification digs confirmed the presence of 20 anomalies reported by the tool.

The UTCD inspection demonstrated the ability of the tool to detect and identify crack-like features in the ERW weld seam. Detection and sizing allows features to be prioritized and may prove to be a viable alternative to hydrostatic testing.

On site analysis of the environmental, pipe and coating condition, and inspection of the pipe surface for integrity concerns proved to be a valuable tool in correlating UTCD tool results to conditions surrounding the pipe. The field investigation and destructive testing performed provided invaluable information for correlating ILI data and will be used to improve analysis and modeling algorithms.

References:

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2. 49 CFR Part 195, Federal Register Vol 65, No. 232
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4. PIXUS Screen shots. PIXUS is a trademark of NDT Systems and Services AG