Leveraging Destructive Testing to Enhance Detection and Identification of Complex Cracking in LF-ERW; Case Study Phase II

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PPIM 2025
PIPELINE PIGGING & INTEGRITY MANAGEMENT
JANUARY 27-31 • HOUSTON

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https://doi.org/10.52202/078572-0023

https://doi.org/10.52202/078572-0023

Abstract

Pipeline operators rely on a variety of strategies to maintain the safety and integrity of their pipeline systems, with inline Inspection (ILI) and Non-destructive Examination (NDE) being crucial components. However, these methods can encounter challenges and limitations when identifying and sizing complex features, such as off-axis cracking. What happens when NDE evidence suggests a systematic measurement bias relative to ILI? Can operators still use this data within their Integrity Management Programs (IMP)? Moreover, can this NDE data be effectively leveraged to develop new rules for ILI analysis processes?

Last year, NDT Global, in collaboration with Phillips 66, developed a Phase I systematic method to identify crack complexity in previously detected and undersized features based on NDE campaign results. This novel methodology integrated years of accumulated knowledge from ILI survey data from various pipelines with insights from applying sophisticated in-ditch NDE techniques developed for complex features.

In Phase II, as discussed in this paper, the investigation advances further by validating the Phase I methodology using destructive lab testing results. The metallurgical evaluation includes nine ILI-reported linear anomalies that were previously examined non-destructively in a 6" pipeline. The destructive testing aims to determine whether NDE accurately identified and sized these anomalies and whether the original ILI results were biased in the first instance. Additionally, this phase explores methods to assess the Probability of Sizing (POS) for out-of-specification features and suggests potential adjustments to ILI tool sizing curves when truth data is available.

This study highlights the successful partnership between NDT Global and Phillips 66 in advancing pipeline integrity management, offering valuable insights for the future of pipeline safety and reliability.

Introduction

Pipeline operators employ various strategies to ensure the operational safety of their pipeline systems. A crucial element of this strategy involves In-Line inspection (ILI), non-destructive examination (NDE) and, if necessary, destructive testing in laboratory.
Axial cracking is the predominant form of cracking found in pipelines; detection and sizing of such planar linear imperfections using Ultrasonic Pulse Echo technology has been a proven methodology for more than 25 years. Planar anomalies are imperfections that occur in a two-dimensional plane. However, characterization and sizing of features that have a tilt from the radial direction or a skew from the axial orientation (Figure 1) could pose a challenge for this technology (Wargacki, C. et al. 2020).

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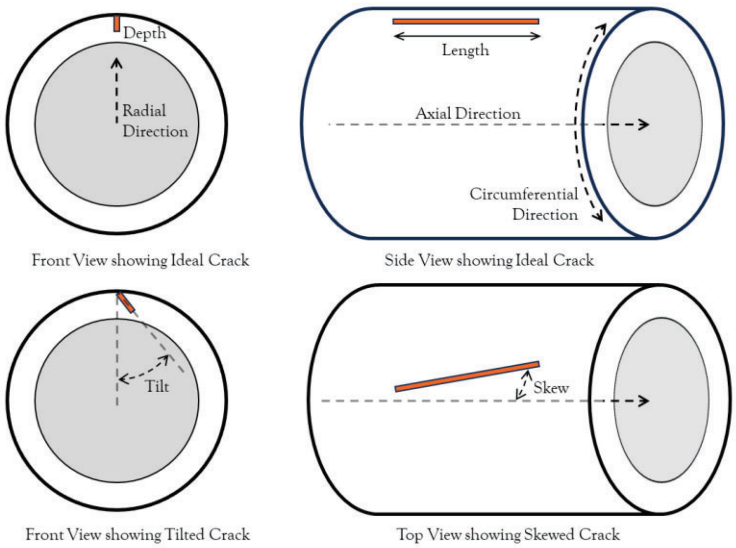

Figure 1. Crack definitions and terms. Schematic of tilted and skewed ideal cracks.

Phillips 66 contracted NDT Global to run a high-resolution axial crack inspection that resulted in a considerable number of reported anomalies in the longitudinal weld. Most of these anomalies were showing data signals that indicated complex geometries. In the aim of safety, NDT Global, in collaboration with Phillips 66, developed a procedure through advanced signal analysis for applying pattern recognition based on NDE to better understand the challenging anomalies present in the line. The research and execution of the project was structured in 2 phases:

Phase 1 – ILI data signal pattern analysis based on NDE results.

Phase 2 – Validation of Phase 1 categorization methodology with appropriate field verification and destructive testing in laboratory.

This paper continues the case study presented in: Novel approach for detecting and identifying complex cracking in LF-ERW pipe, a real case study (Aymerich, J. et al. 2024). It includes the addition of destructive lab results of 7 pipeline coupons, further correlation to NDE results and, the previous ILI pattern analysis.

Background

In December 2021 a high-resolution axial crack inspection was conducted in a 6" vintage pipeline with a predominant wall thickness of 0.188". The pipeline was installed in 1951 with low-frequency electric resistance welded (LF-ERW) pipes. It is important to note that small diameter pipelines pose difficulties for both ILI and field verification NDE techniques. On the ILI side, mechanical tool designs are limited, making the Ultrasonic Pitch and Catch technique complex. For NDE, challenges include a wide heat-affected zone with a tendency to contain complex crack geometries, a small wall thickness with significant pipe curvature, and the high number of reflections from impurities within the steel.

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After the ILI results, in-ditch NDE was conducted at selected locations, leading to several anomalies verified in the field as 'hook cracks' and one as an internal, surface-connected crack.

'Hook cracks' are one of the weld anomalies that poses a threat for LF-ERW seam welds. These complex geometry cracks can be caused by separations resulting from imperfections parallel to the surface in the edge of the skelp, which turn toward the internal or external surface. 'Hook cracks' can also originate from manufacturing related anomalies in the bond line (lack of fusion) or cracking in the upset region of the weld, that can grow along the flow line and then jump across other planes of inclusions ("stepwise cracking").

Based on these NDE results a pattern recognition methodology was developed, and a revised list of reported features was sent to the operator differentiating the possible 'hook cracks' features. Phillips 66 reviewed the provided listing from NDT Global and performed a risk-based assessment to decide which likely/possible/unlikely 'hook cracks' required remediation and included them in their dig program.

Measurement principle and the impact of complex crack geometry on ILI data

Conventional ultrasonic crack inspection tools rely solely on the Pulse-Echo (PE) technique, which uses piezo-electric transducers to generate a 45° shear wave in the pipe wall. This wave reflects off flaws and returns to the transmitting sensor. This idealized hit-and-reflection is called the Corner Echo. Figure 2 is a schematic of a clockwise (CW) and a counterclockwise (CCW) sensor generating a corner echo from an ideal external crack. Ideal cracks are radially oriented, axially aligned, and connected to the surface at a 90-degree angle.

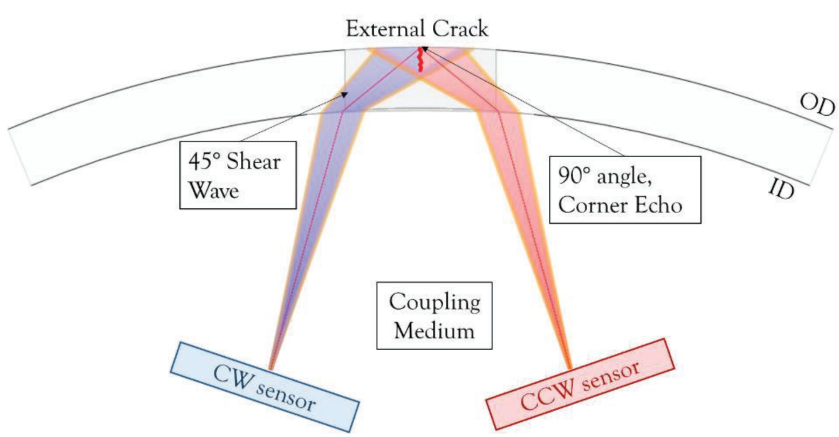

Figure 2. Schematic at scale of clockwise and counterclockwise UT sensors interacting with an ideal crack. Wall thickness equals to 0.188". Sensor diameter equals to 0.590".

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A typical ultrasonic crack inspection uses both CW and CCW sensors working independently. This setup provides redundancy in the data and additional data pattern characteristics of a crack's possible geometry, e.g., the amplitudes are significantly different, or the signal patterns differ. However, due to the limitations of the technology, the PE technique can only accurately size cracks with ±10° of tilt and ±5° of skew (Figure 1). Anomalies deviating from the axial and/or radial orientation could pose a challenge for this technology. Defects with geometries outside of the technique's specifications (i.e., tilted or skewed cracks) are frequently undersized (Willems et al. 2017).

Evaluating cracks from both sides of the weld provides some insight into the geometry of the flaws, which could indicate if a crack is tilted or skewed. It is generally assumed that when the amplitudes of the reflection from a crack from both sides of the weld behave similarly, then the flaw is not tilted. When the amplitudes are significantly different, or the signal patterns differ, the anomaly may be tilted or have a complex geometry. A bond line that is not purely perpendicular to the surface can make the identification of an anomaly type more difficult because then, anomalies along the bond line are also tilted (**Figure 8**).

Comparatively, evaluation of a weld with NDE typically involves visual testing and magnetic particle testing on the external pipe surface, followed by ultrasonic testing (UT) based on shear waves i.e., shear wave UT or phased array UT (PAUT).

A shear wave UT inspection requires manually scanning the weld from both sides. This is a pulse-echo measurement, similar to the In-Line inspection technology discussed above. PAUT typically uses sectorial scans, where the angle is electronically modulated between a specific range. This works for ideal defects, but there are limitations regarding embedded cracks and planar, but tilted, anomalies with a directional reflectivity. As a result, detection of tilted or embedded cracks can depend on the probe's angle for shear wave UT and on the probe's position for PAUT sectorial scans (**Figure 3**). Note, that the tilted reflector may be missed depending on the probe's angle (for UT) and on the probe's position (for PAUT sectorial scans), as the reflections are guided away from the probe.

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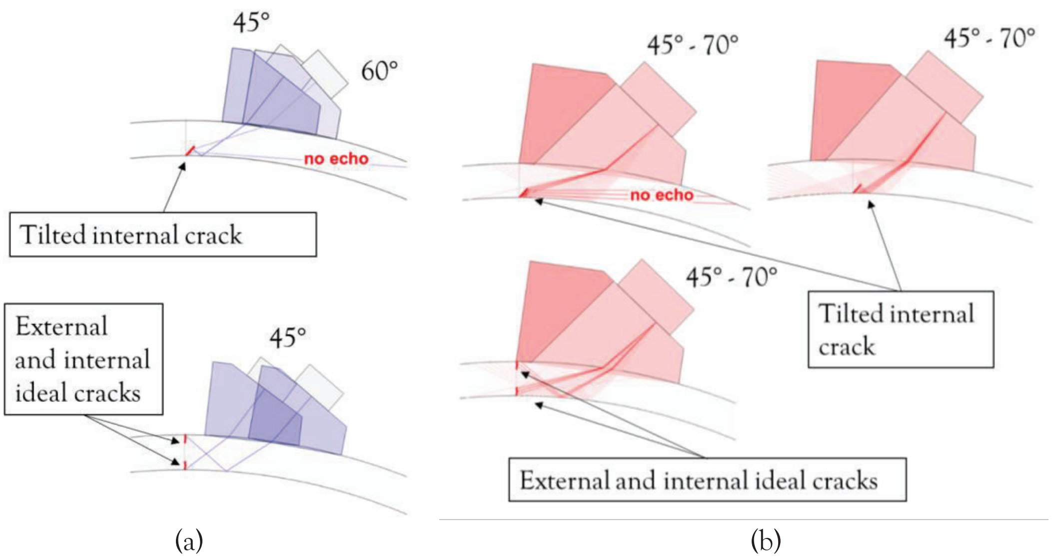

Figure 3. Sound paths for UT (a) and PAUT (b) for tilted cracks (top) and radial, surface-connected cracks (bottom).

Phase 1 summary

As previously mentioned, in-ditch non-destructive examination (NDE) inspections were conducted using a PAUT setup. The NDE vendor (Vendor 1) listed several anomalies verified in the field as 'hook cracks' and one internal, surface connected crack. The corresponding locations were analysed in the ILI data to determine patterns and identify possible systematic or distinct behaviours across the different flaws.

Two different patterns were identified in the ILI data for the 'hook' population. For the first one, the ILI data for seam anomalies that are not purely radial and generally include some parallel-to-the-surface component shows different signal behaviour between clockwise (CW) and counterclockwise (CCW) sensors, either in amplitude, signal pattern behaviour or both (**Figure 4**). The second pattern identified was not clearly indicating a hook component in the flaw, even though the anomalies were field verified as 'hook cracks'. This group of anomalies showed the same signal and patterns in the ILI recorded data from both sides of the weld. However, these indications followed a pattern of three linear reflections showing the highest recorded amplitudes alternating between the expected external and internal Time of Flight (TOF) windows (**Figure 5**), indicating some level of complexity or multiple reflectors. **Figure 4** and **Figure 5** show B-Scans where each sensor recording is color coded by amplitude, the darker the color the higher the amplitude. This recorded amplitude is depicted in front of their time of flight from the sensor and back (y axis), and relative distance to the referenced girth weld (x axis).

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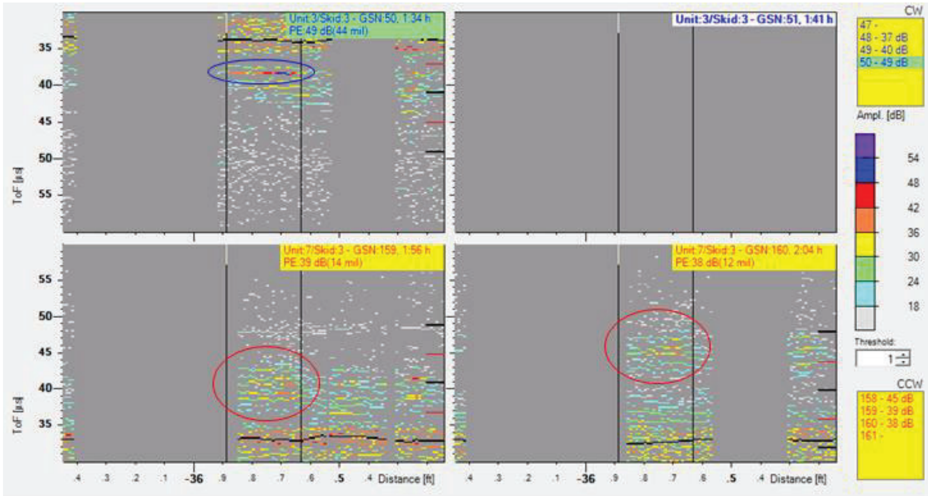

Figure 4. B-Scan data for a verified hook crack following the first signal pattern identified. Upper scans correspond to CW sensors and bottom scans to CCW sensors.

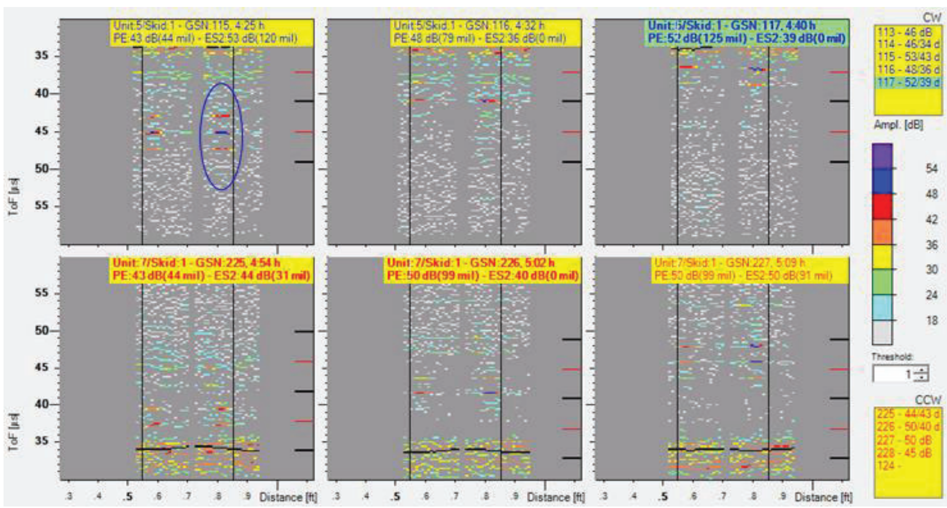

Figure 5. B-Scan data for a verified hook crack following the second signal pattern identified. Upper scans correspond to CW sensors and bottom scans to CCW sensors.

This pattern recognition methodology generated from the NDE-inspected 'hook cracks' was applied to all reported non-repaired anomalies and enabled the identification of 22% potential 'hook crack' anomalies among this population.

The outcome that Phillips 66 was intending to get out of phase 1 was risk reduction. Phillips 66 took the stance of digging all 'likely/possible hook cracks' discovered during phase 1 in line with their goal of risk reduction. The results of the dig campaign, as well as a lab report from a cutout were shared with NDT Global to complete phase 2 of the analysis.

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Phase 2

Differences identified between NDE vendors

The operator selected these potential 'hook crack' anomalies for non-destructive examination. For this new dig campaign, the operator decided to change the NDE vendor (Vendor 2). The general setup for Vendor 2 NDE was using Total Focusing Method (TFM), which differs from PAUT. For a TFM setup, there are no distinct angles. Instead, the setup uses phased array UT (PAUT) probes, generating a high number of different sound paths between the individual PAUT elements (**Figure** 6). The inspected area (TFM zone) is represented by a grid, where the signals from all sound paths are merged, based on the wave mode and theoretical travel times for each individual grid cell. In **Figure 6**, PAUT (left) shoots separately with different angles to cover the whole weld profile. TFM (right) transmits and receives with each element separately. The received signals are superimposed separately with optimized delays for each grid cell within the TFM-zone, allowing optimal focusing throughout the zone.

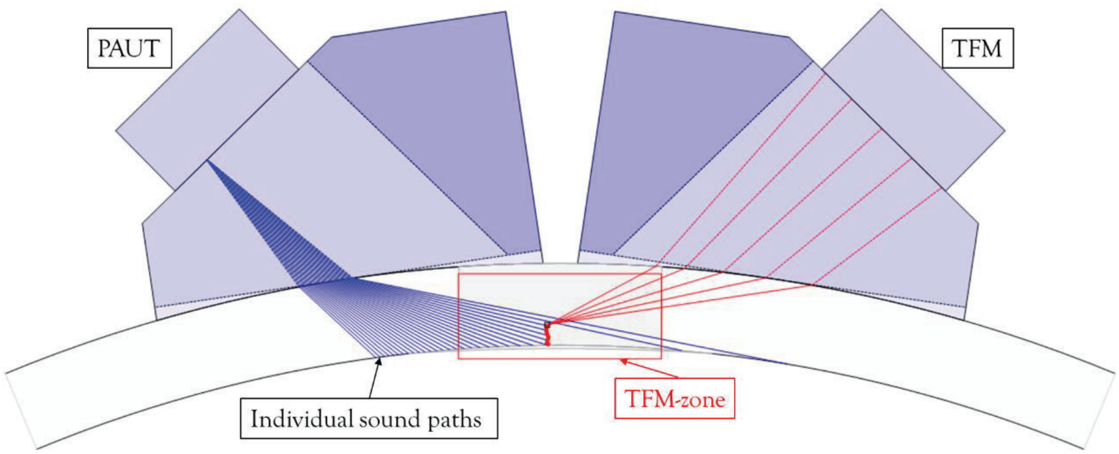

Figure 6. Scheme of PAUT and TFM techniques.

Table 1 summarizes the NDE results for the potential 'hook crack' anomalies.

Table 1. NDE results for the potential 'hook crack' anomalies

ILI Phase 1 results	NDE Vendor 2 results
Potential 'hook crack' anomalies	55.89% Lack of fusion
	23.53% 'Hook crack'
	20.58% Crack

Consequently, NDT Global data experts reviewed ILI signal footprints for these anomalies to confirm that they were showing the same signal behaviour and data patterns as the previous features verified as 'hook crack' anomalies by Vendor 1.

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Destructive testing to determine ground truth

To further understand the nature of the anomalies present in the pipeline, and to verify the NDE with lab testing results, Phillips 66 decided to commission a metallurgical evaluation of 7 pipeline coupons, including a total of 9 linear anomalies that were previously non-destructively examined and identified as 8 'hook crack' anomalies and 1 LOF anomaly. The metallurgical evaluation included the determination of whether the NDE had correctly called out the anomaly types and locations, the measure of the depth of each anomaly, and the determination of whether any crack growth had occurred in-service. The position and axial length of each indication was confirmed using wet fluorescent magnetic particle inspection (MPI) before being chilled in liquid nitrogen and broken open.

The summary of the laboratory destructive results is that of the 9 indications examined, 6 were found to be weld bond line LOF anomalies. An example is shown in **Figure 7**, while the 3 remaining indications were found to be surface laps. An example is shown in **Figure 8**. The surface laps likely resulted from improper weld formation. One of the three also shows evidence of hot tearing in the weld fusion zone. No evidence of in-service crack extension was observed during the metallurgical examination. (Stress Engineering Services Inc. 2023-2029-RP-02_Rev4)

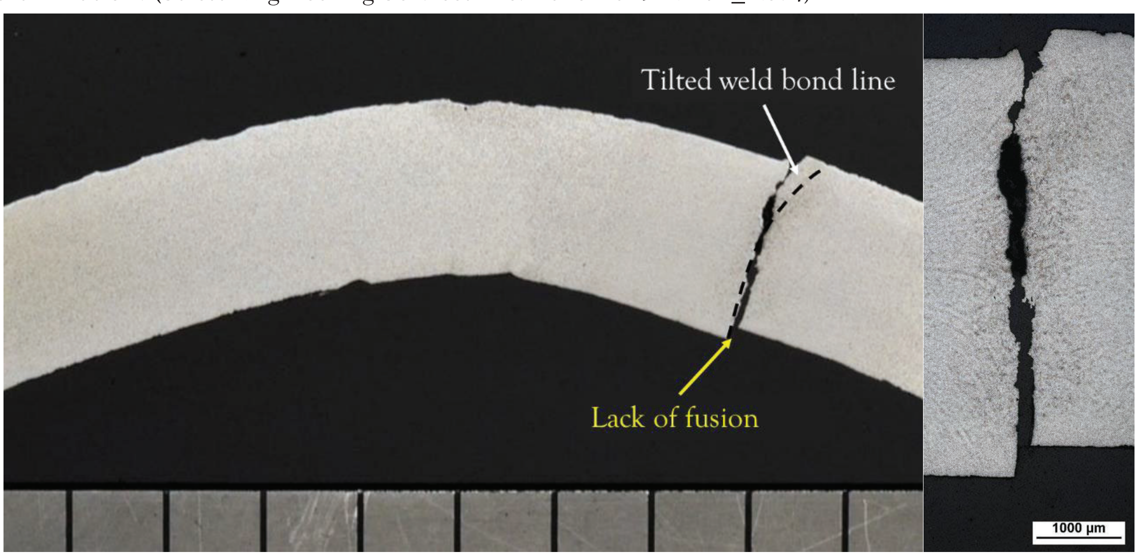

Figure 7. Full-thickness macro and micro photograph of the transverse metallographic for one of the destructive tested anomalies identified as LOF. Scale divisions are 1/10 inch.

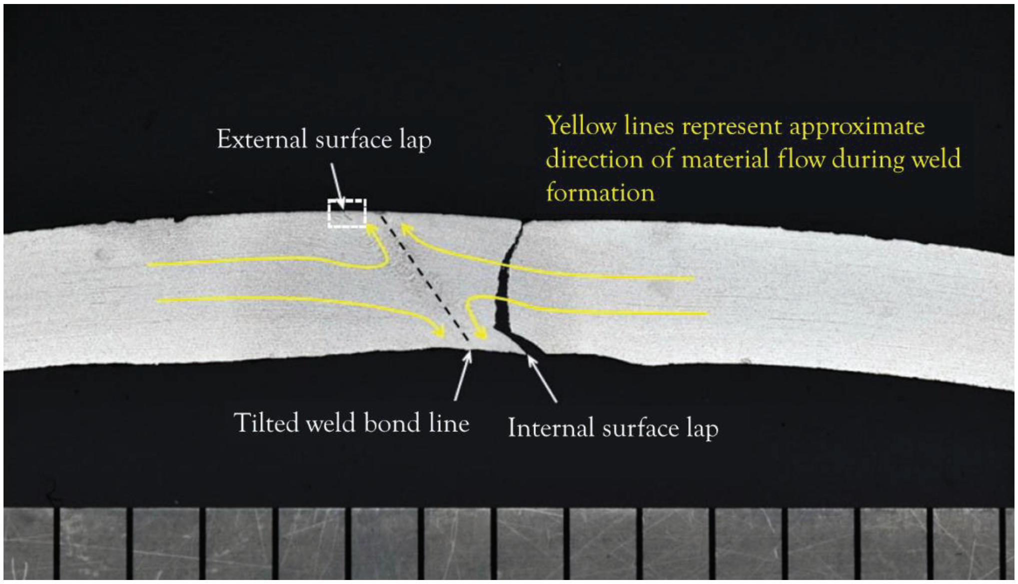

Figure 8. Macro photograph of the transverse metallographic for an anomaly identified as surface lap. Scale divisions are 1/10 inch.

The 6 planar anomalies that were found to be LOF, were situated on the bond line of the longitudinal seam weld and they had resulted from a localized lack of fusion, probably because of insufficient preparation of the strip edge prior to welding or because the strip edge was not heated sufficiently to cause melting. In addition, some of the samples show a tilted weld bond line probably caused by uneven forming pressure or misalignment of the strip edges during the manufacturing welding process.

However, for the 3 remaining anomalies it was discovered that they were not located at the weld bond line like the LOF defects. As can be seen in **Figure 8** and **Figure 9** examples, the anomalies took the form of a sharp curved lap extending from the pipe surfaces and are located to the side of the bond line. The bond lines of these anomalies were tilted almost 45 degrees from the ideal radial plane, indicating that the external surface layer of one strip had been forced over the other during weld formation. Microstructural banding indicated that the material on the opposing side of the bond line was forced to fold back on itself by the advancing strip edge producing a sharp unfused lap in the pipe surface. (Stress Engineering Services Inc. 2023-2029-RP-02_Rev4)

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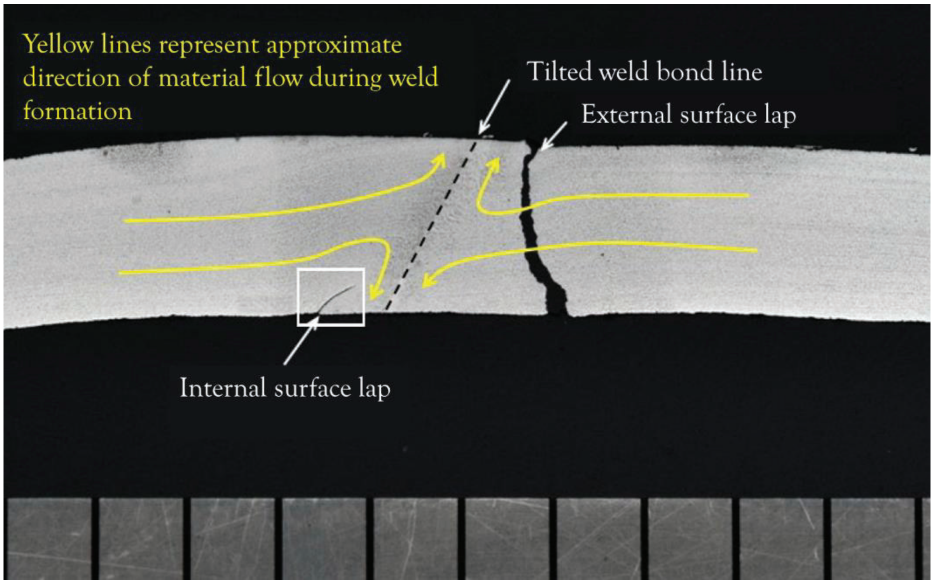

Figure 9. Macro photograph of the transverse metallographic for an anomaly identified as surface lap. Scale divisions are 1/10 inch.

It is important to note that considering the metallurgical report these lap anomalies differ from 'hook crack' anomalies in that they are formed by the folding of the external and internal surfaces of the pipe (**Figure 10**), as opposed to cracks caused by separations resulting from imperfections in the edge of the skelp, parallel to the surface, which turn toward the internal or external surface during weld upset.

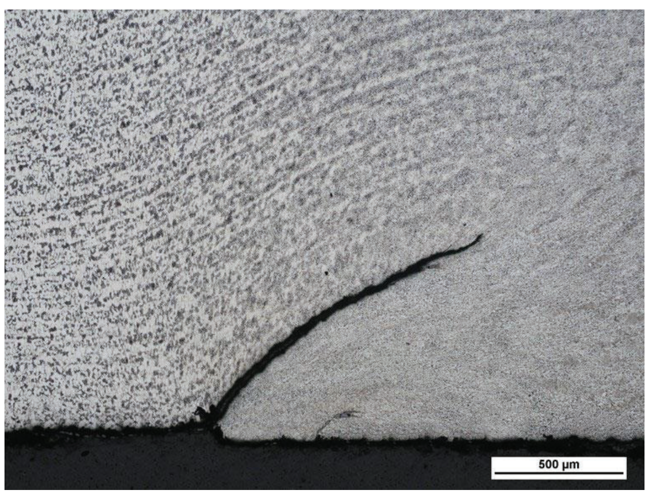

Figure 10. Detail of an internal surface lap

Ground truth enables characterization using pattern analysis

From the ILI data point of view, these lap anomalies close to the bond line show the same signal behaviour as a 'hook crack.' In this case, data signals would differ between the clockwise (CW) and counterclockwise (CCW) sensors, either in amplitude, signal pattern behaviour or both.

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From the CW sensor perspective, the corner echo is received by the transducer. This pattern indicates a linear feature with high amplitudes. However, from the CCW sensor perspective, multiple signals would be received by the transducer reflecting from the non-radial component of the anomaly leading to 'noisy' linear indications (**Figure 11**) that make the data look 'cloudy'.

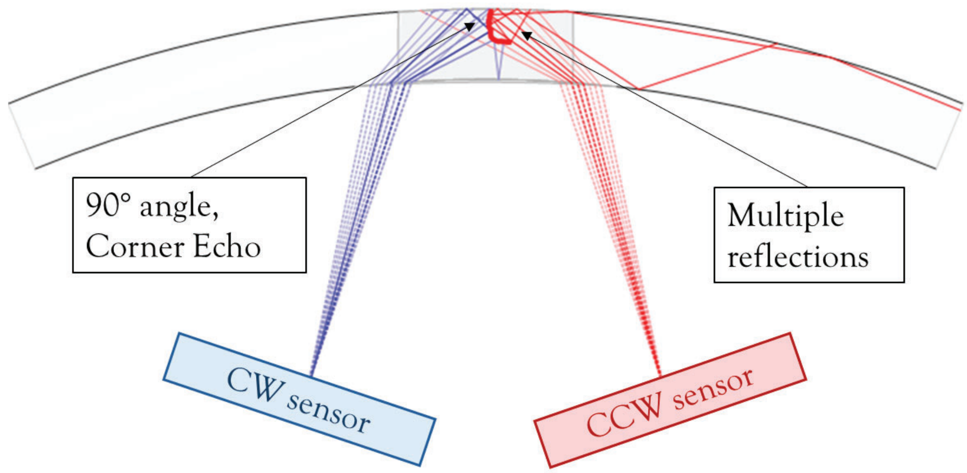

Figure 11. Scheme at scale of a 'hook crack' detected by clockwise and counterclockwise sensors. Colour lines simulate the sound beam, and the stronger ones indicate reflections from the flaw back to the sensors.

In addition, as can be seen in **Figure 8**, surface lap anomalies are not located in the bond line but to the side of it. Due to their relative position to the weld centre, the signals of the internal or external bond line-surface contact are blocked by the lap geometry. Therefore, a reduced amplitude sound wave is reflected from the contact between the weld and the surface in the multiple sensor shots along the anomaly (**Figure 12**).

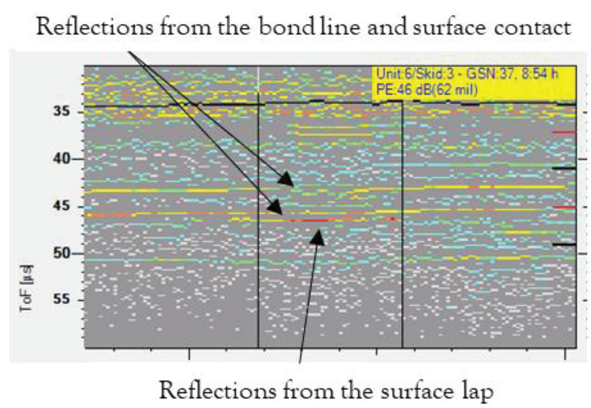

Figure 12. B-Scan ILI data for a CW sensor for a verified internal surface lap.

The mentioned above ILI data signal pattern visible in the surface laps, adds an additional layer of characterization that makes them potentially identifiable among the ILI anomalies listed for the pipeline.

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Nevertheless, all anomalies listed as potential 'hook cracks' that were matching the second pattern identified in Phase 1 based on the NDE results from Vendor 1, were proved to be lack of fusion anomalies not related to 'hook cracks' by the destructive testing laboratory results. Therefore, the second pattern was removed from the list of characteristics for potential 'hook crack' and 'surface lap' identification.

Leveraging the destructive lab results and the knowledge acquired on all these pattern recognition processes; the final step was to apply the identification procedure mentioned above to all anomalies detected in the pipeline. NDT Global performed a below reporting thresholds (BRC) analysis on more than 3000 anomalies to determine which of them could potentially be 'hook crack' or 'surface lap' anomalies. BRC anomalies are those anomalies that, despite being detected and sized, do not meet the depth and length required to be included in the standard reporting list. After the complete review, the final call for possible 'hook or lap' anomalies was reduced to less than 20 anomalies that show hints of complexity and were blocking the bond line-surface contact reflections.

Phillips 66 will be reviewing the final listing provided by NDT Global and performing a risk-based assessment to decide which potential 'hook crack or surface lap' anomalies need remediation and include them in their next dig program. The utilization of additional analysis methods results in a higher degree of confidence in the ILI results. In combination with destructive testing validations, this in-depth analysis better informs decision-making, ultimately leading to a reduction in the number of assumptions, resulting in a better management of the pipelines' integrity.

Ground truth enables performance analysis and sizing curves analysis

The starting point of this investigation was the NDE result list from Vendor 1 where 33 anomalies were identified as 'hook crack' in the field and the depth sizing of these anomalies were raising concern about the performance of the ILI tool used for the inspection. As can be seen in **Figure 13** the unity plot for ILI reported depth compared to the Vendor 1 NDE depth shows a clear tendency for the ILI tool to underestimate the field verified depths. It needs to be noted that Vendor 2 results were taken using TFM methodology after Phase 1 of this investigation was published. The dashed red lines in the following figures are the tool tolerances specified in the NDT Global performance specification at 80% confidence level and each anomaly error bar is based on a field depth tolerance of ±25 mils at 80% confidence level.

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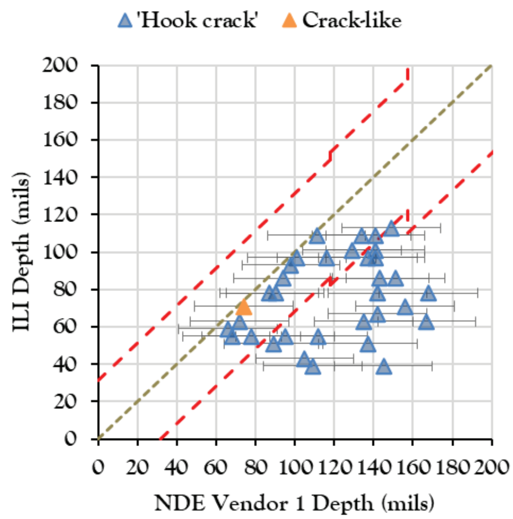

Figure 13. Unity plot for NDE Vendor 1 (left) and Vendor 2 (right) results compared to ILI results.

The laboratory destructive test results were shared with the NDE vendors to give them the opportunity to review the field data and adjust the identification and depth sizing of the reported anomalies based on the metallurgical results. **Figure 14** shows the unity plot for ILI reported depth compared to the Vendor 1 and Vendor 2 NDE reviewed depth based on the lab results. It can be observed that on the right-hand side, the regraded depths for the Vendor 1 field data are close to what the ILI tool properly sized in the first instance. The regraded depths for Vendor 2, which were sized using the TFM method, have very little changes. In addition, Vendor 2 added some additional anomalies observed in the field that were also included in the ILI results list.

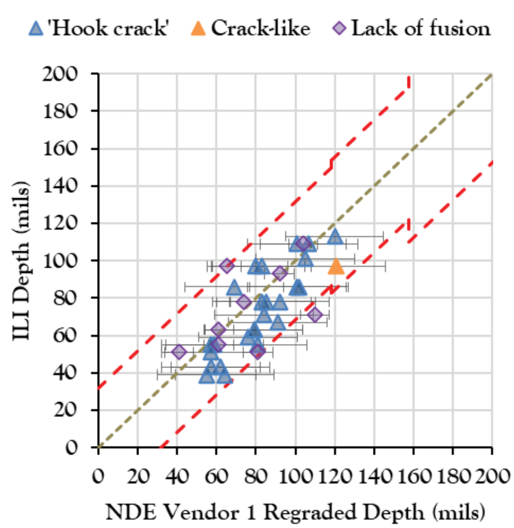

Figure 14. Unity plot for NDE Vendor 1 (left) and Vendor 2 (right) regraded results compared to ILI results.

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Following the same idea, as can be seen in **Figure 15**, the ILI depth results compared to the anomalies' actual depth based on the metallurgical report show that the 6" high resolution UT tool was properly sizing the anomalies and no regrade was needed. Anomalies depicted with an orange edge are anomalies out of the performance specification (PS) of the tool by length and/or depth, meaning that their actual depth was lower than 39 mils and/or their actual length was lower than 0.98 in. at the time of the in-line inspection.

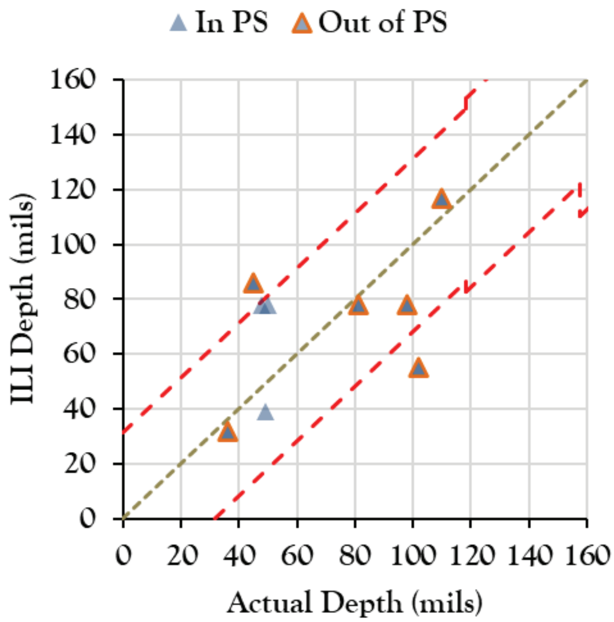

Figure 15. Unity plot for laboratory results compared to ILI results.

If the original NDE Vendor 1 and Vendor 2 results are plotted against the reflected amplitude of the anomalies in the ILI data, different sizing curves can be obtained based on each NDE population. Sizing curves stablish the relation between the amplitude recorded by the ILI tool and the predicted depth of the anomalies. **Figure 16** shows the laboratory depth results in front of these different sizing curves. It can be observed that the ILI standard sizing curve (blue dashed line) is the best fitting to the truth depth results sizing curve (green line).

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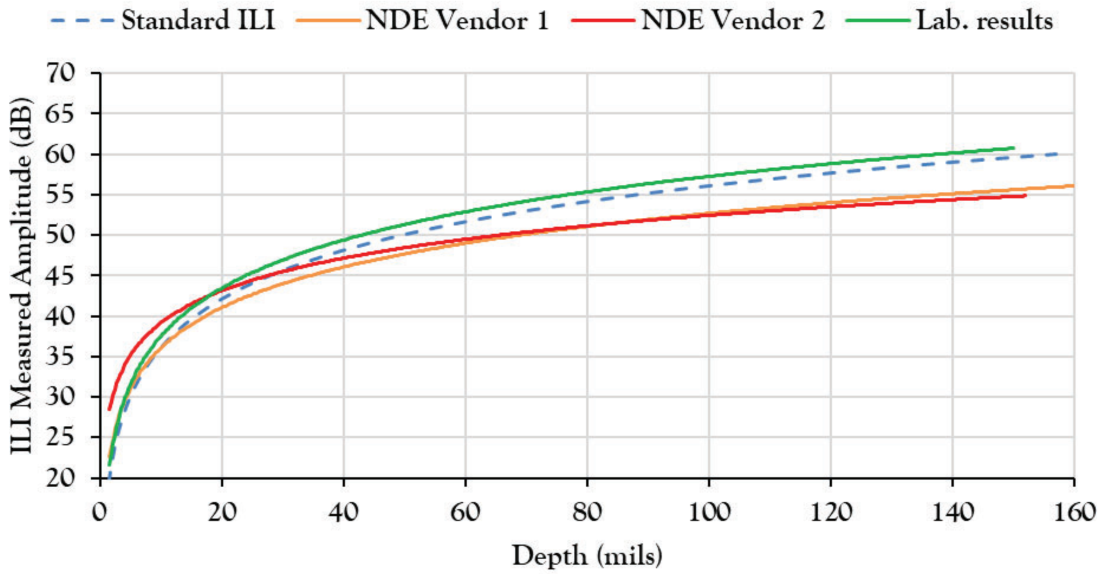

Figure 16. Different sizing curves based on the NDE results from Vendor 1 and 2, and the measured amplitudes for the ILI anomalies.

NDE and lab results validation

Following the method described by API Standard 1163, the combined tolerances were determined from the contractual feature specification of the ILI tool and the tolerances of the field measurements. For the high-resolution UT tool used for the inspection, the depth sizing accuracy at a certainty of 80% depends on the feature depth **(Table 2)**.

Table 2. ILI tool depth sizing accuracy

Feature depth	Depth sizing accuracy
39 mils to <118 mils	±31 mils
118 mils to <157 mils	±35 mils
>157 mils	±47 mils

For PAUT and TFM, measurement tolerances for crack depth were considered as ±20 mils, based on considerations in Table 2 of the Recommended Practice POF 310 Field Verification for ILI.
The findings are based on the regraded NDE results from Vendor 1 and 2, and on the laboratory results. Which add up a total of 80 anomalies. 72 of the 80 measurements were within tolerance, yielding p_{upper} = 94.42% and p_{lower} = 82.96%. These results exceed the certainty of 80%, corresponding to Outcome 3 of the level 2 validation described in API Standard 1163:2021. The ILI performance specification is feasible.

There are sufficient field results to proceed with a level 3 validation analysis. Level 3 validation analysis, as described in API Standard 1163:2021, seeks an estimation of the actual ILI performance

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as indicated by the available validation measurements. The statistical evaluation concluded that the tolerance interval for a given ILI measurement is [-26 mils, 44 mils]. Therefore, the actual tool tolerance is ±35 mils with a certainty of 80%.

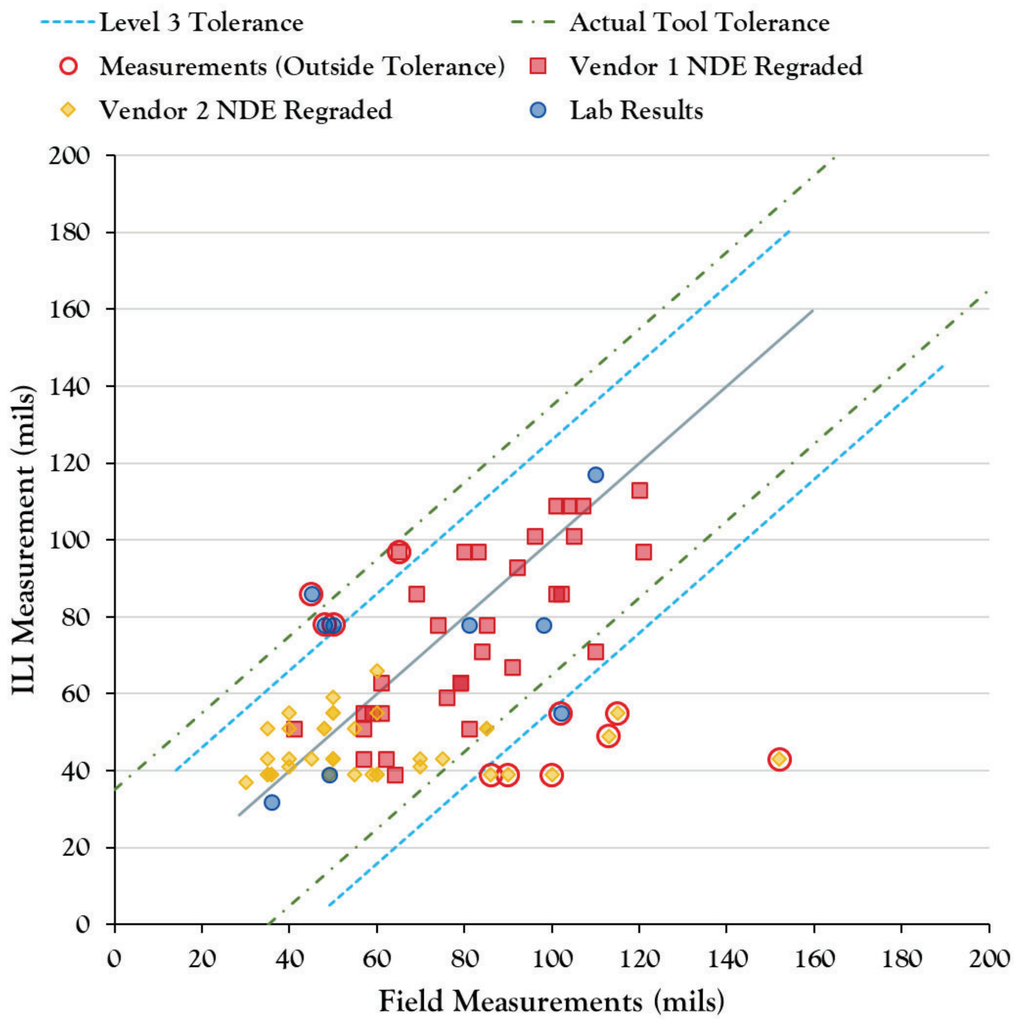

Figure 17. Level 3 validation unity plot for lab results and NDE vendor 1 and 2 regraded results in front of the ILI results.

Conclusions

1. **Avoid Adjusting ILI Sizing Curves Solely Based on NDE:**

Modifying ILI sizing curves based solely on NDE results can lead to significant inaccuracies (**Figure** 16**),** introducing a general bias in depth estimations. Adjusting ILI sizing curves should rely exclusively on ground-truth data obtained from confirmed, peer reviewed sources, and, preferably, direct measurements (e.g., destructive testing). Additionally, such adjustments must be treated as specific to the asset in question, ensuring data relevance and integrity.

While it may be possible to extrapolate these adjustments to other assets, doing so requires a rigorous sensitivity analysis to account for variability and to ensure applicability.

2. **The Value of Metallurgical Destructive Testing:**

Destructive testing of pipeline samples provides accurate data essential for verifying and enhancing ILI results. Combining these results with advanced ILI data analysis techniques improves confidence in the findings. By considering the complete context of an asset and its history, this approach reduces the reliance on assumptions, enabling effective and reliable pipeline integrity management.

3. **Adherence to a Systematic Methodology:**

Employing a structured and systematic framework that accounts for potential biases introduced by NDE and controls key variables is critical. Following established protocols, such as the ones described in API 1163, promotes consistency, avoids shortcuts and overall reduces exposure to errors. By avoiding premature assumptions and adhering to a disciplined methodology minimizes the risk of unnecessary or drastic actions.

4. **From Hypothesis to Conclusion, Evaluating Accuracy:**

Transitioning from the hypothesis that "ILI results are inaccurate" to demonstrating that "ILI results are correct, and the NDE measurements may be flawed" requires methodical investigation. This entails scrutinizing all data sources, identifying discrepancies, outliers and validating the accuracy of each technique used.

5. **Limitations of Field Verification Tools and Techniques:**

Field Verification practices could assume that some techniques are universally suitable, which is not always the case. Factors such as the curvature of the pipe or asset specific conditions may render certain probes or NDE techniques as suboptimal for the application. Recognizing these limitations is essential to ensuring accurate validations and reliable integrity assessments.

Phillips 66 benefited in going through this exercise with NDT Global by achieving a greater level of confidence in identifying 'hook cracks'. In addition, confirming that the sizing originally reported by the ILI was within performance specification. Phillips 66 will definitely consider this higher-level analysis during future inspections on this line, and other lines containing similar defects.

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Abbreviations summary

Table 3. Abbreviations summary.

Abbreviation	Description
CCW	Counterclockwise
CW	Clockwise
ILI	In-Line inspection
IMP	Integrity management system
LF-ERW	Low-frequency electric resistance welded
LL	Longitudinal-longitudinal (TFM mode)
NDE	Non-destructive examination
PAUT	Phased array ultrasonic testing
PE	Pulse-echo
TFM	Total focusing method
TT	Transversal-transversal (TFM mode)
TOF	Time Of Flight
BRC	Below reporting criteria
PS	Performance Specification
LOF	Lack Of Fusion
MPI	Magnetic Particle Inspection

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