Seam Cracking IMP Enhancements with an Innovative and Accurate Time-Based Crack Sizing ILI Tool

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

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https://doi.org/10.52202/078572-0040

Proceedings of the 2025 **Pipeline Pigging and Integrity Management Conference.**
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https://doi.org/10.52202/078572-0040

Abstract

Pipeline operators face several challenges during the implementation of a seam cracking integrity management program (IMP). Some of these challenges are related to improving the confidence on non-destructive examination (NDE) dig data, in-line inspection (ILI) tool data analysis and crack sizing and implementing crack assessment methodologies under a risk-based assessment framework. Overcoming those challenges is key for the development of an effective and efficient dig program and long-term asset management strategy.

As part of the seam cracking IMP enhancements, Imperial Oil Ltd. (IOL) ran a new and innovative crack detection tool that was developed and recently presented by ExxonMobil Technology and Engineering (EMTEC) at the 19th Pipeline Technology Conference. Although the new ILI tool has shown to be highly accurate, the success of the enhanced seam cracking IMP was the result of the implementation of supporting integrity programs to ensure the right information and assessments were being used.

This paper discusses the steps that were followed for the implementation of a successful seam cracking IMP on a small diameter, high frequency electric resistance welded (HF-ERW), thin wall pipeline. Details about the new ultrasonic ILI technology with consistent and reliable tip diffraction sizing capability, the implementation of a structured NDE and validation program, the deterministic and probabilistic evaluation of reported seam weld anomalies using the PRCI MAT-8 methodology, the impact from ILI tool measurement error on the probabilistic assessment results. and the implementation of a risk-based approach for dig selection and definition of a long-term seam cracking management plan, are included in this document.

Background

Several challenges have been identified by pipeline operators when implementing pipeline integrity management programs for long seam weld anomalies. Some of these challenges are even more significant when small diameter, thin wall pipelines are part of the pipeline system. Some of the opportunities discussed in this paper include improving the confidence on NDE dig data and ILI tool crack sizing, evaluating and implementing deterministic and probabilistic fracture mechanics-based crack assessment methodologies, and applying risk-based approach for managing the seam cracking pipeline integrity threat.

Accurate and reliable height sizing of crack-like imperfections on the long seam is required for proper risk management in pipelines. ILI sizing errors that underestimate the imperfection height present an integrity risk, while sizing errors that overestimate the imperfection height present a financial risk [1]. Typical amplitude-based UTCD ILI tools, tested using calibration spools with synthetic flaws, are the most common technology used nowadays. The API 1163 Level 2 validation analysis of the testing program resulted in an Outcome 2 (rejected the stated performance specification). In order to

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overcome this challenge, a new time-based tip diffraction UTCD ILI tool for small diameter liquids pipeline was designed, built, tested and run. The technology showed consistent and reliable results based on flaws in the calibration spool and anomalies identified by NDE during field investigation.

NDE field assessment of crack-like imperfections in the long seam are highly dependent on the NDE technician ability and expertise, as well as having the right equipment with the appropriate calibration. It is not uncommon that there are significant variations in reported imperfection height from one NDE technician to another. To overcome this challenge, a structured in-the ditch (ITD) NDE QA/QC program was developed and implemented to ensure the quality and accuracy of non-destructive examination results. Quality ITD NDE data can then be used to assess UTCD ILI tool performance and conduct FFS assessments. The ITD NDE QA/QC program captures relevant data about NDE technician performance, NDE vendor qualification, NDE procedure effectiveness, and NDE technology effectiveness.

The implementation of the recently developed PRCI MAT-8 model to assess crack-like imperfections in the long seam weld brings significant advantages [2]: a) the MAT-8 model has the strongest physical basis when compared to other crack assessment methodologies , b) the MAT-8 model works reasonably well in the fracture-controlled regime , c) the MAT-8 model can incorporate residual stresses , and d) the MAT-8 model can be used in deterministic and probabilistic assessments. More accurate crack assessment results can be used to improve the selection of potential anomalies for investigation.

Probabilistic crack assessment results can be used in combination with a consequence analysis to identify a risk level per anomaly during a specified time span (e.g., every year for up to 10 years from the ILI assessment). A more efficient and effective risk-based dig program can be prepared once the risk level has been validated.

Industry Experience

Amplitude-based UTCD ILI tools are widely used in the pipeline industry to assess crack-like imperfections in the long seam. The typical amplitude-based UTCD tool can reliably size crack-like imperfection with ±10° of tilt and ±5° of skew meeting tool performance specification. However, height sizing of crack-like imperfections with larger tilt and skew can be outside tool performance specifications.

Other factors such as shape, surface condition, difference between calibration and pipe material properties, and seam weld pipe geometry changes also influence height sizing of crack-like anomalies. These influences can lead to sizing accuracies falling outside of expected tolerances [3].

Previous studies showed high uncertainty associated with height sizing of crack-like indications in the long seam weld and difficulties associated with height sizing on the weld [4]. Loss of sensor contact

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and change of the incident angle for amplitude-based UTCD tools at a misaligned seam of just a few degrees can reduce ILI accuracy by 50% [5].

Figure 1 shows the result of an ultrasonic model prediction of signal amplitude versus flaw tilt, based on a 45° shear wave, 6 mm diameter probe, and 3.5 mm height notch in an 8-inch pipe with a 5 mm wall thickness. For some situations, a 6dB amplitude drop (e.g., tilt > 10°) may result in a sizing change of 1-2 mm. Change in height sizing can have significant impact on the burst pressure and remaining life calculations, which can result in over or under estimation of a remediation program.

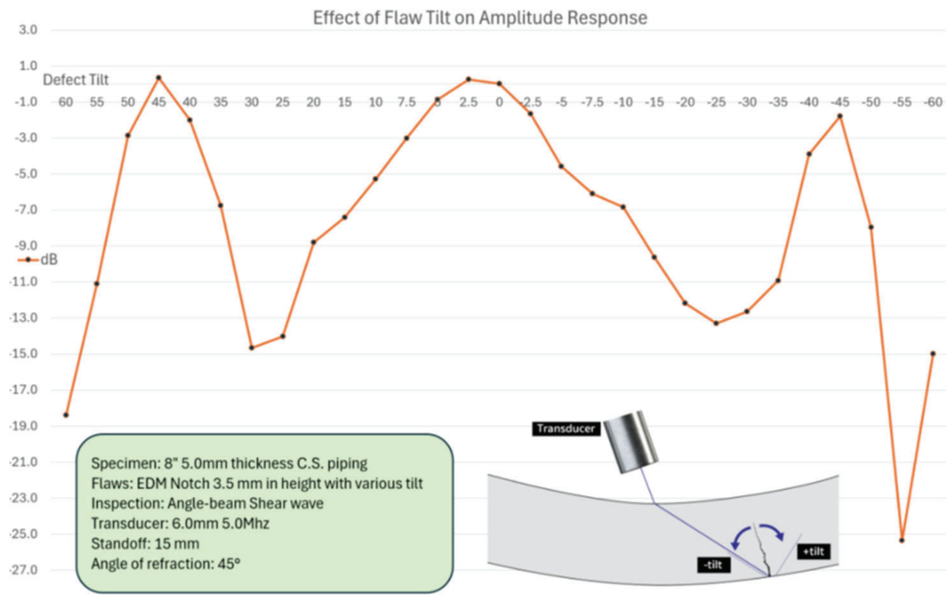

Figure 1. Effect of flaw tilt on reflected amplitude from 45° shear wave [3].

ExxonMobil Technology and Engineering (EMTEC) undertook a program to assess the performance of amplitude-based UTCD tools. This validation was completed using calibration spools with synthetic (e.g., manufactured) flaws [6]. ILI tool performance analysis was completed following the API 1163 methodology at 80% certainty and 95% confidence level. The API 1163 Level 2 analysis resulted in Outcome 1 (Spec. Rejected) as shown in Figure 2. The API 1163 Level 3 analysis showed an under-sizing of 0.52 mm and a tolerance of 1.71 mm at 80% confidence interval and 95% confidence level, resulting in a measurement error of 2.23 mm [3].

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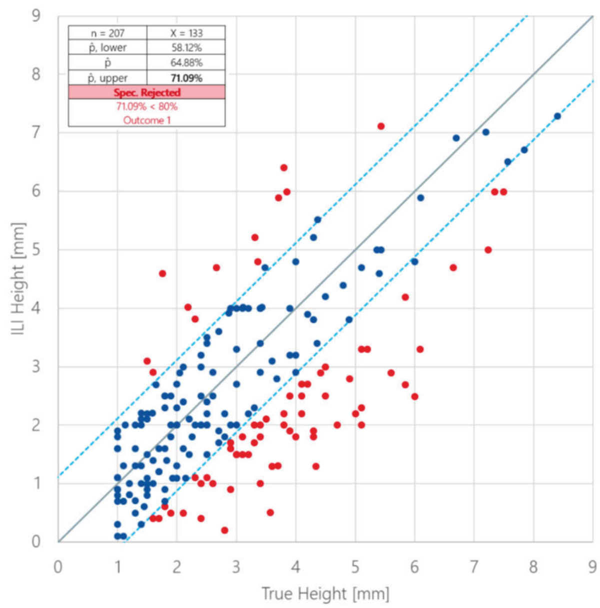

Figure 2. API 1163 Level 2 – Amplitude-based UTCD Industry Performance [3].

The impact of height sizing accuracy can be seen in Figure 3. This figure shows an example of critical crack size curves for an 8-inch pipeline with nominal wall thickness of 6.4 mm and pipe grade API 5L X52. From this plot, it can be seen that a 2.2 mm measurement error introduces significant conservatism in the crack assessment results, even higher than the equivalent hydrotest pressure level [3].

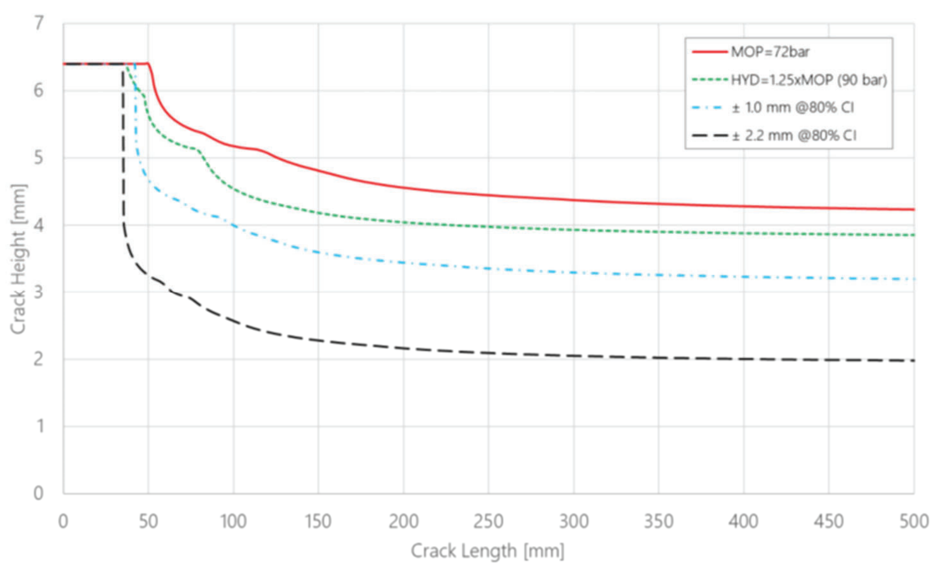

Figure 3. Impact of height sizing in deterministic calculations [3].

New ILI tool technology – Time Based Tip Diffraction Sizing

EMTEC and the ILI vendor Dexon Technology undertook the task of designing and commissioning a new UTCD ILI tool technology for small diameter pipelines, with the goal of improving crack sizing accuracy and reliability. The new tool applies time-based tip diffraction technology which has been considered one of the most accurate crack sizing methods within ultrasonic testing due to its direct measurement of flaw position [3]. Figure 4 shows a representation of this technology.

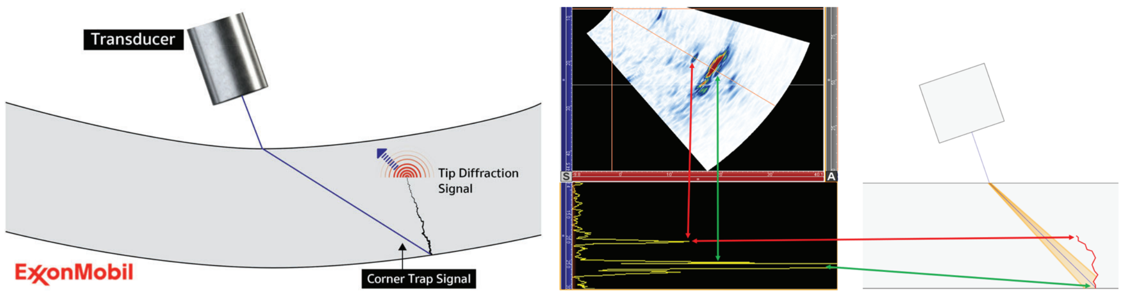

Figure 4. Tip diffraction signal representation [3]

This new ILI tool technology was recently presented during the 19th Pipeline Technical Conference. Advantages and disadvantages of this technology are discussed in more detailed in the published paper. One of the most interesting advantages of using time-based tip diffraction technology is that the direct measurement by tip diffraction is largely unaffected by variables such as flaw tilt, skew, and shape [3].

Several parameters were evaluated during the tool design stage, including type of sensors, density of ultrasonic sensor arrays, hardware and software requirements for data management, requirements for semiconductors and electronics, and mechanical design among others. The new UTCD tool uses 4.5 mm diameter transducers, with a frequency and stand-off calculated to ensure inspection in the focal zone. These transducer attributes support the ability to provide accurate flaw placement, consistent amplitude, and ensures consistent refraction even with small pipe diameters [3].

An analysis of the critical flaw size and sizing tolerance was conducted to understand sizing requirements. Table 1 shows the target performance specification [3].

Table 1. New UTCD ILI tool target performance specification [3]

	Axial Crack	Units
Circumferential sampling distance	1.0	mm
Axial sampling distance	2.6	mm
Crack height detection threshold >90% POD	1.0	mm
Crack height detection threshold >90% POD	25.0	mm

 https://doi.org/10.52202/078572-0040

Height sizing accuracy at 80% certainty	±1.0	mm
Length sizing accuracy at 80% certainty	±25.4	mm

The design process of the novel ILI technology included the use of calibration spools. Complex shaped synthetic flaws of precise morphology, size and orientation, are introduced in a pipe spool using advanced manufacturing and welding techniques. These synthetic flaws can be considered as "truth data". Calibration spools with synthetic flaws were designed and manufactured targeting the type of anomalies to be assessed in a ERW pipeline. Calibration spools have demonstrated to provide useful and accurate assessments of UTCD ILI tools and in-the-ditch (ITD) UT operators [6]. The use of a calibration spools for ILI tool performance assessment has been shown to accomplish several objectives [6,7]:

a) Improve the estimate for POD performance,
b) Reduce the number of and resulting cost associated with required validation digs,
c) Reduce time to complete validation and make integrity decisions,
d) Improve ILI measurement performance knowledge over a broad range of flaw size, type and position,
e) Enable more reliable and accurate fitness for service and integrity assessments, and
f) Provide probabilistic inputs for quantitative reliability and risk assessments.

The new ILI tool was tested in different phases. During the initial phase, the tip diffraction ILI tool testing began with a bench top prototype providing partial pipe coverage which was mechanically pulled through a calibration spool with EDM notches and synthetic cracks. Following the successful proof of concept, further evaluation using additional calibration spools was completed. Finally, the tool was pulled through a calibration spool with complex crack-like flaws from vintage ERW pipeline.

The next phase of the testing included running the tool in a flow loop using three (3) calibration spools. The number, size and shape of manufacturing flaws were engineered to effectively assess UTCD ILI tool performance [6,7].

Three (3) calibration spools were used to validate tool performance during this phase. A mixture of EDM notches and synthetic flaws (e.g., penetrators and hook cracks) were introduced in calibration spools 1 and 2. The third calibration spool contained mainly EDM notches. API 1163 Level 2 and Level 3 analyses were completed to evaluate tool performance using the API 1163 validation spreadsheet [8]. The assessment accounted for NDE field measurement error using an estimate of 0.3 mm for the synthetic flaws [6].

The API 1163 Level 2 analysis resulted in Outcome 2 (Spec. not rejected) as shown in Figure 5, and the Level 3 results indicated an over-sizing bias of 0.35 mm and a tolerance of 1.05 mm. Once the final phase of the testing program was completed, the novel ILI tool was ready to be commissioned.

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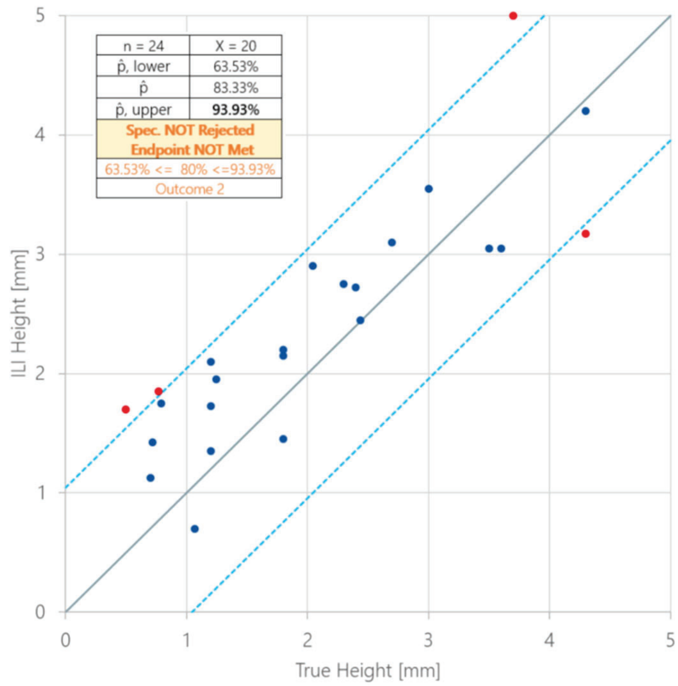

Figure 5. API 1163 Level 2 Factory Test results [3]

Seam Cracking IMP enhancements and implementation

As part of IOL's IMP continuous improvement process, significant enhancements were implemented in IOL's Seam Cracking IMP. These enhancements include the following activities:

a) Conducting an UTCD ILI using the new tool technology for small diameter (NPS 8) pipelines,
b) Implementing a systemic and systematic approach for in-the-ditch (ITD) non-destructive examination (NDE),
c) Verification of sizing and characterization of crack-like imperfections from both ILI vendor and NDE technician,
d) Adoption of the PRCI MAT-8 fracture-based crack assessment methodology for deterministic and probabilistic assessments, and
e) Optimization of remediation programs based on risk.

Most of the abovementioned activities were identified as improvement opportunities by pipeline operators in the recently released PRCI Project "Understanding Why Cracks Fail" [5]. The Seam Cracking IMP enhancements were implemented on a NPS 8, 4.78 mm (0.188") NWT, API 5L X52, 1974 vintage, HF-ERW pipeline.

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In-Line Calibration Spool

A calibration spool was designed and built to match the pipeline specifications. This calibration spool was different to those ones used during the testing phases of the new time-based tip diffraction ILI tool. The calibration spool was fabricated using NPS 8, 4.78 mm, API 5L X52, PSL 2, HF-ERW line pipe. Fifty-two (52) synthetic crack-like imperfections were introduced in the pipe body and long seam weld. These imperfections included penetrators, hook cracks, EDM notches and crack fields, as shown in Figure 6. The calibration spool was attached to the receiver end of the pipeline to represent "end of run" conditions for the tool. Figure 7 shows the calibration spool design that was used for the ILI tool run.

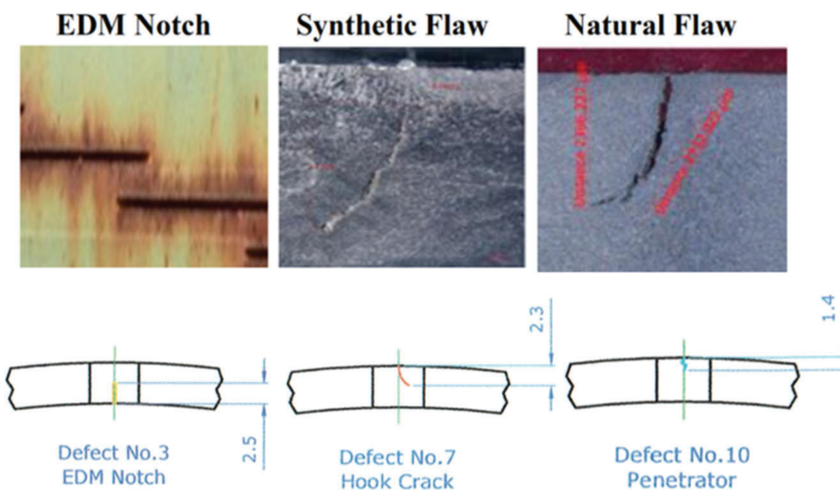

Figure 6. Example of synthetic flaws introduced in the calibration spool

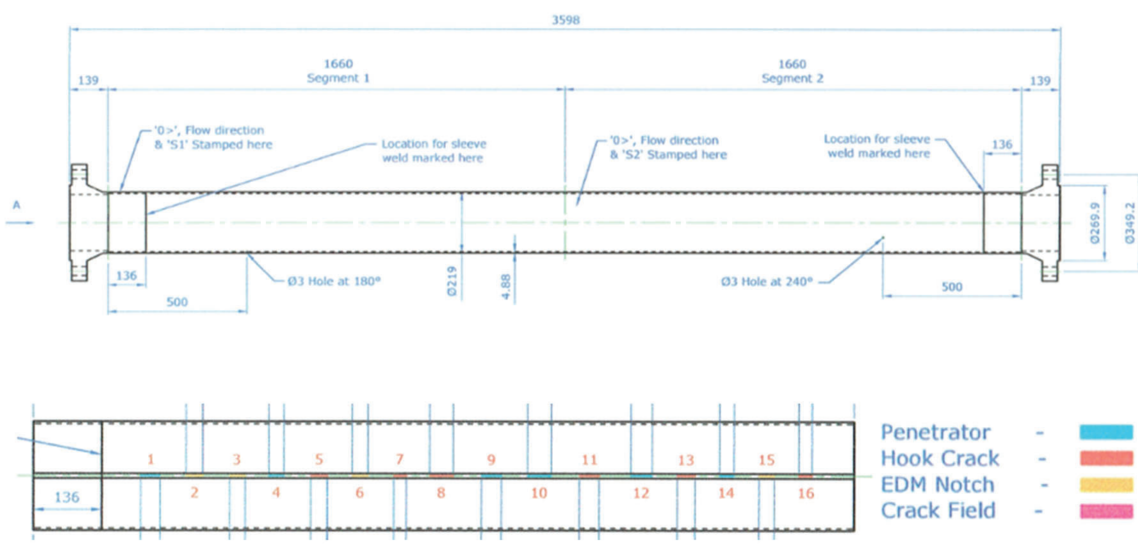

Figure 7. Calibration spool with manufactured synthetic flaws

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In-The-Ditch (ITD) Non-Destructive Examination (NDE) Program

NDE field assessment of crack-like imperfections in the long seam are highly dependent on the NDE technician's capability and expertise, as well as having the right equipment with the appropriate calibration. It is not uncommon that there are significant variations in reported imperfection height and morphology (e.g., LoF, Hook Crack, etc.) from one NDE technician to another. Although those assessed features will be repaired, it is critical to gather the correct ITD NDE data to enable accurate tool performance analysis. Quality ITD NDE data will also support discussions with the ILI vendor and potentially support any effort to re-analyse the ILI data if required.

A structured ITD NDE QA/QC program was developed and implemented to ensure the quality and accuracy of non-destructive examination results. The program covers procedure and technician qualifications, NDE report inspection protocols and quality control, and program exception procedures. The purpose of this program is to ensure that only qualified procedures and technicians perform ITD NDE on the pipeline assets and results of the inspection activities are properly documented. The ITD NDE QA/QC program is also used to monitor the NDE technician performance, NDE procedure effectiveness, and NDE technology effectiveness as part of a continual improvement process.

NDE vendors and technicians are qualified before performing field work. The goal is to verify that NDE vendor's process, procedures, technology, and methodology can deliver the desired performance and accuracy. NDE vendor procedures are qualified for each specific examination method, including VT, MT, PT, UT, SW UT, PAUT, TOFD and FMC/TFM among others. The NDE vendor procedures, include detailed calibration processes and provide a description of how the examination is to be performed in the field. The NDE vendor procedures will also include equipment requirements, calibration details, equipment condition, and details related to the performance of the task. The NDE vendor procedures are submitted for the Company's internal review by a NDE SME.

NDE technicians are qualified following the Technician Qualification Process (TQP). The TQP verifies the competency of the NDE technician prior to performing field work. The following tasks are conducted as part of the TQP:

a) Desktop review: Training, education, certifications, and experience of NDE technicians is reviewed to ensure minimum requirements for performing each specific examination method are met. The NDE technician is required to pass a hands-on qualification exam witnessed by a Company SME.

b) Qualification exam: When testing for anomalies in the long seam, a set of sample defect coupons with synthetic and natural flaws is chosen (Figure 9). The set of samples will be of similar material, diameter, manufacture, condition, and feature size parameters to those in the pipeline being assessed in the field. Type of flaws include ID and OD connected, hook flaws, lack of fusion, and mid wall LoF, among others. Examination results are documented and communicated to the NDE vendor and technician. Qualified NDE technicians are then allowed to conduct field assessments.

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Figure 9. Example of defect sample coupons used in the ITD NDE Program

The following NDE techniques were chosen to field assess crack-like imperfections (e.g., hook flaws, LOF) in the long seam of the NPW 8, 4.78 mm (0.188") NWT pipeline:

a) Standard NDE techniques: VT, MT, UT, SW UT,
b) Advanced NDE techniques: Encoded PAUT, manual PAUT from both sides of the long seam (90 & 270 skew), TOFD, and FMC/TFM (90 & 270 skew, T-T, TT-TT and TT-T modes).

The use of advanced NDE techniques within a stringent ITD NDE QA/QC program allows for an accurate identification, sizing and characterization of complex crack-like imperfections in the long seam. Recently, a real study case was presented during the 2024 PPIM which describes some of the advantages of using PAUT and FMC/TFM related to the identification of possible characteristics of hook flaws [9]. Equipment calibration, curved and flat wedges specifications, encoded PAUT data, screenshots from PAUT, TOFD, and TFM/FMC, were used to size crack-like imperfection height and identify crack-like morphology and position.

It is common understanding in the industry that height sizing using PAUT is impacted by variables such as pipe wall thickness, equipment calibration, and the NDE technician's ability and experience, among others. A comparison of PAUT reported heights and ground (true) heights for NPS 12, 4.78 mm NWT (0.188"), 317 MPa, 1960's vintage pipeline was completed and presented during the 2024 IPC [10]. Most of the crack-like imperfections included in the study had a PAUT reported depth of 2.5 mm (52.3% WT) or less. It was noted that the PAUT measurements tended to be non-conservative and 95% of the PAUT readings were within 0.6 mm of their ground (true) depths. The study also identified that PAUT sizing is highly dependent on NDE technicians experience and ability. Findings from this study are aligned with previous work completed by PRCI in 2019. The research project reported a standard deviation associated with field measurement of 0.53 mm [11].

ITD NDE data was reviewed by EMTEC and EMPCo NDE SMEs to verify height sizing accuracy. Review of the results revealed that most of the imperfection's height and characterization through the pipe wall being reported by the NDE technician was aligned with the NDE SME imperfection sizing and morphology. A comparison of the ITD NDE data and the NDE technician qualification records resulted in a ±0.50 mm field measurement error estimation. The estimated measurement error corresponds to ±10.5% NWT and was considered to be reasonable and aligned with previously reported field measurement error.

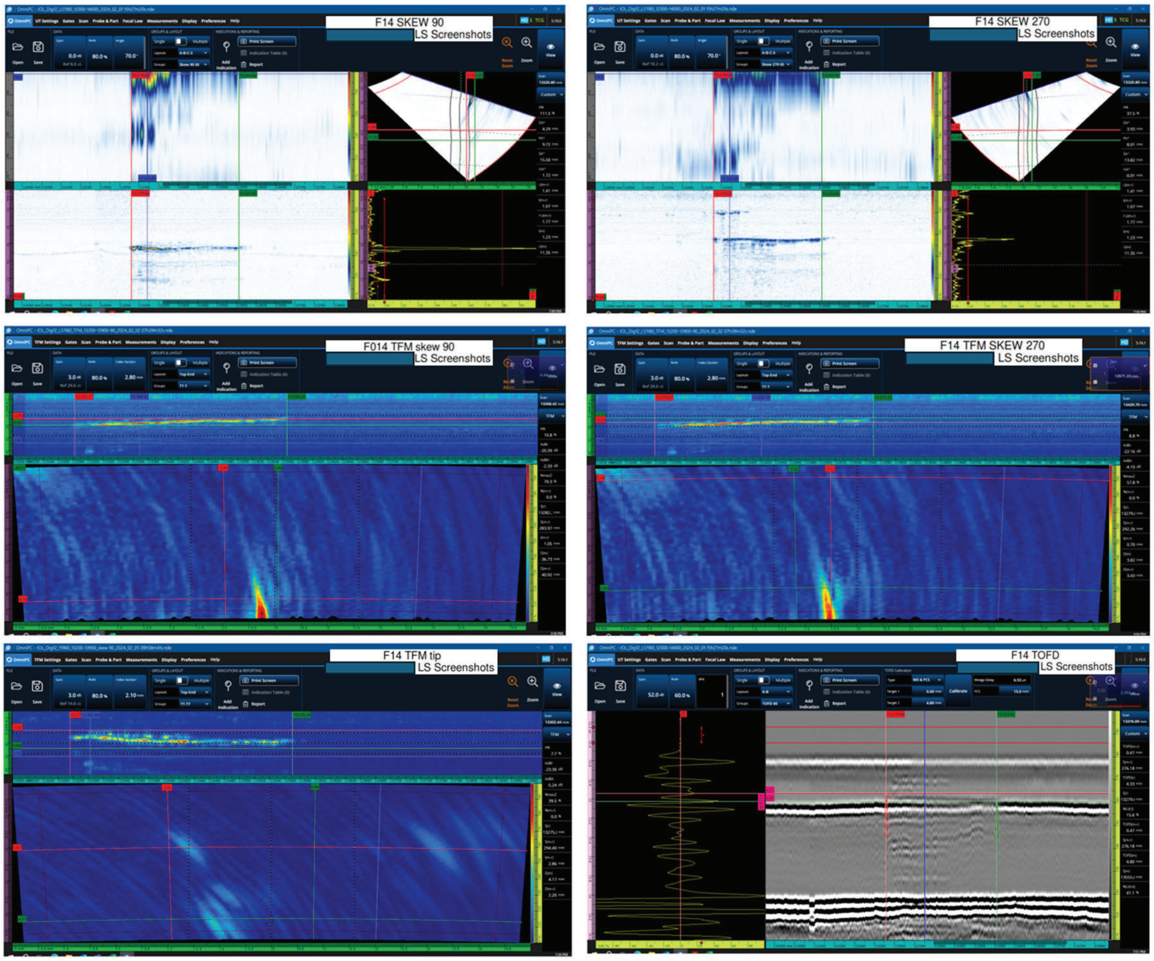

Figure 10. Example of PAUT, TFM/FMC and TOFD screenshots

In-line Inspection and ILI tool performance analysis

The NPS 8, 4.78 mm NWT, HF-ERW, 1974 vintage pipeline was in-line inspected using the novel tip diffraction technology-based ILI tool in July 2022. This ILI was targeting mainly lack of fusion and hook flaws which have previously been reported on this pipeline. As the new time-based tip diffraction ILI tool was going to be run for the first time on a pipeline, it was decided to conduct an additional ultrasonic crack inspection using the already established amplitude-based technology with the understanding of the challenges associated with in-line inspecting small diameter, thin wall pipelines [3,9]. ILI tool performance results of the new ILI tool technology are discussed hereafter.

The minimum and maximum tool velocities recorded during the inspection were 0.5 m/s and 1.2 m/s respectively. The average recorded tool velocity was 0.8 m/s. The new ILI tool did not record

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data loss, and all sensors performed as expected. The ILI tool run as accepted following guidance in Pipeline Operators Forum POF 2016.

The initial ILI tool performance analysis was completed using the ILI reported absolute measured height and the known (true) height of the flaws in the calibration spool. The mid-wall and short through wall flaws were detected and sized by the new ILI tool. These flaws were not included in the sizing analysis because of the number of flaws was too small and the mid-wall imperfections were not relevant to the ILI tool specification.

API 1163 Level 2 and Level 3 analyses were completed. An ILI tool sizing accuracy and NDE measurement error of ±1.0 mm at 80% certainty and ±0.3 mm respectively was used. The API 1163 Level 2 analysis resulted in an Outcome 2 (specification is not rejected). The calculated upper ($\tilde{p}$, upper) and lower ($\tilde{p}$, lower) binomial confidence interval endpoints were 99.04% and 75.53% respectively. The API 1163 Level 3 analysis showed an insignificant bias of 0.04 mm (ILI Undercall) and a tolerance of ±1.12 mm at 80% certainty and 95% confidence. Refer to Figure 11. The performance of the new tip diffraction ILI tool was aligned with the results obtained during the development and testing phases.

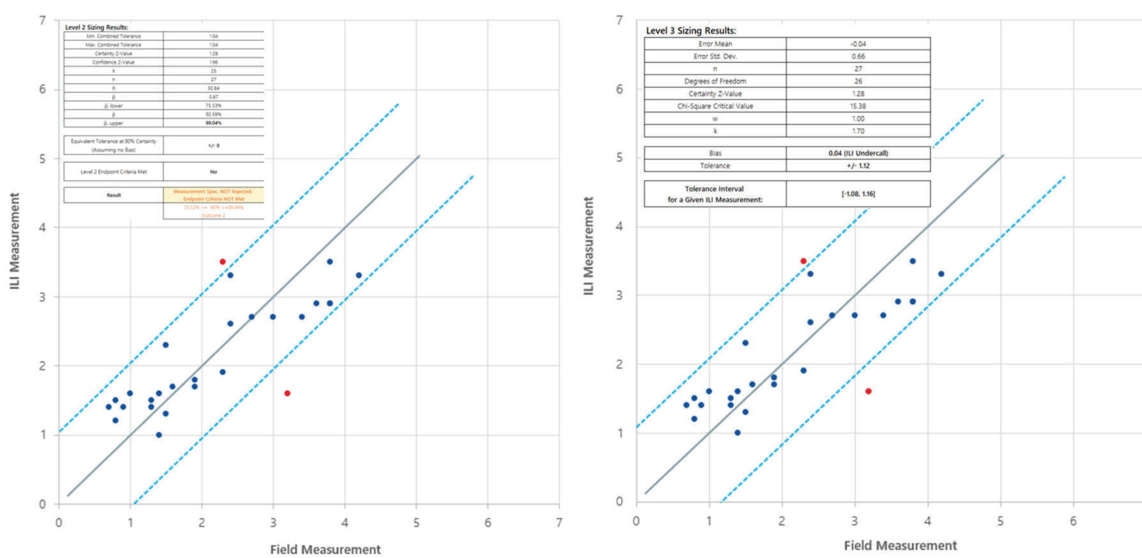

Figure 11. API 1163 Level 2 (a) and Level 3 (b) analyses results for calibration spool anomalies

A preliminary deterministic crack assessment using the API 579 Level 2 methodology was conducted to identify anomalies for additional investigation via excavation. The proposed investigative dig program included six (6) locations. These digs provided ITD NDE data to be used to further assess the performance of the new ILI tool. ITD NDE data was also used to evaluate the NDE technician's ability for identifying, sizing, and characterizing long seam weld imperfections via NDE SME review of results. These two (2) activities were completed simultaneously as the dig program was being carried out.

API 1163 Level 2 and Level 3 analyses were completed for a larger number of anomalies following the excavations. An NDE measurement error of ±0.5 mm was used for the anomalies identified in the field while the ILI tool sizing accuracy and NDE measurement error remained the same for the calibration spool anomalies.

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The API 1163 Level 2 analysis resulted in an Outcome 2 (specification is not rejected). The calculated upper ($\tilde{p}$, upper) and lower ($\tilde{p}$, lower) binomial confidence interval endpoints were 90.42% and 78.45% respectively. The API 1163 Level 3 analysis showed a bias of -0.48 mm (ILI Overcall) and a tolerance of ±0.86mm at 80% certainty and 95% confidence. Refer to Figure 12.

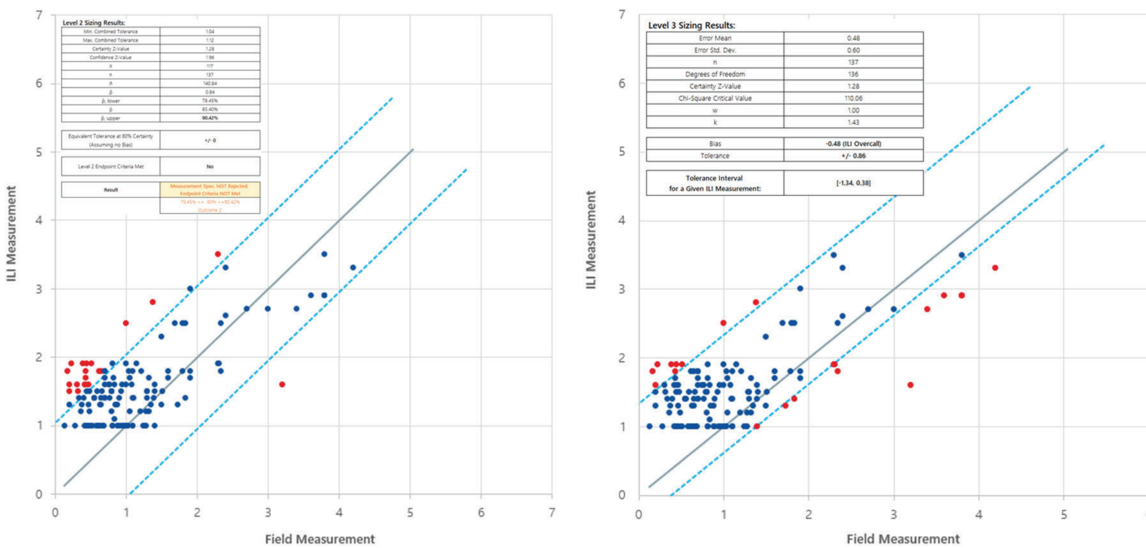

Figure 12. API 1163 Level 2 (a) and Level 3 (b) analysis results for calibration spool and ITD NDE anomalies.

The API 1163 Level 2 and Level 3 results were reviewed with EMTEC SMEs, and senior ILI analysts and NDE technicians from the ILI Vendor. It was noted that the bias was significantly different than the one calculated during the testing phase. The ILI vendor reviewed all available ITD NDE data and after several technical discussions between IOL, EMTEC and the ILI vendor, it was concluded that an ILI data re-analysis was justified. It is important to highlight the relevance of the ITD NDE QA/QC program to obtain quality data that can be used to improve the ILI data analysis.

Using the revised height sizing provided in the ILI report, API 1163 Level 2 and Level 3 analyses were conducted. The API 1163 Level 2 analysis resulted in an Outcome 3 (specification is exceeded). The calculated upper ($\tilde{p}$, upper) and lower ($\tilde{p}$, lower) binomial confidence interval endpoints were 99.3.0% and 90.64% respectively. The API 1163 Level 3 analysis showed an insignificant bias of -0.08 mm (ILI Overcall) and a tolerance of ±0.82mm at 80% certainty and 95% confidence. The tolerance internal for a given ILI measurement was estimated in the range from -0.9mm to 0.74mm. Refer to Figure 13. These results are better than expected and encouraging of using the novel ILI tool technology in other small diameter pipelines. IOL continues investigating additional anomalies as part of its seam cracking IMP enhancements. The API 1163 Level 2 and Level 3 analyses will be revised as additional ITD NDE information is made available.

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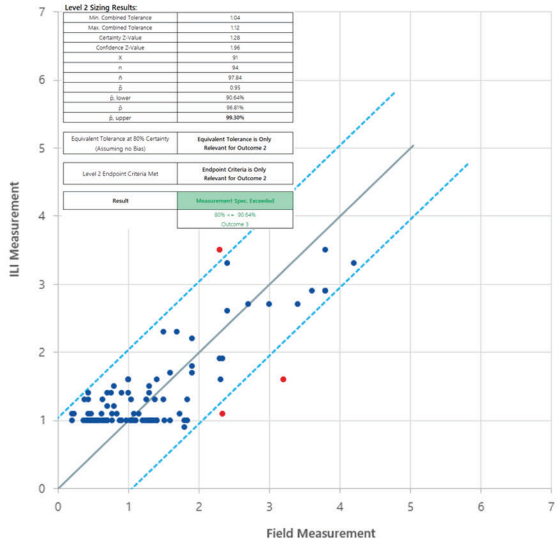

Figure 13. API 1163 Level 2 (a) and Level 3 (b) analyses, after resizing, for calibration spool and ITD NDE anomalies

Further refinement of the API Level 2 and Level 3 analyses was completed by removing mid-wall anomalies and any imperfection sized in the field to be less than 1.0 mm. Results can be seen in Figure 14. An Outcome 3 (Measurement Specification Exceeded) was obtained from the API 1163 Level 2 analysis. The API 1163 Level 3 analysis now showed a slight tendency to undercall crack-like imperfections (bias of 0.28 mm) with a tolerance of ±0.88 mm, insignificantly different than the previously calculated tolerance of ±0.82 mm at 80% certainty and 95% confidence. Due to the calculated bias, the tolerance interval was estimated as [-0.6mm, 1.15mm].

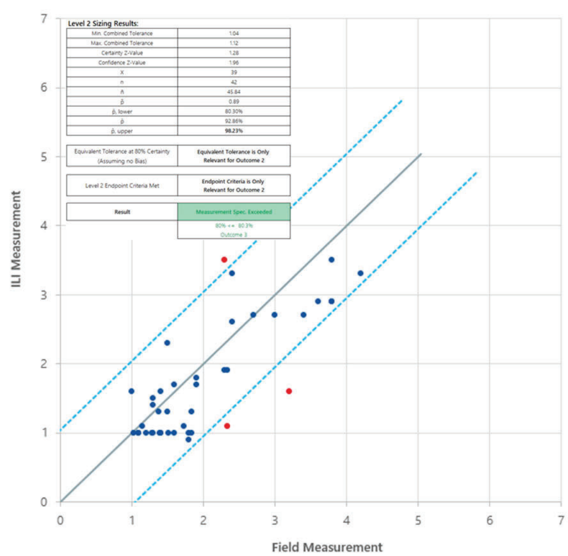

Figure 14. API 1163 Level 2 (a) and Level 3 (b) analyses, after resizing, for calibration spool and ITD NDE anomalies, without mid-wall and less than 1.0 mm height anomalies.

An API 1163 Level 3 analysis using the Bayesian model was also completed [12]. This method allows for a variable slope which provides the most likely anomaly height based on the available data. For example, an ILI call of 2.0 mm is expected to be with a range of from 1.10 mm to 3.18 mm with an

80% confidence interval, as shown in Figure 15. Results from the API 1163 Level 3 Bayesian analysis were used as input in the probabilistic assessment of crack-like imperfections.

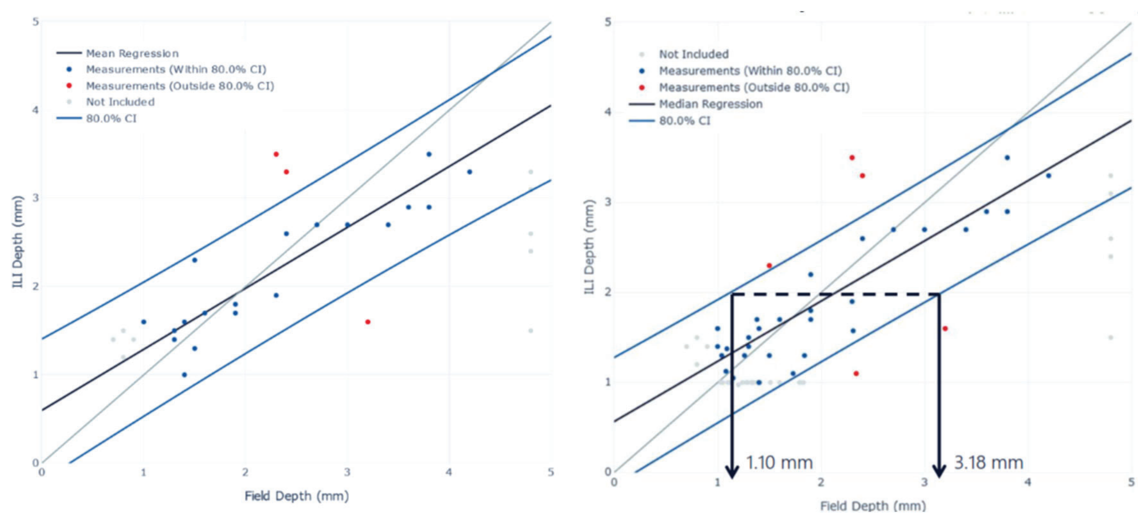

Figure 15. API 1163 Level 3 Bayesian model analyses. Calibration spool anomalies only (a), and calibration spool plus ITD NDE anomalies.

Integrity assessment of crack-like anomalies

Deterministic and probabilistic assessments using the PRCI MAT-8 model were completed for those imperfections reported by the novel ILI tool technology. Deterministic assessment results with and without the specified tool sizing accuracy (e.g., ±1.0 mm height sizing accuracy at 80% certainty) were used to identify potential anomalies candidate for investigation, following the API 1176 criteria. No immediate conditions were identified, thirty-three (33) anomalies were categorized as 365-day condition and the remaining anomalies were categorized as scheduled condition, with 10 of those subcategorized as scheduled condition less than or equal to 5 years from the ILI date. Deterministic results suggested a dig program to investigate forty-three (43) anomalies. If a tool height sizing accuracy of ±2.2 mm (calculated height sizing accuracy for amplitude-based ILI tools) were used, the number of anomalies candidate for investigation would have significantly increased.

Burst pressure calculations using the equivalent length methodology were also completed for a selected number ILI reported crack-like imperfections. The methodology is part of the on-going PRCI MAT-8 fracture model improvements under the PRCI Consortium Project JCAS-01. It was observed that predicted burst pressures using the semi-elliptical shape assumption were up to 1.5 times higher than those calculated using the equivalent length crack profile. As shown in Figure 16, Feature FID 01 has a greater increase in burst pressure using the feature's equivalent length compared to its original length than feature FID 02. This is due to the equivalent length of feature FID 01 only being slightly shorter than its original length, resulting in a slight increase in burst pressure. Feature FID 02 however has an equivalent length that is much less than its original length, resulting in a greater increase in burst pressure.

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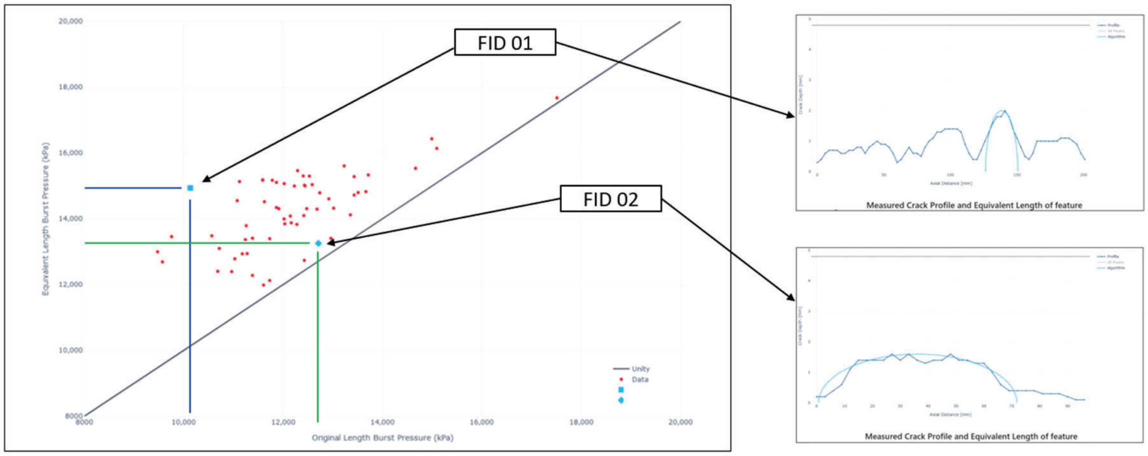

Figure 16. Predicted burst pressure based on crack depth profile and assumed semi-elliptical shape.

A probabilistic crack assessment was completed to calculate the likelihood of failure for each crack-like anomaly. The probabilistic assessment methodology has been discussed in previous publications [13,14,15]. The probabilistic assessment allows to consider the past hydrotest and changes in operating pressures, which are not possible to account for using the deterministic assessment approach. Burst and small leak failure modes were evaluated using the probabilistic assessment methodology.

The probability of failure (PoF) of each crack-like anomaly reported by the novel tip diffraction ILI tool was calculated using a structural reliability model developed as part of the PRCI Consortium Project JCAS-01. The probabilistic model uses Monte Carlo simulation with 1 million iterations per anomaly. Leak and burst PoF are calculated in each year (up to 10 years) after the ILI date or the ILI assessment date.

One of the sources of uncertainty for the crack-like anomalies considered in the probabilistic assessment is the ILI tool sizing accuracy. This measurement error is dependent on the anomaly's ILI tool technology, size, location, and morphology (among other factors), and could have significant impact (e.g., an order of magnitude) on the remaining life estimates [13]. Figures 17 shows the estimated PoF of the same crack-like anomaly for burst and leak failure modes over the next 10 years using different ILI tool sizing accuracy. A difference of almost 2 order of magnitude is observed for each year for the next ten years highlighting that the greater the ILI tool tolerance interval, the higher the probability of failure.

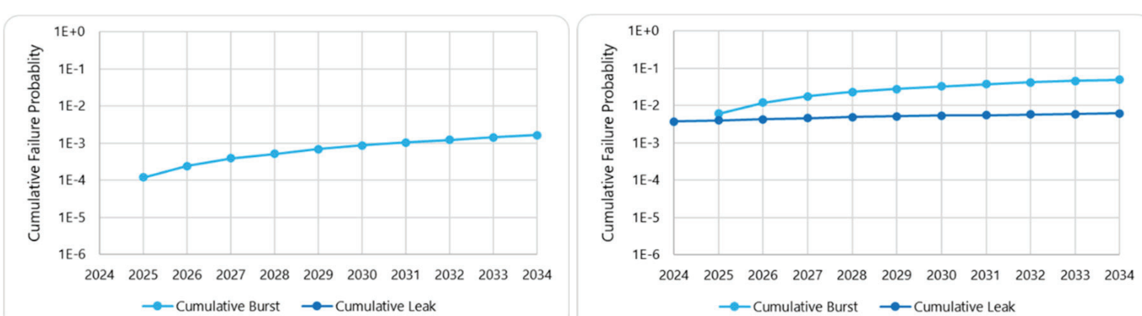

Figure 17. Burst and leak POF estimates for a crack-like anomaly using an ILI tool sizing accuracy of ±1.0mm (left), and 2.2mm (right).

Several sensitivity cases were completed to evaluate the impact of different parameters used in the probabilistic crack assessment methodology. Among the different scenarios, a sensitivity analysis was conducted to compare the impact from ILI tool accuracy and NDE data for the cases where the pipeline was and was not hydrotested within the last 5 years. The NDE measurement error was kept the same as previously discussed (±0.3mm for calibration spool flaws and ±0.5mm for ITD NDE flaws). The ILI tool accuracy was evaluated using a tool height sizing accuracy at 80% certainty of ±1.0 mm and ±2.2mm.

For the scenario with hydrotest, 68.1% of the anomalies have an estimated PoF in the range from 1E-06 to 1E-07 when the tool height sizing accuracy is ±2.2mm, whereas 90.5% of the anomalies are in the same PoF range when the tool height sizing accuracy is ±1.0mm. This difference is even more relevant for the no hydrotest case. For this scenario, 48.8% and 8.4% of the assessed crack-like imperfections respectively were categorized in the range from 1E-03 to 1E-04 which corresponds to almost 2 order of magnitude difference. Results can be seen in Figure 18.

It was observed that the rate of change in probability from one year to another is slower for the ±1.0mm than for the ±2.2mm case. Figure 19 shows the change in PoF for the next 10 years for the two (2) evaluated tool height sizing accuracies whit a hydrotest within the last 5 years. The crack-like imperfection will reach a higher PoF faster when the tool sizing accuracy is ±2.2mm for both cases (with and without hydrotest). Provided that anomalies for investigation are chosen based on when the PoF changes from one probability range to another, depending on the PoF acceptance threshold, it is likely that additional investigations might be required for the ±2.2mm case rather than for the ±1.0mm case.

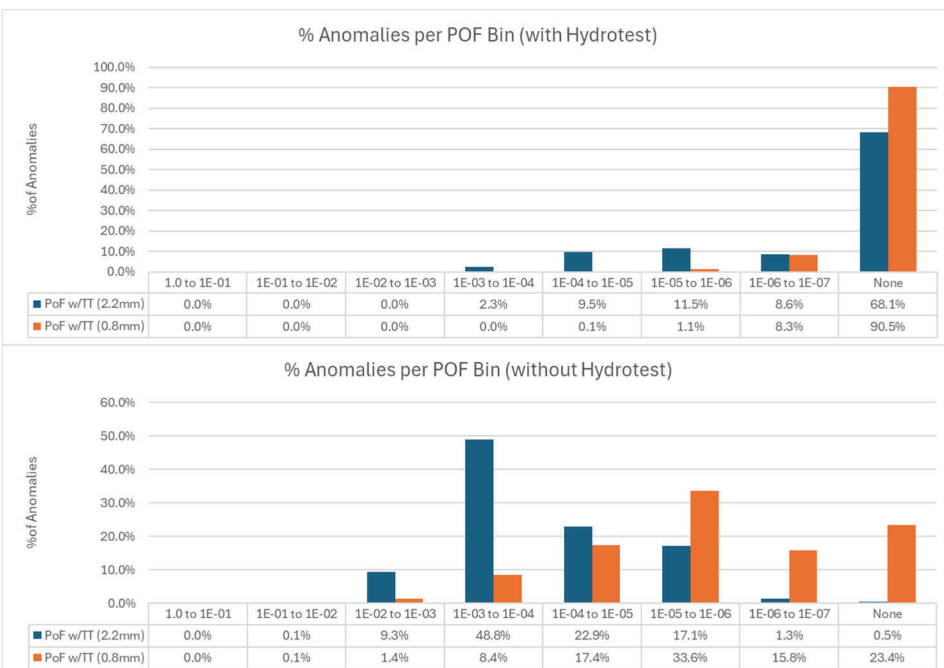

Figure 18. Burst POF with and without hydrotest for an ILI tool sizing accuracy of ±1.0mm (a), and 2.2mm (b).

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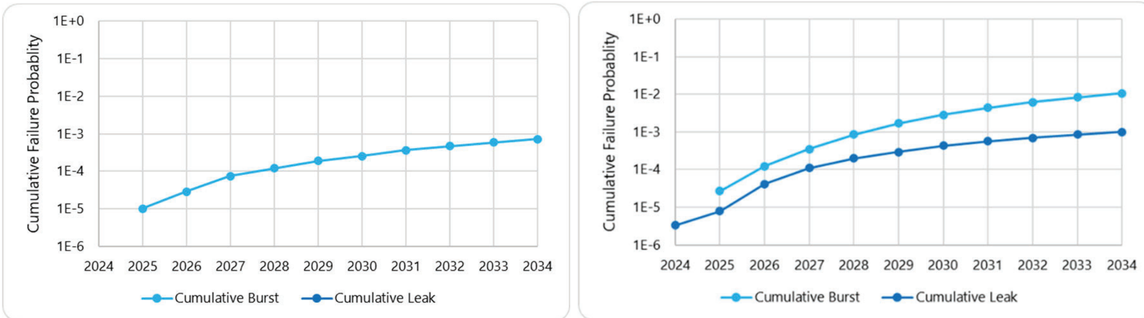

Figure 19. Burst and leak POF estimates for a crack-like anomaly after hydrotesting using an ILI tool sizing accuracy of ±1.0mm (left), and 2.2mm (right).

Seam weld anomaly risk assessment

CSA Z662-23 requires Pipeline Operators to have a risk management process that identifies, assessed and manages the hazards and associated risks for the life cycle of the pipeline system [16]. Once the PoF has been calculated, a consequence analysis per anomaly was conducted for both failure modes (e.g., burst and leak). The consequence analysis considered the impact on people, property, the environment, or combinations of these factors. A risk level per anomaly was determined by the combining the calculated PoF and the results from the consequence analysis.

The estimated probability of failure and consequence were plotted in a risk matrix to determine the risk level per anomaly. This methodology was completed for each year (up to 10 years) after the ILI date and/or the ILI assessment date. Anomalies were selected for investigation based on their risk level and risk tolerance thresholds. Following the risk-based approach, a smaller number of anomalies were candidates for investigation when compared to the deterministic approach.

Conclusions

A novel ILI tool using the time-based tip diffraction technology was successfully run in a small diameter, thin wall pipeline. The ILI tool validation results showed that the performance specification of the novel technology was not rejected for the Level 2 analysis of the anomalies in the calibration spool and exceeded performance specification for the combination of anomalies in the calibration spool and ITD NDE.

Accurate heigh sizing of anomalies in the long seam was achieved with the novel time-based tip diffraction ILI tool. It appears that heigh sizing of complex anomalies, such as hook flaws, was not significantly impacted by anomaly skew and tilt.

A stringent ITD NDE QA/QC program, including the use of advanced NDE techniques for identification, sizing and characterization of imperfections in the long seam demonstrated to be highly useful. Fruitful conversations with different stakeholders involved on the detection and sizing of long seam anomalies (e.g., ILI vendor and analysts, NDE technician, NDE SME) were the result of quality ITD NDE data. A re-analysis of ILI data resulted on a tool performance which exceeded the specifications.

https://doi.org/10.52202/078572-0040

The implementation of the seam Cracking IMP Enhancements was only possible through close collaboration between all stakeholders. Honest and open communication was critical during all phases of the program.

There are significant advantages from having accurate sizing of imperfections. Deterministic and probabilistic assessment results are more accurate and result in more effective and efficient investigative programs. The probabilistic assessment methodology allows for the use of a risk-based methodology which considers probability of failure and consequence for each anomaly. The probabilistic assessment methodology also allows to account for past hydrotest and changes in operating conditions. Dig programs based on probabilistic assessments, consequence analysis and risk evaluation are compliant to the Canadian standard CSA Z662-23.

Acknowledgement

The authors want to acknowledge the extraordinary contributions to the new tool development and testing, calibration spool design and fabrication, technical support and teamwork from Joe Krynicki and Gus Gonzalez (EMTEC). We also want to recognize the support from the Mark Hlousek and Allison Dowling (Pipeline Integrity Team, IOL), Ethan Hari and the Pipeline Integrity Execution Team (IOL), Shivam Singh, Juan Espiga and Troy Huynh (EMPCo), Thomas Dessein and Ben Nowell (Integral Engineering) and the NDE Technicians Scott Beavan and Blair Casey (Acuren).

Acronym summary

Table 2. Acronym summary

Acronym	Description
API	American Petroleum Institute
EDM	Electrical Discharge Machined
EMTEC	ExxonMobil Technology and Engineering
EMPCo	ExxonMobil Pipeline Company
FMC	Full Matrix Capture
HF-ERW	High Frequency Electric Resistance Welded
ID	Inside Diameter
IMP	Integrity Management Program
ILI	In-line Inspection
IOL	Imperial Oil Limited
IPC	International Pipeline Conference
ITD	In-The-Ditch
LF-ERW	Low Frequency Electric Resistance Welded
LoF	Lack Of Fusion
mm	millimetre
m/s	Meters per second
MT	Magnetic Particle Testing
NDE	Non-Destructive Examination
NPS	Nominal Pipe Size

https://doi.org/10.52202/078572-0040

NWT	Nominal Wall Thickness
OD	Outside Diameter
PAUT	Phased Array Ultrasonic Testing
POD	Probability of Detection
PoF	Probability of Failure
PRCI	Pipeline Research Council International
POF 2016	Pipeline Operators Forum 2016
PT	Penetrant Testing
QA/QC	Quality Assurance / Quality Control
SME	Subject Matter Expert
SWUT	Shear Wave Ultrasonic Testing
TFM	Total Focus Method
TOFD	Time of Flight Diffraction
TQP	Technician Qualification Process
UTCD	Ultrasonic Crack Detection
UT	Ultrasonic Testing
VT	Visual Testing
WT	Wall Thickness

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