Pipeline Integrity Management of CSCC using multiple ILI technologies

by Ron Thompson[1], Ray Gardner[2], Katrina Dwyer[2], Richard Gonzales[2], Andrew Corbett[1], Guillermo Solano[1]

1. Novitech Inc, Vaughan, ON, Canada.
2. Xcel Energy, Denver, CO, USA.

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Abstract

This paper is the continuation of a 3 year-long study in the use of magnetic based ultra-high sampling density in-line inspection (ILI) systems (up to 2,000 samples per square inch) to detect and size circumferential stress corrosion cracking (CSCC). The objective of the study is to enable a shift from the CSCC direct assessment approach to diagnostics by an ILI measurement system.

This phase of the study focuses on the detection of CSCC by multiple ILI systems that integrate axial and circumferential magnetic flux leakage (AMFL and CMFL) along with internal depth detection sensor arrays (IDD), a high precision geometry measurement unit (HP-GMU) and inertial mapping data (IMU).

To date a total of seven line segments have now been inspected for CSCC collecting a total amount of data exceeding 1 TB. This paper focuses on the five line segments inspected for Xcel Energy and the results from two other operators have been include in our data base. Individual line segments had collected data sizes that often exceeded 200 GB. This also required the development of detection and sizing algorithms along with data analysis processes that can categorize and prioritize relevant CSCC. This process was performed to differentiate CSCC amongst the hundreds of thousands of detected magnetic anomalies in any given line.

Included in this study are the CSCC inspection results from over 200 miles of natural gas pipelines in in NPS 6", 8" and 10" segments. These results are utilized to review susceptibility factors for CSCC and discuss best practices for excavation and inspection of CSCC anomalies. Field non-destructive examination (NDE) and metallurgical analysis from identified anomalies have been used to baseline the system's probability of detection (POD) and probability of identification (POI) of critical and sub-critical CSCC.

Introduction

In 2015, colonies of CSCC were coincidently discovered during in-line inspection verification digs for a natural gas pipeline. The CSCC colonies were located in close proximity to external metal loss anomalies but were not detected by the in-line inspection tool. The subject pipeline was constructed in 1965 of 6.625-in OD x 0.188-in WT, Grade X42 line pipe and is located in an area of rugged mountainous terrain. A subsequent selective digging program was established utilizing the following susceptibility criteria [1]:

- Coating Type
- Presence of External Corrosion (indicating coating disbondment)
- Terrain with elevation changes and/or stream crossings
- O'clock position of metal loss
- Severity of Metal Loss

Although the selective digging program was successful in identifying additional locations of CSCC, it was insufficient to predict the severity of CSCC or confirm that all CSCC indications had been examined.

To reliably detect and quantify CSCC in susceptible pipeline systems, an advanced MFL ILI system was developed with initial viability studies performed in 2018, evaluating tool performance on pull test over manufactured circumferential slots and actual CSCC samples [2].

In 2019 the ILI system was run on a pipeline segment that, through susceptibility analysis, ranked high for occurrence of CSCC. The pull test baseline was used to identify and prioritize 30 CSCC candidates which were excavated and removed from the pipeline. All CSCC findings were non-destructively field tested and a selected number of candidates were laboratory verified for sizing and evaluation of the tool performance [3].

These results were used to implement ILI runs of the new technology on five segments of pipeline and remedial action was taken per the criticality rankings provided by the ILI tool. The target pipe areas were cut out and evaluated using both non-destructive and destructive methods to validate the results, which are explored in this paper.

1. Integrated ILI design for the detection of CSCC, long seam flaws, metal loss, deformations and other anomalies.

The completion of five successful runs along with field confirmation and laboratory sizing of 78 occurrences of CSCC validated the targeted tool specifications concluding the design cycle for this portion of the study.

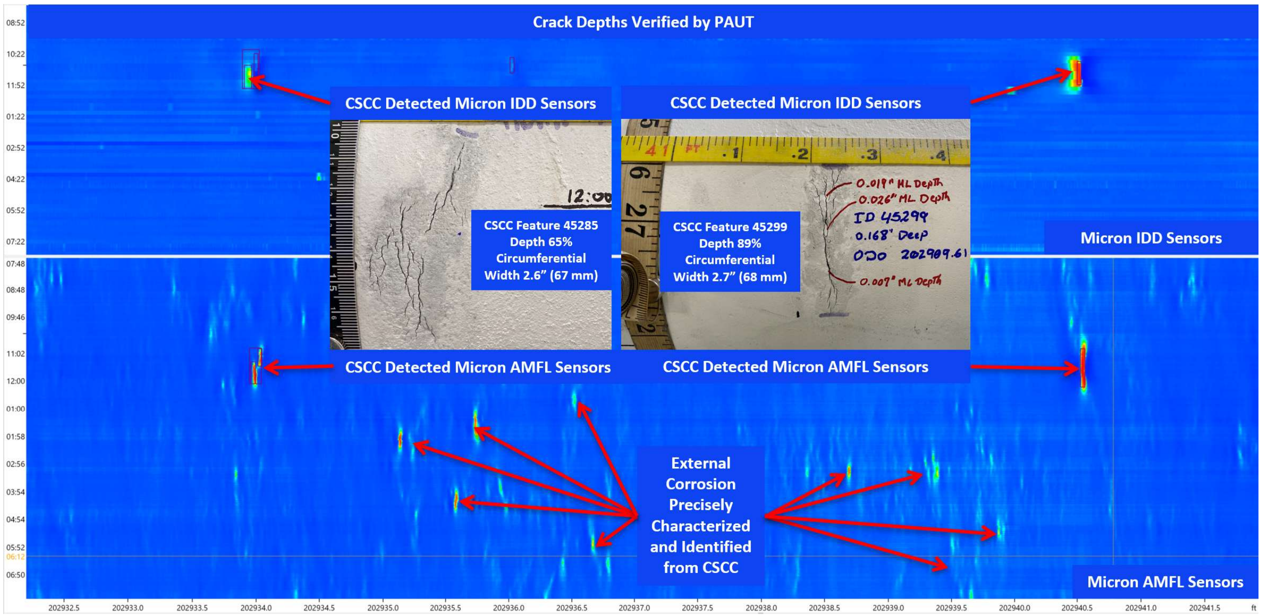
In summary, to reliably detect CSCC, the ILI system was designed with:

- A combined sample density of up to 2,000 readings per square inch from AMFL, CMFL, IDD and Geometry modules.
- A purposed build data acquisition electronic system for all modules with broad dynamic range that uses no data compression as all recorded samples are required to identify and quantify cracks and other very small anomalies.
- The capability to integrate AMFL and CMFL inspections both in the tool hardware as well as in the analysis software (either in single or separate runs) to discriminate CSCC from other anomalies. In this respect the system performs a comprehensive inspection of metal loss, long seam flaws, mechanical damage, and deformation threats.

The ILI system also required new analysis processes and software to facilitate the evaluation of AMFL, CMFL, Geometry, and IDD sensor modules simultaneously. Critical enhancements in this respect included judicious use of algorithm-based analysis and manual signal review to properly sort and identify pipe anomalies amongst the hundreds of thousands of recorded features with each run.

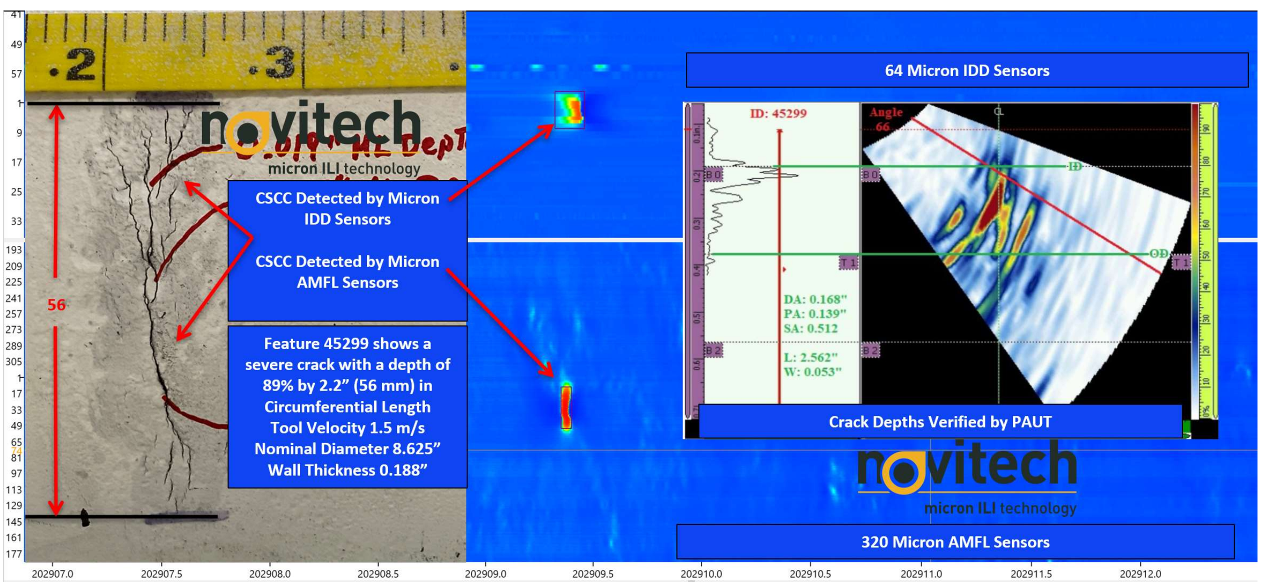
The sensitivity and sample density of the tool hardware resulted in large record files of all the magnetic signals generated by imperfections as minute as pipe surface roughness, debris, and other foreign elements present during the run. To confirm the robustness of the ILI hardware as well as the analysis software and reporting process, additional ILI pull testing was performed in the cut-out sections, prior to any destructive testing. The signal repeatability was found to be within 10% by amplitude from the AMFL responses confirming the ability of the entire system to accurately detect and discriminate relevant pipe anomalies.

Figure One below provides an example of the graphical representation for the AMFL and IDD signal responses as detected by the tool (amplitude based). The overall system provides a distinct response to an anomaly vs. the background level allowing for clear identification and discrimination of CSCC colonies, even when surrounded by hundreds of metal loss anomalies.



<u>Figure One:</u> Discriminating CSSC Amongst Hundreds of Metal Loss Anomalies

<u>Figure Two</u> below illustrates how the integrated multi-modular approach confirms the presence of CSCC while ruling out false positives such as sensor lift off and surface roughness. Specifically, the combined AMFL and IDD sensor modules are also being used to help rank the severity of CSCC from detectable, severe, to very severe.



<u>Figure Two:</u> Severity Ranking Using both AMFL and IDD Sensor Systems

<u>Figure Three</u> further illustrates CSCC detectability, with a high POD and POI. At this location, the ILI system successfully identified the occurrence of 12 CSCC locations in a row that were axially aligned and in close proximity to each other.

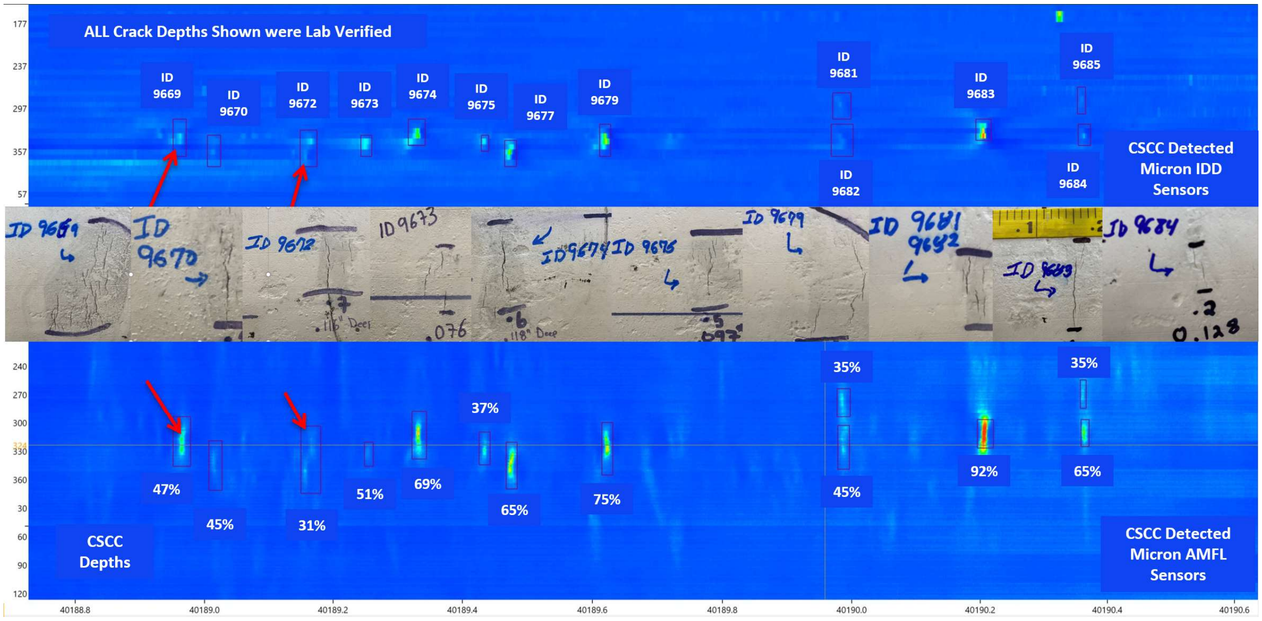


Figure Three: **Conformation of High POD and POI Showing 12 Consecutive CSCC Locations**

Figure Four illustrates the ILI system's resolution, as individual crack colonies that are separated by approximately 0.5" (12.7 mm) or more can be differentiated from each other and identified as individual crack anomalies. AMFL signals from tighter crack clusters blend into a single reportable anomaly.

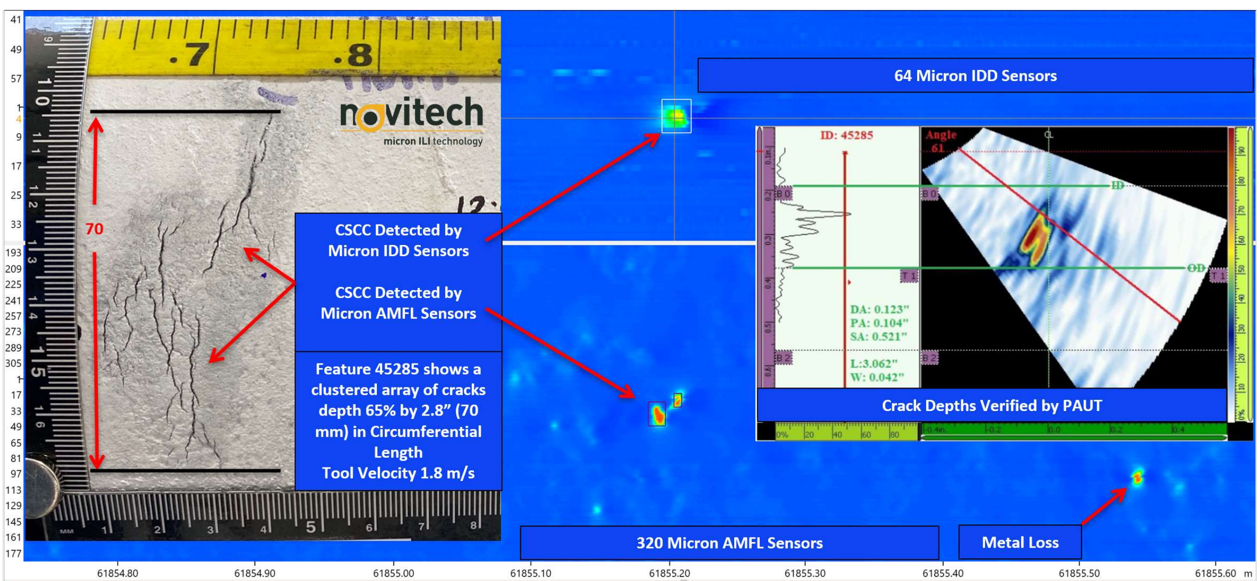


Figure Four: **Detectable Resolution Between Cracks**

2. Integrity Excavations, NDE Results

The ILI data analysis provided a list of CSCC candidates categorized and prioritized as critical and subcritical flaws based on the amplitude signal response. While the threshold for defining the severity ranking can vary depending on the pipeline, the low number of CSCC occurrences per sector reported by the tool allowed for the excavation and verification of all CSCC candidates.

In this phase of the study a total of 81 CSCC candidates identified by ILI in NPS 6" and 8" segments were excavated. These locations where removed from service resulting in multiple cut out sections totalling hundreds of feet of pipe.

Field evaluations were carried out using black and white MPI in all exposed areas to detect both the targeted colonies as well as any potential false negatives. Of the 81 CSCC candidates, 78 CSCC indications were located, with depths ranging from 30 to 100%, along with one additional colony which was not reported by the ILI system. Three false positives were identified as low-level external metal loss.

The indications were sized using phased array ultrasonics (PAUT) under near laboratory conditions and subsequently cross sectioned for final verification. Upon noticing discrepancies between the initial PAUT sizing and the laboratory results a second set of PAUT tests were performed by a different vendor, utilizing higher specification equipment, higher frequency probe and new calibration set ups. These configurations are further discussed in section 3.1.

Noting the discrepancies between both sets of PAUT measurements and between PAUT and the laboratory results, it appears that some of the CSCC targets presented geometries or were positioned in a way that were not optimal for the PAUT setup while the MFL based ILI system seemed less affected by it. These conditions include:

- Off-angle CSCC, specifically following the helical tenting of the tape coat used in the carrier pipe.
- CSCC colonies composed of two offset segments in the process of coalescing.
- CSCC cracking with multiple branching or off angles resulting in weak tip ultrasonic reflectors.

3. Metallurgical Results

To date a total of 25 CSCC colonies have been destructively tested to size both the overall depth of the crack colony as well as minimum and maximum crack openings at the pipe's surface and throughout the body of the crack. Characterization of the cracks included cross-sections taken on multiple planes, crack width measurements and face break samples. Between two and four cross sections, no more than 0.5 inches apart, were made in each colony as well as some face breaks to ensure the deepest ligament of the crack was exposed.

The transgranular crack morphologies and minor branching for all the samples matched well with stress-corrosion cracking (SCC) [4]. Crack openings were found to be ranging from 11 to 183 microns as shown below in **Figures Five** and **Six** below.

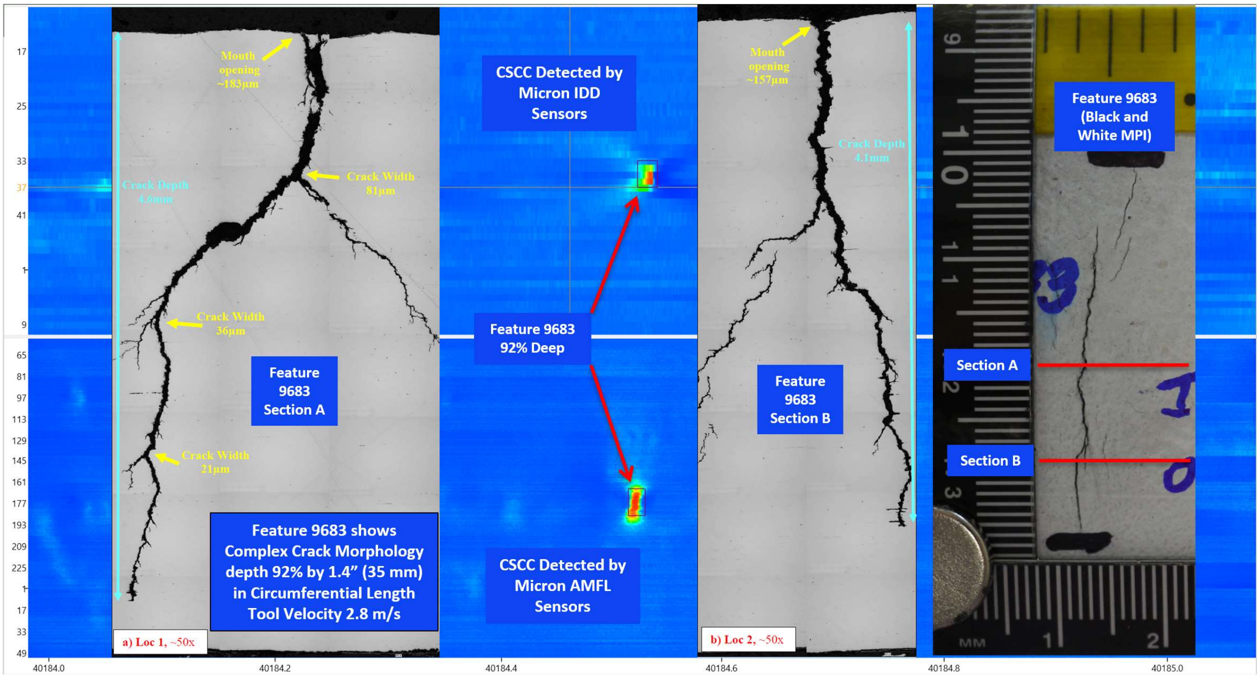


Figure Five: Crack openings were found to be ranging from 11 to 183 microns

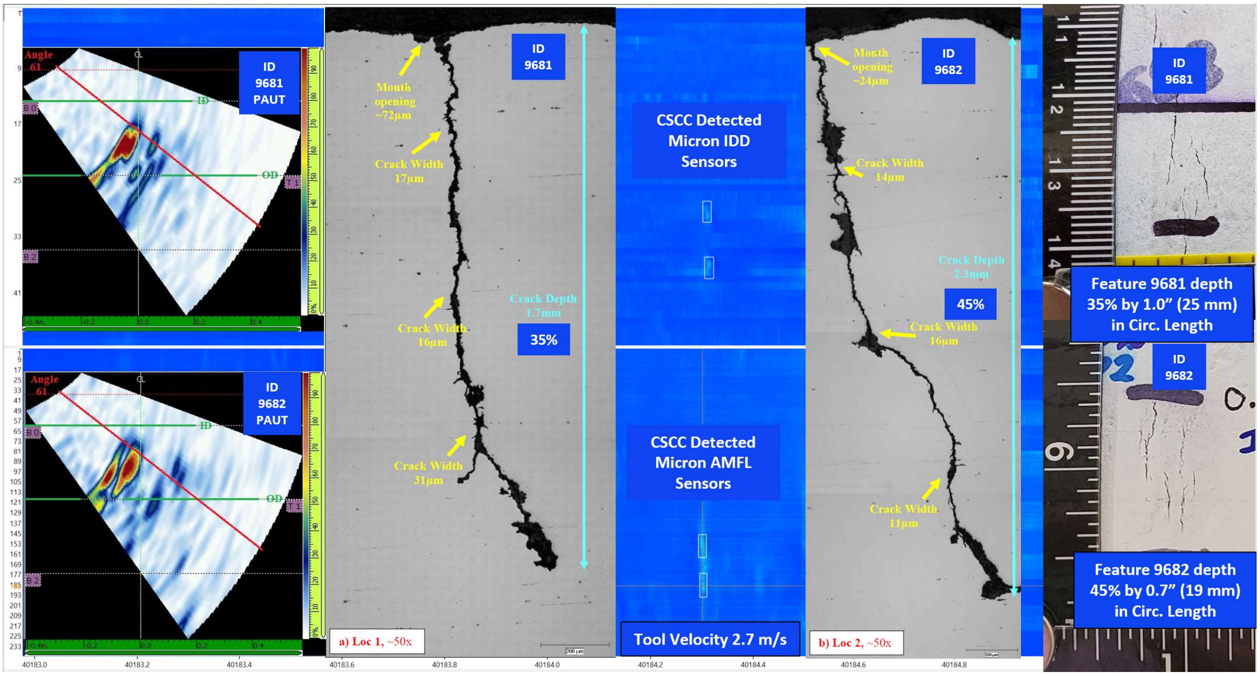


Figure Six: Crack openings were found to be ranging from 11 to 183 microns

3.1 Discussion on the use of Phased Array Ultrasonics for sizing and Metallurgical results for re-calibration of ILI data

PAUT sizing was used throughout the field evaluations of CSCC performed in this study, with each colony measured on two separate occasions by different NDE vendors. Each time the pipeline surface was interrogated with a sectorial scan, utilizing 5 MHz, 7.5 MHz, and 10 MHz probes, in 16 and 32 element configurations, with search units Olympus Omniscan MX2 and X3.

While the combination of the latest scanner (Onmiscan X3), with the 10MHz 32 element probe provided, on average, better results, the current samples showed measuring errors between 10 and 20% with outliers where both phased array instruments doubled the actual depth of the colony or undersized it by 48%.

Table One below shows a comparison of depth variation between two different PAUT operators and NDE companies on the same CSCC features verses laboratory results. Only about two thirds of the time the PAUT depth prediction was found within +/- 20% from the laboratory results. Some errors were found to be 40 to 48% off the laboratory results.

PAUT vs Lab Results

Item No.	Feature No.	Lab Depth	NDE Company 1 PAUT Depth	NDE Company 1 PAUT Error	Error %		Item No.	Feature No.	Lab Depth	NDE Company 2 PAUT Depth	NDE Company 2 PAUT Error	Error %		Item No.	Feature No.	Lab Depth	NDE Company 1 and 2 Error %
1	4522	54%	61%	-7.0%	7.0		1	4522	54%	N/A	N/A	N/A		1	4522	54%	7.0
2	4580	40%	88%	-48.0%	48.0		2	4580	40%	N/A	N/A	N/A		2	4580	40%	48.0
3	4581	41%	77%	-36.0%	36.0		3	4581	41%	N/A	N/A	N/A		3	4581	41%	36.0
4	4582	39%	50%	-11.0%	11.0		4	4582	39%	N/A	N/A	N/A		4	4582	39%	11.0
5	4583	39%	79%	-40.0%	40.0		5	4583	39%	N/A	N/A	N/A		5	4583	39%	40.0
6	4584	39%	65%	-26.0%	26.0		6	4584	39%	N/A	N/A	N/A		6	4584	39%	26.0
7	4595	47%	91%	-44.0%	44.0		7	4595	47%	53%	-6.0%	6.0		7	4595	47%	44.0
8	9669	47%	52%	-5.0%	5.0		8	9669	47%	44%	3.4%	3.4		8	9669	47%	9.1
9	9670	44%	54%	-10.0%	10.0		9	9670	44%	52%	-8.1%	8.1		9	9670	44%	31.0
10	9672	31%	62%	-31.0%	31.0		10	9672	31%	58%	-27.0%	27.0		10	9672	31%	11.0
11	9673	51%	40%	11.0%	11.0		11	9673	51%	59%	-8.0%	8.0		11	9673	51%	6.0
12	9674	69%	63%	6.0%	6.0		12	9674	69%	69%	-0.1%	0.1		12	9674	69%	15.0
13	9675	37%	52%	-15.0%	15.0		13	9675	37%	56%	-19.4%	19.4		13	9675	37%	13.7
14	9677	64%	79%	-15.0%	15.0		14	9677	64%	65%	-1.4%	1.4		14	9677	64%	5.0
15	9679	75%	80%	-5.0%	5.0		15	9679	75%	65%	9.6%	9.6		15	9679	75%	26.0
16	9681	35%	61%	-26.0%	26.0		16	9681	35%	43%	-8.0%	8.0		16	9681	35%	19.0
17	9682	45%	64%	-19.0%	19.0		17	9682	45%	46%	-1.0%	1.0		17	9682	45%	16.0
18	9683	92%	76%	16.0%	16.0		18	9683	92%	65%	27.1%	27.1		18	9683	92%	3.0
19	9684	65%	68%	-3.0%	3.0		19	9684	65%	43%	22.4%	22.4		19	9684	65%	3.0
20	9685	35%	56%	-21.0%	21.0		20	9685	35%	41%	-6.5%	6.5		20	9685	35%	21.0
					395.0							148		7	4595	47%	6.0
			Average Error		19.8					Average Error		10.6		8	9669	47%	3.4
														9	9670	44%	8.1
	60.0%	Percent with Errors less than 20%						78.6%	Percent with Errors less than 20%					10	9672	31%	27.0
														11	9673	51%	8.0
														12	9674	69%	0.1
														13	9675	37%	19.4
														14	9677	64%	1.4
														15	9679	75%	9.6
														16	9681	35%	8.0
														17	9682	45%	1.0
														18	9683	92%	27.1
														19	9684	65%	25.4
														20	9685	35%	14.5
																	549.8
														Combined NDE Companies 1 and 2			16.2
														Average Error from Both			
														Combined NDE Companies 1 and 2			67.6%
														Percent with Errors less than 20%			

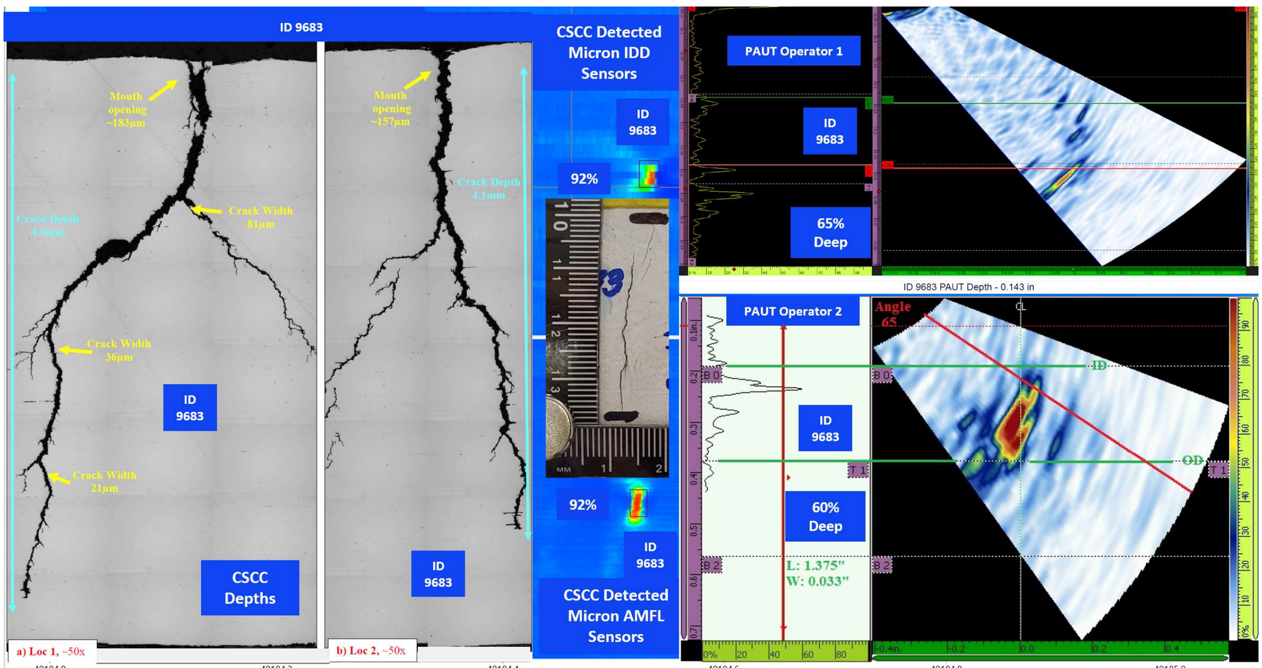
<u>Table 1:</u> PAUT Compared to Laboratory Results

It appears that certain crack morphologies were not represented or expected in the typical calibration set ups used for the PAUT equipment (artificial notch type slots on curved pipe of the same diameter and thickness as the target pipe) and thus were not sufficiently reflective (off angled) to be detected in either PAUT scan despite the inspection range of +30 to +70 degrees.

While undoubtedly PAUT can yield repeatable and accurate results, the current practice (specific combination of PAUT search unit, probe, calibration standard and type of scan) failed to provide sizing data of sufficient accuracy and reliability to calibrate and refine ILI sizing algorithms.

Until a larger sample of verifiable data is collected, the calibration and adjusting of ILI sizing algorithms for CSCC in this system has been established against actual metallurgical information, from confirmed face brake or multiple cross-sections that provides as close to actual the extent of any CSCC indication.

<u>Figure Seven</u> shows two separate PAUT scans that consistently undersized a CSCC indication at 60-65%, while laboratory results proved it to be 92% in depth.



<u>Figure Seven:</u> PAUT Compared to Laboratory Results

3.2 Detection Accuracy – POD of the ILI system

The current data base sample size confirms the pull test results and shows that the integrated ILI test has a consistent detection threshold for CSCC of 0.8” (20 mm) or longer and of 30% depth or greater, with crack openings as small as 0.001” (25 microns). The accuracy of the system allows for sizing and categorization of CSCC occurrences that can be used by the pipe operator to implement engineering and repair analysis, per prevalent regulation guidelines.

Confirmation of the tool specification allowed for final calculation of the system’s POD per

$$\text{POD} = \frac{Number\ of\ True\ Positives\ (whith\quad spec)}{Number\ of\ true\ positives + Num\quad of\ False\ Negatives}$$

3.3 Detection Accuracy – False Positives of the ILI system

As we continue to perform research and build our current data base size of real crack investigations, false positives have been minimized to less than 1 in 10 locations that were identified as having CSCC.

3.4 Unreported or Mis-Characterized CSCC

To date we have had very few mis-characterized or unreported CSCC anomalies. The total number of mischaracterized CSCC locations is 3 out of a total 81 validated locations. The unreported CSCC were found to be either less than 30% deep or less than 0.8" in circumferential width and therefore below the detection threshold of the current ILI system.

4. Detection and Sizing of Off angle CSCC to the Magnetic Field

The ILI system proved capable of tolerating misalignment in the crack positioning so that off angle occurrences of CSCC, which can follow the tape coat helical pattern, can be detected. The analysis of these off-angle cracks showed them to have similar amplitude responses as perfectly circumferentially oriented cracks and thus were identified with a similar level of confidence.

Figure Eight demonstrates the detection of a crack that is at 22 degree's off angle to the circumferential axis of the pipe. The AMFL and IDD magnetic field and signal response vs. background level is clearly visible and was precisely quantified.

While the ability to detect off-angle cracking improves with ILI hardware design, particularly its sensor positioning, it is the overall test methodology, of magnetic flux leakage, which does not require the indications to be positioned perfectly perpendicular to the direction of lines of magnetic flux. In this respect the ILI MFL system can be relied upon for detection of a range of flaws that extend beyond those manufactured anomalies against which the system was originally tested and benchmarked with.

This translated into real world performance whereby crack occurrences that are off angled to the circumference or cracks with multiple or radially skewed branches are detected as reliably as a single branch predominantly through wall radial crack. The ILI MFL sizing capability does not rely in the detection of signals from the crack tips as the ultrasonic technique used in the PAUT field verification did.

The very high sampling rates used in all modules of the ILI system played a significant role in the reliability and confidence level of the tool. With this very high sampling density the ILI system maintained its CSCC detection capability at tool velocities up to 11 mph (5 m/s).
As an example, the indication shown in **Figure Eight** was detected with the tool traveling at 10 mph (4.5 m/s). Given that this study was conducted in natural gas transmission and distribution lines this was particularly valuable as the tool velocity can often exceed 9 mph (4 m/s).

For all its strengths and broad spectrum of operation, the ILI MFL system can struggle to detect very small flaws in pipes with nominal wall thicknesses greater than 0.375" (9.5 mm). This limitation is a consequence of the designed flux density and magnetic saturation levels that were optimized for wall thickness in the range from 0.125" to 0.365" (3.2 to 9.3 mm).

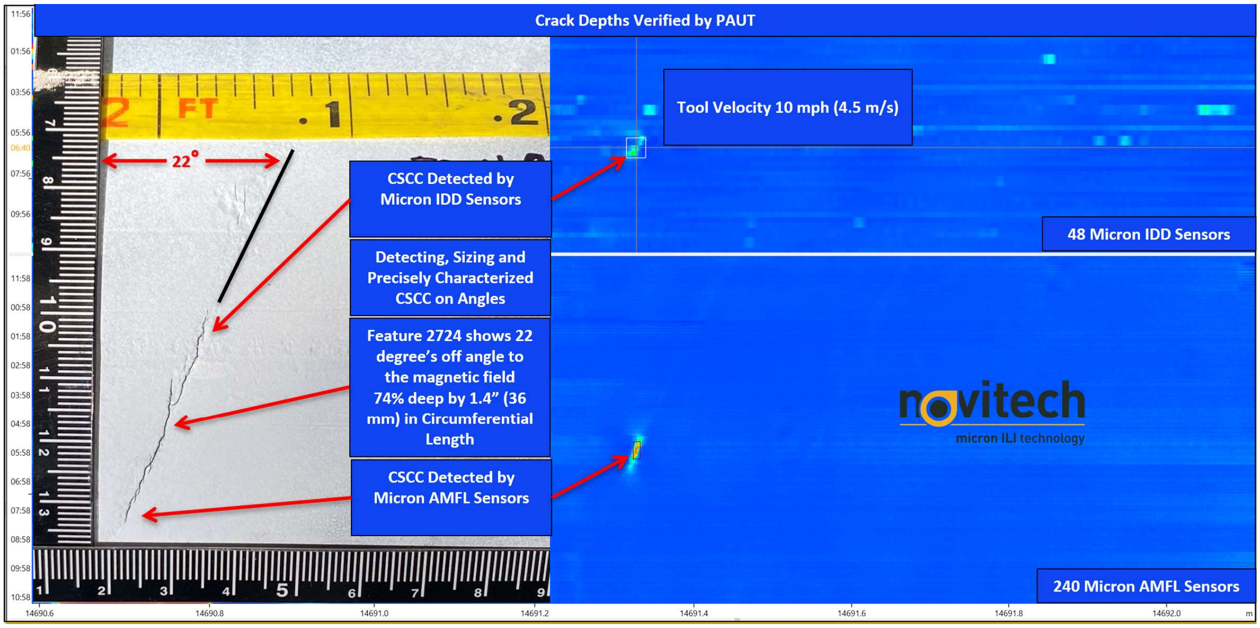


Figure Eight: Detection and Sizing of Off Angle CSCC at 10 mph (4.5 m/s)

5. Management of CSSC in a complete pipeline system

Since the time of initial discovery, Xcel Energy has completed five successful in-line inspection runs utilizing magnetic based ultra-high sampling density in-line inspection technology for the detection of CSCC. These runs covered over 200 miles of natural gas pipelines in in NPS 6", 8" and 10" segments and have confirmed 78 CSCC indications. This data, though not inclusive of all pipeline configurations, can be utilized to provide guidance for improved susceptibility criteria for prioritization of pipelines to be assessed for the threat of CSCC.

Comparing the susceptibility criteria utilized for the initial selective digging program with locations of confirmed CSCC following in-line inspection, good alignment is seen with coating type, presence of external corrosion, terrain with elevation changes, and o'clock position. Severity of metal loss was initially selected as a prioritization criterion considering that corrosion is time based and the depth of metal loss would be an indicator of the duration of time the coating had been dis-bonded allowing greater time for CSCC to develop. Although presence of external metal loss has proven a key indicator, the majority of identified CSCC indications have been in areas of minor metal loss and have not aligned with areas of more severe external metal loss.

Finally, the initial susceptibility criteria did not address factors such as the pipeline diameter or wall thickness which impact the bending strength of the pipeline. Although the data is not inclusive of all pipeline configurations, bending strength, or the pipeline's ability to resist environmental forces such as those caused by ground movement, does appear to impact the susceptibility of a given pipe segment to the threat of CSCC.

6. Considerations for the Excavation and Examination of CSCC

Following completion of in-line inspection runs, excavations were conducted to confirm CSCC indications. Given that CSCC indications are commonly found in areas of rugged terrain subject to earth movement and elevated pipeline bending stress, excavation and in-situ examination presents unique challenges. These include but are not limited to access constraints, changing pipeline conditions and operations and reliability considerations.

In many cases, residual bending stress in the pipeline resulted in the pipeline shifting up to 14 inches as overburden was removed. Additional temporary pipe support material was retained onsite during excavation to ensure the pipe could be adequately supported for in-situ examination. Further, when pipeline cut-outs were performed, attention was given to stabilize the pipe to manage additional shifting. **Figure Nine** shows pipeline shifting following an initial pipeline cut.

Figure Nine: CSCC Indication Excavation Before and After Initial Pipe Cut

Following excavation, the below steps were utilized for in-situ examination of CSCC candidate anomalies:

a) Identify CSCC target area(s) called out by ILI. Use caution when removing coating with wire wheel or other mechanical devices to prevent masking of CSCC indications.
b) Prior to examining suspected CSCC anomalies using NDE methods, information such as date, anomaly id, odometer, flow, pipeline name, anomaly o'clock position, distance to upstream/downstream weld, and long seam orientation should be written on the pipe or on another form of documentation that can be included in a picture.
c) In-situ black and white MT was utilized to confirm the presence of CSCC.
d) Map all CSCC target areas provided in the dig sheet(s).
e) Compare the ILI predicted CSCC areas to the 'as found' in the pipe results.

Conclusions

This paper continues a three-year effort in the development and implementation of ILI technology for the reliable identification, management, and repair of CSCC.

Based on the combined research between Xcel Energy and Novitech, the ILI system can successfully discriminate CSCC occurrences from other pipe anomalies such as metal loss, as well as rank CSCC severity into three categories': subcritical, significant, and severe.

The repeatability from pull testing showed consistent amplitude measurements from existing CSCC samples; a pipeline operator may consider monitoring of subcritical CSCC colonies as part of their integrity management system. Further R&D work is underway to continue to improve the accuracy and the severity rankings and allow for monitoring of what is believed to be subcritical CSCC.

CSCC management by ILI technology is supported by:

- A data base of 84 confirmed CSCC anomalies originally detected by ILI.
- Only 3 false positives out of 81 CSCC locations. The false positives were found to be metal loss.
- Only 1 occurrence of CSCC that was not ILI detected, found in the vicinity of CSCC reported by the tool. In this location the depth was predicted to be less than 30% by PAUT and the circumferential width less than 0.8" (20 mm).
- Achievable POD ≥ 90% for CSCC ≥ 30% in depth and 0.8" (20 mm) of circumferential width.
- Achievable POI ≥ 90% for CSCC ≥ 30% in depth 0.8" (20 mm) of circumferential width.
- Detection of CSCC begins at ≥ 30% in depth and 0.8" (20 mm) of circumferential width.
- Preliminary depth sizing accuracy from field verifications and laboratory analysis is (± 20%).
- Preliminary circumferential width sizing accuracy (± 0.4" (10 mm).
- Laboratory verified minimum crack opening for all ILI reported CSSC from 0.001" (25 µm).
- Expected wall thickness range for reliable detection and sizing 0.120" (3 mm) to .280" (7.1 mm).
- Confirmed ILI tool velocity of up to 11 mph, (5 m/s) in the wall thickness range of 0.188 to 0.219" (4.8 to 5.6 mm).
- Run to Run Repeatability ± 10% on real CSCC ≥ 30% in depth (from R&D pull testing).

The use of a reliable diagnostic system allowed for the simplification of the CSCC field program with direct detection supplanting desktop analysis that are solely based on susceptibility factors and geotechnical data.

While it is understood that the larger the sample data base of CSCC occurrences incorporated into the development of the tool will promote further advancements and refinement of the identification and sizing algorithms as well as hardware enhancements, it is noted that CSCC occurrences are not as prevalent as axially oriented cracking [1] and thus the study of the subject, for the time being, will likely continue to be based on comparable sample size to the one presented here.

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