Integrity Management of off-axis SCC Through an ILI System and Engineering Assessment

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Abstract

The discovery of larger populations of stress corrosion cracking (SCC) in orientations other than the axis of the pipe in the early 1990's triggered several new studies into the factors associated with off-axis cracking. Since most of the crack colonies appeared to be close to 90° degrees to the axis of the pipe, the investigations focused on circumferentially oriented SCC (CSCC). Notwithstanding, there have been many documented cases of cracks at angles other than 90° degrees to the pipe axis, notably at the same angle of the spirally applied tape in tape-coated pipelines.

CSCC management programs have been developed using axial SCC models and use a combination of quantitative and qualitative data involving bend strain along with susceptibility criteria, and areas of pipe movement, and ILI where available. As CSCC investigative and remedial work continue, off-axis cracking started to be found in larger numbers, with skew angles to the axis of the pipe ranging from 90° to 45°. These skew angles can exceed the specified detection range of currently available ILI tools, leaving operators without a diagnostic option for detecting or modelling these types of features.

This study illustrates the successful detection and management of both circumferential at 90° and off-axis SCC at 45° to 90° by using a new magnetic based ILI system that, in addition to length and depth sizing, can also measure the primary crack colony skew angle. The determination of all these crack attributes, particularly the skew angle, enables modelling the interaction between axial and hoop stresses, to determine the pipeline's remaining strength.

The diagnostic data for the excavation program was obtained from a magnetic based ILI technology that included three sensor systems: AMFL, CMFL, and IDD-SM℠. This technology provided crack length and depth sizing with an accuracy of ±15mm (0.580in) and ± 15% wall thickness (WT) respectively and, the measurements of the primary CSCC colony skew angle with a target accuracy ± 10° degrees.

The paper also provides an update to the program presented earlier in 2021/22 PPIM publications [3,4].

Introduction

The discovery of larger populations of stress corrosion cracking (SCC) in orientations other than the axis of the pipe in the early 1990's triggered several new studies into the factors associated with off-axis cracking. Most of the crack colonies appeared to be close to 90° to the axis of the pipe and the investigations focused on circumferentially oriented SCC (CSCC). However, there have been many documented cases of cracks at angles other than 90° to the pipe axis, notably at the same angle of the spirally applied tape in tape-coated pipelines. These off-axis cracks have been incorporated into the models developed to address CSCC.

These skew angles can exceed the specified detection range of currently available ILI tools, leaving operators without a diagnostic option for detecting or modelling these types of features. However, the availability of new magnetic based Micron ILI Technology® that has emerged in recent years has allowed operators to not only collect more accurate data on CSCC location and dimensions, but now also measurement of the angle of the crack colonies. The more accurate defect characterization can enhance understanding of the contributing factors to circumferential and off-axis cracking and

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support the management of geohazards as it is possible to identify potential ground movement at locations that were not highlighted by geotechnical desktop and field investigations.

CSCC management programs have been developed using axal SCC models and use a combination of quantitative and qualitative data involving bending strain along with susceptibility criteria, areas of pipe movement and, when available, ILI. As CSCC investigative and remedial work continue, off-axis cracking started to be found in larger quantities, with skew angles ranging from 45° to 90°.

This study follows a six-year effort that illustrates the successful detection and management of both circumferential at 90° and off-axis SCC at45° to 90° by using a new magnetic based ILI system that, in addition to length and depth sizing, can now also measure the primary crack colony skew angle. The determination of all these crack attributes, particularly the skew angle, enabled modelling the interaction between axial and hoop stresses, to determine the pipeline's remaining strength.

The diagnostic data for the excavation program was obtained using magnetic based ILI technology that included three sensor systems: AMFL, CMFL, and IDD-SM℠. This technology reliably provided crack length and depth sizing with an accuracy of + 15% WT and, for this study, the measurements of the primary colony skew angle with a target accuracy + 10° were also documented.

1. SCC in Orientations Away from the Axis of the Pipe

While less common than axial SCC, CSCC has been observed in pipelines in Canada, the United States, and two European countries since in the early 1990's. In some cases, the CSCC has been of sufficient size to cause in-service leaks and ruptures. As the orientation of CSCC is perpendicular to the maximum tensile stress, the axial stresses at the locations of the cracks must have been greater than the hoop stress. The Poisson effect and thermal effects can account for about half of the axial stresses. Evidence from the field studies suggests that there are three probable sources of additional axial stresses that can promote CSCC: residual stresses in bent pipe, axial stresses caused by movement of unstable soil on slopes, and residual stresses opposite to rock dents [1,2].

Most leaks or ruptures due to SCC originate at clusters of cracks that are oriented in the longitudinal, or axial, direction of the pipe. This mode of failure has been under investigation since 1965, when high-pH SCC was first discovered, then in 1986 when near-neutral-pH SCC (sometimes called low-pH SCC) was discovered. As a result, both forms of SCC are reasonably well understood in terms of causes and mitigation. However, historically there have been a comparatively smaller number of failures due to SCC that were oriented in the circumferential and off angle direction, and methods to manage this form of SCC are not so well established.

In 2013, a project was conducted for the Pipeline Research Council International (PRCI) to examine records of cases where CSCC was discovered, to learn more about the causes, and to consider ways to manage the problem. The results provided some guidance to pipeline companies for locating and treating CSCC and to ILI vendors for developing and evaluating tools for locating, identifying, and sizing CSCC [1].

The study documented CSCC incidents in both natural gas and liquid pipelines. The locations of those pipelines included Alberta, Ontario, and Saskatchewan, Canada; Arizona, Kentucky, South Carolina, and Tennessee, USA; and two southern European countries.

Early CSCC incidents occurred on steep slopes, but later also discovered on terrain that has been described as flat or undulating or with slopes between 0° and 10°. Stress-corrosion cracks invariably orient themselves perpendicular to the maximum stress. Typically, the hoop stress in a pipeline is

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greater than the axial stress. Therefore, most SCC is oriented in the axial direction. The circumferential orientation of SCC means that there was an unusual state of stress in the pipeline where the cracks occurred. CSCC will not occur unless the axial stress is greater than the hoop stress. If it is not, there may either be no cracking or axial cracks. There are several sources of axial stress in a pipeline; some are common to all pipelines and others occur in comparatively rare circumstances. The known sources of stress are internal pressure, pipeline installation temperature vs operating temperature (compressive thermal stress) and additional axial stress from field bends, movement of unstable soil on a slope, and rock dents at the bottom of the pipe causing tensile stresses at the top.

Since the completion of the PRCI work CSCC investigative and remedial work continues. The overall susceptibility, location, and secondary stress drivers for the development of CSCC are still under investigation. This is underlined by more recent off-axis crack findings in larger numbers, with skew angles to the axis of the pipe ranging from 45° to 90° and in areas of flat terrain with no obvious source of stress to explain crack orientation. The findings indicate further need for updating the knowledge base and possibly the susceptibility models.

Furthermore, the skew angles can exceed the specified detection range of currently available ILI tools, leaving operators without a diagnostic option for detecting, modelling and understanding the severity of these types of features.

2. CSCC and Off-Axis Cracking Characterization

The latest development and advancement of ILI technology enables better detection and characterization of both circumferential at 90° and off-axis SCC (45° to 90°) to support pipeline operators in further investigate the susceptibility of the pipelines to CSCC and then allow further improvement of the management practices.

The magnetic based ILI system that has been advancing over the past several years can now, in addition to length and depth sizing, measure the primary crack colony skew angle. The determination of all these crack attributes, particularly the skew angle, enables modelling the interaction between axial and hoop stresses, to determine the pipeline's remaining strength. The technology includes three sensor systems: AMFL, CMFL, and IDD-SMSM with reliable crack length, depth sizing and the measurements of the primary colony skew angle. The technology now can provide five data sets on one tool (AMFL + CMFL + IDD-SMSM + Geometry + IMU).

It is a long-established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

2.1 Detection

The current data base sample size updated with results from inspections between 2017 and 2023 confirms the findings from the pull tests and shows that the integrated ILI technology has a consistent detection threshold for CSCC of 0.5-in (12.5-mm) or longer and of 25% WT depth or greater, with

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crack openings as small as 0.001-in (0.025-mm, 25-microns). Of note is the fact that the crack opening was historically required to be a minimum of 0.010-in (0.25-mm, 250 microns) for an MFL based system to detect CSCC features. Research with the new advances in magnetics has allowed to break this barrier, allowing the magnetic based technology to be considered for reliable detection of CSCC. The enhanced results from the surveys can support the pipeline operators in further studies of cracking behaviour, implement engineering, and repair assessment according to prevalent regulation guidelines. Confirmation of the tool specification allowed for final calculation of the system's POD to over 95%.

2.2 Identification and Sizing

As more excavations are being completed the number of unreported and misclassified features is decreasing. At the time this paper was written, false positive features have been minimized to only 2 in 400 CSCC locations.

Similarly, the total number of false negative CSCC feature locations was 1 out of a total 227 validated locations. There were also 12 unreported CSCC features found, however they were identified to be below tool specification and therefore below the detection threshold of the technology.

Based on the 227 field validated features the depth sizing accuracy has been improving with +15% WT accuracy and length sizing (circumferential crack length) at +15 mm (0.59-in) accuracy.

3. Off Axis Cracking - Excavation Program Results

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 1 demonstrates the detection and discrimination of CSCC cracks that are at 35° and 45° off angle to the circumferential axis of the pipe. The AMFL and IDD-SM℠ magnetic field and signal response vs. background level is clearly visible and was precisely quantified as well as AMFL data that clearly depicted the areas that were external corrosion.

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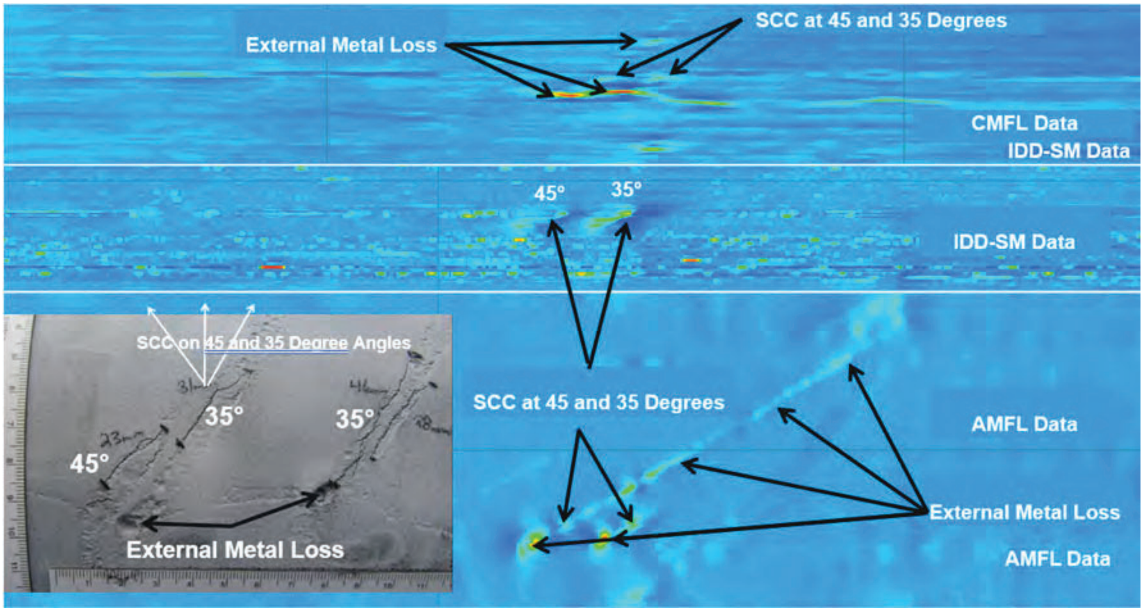

Figure 1. Detection of an Off Angle CSCC features.

While the ability to detect off-angle cracking improves with ILI mechanical design, particularly its sensor positioning, it is the overall test methodology of the magnetic flux leakage, which does not require the indications be positioned perfectly perpendicular to the direction of lines of magnetic flux, that enables such accuracy for detection. In this respect, the magnetic based system can be relied upon for detection of a range of flaws that extend beyond those manufactured anomalies against which the system was originally evaluated and benchmarked with. The ability to characterize from 45° to 90° degrees cracks, fully including the feature angle, can now enable the operators to better prepare for the excavation programs and how to approach defect assessments.

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 through wall radial crack. The magnetic based inspection technology sizing capability does not rely in the detection of signals from the crack tips as the ultrasonic technique used in the Phased Array Ultrasonic (PAUT) field verification did. Figure 2 below shows another example of an off-axis crack detected by the ILI system.

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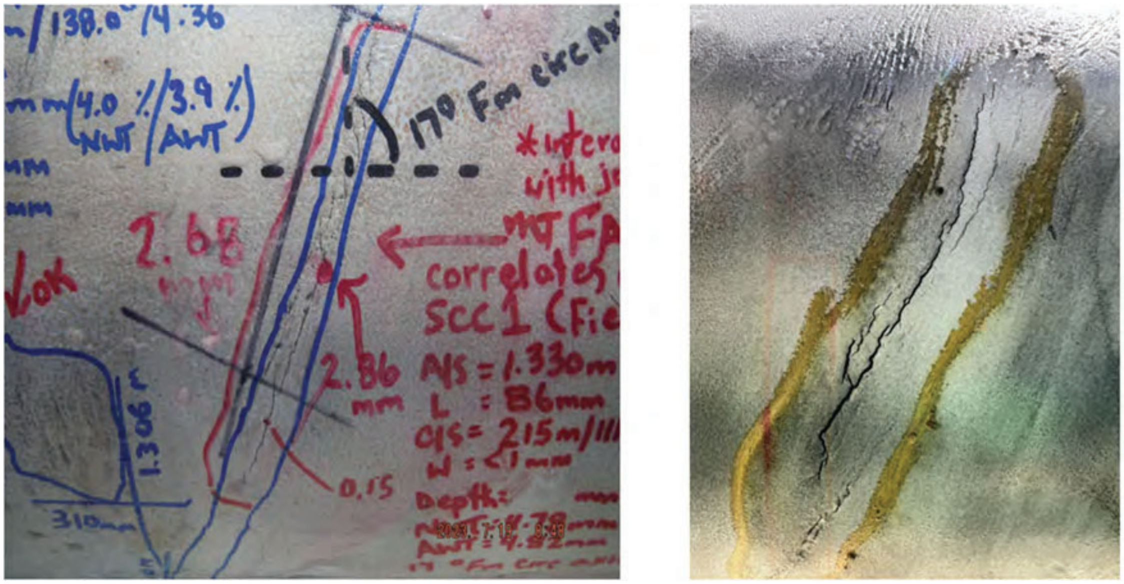

Figure 2. Example of CSCC Features Located at 17° and 27° off the Pipe Circumference.

As more excavations are completed, pipeline operators started to collect additional data at the digs sites to further understand the stresses contributing to the crack orientation. Since the crack feature orientation indicates the presence of additional sources of stress on the pipe and additional investigation is needed for appropriate mitigation activities. These investigations are even more relevant for areas where the CSCC is located in straight pipe with no obvious geotechnical or IMU bending strain indications. This presents unique challenges for the excavation and in-situ examination.

An example of a feature located in such an area is show in Figure 3 below.

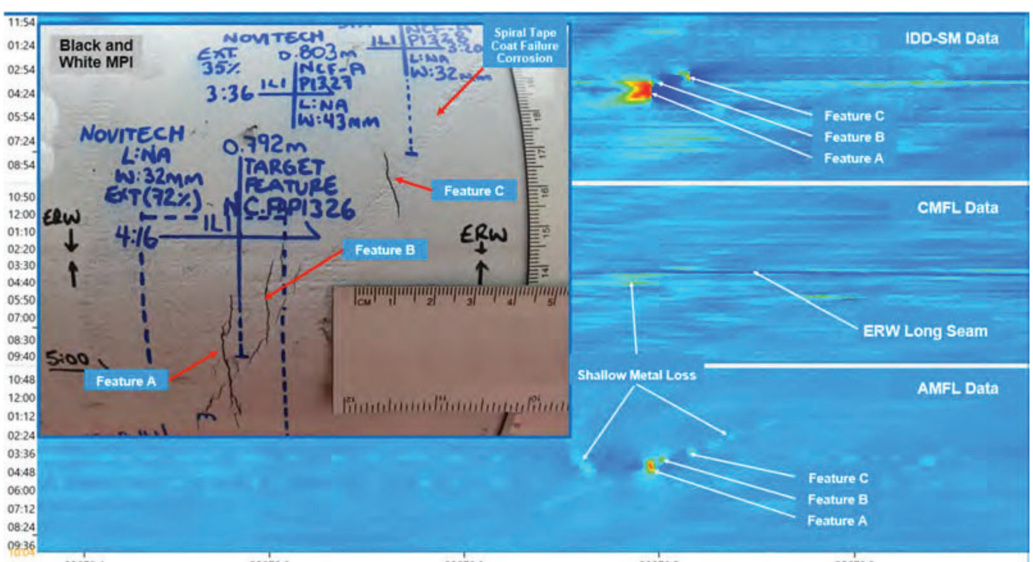

Figure 3. CSCC Feature in an Area with no Obvious Bending Strain Indication.

SCC features are very often found in colonies or groups of cracks in close proximity to one another. The CSCC features exhibit similar behaviour where the cracks are not only found as an individual indication, but also as colonies with several cracks in close to one another. An example of such a group of cracks is shown in Figure 4 below, where the dominant cracks are well visible in the data.

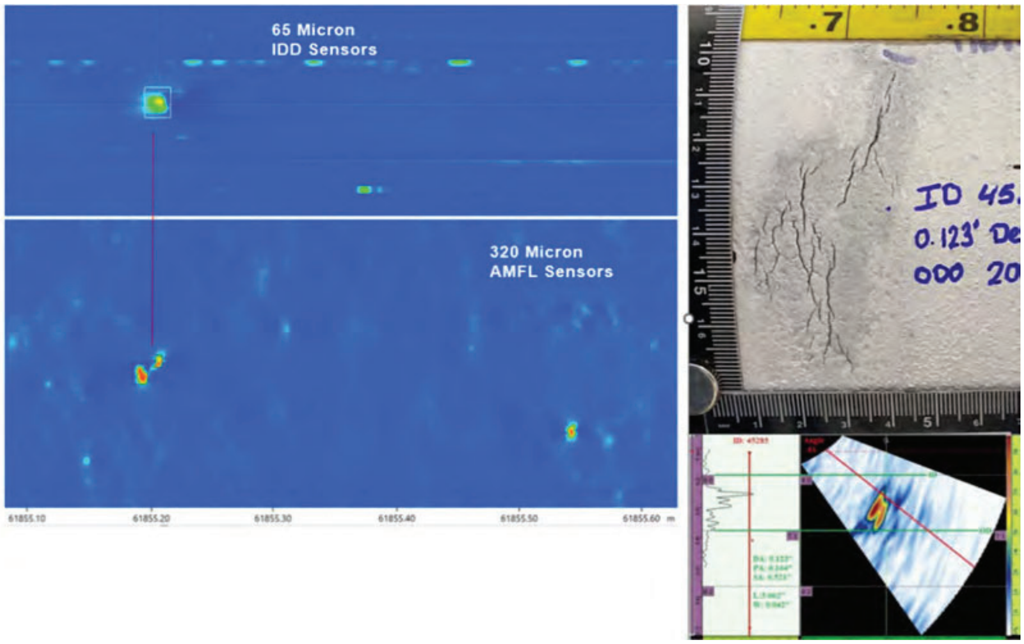

Figure 4. CSCC Feature Colony/Cluster.

The resolution of the MFL system, combined with the use of up to five data sets, AMFL, CMFL, IDD-SM℠, Geometry and IMU, can allow for de-clustering a crack colony when spacing between features exceeds 20 mm, while sizing each of them accurately. This characteristic of the findings may prove especially useful when assessing the severity of the colonies/cracks as both depth and length of the dominant cracks are available. Another example of the CSCC colonies is shown in Figure 5 below. Four distinct areas of CSCC are visible in the data and then upon excavation shown as four separate crack features/colonies.

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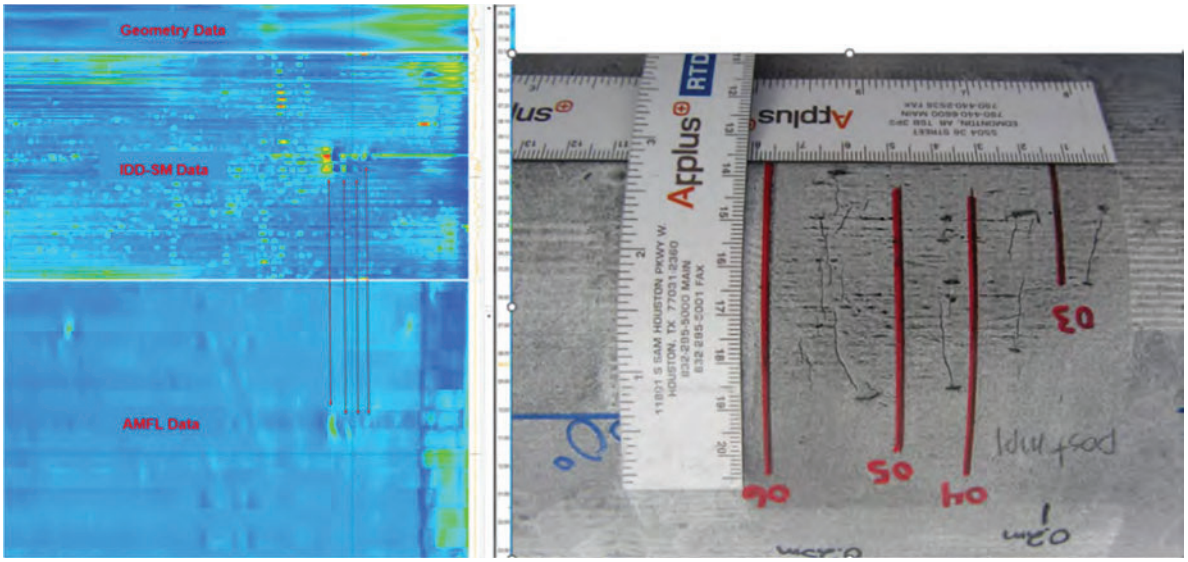

Figure 5. CSCC Features in Close Proximity, with clear separation between them in the data, avoiding over-clustering of the colony.

As an initial effort to determine the extent or ratio to which cracks appear either perfectly circumferential or at off angles, a sample of features that ranged in depth from 60 to 80% where plotted against its predicted angle from the vertical and its predicted skew angle verified through excavations. Figure 5 below shows a summary of the findings. While most of the features were located between zero° and 10° off the pipe circumference, 17% of them were found at skew angles greater than 11° and up to 45°.

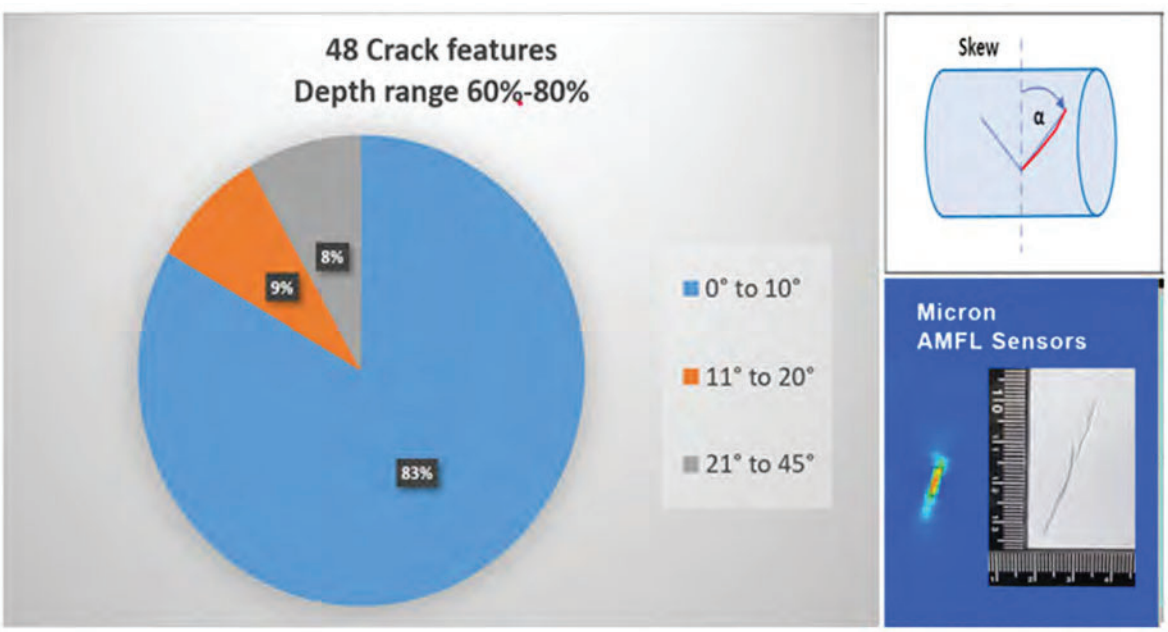

Figure 6. Summary of the Most Recent off Angle CSCC Findings, and first database of confirmed cases and ratios of circumferential SCC to off-axis SCC.

4 CSCC Integrity Management Considerations

While CSCC has been a rare cause of pipeline failures, extensive efforts to manage CSCC were not necessary unless there was a history of CSCC in a particular pipeline. However, in view of the most recent findings and because of the availability of the novel MFL technology, CSCC investigations are increasing.

With more precise detection, CSCC has now being found in more regions of North America and in much larger quantities. The locations of those pipelines include British Columbia, Alberta, Ontario, Canada; Arizona, California, Kentucky, South Carolina, Texas, Oklahoma and Colorado, USA.
Since the time of initial discoveries pipeline operators have now completed over 400 successful in-line inspection runs utilizing the Micron MFL inspection technology. These runs covered over 14,000 miles of natural gas and liquid pipelines in in NPS 6-16 segments and have confirmed over 600 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.
The improved specification for detection, sizing, characterization, and skew angle measurement, can be used to better assess crack severity. While historically the crack severity was determined in a manner similar to that used for axial SCC, the feature angle off the pipe axis does play a role in the severity ranging and assessment and can now be included in the evaluation methodology. However, more work is still required to incorporate this information in the assessment models.
Comparing the susceptibility criteria utilized for the initial selective digging program with locations of confirmed CSCC following in-line inspection, good alignment can be seen with coating type, presence of external corrosion, terrain with elevation changes, and o'clock position. Since 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, the severity of metal loss was initially selected as a prioritization criterion. This is proving to be incorrect as, 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.
More work is still required to better understand and manage and mitigate the area where no obvious geotechnical or ground movement was observed, where safe excavation pressure and repair options are still not well defined.

Summary

This paper summarizes the six-year effort in the development and implementation of ILI technology for the reliable detection, identification, management, and repair of CSCC.

Based on the results to date, the new magnetic based ILI system can successfully detect, accurately size and discriminate CSCC occurrences from other pipe anomalies such as metal loss as well as now report CSCC skew angle with $\pm 10°$ accuracy, enhancing crack severity ranking and predicted burst pressure calculations.
In addition to skew angle measurement, the field findings indicate that the resolution of the MFL system, combining up to 5 data sets, AMFL, CMFL, IDD-SM℠ , Geometry and IMU allows not only to discriminate the main individual features but also to de-cluster crack finds when there is more than 20 mm spacing between them. This characteristic of the findings may prove particularly useful when determining the severity of the colonies/cracks as both depth and length of the dominant cracks are available.

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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.

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],[2] 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.

As previously stated, pipeline operators plan more investigations to better model, manage, and mitigate areas where CSCC has been detected, especially in locations where no obvious geotechnical or ground movement was observed during field investigations.

Acknowledgments

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