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America's Evolving Oil and Natural Gas Transportation Infrastructure
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Topic Paper #4-4

CRACK DETECTION AND MANAGEMENT

Prepared for the
Technology Advancement and Deployment Task Group

On December 12, 2019 the National Petroleum Council (NPC) in approving its report, *Dynamic Delivery – America's Evolving Oil and Natural Gas Transportation Infrastructure*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Permitting, Siting, and Community Engagement for Infrastructure Development Task Group. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 26 such working documents used in the study analyses. Appendix C of the final NPC report provides a complete list of the 26 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper (Prepared for the National Petroleum Council Study on Oil and Natural Gas Transportation Infrastructure)		
4-4	**Crack Detection and Management**	
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SUMMARY

In-line inspection supported by in-the-ditch non-destructive examination has become a critical means of detecting and managing pipeline crack defects. Industry efforts to advance these technologies have improved the ability for tools to properly detect and size crack features. Crack detection and measurement challenges include detection certainty, proper threat identification, measurement uncertainty, data quality, crack evaluation, and others requiring additional research and development. This topic paper addresses additional development needed for in-the-ditch non-destructive examination tools.

I. INTRODUCTION

Pipeline companies use in-line inspection technology to detect and assess the potential impact of various cracking threats as a critical portion of their integrity programs. In-line inspection is supported by external, in-the-ditch nondestructive examinations (NDE), which are used to collect additional integrity information and to validate the in-line inspection results. The complexity of accurately detecting and measuring complex crack morphologies can pose challenges to existing technologies, which may limit integrity management confidence and efficiency. There has been significant research in this area to develop tools and assessment techniques to allow for the effective management of crack threats using a combination of in-line inspection and in-the-ditch NDE of the pipeline. This paper describes the technologies used for integrity management, technology and challenges associated with in-line inspection and in-the-ditch NDE technologies and how they are used together to support crack management, and industry challenges associated with these technologies.

II. IN-LINE INSPECTION TECHNOLOGY

As established in industry standards[1], in-line inspection has become a proven and efficient method to nondestructively inspect pipelines. The American Petroleum Institute's Standard 1163 serves as an umbrella document to be used with and complement companion standards, such as those developed by the National Association of Corrosion Engineers[2] and the Association of Nondestructive Testing[3]. These industry standards enable service providers and pipeline operators to provide rigorous processes that consistently qualify the equipment, people, processes, and software used in the in-line inspection industry. These documents provide general guidelines for application of inspection technology for all anomaly types that can threaten pipeline integrity.

While many in-line inspection technologies have proven to be effective at locating and characterizing anomalies in pipelines, pipeline operators have become aware of limitations in existing crack inspection technologies. For crack inspections, vendors specify the generalized performance of their tools, including minimum detectable crack size, probability of detection, probability of identification, and sizing accuracy. Actual tool performance will vary, either better or worse than the specification, depending on pipe properties, pipe/weld fabrication variables, and specific inspection variables, including tool setup, product type, flow rate, and data analysis. Therefore, it is necessary to verify results for pipeline inspections, and it is recommended to correlate data to findings from previous in-line inspections and in-the-ditch NDE. Similar to the limitations of hydrostatic testing, in-line inspection detection and sizing may have limitations for specific crack geometries such as short, deep anomalies that have inherently high failure pressures but can result in leaks. Certain weld geometries and types, with flaw morphologies particular to certain manufacturers and vintages can greatly affect the ability of an inspection tool to detect, characterize, and size crack threats. The uncertainties associated with these complex measurements can be accounted for within assessment through use of appropriate safety factors, probabilistic analysis, and/or decision making based on risk-based approaches.

Crack-detection in-line inspection tools are evolving to meet the inspection challenges needed to ensure safe pipeline operation. Ultrasonic technologies, which leverage high frequency sound waves coupled into the pipeline, are the most commonly used tools for in-line crack detection. The two most prominent categories of ultrasonic tools are liquid-coupled angle beam ultrasonic and electromagnetic acoustic transducer tools. This section discusses these two technologies, their capabilities, and technical challenges associated with these measurements.

a. Angle Beam Ultrasonic Inspection Technology

Angle beam ultrasonic inspection methods are commonly used in many industries for detecting cracks in metals, and implementation for in-line pipe inspection became commercial in

[1] American Petroleum Institute Standard 1163: In-line Inspection Systems Qualification.

[2] National Association of Corrosion Engineers Standard SP0102: In-Line Inspection of Pipelines.

[3] American Society for Nondestructive Testing Standard ILI-PQ: In-line Inspection Personnel Qualification and Certification.

the mid-1990s. This technology transmits sound waves (with frequencies on the order of a few megahertz generated by piezoelectric transducers) into the pipe wall and then collects the reflected signal to identify and measure cracks. These systems require the pipeline to contain liquid media for coupling the ultrasound from the transducer into the pipe, which complicates the utilization of this technology for natural gas pipelines. The principle is illustrated below in Figures 1 and 2, which show how inner and outer diameter cracks can be detected. This technology has the capability to identify several crack morphologies and crack-like anomalies, including stress corrosion cracks, fatigue cracks, electric resistance weld bond line anomalies (including lack-of-fusion, cold welds, and penetrators), and hook flaws including associated cracks within the heat affected zone.

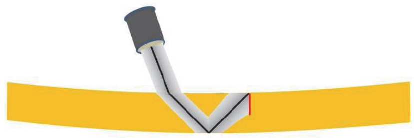


Figure 1: Inner Diameter Crack Detection Using a 45° Shear Wave (Full Skip)

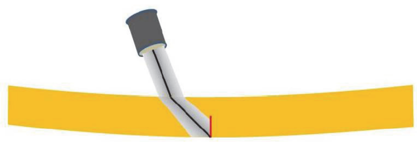
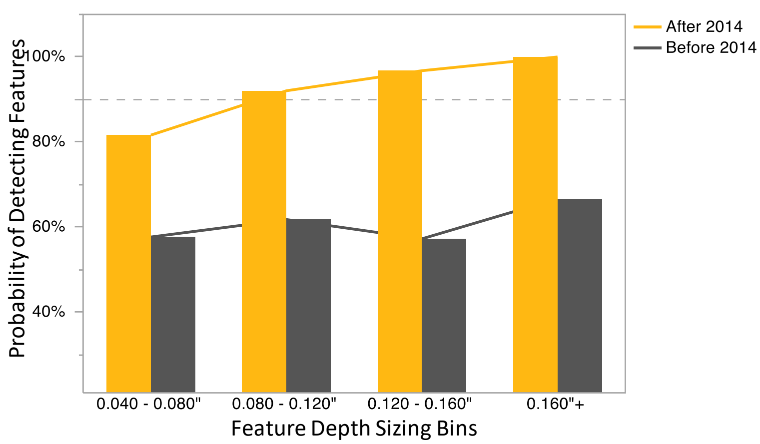


Figure 2: Outer Diameter Crack Detection Using a 45° Shear Wave (Half Skip)

The dimensions of detectable crack-like features using angle-beam ultrasonic technologies have steadily decreased as electronics and sensor technology have improved. Increases in sensor density and recognition software algorithms, including field data feedback and machine learning, have improved the probability of detecting, sizing, and characterizing crack features. As can be seen in Figure 3, one operator had noted measurable improvements in ultrasonic inspection probability of detection since 2014, and this trend is expected to continue.



Source: Enbridge

Figure 3: Ultrasonic Inspection Performance Changes Based on Crack Depth Over Time[4]

Similar performance trends have been observed by the same operator for sizing as shown in Figure 4, which compares the asset-specific performance from in-line crack inspections occurring before and after 2014. For three separate assets (labelled A, B, and C), a statistically significant amount of field data was gathered to validate the in-line inspection results, which are presented in terms of probability of detection and probability of sizing within vendor claimed tool tolerance. The results presented in Figures 3 and 4 demonstrate that the operator observed significant improvement in both measurements of tool performance for three separate assets.

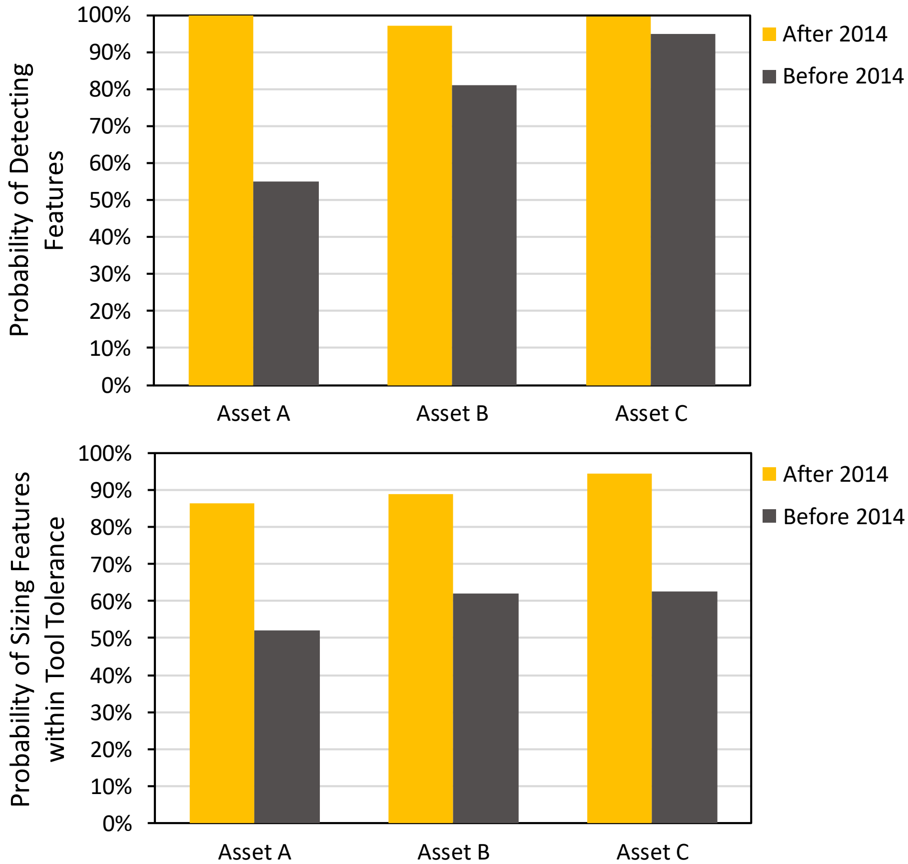


Figure 4: Changes to Ultrasonic Inspection Performance Based on Asset Over Time[5]

Pipeline operators are working with in-line inspection tool vendors to continuously improve tool performance by providing in-the-ditch NDE results, sections of vintage pipe for pull-through testing, and cooperatively improving crack threat management methods based on in-line inspection data analysis enhancements. Additionally, a recent Pipeline Research Council Interna-

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[4] Figure provided by Enbridge Pipelines.

[5] Figure provided by Enbridge Pipelines.

tional project[6] highlights the overall capabilities of crack tool technology and outlines the performance capabilities of various in-line crack inspection tools from different vendors.

Through the years of testing and validation with respect to ultrasonic crack tools, improvements in overall performance have been recognized. Importantly, this technology has been incorporated into industry standards which allows for broad usage of the technology for liquid pipeline operators. The broad usage and availability of ultrasonic technology with multiple vendors fuels innovation and development of new and improved methods of meeting inspection needs. However, there are still many challenges associated with tool performance and capabilities[7]. These challenges include:

Detection certainty, where depending on pipe properties, a near-critical defect may be near or below detection thresholds. Complicated weld geometries, including trim, misalignment, curvature mismatch, or stacking of features (internal, external, embedded on approximately the same through-thickness plane) present challenges to crack inspections, and certain types of adjacent features may be shielded and not properly detected. This means that in some cases, there is a chance that the inspection will not find certain types or sizes of features on the pipeline, potentially increasing the difficulty in an operator reaching its reliability targets.

Proper threat identification, where it can be challenging to differentiate between different flaw types, which is important for proper feature assessment and growth modelling. Differentiating stress corrosion cracking from corrosion features continues to be a challenge for in-line inspection, as the reflected signals can appear similar in amplitude and attributes. Differentiating non-injurious weld anomalies from injurious cracks continues to present a challenge to both in-line and in-the-ditch NDE, since the ultrasonic signal return from the reflection across a non-injurious anomaly can be virtually identical to an injurious feature. Similar challenges exist for seam weld anomalies (such as lack of fusion, hook cracks, toe cracks, seam weld corrosion), circumferential cracking, girth-weld cracking, and identifying cracks in dents.

Measurement uncertainty leads pipeline operators to excavate some reported anomalies that do not need to be excavated and not excavate others that could be more serious. Outlier investigation, comparing features that do not align between the in-the-ditch NDE and in-line inspection, is an important factor in validation and calibration of crack inspections and identifying uncertainties. If an inspection is found to under-size reported anomalies, operators could take false confidence in the integrity of their pipeline systems, which could be a concern when anomalies are reported to be minor but found to be much deeper and/or more serious. Oversizing of features could lead to overly conservative assessment and inefficient dig programs. Thus, ade-

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[6] Pipeline Research Council International Project NDE-4E: ILI Crack Tool Reliability and Performance Evaluation.

[7] Additional information regarding inspection challenges are available in American Petroleum Institute Recommended Practice 1176: Assessment and Management of Cracking in Pipelines.

quate validation of inspection data[8] through use of in-the-ditch NDE and/or comparison between different ILI tool runs is important, and any remaining uncertainties can be accounted for within probabilistic and risk-based assessments to help ensure that integrity decision making is as accurate as possible.

Data quality issues can reduce the overall reliability and accuracy of an in-line inspection but are not always readily apparent when reviewing a data set. As a result, operators can make erroneous decisions about the severity of anomalies and the need for repair or remediation. Data quality can be affected by debris in the pipeline, challenges associated with product type surrounding the tool (limiting the effectiveness of the fluid coupling or altering the sound transmission speed), or inspection tool speed excursions. Significant effort is made by both vendors and operators to minimize these data quality concerns, but continued data validation and verification is important to maximize the accuracy of feature assessment.

Crack evaluation techniques are essential to feature assessment and require an accurate understanding of factors that can make a crack threatening. In some cases, existing assessment models have not been fully proven or have known limitations which lead to excessive conservatism within the assessments. Crack evaluation methods are evolving through continued industry research based on field findings, laboratory results, and analytical studies. These lead to enhancement of existing assessment methods and development of new ones. Continued development is required to ensure that all crack feature morphologies can be analyzed effectively and that there are clear and consistent assessment methodologies available within the industry.

Other considerations related to the industry on a broader scale can impact the development and use of crack inspection technology. Market forces can impact competition levels between vendors and may impact the cost and availability of tools which can be used by operators. This may also hinder innovation for vendors as development is costly, and the economic risks can be significant. Industry collaboration and effective partnerships between inspection technology vendors, operators, and regulators may help to foster innovation in this field while minimizing the associated business risks for any one group.

b. Electromagnetic Acoustic Transducer Inspection Technology

Electromagnetic acoustic transducer (EMAT) based in-line inspection generates ultrasonic waves directly in the pipe wall, removing the need for the liquid couplant required with more conventional ultrasonic transducers. This is a relatively new technology to the industry, as it was first prototyped in the 1980s and did not become commercially available until 2003. However, it is rapidly increasing in popularity as removing the need for liquid couplant makes it more applicable to the inspection of gas lines than more conventional ultrasonic technologies. Also, this technology has been proven to find smaller subcritical cracks that have not been identified by hydrostatic testing, as hydrostatic testing only finds critical cracks.

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[8] American Petroleum Institute Standard 1163, In-line Inspection Systems Qualification provides guidance for validation of in-line inspection results.

In this technology, a coil induces eddy currents in the presence of a magnetic field, resulting in oscillating Lorentz or magnetostrictive forces that excite ultrasound waves in the metal. Figure 5 illustrates the principles used for these measurements.

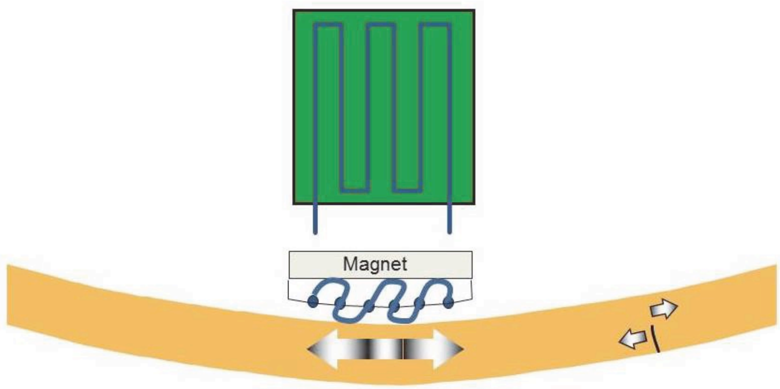

Figure 5: Electromagnetic Acoustic Transducer Schematic

Although EMAT technology has been selectively used by gas/liquid operators since early the 2000s, there still remain challenges for this technology, similar to other ultrasonic inspection tools[9]. Some of these challenges include detection certainty, proper threat identification, measurement uncertainty, data quality, and crack evaluation as described in the previous section for angle beam ultrasonic technologies. While EMAT may have specific strengths and/or weaknesses associated with these challenges, these topics must be addressed and considered as part of any crack inspection. Other challenges associated with the EMAT tool specifically include:

Cost and tool availability, which can be a challenge with this technology as, compared to conventional ultrasonic inspections, there are fewer vendors and limited tool sizes. Operators may choose other technologies if inspections using EMAT are too costly or tools are not available within required timeframes, operators may choose other more available technologies if safe to do so. This may impair industry adoption of this technology and could slow further development and validation.

III. In-the-Ditch Non-Destructive Evaluation Technology

From outside the pipe, non-destructive evaluation methods are used to detect, characterize, and size anomalies identified by in-line inspection as possibly being cracks. These in-the-ditch NDE occur after the pipe is fully exposed through excavation of the pipe followed by removal of coatings and cleaning of the pipe, using methods that will minimize any alteration of any existing cracks. Many ultrasonic and electromagnetic methods are available for sizing cracks in the ditch, such as classic shear wave, time-of-flight diffraction, phased array ultrasonic, eddy current, full matrix capture, electro-magnetic field imaging, computer tomography, large standoff

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[9] Additional information regarding inspection challenges are available in American Petroleum Institute Recommended Practice 1176: Assessment and Management of Cracking in Pipelines.

magnetometry, and others. Operators often employ these techniques alongside other methods such as magnetic particle inspection to fully identify any cracks present within the inspection location.

The accuracy of in-the-ditch NDE methods varies, with some results showing accuracies in the range of 10% of wall thickness under ideal conditions, while some blind tests show minimal correlation with depth as determined by metallurgical sectioning. In-the-ditch NDE methods are most accurate when cracks are more isolated as the accuracy can be significantly compromised if the most significant crack is in the middle of a large colony with many nearby cracks as shown in Figure 6. The skill and training of the inspector are also significant factors in the quality of results that are achieved. While absolute depth sizing of cracks can have inaccuracies, the methods can typically determine the relative size of cracks throughout a pipeline. The crack length measurements as determined in-line and in-the-ditch often differ, as in-the-ditch measurement methods (such as magnetic particle inspection) include very shallow portions of a crack that are below the detection threshold of the in-line inspection tool. In these cases, the crack depth measured in the ditch will be longer than that measured by the in-line inspection. Calibration of non-destructive evaluation methods for cracks removed from service can be used to help improve the accuracy of the results.

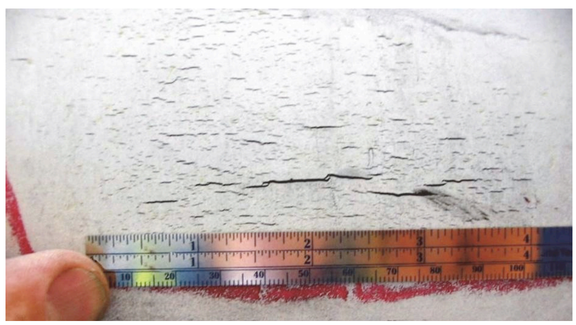

Figure 6: Example of a Crack Cluster Caused by Stress Corrosion Cracking

The application of in-the-ditch NDE methods has more dependence on the inspector than in-line inspections, in both the way they are applied and results that are achieved. Operators have found value in having written procedures for information collection associated with each inspection method. Inspectors should have certifications of proficiency in the inspection modality used; one such certification is a Level II or III certification from the American Society for Nondestructive Testing. Operators can request inspectors have additional performance demonstrations for specific technologies or crack types. Procedures and recorded data should be consistent from one year to the next for comparison of results and detection of changes. For inspector safety, pipeline pressures should be evaluated and often lowered when field personnel are performing non-destructive examination. Further guidance for this examination can be found in relevant industry standards.[10]

[10] American Society of Mechanical Engineers Standard B31.4 Pipeline Transportation Systems for Liquids and Slurries.

An example of the performance of typical non-destructive examination for crack depth measurements as observed by one operator is shown in Figure 7. The top plot compares metallurgical measurements of crack depth (determined through laboratory tests or from grind measurements) with field measurements using conventional tools. The bottom plot shows the probability density function of the measurement error, comparing the field measurements with the assumed true metallurgical measurements. The blue distribution labelled "Predicted Performance" is the expected performance based on correlations developed by the Pipeline Research Council International, while the red distribution labelled "Actual Performance" shows the measured values. Based on comparison of these distributions, this data shows that for this operator, the field measurements over-reported the crack feature depth 73 percent of the time, with an average overcall of 0.023 inches. Since metallurgical confirmation is not always available to operators, they are often left to trust the field measurements as accurate when making integrity decisions. This presents a challenge when this data is used to fairly grade the performance of in-line inspection technologies and characterize their measurement certainty. These findings align with independent research results conducted by the Pipeline Research Council International.[11]

[11] Pipeline Research Council International Project IM-3C: Assessment of NDE Technologies for Detecting, Discriminating, and Sizing ERW Pipe Seam Anomalies.

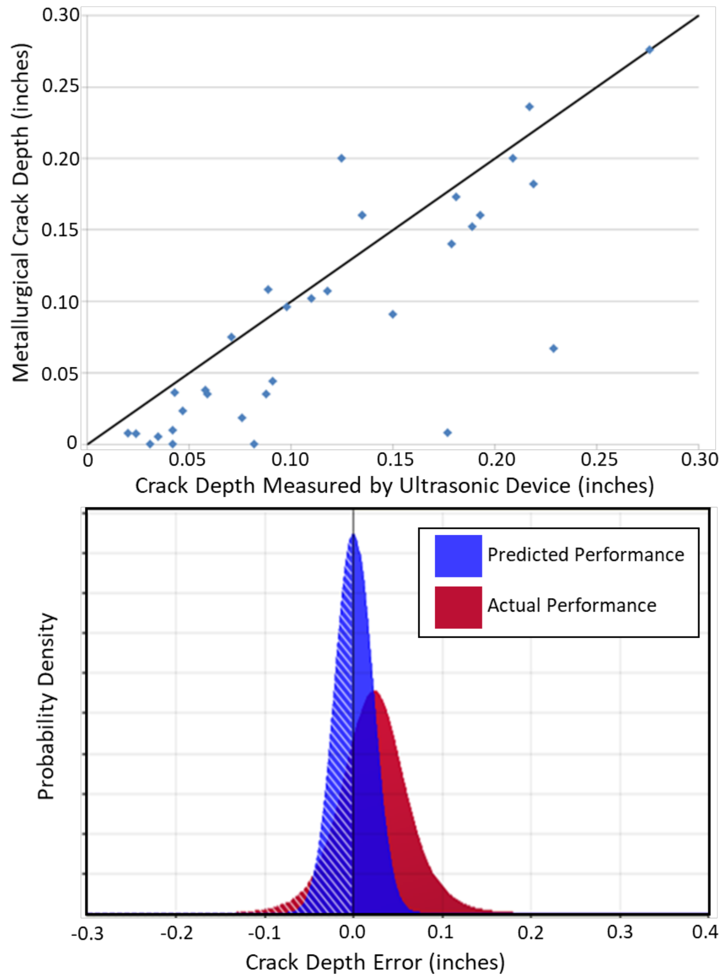

Figure 7: Example of In-the-Ditch NDE Evaluation Performance Statistics[12]

The drivers behind the observed variation in in-the-ditch NDE for crack size include human factors and biases (e.g., challenging physical conditions during measurement); problematic or complex weld geometries (e.g., observed external and internal cracks); the presence of multiple cracks in proximity (e.g., lateral or stacked features); and inherent errors in measurement technology. Another challenge in evaluating these cracks is to differentiate between weld anomalies that are subject to growth with stable, non-injurious ones that can impact assessment and integrity decision making. There are also logistical challenges associated with field measurements, as some technologies are less deployable than others, which may limit their availability for certain measurement locations.

Continued research and development of improved in-the-ditch NDE technologies such as enhanced automation, emerging new technologies, and machine learning, are expected to en-

[12] Figure provided by Enbridge Pipelines.

hance measurement capabilities and accuracy. Ideally, these enhancements will allow for highly reliable correlations to support validation of emerging in-line technologies for crack inspection.

IV. In-line Inspection to Nondestructive Examination Comparison

Industry guidance[13] is available which outlines methods for validating in-line inspection performance, typically illustrated with unity plots. A typical depth unity plot for an ultrasonic crack tool is shown in Figure 8, where the tool reported depth (horizontal axis) is compared with the depth determined by the field measurements (vertical axis), which are typically assumed to be accurate for this analysis. A series of angled lines are shown, which identify the unity line, and different zones representing different multiples of the in-line inspection tool's measurement tolerance, which are accounted for within the assessment. Features above the unity line are under-called (where the features are more severe than identified by the inspection tool), while features below the line are over-called (where the features are not as severe as identified by the inspection tool). The color and shape of the points on the graph identify false positives, which are features identified by the in-line inspection but were not found on the pipe; unreported features, which are features identified in the ditch but missed by the in-line inspection as they are classified as falling below the tool's detection threshold; false negatives, which are features identified in the ditch but missed by the in-line inspection despite falling within the tool's detection threshold; and true positives (measured by different in-the-ditch techniques), which were identified by both inspection types. These plots are used to identify any biases in the tools and identify any outlier features that should be investigated further. These comparative inspection results are often shared with the inspection vendors to help validate their processes or optimize their algorithms.

[13] American Petroleum Institute Standard 1163: In-Line Inspection Systems Qualification.

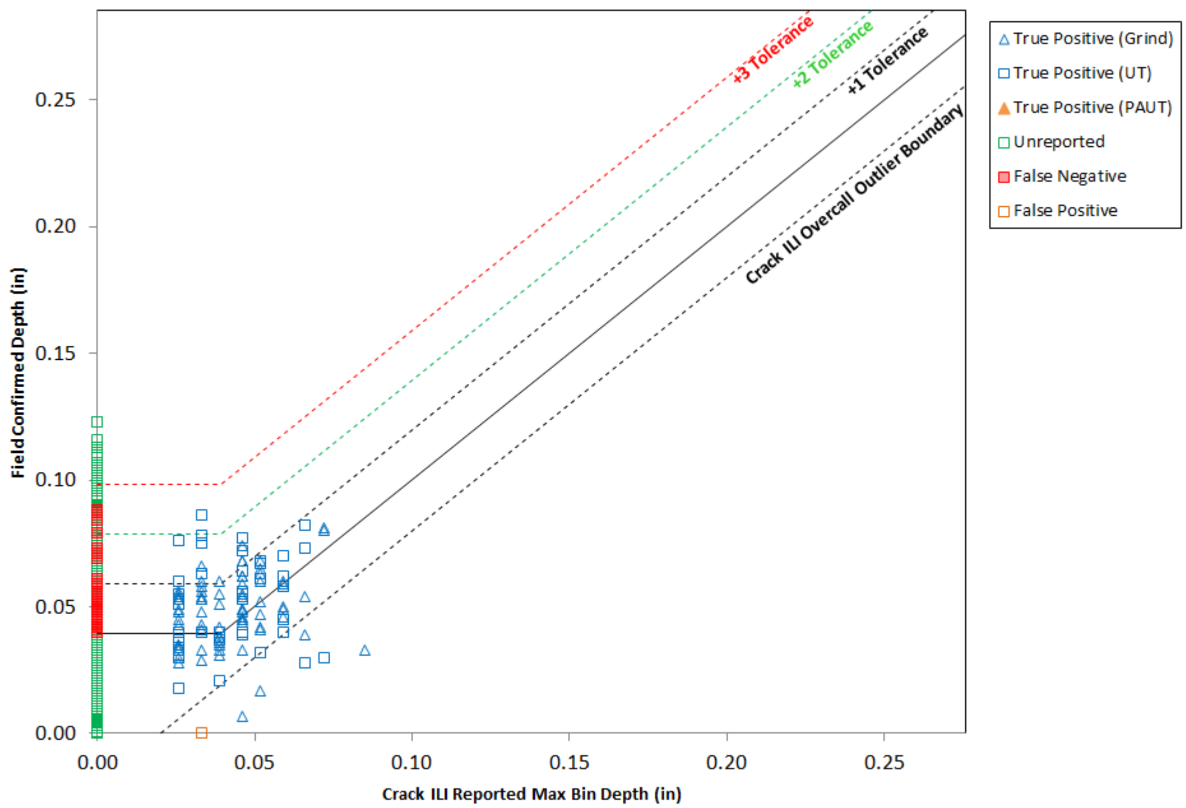

Figure 8: Example Crack Depth Unity Plot[14]

The more telling unity plot for crack management is generated through evaluating the safety factor of each feature calculated by taking the ratio of their failure pressure and the line's operating pressure. The safety factor calculated using in-the-ditch (vertical axis) and in-line inspection (horizontal axis) measurements can be compared to identify features falling into zones of concern as shown in Figure 9. Here, different assessment methodologies and assumptions can be used to determine if they have an impact on the perceived overall safety of the line. Any points above the unity line represent a conservative crack assessment methodology, meaning that the combination of tool performance, assumptions, and calculations result in assuming that the feature was more severe than what was actually found in the ditch. Points below the unity line mean that the assessment methodology did not adequately account for the uncertainties in the system and there may be safety concerns. Any features that fall within this region will typically be subject to additional review and may trigger changes to the assumptions used for the whole assessment. This type of plot provides a means of checking the accuracy and overall level of safety based on the complete crack management methodology and is an important part of outlier identification and analysis.

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[14] Figure provided by Enbridge Pipelines.

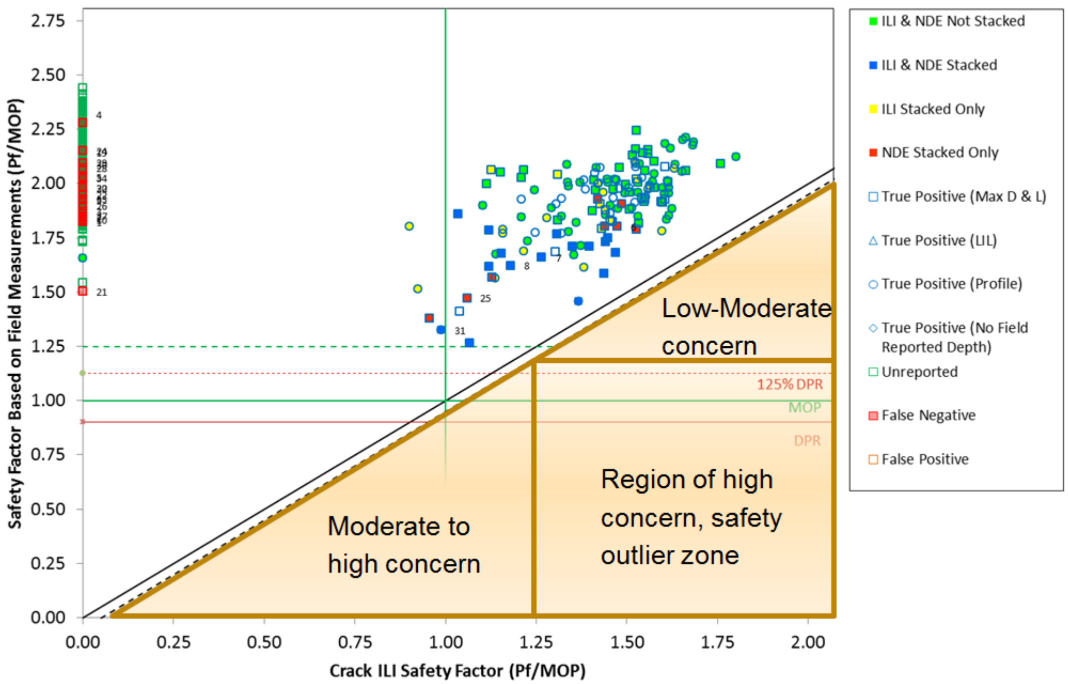

Figure 9: Typical Fitness Safety Factor Unity Plot[15]

When performing their crack assessments based on in-line inspection results, some operators incorporate additional safety layers such as incorporating the tool tolerance into the measured value and/or assuming an elliptical flaw shape when computing a feature's safety factor. Figure 10 helps illustrate that elliptical flaw shapes (similar to Crack B) typically have a lower factor of safety than more realistic shapes (like Crack A) due to the extent of the damage to the pipe, meaning that assuming an elliptical shape adds an inherent additional degree of safety within the assessment. Thus, when the actual crack profile is taken into account, the field factor of safety is often found to be significantly higher than predicted through the more conservative assumptions often used within operator's initial analyses.

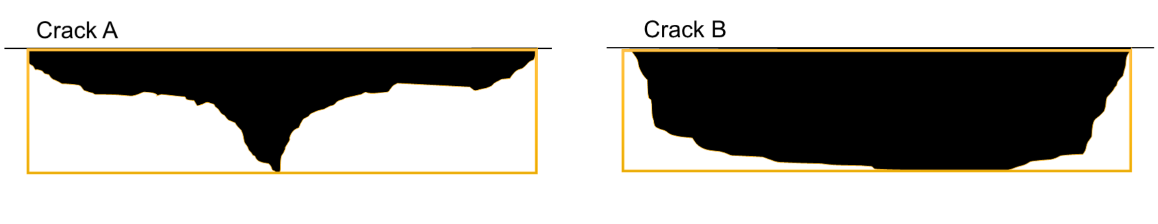

Figure 10: Comparison of Potential Cross-Sectional Crack Shapes

While the probability of detection using field measurements has historically been better than in-line inspection, recent technological advances in in-line inspection feature characterization and sizing performance have narrowed the gap between in-line inspection in-the-ditch NDE

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[15] Figure provided by Enbridge Pipelines.

performance. In-the-ditch NDE requires similar technological advancement to improve performance and reliability. This is a challenge as traditionally, in-line inspection is validated through the use of the field measurements. Accounting for field measurement uncertainty, which has been shown recently to be less reliable than the in-line inspection in several instances, can result in over-prescribed maintenance and low program efficiency. Technological advances in field measurements are not currently matching in-line inspection advancement, potentially limiting validation methods for emerging in-line technologies, which are expected to have less uncertainty than the current field techniques. Thus, as in-line inspection technology advances, new validation techniques may be required to ensure that the in-line inspections are performing properly and meeting their specifications.

For cases where the in-line inspection tool is not performing up to its specifications, the results can be updated to remove biases and recalculate fitness for service or remaining life.[16] These updates often only require a depth adjustment over a certain depth range and may be simple to implement into an integrity program. However, even simple corrections to fitness for service assessments can have significant consequences and so should be used with caution and verified through consultation with the in-line inspection vendor or industry standards.

Effective crack management programs use a combination of in-line and field inspections to identify features and validate performance. While both technologies currently have limitations, advancement in both in-line and field crack inspection is expected to help enhance the effectiveness and efficiency of crack management programs. As the industry continues to see improvements in measurement accuracy, confidence in the results will improve, which should help decrease uncertainty and minimize the need for conservative assumptions and over-prescribed maintenance.

V. Discussion

Crack in-line inspection tool technology is rapidly improving, and operators are embracing these tools for crack management, either exclusively or in combination with hydrostatic tests and direct assessment. While field non-destructive examination advancement is not matching the trajectory of in-line inspection advancements, the industry is optimistic that field performance can and will improve steadily over time. A recent Pipeline Research Council International study[17] concludes that the field non-destructive examination techniques evaluated show an average error of ~1mm, and a standard deviation of ~1mm, with a strong bias for ultrasonic tools to overcall feature depth. This is consistent with observations made by operators at the 2018 and 2019 Operator's Crack Forum: field non-destructive examination sizing is less accurate than the in-line inspection sizing in the majority of recent cut-outs. This makes data validation of internal and deep external features, which relies on field measurements, challenging for in-line tools.

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[16] Guidance on the validation and assessment of in-line inspection results can be found in the American Petroleum Institute Standard 1163: In-line Inspection Systems Qualification.

[17] Pipeline Research Council International Project IM-3C: Assessment of NDE Technologies for Detecting, Discriminating, and Sizing ERW Pipe Seam Anomalies.

Many of the challenges faced by in-line and field inspections are shared, such as economic roadblocks and ultrasonic technology limitations. While field inspections have the benefit of direct access to the pipe exterior, human factors and environmental conditions are factors in quality of inspections. By virtue of the sheer number of features analyzed, in-line inspections have the advantage in achieving crack detection and sizing consistency. Thus, through leveraging each technique's relative advantages, the combination of in-line and field measurements has the potential for highly accurate crack detection and measurement.

With the use of the electromagnetic acoustic technology and emerging crack tool technologies becoming of greater interest to operators, there are concerns with successfully implementing them given current regulations. While regulators are working to ensure maintenance of public safety, the uncertainty in the regulatory framework for approval may lead to challenges with testing and implementing new technologies for individual operators and the industry as a whole. Research and development projects sponsored by PHMSA and other industry groups (such as Pipeline Research Council International and the American Petroleum Institute) have been a critical component in targeting current industry gaps and proving capabilities of new technologies to operators and regulators. These paths should continue to be pursued to help encourage the development of emerging technologies and help bridge the gaps of challenges associated with current crack tool technologies.

Future advancements in machine learning and facilitated data feedback loops are likely to promote success in improving both in-line and field inspection performance and are a focused development area for both operators and vendors. For example, one operator has leveraged facial recognition algorithms to automate analysis of field photographs while an in-line inspection vendor is employing artificial intelligence algorithms to improve signal analysis methods. In addition, encoded phased array ultrasonic tools and laser scans are already hastening and expanding data analysis and feedback loops.

Given the broad challenges that crack management poses on various operators for both hazardous liquids and gas pipelines, available technologies have not been integrated consistently within an operator's crack management program. It is recommended that operators look to use recommended practices of crack management[18] for guidance and development of an effective integrity management program. The consistency of a crack management program would help drive a broader use of proven technologies to promote their advancement within the industry.

Operators, vendors, academia, research associations, and government agencies are working harmoniously to advance the science behind effective and efficient crack threat management. Unprecedented levels of cooperation, sharing, and investment in the future are being realized throughout the pipeline industry. Due to these advancements, operators are embracing a reliability target for liquid pipelines with regard to the cracking threat that is at a similar level to that achieved in other safety-critical industries.

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[18] American Petroleum Institute Recommended Practice 1176: Assessment and Management of Cracking in Pipelines.