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Enhancement of pipeline integrity assessment of buried unpiggable pipelines with non-contact magnetic gradient tomography method (MTM-G)

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Abstract

The invention of non-contact magnetic gradient tomography has significantly improved the corrosion assessment of buried oil and Gas pipelines. This technology uses magnetic field strength from aboveground to identify external corrosion metal loss, external stress corrosion cracks and areas of geohazard risks. MTM-G can be effective in the detection of anomalies associated with the mechanical stresses, directly measured by a natural magnetic response from the pipeline material and without necessity assess to the size of each defect. For pipeline integrity management programs, the local stresses are registered directly and conventional safety parameters (like Psafe, Tsafe, SCF, and ERF) are assessed through direct magnetic response measurements. The invention of this technology would help operators easily prioritize areas of concern and prevent failures, especially on non-piggable pipelines. Combining MTM-G with existing pipeline integrity assessment methods would aid in the management of corrosion in oil and Gas midstream, upstream, and downstream difficult-to-pig pipelines. This technology is also supplemented with inline inspection on piggable pipelines to help pinpoint and prioritize defects, especially on critical assets in high-consequence locations. This paper presents the usage of this technology to enhance the integrity assessment of both piggable and unpiggable pipelines. The results from these case studies are good news for unpiggable pipeline operators who have been looking for improved ways to ensure effective pipeline integrity management of their unpiggable assets.

Keywords: Corrosion, Direct Assessment, Inspection, Non-contact Magnetic Tomography (M-TMG), Pipeline Integrity.

1. Introduction

1.1. Pipeline integrity assessment techniques

The primary causes of pipeline failures include corrosion, cracking, weld defects, and external factors. Various techniques are utilized to assess pipeline integrity, such as Hydrostatic Pressure Testing, Inline Inspection (ILI), and Direct Assessment methods (DA). Among these, Hydrostatic Pressure Testing is an intrusive, destructive and non-predictive method used to determine the location of the faults after removing the pipeline. In contrast, inline inspection uses tools inserted into the pipeline, such as pigs, which send signals received from the outside and determine the status of the pipes. Such techniques are non-destructive and reactive but still intrusive and cannot be used in all pipelines. The ILI techniques are the most commonly used for piggable buried pipelines to determine the location and type of corrosion defects and carry out corrective actions.

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Finally, direct assessment techniques are non-intrusive, non-destructive and predictive techniques used from outside of the pipeline to predict the status of the pipes and the probable location of the faults. The direct assessment methodologies are recommended by the Association for Materials Protection and Performance (AMPP) for difficult-to-pig pipelines to address issues related to external and internal corrosion as well as stress corrosion cracking. Based on the type of the corrosion assessed, these methodologies are referred to as External Corrosion Direct Assessment (ECDA), Internal Corrosion Direct Assessment (ICDA) and Stress Corrosion Cracking Direct Assessment (SCCDA) techniques and can be used for both piggable and difficult to pig pipelines.

In general, direct assessment methodology involves four steps. In the first step, referred to as pre-assessment, data gathering is carried out to determine and integrate corrosion factors. The second step, referred to as direct assessment, involves field operations using equipment and access to the pipeline. In this step, direct assessment techniques are used to identify the suspected corrosion areas. The third step involves a direct and detailed examination to verify and confirm the suspected sites and most probable corrosion locations and mainly involves exposing the pipeline for an in-depth inspection. Finally, the fourth and final step is a post-assessment carried out using the data gathered from the previous steps to evaluate the performance of the techniques as well as the overall status of the pipeline and the necessary corrective actions. Evaluating the likelihood of external corrosion on buried coated and cathodically protected pipelines relies on ascertaining the level of cathodic protection, coating condition and soil corrosivity. The basis of this method is the fact that under ideal conditions, locations with adequate cathodic protection should have a low likelihood of external corrosion per AMPP SP0169-2013 while locations with inadequate CP due to coating anomalies, and a highly corrosive environment should have the highest likelihood of external corrosion. Evaluation of stress corrosion cracking likelihood on onshore coated and cathodically protected pipelines also relies on previous historical data of SCC, operating stress levels, distance from compressor/pump stations, operating temperature (especially for high-pH SCC) as well as age and coating type of the pipeline. This is because SCC occurs only if the pipeline is exposed to all conditions required for SCC. Figure 1 shows the schematic of the most probable locations (MPLs) predicted using different direct assessment (DA) techniques for a pipeline [1].

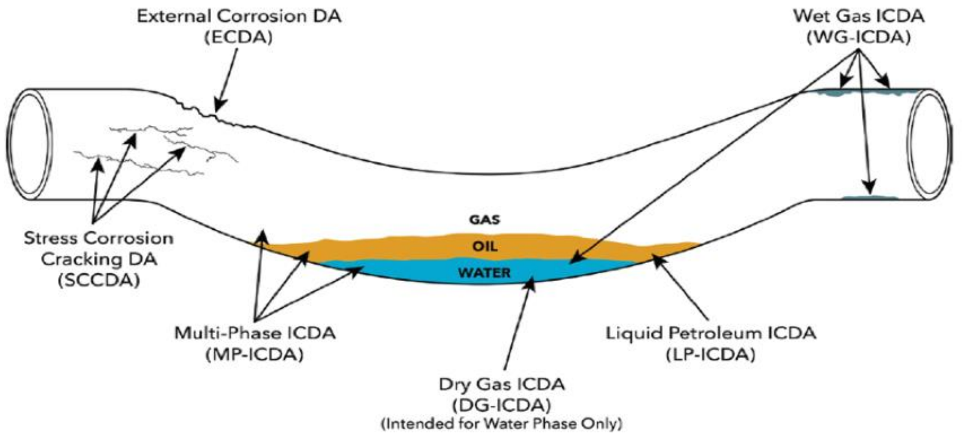


Fig. 1. The schematic of Most Probable Locations (MPLs) for corrosion determined using Direct Assessment (DA) techniques [1]

1.2. Non-contact magnetic gradient tomography method (MTM-G)

General inspection methods used to assess pipeline integrity have several limitations including the need for mandatory internal or external contact with the pipeline, the need to isolate the pipeline and stop the operations, the need to prepare the pipeline, the need for launchers and receivers for pigs or crawlers, and being unsuitable for certain pipelines including buried and unpiggable pipelines. These techniques also might fail to detect critical anomalies outside of their detection range. To overcome these limitations, non-contact assessment methods such as the Non-Contact Magnetic Gradient Tomography Method (MTM-G) could be used. Non-contact Magnetic Gradient Tomography Method (MTM-G) is a non-destructive testing (NDT) technology used for detecting anomalies and evaluating the integrity of pipelines. This technique can be applied to inspect above-ground, underground, and offshore pipelines, irrespective of their type and size. The basis of the MTM-G method is detecting magnetic anomalies caused by stress applied to pipelines. The shape change of a ferromagnetic material during magnetization is characterized as magnetostriction. Inverse magnetostriction, known as the Villari effect, characterizes the change of magnetization when mechanical stress is applied to the material. This effect can then be detected by a detector aboveground and used to predict the mechanical stress responsible for the anomalies. Figure 2 shows a simple schematic of the MTM-G technique [2-6].

Fig. 2. A simple schematic of the MTM-G method showing localized magnetic dipoles caused due to stress (red dots) which are then detected by the aboveground equipment.

This technique provides advantages such as having only a detector thus not requiring access to the pipeline, and the ability to predict the severity and location of the anomalies. This study provides an overview of recent enhancements in the MTM-G technique, making it one of the useful tools for inspecting buried and unpiggable pipelines.

2. Material and Method

The Magnetic Tomography Method (MTM) uses mathematical methods to determine the spatial distribution of stress, mechanical load and structure changes in the metals [7]. However, this method is susceptible to the background noise caused by coatings, soil composition and other external factors. To rectify this problem, changes in the magnetic gradient were measured to improve the accuracy of the results, creating a novel technique referred to as the Magnetic Gradient Tomography Method or MTM-G. This technique measures the changes in the magnetic field over a buried pipeline to determine the location of mechanical stress anomalies. To this end, a series of magnetometers are used (usually three), which are moved above the ground by the operator. Any changes in the magnetic field above the background signal are detected and measured. The operative MTM-G equipment also includes a GPS device to help map the location of magnetic anomalies based on the geographical position. The data is then sent to a computer system for analysis and assessment. Figure 3 shows the schematic of the MTM-G measurement equipment used for pipeline assessment. As can be seen, any mechanical stress anomalies are detected as magnetic signals.

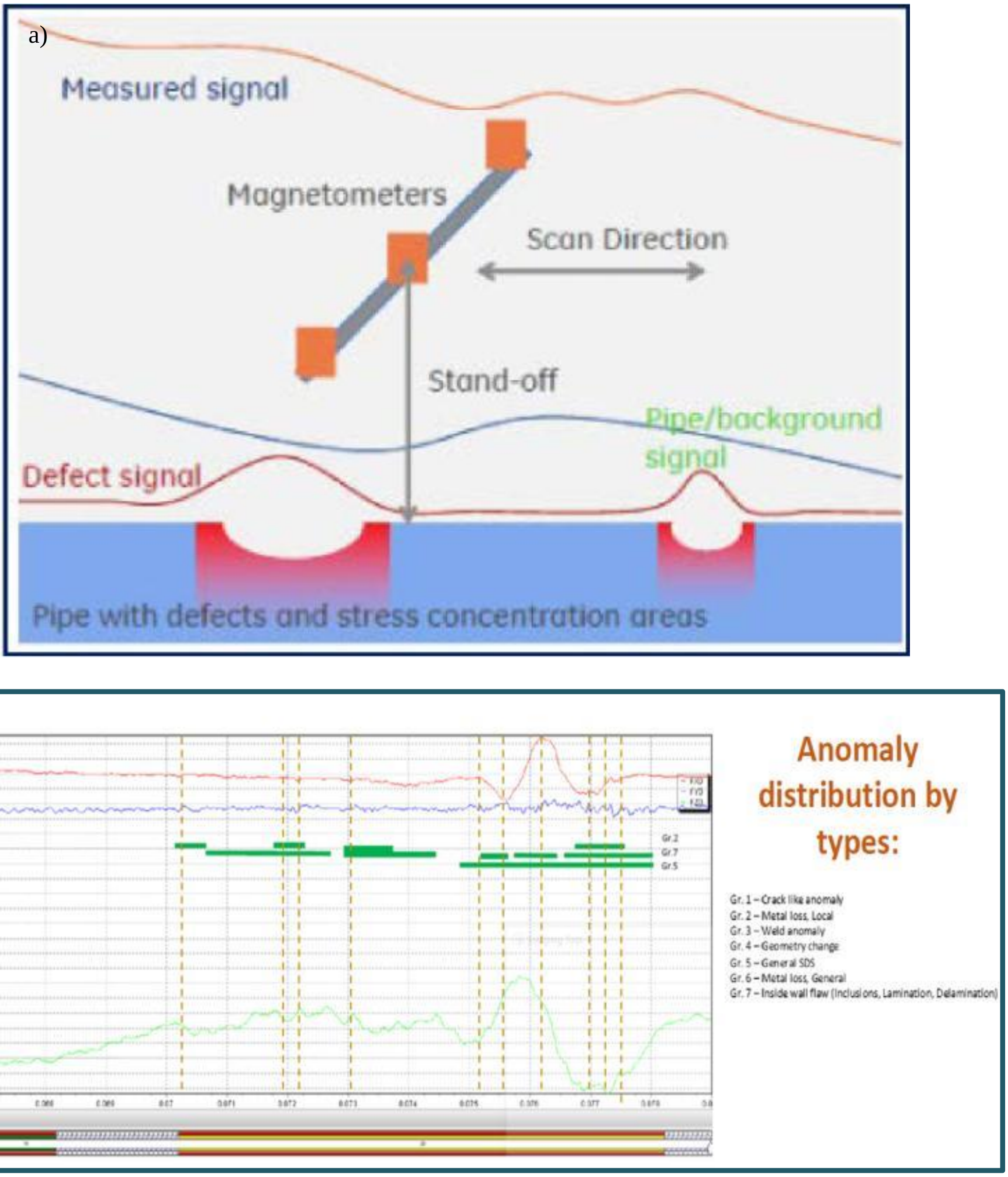


Fig. 3. a) Schematic of MTM-G equipment used for pipeline assessment. b) Presentation of MTM-G anomalies [2]

As mentioned previously, the MTM-G technique is a non-contract assessment method, meaning there is no direct contract between the pipeline and the equipment. Furthermore, this technique only measures the change in magnetic properties. Therefore, the composition of the soil as well as the depth of the pipeline can affect the strength and sometimes mask the signal from the stress anomalies, meaning that the MTM-G technique has a limited range and cannot be currently used for pipes buried below 7 meters. The signal obtained from the MTM-G measurements can then be analysed to determine the probable type of defect, and its probable severity as well as the predicted metal loss percentage for that defect. Table 1 shows the different types of anomalies detected using the MTM-G technique.

Table 1. Different anomalies detected using the MTM-G technique

Crack-like Defects	Guide marks, blisters, laps, SCC defects, etc.
Metal Loss *	Local characteristics (comparative to the outer pipeline diameters) for the hoop stress changes with the corrosion or non-corrosion type flaws: - Localized corrosion and the resulting pits - Metal loss due to local corrosion damage - Local change in nominal wall thickness - Erosion corrosion and selective leaching
Weld anomalies	Pores, lack of fusion, cracks, edge displacement, cutting inside of the weld or close to the head-affected zones (HAZs),
Geometry changes	Compression marks, corrugations, ovality, corrugated pipes, mechanical damage, dents, scores, etc.
Stress-Deformed condition	Sections with deviation in general stress-deformed conditions caused by sagging, free-spanning, bending, longitudinal, circumferential or twisting loadings due to landslides, soil movement, etc.
Discontinuity	Laminations, non-metallic inclusions, bubbles, swelling due to hydrogenating media

* It is worth noting that the metal loss determined by the MTM-G technique is a predictive value calculated using the MTM-G data. The MTM-G technique does not measure metal loss directly.

After measurement, anomalies are assigned a risk factor, F, based on their severity and importance and divided into three categories inadmissible anomalies requiring urgent repair, admissible anomalies requiring a repair schedule and good anomalies without any need for repair. Figure 4 shows the measurement results for a pipeline with the anomalies raked with three different colours relative to an above-ground marker (AGM). The ranking of anomalies and their respective risk factor (F) range are presented in Table 2.

Table 2. The ranking of anomalies detected by the MTM-G technique

Anomaly Range	Category	Risk Factor (F) range	Recommendation
1	Inadmissible	0-0.2	In need of urgent repair
2	Admissible	0.2-0.55	In need of scheduled repair
3	Good	0.55-1.0	Can be operated without repair

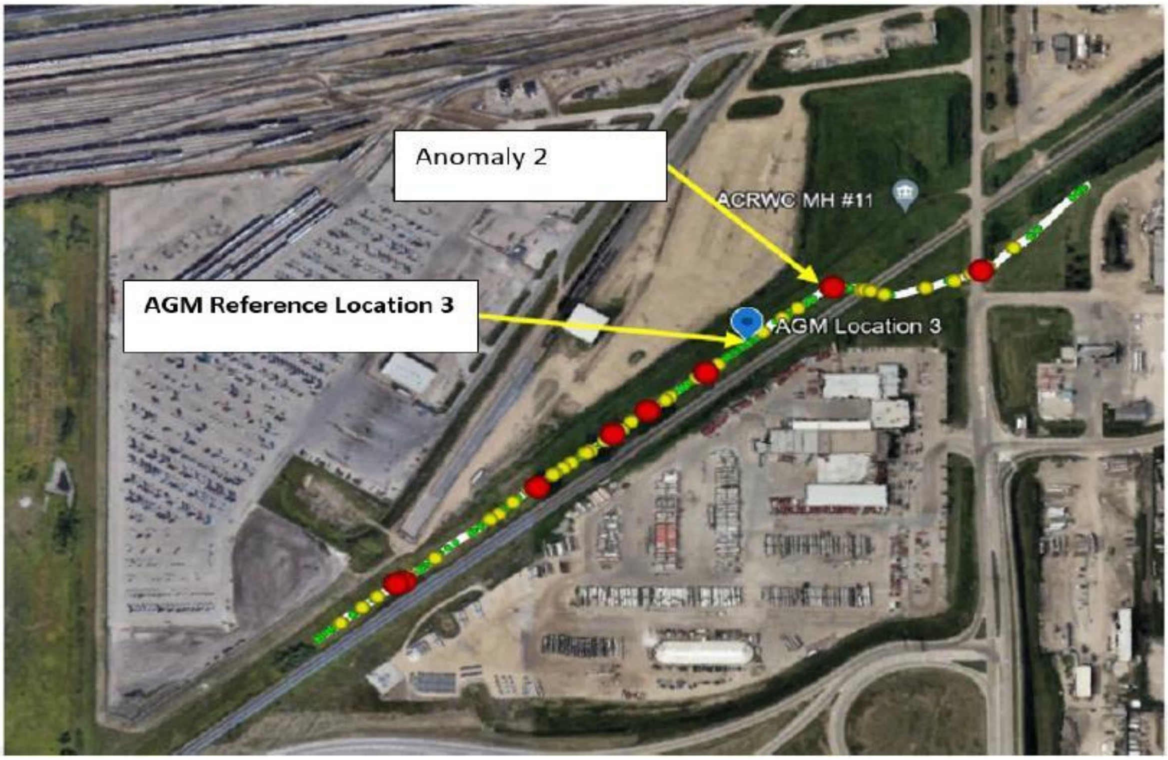


Fig. 4. The result of the MTM-G assessment of a buried pipeline with anomalies colour-coded based on their ranking and relative to an Above-Ground Marker (AGM)

3. Findings and Discussion

3.1. Current state of direct assessment techniques

As mentioned before, Direct Assessment (DA) techniques are categorized based on the type of corrosion they are used to detect. As expressed by the AMPP SP0169-2013 standard, external corrosion is expected on buried metallic pipelines without suitable cathodic protection. Therefore, External Corrosion Direct Assessment (ECDA) techniques are used to determine the locations susceptible to external corrosion by measuring the levels of cathodic protection. The ECDA techniques focus on locating areas of inadequate cathodic protection, coating defects and high soil conductivity using robust overline survey techniques [8]. The detected anomalies are then categorized based on their predicted severity for direct evaluation. Figure 5 shows the presentation of coating anomalies in different ECDA techniques (a) and the same area evaluated in a direct examination (b). As can be seen, the results of all ECDA techniques match each other and the actual location of the detected defect on the pipeline.

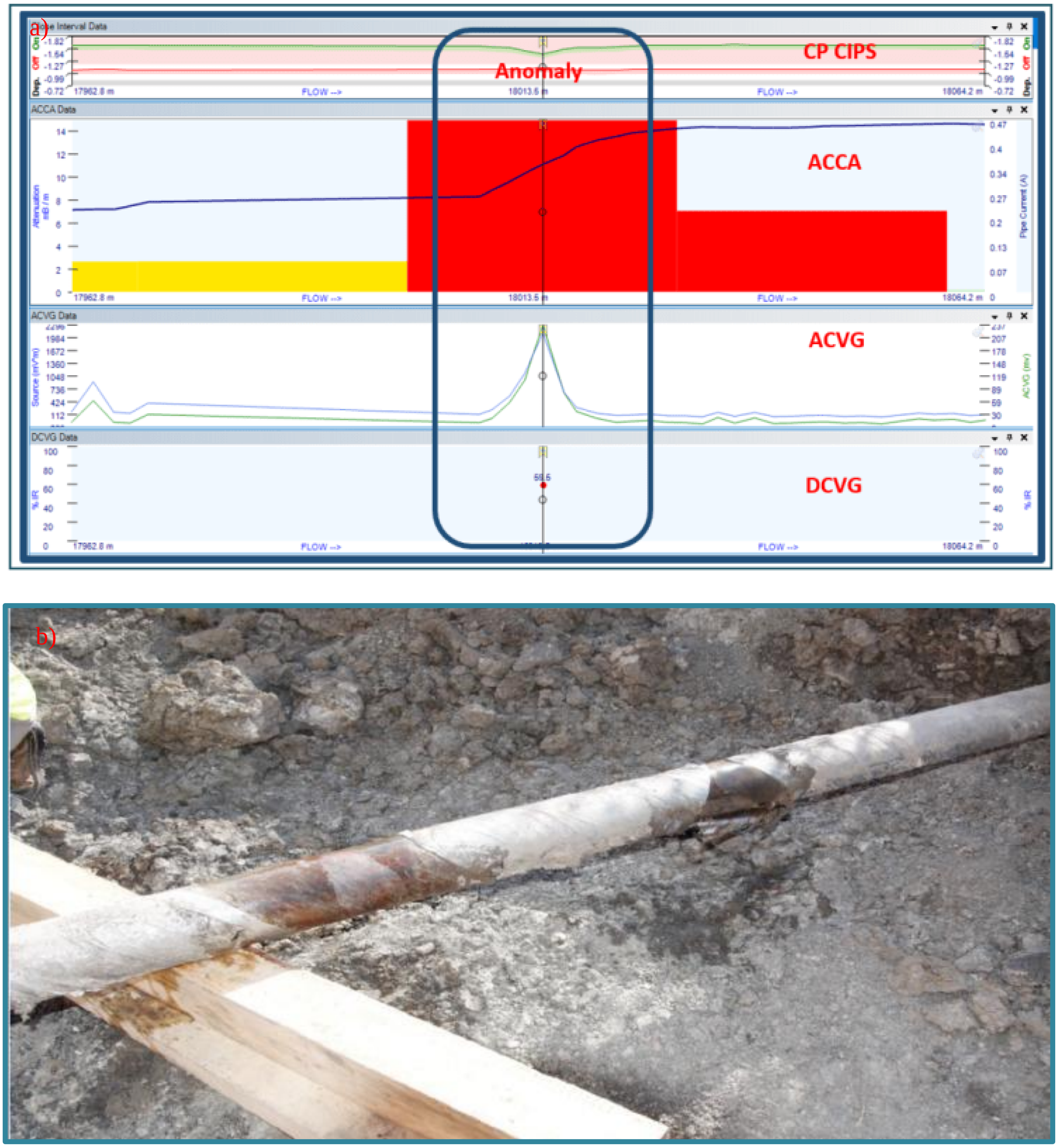


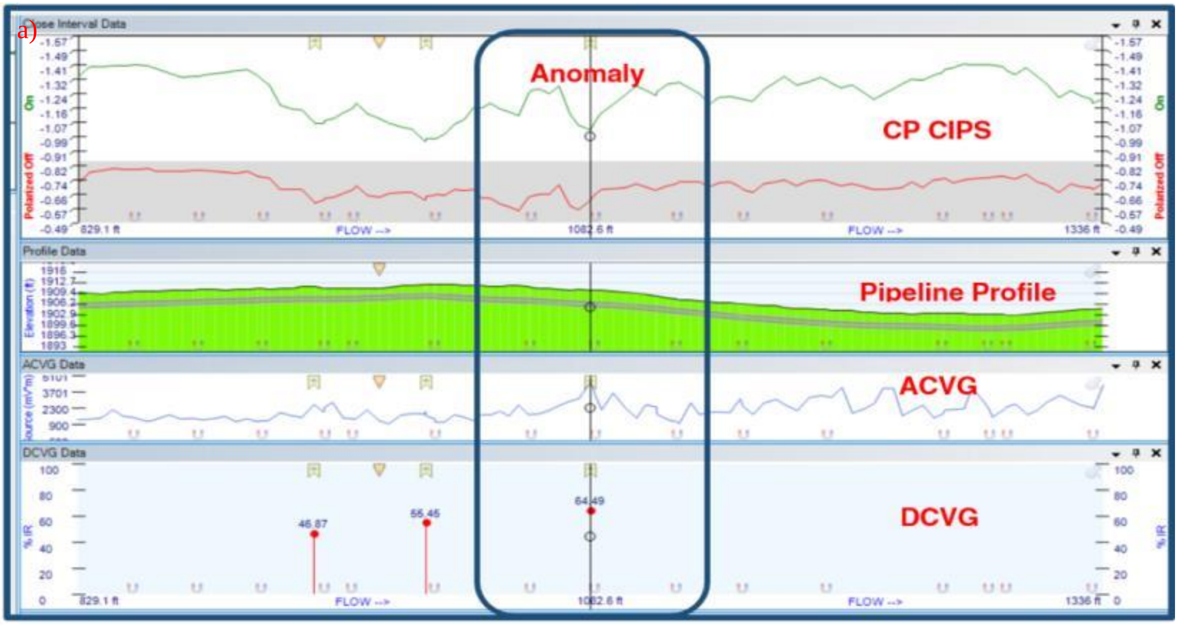
Fig. 5. a) The coating anomalies presented in the ECDA techniques and b) the same location after direct examination, validating the ECDA results [9]

Similar to the ECDA, the Internal Corrosion Direct Assessment (ICDA) techniques can, especially for inaccessible and difficult-to-pig pipelines. These ICDA techniques rely on the evaluation of pipeline profile history, and operation reports as well as validated predictive corrosion models. These techniques are based on the assumption that a lack of serious corrosion damage at initial accessible locations in the pipeline can be used to make inferences regarding the remaining downstream length of the pipeline. The applicability of these assessment techniques is dependent on the defect type. Table 3 shows different ICDA techniques and related standard guidelines. It is worth noting that in all ICDA techniques, the most susceptible location for internal corrosion is predicted and later validated along with the total metal loss using direct examination of the pipeline [10]

Table 3. Applicable ICDA techniques for different types of defects

Standard	**Type**	**Defects**
AMPP SP0116-2016	Multiphase Flow ICDA	General and localized internal corrosion attacks throughout the pipeline region
AMPP SP0110-2018	Wet Gas Internal Corrosion Direct Assessment (WG-ICDA)	General and localized internal corrosion attacks throughout the pipeline region
AMPP SP0206-2016	Dry Gas Internal Corrosion Direct Assessment (DG-ICDA)	General and localized internal corrosion attack at water accumulation sites
AMPP SP0208-2008	Liquid Petroleum Internal Corrosion Direct Assessment (LP-ICDA)	General and localized internal corrosion attack at the water and solid accumulation sites

Finally, Stress Corrosion Cracking Direct Assessment (SCCDA) techniques are used to determine the probability of SCC damage in difficult-to-pig pipelines. These techniques are also based on the previous SCC history of the pipeline, operating stress levels, distance from compressor or pump station as well as operating temperature, pipeline age and type of the coating. These historical data are then used to predict the probability and severity of SCC damage in the pipeline and their results are later verified using direct examination of the pipeline. Figure 6 shows the SCC prioritization results from the predictive models (a) and the evidence of the SCC damage used to verify the model (b) [11].



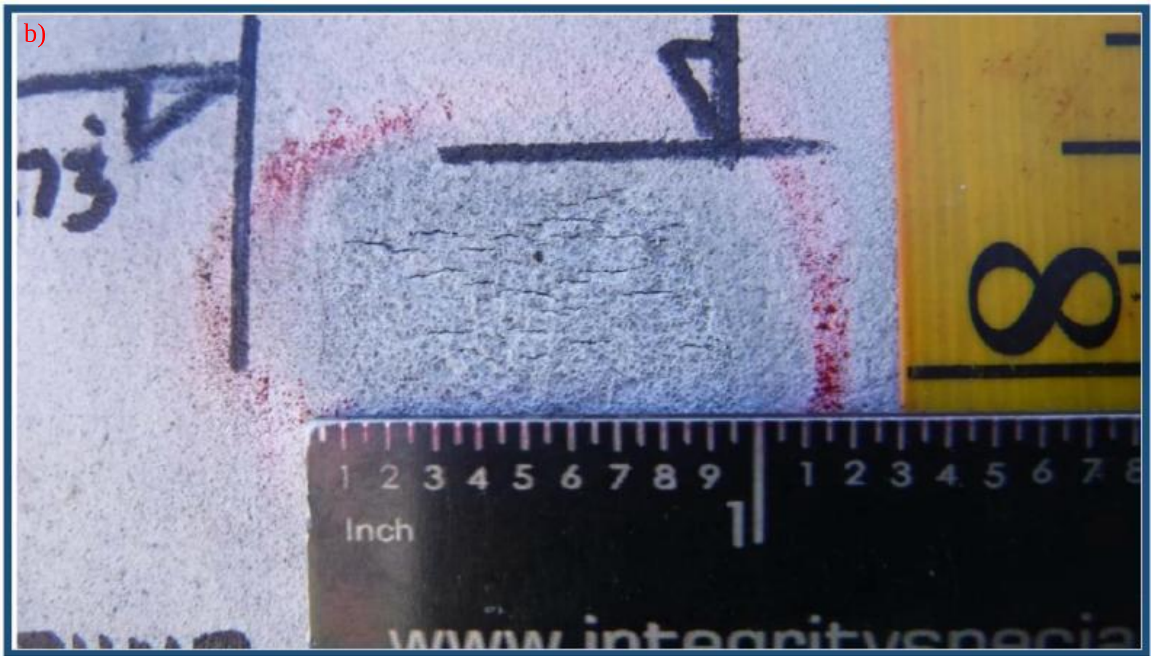
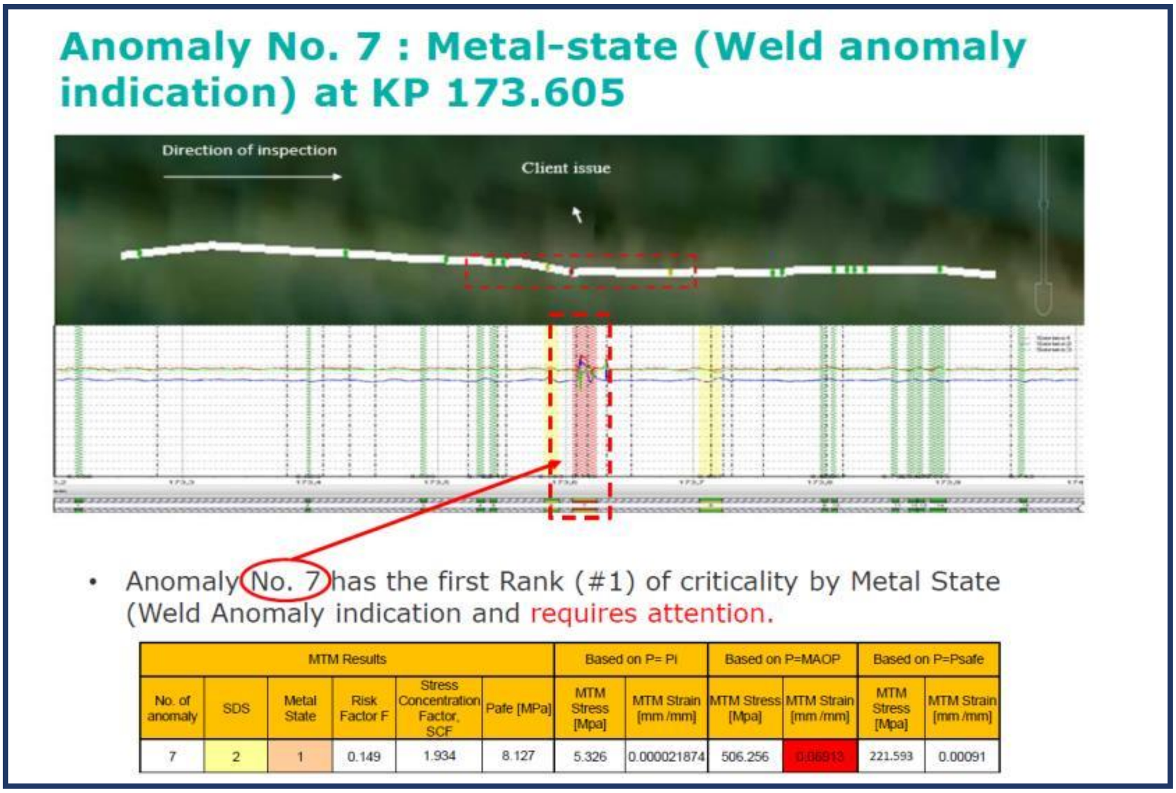


Fig. 6. a) The probable SCC location based on predictive models and b) the SCC damage uncovered at the same location after direct examination [11]

3.2. MTM-G and pipeline integrity assessment improvements

Due to the limitations of the Direct Assessment techniques mentioned above, attempts have been made to use other tools and techniques to enhance and improve direct assessment of the pipelines. The MTM-G technique is one such technique that can result in significant improvement of pipeline assessment and be used in the direct assessment methodology. It is, however, worth noting that all assessment techniques have their strengths and weaknesses, and it is imperative to select the appropriate tool for the condition. The MTM-G technique, as a direct assessment technique, can be used to evaluate the status of the pipelines and can be applied for both on-shore and off-shore pipes. Figure 7 depicts the presentation of anomaly locations based on the level of detected stress and strain.



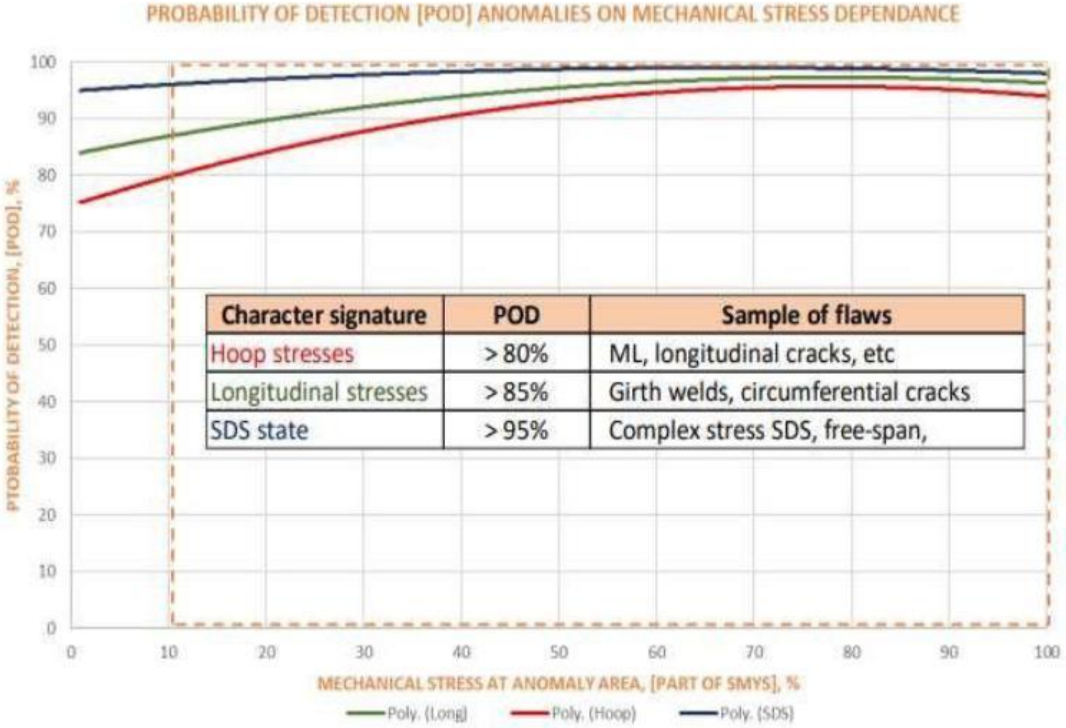
Anomaly No. 7 : Metal-state (Weld anomaly indication) at KP 173.605

- Anomaly No. 7 has the first Rank (#1) of criticality by Metal State (Weld Anomaly indication and requires attention.

MTM Results						Based on P= Pi		Based on P=MAOP		Based on P=Psafe	
No. of anomaly	SDS	Metal State	Risk Factor F	Stress Concentration Factor, SCF	Pafe [MPa]	MTM Stress [Mpa]	MTM Strain [mm /mm]	MTM Stress [Mpa]	MTM Strain [mm /mm]	MTM Stress [Mpa]	MTM Strain [mm /mm]
7	2	1	0.149	1.934	8.127	5.326	0.000021874	506.256	0.06913	221.593	0.00091

Fig. 7. Detection Anomaly with MTM-G Technology [12]

The main limitation of the MTM-G technique is that it should be used for ferromagnetic pipe materials, such that the magnetic signals used in this method are affected by the depth of the pipeline, making it unavailable for ferromagnetic pipelines buried deeper than 7 meters. It is worth noting, however, that this effective depth was improved in recent years from the initial 4 meters at the advent of this technique to the 7 meters and might be improved in the future. Furthermore, installing the MTM-G equipment on submersibles can remove the influence of the water depth for off-shore pipelines. The MTM-G technique is capable of detecting and identifying a wide range of anomalies as stated above. Furthermore, the probability of detection (POD) for the anomalies is dependent on the type of mechanical stress responsible for the signals as well as the amount of stress. Figure 8 shows the probability of detection for different types of stress anomalies versus the stress value.



Character signature	POD	Sample of flaws
Hoop stresses	>80%	ML, longitudinal cracks, etc
Longitudinal stresses	>85%	Girth welds, circumferential cracks
SDS state	>95%	Complex stress SDS, free-span,

Fig. 8. Changes in the Probability of Detection (POD) for different stress anomalies versus the mechanical stress at the anomaly area

The recent improvement in the detection algorithms used in the MTM-G technique means that this technique is capable of detecting various types of anomalies and providing an integrity summary for the pipeline. Combined with the GPS positioning data obtained through the test, this can help prioritize and classify the anomalies and report the strain on the pipeline. This information can be then used to schedule repairs or plans for direct inspections and verification of the results. Table 4 shows a summary of the MTM-G report for a pipeline as well as the assessment results.

Table 4. Summary of MTM-G assessment report for a pipeline. The metal state numbers indicate 1 for inadmissible, 2 for admissible and 3 for good (without need for repair)

Information about anomalies						Stress Concentration Factor (SCF)	Nomila WT (mm)	Metal loss assessment	
No.	Metal Conditions	Risk Factor F	KP Start (m)	KP End (m)	Length (m)			Metal loss (% of WT)	Remaining thickness (mm)
1	2	0.290	157.9	161.4	3.6	1.763	5.2	43.29	2.93
2	2	0.442	226.6	230.3	3.4	1.516	5.2	34.02	3.40
3	2	0.355	252.1	256.6	4.5	1.622	5.2	38.34	3.18
4	2	0.280	348.8	351.1	2.3	1.853	5.2	46.02	2.79
5	1	0.161	360.5	368.9	8.4	1.912	5.2	47.7	2.70
6	2	0.311	464.3	472.0	7.6	1.630	5.2	38.64	3.17
7	1	0.113	504.8	509.3	4.6	2.172	5.2	53.95	2.38
8	1	0.176	511.6	513.6	2.1	2.126	5.2	52.97	2.43
9	3	0.635	567.3	570.4	3.0	1.297	5.2	--	--
10	2	0.510	645.5	547.0	1.5	1.512	5.2	33.86	3.41

Combining the MTM-G technique with the Inline Inspection (ILI) techniques can help provide a significant amount of data regarding the integrity of the pipelines. The MTM-G technique provides mechanical stresses present in the pipeline including hoop, longitudinal com complex stress combinations such as bending and sheer stresses; while the inline inspection is more suitable for detecting physical and geometrical anomalies. Therefore, the MTM-G technique can be used to get an overview of the pipeline before using ILI techniques to inspect the suspected defective areas. An integrated approach using MTM-G stress assessment and ILI detection information can help with making informed decisions regarding repair and maintenance schedules. Additionally, the location of pigs stuck in the pipeline can be detected with a high level of precision using the MTM-G technique. Improvements in the MTM-G detection algorithms have also made this capability that although this technique does not directly measure the metal loss of corrosion features on the pipeline, however, the projected metal loss values obtained from stress analysis algorithms are comparable to the values determined after direct inspection by ILI techniques. In this regard, Figure 9 shows a comparison between metal loss values determined using the MFL technique and projected values obtained by the MTM-G technique. As can be seen, these values are comparable with one another, with the MTM-G projected values being slightly higher, making this technique a suitable technique with an acceptable margin of safety for evaluating pipeline integrity.

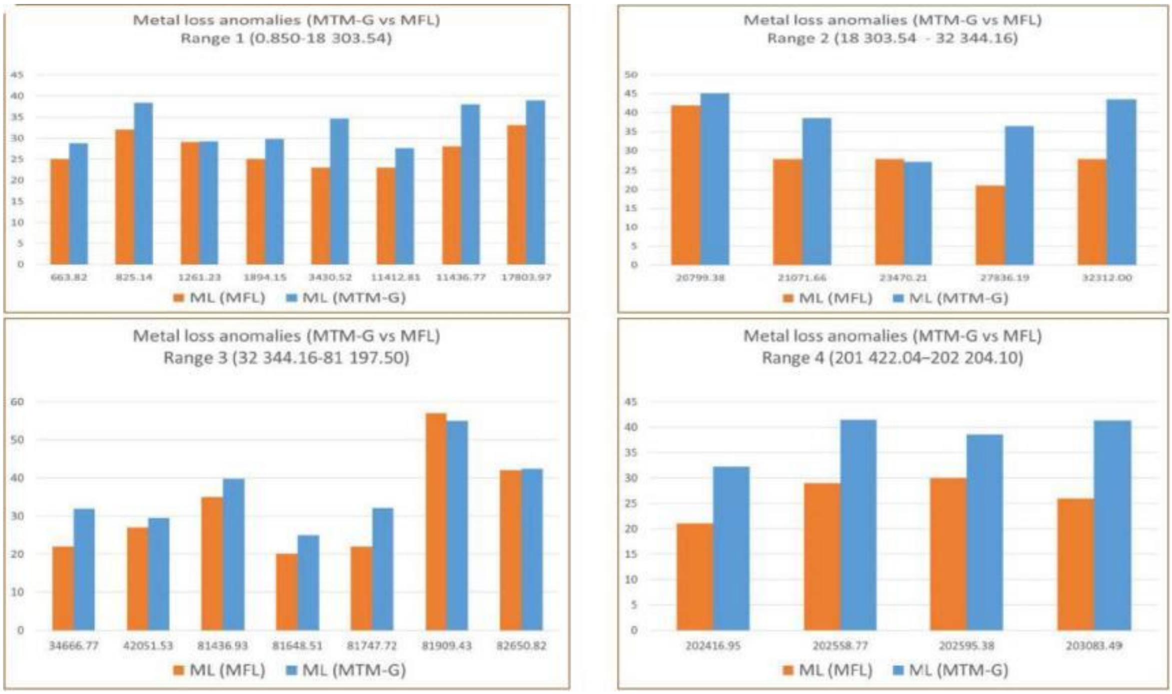


Fig. 9. Comparison between metal weight loss values measured using the MFL technique and projected using the MTM-G technique [12]

4. Conclusion

- Based on preliminary findings regarding the detection of external corrosion cracks and projected metal loss using the MTM-G technique, this technology can help improve pipeline integrity assessments in the Direct Assessment methodology and increase the confidence of assessments for unpiggable pipelines.

- Results from real-life case studies using MTM-G have shown this technique's strong capabilities in the identification and characterization of external metal loss and cracks which, when combined with other assessment methods, help prioritize areas of concern.
- An integrated approach combining ILI and MTM-G techniques can significantly enhance pipeline integrity assessment for critical pipelines requiring urgent attention. This integrated approach can help make informed decisions regarding pipeline operations and maintenance schedules and can facilitate risk assessment by pipeline operators.

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References

[1] AMPP Direct Assessment Course Training, AMPP 2016, Houston, TX; AMPP

[2] Xu, T. (2018). Understanding quantitative performance of large standoff magnetometry in detecting live gas pipeline anomalies with stress estimation. In International Pipeline Conference (Vol. 51869, p. V001T03A020). American Society of Mechanical Engineers.

[3] McDonnell, S., Onuoha, C., Pozniak, E., & Shankar, V. (2018). Identifying stress concentrations on buried steel pipelines using large standoff magnetometry technology. In International Pipeline Conference (Vol. 51869, p. V001T03A003). American Society of Mechanical Engineers.

[4] McDonnell, S., Tolentino, J., Onuoha, C., Paulson, P., Pozniak, E., Wegner, M., ... & Sim, W. (2017). Improved Methodology for Identification of Buried Casings using Indirect Inspection Method. In NACE CORROSION (pp. NACE-2017). NACE.

[5] Onuoha, C., McDonnell, S., Pozniak, E., Shankar, V., & de Guzman, L. (2018). Advancements in stress corrosion cracking direct assessment using an integrated approach. In NACE CORROSION (pp. NACE-2018). NACE.

[6] Onuoha, C., Pozniak, E., McDonnell, S., Shankar, V., Lich, T., & Jawed, M. (2020). Use of large standoff magnetometry in pipeline integrity investigations. In NACE CORROSION (pp. NACE-2020). NACE.

[7] Liu, L., Yang, L., & Gao, S. (2022). Propagation Characteristics of Magnetic Tomography Method Detection Signals of Oil and Gas Pipelines Based on Boundary Conditions. Sensors, 22(16), 6065.

[8] Onuoha, C., Pozniak, E., Shankar, V., & White, C. Innovative Overline Survey Techniques for the Water and Wastewater Industry. In Pipelines 2021 (pp. 336-345).

[9] Onuoha, C., Pozniak, E., McDonnell, S., Shankar, V., de Guzman, L., & Jawed, M. (2020). Process Improvements in Direct Assessment Programs. In NACE CORROSION (pp. NACE-2020). NACE.

[10] Onuoha, C., Pozniak, E., McDonnell, S., Shankar, V., de Guzman, L., & Li, H. (2021). Optimization of Internal Corrosion Assessments in Crude Oil Pipelines with Internal Corrosion Predictive Model. In NACE CORROSION (p. D091S037R001). NACE.

[11] Onuoha, C., McDonnell, S., Pozniak, E., & Shankar, V. (2019). Integrity Assessment Case Studies of Time-Dependent Threats. In NACE CORROSION (pp. NACE-2019). NACE.

[12] C. Chukwuma, D. Onuoha, D. Nnamdi, AMPP Conference 2024, pp. C2024-20874, 2024, New Orleans, Louisiana,