Addressing Dents in Difficult-to-Inspect Natural Gas Pipelines: Enhancing Safety and Integrity with Robotics, Laser Technology, and Advanced Analytics

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Abstract

The identification and management of dents, mechanical damages, and deformations remain a persistent challenge for pipeline operators. In addition to excavation and visual inspection, in- line inspection (ILI) is typically required to accurately detect and assess the size of dents. To appropriately manage risk, Enbridge Gas Inc. (Enbridge Gas Ontario) initiated targeted assessments on a select subset of distribution pipelines to obtain detailed insights into the pipeline's overall health. Many of these pipelines, located in both urban and agricultural areas, are particularly vulnerable to third-party damage.

This paper will explore the process of selecting and executing in-line inspection tools, with a focus on the integrity results derived from the Intero Laser Deformation Sensor (LDS), integrated into the Pipe Explorer robotic crawler fleet. The laser-based system offers a high-resolution dataset by projecting a continuous laser ring inside the pipeline. This technology enables the profiling of dents with complex geometries, such as multi-apex and skewed dents, and supports advanced processing techniques, including strain analysis in accordance with the ASME B31.8 standard.

Introduction

The prospect of constructing new pipelines or replacing existing ones is becoming increasingly challenging. In addition to the significant cost implications, these efforts are often hindered by public opposition, economic / environmental policy shifts, such as the push for net zero & growing municipal gas bans on new developments across North America[1], and other factors. As the existing pipeline infrastructure continues to age, pipeline operators are actively seeking ways to assess and safely extend the lifespan of their assets. In collaboration with regulators, pipeline integrity management programs are continuously evolving to ensure the safe, reliable, and cost-effective transportation of product through these critical networks.

Although not required by governing regulations, Enbridge Gas Ontario has implemented a targeted integrity program that incorporates in-line inspection (ILI) for its distribution pipelines in Ontario, Canada, with a focus on risk-based prioritization. The risk assessment inputs and approach used for prioritization are regularly monitored and adjusted based on the latest pipeline health data and findings. Over the last decade, Enbridge Gas Ontario has been utilizing Intero's robotic in-line inspection (ILI) services to conduct targeted integrity assessments of its difficult-to-inspect (DTI) assets.

This paper will review the assessment process and results from 2024 inspections, concentrating on dent identification, sizing, and strain analysis.

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[1] Alex Robinson. (2024, May 6). Despite backlash, bans on gas use in new buildings keep spreading. Retrieved from Corporate Knights: https://www.corporateknights.com/buildings/gas- ban-us-backlash/

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Enbridge Gas Ontario

Enbridge Gas Ontario is Canada's largest natural gas storage, transmission and distribution company based in Ontario, with 2023 marking its 175th anniversary of serving customers. The distribution business provides safe, affordable, reliable energy to about 3.9 million customers. The storage and transmission business offers a variety of storage and transportation services to customers at the Dawn Hub, the largest integrated underground storage facility in Canada and one of the largest in North America.

In 2024, Enbridge Gas Ontario looked to perform targeted ILI assessments on select assets in Southern Ontario, Canada. The pipelines selected consisted of NPS 8, NPS 10 and NPS 12 diameters mostly installed between the 1940's – 1960's, with varying wall thicknesses and material properties. The threat potentials included external corrosion, construction related, and third-party mechanical damage including dents and deformations. These pipelines are situated in urban and agricultural settings. Varying depth of cover and continuous agricultural land management increases the risk of potential interaction and mechanical damage. In urban settings, the pipelines typically maintain an increased depth of cover, however, the risk of mechanical damage is maintained due to potential interaction from installation and maintenance of adjacent buried utilities, and other construction activities.

These pipelines were classified as difficult to inspect (DTI) due to several challenges, including:

- The absence of existing launchers and receivers
- Limited availability of historical construction records
- The potential presence of restrained or unrestrained mechanical couplings, as well as other un-piggable features, such as in-service bypasses, spherical tees, and bottom-out fittings

Difficult to Inspect

Difficult to inspect pipelines contain compounding challenging attributes which may prohibit the assessment using conventional free-swimming ILI technology:

- The infrastructure is inadequate, as there is no existing launcher or receiver, and there is a lack of sufficient space to accommodate a permanent installation.
- Restrictive operating conditions, including low or absent flow and insufficient pressure, significantly hindering the feasibility of free-swimming technology.
- The absence or incompleteness of pipeline records elevates the risk associated with the use of free-swimming technology, potentially compromising safety and operational efficiency.
- The presence of various obstructions, such as fittings and installations (including drips, unbarred tees, short-radius or miter bends, valves, diameter changes, and similar elements), can significantly impede the flow and integrity of the pipeline system.

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Prior to ILI, Enbridge Gas Ontario's integrity program included cathodic protection surveys such as Close Interval Potential Survey (CIPS), Direct Current Voltage Gradient (DCVG), and Depth of Cover (DOC).

In 2024, Enbridge Gas Ontario aimed to assess a minimum of 6 miles (10 kilometers) of pipeline to create a statistically significant sample that could be integrated into their risk assessment. The goal was to achieve this assessment without disrupting the flow or requiring pipeline outages for modifications. Intero's Pipe Explorer robotic crawlers were selected for this task, as they are not constrained by the difficult-to-inspect (DTI) attributes mentioned earlier. Additionally, these robotic crawlers can operate under live pressure and flow conditions, ensuring no downstream impact during the inspection process.

Intero's Pipe Explorer Robotic ILI

Intero's Pipe Explorer robotic crawlers have been inspecting challenging pipelines since 2011, following years of development and investment led by NYSEARCH, and the Northeast Gas Association.[2] The Pipe Explorer robots are tetherless, self-propelled, bidirectional, and can launch and receive through a size-on-size hot tap fitting. The robots bypass 50% flow, while collecting magnetic flux leakage (MFL), laser deformation (geometry), and video data in live pressure and flow conditions.

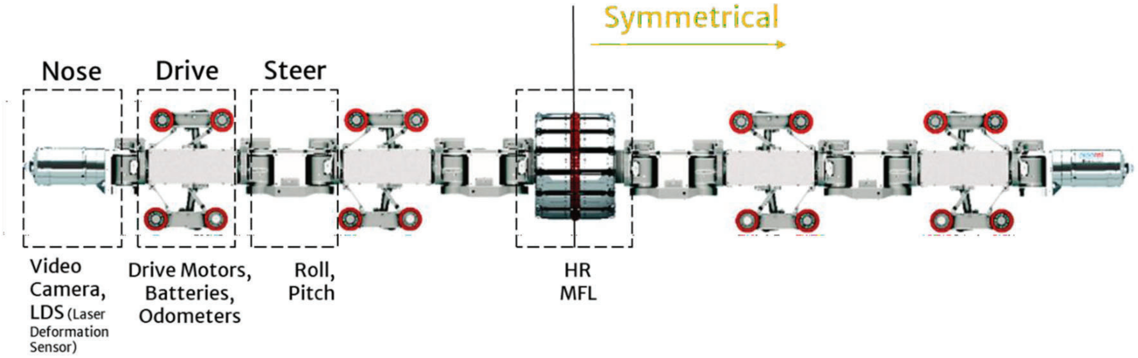

Figure 1. General anatomy of Pipe Explorer

The Pipe Explorer robots retain similar anatomy (Figure 1) across the fleet and can inspect pipelines from NPS 6 through NPS 36 in diameter. The center of the robot carries the MFL sensors. This sensor can be controlled and manipulated to collapse and de-magnetize to allow for the negotiation of challenging bends and mechanical features, including 90-degree miter bends and un-barred tees. The drive modules expand and contract to push against the pipe wall and create traction for the robot to drive upstream or downstream of the pipe. The steer modules roll and pitch to accommodate challenging bend groups and mechanical features.

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[2] Commercial Applications. (n.d.). Retrieved from NYSEARCH: https://www.nysearch.org/commercial_products.php

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The noses, located on the front and rear of the robot, transmit a real-time video stream to the operator as well as capture deformation data with the Laser Deformation Sensor (LDS).

The laser deformation sensor projects a laser ring on the inside of the pipe, as seen in Figure 2. Any deflections from nominal are detected and sized accordingly, producing length, width, and depth parameters. Unlike conventional gauge tools which use discrete mechanical fingers to sweep along the surface of the pipe, LDS is contactless and maintains a continuous laser arc allowing for higher circumferential resolution.

Figure 2. Laser Deformation Sensor (LDS) inside open pipe

The Pipe Explorer robots are battery powered and can also be recharged using In-Line Charging (ILC) technology to extend the inspection range.

Methodology

Robotic ILI

Size-on-size hot tap fittings (such as TDW Stopples or Mueller Line Stoppers) installed near regions of interest allow for robot entry and exit points. The Pipe Explorer robots can inspect approximately 3,200ft (1km) of pipe around each entry point (without in-line-charging).

The fitting locations for a NPS 12 pipeline were selected by Enbridge Gas Ontario following the schematic in Figure 3.

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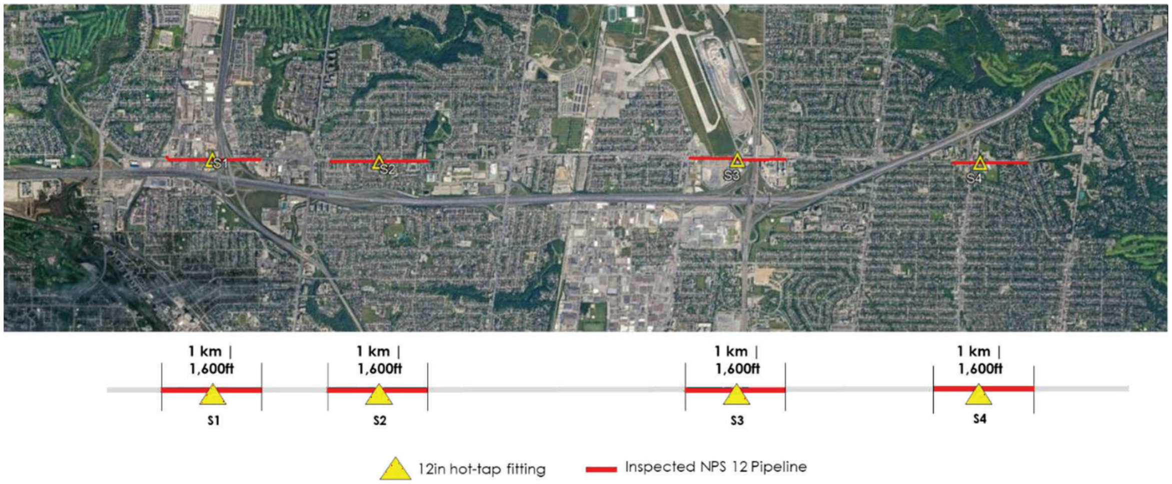

Figure 3. Hot tap fitting placement for robotic ILI inspection

This inspection methodology was also applied to the additional NPS 8, NPS 10, and NPS 12 pipes in Southern Ontario, Canada, using respective size on size hot tap fitting locations.

Dents and Dent Strain Analysis

Dents are the result of mechanical damages caused by external forces applied on a pipeline.

Dents are permanent and plastic deformations and can be further categorized as smooth (smooth change in curvature), kinked (abrupt change in curvature), plain (smooth dent without wall thickness reduction or interaction with seam or girth weld) [3], unconstrained (free to rebound / re-round when indenter removed), and constrained (not free to rebound / re-round as indenter remains present e.g. rock dent). [4] Dent severity can be approximated by curvature strain models, such as that outlined in ASME B31.8 (2018). By assessing the curvature strain of the damaged plastic region and comparing it to the material strain limit, the possibility of indentation cracking can be evaluated.[5] Dent strain values can quantify risk of failure, prioritize repair, or allow for further monitoring.

The axial and circumferential planes produced from ILI geometry data, are used to analyze maximum equivalent strain at each dent. The following strain components are considered:

- Axial Membrane
- Axial Bending
- Circumferential Membrane
- Circumferential Bending

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[3] Pipeline Operators Forum. (2021). Specifications and requirements for in-line inspection of pipelines. Retrieved from https://pipelineoperators.org/documents

[4] Andrew Cosham, Phil. Hopkins. (2003). The Effect of Dents in Pipelines – Guidance in the Pipeline Defect Assessment Manual. Proceedings ICPVT-10. Vienna, Austria.

[5] Brian Leis, A. A. (2023). Dent strain and stress analyses and implications concerning PIRP 1183. *Journal of Pipeline Science and Engineering*, 2.

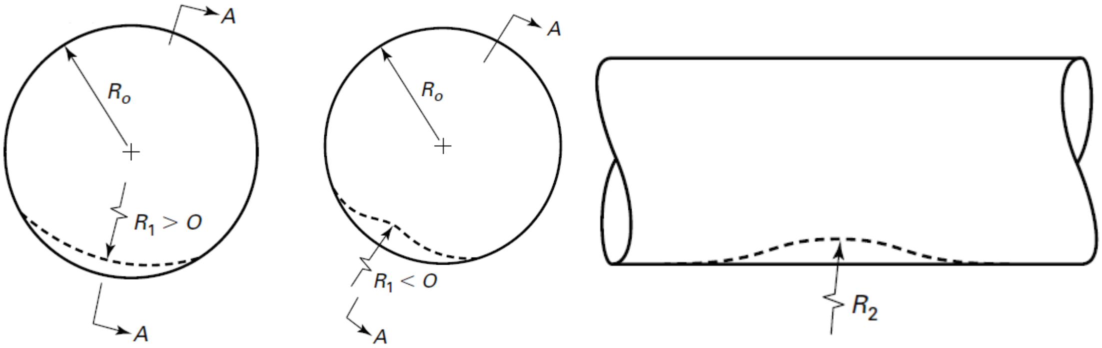

Figure 4. Dent strain components along pipe wall[6]

Strain parameters (illustrated in Figure 4) and calculations are defined through ASME B31.8[6]:

a) Circumferential Bending Strain: $\varepsilon_1 = \left(\frac{1}{2}\right) t \left(\frac{1}{R_0} - \frac{1}{R_1}\right)$

b) Longitudinal Bending Strain: $\varepsilon_2 = -\left(\frac{1}{2}\right) t \frac{1}{R_2}$

c) Extensional Longitudinal Strain $\varepsilon_3 = \left(\frac{1}{2}\right)\left(\frac{d}{L}\right)^2$

d) Inside pipe surface Strain $\varepsilon_i = \sqrt{\varepsilon_1^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2}$

e) Outside pipe surface Strain $\varepsilon_o = \sqrt{\varepsilon_1^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2}$

R_0 is the nominal pipe surface radius
R_1 is the circumferential radius of curvature in the dent
R_2 is the axial radius of curvature in the dent
t is the wall thickness
d is the dent depth
L is the dent length

Prior to processing ILI data, advanced filtering is applied to reduce noise while retaining the original dent profile. The accuracy of the results is proportional to the quality of the geometry data. Less variability and noise and higher circumferential resolution allows for increased accuracy.

Enbridge Gas Ontario requested dent strain analysis to be performed on sharp dents defined as L/d <20.

Robotic ILI Execution

Hot tap fittings were installed at each designated location. Once ready for inspection, Intero's temporary launcher was erected, robot loaded into the barrel, equalized, and launched. The launch & receive setup is shown in Figure 5 & Figure 6. Intero operators controlled the Pipe Explorer robot to inspect 1,600ft (500m) out, and then return to the stopple fitting. Each inspection day, an additional 1,600ft (500m) of data was collected. This was repeated for 24 inspection days through

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[6] The American Society of Mechanical Engineers. (June 1, 2010). *Gas Transmission and Distribution Piping Systems, ASME B31.8-2010*

the spring & summer of 2024, inspecting a combined ~7 miles (11.3km) of NPS 8, NPS 10, and NPS 12 pipelines.

Figure 5. NPS 12 launch and receive site with Intero temporary launcher | Rural site

Figure 6. NPS 12 launch and receive site with Intero temporary launcher | Urban site

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Results

The results will focus on examples accumulated through the 2024 Robotic ILI execution. Each sharp dent profile was evaluated for equivalent dent strain. These dents are summarized in the Table 1 below:

Table 1. Summary of select dent sizing and dent strain

Name	Orientation (hh:mm)	Length mm in	Width mm in	Depth (%OD)	WT mm in	Sharpness L/d < 20	Max Eqv. Strain (%)
D001	10:50	129.5 5.10	60.8 2.39	3.5	5.56 0.219	13.6	2.9
D002	06:18	127.9 5.04	81.0 3.19	2.6	6.80 0.267	13.0	4.7
D003	08:26	76.1 3.00	82.1 3.23	1.7	5.56 0.219	16.4	3.1
D004	05:21	40.8 1.61	59.1 2.04	1.5	7.00 0.276	10.0	5.9

D001

Figure 7 illustrates a video screenshot alongside the laser profile of dent D001 the inside of a NPS 10 pipe with a nominal curvature overlayed (dotted red). At 3.5% depth, the dent is subtly visible through the camera at the ~11:00 position. The laser profile data is processed to output circumferential ID measurements represented in a heatmap scale. The axial sample resolution is set to 0.05in (1.27mm). The processed heatmap output is displayed in the Figure 8. In D001, the 3.5% depth dent is outlined in turquoise. The dotted purple boxes represent other adjacent dents which were identified and sized in the same manner. These dents span from the 11:00 to 3:00 position.

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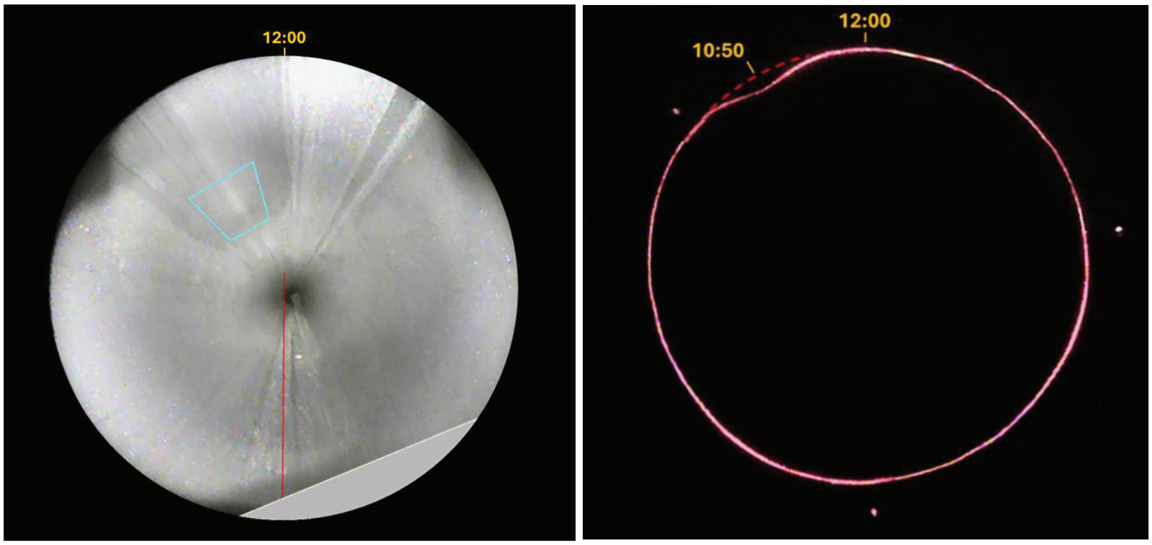

Figure 7. D001, NPS 10, 3.5% depth | Dent visible through video & profile outlined by LDS

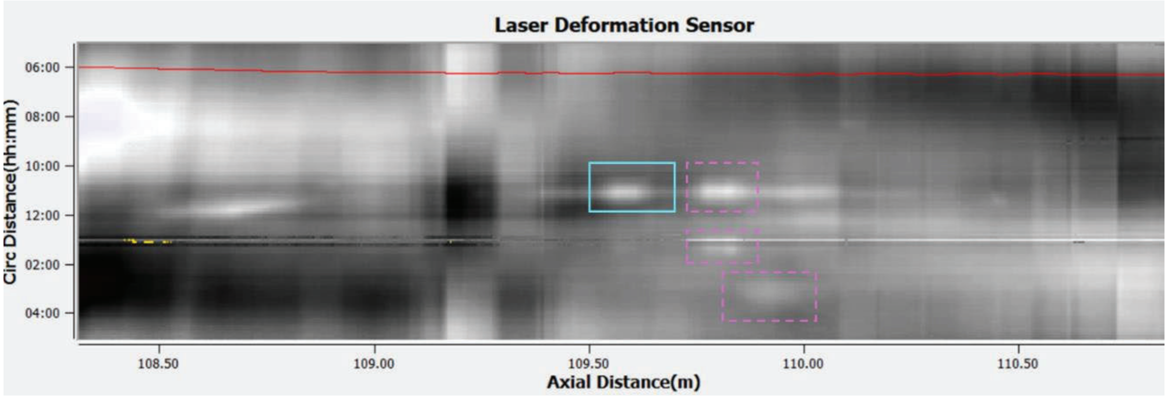

Figure 8. D001, NPS 10, 3.5% depth | Laser Deformation Sensor data

The dent strain was analyzed based on the methodology outlined by ASME B31.8. ID/OD equivalent strain was calculated at each axial sample along the dent. Maximum equivalent dent strain, (largest ID/OD strain) was calculated to be 2.9%.

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D002

D002 was estimated to be 5in x 3.2in (128mm x 81mm) (L x W), and a dent depth of 2.6%. Figure 9 illustrates the MFL (top) and LDS data (bottom). The magnetic signature of the dent is visible as the MFL sensor is disturbed while traversing the dent region. MFL data can be used as a dent detection redundancy, however, the data cannot be used for determining the dimensions of the dent.

The dent profile outlined in the LDS data is more subtle when compared to MFL (2.9% dent depth represented on heatmap scale). A close-up view of the box with high contrast is visible on the right corner of the figure. The circumferential profile across the single axial sample is included under the signature (blue dash). This output shows a consistent, low-noise profile minimizing the requirement of filtering / smoothing for dent strain analysis. The maximum equivalent strain was calculated to be 4.7%.

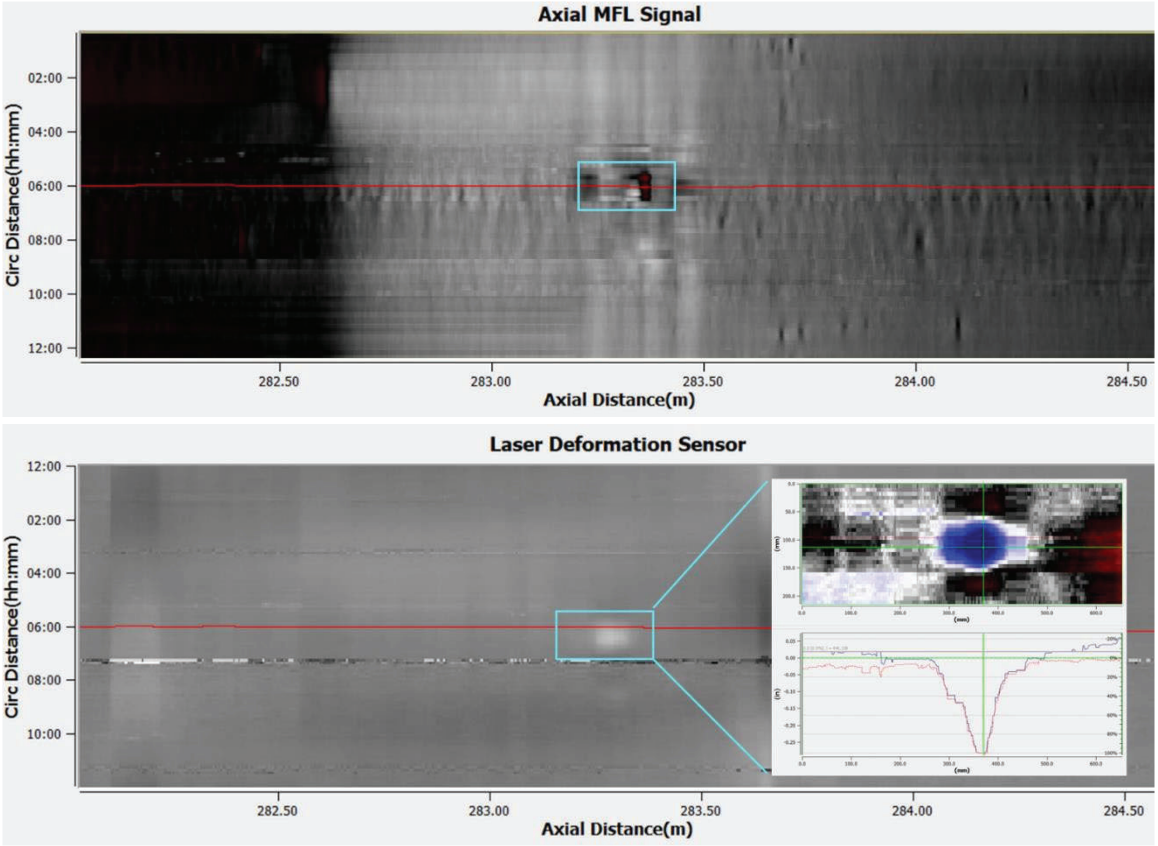

Figure 9. D002, NPS 10, 2.6% depth | MFL & Laser Deformation Sensor data

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D003

D003 was sized at 3in x 3.2in (76mm x 82mm) (L x W), and a dent depth of 1.7%. As visible in the MFL and LDS plots in Figure 10, the dent is skewed and multi-apex. Dent strain analysis calculated a maximum equivalent strain of 3.1%.

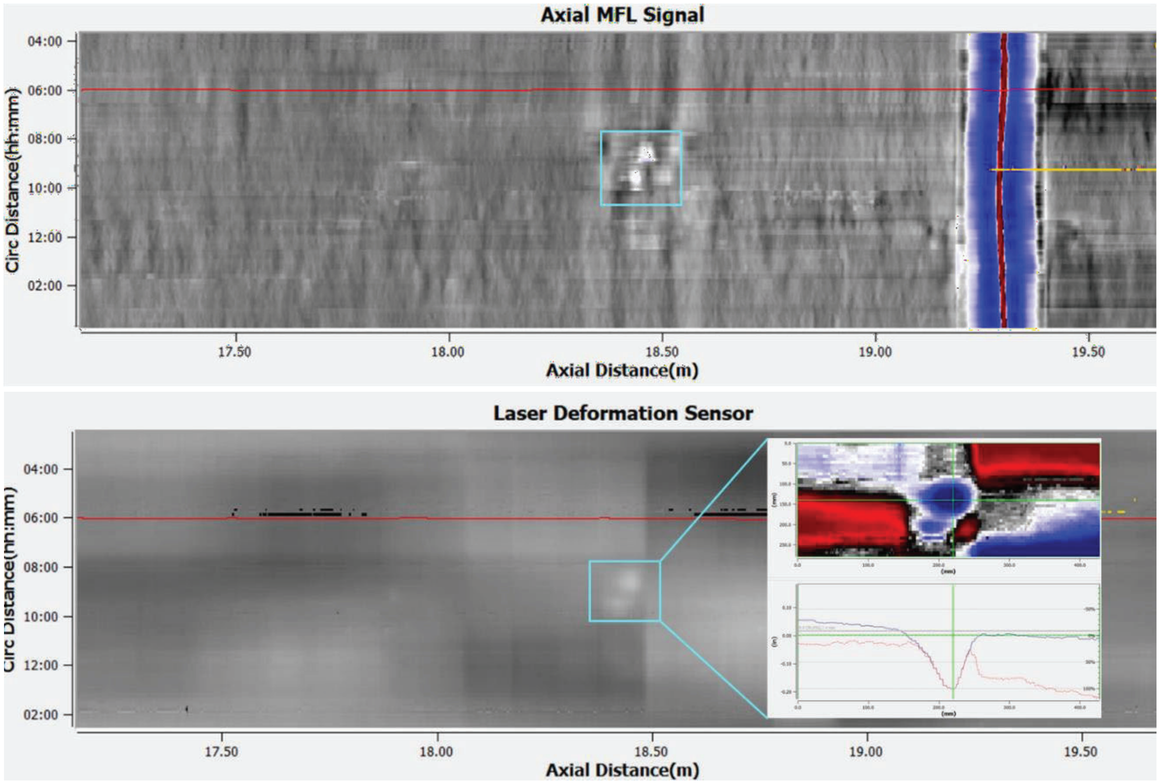

Figure 10. D003, NPS 10, 1.7% depth | MFL & Laser Deformation Sensor data

D004

D004 was sized at 1.6in x 2in (41mm x 60mm) (L X W), 1.5% deep, and located near 05:30 orientation. The dent is not easily discernible in the video (Figure 12). The video screenshot was taken on the return inspection back towards the stopple. The striations on the pipe surface are from the outbound travel of the centering wheels of the MFL sensor. The red line indicates gravity 06:00. The dent is visible in the MFL plot, as well as the LDS plot (Figure 11). The dent was located near the 06:00 position of the pipe suggesting that it may have been formed during the construction / installation phase. Although shallow at 1.5% depth, the maximum equivalent strain was calculated to be 5.9% - the highest from the sample group examined in this paper.

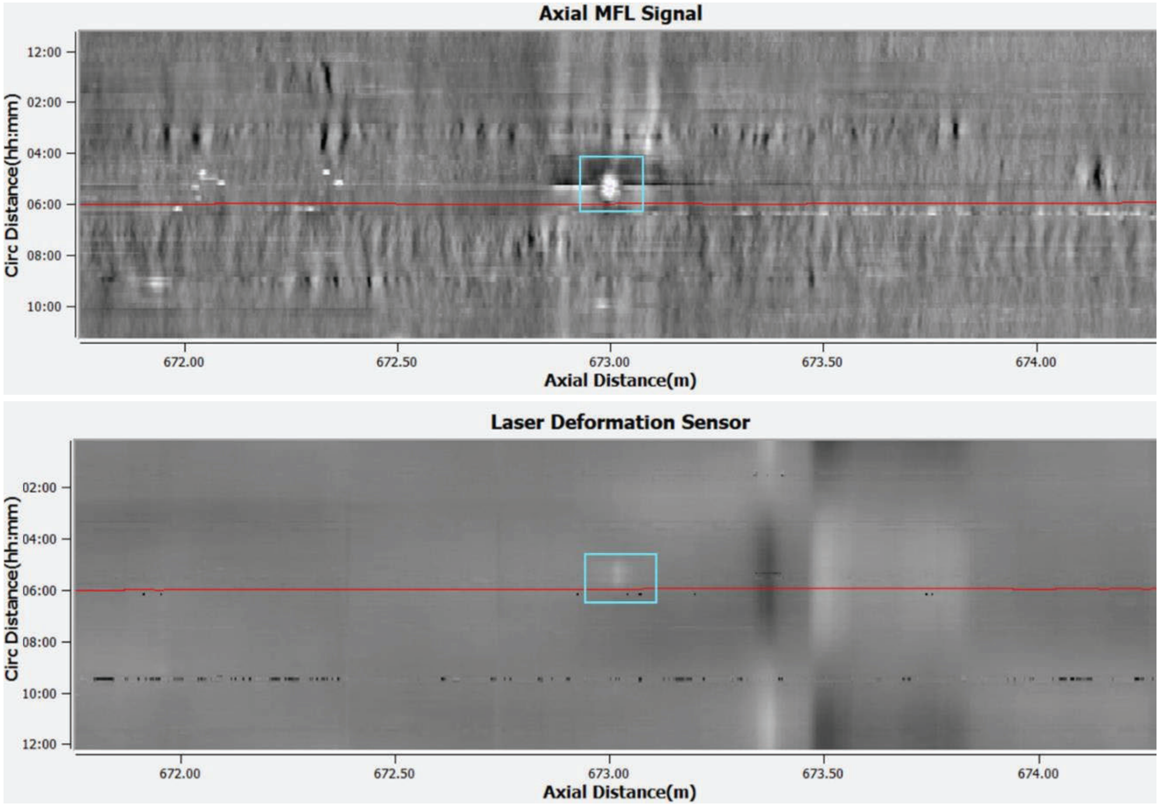

Figure 11. D004, NPS10, 1.5% depth | MFL & Laser Deformation Sensor data

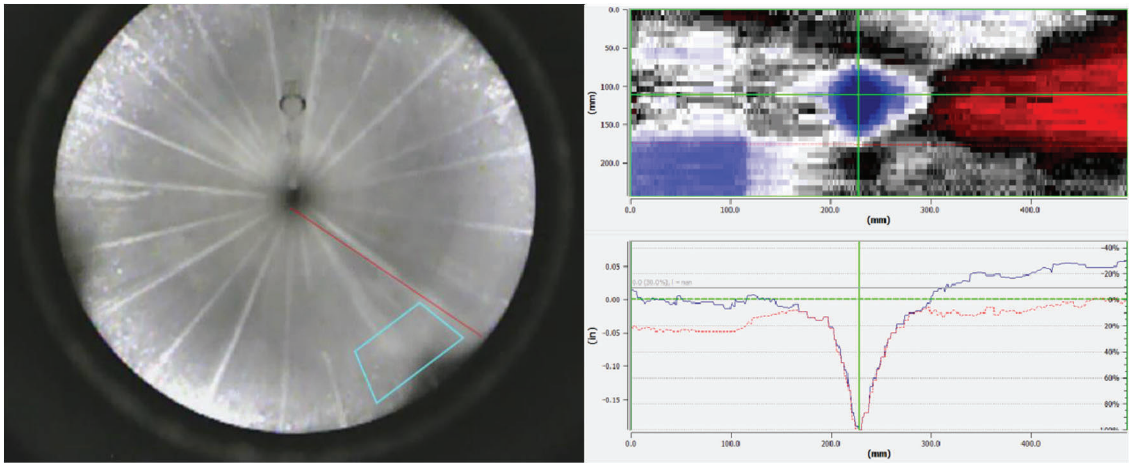

Figure 12. S2 D004, NPS10, 1.5% depth | Video Screenshot & LDS Profile

Action Items

No dents reported met immediate action criteria. The ILI data, including the dent strain figures, will be used to update the risk assignment. Enbridge Gas Ontario continues to monitor all indications and establish the necessary requirements moving forward.

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Summary

Enbridge Gas Ontario continues to collect targeted information of their distribution pipelines to properly manage the risk and integrity of their assets. Through robotic in-line inspections, corrosion (MFL), dent/deformation (LDS), and video data were obtained for a cumulative ~7 miles (11.3 km) of pipelines in Southern Ontario, Canada, ranging from diameters of NPS 8 to NPS 12. These difficult-to-inspect pipelines were inspected using Intero's Pipe Explorer robots, without interrupting gas service. The robots entered and exited the pipe through size-on-size hot tap fittings and inspected 3,200ft (1 km) around each hot tap.

Alongside metal loss indications, dent sizing (length, width, depth) and strain analysis were performed on all sharp dents, including skewed & multi apex. The maximum equivalent dent strain percentage is valuable in gauging and ranking dent volatility. The results from the ILI data shape and adjust risk assessment & prioritization.

The in-line inspection (ILI) data enables Enbridge Gas Ontario to make informed, data-driven decisions that enhance the safety and longevity of their pipeline network. This paper also demonstrates the effectiveness of the laser deformation sensor in detecting and estimating third-party damages to pipelines. Unlike traditional mechanical sensors, which may be limited by spacing, the laser deformation sensor provides a higher-resolution profile of dents. This improved resolution enhances the accuracy of subsequent advanced analyses, such as strain assessment, leading to more precise evaluations of pipeline integrity.

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