Development of Dual Field Magnetic Flux Leakage (MFL) Inspection Technology to Detect Mechanical Damage

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The Pipeline Research Council International, Inc. (PRCI), in coordination with Battelle Memorial Institute – Columbus Operations (Battelle) and Rosen Inspection, has completed a research project entitled "Development and Testing of Dual-Field Magnetic Flux Leakage Inspection Technology to Detect Mechanical Damage." This research project is part of a "Consolidated Research & Development Program on In-Line Inspection Technologies for Mechanical Damage Detection", which was completed in collaboration with the United States Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT PHMSA) under contract DOT Project DTPH56-06-T-000016.

Executive Summary

This report details the development and testing of a dual magnetization in-line inspection (ILI) tool for detecting mechanical damage in operating pipelines, including the first field trials of a fully operational dual-field magnetic flux leakage (MFL) ILI tool. Augmenting routine MFL corrosion inspection of pipelines using high magnetic fields, this in-line inspection technique detects and assesses mechanical damage using a second lower magnetic field.

Nearly all commercially available MFL tools use high magnetic fields to detect and size metal loss such as corrosion. A lower field than commonly applied for detecting metal loss is appropriate for detecting mechanical damage, such as the metallurgical changes caused by impacts from excavation equipment. The lower field is needed to counter the saturation effect of the high magnetic field, which masks and diminishes important components of the signal associated with mechanical damage. At low fields, other properties such as pipeline chemical composition, grain structure, and fabrication methods can also be detected.

The high and low magnetic field level provides two signals that can, with proper interpretation, increase safety and reduce operational cost. Application of this technology will detect and provide data on shallower dents (i.e., less than 2% of the pipe diameter) with potentially service limiting secondary features such as cold working and gouging that may not be detected with standard deformation tool analysis. The dual magnetization approach also provides indications of residual stresses associated with re-rounding of the dented region, either immediately after impact (removal of the indenting feature) or from pressure cycling associated with standard pipeline operations. The method can also provide valuable information on deep dents; if these anomalies do not have any secondary features or residual stresses associated with dent re-rounding which could potentially cause a leak or rupture, unnecessary excavation and evaluation can be avoided.

The dual field inspection technology was successfully transferred from a research and development prototype to a commercial in-line inspection company. This involved configuring a pair of pipeline ready MFL magnetizers with the appropriate sensors and data recording equipment as well as implementing data analysis algorithms. The commercial tool was initially tested using pull testing under controlled conditions to ensure tool performance matched previous results. Following the pull tests and confirmation of the dual-field MFL tool performance, two operating pipeline segments were inspected and field excavations were performed for direct examination of mechanical damage features identified to confirm technology performance.

The commercial implementation of the dual field technology was used on two 30-inch diameter operating pipelines, one liquid and the other natural gas. The analysis method sorted through nearly 500 dents on the two pipelines, with only a few indicating the potential for mechanical damage. For the first pipeline, thirteen excavations were performed and eighteen anomalies were examined. No visual signs of excavator damage were found; the source of the damage was attributed to rocks for most of the anomalies. Three of the anomalies had metal loss range from 3% to 9% of the wall thickness. One anomaly had minor gouging from a rock. These results enabled the calibration of the analysis algorithms. For the second line, two excavations were performed; one at a location with gouging expected, the other excavation was at a dent with

similar depth but no secondary features identified by the dual field tool. There was a gouge confirmed first excavation based on the in ditch data and no gouge reported for Dent 2, consistent with the ILI tool run results.

The results of the project confirm the performance capabilities of dual-field MFL ILI technology for detecting mechanical damage in operating pipelines. The use of a dual magnetization approach allows for the identification of secondary features and changes in pipe material and metallurgical properties that may not be provided by standard geometry/caliper tools or single field, high magnetization MFL. The development of dual-field MFL ILI technology provides the pipeline industry with a broader range of tools for pipeline inspection when mechanical damage is identified as a threat to be addressed as part of an integrity management plan. Continued development and improvements in pipeline inspection technologies will support decisions on repair, remediation and rehabilitation of mechanical damage and other features and improve pipeline safety.

Inspection of pipeline systems requires an integrated approach that includes the use of non-destructive examination (NDE) methods, techniques, and technologies for direct examination of features on pipelines that are identified using ILI tools. This project included verification of the performance of the dual-field MFL technology for detecting mechanical damage and its related effects on the pipeline using emerging in ditch technologies. The technologies included those being funded and supported through separate collaborative efforts of PRCI and DOT, such as the MWM technology. Additional parallel work on calibration samples, and assessment algorithms are being developed concurrently under PRCI funding. The commercialization of dual field is only one part of the industry wide effort to address mechanical damage on operating pipelines.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

To minimize the risk of failure, pipelines are closely monitored and inspected. One of the primary inspection methods utilized by the pipeline industry is in-line inspection (ILI), consisting of pipeline inspection tools, commonly referred to as pigs, being inserted and propelled through the pipeline by the flowing material. The most common ILI technology, magnetic flux leakage (MFL), uses magnetic components to induce magnetic flux within the pipeline wall. Anomalies in the wall of the pipeline tend to disrupt the uniform flow of the flux and create a leakage of magnetic flux which can then be detected by sensors.

MFL ILI technology can operate autonomously for hundreds of miles and is sufficiently rugged to withstand the pipeline operating environment. Currently, MFL tools are primarily designed to inspect for corrosion. However, alternative MFL-based tools have the potential of addressing many of the threats listed in ASME B31.8S, including mechanical damage. There are two primary forms of mechanical damage: damage due to contact with machinery and damage related to rocks. The primary feature created is a dent in the pipe wall. The dents can also be associated with secondary features, such as corrosion or gouging. Damaged regions are also affected by re-rounding of the dented area. Re-rounding can occur immediately upon removal of the object that creates the damage or can be the result of pressure cycling on the pipeline. Advancements in the application of MFL ILI have led to the use of this technology for mechanical damage detection.

Prior research by Battelle completed for DOT-PHMSA and PRCI demonstrated that the use of dual MFL fields for detecting the primary forms of mechanical damage. In particular, a high saturating field and a lower field, are used to expose regions of cold work where the ductility of the steel has been exhausted and the re-rounding of the damaged region applies a tensile load to the anomaly. Dual-field MFL technology has been tested at Battelle's Pipeline Simulation Facility (PSF) and the results of prior studies confirmed that a decoupled signal process can be applied to the MFL ILI data/signals to identify mechanical damage features in pipelines.

Building on the prior research, this project involved configuring a fully field ready dual field MFL inspection pig and testing this in operating pipelines, including one natural gas pipeline and one pipeline in hazardous liquids service. DOT-PHMSA and PRCI selected Rosen Inspection as the technology development partner for this project to build a 30-inch diameter dual-field MFL ILI tool. This involved configuring a pair of pipeline ready MFL magnetizers with the appropriate sensors and data recording equipment as well as implementing data analysis algorithms. The commercial tool was initially tested under controlled conditions using a pull testing to ensure tool performance matched previous results. Following the pull tests and confirmation of the dual-field MFL tool performance, two operating pipeline segments were inspected and field excavations were performed for direct examination of mechanical damage features identified to confirm technology performance.

The data collected during the project provided a preliminary demonstration that dual-field MFL ILI technology can detect mechanical damage features and distinguish between those features that don't require response (benign features) and those that require some action to be taken (monitor or repair). The decoupling of the high and low magnetic fields allows for identifying changes in the metallurgical properties and magnetic permeability in the damage region. These data can now be evaluated to identify:

- Re-rounded dents that are less than 2% of the pipe diameter that have high residual stresses due to re-rounding and may require attention; and
- Dents that are greater than 6% of the pipe diameter but may not require repair.

The dual-field MFL ILI data were supported by a set of in ditch examinations and direct inspection of selected dents to confirm the tool performance.

2.0 Technical Approach

The work performed in this project established the capability of the dual magnetic field MFL technology to detect mechanical damage and discriminate between critical and benign anomalies.

The milestones associated with assessment of the dual magnetization technology include the following:

Selection of a tool diameter. The tool size was selected based on a commonly applicable pipe diameter and the availability of appropriate pipelines which served as the full scale test case. A 30 inch diameter was selected as the most appropriate.

Design and build a dual magnetization tool. An inspection vendor was competitively selected to build a dual magnetization inspection tool; three vendors bid and Rosen Inspection was selected. Rosen implemented both the dual magnetization technology and the analysis software related to examining the data collected by the tool.

Test tool with pull tests. The performance of the tool was confirmed with the pull tests with dents made with the same process used in the tool development.

Run dual magnetization tool in two operating pipeline. The dual magnetization tool was run through two operating pipelines with known histories of mechanical damage. Historical inspection data gathered by previous conventional MFL and deformation tools served as base information for selecting the candidate pipelines.

Data analysis. The data was analyzed in four ways:

- Deformation analysis to determine dent depth, length, and circumferential extent
- Metal loss analysis to determine the geometry of corrosion and removed metal
- Combination analysis, examining the deformation and metal loss data together
- Decoupling analysis, which examines the information added by the low magnetic field including material property changes, residual stress and cold work in addition to the metal loss and deformation data.

Analysis of mechanical damage defects. Investigative digs were conducted where appropriate. Standard and emerging in the ditch methods for field investigations were tested as part of this task.

3.0 Background

Mechanical damage to pipelines from outside forces, if undetected, can lead to leaks and occasionally ruptures. This damage can be caused over time by rocks or abruptly by excavation equipment. A majority of the anomalies due to outside forces are not injurious. However, a successful inspection tool must be able to both detect critical anomalies and dismiss benign anomalies.

In the United States, action in response to mechanical damage in pipelines is regulated by the Code of Federal Regulations (CFR) Title 49 Part 186-199 from the Department of Transportation. These regulations focus on dent depth, which can be detected and characterized using a caliper pig whose arms attempt to follow the contour of a dent. However dent depth alone may not accurately reflect the risk (risk is defined as the probability of failure multiplied by the consequences) associated with a mechanically damaged pipeline section, such as in a dent which has a shallow depth due to re-rounding and has a cold worked region which reduces ductility. Residual stress and metallurgical damage need to be considered to properly assess severity[1].

The pipeline industry commonly uses caliper tools to assess dents in pipelines; which measure deformation of the inner surface of the pipe. MFL tools are commonly used to detect and size metal loss anomalies such as corrosion. Some newer commercial MFL tools incorporate deformation sensors to identify dents with metal loss. However, these commercially ready technologies may not detect all anomalies that could lead to failure and falsely identify harmless mechanical damage anomalies as critical.

A new magnetic flux leakage (MFL) inspection tool that performs an inline inspection to detect and characterize both metal loss and mechanical damage defects has been developed through recent research. This tool combines mechanical damage assessment as part of a routine corrosion inspection with minimal additional inspection complexity. The design is based on results of jointly-sponsored DOT/PRCI project that performed theoretical and experimental studies which showed that detecting and assessing mechanical damage can be accomplished by applying a low magnetic field level in addition to the high magnetic field employed by most inspection tools.

Most current MFL inspection tools use high magnetic fields and detect metal-loss, however high field MFL signals are minimally influenced by residual stress and metallurgical damage. In order to detect MFL signals due to residual stresses and metallurgical damage, a low field level is optimum. However pipe wall geometry also influences the MFL signal from a low applied field. This results in the need to decouple the high field signal from the low field signal, with the resulting signal being predominantly influenced by residual stress and metallurgical damage. It will be possible to detect the effects of residual stress and metallurgical damage on a MFL signal using a dual field tool that can induce both high and low field levels together with a decoupling algorithm.

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[1] Leis, B., Forte, T., and Zhu, X., "Integrity Analysis for Dents in Pipelines," Proc. of IPC'04, IPC04-0061, Oct 2004.

Unlike conventional caliper tools, the dual magnetization tool measures both dent depth and changes to the pipe material such as residual stresses, material property changes, and gouges. In particular, the processed signal can expose a region of cold work where the ductility of the steel has been exhausted and the re-rounding of the dent applies a tensile load to the anomaly. These characteristics of the damaged steel are expected to be major precursors to cracking of the pipe wall, which can potentially lead to leak or rupture conditions. This will allow for more accurate detection, identification and characterization of features that are accompanied by metallurgical damage and residual stresses such as dents that have under gone pressure cycling and have re-rounded due to a pipes internal pressure.

A dual field MFL ILI tool was constructed by Rosen Inspection for the project which is composed of a high field unit at the front of the tool, low field unit in the center, and lastly a caliper arm unit that is upstream of both magnetizers and which can describe existing dent geometry. The magnetizer units create a predominantly axially oriented field in the pipe wall. According to the specifications for the project, the measured high field should be between 140 to 180 Oe (11.1 – 14.3 kA/m), while the measured low field should be between 50 and 70 Oe (4 – 5.6 kA/m). The field levels are easily achievable for wall thicknesses up to 0.5 inches.

4.0 Tool Design

This project entailed building a dual magnetization MFL tool and testing in an operating pipeline. This tool collects three types of data:

- Deformation data using high resolution caliper arms, which is commonly used to determine dent dimensions including depth, length and circumferential extent
- High field MFL data, which is commonly used to determine metal loss geometry
- Low field MFL data, which is added to detect material property changes, residual stress and cold work.

This characterization data is achieved using a single tool that measures the size and shape of the damage, metal loss associated with the damage (if any, such as corrosion or gouge) and the local stresses caused by damage due to the initial impact and re-rounding. Combining these parameters provides a substantially enhanced understanding of damage severity. The dual field tool consists of a high field magnetizer section downstream of a low field magnetizer section, and a caliper arm section (RoGeoXt) upstream of both magnetizers. The tool is 4.98 m in length, is designed for a 30 inches diameter pipeline, can pass through bore restrictions 80% of the internal diameter and up to 1.5D bends. The principle tool design is shown in Figure 1. The high field unit is at the front of the tool, low field unit is the middle module and a caliper arm unit is at the rear of the tool. Modular Rosen corrosion detection pig (CDP) and RoGeoXt units are used for the magnetizer and caliper arm section respectively.

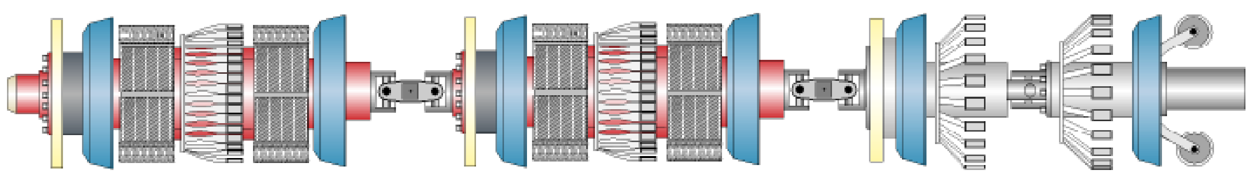

Figure 1. Complete Rosen dual magnetization tool, consisting of two-magnetizer section and a caliper arm section.

The caliper arm unit follows the low field unit and consists of two planes of caliper arms that are circumferentially offset in order to ensure 100% circumferential coverage. The geometry of an ID anomaly is determined by combining the angle measurement from a caliper arm, together with the liftoff measurement provided by the eddy current coil in a caliper arm head. This combined measurement allows a caliper arm to obtain a more accurate picture of the geometry of a dent, than an angle measurement alone would, and helps compensate for the deficiencies of a caliper arm alone, such as bounce, under operating conditions.

4.1 Magnetizer Design

The magnetizer design is a four-pole design consisting of separate low field and high field sections, with the high field section downstream of the low field unit. The magnetizer is designed to help isolate the magnetic field created by each of the high and low field sections, minimizing the possibility of the field from one magnetizer changing the field produced by to the other section. To limit affects, the poles are arranged so that the polarity of the low field pole is the same as the polarity of the neighboring high field pole.

Since an unknown remnant magnetization can exists in the pipe due to previous MFL inspections, it is important to have the high field MFL unit first, downstream of the low field magnetization unit. If the low field section were downstream of the high field section, the unknown remnant magnetization would affect the induced low field, making it unpredictable. However, by placing the high field section downstream of the low field section, a constant remnant magnetization can be established, thus allowing a consistent low field level to be induced in a section of pipe wall with uniform characteristics.

The high field unit is designed to achieve a field strength within the range of that used by standard Rosen MFL ILI tools, so its design presented a more standard challenge and is more straightforward than that of the low field unit.

The low field unit is designed to achieve a field strength of 50 – 70 Oe (4 to 5.6 kA/m). Several options were explored through magnetic finite element modeling in order to obtain the desired magnetic field strength from the low field unit. It was found that the optimum method to achieve the specified magnetic field strength over the existing wall thickness range is to reduce the effective strength of the magnet packages by removing some of the magnets. Using this method, the finite element model created predicts that the specified field strength will be achieved through the specified wall thickness range.

However at lower magnetic field strengths there is a greater variance in the resulting magnetization for different pipe wall materials than at higher field strengths where saturation is approached. This may lead to discrepancies between finite element predictions and pull test and inspection results.

4.2 Signal Processing

Prior work has shown that the flux leakage signal from various anomalies is a function of magnetization level[2-3.] As illustrated in Figure 2, flux leakage from geometric changes, such as denting, metal loss, and wall thinning, can be isolated at high magnetization levels, usually well above the knee of the magnetization curve. Flux leakage signals from anomalies that change the magnetic properties, such as cold work, plastic deformation, and residual stress, are better detected at low magnetization levels usually near the “knee” of the magnetization curve. Unfortunately, the geometric portion of the anomaly is also contained in the flux leakage signal acquired at low magnetization levels. A multiple magnetization level approach has been developed to isolate information from both types of anomalies. Classifying and sizing the

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[2] Davis, R. J., et al., “The Feasibility Of Magnetic Flux Leakage In-Line Inspection as a Method To Detect and Characterize Mechanical Damage,” GRI Report GRI-95/0369, 1996.

[3] Davis, R. J. and J. B. Nestleroth, “The Feasibility of Using the MFL Technique to Detect and Characterize Mechanical Damage In Pipelines,” *Review of Progress in Quantitative Nondestructive Evaluation*, Volume 16, Plenum New York, 1997.

damage requires additional signal processing. The measured signals must be decoupled into their geometric and magnetic components. Once decoupled, the unique signatures become more readily apparent.

4.2.1 Decoupling

There is an optimum magnetization level where the effects of magnetic deformation are greatest. This point is below the knee of the B-H curve, between 50 and 70 Oersteds. At high magnetization levels, at or above 150 Oe, the effects of magnetic deformation disappear. A signal measured at the lower magnetization level contains information on both the geometric and magnetic deformation. It is referred to as a mixed signal. At a high magnetization level, where the effects of magnetic deformation disappear, the signal contains information on only the geometric deformation. Figure 2 shows the magnetic deformation's effect on the B-H curve and its effect on the MFL signal for a simple gouge with removed metal.

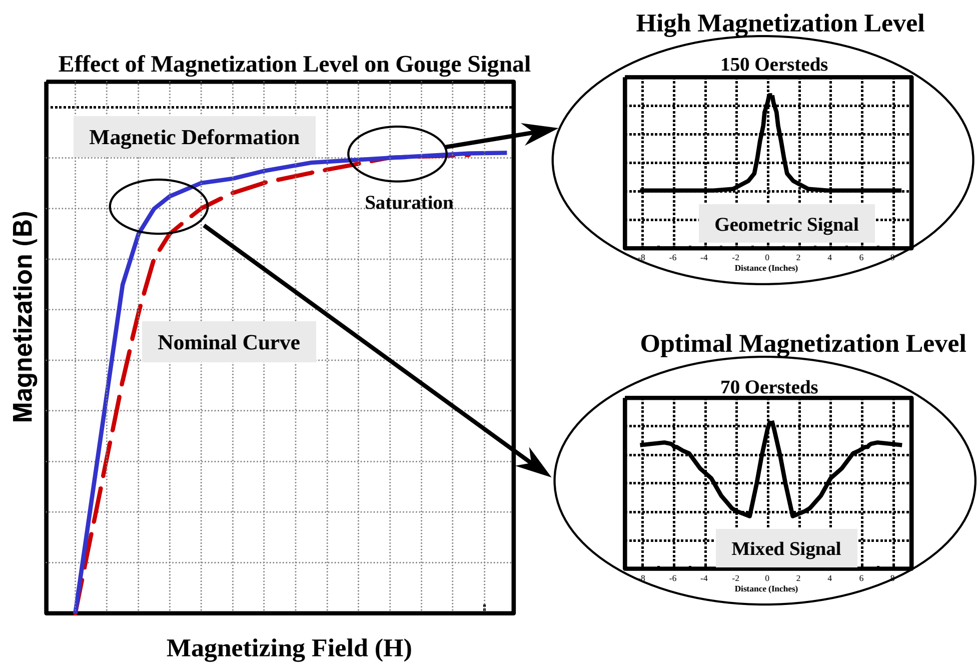

Figure 2. The general effect of magnetic deformation on the B-H curve and its effect on the MFL signal.

The decoupling procedure is illustrated in Figure 3. First, the MFL signal is measured at the low magnetization level, i.e., the level at which the effects of magnetic deformation are greatest. Since geometric deformation also produces flux leakage at this magnetization level, the measured signal is a complex mixture containing information on both the geometric and magnetic deformation. Second, the MFL signal is measured at a high magnetization level. At high magnetization levels, effects of magnetic deformation vanish and the MFL signal is due to only defect geometry. Then, the high magnetization level signal (geometric signal) is "scaled down" to the lower magnetization level of the mixed MFL signal. This scaled geometric signal is the hypothetical MFL signal caused by the defect geometry at the low magnetization level.

Finally, the scaled geometric signal is subtracted from mixed MFL signal. The result is the signal caused only by the magnetic deformation.

4.2.2 Scaling

Since only signals at the same magnetization level can be meaningfully added or subtracted, a procedure must be established to adjust one of the signals. Scaling is the process whereby the geometric signal measured at a high magnetization level is used to determine the geometric signal at the lower magnetization level. This scaled geometric signal is the hypothetical MFL signal at the lower magnetization level in the absence of magnetic deformation. Subtracting the scaled geometric signal from the mixed signal will reveal the signal caused by magnetic deformation.

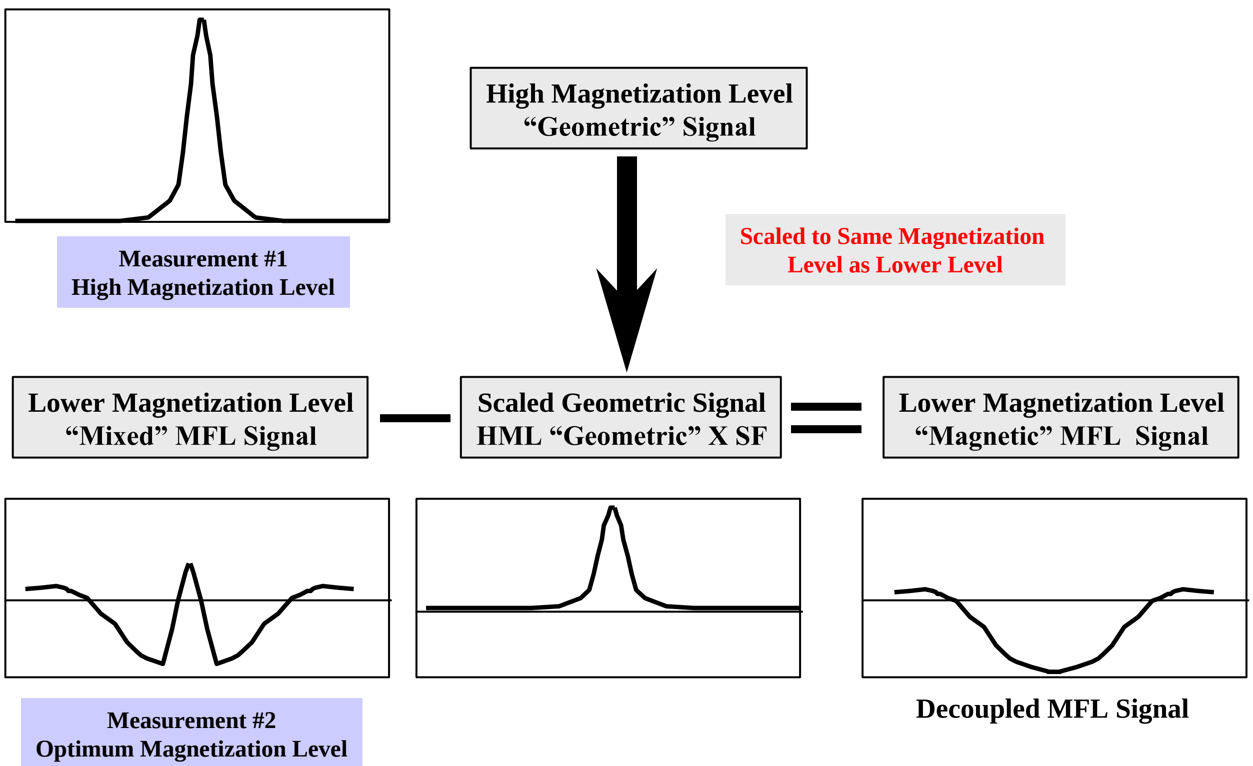

Figure 3. Illustration of the decoupling process.

Scaling requires specific knowledge of how the geometric component of an MFL signal changes with magnetization level. Generally, the signal changes its amplitude and shape. The shape change can be viewed as a nonuniform amplitude change across the signal. For example, the center of the signal may have a greater amplitude change than the ends of the signal, giving rise to the change in shape.

To simplify the scaling process, the magnetization bias is noted and removed for both the high and low signals at the beginning of the process. Sensors near the surface of the pipe wall measuring the axial component of the magnetic field provide an estimate of the bias level. The amplitude of the bias signal is proportional to the magnetization level but is dependent on sensor design variables including liftoff.

The decoupling of the flux leakage signals with the bias removed works as follows. The low magnetization level signal with the bias removed is referred to as the mixed flux leakage signal, MFL_{MIX}. The high magnetizing level signal with the bias removed is called the geometric flux leakage signal MFL_{GEOM}. The MFL_{GEOM} is translated to the lower magnetization level by a scaling function, SF. This scaled geometric signal is then subtracted from the mixed signal. The result is a signal due to the magnetic deformation only, MFL_{MAG},

$$MFL_{MAG} = MFL_{MIX} - SF \times MFL_{GEOM} \quad (1)$$

This signal is referred to as the decoupled signal. This signal is most important since it will reveal the presence of gouging.

4.2.2.1 The Scaling Function

The equivalent geometric signal at low magnetization signal, MFL_{EQG}, is given by

$$MFL_{EQG}(x,y) = SF(x,y) \times MFL_{GEOM}(x,y) \quad (2)$$

where x and y are the spatial coordinates of each signal. The coordinate references can be important. If the shape of the signal changes with magnetization, each two-dimensional spatial coordinate of the signal must be scaled differently. If the shape of the signal does not change, the entire signal is equally scaled. In this case, the scaling function is independent of the coordinates and becomes a simple scalar function.

The bias level must be measured to determine magnetization level, and it must be subtracted out of the geometric signal before the resultant signal is multiplied by the scaling function to give the scaled geometric signal without bias. The scaled geometric signal without bias is subtracted from the measured mixed MFL signal without bias to yield the decoupled signal.

4.2.2.2 Determining the Scaling Function

The scaling function is dependent on the magnetization level, defect geometry, and tool design. At lower magnetization levels, the geometric component of the MFL signal cannot be directly measured as a function of these parameters. However, finite element modeling techniques work well for parameter isolation and were used to study these variables. Accordingly, 20 mechanical damage defect geometries were modeled and their geometric signals computed as a function of magnetization level. These 20 geometries included dents, gouges, and dents with gouges. The dent depths ranged from 1/8 to 1 inch deep, gouge depths ranged from 1 to 10% of wall thickness, and defect lengths/widths ranged from 1.0 to 6.0 inches.

Based on the modeling results, the scaling function for each coordinate can be written as:

$$SF(x,y) = F_1(ML) + F_2(DD) + F_3(OGF) + F_4(OV) \quad (3)$$

where SF(x,y) is the scaling function at spatial coordinate (x,y), F_n is a Function of n^{th} order importance; ML = Magnetization Level; DD = Defect Depth; OGF = Other Geometric Factors (e.g., Length, Width); and OV = Other Variables (e.g., Sensor Design, Magnetizer Velocity). Note that each F_n may be spatially dependent.

4.2.2.3 Approximating the Scaling Function

The exact scaling function is a two-dimensional function dependent on many parameters. Determining the exact scaling function given the limited modeling set is difficult. Therefore, for this project, the scaling function was approximated. Two approximations were made.

The first approximation is that the scaling function is independent of a signal's spatial coordinates. For the geometries studied, the results showed that the signal shape does not appreciably change as a function of magnetization level. This fact implies that the amplitude scaling is roughly uniform over the whole signal. Therefore, the two-dimensional scaling function can be approximated by a scalar function. The success of this approximation depends on the geometry of the defect. Experiments have shown that for dent depths less than 0.75 inch and gouges less than 10% deep, this approximation is very good while performance degrades for dent depths between 0.75 and 1.00 inch deep and gouges up to 20% deep. It becomes less exact for deeper dents and gouges. This phase of work assumed that the scaling function is a scalar quantity.

The second approximation is to ignore all variables except magnetization level. To a first order, the scaling function primarily depends on the level from and the level to which the signals are being scaled.

With these approximations, the scaling function can be written as a scalar dependent only on the magnetization levels:

$$SF(LML, HML) \approx A(LML)e^{-\alpha(LML)\,\mathrm{HML}} \tag{4}$$

where LML and HML refer to low and high magnetization levels, respectively.

The terms A and α are functions of the low magnetization level. However the scaling function depends on the high field as well as the low field, hence the coefficients, a_i's, in Equation 5 are functions of the high field level as shown in Equation 6. By combing Equations 5 and 6 together, the scaling factor is derived as shown in Equation 7.

$$SF = \sum_{i=0}^{2} a_i(M_{High}) \cdot M_{Low}^{i} \tag{5}$$

$$a_i(M_{High}) = \sum_{j=0}^{2} b_{i\,j} \cdot M_{High}^{j} \tag{6}$$

$$SF = \sum_{j=0}^{2}\ \sum_{i=0}^{2} b_{i\,j} \cdot M_{High}^{j} \cdot M_{Low}^{i} \tag{7}$$

The above form is a valid solution to the first-order scalar SF used in the decoupling process. This was implemented by Rosen to process the high and low magnetization signals.

5.0 Pull Tests

Pull tests were performed to confirm the newly designed tool provided signals comparable to the results produced from the initial prototype tool that was developed and tested. Since the design of the dual-field MFL ILI tool developed for this project was based on an operating pipeline that is 30 inches in diameter, new dents had to be made. A three (3) meter long section of pipe that was dented in a manner similar to dents used in the development of this technology and used in the pull tests was obtained and mechanical damage features were introduced in the pipe wall. Pull tests were performed on this 3 meter pipe and another section of pipe (also with a nominal diameter of 30 inches) that was removed from an operating pipeline and contained a single dent. The pull tests were performed at a speed of 0.5 m/s (1.6 ft/s). The dented section removed from service has a dent 1.7 % of the nominal diameter, which is estimated to have re-rounded approximately 1% after excavation based on pre-excavation ILI geometry data. The 3 meter section of pipe was welded between two five meter long sections; and all three sections were cut from similar pipe material. The section of pipe that was removed and contained the single dent was welded onto the end of one of the five meter long sections. The pipe section placement was designed to ensure that when the pipe wall surrounding a dent is magnetized each of the magnetizer poles will be on a section of wall with the same thickness and material properties. Additionally although the former in-service section of pipe is at the end of the pull test pipe assembly, the dent is in the middle of this section, and thus the poles of a magnetizer section were in contact with the pipe steel as the magnetizer traversed the dent and not beyond the pipe in the air.

The defects in Figure 4 and Table 1 were installed in the following order by Battelle, under 600 psi internal pressure: 7, 3, 9, 5, 1, 2, 6, and 10 – defects 4 and 8 were installed without the pipe being pressurized. Between defect installations, the pressure was reduced, and defects that were installed earlier underwent more pressure cycles.

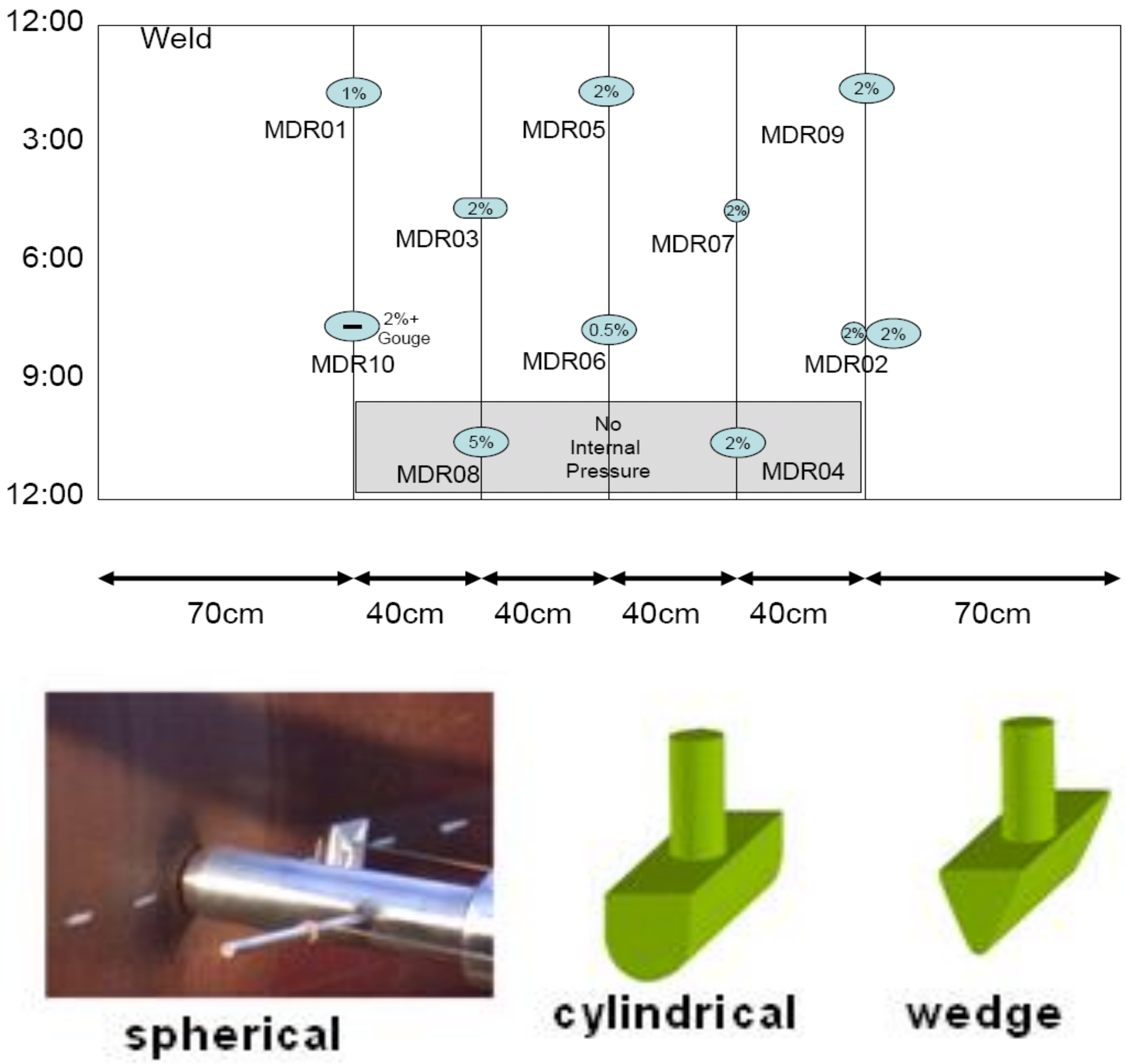

Figure 4. Dent layout used for pull tests. Dent layout consists of 10 dents from 0.5% to 5% outer diameter made with the three indenter geometries shown.

Table 1. Dent Geometry, Depth, and Presence of Applied Internal Pressure

ID	Tool	Depth	Pressure
MDR-01	Cylindrical	1%	Yes
MDR-02	Cylindrical + Spherical	2%	Yes
MDR-03	Wedge	2%	Yes
MDR-04	Cylindrical	2%	No
MDR-05	Cylindrical	2%	Yes
MDR-06	Cylindrical	0.5%	Yes
MDR-07	Spherical	2%	Yes
MDR-08	Cylindrical	5%	No
MDR-09	Cylindrical	2%	Yes
MDR-10	Cylindrical	2%	Yes

Three of the dents created for the pull tests were designed to have the same geometry and nominal depth as dents that Battelle has previously used in the development the DOT/PHMSA prototype dual field tool. These dents allow a comparison between the low and high field MFL signals Battelle has obtained with a prototype dual field tool and the signals obtained by Rosen during the current pull tests. The Battelle[4] signals used in this comparison are displayed in Figure 5, and the signals Rosen obtained during the current pull tests are displayed in Figures 6 and 7. MFL signals from dents previously obtained by Rubenshteyn[5] during graduate research and used for comparison are displayed in Figures 8 and 9. Certain signal patterns are common to all three sets of data, and are also representative of past Rosen experience. By comparing the signals in Figures 5 to 9 along the axial centerline (moving in the x axis direction at a central y coordinate), where the dents reach their maximum depth, it can be seen that all the signals share a common pattern of two peaks (local maxima) above the background level, with a dip in the middle between the peaks. However, the Battelle signals contain additional signal features compared to the signals obtained from the current pull tests.

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[4] Nestleroth, J. B., R. J. Davis, and S. A. Flamberg, Mechanical Damage Inspection Tool Using Dual Magnetization Flux Leakage Technology, Department of Transportation Report Agreement DTRS56-02-T-0002, March 2005.

[5] Rubinshteyn, A., 2005, "Magnetic Flux Leakage Investigation of Dents," M.Sc. thesis, Queen's University, Kingston, Ontario, Canada

The difference between the current Rosen pull test results and the features from prior Battelle pull tests with a prototype tool can be influenced by factors such as differences between the pipe steel material properties, the fact that the pipe was pressurized during Battelle pull tests, differences between the applied magnetic fields, differences in the diameter of the pull test pipe sections, differences between the magnetizer and probe arrangements in the ILI tools and the lower speed of the Battelle pull tests (0.1 m/s or 0.3 ft/s).

However based on the fact that signal patterns similar to the signals from both the prior Battelle pull tests and the current Rosen pull tests were previously obtained during independent research, both signals are valid examples of signals from dents and their differences can likely be attributed to one or more of the factors listed above.

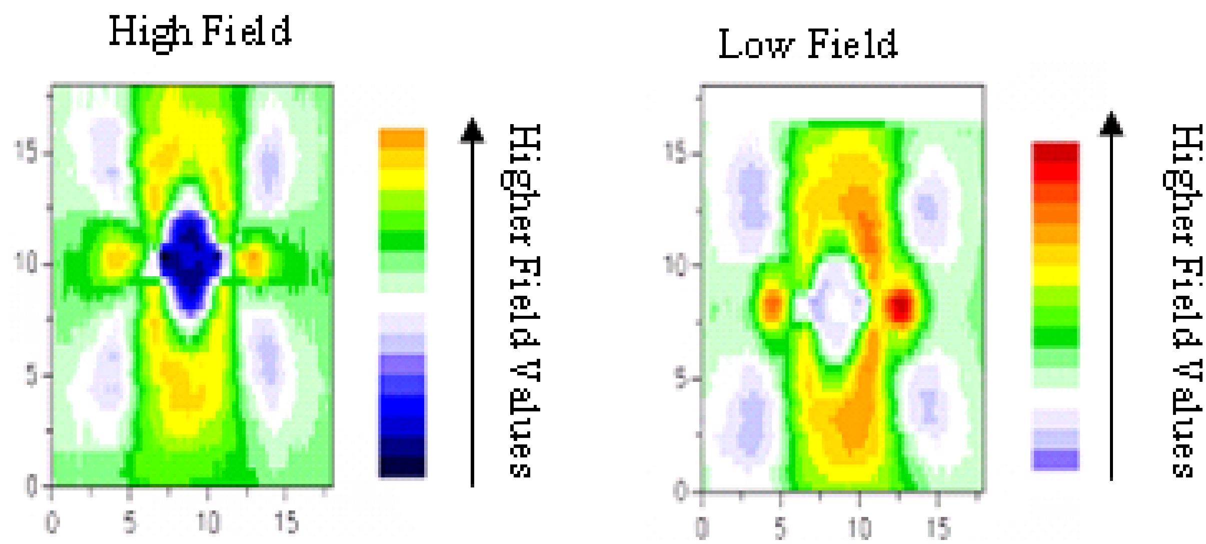


Figure 5. Battelle high and low field MFL signals at applied fields of approximately 150 and 75 Oe (11.9 and 5.9 kA/m) respectively from a dent with the same depth and geometry as Dent 5 in Figure 4.

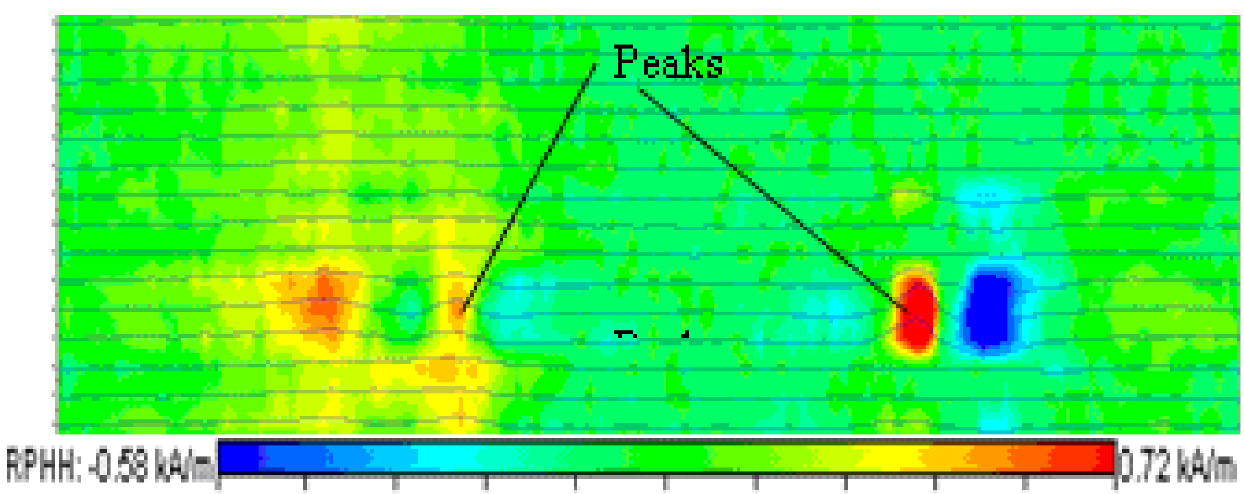


Figure 6. MFL signal from Dent 5 with background subtracted at an applied field of 170 Oe (13.5 kA/m). Obtained during Rosen pull tests. Indicated peaks with dip between them are characteristic of Rosen MFL signals from smooth, deep, dents.

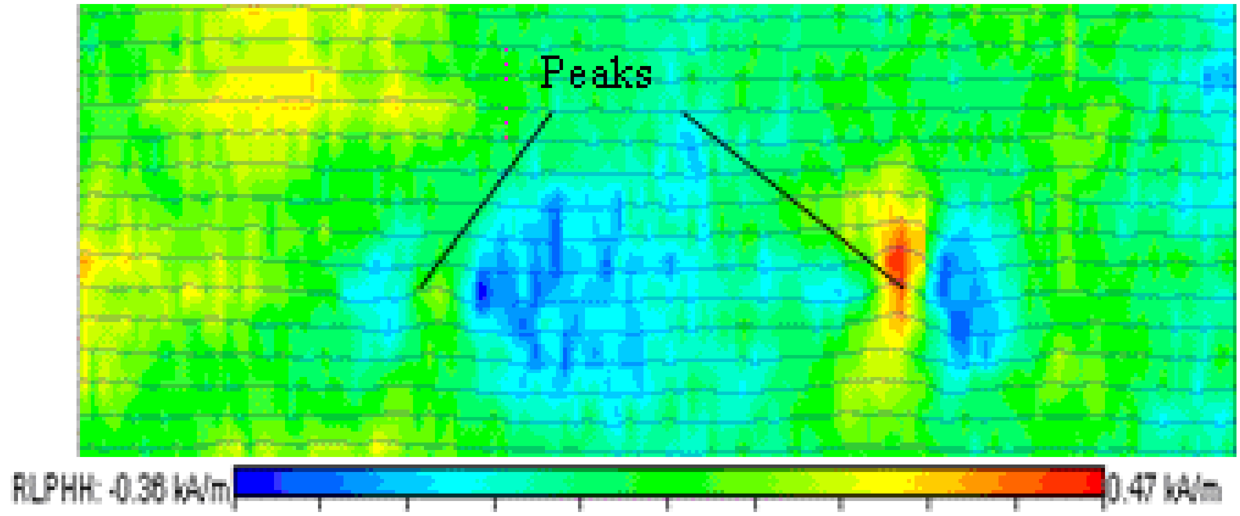


Figure 7. MFL signal from Dent 5 with background subtracted at an applied field of 73 Oe (5.8 kA/m). Obtained during Rosen pull tests. Indicated peaks with dip between them are characteristic of Rosen MFL signals from smooth, deep dents.

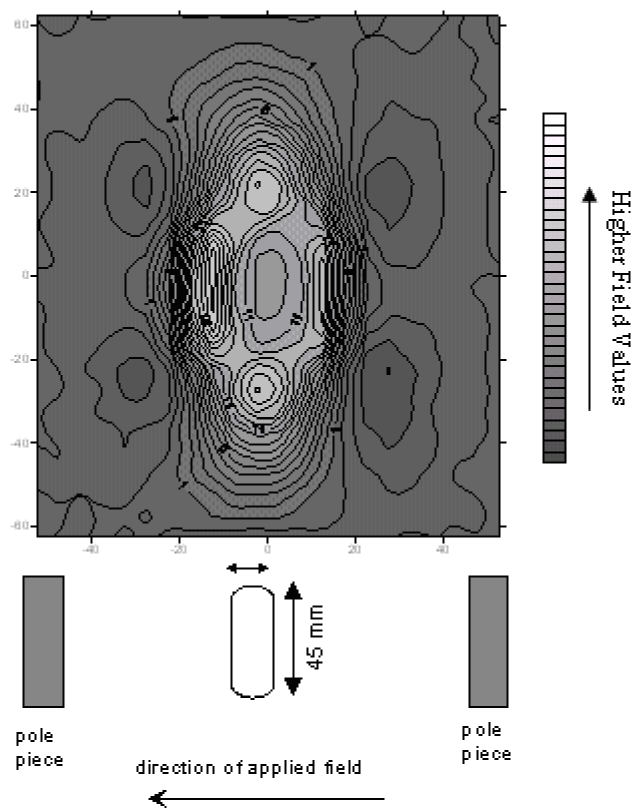


Figure 8. MFL signal from a plain dent with background subtracted. This signal is from independent research by Rubinshteyn and contains the same signal patterns as the MFL signals obtained by Battelle in Figure 5. This indicates that the Battelle signals are valid examples of MFL signals from dents

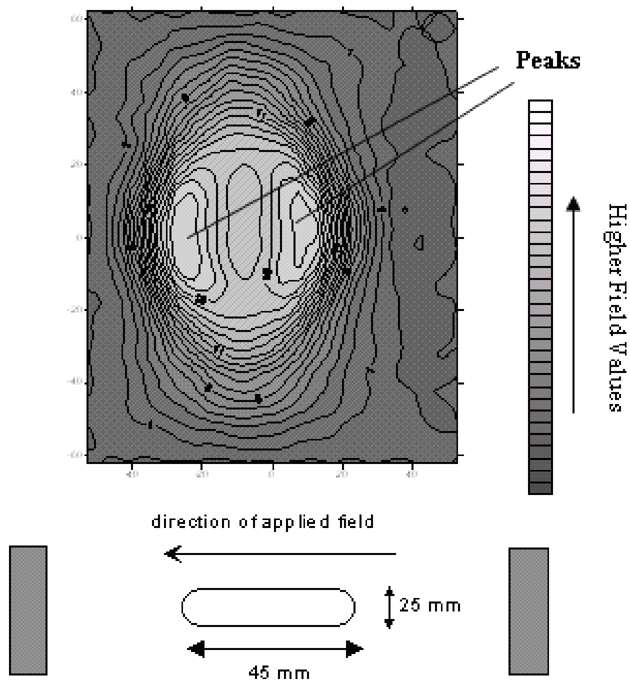


Figure 9. MFL signal from a plain dent with background subtracted. This signal is from independent research by Rubinshteyn and contains the same signal patterns as the MFL signals obtained by Rosen in Figure 6, note the peaks. This indicates that the Rosen signals are valid examples of MFL signals from dents too

By comparing the decoupled signal from the dent in the former in-service line that was cut out and provided for the project, shown in Figure 10, with a decoupled signal obtained by Battelle as part of a separate research program, shown in Figure 11, certain decoupled signal patterns can be identified. In particular, the re-rounding and pressure cycling signal patterns are identified in Figure 10, due to their position relative to the other signal patterns, their polarity, and their shape.

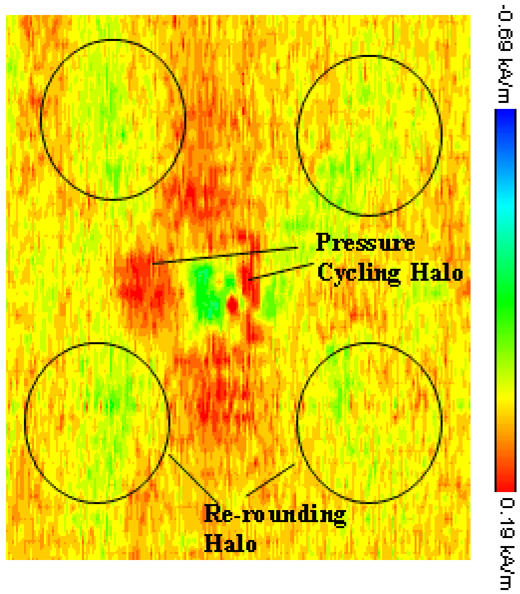


Figure 10. Decoupled pull test results with background subtraction from pipe section with a natural dent from a former in-service pipeline. Applied high and low fields are 188 Oe and 80 Oe (15 kA/m and 6.4 kA/m) respectively. The re-rounding halo is composed of the four-circled areas

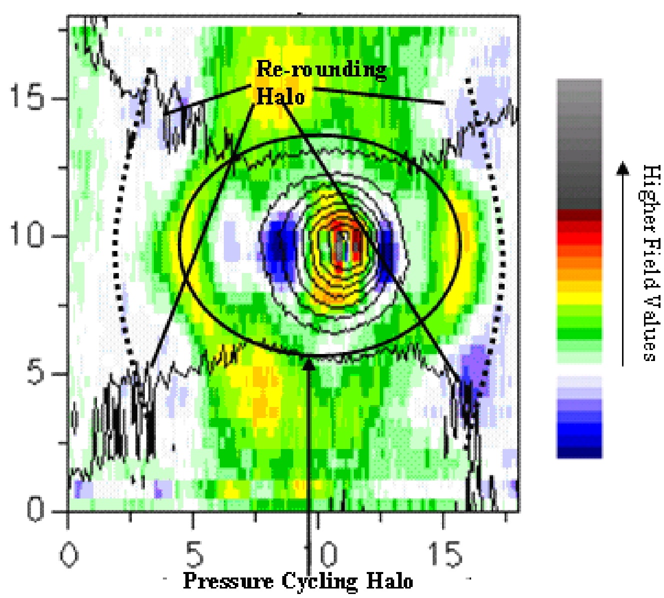


Figure 11. Independently obtained decoupled signal from a plain dent is shown for comparison to Figure 10. The pressure cycling and re-rounding halo signal patterns can be identified in both figures. The blue pressure-cycling halo is negative with respect to the background.

The fact that the pressure cycling halo has been correctly identified is supported by the fact that the pressure cycling halo amplitude decreases when comparing a signal that has undergone pressure cycling to one that has not as discussed below.

Dent 9 in Figure 12 can be compared to Dent 4 in Figure 13 to see what the effects of internal pressure and pressure cycling are on the decoupled signal, as all three dents have the same geometry and approximately the same depths, but Dent 4 was made in unpressurized pipe and did not undergo pressure cycling while Dent 9 was made while the pipe was pressurized and underwent pressure cycling. There is less of a pressure-cycling halo in Dent 9 compared to Dent 4: the average amplitude of the pressure-cycling halo in Dent 9 is approximately 50% greater than in Dent 4.

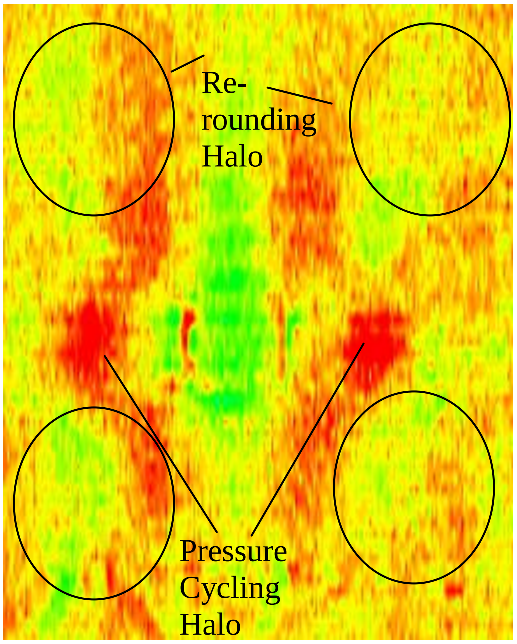


Figure 12. Decoupled pull test results with background subtraction corresponding to Dent 9 in Figure 4 and Table 1. Applied high and low fields are 170 Oe and 73 Oe (13.5 kA/m and 5.8 kA/m) respectively. The pressure cycling and re-rounding halo signal patterns are identified. The re-rounding halo is composed of the four-circled areas.

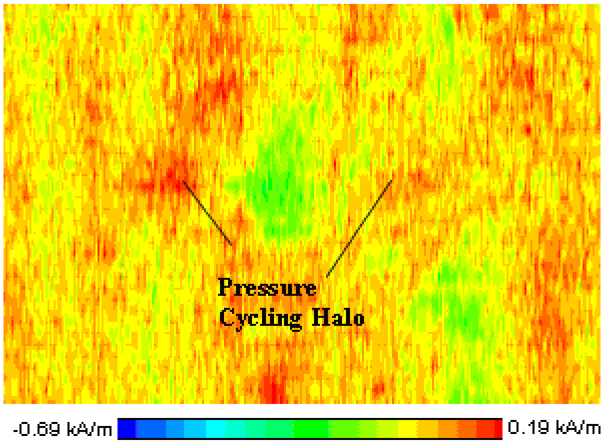


Figure 13. Decoupled pull test results with background subtraction corresponding to Dent 4 in Figure 4 and Table 1. Applied high and low fields are 170 Oe and 73 Oe (13.5 kA/m and 5.8 kA/m) respectively.

The signal pattern, which surrounds a dent, and consists of four separate negative areas has been identified as the re-rounding halo in Figure 10 based on its position with respect to the pressure cycling halo and polarity (compare to the signal in Figure 11). This signal appears outside of the pressure cycling halo, which is in accord with the description provided by Battelle. The same type of negative signal is absent at other locations along the circumference with the same axial position as the rightmost portion of the re-rounding halos in Figure 10 other than near the dent. This supports the conclusion that this signal pattern is indeed the re-rounding halo and not noise.

In Figures 14-16 the signal from the gouge is compared to a typical decoupled mechanical damage gouge signal obtained by Battelle. The gouge created for the pull test was made with a chisel and hammer and has several gouging and plowing portions, since it was chiseled in several steps, and not in one fluid motion. However the decoupled gouge signal from the pull test does contain a dipole, which is the decoupled signal pattern identified by Battelle as being representative of a gouge. The overall length of the gouge signal, 6.6 cm, is close to the length of the length of the actual gouge, which was about 5 cm.

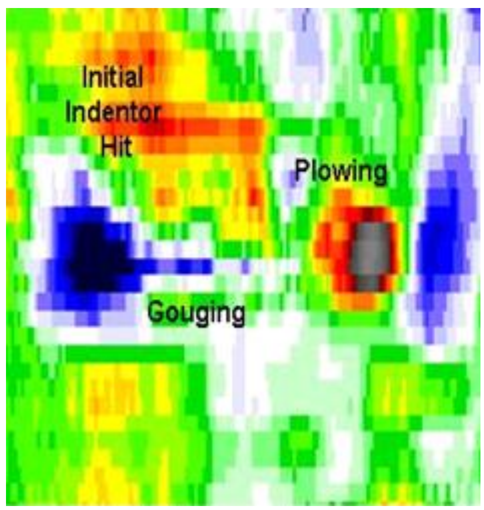


Figure 14. Decoupled signal from a gouge obtained by Battelle. [2]

Figure 15. Photograph of gouge used in current pull tests.

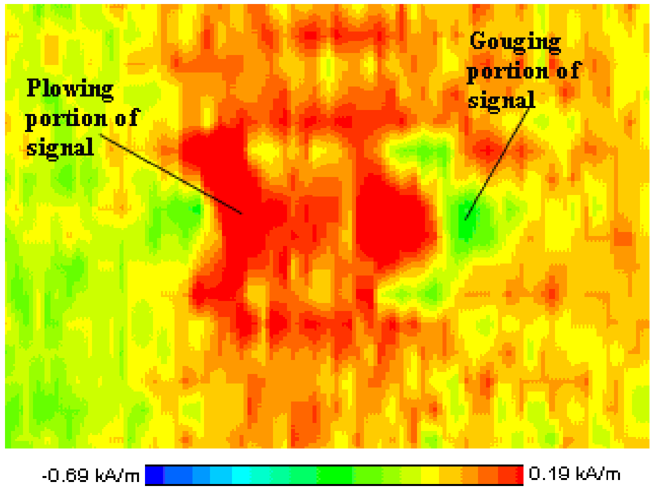


Figure 16. Decoupled pull test results with background subtraction from gouge shown in Figure 15 with the same orientation. Applied high and low fields are 170 Oe and 73 Oe (13.5 kA/m and 5.8 kA/m) respectively. The decoupled Battelle gouge signal in Figure 14 is for comparison.

The following are further findings based on an analysis of the decoupled signals and may be useful in the analysis of the dual field inspection:

The shallowest dent in Figure 4, Dent 6 (0.5%), did in fact produce a decoupled signal with the re-rounding and pressure-cycling halos present as shown in Figure 17. This indicates that dents as shallow as 0.5% will be detectable in the decoupled inspection.

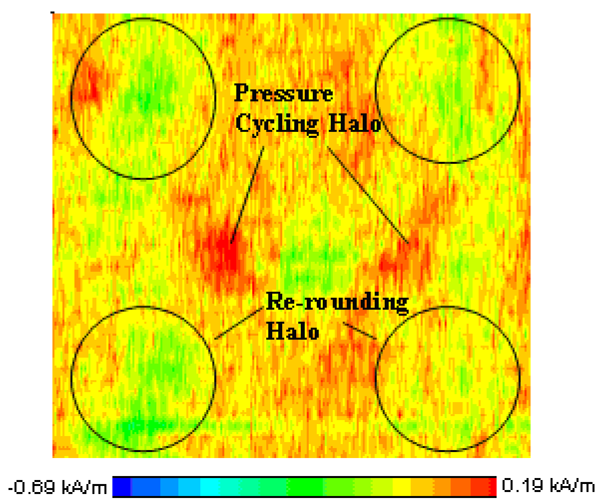


Figure 17. Decoupled pull test results with background subtraction corresponding to Dent 6 (0.5%) in Figure 4 and Table 1. Applied high and low fields are 170 Oe and 73 Oe (13.5 kA/m and 5.8 kA/m) respectively. The pressure cycling and re-rounding halo signal patterns can be identified although the dent is shallow.

Dent 2 was made with two dents side by side, which have the same geometries and depths as dents 5 and 7, to see what effect this will have on the decoupled signal. In Figure 18, the signal pattern is unclear, but it does look like the decoupled signal patterns from two individual dents placed next to one another with partial overlap. For example, there appear to be three areas that are positive with respect to background, that are likely composed of the individual pressure cycling signals. The area in the middle of the signal where one would expect overlap between the individual pressure cycling signals does in fact have an average amplitude approximately 50% greater than the individual pressure cycling signal from Dent 9.

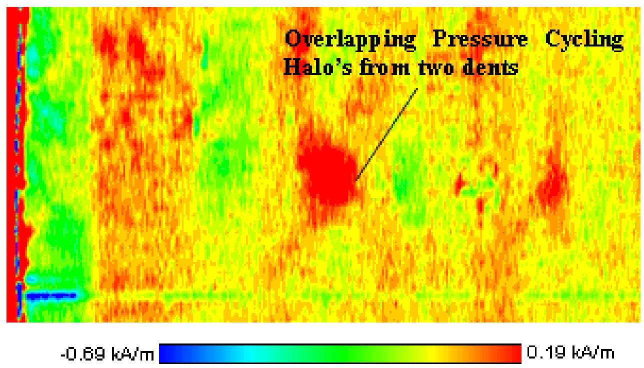


Figure 18. Decoupled pull test results with background subtraction corresponding to Dent 2 in Figure 4 and table 1. Applied high and low fields are 170 Oe and 73 Oe (13.5 kA/m and 5.8 kA/m) respectively. The area where two pressure cycling halos from neighboring dents overlap is identified.

A dual field tool design to produce a decoupled MFL signal primarily influenced by stress and metallurgical damage from mechanical damage has been built and tested through a pull test in preparation for a dual field inspection. The dual field technology was developed by Battelle and signal patterns that have been identified by Battelle as typical of decoupled signals from mechanical damage, in particular the re-rounding and pressure cycling halo's, have been identified in the pull test results at the field levels used. The field levels were further adjusted before the inspection.

6.0 Software and Algorithm Development

An algorithm that applies the scaling factor, as provided by PRCI and created by Battelle, to the high field data and creates a decoupled signal by combining the high and low field results has been implemented into standard Rosen software.

A decoupled signal search using the search algorithm, also provided by PRCI and created by Battelle, can be done using a Matlab GUI for which further improvements are possible depending on the decoupled signal quality. A direct and independent search on the decoupled signal is challenging – evaluating the dual field data requires expertise and a comprehensive view of all data recorded (high and low field data, along with caliper arm data). Additionally, a complete priority ranking depends on data quality and the signal to noise ratio.

The Matlab GUI searches a data matrix, allowing value extraction from the decoupled signal which is used to support the priority classification algorithm. The data extraction is used to determine the following parameters: feature type, gouge length, peak amplitudes, dent depth based on halo information and the severity index. These parameters serve the priority classification algorithm provided by PRCI and created by Battelle. The priority classification algorithm can be viewed as a decision tree which is used to arrive at a priority classification using inputs derived from the decoupled signal.

ROSEN's standard evaluation environment is shown in Figure 19, and a similar environment will be used to evaluate the data from the in-line inspections.

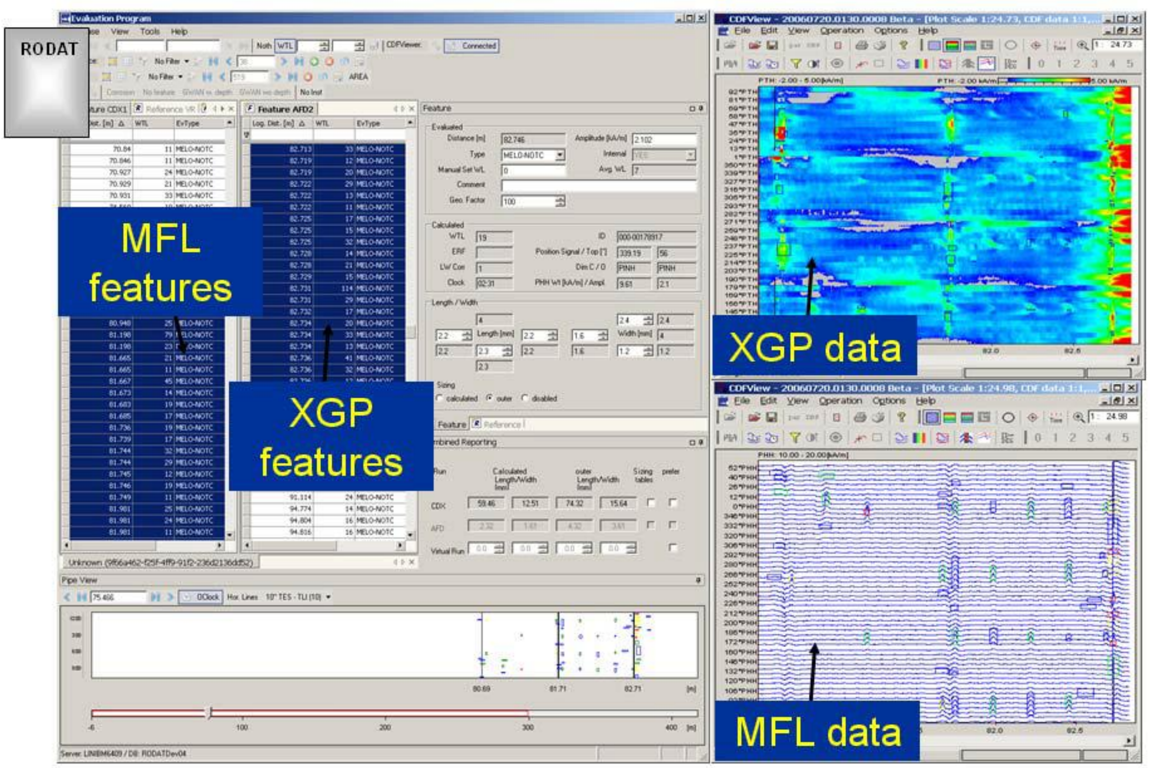


Figure 19. Example of a standard ROSEN evaluation environment, displaying caliper arm (XGP data), MFL data, and lists of MFL and XGP features that are created based on this data.

7.0 Inspection Results Operating Pipeline 1

Based on the results of the pull tests and analysis of the data by Rosen, a fully field ready and deployable 30" diameter dual-field field MFL ILI tool was built by Rosen and two separate pipelines were identified for running the tool. The pipeline selected for the test included a pipeline in liquid service operation and a natural gas pipeline. The first run of the dual-field tool run was in a 30" diameter liquids pipeline and was completed in May 2008. A range of reported features were recommended for direct inspection through in the ditch assessment and measurement to assess algorithm performance. The basis for selecting the features for inspection and dig classification and prioritization is described below and the final list was reviewed with the Project Team. Details regarding observations made in the field are presented in the following sections.

Direct Assessment Findings – Line 1

All excavations were completed during the 13th quarterly reporting period (August through October 2009). The goal was to determine the capability and limitations of the dual field technique and analysis methodology. If needed, the analysis methods would be improved for tool variation and actual pipeline conditions. A total of 18 anomalies were examined at 13 excavation sites and inspected along an approximately 100 mile segment of pipeline. Field data were collected following standard field procedures for in the ditch inspection of pipeline defects.

All field data were compiled, reviewed, and subjected QA/QC evaluation by the Project Technical Team. Details regarding the field inspection results and comparison to the ILI tool run data and dual-field MFL signals are provided below.

There are four steps to determine the relative severity of an anomaly. They are:

1. Detection, where identification of potential mechanical damage is achieved through use of caliper information and dual field data
2. Recognition, where the presence of mechanical damage is determined from the decoupled signals
3. Analysis, where features from the decoupled signals are extracted including measurements of the re-round halo, gouge signal and pressure cycling
4. Prioritization, where a decision tree is used the rank the mechanical damage anomalies into 5 categories from low to high priority

This methodology was implemented by Rosen in their data analysis software and used to analyze the data from the dual-field tool run in Line 1. The data from Line 1 consisted of 100 miles of 30 inch diameter pipeline. A total of 384 features were identified for assessment using the analysis procedures. Features were identified based on both the presence of a deformation signal and the anomalous magnetic signal that differs from the classical metal loss signal. Of the 384 features identified, 182 were recognized as potential mechanical damage anomalies from the decoupled signals. Further evaluation of these 182 anomalies was performed to extract features needed for prioritization.

All of the anomalies had a dent depth of 2% of pipe diameter or less; therefore none of the identified anomalies needed remediation. However, some of the anomalies exhibited differences in the decoupled signal that could be an indication of potential mechanical damage. For the full verification of the tool, it was desired that some of the dents would be greater than 2% on the top of the pipe that would require assessment. One of the main features of the dual field technology is the ability differentiate benign smooth dents from more potentially severe anomalies with cold working and gouging for dents that are greater than 2%. Unfortunately, deep anomalies were not available and this capability could not be evaluated using the inspection data for this pipeline.

The verification strategy focused on evaluation of anomalies with the largest indications of microstructural changes at dents found in the pipeline; these were called the high priority anomalies. It is important to note that a high priority anomaly does not necessarily mean the anomaly requires remediation (as indicated above, all dent depths were less than 2% of pipe diameter). The designation as a high priority anomaly is only for the ranking structures used for the project and relates specifically to the dual-field signals. The high priority anomalies exhibited a greater change in the magnetic signal features than the other anomalies. All 182 anomalies that were recognized as potentially being mechanical damage by Rosen analysts were reexamined by Battelle staff that developed the protocol and Rosen engineers. After sorting the data, a list of 30 anomalies was presented to the pipeline operator for consideration for field verification and inspection. Since none of the anomalies required field assessment, a subset was selected to support verification of the dual-field tool. The final list included eleven high priority locations, two moderately high priority locations and one moderate priority location for excavation. Four sites had two or three anomalies that were close enough to be examined in a single excavation site. One site was previously excavated in 2004.

In summary, thirteen excavations were performed and eighteen mechanical damage anomalies were examined in 2009. The results of the inspections at each excavation are shown in Attachment 1 includes photographs of several of the anomalies inspected in the field. No visual signs of excavator damage were found; the source of the damage was attributed to rocks for most of the anomalies. Three of the anomalies had metal loss range from 3% to 9% of the wall thickness. One anomaly had minor gouging from a rock.

Analysis of the data showed a clear difference in the decoupled signals for dents with nominally the same dent geometry. Figure 20 shows the decoupled data in color and caliper data with lines for a moderate and a high priority anomaly as determined by the dual field methodology. Comparing the caliper data for both anomalies, the image on the right shows a slightly deeper, wider and more abrupt dent. This anomaly was rated as a moderate priority because the dual field magnetization technique did not detect any microstructural change or gouging at the deepest part of the dent. The image on the left shows a distinct signal at the deepest part of the dent that usually correlates with cold working of the steel; this signal caused the anomaly to be rated as a high priority. Both images show the stress signal at the shoulder of the dent (larger red areas), and a re-round signal away from the dent (large blue and grey area). The image on the right is very similar to some of the more severe anomalies created in test samples used for the development of the dual magnetization technology.

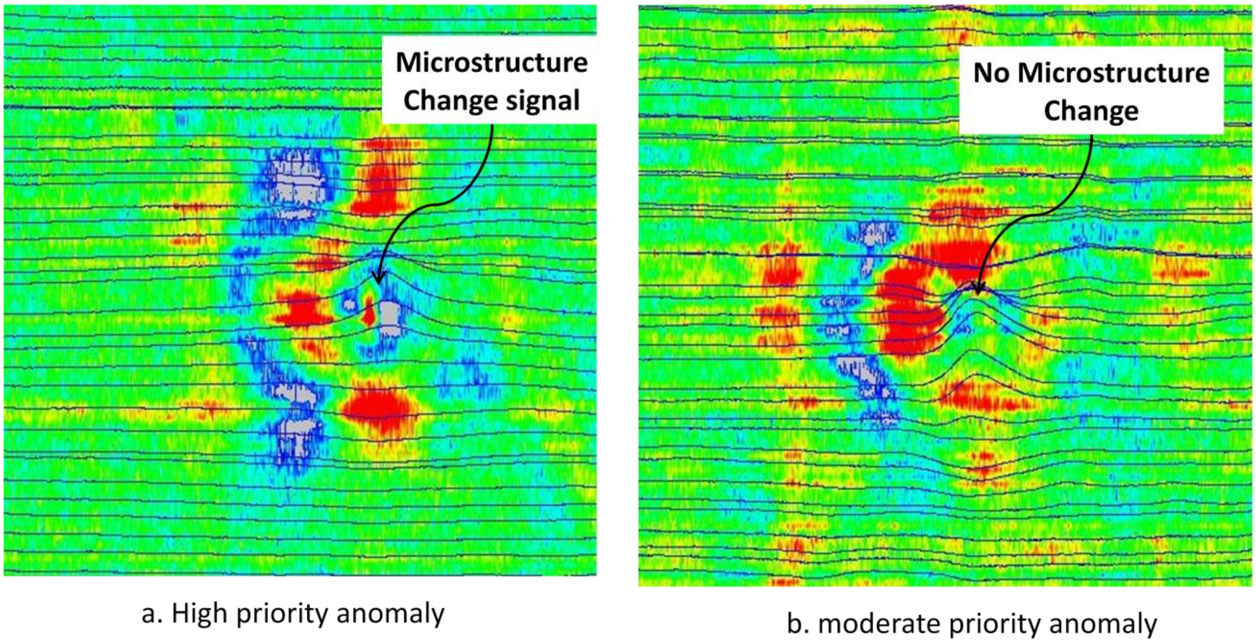


Figure 20. Decoupled MFL data in color and caliper data in lines for two dents on 30-inch liquid pipeline.

The in-the-ditch assessment methods used during field inspection did not find any signs of a microstructural change, gouging, cracking, or any other reason for the signal change in the decoupled signal. These anomalies (i.e., dents) were relative limited in size and many of the subtle features may not have been easily observed using the visual assessment methods. As reported above, one of the dents showed visual indications of minor rock gouging.

There are limitations in the current standard in ditch assessment technologies/methods for characterizing the effects of cold working, strain hardening, and residual stresses in pipelines impacted by mechanical damage. New, more sensitive nondestructive testing methods are being developed and were evaluated during the in ditch inspections performed for the anomalies identified for the dual-field MFL tool run in Line 2. These methods are needed to detect and characterize the pipe condition and properties (to the extent possible) at dents. These data will improve the understanding of the dual-field MFL signals and provide better correlation between ILI and in ditch measurements

Conclusion – Line 1

While this first field demonstration of the dual field MFL technology did not uncover any severe mechanical damage anomalies, many aspects of the tool were demonstrated. The signal patterns from the data obtained in the Line 1 tool run were very similar to the signals reported during the development of this technology. The decoupling algorithm and assessment methodology that was developed on pull through data were able to be implemented by a commercial inspection vendor and were useful in assessing data from an operating pipeline. Using features from the decoupled signals, the anomalies could be differentiated and prioritized.

The results show that the dual magnetization method is sensitive to metallurgical and stress changes at anomalies in an operating pipeline. Understanding these conditions is a key element of an operator's integrity management program, and is very valuable for the assessment of mechanical damage anomalies. Additional work is required to establish thresholds to differentiate benign mechanical damage anomalies from actionable anomalies.

Pipeline 1 Metallurgical and Mechanical Analysis

The project initially included this task for features that showed cold working or other indications where additional detailed analysis of the stresses and strains in the pipe structure, relative to the decoupled dual-field tool signal, would provide supporting information and data to further validate the ILI tool performance. Due to the absence of any features of substantial signal or indications of material property and/or metallurgical changes to the pipe, there were no opportunities for a cut out of a section of the line inspected and subsequent detailed metallurgical or mechanical analysis. In addition, other projects being implemented by PRCI and in partnership with DOT have addressed the metallurgical and mechanical analysis of mechanically damaged pipe, including work completed under DOT OTA DTPH56-05-T-001 (Understanding Magnetic Flux Leakage Signals for Mechanical Damage) and DTPH56-08-T-00011 (Structural Significance of Mechanical Damage). These projects included very detailed characterization of the damaged region associated with dent+gouge mechanical damage, including sectioning of damaged pipe test samples (created specifically for full-scale burst an fatigue failure of dent+gouge features) and complete materials and metallurgical characterization to identify material properties and changes in structure/microstructure as a result of the damage. In addition, neutron diffraction analysis has been performed on a series of the cut outs from the dent+gouge test pipes created for full-scale laboratory testing and has shown a correlation in the materials characterization data and metallurgical changes in the damaged region and the through wall residual stresses measured using neutron diffraction. With the availability of the above information, the Project Team elected to utilize these data and deferred pipe cut outs as a matter to be addressed if needed going forward.

Pipeline 1 Critical Comparisons

For the features identified, the results from the commercial dual-field MFL tool did compare well to the results of the prior tool development work performed by Battelle on a prior PRCI and DOT project. However, not all defect classes (based on the prioritization and ranking using the decision tree) were found on the section of pipeline inspected by the dual-field tool, such as dents greater than 2% on top of pipe with and without gouges.

Pipeline 1 Data Comparison –Correct/Enhance Algorithm

While the Rosen tool performed very similar to the prototype tools developed by Battelle and the prior PRCI and DOT project, changes to the algorithms were made during the data evaluation process. Thresholds for cold working and re-rounding were established for the analysis process. The data were examined based on the Line 1 excavation and ILI tool run data, and no additional changes were required to the algorithm based on those results. As indicated several times earlier in this report, the anomalies were limited in extent and there were no unexpected conditions or data that warranted further evaluation and adjustment to the data processing algorithms.

8.0 Inspection Results Operating Pipeline 2

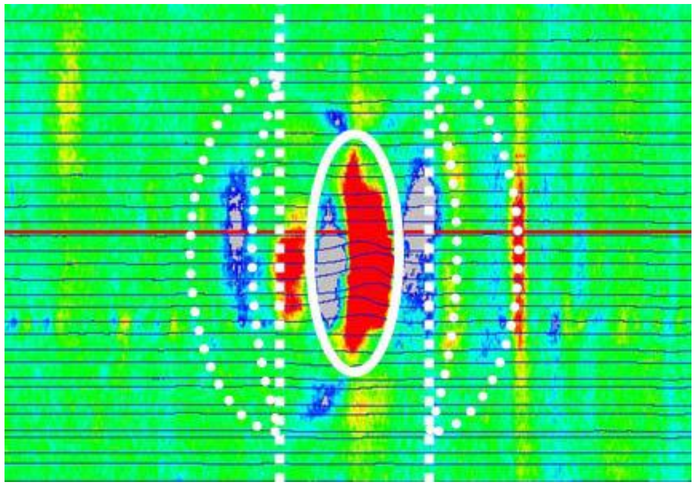
Rosen performed an analysis of the data from the dual-field MFL tool run in Pipeline 2, a natural gas pipeline, after completing the ILI tool run in April 2010. The results were compared to data from the in-field direct examination of the features selected for excavation. One of the items to be addressed in the Pipeline 2 tool run and dig proposal for the direct inspection of features for the natural gas line was identifying any alternative in ditch methods for measuring material properties. The dual-field MFL tool provides indications of areas where the materials properties of the pipe are affected by mechanical damage, such as small-scale gouging and cold working, however, there are limited comparable methods of measuring, and quantifying those affects in the field. During the course of implementing this project, several innovative technologies and approaches have evolved to support the verification of the ILI data from the dual-field tool and were applied during the Pipeline 2 in ditch inspection work.

The second dual field run, conducted in April 2010, used the same tool configuration as the first run in May 2008 (Pipeline1) and attained signals patterns very similar to the signals during the first run and the initial work and tests conducted during the development of this technology in the beginning of 2008. For consistency in the new evaluation process, the same R&D engineer has evaluated both data sets. This allows a better comparison of Pipeline 1 with Pipeline 2. A standardized report for dual field analysis was developed; the report for Pipeline 2 is in Attachment 2.

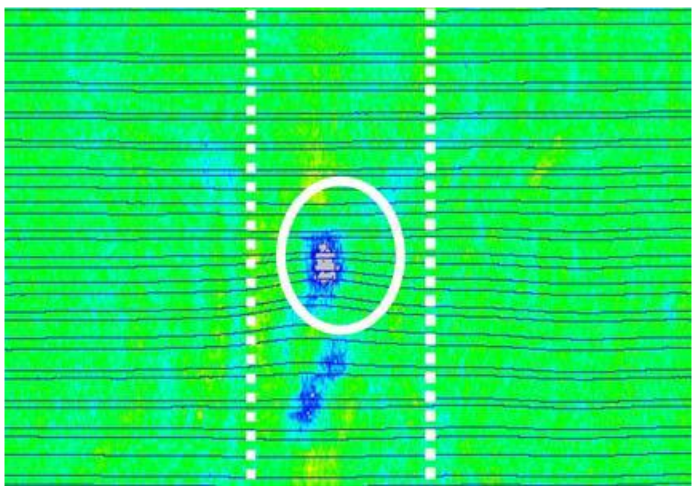
Line 2 Data Analysis

Rosen analysis of the data from the dual-field MFL tool run in Line 2 showed 85 features identified based on the dual-field MFL signals. Rosen's evaluation was targeted on identifying a range of defects to validate and emphasize the dual-field tool capabilities for detecting mechanical damage defects characterized by cold working, strain hardening, and/or residual stresses. The inspection features are included as Table 1 in Attachment 2. Rosen and Battelle completed further analysis of the Pipeline 2 dual-field MFL data to identify the priority features for in ditch inspection. Of the 85 features identified in Rosen's preliminary analysis, Battelle targeted 8 features for potential in-ditch inspection and ranked and prioritized the features. These 8 features were evaluated by PRCI's Project Team to identify which will be excavated and to determine the most appropriate in ditch methods for validation of the dual-field technology. Two final sites selected for direct inspection.

Figure 21 shows the two ID anomalies (dents) with a high priority and low priority ranking. Decoupled signal data is shown with the color image and caliper data are overlaid in line view. The outline of the dent is shown with the solid white line. The original dent length before rerounding is indicated by the dashed vertical lines in both images, and the reround halo is only seen in the high priority anomaly. Dent depths were similar for the two dents, however, the dent strain as seen in the disturbance in line data is higher for anomaly identified as high priority in by the dual field analysis. In-the-ditch measurement methods will assist in further identifying possible micro-structural changes.



a.) high priority anomaly



b.) low priority anomaly

Figure 21. Decoupled data in color scan and caliper data overlaid in the lineview.

Line 2 Critical Comparisons

Applus RTD provided mechanical damage scanning and analysis for the two locations selected for direct inspection. Scanning of the pipeline was also performed by JENTEK Sensors, leveraging work sponsored by PHMSA under other related PHMSA R&D contracts. Applus RTD used the Handyscan 3D laser-based system to accurately and efficiently measure and assess mechanical damage on the external surface at locations agreed to between the pipeline operator, RTD, and the Project Team. Applus RTD coordinated its field measurements with those of JENTEK Sensors, Inc. to perform measurements at the excavation locations to assess MWM-Array (variable wavelength array VWA001, variable wavelength array VWA003 and/or MWM-Array FA24) performance for mechanical damage profilometry and residual stress/microstructure mapping. The complete inspection results for the external assessment are in Attachment 3.

Dent 1, shown in Figure 22, is a bottom side dent with a plow/gouge signal and re-rounding halos from the ILI tool run data. The dent was marginally above 2% in depth and showed residual strains of greater than 6%. Dent 2, shown in Figure 23, was a top side dent with an adjacent hard spot and pressure cycling halos. The three dimensional (3-D) laser scan representation of dent 1 and dent 2 are shown in Figures 24 and 25 respectively. The VWA001 MWM-array scans of dent 1 and dent 2 are shown in Figures 26 and 27 respectively. The FA24 MWM-array scan was performed for dent 2 only and is shown in Figure 28.

Figure 22. Photogaph of Dent 1. This is a bottom side dent at 07:20.

Figure 23. Photogaph of Dent 2. This is a top side dent 12:20. The pipe is wrapped in plastic.

Figure 24. Three dimensional (3-D) laser scan representation of Dent 1.

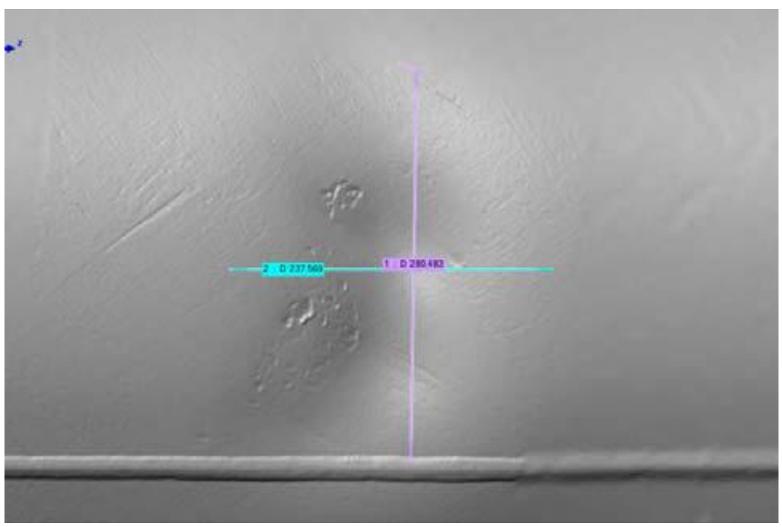


Figure 25 Three dimensional (3-D) laser scan representation of Dent 2.

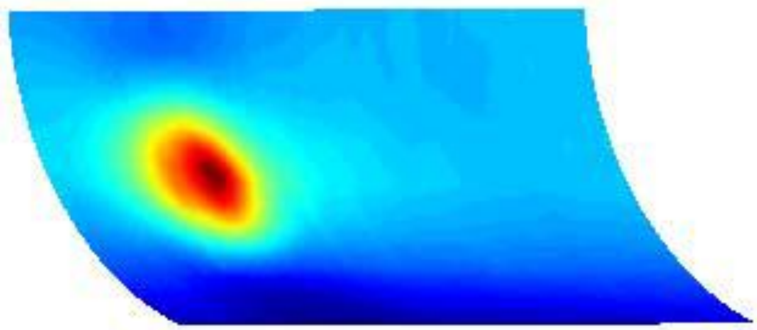


Figure 26. VWA001 MWM-array scans of Dent 1.

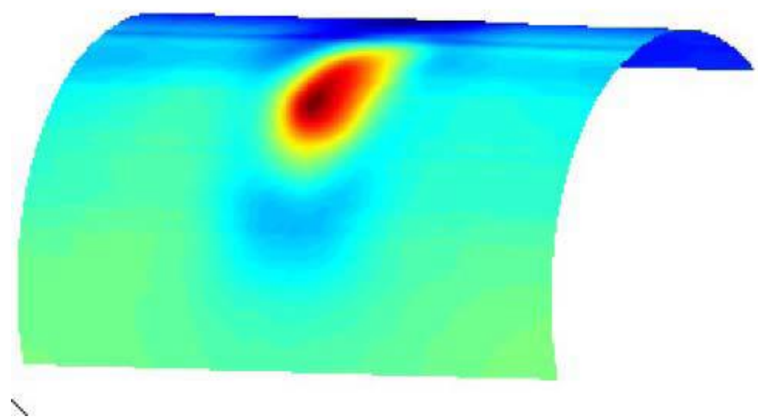


Figure 27. VWA001 MWM-array scans of Dent 2.

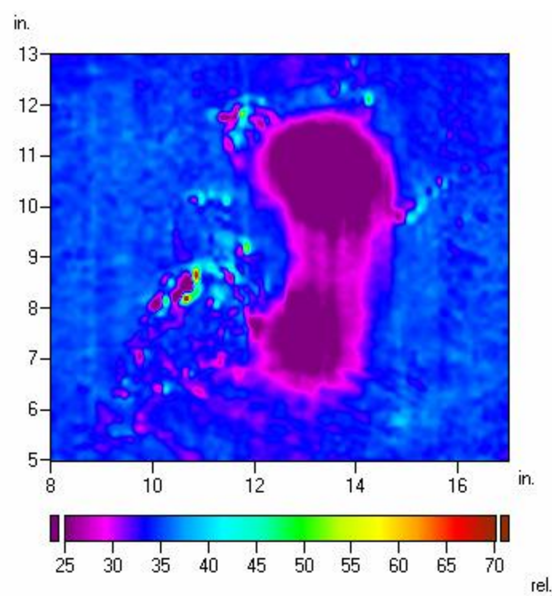


Figure 28. FA24 scan taken circumferentially in and surrounding the dent. Variations in permeability can be indicators of stresses, material changes (hard spots), and cracks.

The in-ditch inspection data confirm that the dual-field MFL ILI tool is effectively identifying mechanical damage features with secondary indications such as metal loss, residual stresses, and permeability variations. There was a gouge confirmed at Dent 1 based on the in ditch data and no gouge reported for Dent 2, consistent with the ILI tool run results. In addition, the ILI tool effectively characterized the features, with the length, depth, and width as determined by the in ditch tools showing good correlation with the ILI data. The tables below show the comparisons of the in ditch measurements for mechanical damage features to the ILI data.

Table 2. The Length, Depth, and Width of Dents as Measured by the Dual Field Tool, the Handyscan and the MWM-Array for Dent 1

DENT 1	ILI	Handy Scan	Difference	MWM-array	Diff.
Dent Length (mm)	207	444.17	237.17	576.102	369.102
Dent Width (mm)	171	221.39	50.39	227.167	56.167
Dent Depth (mm)	19.05	22.87	3.82	20.281	1.231
Dent Depth (%WT)	2.5	3	0.5	2.63	0.13

Table 3 The Length, Depth, and Width of Dents as Measured by the Dual Field Tool, the Handyscan and the MWM-Array for Dent 2

DENT 2	ILI	Handy Scan	Difference	MWM-array	Diff.
Dent Length (mm)	187	237.57	50.57	307.81	120.81
Dent Width (mm)	212	280.48	68.48	309.326	97.326
Dent Depth (mm)	17.53	23.62	6.09	22.956	5.426
Dent Depth (%WT)	2.3	3.1	0.8	3	0.7

The data show that there are some discrepancies with the length and width measurements, but that the depth data show good correlation. Assuming that the 3D and MWM-array data are within reasonable ranges of accuracy with limited uncertainty, they likely provide the best measure of the true feature dimensions rather than the ILI data. These data have been provided to Rosen Inspection and are under evaluation with regard to improving tool performance. Tool performance could include adjustments and further engineering for sensors (placement, number, etc.) and adjustment to the data processing software and algorithms.

Line 2 Tool Improvements

As indicated above, the inspection data has been delivered to Rosen Inspection following the completion of the field inspection work and Rosen has completed work on assessing the needed improvements to the ILI tool. Based on these results, the appropriate improvements to the tool were made.

9.0 Conclusion

The dual field inspection technology was successfully transferred from a research and development prototype to a commercial in-line inspection company. This involved configuring a pair of pipeline ready MFL magnetizers with the appropriate sensors and data recording equipment as well as implementing data analysis algorithms. The commercial tool was initially tested using pull testing under controlled conditions to ensure tool performance matched previous results. Following the pull tests and confirmation of the dual-field MFL tool performance, two operating pipeline segments were inspected and field excavations were performed for direct examination of mechanical damage features identified to confirm technology performance.

The commercial implementation of the dual field technology was used on two 30-inch diameter operating pipeline, one liquid and the other natural gas. The analysis method sorted through nearly 500 dents on the two pipelines, with only a few indicating the potential for mechanical damage. For the first pipeline, thirteen excavations were performed and eighteen anomalies were examined. No visual signs of excavator damage were found; the source of the damage was attributed to rocks for most of the anomalies. Three of the anomalies had metal loss range from 3% to 9% of the wall thickness. One anomaly had minor gouging from a rock. These results enabled the calibration of the analysis algorithms. For the second line, two excavations were performed; one at a location with gouging expected, the other excavation was at a dent with similar depth but no secondary features identified by the dual field tool. There was a gouge confirmed first excavation based on the in ditch data and no gouge reported for Dent 2, consistent with the ILI tool run results.

The results of the project confirm the performance capabilities of dual-field MFL ILI technology for detecting mechanical damage in operating pipelines. The use of a dual magnetization approach allows for the identification of secondary features and changes in pipe material and metallurgical properties that may not be provided by standard geometry/caliper tools or single field, high magnetization MFL. The development of dual-field MFL ILI technology provides the pipeline industry with a broader range of tools for pipeline inspection when mechanical damage is identified as a threat to be addressed as part of an integrity management plan. Continued development and improvements in pipeline inspection technologies will support decisions on repair, remediation and rehabilitation of mechanical damage and other features and improve pipeline safety.

Inspection of pipeline systems requires an integrated approach that includes the use of non-destructive examination (NDE) methods, techniques, and technologies for direct examination of features on pipelines that are identified using ILI tools. This project included verification of the performance of the dual-field MFL technology for detecting mechanical damage and its related effects on the pipeline using emerging in ditch technologies. The technologies included those being funded and supported through separate collaborative efforts of PRCI and DOT, such as the MWM technology. Additional parallel work on calibration samples and assessment algorithms are being developed concurrently under PRCI funding. The commercialization of dual field is only one part of the industry wide effort to address mechanical damage on operating pipelines.

Attachment 1 – Run 1 Results

ATTACHMENT 1

RESULTS OF EXCAVATIONS FOR MECHANICAL DAMAGE FEATURES

Dual-Field MFL Tool development and Verification

Line 1

Excavation Data and Photographs of Selected Features

Pig Distance	Caliper dent depth	Field Depth	ILI o'clock	Field Clock	Plow/gouge signal	Rerounding halo signal	Pressure cycling halo	Metal loss	Priority	FIELD Comments and Observations
2,139	1.10%	0.15%	05:29	5:45		**T**	**T**		**HIGH**	Dent start 8.3' from GW, end 9.1' - 10in long, 0.045" deep 165-180 deg, 4.5" circ. width. **See Photo #1**
2,820	1.40%	0.83%	01:39	1:57	**F**	**T**	**T**		**HIGH**	Dent start 9.7' from GW, end 11.15' - 16.5in long, 0.250" deep, 53-64 deg, 3.5" circ. width minor corrosion at dent - 0.008in
3660 3662	2.00%	0.55%	5:31	5:40	**T**	**T**	**T**		**HIGH**	**dent 1** - 0.109" deep - from 8.1' to 8.9', 9"L, 170-180 deg, 5" circ. width, no thinning **dent 2** - 0.036" deep - from 10.5" to 11.2', 10"L, 160-180 deg, 7" circ. width, thinning-9% **dent 3** - 0.165" deep - from 11.55' to 12', 8"L, 46-65 deg, 8.4" circ. width, no thinning **See Photo #2**
28,930	1.30%	1.20%	12:59	1:28	**F**	**T**	**T**		**MOD. HIGH**	Dent start 11.65' from GW, end 12.75' - 1.1ft long, 0.360" deep, 31-57 deg, 9" circ. width no corrosion observed - rock indenter **See Photo #3**
36,786	0.60%	0.55%	03:08	3:25	**F**	**T**	**F**		**MOD. HIGH**	no corrosion observed - rock indenter Dent start 1.95' from GW, end 2.95' - 12in long, 0.265" deep, 88-117 deg, 9" circ. Width
45,865	1.30%	0.48%	12:59	1:16	**F**	**T**	**F**		**MOD. HIGH**	no corrosion observed - rock indenter **dent 1** - 0.143" deep - from 24.65' to 25.32', 8"L, 29-47 deg, 6" circ. width, no thinning
45,867	2.00%	1.05%	12:57	1:22	**T**	**T**	**T**		**HIGH**	no corrosion observed - rock indenter **dent 2** - 0.314" deep - from 27' to 27.8', 0.8ftL, 30-52 deg, 7.75" circ. width, no thinning
72,741	1.40%	1.03%	12:13	12:31	**F**	**T**	**F**		**MOD.**	no corrosion observed - rock indenter Dent start 13.35' from GW, end 14.1' - 9in long, 0.309" deep, 5-26 deg, 6.5" circ. width

Pig Distance	**Caliper dent depth**	**Field Depth**	**ILI o'clock**	**Field Clock**	**Plow/gouge signal**	**Rerounding halo signal**	**Pressure cycling halo**	**Metal loss**	**Priority**	**FIELD Comments and Observations**
120,381	0.90%	0.69%	12:53	1:32	**T**	**T**	**T**	**T**	**HIGH**	rock indenters **<u>dent 1</u>** - 0.208" deep - from 35.35' to 35.85', 6"L, 38-54 deg, 5" circ. width, max thinning 0.023in
120,383	1.30%	0.99%	12:35	12:47	**T**	**T**	**F**		**HIGH**	**dent 2** - 0.298" deep - from 37.9' to 38.6', 7"L, 11-36 deg,9" circ. width, no thinning
207,241	0.80%	1.16%	3:24	3:42	**T**	**T**	**T**		**HIGH**	no corrosion observed - unknown indenter Dent start 7.9' from GW, end 8.75' - 0.85ft long, 0.349" deep, 98-124 deg, 7" circ. width
210,453	1.40%	0.58%	07:15	5:40	**T**	**T**	**T**		**HIGH**	no corrosion observed - rock indenter Dent start 18.325' from GW, end 19.24' - 0.915ft long, 0.175" deep, 214-239 deg, 7.5" circ. width
217,354	0.80%	1.10%	3:19	5:40	**T**	**T**	**T**		**HIGH**	0.331" deep, minor gouges - rock indenter Dent start 36.6' from GW, end 37.4' - 9.5" long, 100-135 deg, 9" circ. Width. **See Photo #4**
272680 272682	0.90%	1.06%	03:24	3:45	**T**	**T**	**T**		**HIGH**	dug in 2004 - 5pics - 2 dents in photos but only details in report for one dent <u>from 2004 report</u>: Smooth dent / No metal loss or cracking associated with dent. Minor laminations and inclusions in dent area. **<u>dent 1</u>** - start 13.80' from GW, end 16.25', 29.4" long, 1.06% deep, centre at 03:45 (range: 03:00 to 04:15), 10.5" circ. extent **<u>dent 2</u>** - from pictures, appears to be about 10-11ins d/s of u/s dent; same orientation
690,223	0.80%	0.77%	5:36	5:40	**W**			**T**	**HIGH**	0.230" deep - rock indenter Dent start 23.4' from GW, end 24.5' - 1.1ft long, 160-180 deg, 8.1" circ. width

Photo #1

Photo #2


Photo #3
MP 1271.7308
Flow
31°
9" wide
57°
13.2" Long

Photo #4


MP 1313.
.331" D x
Neodymium Magnet
Neodymium Magnet
Empire
Guaranteed Accurate to .00050"/inch
em71.24 6061 Aircraft Aluminum Chassis

Attachment 2 – Line 2 Inspection Report

ROSEN

Mechanical Damage Survey Report

PRCI Project Ref: MD-1-1
Contract Number: DTPH56-06-000016 – Project A

The Inline Inspection has been performed in a 30" Natural Gas Pipeline in Canada.

CDX Survey Date: April 18, 2010

ROSEN

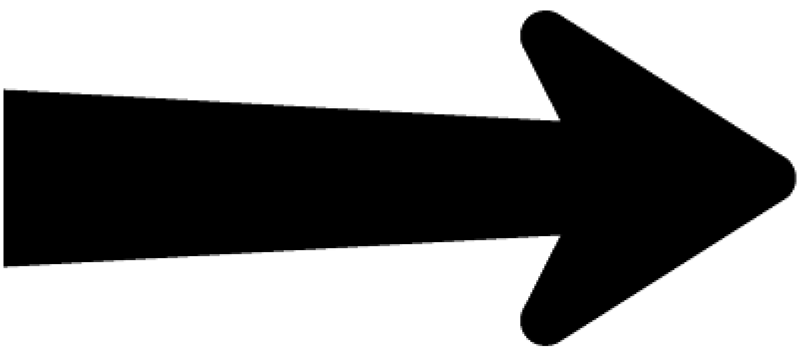
Mechanical Damage Survey Report

PRCI Project Ref: MD-1-1

Contract Number: DTPH56-06-000016 – Project A

The Inline Inspection has been performed in a 30” Natural Gas Pipeline in Canada.

CDX Survey Date: April 18, 2010



Client PRCI
Project No DTPH56-06-000016 – Project A
Line Name Pipeline 2
Inspection Type Dual Field MFL with Caliper
Inspection Date April 18, 2010
Report Date August 30, 2010
Revision Number 0

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Approved by:

	Date	**Pages**	**Description**	**Prepared by**	**Checked by**	**Approved by**
A	Aug 30, 2010	106	Submission			
B	December 13, 2010		Revision – PRCI comments			

Table of Contents

1 | Introduction

This report presents the results of an in-line inspection (ILI) completed using dual-field magnetic flux leakage (MFL) technology for detecting mechanical damage. The inspection was performed in a 30" diameter natural gas pipeline located in Canada, and was conducted in April 2010. This report is focused on the outcome of the mechanical damage assessment.

The inspection activities included the following:

- Cleaning and Gauging with a ROSEN BIDI Pig (CLP)
- Metal loss mapping and high resolution geometry inspection with the ROSEN Corrosion Detection & eXtended Geometry Combo Pig (CDX)
- Hi-res XYZ mapping
- Mechanical Damage Detection and analysis

A diagram showing the configuration of the dual-field MFL tool is shown below in Figure1.

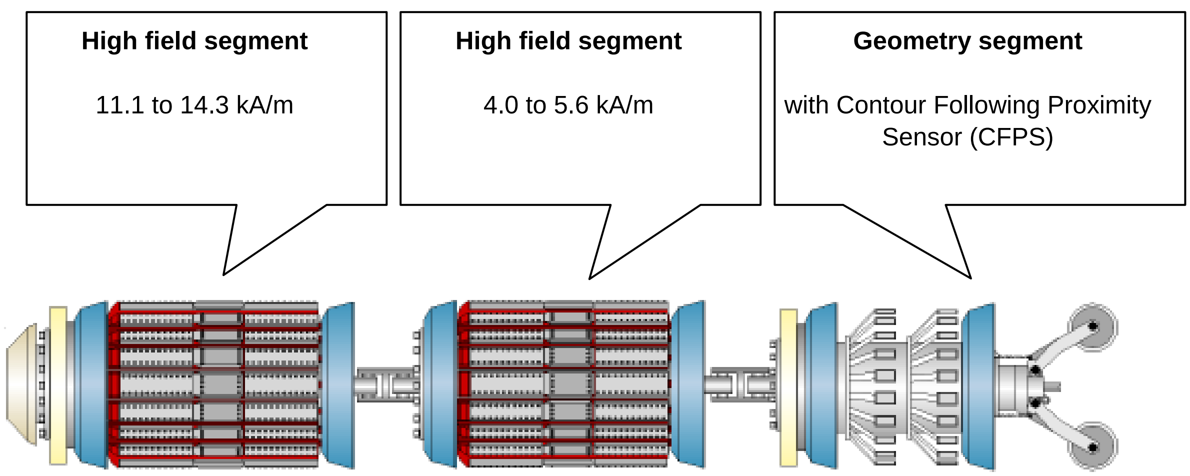


Figure 1: tool print of the 30" dual field MFL tool with high resolution caliper segment and XYZ mapping unit onboard

The data is automatically searched for pipeline anomalies using ROSEN Automated Feature Search Software (AFS). Thereafter, data evaluation personnel interactively verify the results utilizing proprietary software. Feature locations with mechanical damage parameters have been evaluated by applying Battelle's dual magnetization methodology utilizing ROSEN's hardware and software technology. All results are stored in database files (dbf).

This mechanical damage report includes the results of all inspection runs performed by ROSEN in the pipeline during these inspection activities including:

- High Resolution Dual Magnetization
- High Resolution Geometry
- Hi-res XYZ mapping

The recorded CDX distance is used as the master distance for reporting all inspection results. All anomalies that meet or exceed the reporting thresholds established for this project (i.e., anomalies) are listed in this report.

All distances are given in metric units. Upstream distances are designated with a minus sign (-). All anomalies are referenced to the upstream girth weld.

The CDX center distance of the first valve in the launcher station has been set to 0.00 meters to aid in field measurement efforts.

A Management Summary is provided in Section 2. Detailed inspection results are given in Section 4.

2 | Management Summary

This section describes the general condition of the inspected pipeline. For more detailed findings please refer to Section 4.

2.1 Management Summary Statement

In total, 85 locations have been selected for the evaluation of mechanical damage according to Battelle's dual magnetization methodology, proximity to hard spots, as well as metal loss and dent strain. Battelle's principles, technology, signal structure and evaluation methodology are derived from 'The Manual for the Detection, Classification, Analysis and Severity Ranking of Mechanical Damage Defects', R. J. Davis and J. B. Nestleroth, Battelle, July 2003.

Three mechanical damage features appear to be dents in close proximity with metal loss.

Dent strain analysis has been performed on all reported mechanical damage features. The dent strain values supplied represent the total internal and external dent strain and have been calculated in accordance with ASME B31G, but considering the suggested change in the formula.

2.2 Inspection Findings Summary

The findings of the inspection activities performed in this line segment are listed below. Different levels of the 'Severity Ranking' are in accordance with Battelle's methodology, where varieties of the decoupled signal pattern as well as caliper and corrosion information are considered. More details about this decision making process is given in Chapter 5.

Mechanical Damage Anomalies

Severity Ranking	All Anomalies	Gouge Signal	Re-rounding Signal
none	1	0	0
low	29	0	0
moderate low	0	0	0
moderate	8	0	6
moderate high	24	9	17
high	23	21	21
Total	**85**	**30**	**44**

Deformation Anomalies

Dents:	82
Dents detected with metal loss:	3
Total:	**85**

Deformation's Dent Strain Parameters

greater than 5%:	14
between 3% and 5%	54
smaller than 3%	17
Total:	**85**

2.3 Inspection Parameters

This section summarizes the parameters applicable to the dual-field MFL ILI activities carried out on this pipeline section in April 2010.

2.3.1 Pipeline Information

nominal diameter (NPS) [inches]	30
type of pipe	Longitudinal
grade	API 5L X70
minimum bend radius	6.0 D
length [km]	123.749

2.3.2 Data Quality Summary

The data recorded during the CDX inspection, performed on April 18, 2010, was accepted and used for evaluation purposes. The tool velocity was within the specified range of 0.5 to 5.0 m/s for the entire length of the tool run. The required magnetization values of the high field (11.1 – 14.3 kA/m) and the low field (4 – 5.6 kA/m) were also achieved over the complete length of the tool run. The total distance recorded by the CDX tool was 123,740.94 m.

Please refer to Chapter 3 for more information.

3 Inspection Activities and Data Quality

3.1 Metal Loss & eXtended Geometry Inspection (CDX)

The pipeline was inspected with the ROSEN Corrosion Detection & eXtended Geometry Combo Pig (CDX). One (1) CDX run was performed during the inspection.

Please note the following CDX run one (1) information:

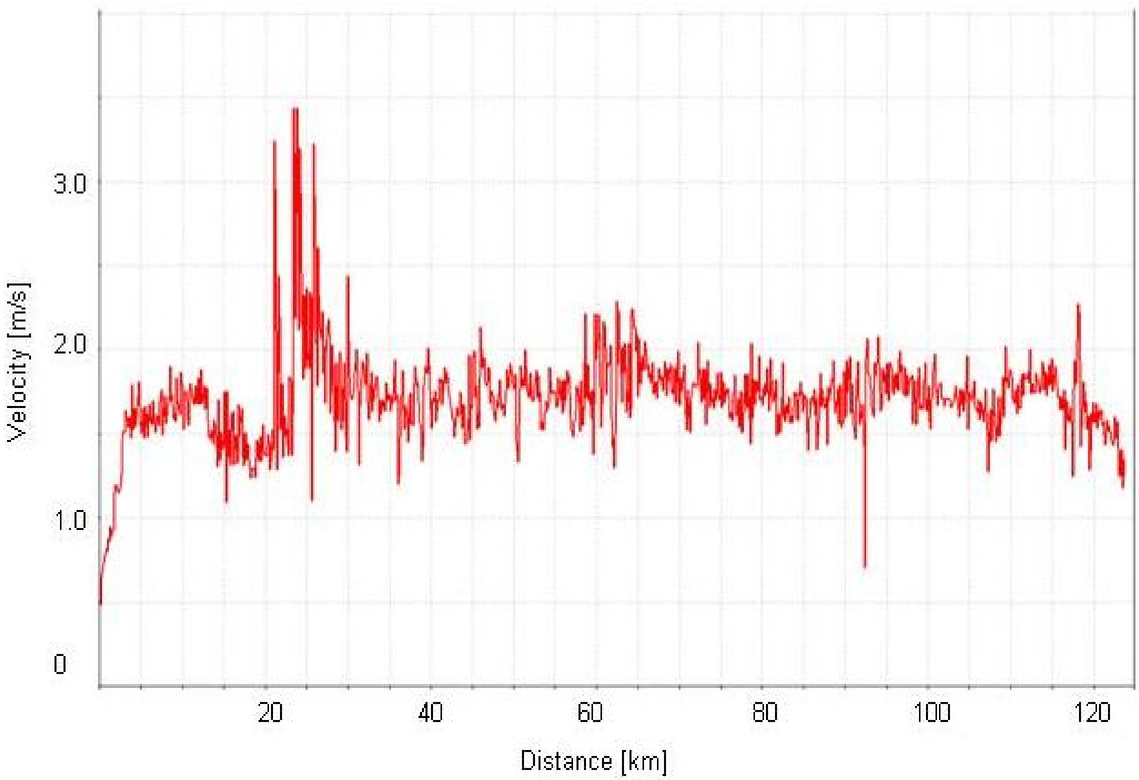
Inspection Conditions	
Launching Date/Time	April 18, 2010 / 1:05 PM
Receiving Date/Time	April 19, 2010 / 10:37 AM
Duration	21h 32min
Average Tool Velocity	1.7 m/s
Maximum Tool Velocity	3.4 m/s
Propellant	Natural Gas
Pressure (max.)	4.9 MPa
Temperature	5.0 °C

Tool Condition after the Run	
Cup Wear	None
Debris	Dust
Damage	None

Recorded Data	
Start of Data Recording	-22.599 m
End of Data Recording	123,786.547 m
Recorded Tool Rotation	Acceptable

3.1.1 CDX Tool Velocity

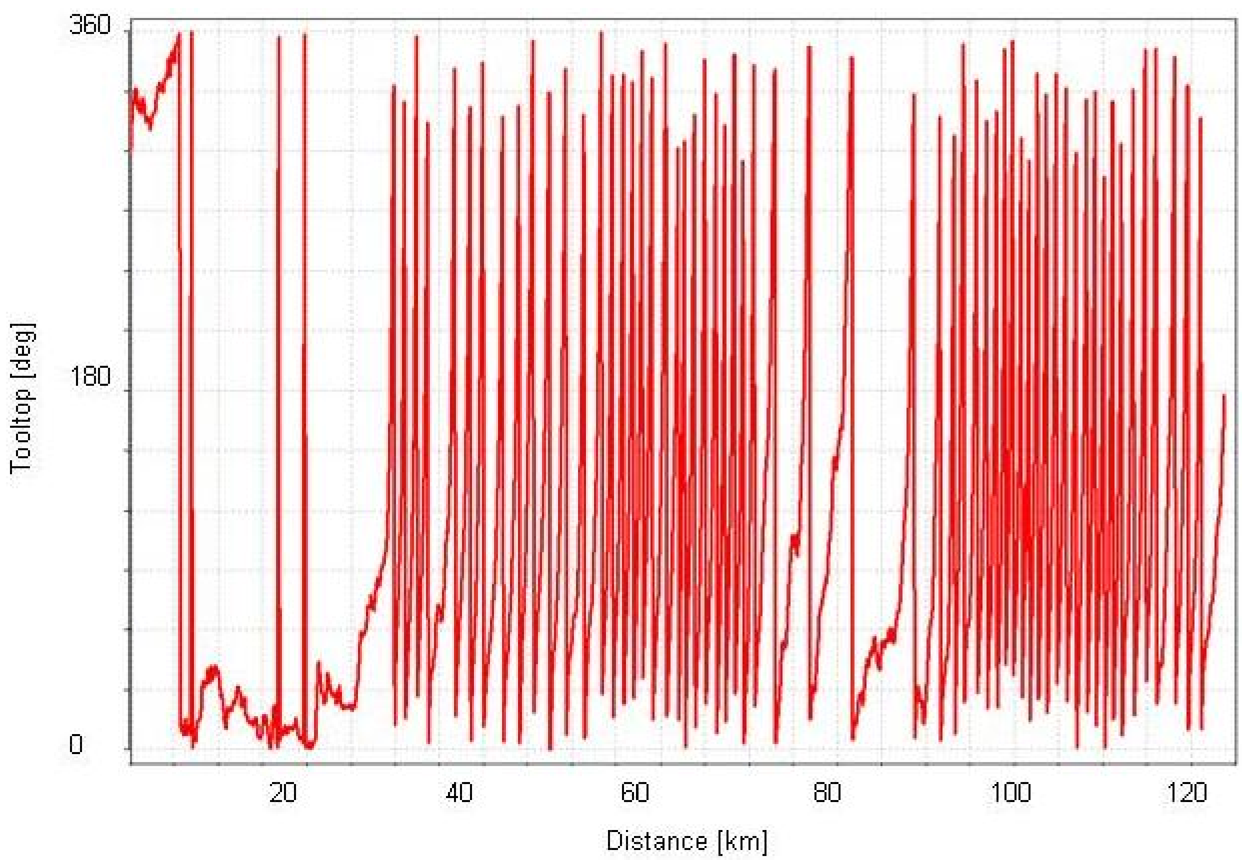
The CDX tool used during this survey was programmed to operate within a velocity range of 0.5 to 5.0 m/s. Generally, in all areas where the velocity is out of range, data quality may be slightly reduced. The following graph displays the minimum and maximum velocity of the tool during the survey, in per joint intervals.



The graph confirms that the tool velocity was within the specified range for the entire length of the run.

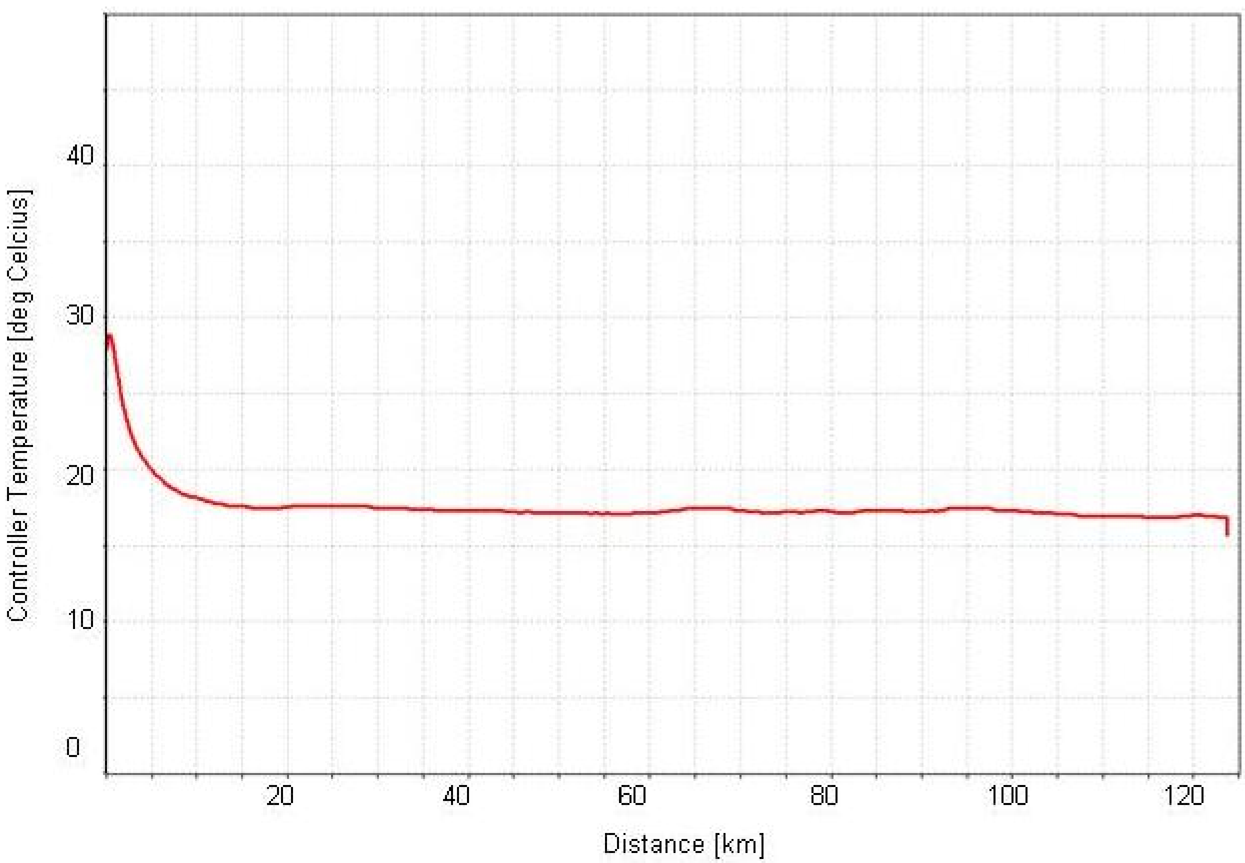
3.1.2 CDX Tool Rotation

The following graph displays the rotation of the CDX tool during the survey. The rotational position, provided in degrees, is measured counter-clockwise looking in the downstream direction.



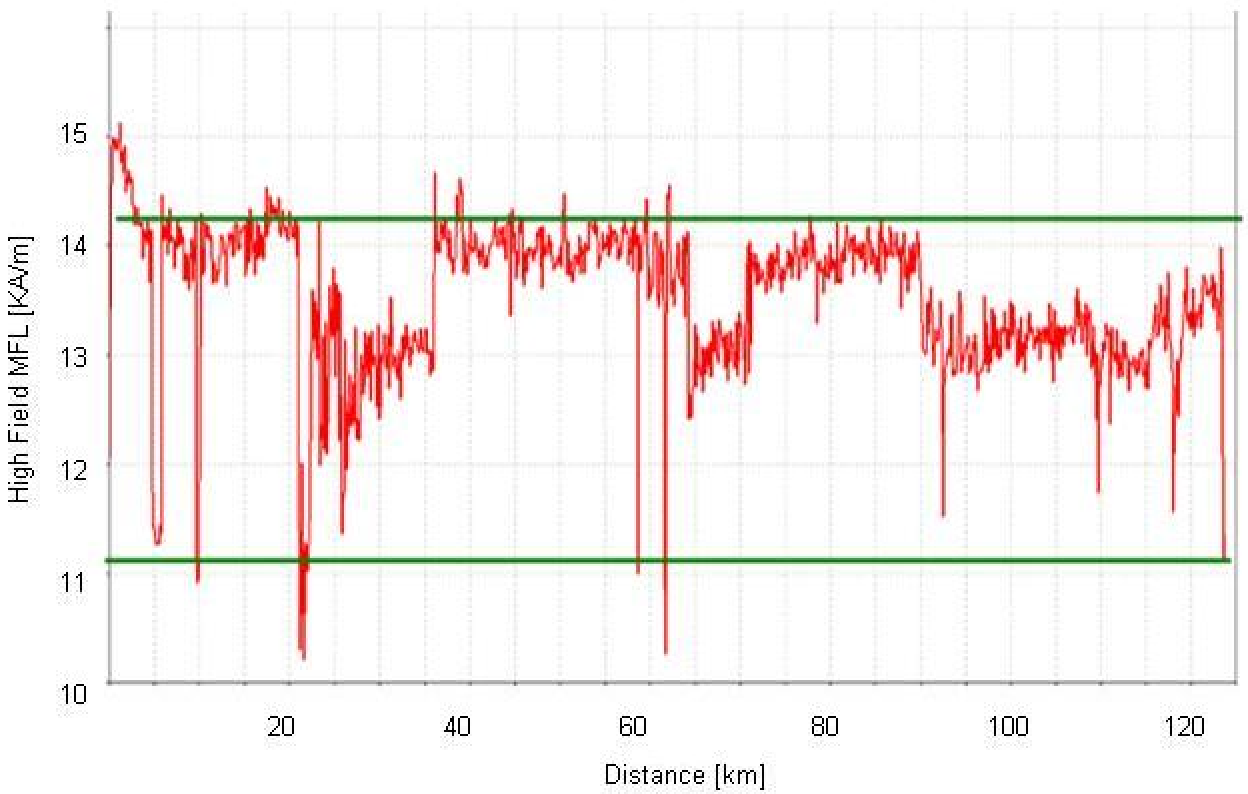
3.1.3 CDX Tool Temperature

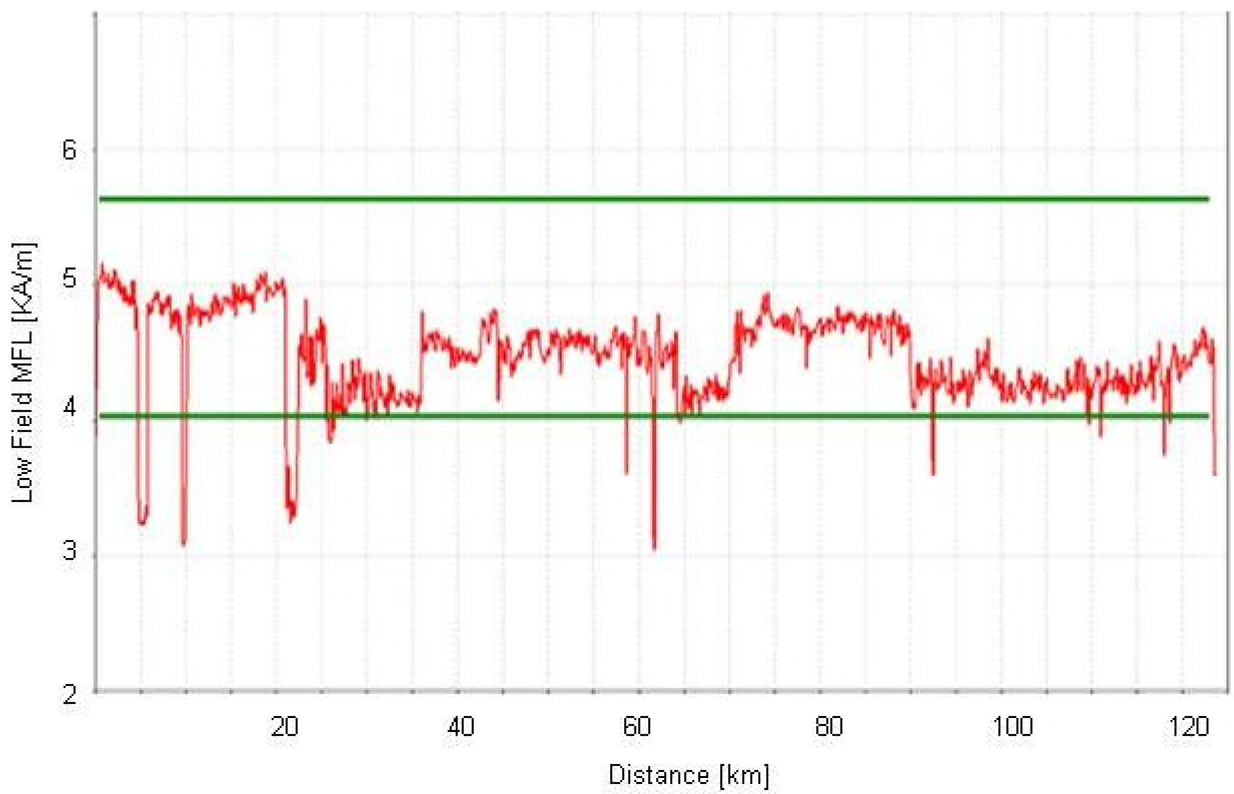
The CDX Tool Temperature graph displays the recorded temperature encountered during the survey. Because the temperature probe is housed inside the tool, it takes approximately 30 minutes for the probe to register the actual product temperature.



3.1.4 CDX Magnetization Levels

The magnetization levels achieved during the Dual Magnetization survey met the specifications for Battelle's Dual Magnetization methodology (green lines), ranging between 11.1kA/m and 14.3kA/m for the high field and between 4.0 kA/m and 5.6kA/m for the low field. Both Magnetization Level graphs display the recorded magnetization level on the pipe wall during the inspection.




6
5
4
3
2
Low Field MFL [KA/m]
20
40
60
80
100
120
Distance [km]

4 | Detailed Inspection Results

The detailed results of the inspection activities are presented in the following formats:

- List
- Screenshots

All distances are expressed in meters [m]. Upstream distances are designated with a minus (-).

4.1 Mechanical Damage Report

This list includes the dents undergone a specific analysis according to Battelle's dual magnetization methodology.

In addition to attributes specific to mechanical damage, the list includes the following information:

- id number
- log distance in meters
- length
- width
- dent depth in %

More details are given in Chapter 5.

4.2 Individually Sentenced Feature Reports (ISFRs) by Severity

ISFRs have been prepared for five (5) locations along the pipeline. These locations were chosen as features of interest and take into account Battelle's priority ranking, dent strain value and gouge signal.

Each ISFR includes the following:

- Feature Location Sheet
- Data Plots
  - of the affected pipe joint (complete circumference)
  - enlargement of the anomaly or event
- Pipe Tally

Additional Information

Please see below for additional information regarding the provided ISFRs (listed in order according to log distance):

ISFR No. 1 at log distance 1,512.246 meters refers to a dent anomaly with a depth of 2.2%, a maximum dent strain of 4.38%, on top of the pipeline, with a gouge signal and with severity ranking of 'high'.

ISFR No. 2 at log distance 6,022.887 meters refers to a dent anomaly with a depth of 2.3%, a maximum dent strain of 8.73%, on top of the pipeline, with a gouge signal and severity ranking of 'high'.

ISFR No. 3 at log distance 16,715.032 meters refers to a dent anomaly with a depth of 1.1%, a maximum dent strain of 2.85%, close to a girth weld, with a gouge signal and a ranking of 'moderate high'.

ISFR No. 4 at log distance 95,798.679 meters refers to a dent anomaly with a depth of 1.0%, a maximum dent strain of 3.72%, on top of the pipeline, with a gouge signal and a severity ranking of 'high'.

ISFR No. 5 at log distance 106,781.743 meters refers to a dent anomaly with a depth of 1.4%, a maximum dent strain of 4.50%, on top of the pipeline, with a gouge signal and a severity ranking of 'high'.

5 | List of Features

The detailed results of the mechanical damage analysis are presented in tabular format after a brief description of the general analysis approach. In addition to specific mechanical damage attributes, the following information is included for each feature:

No.	number of the corresponding dent feature
Center distance [m]	center distance of the dent feature (-box), given in meters
Length [mm]	length of the dent part of feature
Width [mm]	width of the dent part of feature
Dent depth [%]	depth of the dent part of feature
Ext. Strain [%]	external strain of the dent
Int. Strain [%]	internal strain of the dent
O'clock position	orientation of the dent feature, e.g. 12:00 as straight top of pipe

Additional attributes are reported for each feature which all pertain to mechanical damage characteristics. In the Figure 2 below, the idealized model of a decoupled signal is shown. Beside the extracted gouge/plow signal, halo signals are illustrated upstream and downstream (the 'blue half moons'). These halo signals can be negative or positive and they appear as either concave or convex. For illustration purposes, concave (negative) halos appear shaped as ') (' and convex (positive) halos are shaped as '( )'.In Figure 2, the halo signals are negative.

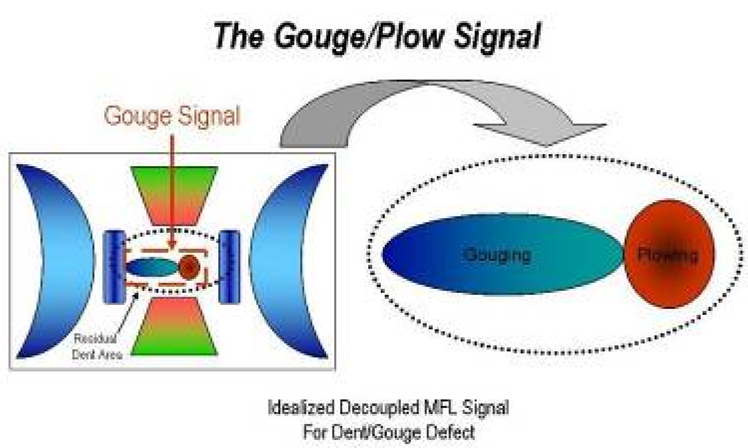


Figure 2: gouge/plow signal as illustrated by Battelle

The analysis process of the mechanical damage technology involves all recorded and processed data with high field, low field, decoupled signal and caliper data. Table 1 on the next page gives an overview of the data sources and their influence on the analysis process. Further, Figure 3 outlines the decision making process with parameters listed in the feature data table (Table 1) and finally leading to the priority ranking of mechanical damage features.

Decoupled Signature	Pattern Type	If Pattern Appears	Analysis of Pattern
Gouge	Dipole Signal	Presence of Gouge	Gouge Length, Severity Index
Rerounding	"Negative" Halo Signal	Rerounding Occured	Maximum Dent Depth, Severity Index
Pressure Cycling	Inner "Positive" Halo Signal	Subjected to Severe Pressure Cycling	None
Dent Wall Stress	Generally "Negative" Signal in Residual Dent Wall	Presence of Wall Stress	Severity Index
Other Stress Patterns	Generally "Positive" Signal Outside Residual Deformation	Presence of Other Stresses	None
Caliper Data	**Pattern Type**	**If Pattern Appears**	**Analysis of Pattern**
Residual Deformation	Residual Dent	Detection of Residual Dent	Residual Dent Depth, Residual Dent Profile
High Mag MFL Signal	**Pattern Type**	**If Pattern Appears**	**Analysis of Pattern**
Metal Loss	Metal-Loss Signature	Pipe Wall Thinning, Metal-Loss	Amount of Wall Thinning, Length of Wall Thinning
Remanent Field	**Pattern Type**	**If Pattern Appears**	**Analysis of Pattern**
MFL Signal	Small Flux Leakage	Large Residual Stress Gradients	Severity Index

Table 1: overview of data sources involved into the analysis approach

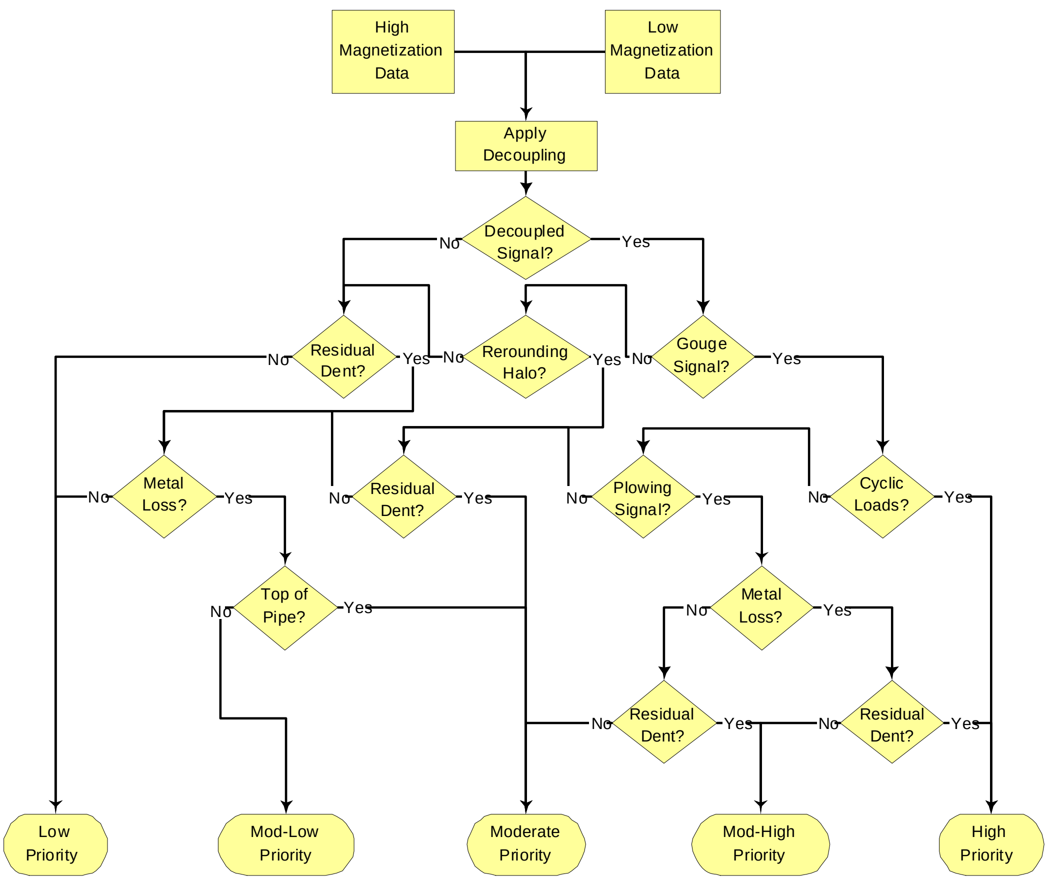


Figure 3: decision making process leading to the final priority ranking of feature

Client PRCI
ROSEN Project No DTPH56-06-000016 – Project A
ROSEN Line Name Pipeline 2
Inspection Type Dual Field MFL with Caliper
Inspection Date April 18, 2010
Report Date December 13, 2011
Revision Number 0

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No	Priority	plow / gouge dipole signal	monopole	dipole length > 2"	re-rounding halo signal	calc. max. dent depth (from halo length) [%]	max. dent depth > 4%	press cycling halo	other stress pattern	re-sidual dent	re-sidual dent >+ 2%	top of line	metal loss	high signal indices	comment
1	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
2	Mod High	FALSE	TRUE	FALSE	TRUE	5.4	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
3	High	TRUE	FALSE	FALSE	TRUE	6.0	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	halo end estimated
4	Mod High	FALSE	TRUE	FALSE	TRUE	6.0	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
5	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	2 adjacent dents
6	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
7	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
8	High	FALSE	TRUE	FALSE	TRUE	5.3	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	
9	High	TRUE	FALSE	TRUE	TRUE	5.9	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
10	Mod High	FALSE	TRUE	FALSE	TRUE	5.0	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
11	High	TRUE	FALSE	FALSE	TRUE	5.3	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	
12	High	TRUE	FALSE	FALSE	TRUE	5.0	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
13	Mod High	TRUE	FALSE	FALSE	TRUE	2.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW, halo start estimated
14	Moderate	FALSE	TRUE	FALSE	TRUE	5.0	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
15	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
16	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW
17	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
18	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
19	Mod High	FALSE	TRUE	FALSE	TRUE	5.7	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
20	Moderate	FALSE	TRUE	FALSE	TRUE	5.6	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
21	Moderate	FALSE	TRUE	FALSE	TRUE	5.5	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
22	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
23	Mod High	FALSE	TRUE	FALSE	TRUE	6.0	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
24	High	TRUE	FALSE	FALSE	TRUE	5.9	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	
25	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
26	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW
27	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
28	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW
29	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
30	Moderate	FALSE	TRUE	FALSE	TRUE	0.0	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW
31	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
32	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
33	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
34	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
35	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
36	High	TRUE	FALSE	TRUE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
No	Priority	plow / gouge dipole signal	monopole	dipole length > 2"	re-rounding halo signal	calc. max. dent depth (from halo length) [%]	max. dent depth > 4%	press cycling halo	other stress pattern	re-sidual dent	re-sidual dent >+ 2%	top of line	metal loss	high signal indices	comment
37	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	adjacent dent ca. 40cm u/s
38	High	TRUE	FALSE	FALSE	TRUE	5.1	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	halo end estimated
39	Mod High	FALSE	TRUE	FALSE	TRUE	5.7	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
40	Moderate	FALSE	TRUE	FALSE	TRUE	4.2	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo start estimated
41	Mod High	FALSE	TRUE	FALSE	TRUE	6.2	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
42	Mod High	FALSE	TRUE	FALSE	TRUE	5.8	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
43	Mod High	FALSE	TRUE	FALSE	TRUE	6.3	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	defect sensor at center of dent, halo end estimated
44	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
45	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
46	High	TRUE	FALSE	FALSE	TRUE	5.6	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	
47	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	close to GW, d/s halo pos ?
48	Mod High	FALSE	TRUE	FALSE	TRUE	6.4	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
49	Moderate	FALSE	TRUE	FALSE	TRUE	3.8	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo start estimated
50	High	TRUE	FALSE	FALSE	TRUE	6.1	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	
51	High	TRUE	FALSE	FALSE	TRUE	5.8	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	halo end estimated, second adjacent dipol (u/s)
52				FALSE		0.0	FALSE		FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	at GW no evaluation possible
53	High	TRUE	FALSE	FALSE	TRUE	5.1	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	halo end estimated
54	High	TRUE	FALSE	FALSE	TRUE	5.0	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	halo end estimated
55	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
56	Mod High	FALSE	TRUE	FALSE	TRUE	5.4	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
57	Mod High	FALSE	TRUE	FALSE	TRUE	6.3	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated

58	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	defect sensor at center of dent
59	High	TRUE	FALSE	FALSE	TRUE	6.6	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	
60	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
61	Mod High	FALSE	TRUE	FALSE	TRUE	5.2	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
62	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
63	High	TRUE	FALSE	TRUE	TRUE	5.8	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	close to GW
64	High	TRUE	FALSE	FALSE	TRUE	5.9	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	halo end estimated
65	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
66	Mod High	FALSE	TRUE	FALSE	TRUE	4.7	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
67	High	TRUE	FALSE	TRUE	TRUE	5.7	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
68	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
69	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
70	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
No	Priority	plow / gouge dipole signal	monopole	dipole length > 2"	re-rounding halo signal	calc. max. dent depth (from halo length) [%]	max. dent depth > 4%	press cycling halo	other stress pattern	re-sidual dent	re-sidual dent >+ 2%	top of line	metal loss	high signal indices	comment
71	High	TRUE	FALSE	FALSE	TRUE	5.4	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	halo end estimated
72	Mod High	TRUE	FALSE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
73	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
74	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	
75	Moderate	FALSE	TRUE	FALSE	TRUE	5.9	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
76	High	TRUE	FALSE	TRUE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	
77	High	TRUE	FALSE	FALSE	TRUE	4.7	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	halo end estimated
78	Mod High	FALSE	TRUE	FALSE	TRUE	5.8	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
79	High	TRUE	FALSE	FALSE	TRUE	5.1	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	halo end estimated
80	Mod High	FALSE	TRUE	FALSE	TRUE	5.3	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	halo end estimated
81	High	FALSE	TRUE	FALSE	TRUE	4.2	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	position of halo start estimated
82	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	defect channel at center of dent
83	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	defect channel at center of dent
84	Low	FALSE	TRUE	FALSE	FALSE	0.0	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	position of halo end estimated
85	High	TRUE	FALSE	FALSE	TRUE	5.6	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	position of halo end estimated

Attachment 3 – Applus RTD Report

Field Comparison Validation of Dual Field Magnetic Flux Leakage (MFL) Inspection Tool for Detecting and Characterizing Mechanical Damage

PRCI Task Order PR-366-103708
PRCI Project Reference. MD-1-1

DRAFT REPORT

November 28, 2011

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SUMMARY

Mechanical damage can pose hazards for pipelines thus effective characterization and analysis of mechanical damage becomes imperative. Regulations in the United States focus on dent depth (e.g. Part 195 of the Code of Federal Regulations or CFR for liquid pipelines). However depth alone may not accurately reflect the risk associated with mechanical damage. Residual stress and metallurgical damage need to be considered to properly assess severity, thus the regulations are general and may not fully consider all relevant details in certain cases as areas of residual stress can create magnetic anisotropy in steel thus altering the pattern of flux around a dent. The current MFL in-line inspection (ILI) technologies tools using a single saturated magnetic field have limitations in mapping mechanical damage, The Dual field MFL tool developed in MD-1-1 research together with dual strength magnetic fields and signal coupling may improve the efficiency to detect and assess mechanical damage. In this project, in-field mechanical damage mapping and analysis was performed on locations identified by the dual field MFL tool developed under MD-1-1 project. A PRCI member company deployed that ILI tool within a natural gas pipeline and two locations containing indications of mechanical damage that were predicted by the ILI tool were selected for subsequent excavation and direct examination to validate the dual field MFL ILI tool capabilities to identify residual stresses and metallurgical damage to the natural gas pipeline. PRCI requested Applus RTD to perform direct examinations at those locations using the Handyscan 3D Laser profilometry system. Additionally, Applus RTD sourced and managed a subcontractor (JENTEK Sensors) to perform measurements at the excavation locations using the Meandering Winding Magnetometer (MWM-Array) technology to evaluate its potential for measuring deformation and indications of residual stress.

Dimensions of mechanical damage, dent deformation as measured by Laser (Handyscan 3D), differed from MWM-Array. MWM-Array depths were smaller than Handyscan 3D depths. Such differences could be due to different reference frames for the two technologies (local reference versus pipeline centerline).

MWM-Array was able to create a 3-Dimentional image of the dent with colour gradients showing depth profile. This effort has shown the capability of MWM-Array to create a 3 dimensional profile of mechanical damage like dents. However this technology still needs to be developed further for which efforts are ongoing under a separate DOT sponsored research program (DOT 460) currently being conducted by the sub-contractor.

In case of hard spots, MWM-Array was able to show a difference in permeability in the areas of hard spot. The results of in-field hardness tests indicated more research would be needed to establish a relationship to correlate any changes in magnetic permeability with metal hardness.

While there are correlations between the data derived from the in-ditch methods for inspecting the dents and the dual field MFL ILI tool, the limited number of digs performed has resulted in a small population of data and no definitive conclusion regarding the performance of either the ILI tool or the in-ditch technologies can be made. Larger sample size with more comparisons can help in establishing better conclusions about the nature of MWM-Array technology or the performance of the ILI tool.

INTRODUCTION

The MD-1-1 research project, which is being jointly performed by Pipeline Research Council International and the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA), included development and testing of a Dual Field Magnetic Flux Leakage (MFL) In-line Inspection Tool (ILI) for detecting and characterizing mechanical damage.

This project involved:

- Building a dual field MFL ILI tool according to the specifications provided by PRCI and creating associated software. The tool consists of a dual field unit downstream of a coupled caliper arm (XGP) unit.
- Performing pull tests of the dual field MFL ILI technology on a 30 inch pipeline segment with mechanical damage features fabricated in the pipe.
- Running the dual field MFL ILI tool through a 30 inch diameter pipeline that is used to transport liquid petroleum products.
- Comparing the reported findings from the ILI tool run to field verification results
- Further optimization of the ILI technology (i.e., sensor and algorithm modifications) using verification results
- Then performing a second dual field inspection of a 30 inch diameter natural gas pipeline.

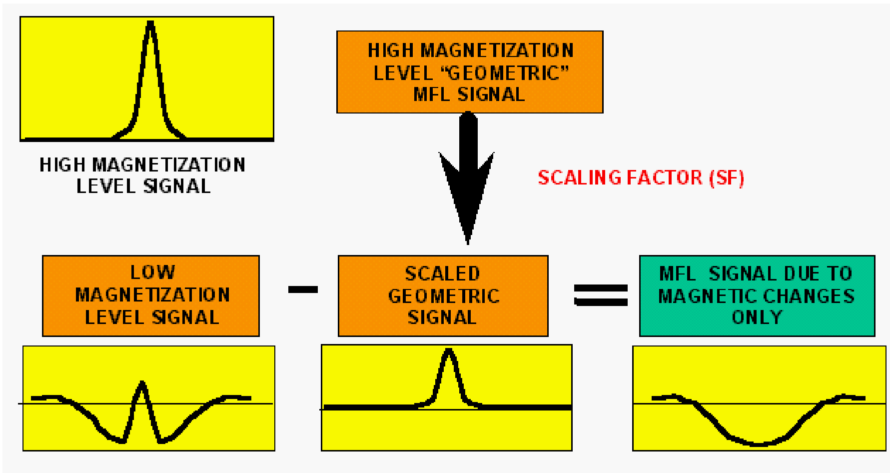
  <u>Goals for tool</u>

  - Identify anomalies that would otherwise go undetected and could ultimately result in failure
  - Better characterization of anomalies that are not service limiting but would require excavation by regulation

Tool Characteristics:

- A high field signal between 11.1 to 14.3 kA/m is primarily influenced by wall geometry including metal loss
- A low field signal between 4 to 5.6 kA/m is influenced by geometry, residual stress, and metallurgical damage

- Scaling the high field signal down to the level of the low field signal and subtracting results in a decoupled signal that is influenced primarily by stress and metallurgical damage
- Decoupling:
- This decoupling method should allow the characteristics of a dent-gouge feature to be more clearly understood at the field levels specified



[1]

Figure 1: Signal quality enhancement by Decoupling

(Testing of a Dual Field MFL Inspection Tool for Detecting and Characterizing Mechanical Damage

| A. Rubinshteyn | October 1, 2008)

The decoupled signal provided by a dual field tool may be useful for a more complete and accurate assessment of defects:

- Inspection outcome is a report that lists the evaluated anomalies and gives them a priority ranking according to a dual field decision making process.
- This decision making process is based on the presence and characterization of certain decoupled signal patterns

Field trials for the dual field ILI tool on operating pipelines were performed as part of the MD-1-1 research. Predictions of mechanical damage based on the dual field MFL ILI tool data were excavated and inspection of two mechanical damage features was performed by Applus RTD to provide supplemental NDE to fully characterize the actual mechanical damage conditions at the ILI prediction locations.

Bending strain calculations were not part of the scope and were performed separately by the pipeline operator.

METHOD OF EXECUTION

PRCI requested Applus RTD to provide mechanical damage scanning and analysis for two locations on an operating natural gas pipeline located near Thunder Bay, Ontario, Canada. The features to be inspected were identified by the Rosen Dual Field MFL Tool from an April 2010 tool run for a PRCI member company. The Rosen Dual Field Tool was developed as part of a PRCI co-sponsored research project and was run in the selected pipeline as part of that project.

Under this project, two locations were identified and directed by the PRCI member company (i.e. the operator of the pipeline) for mechanical damage mapping and analysis (GW 7510 AND GW 5420).These locations were analyzed using 3D Laser technology (Handyscan) by ApplusRTD and Prototype MWM-Array tests were performed by JENTEK Sensors, Inc.

The direct examination locations were within excavations performed and managed by the pipeline operator. Coating was removed by the operator and the pipe surfaces was sand blasted to a NACE 2 surface finish, hoarded and heated to provide pipe surfaces at 50F minimum. Applus RTD provided Conventional NDE Measurements, Laser Profilometry and Hardness survey. Applus RTD used Handyscan 3D laser-based system to accurately and efficiently measure and assess mechanical damage on the external surface at locations directed by the pipeline operator. Bending strain calculations were not part of the scope and were performed separately by the pipeline operator.

Applus RTD performed inspections on 01/26/2011 and on 01/30/2011. The process involved scanning the pipe within the excavation locations and then processing the data at Applus RTD offices in Houston.

Additionally, Applus RTD subcontracted JENTEK Sensors, Inc. (JENTEK) to perform measurements at these two excavation locations to assess MWM-Array (variable wavelength array VWA001, variable wavelength array VWA003 and/or MWM-Array FA24) performance for mechanical damage profilometry and residual stress/microstructure mapping. JENTEK Inc. provided MWM Array Scans and Magnetic Permeability.

JENTEK Inc. performed their inspections on 01/25/2011 and 01/27/2011. JENTEK used the VWA001 MWM-Array to investigate dent profile and the FA24 MWM-Array to investigate Magnetic permeability variation.

The objective of this report is to provide an assessment of the dual field MFL ILI tool as far as assessment of mechanical damage features is concerned, and the subsequent excavation and direct examination to validate its capabilities to identify residual stresses and metallurgical damage to the natural gas pipeline.

RESULTS

GW 7510

Handyscan 3D Data:

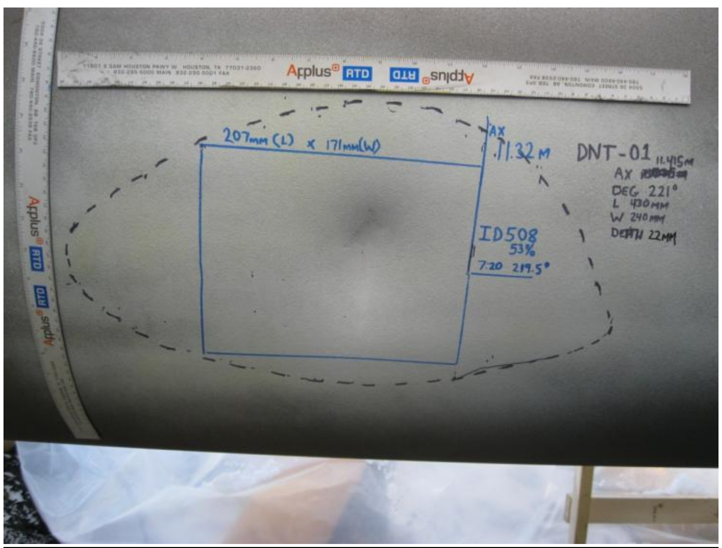


Figure 2: Actual Dent Picture (1)

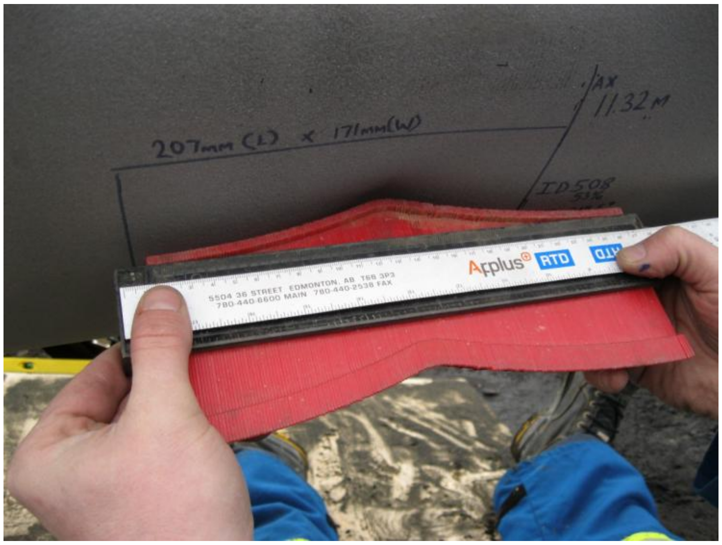


Figure 3: Actual Dent Picture (2)

Inspection Area

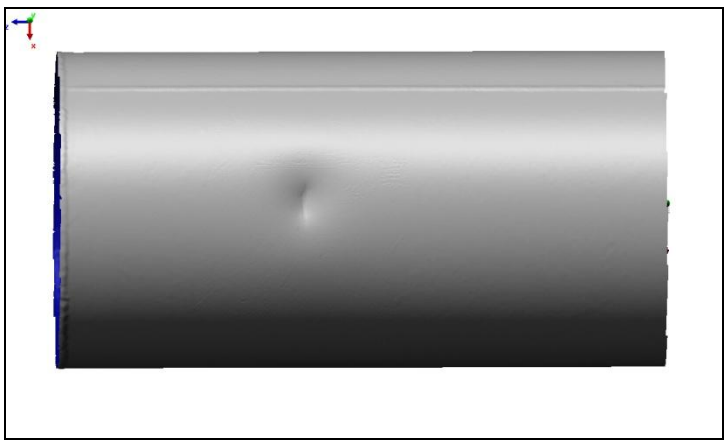


Figure 4: Inspection Coverage (3D Image from Handyscan 3D)

The pipe was mapped for a length of 1.4 meters, full circumference.

One of the key findings of in-ditch inspection was the discovery of a gouge. Its dimensions are given in Table 1.

Color Gradients

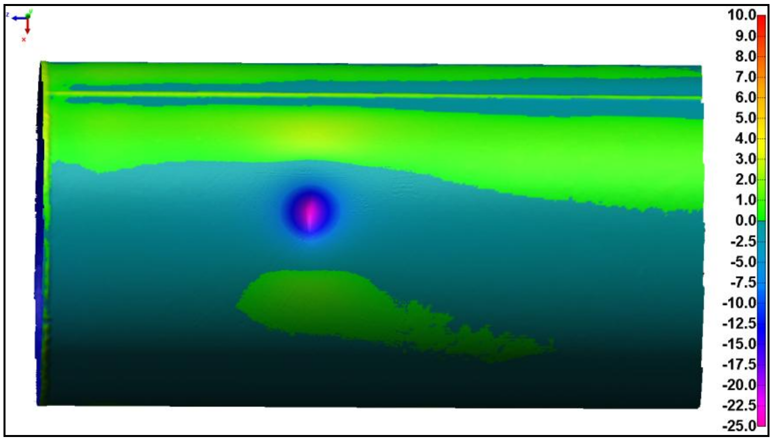


Figure 5: Color Gradient Map

The above images show the difference between the actual pipe body and a best-fit cylinder. The scale on the right (in millimeters) defines positive values as those areas that were larger than the best-fit cylinder, and negative values as those areas that were less than the best-fit cylinder. The minimum value on the scale is NOT the maximum deflection of the pipe as the best-fit cylinder is an ideal cylinder and not a true representation of the original pipe surface prior to deformation.

HandyScan 3D Measurements			
Measurement	Index	Millimeters	Inches
Dent Length	1	444.17	17.49
Dent Width	2	221.39	8.72
Total Depth	3	22.87	0.9
Dent Depth (% WT)	4	3	3
Gouge Length	5	24.76	0.97
Gouge Width	6	83.83	3.3
Gouge Depth	7	0.67	0.026
Gouge Depth (%WT)	8	<1% (.08)	<1% (.08)

Table 1: Handyscan 3D Measurements Girth Weld 7510

Length is measured parallel to the axis of the pipe and through the deepest point of the dent. The ends are chosen where pipe profile no longer shows any deflection.

Width is measured perpendicular to the axis of the pipe and through the deepest point of the dent. This dimension does not account for the curvature of the pipe but it the absolute distance between two points in space. (Figure 9)

Depth is the distance from the original pipe profile, or the highest points if bulging occurred, to the deepest point in the dent and gouge. (Figure 8)

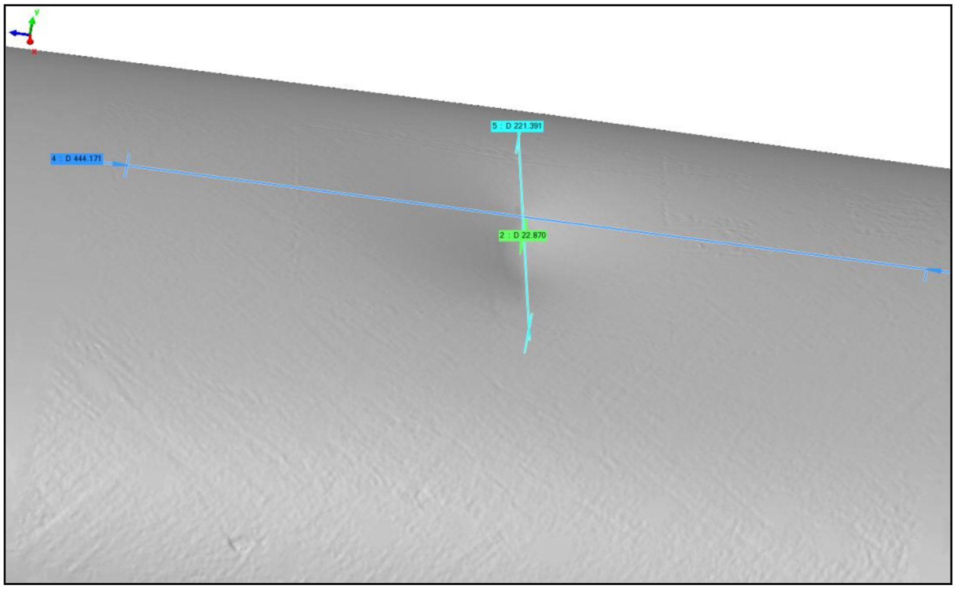


Figure 6: Isometric View of Length, Width, and Depth

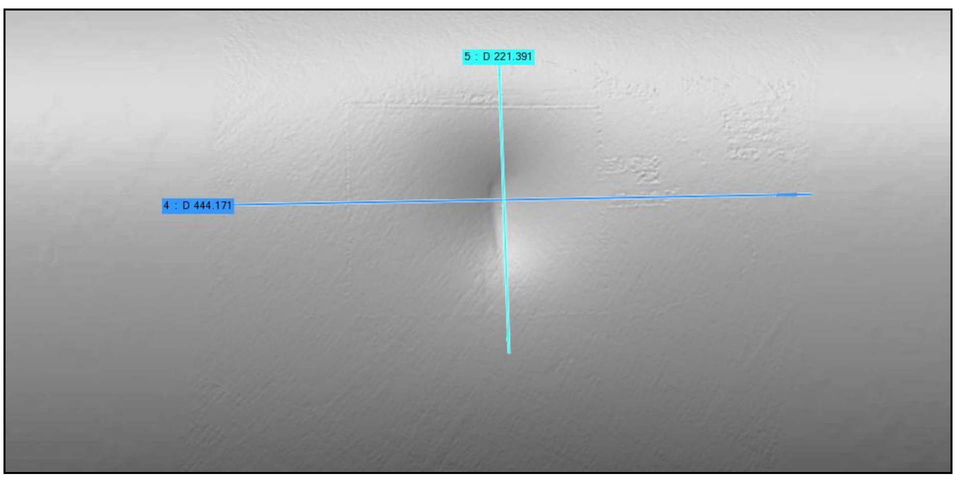


Figure 7: Axial View of Length and Width

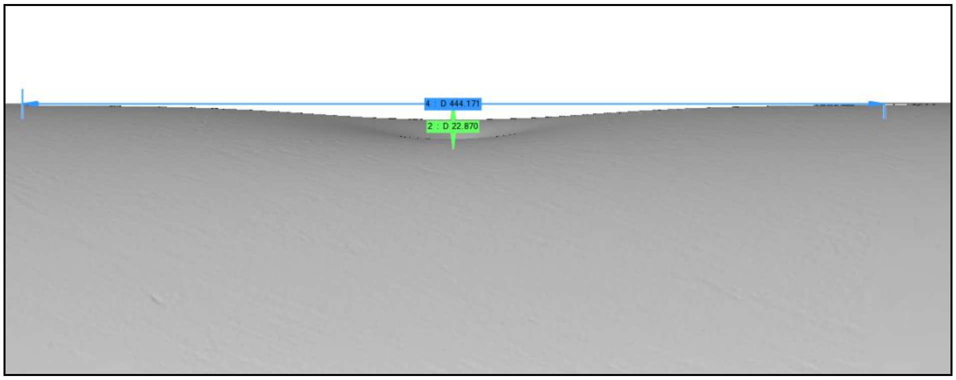


Figure 8: Length and Depth View

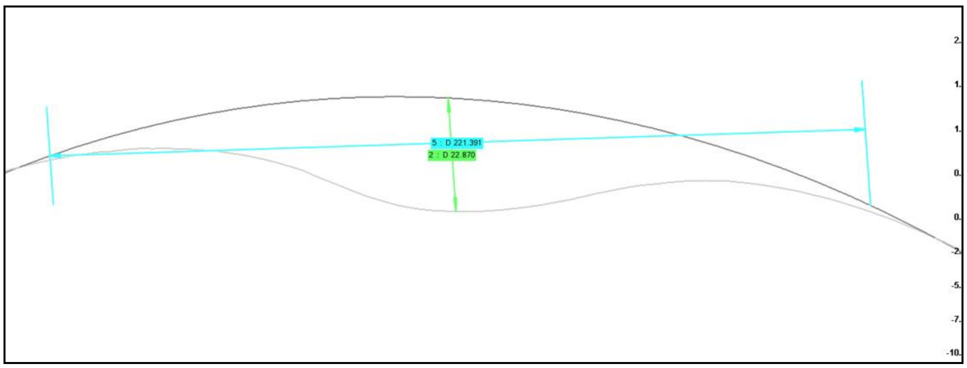


Figure 9: Width and Depth View

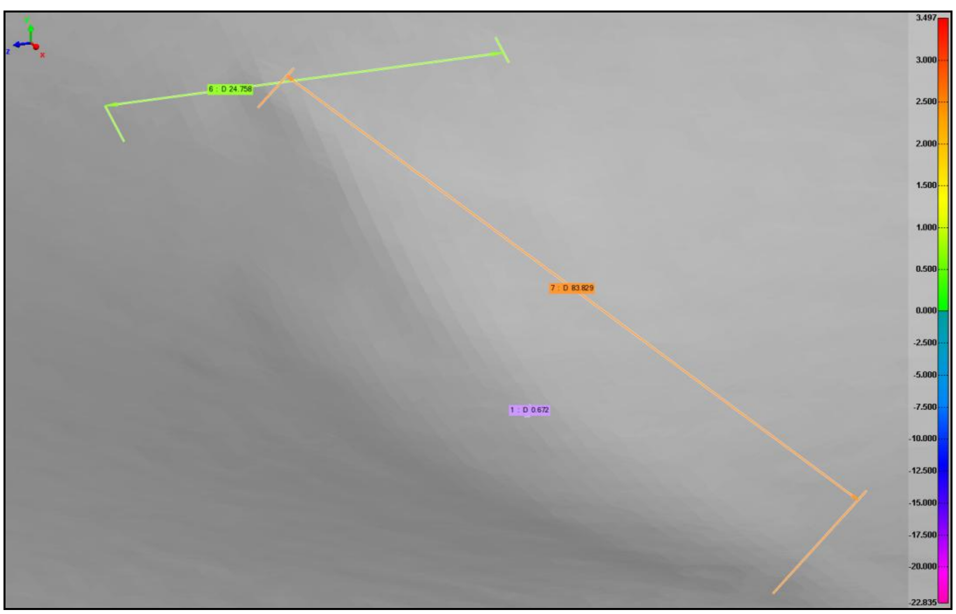


Figure 10: Isometric View of Gouge

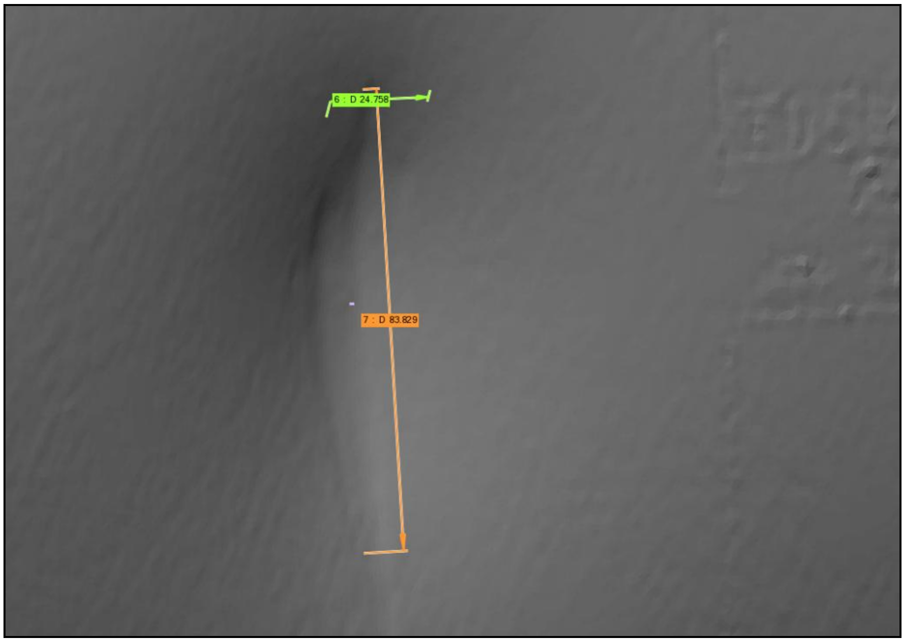


Figure: 11 Axial View of Gouge

MWM-Array data:

For the dent, scans were performed with the VWA001 MWM-Array (Figure 32). Three scans were performed at 5 inch spacing. The scanner covers an 8.25 inch wide scan area, so there is ample overlap between the scans (3.25 inches).

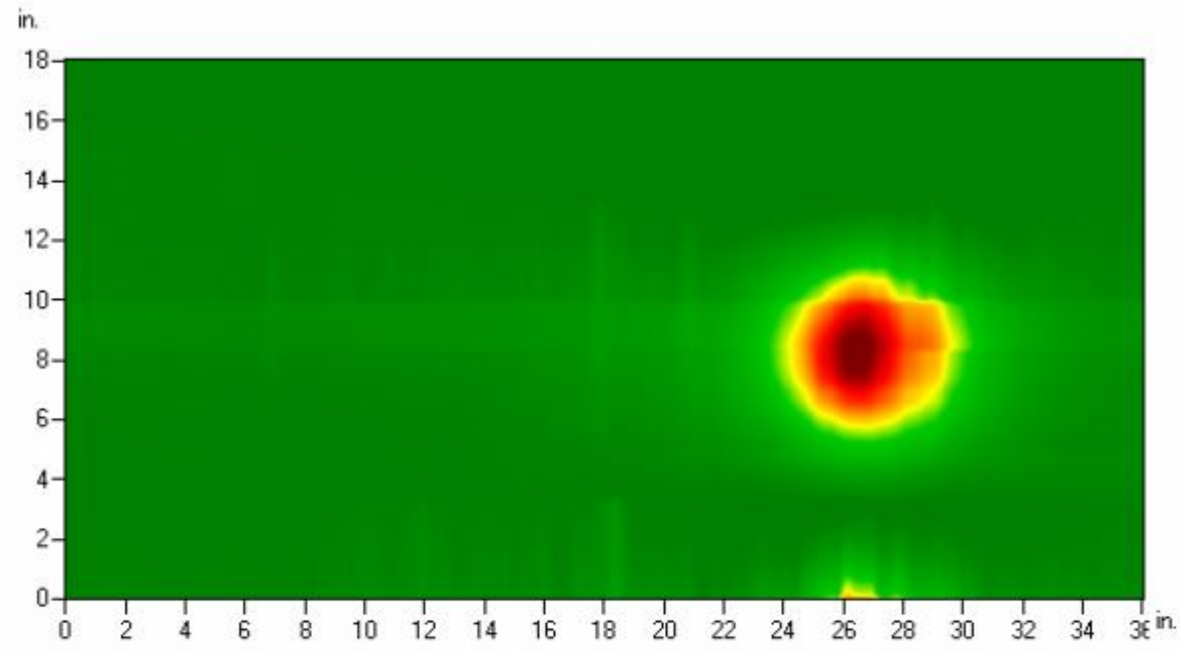


Figure 12: Dent profile image produced with the GridStation software. Color represents the depth of the dent relative to the nominal pipe surface

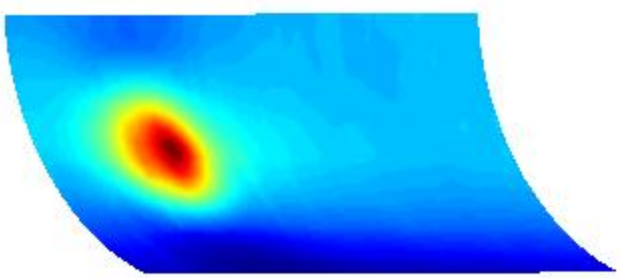


Figure 13: Dent 3D profile produced using the VWA001 data

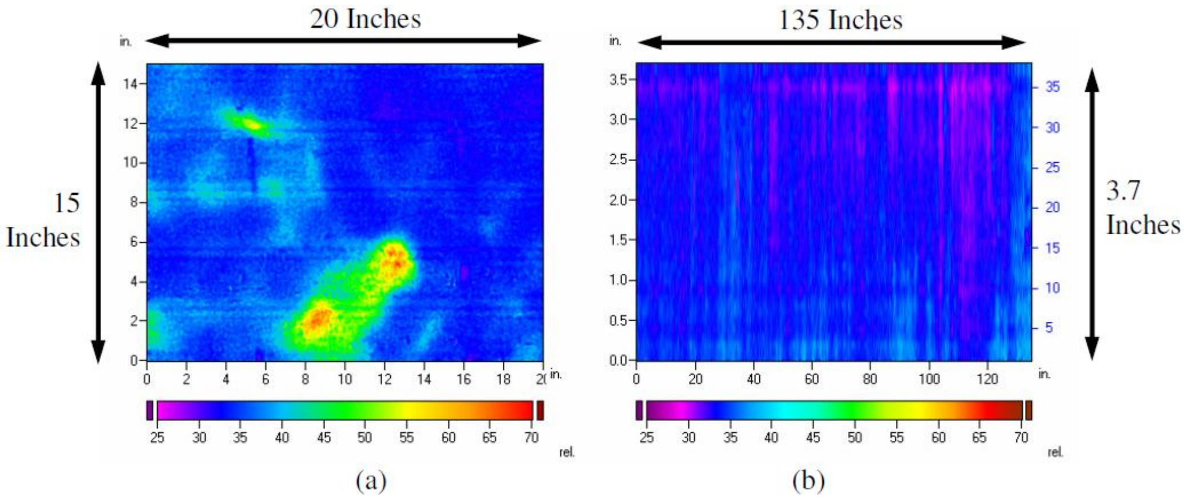


Figure 14: FA24 scans. (a) Permeability measurements in the area of the reported "hard spot". (b) Permeability measurements taken over a 135 inch by 3.7 inch section of pipe. The axes on this image are not on the same scale

GW 5420

Handyscan 3D Data:

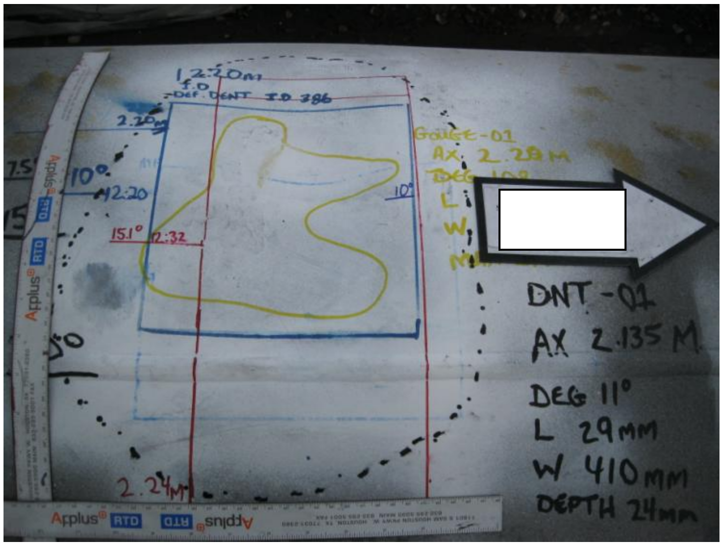


Figure 15: Actual Dent Picture (1)

Figure 16: Actual Dent Picture (2)

Inspection Area

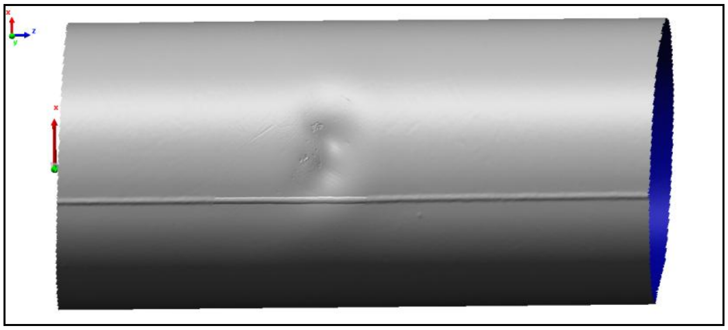


Figure 17: Inspection Coverage (3D Image from Handyscan 3D)

The pipe was mapped for a length of 1.5 meters, full circumference.

Color Gradients

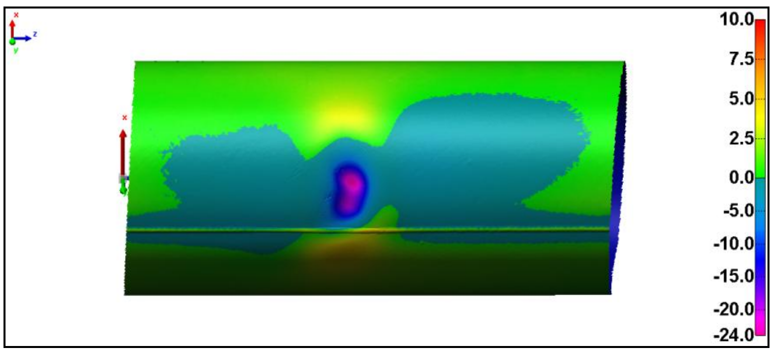


Figure 18: Color Gradient Map

The above images show the difference between the actual pipe body and a best-fit cylinder. The scale on the right (in millimeters) defines positive values as those areas that were larger than the best-fit cylinder, and negative values as those areas that were less than the best-fit cylinder. The minimum value on the scale is NOT the maximum deflection of the pipe as the best-fit cylinder is an ideal cylinder and not a true representation of the original pipe surface prior to deformation.

Handyscan 3D Measurements			
Measurement	Index	Millimeters	Inches
Dent Length	2	237.57	9.35
Dent Width	1	280.48	11.04
Total Depth	3	23.62	0.93
Dent Depth (% WT)	4	3.1	3.1

Table 2: Handyscan 3D Measurements Girth Weld 5420

Length is measured parallel to the axis of the pipe and through the deepest point of the dent. The ends are chosen where pipe profile no longer shows any deflection.

Width is measured perpendicular to the axis of the pipe and through the deepest point of the dent. This dimension does not account for the curvature of the pipe but it the absolute distance between two points in space. (Figure 22)

Depth is the distance from the original pipe profile, or the highest points if bulging occurred, to the deepest point in the dent. (Figure 21)

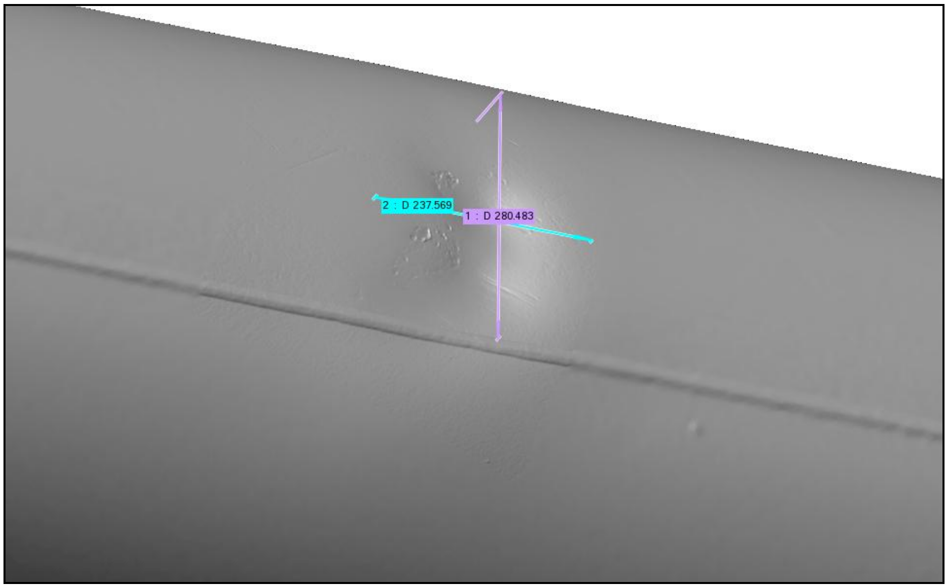


Figure 19: Isometric View of Length, Width, and Depth

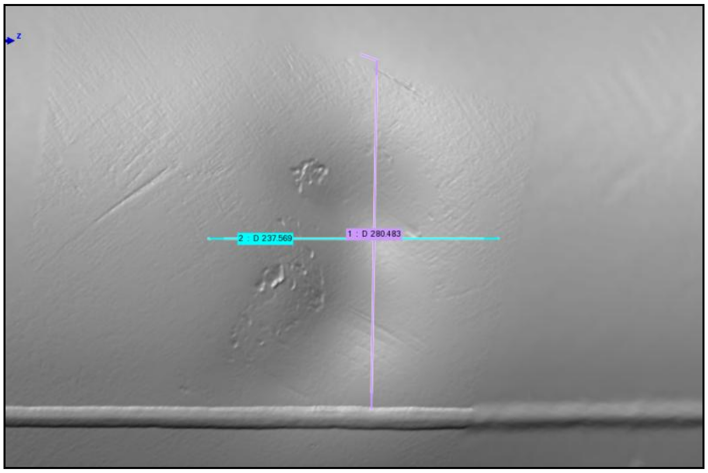


Figure 20: Axial View of Length and Width

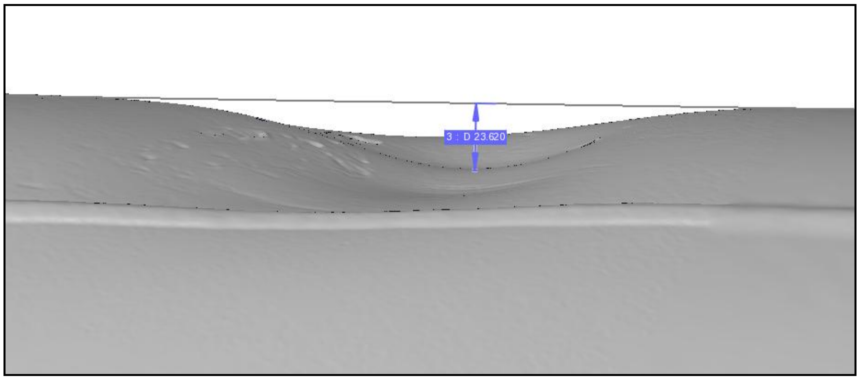


Figure 21: Length and Depth View

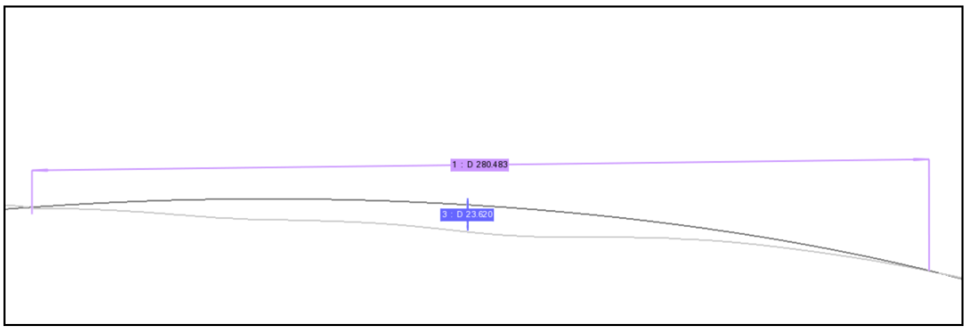


Figure 22: Width and Depth View

MWM-Array data

For the dent, seven scans were performed with the VWA001 at a 5 inch spacing (Figure 23). Set-up of the GridStation system was similar to the previous dig. Note that the scanner covers an 8.25 inch wide scan area, so there is ample overlap between the scans (3.25 inches)

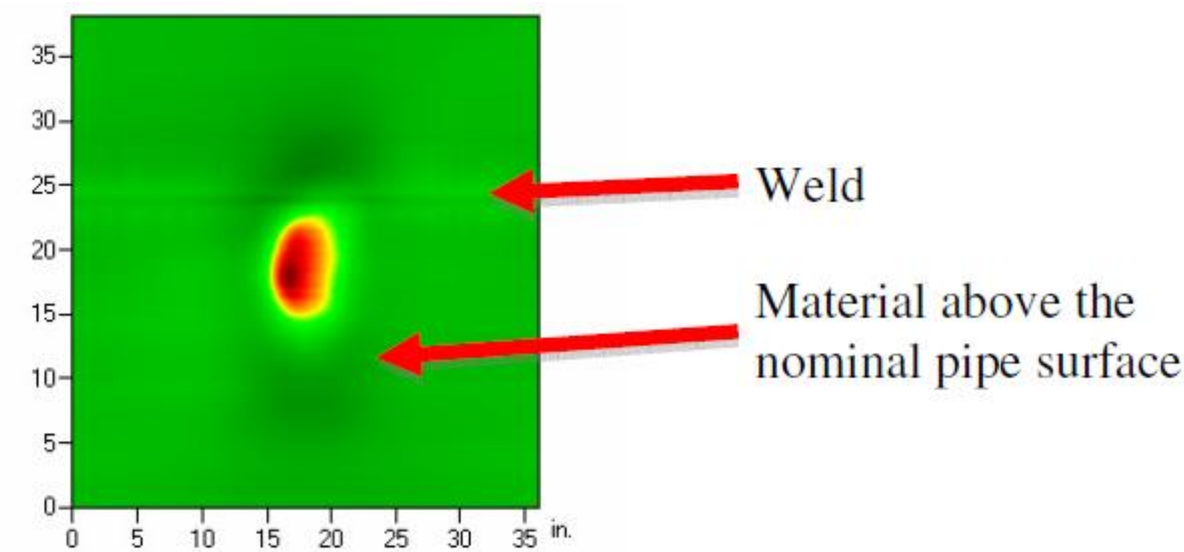


Figure 23: Composite scan image of the dent using the GridStation software. Color represents the depth of the dent relative to the nominal pipe surface. Note the area around the dent where the material protrudes above the nominal pipe surface (darker green).

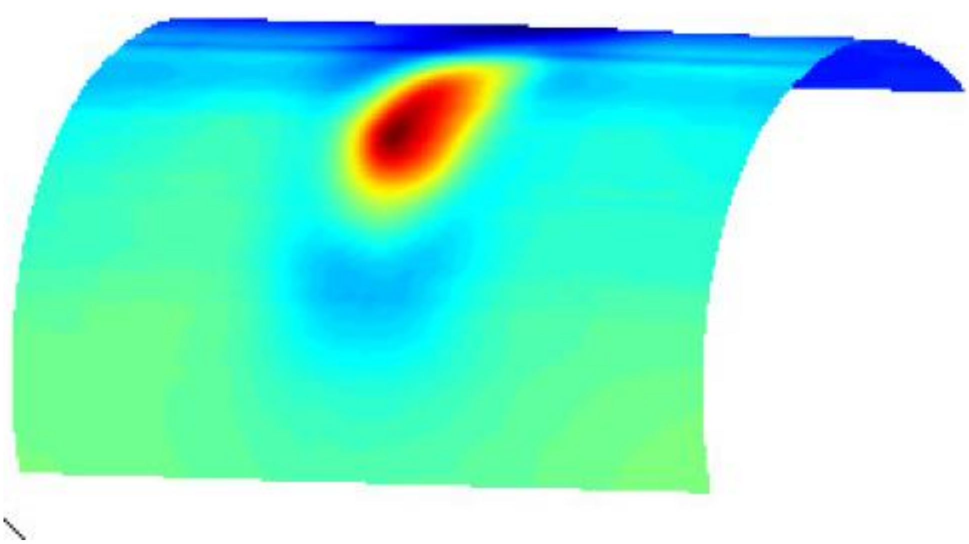
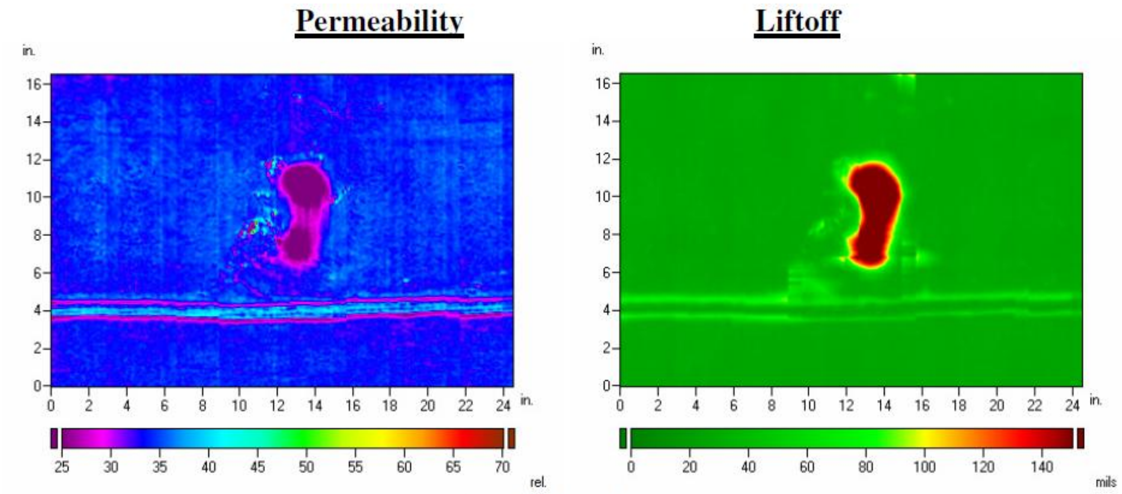
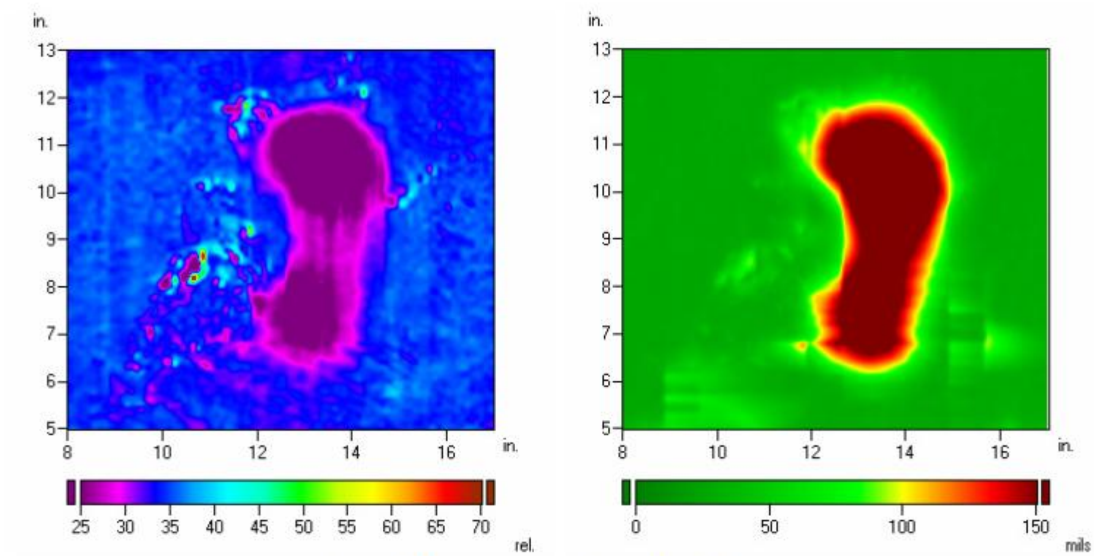


Figure 24: Dent 3D profiles produced using the VWA001 data



(a) – Full axial scan



(b) – Close-up on the dented area

Figure 25: MWM-Array FA24 scans taken circumferentially and surrounding the dent. Variations in permeability can be indicators of stresses, material changes (hard spots), and cracks

Analysis and Conclusion

1. GW 7510

Results of Handyscan 3D:

Handyscan 3D Measurements			
Measurement	Index	Millimeters	Inches
Dent Length	1	444.17	17.49
Dent Width	2	221.39	8.72
Total Depth	3	22.87	0.9
Dent Depth (% WT)	4	3	3
Gouge Length	5	24.76	0.97
Gouge Width	6	83.83	3.3
Gouge Depth	7	0.67	0.026
Gouge Depth (%WT)	8	<1% (.08)	<1% (.08)

Results of MWM-Array:

Measurements obtained by ApplusRTD after processing MWM-Array files from (JENTEK)

MWM Array Measurements		
Measurement	Millimeters	Inches
Dent Length	576.102	22.681
Dent Width	227.167	8.94
Dent Depth	20.281	0.79
Dent Depth (% WT)	2.63	2.63

2. GW 5420

Results of Handyscan:

Handyscan 3D Measurements			
Measurement	Index	Millimeters	Inches
Dent Length	2	237.57	9.35
Dent Width	1	280.48	11.04
Total Depth	3	23.62	0.93
Dent Depth (% WT)	4	3.1	3.1

MWM-Array:

Measurements obtained by ApplusRTD after processing MWM-Array files from JENTEK

MWM Array Measurements		
Measurement	Millimeters	Inches
Dent Length	307.81	12.19
Dent Width	309.326	12.17
Dent Depth	22.956	0.9
Dent Depth (% WT)	3	3

Error Table

1. GW 7510

ILI versus Handyscan 3D

Feature Type	Measurement	ILI		Handyscan 3D		Error (Handyscan - ILI)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	207	8.14	444.17	17.49	237.17	9.35
Dent	Dent Width	171	6.73	221.39	8.72	50.39	1.99
Dent	Dent Depth	19.05	0.75	22.87	0.9	3.82	0.15
Dent	Dent Depth (% WT)	2.5	2.5	3	3	0.5	0.5

ILI versus MWM Array

Feature Type	Measurement	ILI		MWM Array		Error (MWM Array - ILI)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	207	8.14	576.102	22.68	369.102	14.541
Dent	Dent Width	171	6.73	227.167	8.94	56.167	2.21
Dent	Dent Depth	19.05	0.75	20.281	0.79	1.231	0.04
Dent	Dent Depth (% WT)	2.5	2.5	2.63	2.63	0.13	0.13

Handyscan versus MWM Array

Feature Type	Measurement	Handyscan 3D		MWM Array		Error (Handyscan 3D - MWM Array)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	444.17	17.49	576.102	22.68	-131.932	-5.19
Dent	Dent Width	221.39	8.72	227.167	8.94	-5.777	-0.22
Dent	Dent Depth	22.87	0.9	20.281	0.79	2.589	0.11
Dent	Dent Depth (% WT)	3	3	2.63	2.63	0.37	0.37

2. GW 5420

ILI versus Handyscan 3D

Feature Type	Measurement	ILI		Handyscan 3D		Error (Handyscan - ILI)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	187	7.36	237.57	9.35	50.57	1.99
Dent	Dent Width	212	8.34	280.48	11.04	68.48	2.7
Dent	Dent Depth	17.53	0.69	23.62	0.93	6.09	0.24
Dent	Dent Depth (% WT)	2.3	2.3	3.1	3.1	0.8	0.8

ILI versus MWM Array

Feature Type	Measurement	ILI		MWM Array		Error (MWM Array - ILI)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	187	7.36	307.81	12.19	120.81	4.83
Dent	Dent Width	212	8.34	309.326	12.17	97.326	3.83
Dent	Dent Depth	17.53	0.69	22.956	0.9	5.426	0.21
Dent	Dent Depth (% WT)	2.3	2.3	3	3	0.7	0.7

Handyscan versus MWM Array

Feature Type	Measurement	Handyscan 3D		MWM Array		Error (Handyscan 3D - MWM Array)	
		Millimeters	Inches	Millimeters	Inches	Millimeters	Inches
Dent	Dent Length	237.57	9.35	307.81	12.19	-70.24	-2.84
Dent	Dent Width	280.48	11.04	309.326	12.17	-28.846	-1.13
Dent	Dent Depth	23.62	0.93	22.956	0.9	0.664	0.03
Dent	Dent Depth (% WT)	3.1	3.1	3	3	0.1	0.1

MWM-Array was able to create a 3-Dimentional image of the dent with colour gradients showing depth profile. This effort has shown the capability of MWM-Array to create a 3 dimensional profile of mechanical damage like dents. However this technology still needs further developments for which efforts are ongoing under the DOT 460 program.

In case of hard spots, MWM-Array was able to show a difference in permeability in the areas of hard spot. It still needs more research to establish a relationship in order to correlate these changes in permeability with a hardness scale.

While there are correlations between the data derived from the in-ditch methods for inspecting the dents and the dual field MFL ILI tool, the limited number of digs performed has resulted in a small population of data and no definitive conclusion regarding the performance of either the ILI tool or the in-ditch technologies can be made. Larger sample size with more comparisons can help in establishing better conclusions about the nature of MWM-Array technology.

Attachment 1

Handyscan 3D

3D Laser technology is being used frequently for assessment of mechanical damage and external corrosion. The Handyscan 3D is a hand-held 3D laser scanner for characterization of mechanical, corrosion and other damage including dents with metal loss on pipelines and other components (**Figure 26)**. It is a high resolution (0.1 mm or 0.004 in), high accuracy (up to 50 µm or 0.002 in) scanner ideal for mapping and analysis of corrosion and dents/ gouges. Handyscan 3D uses a laser-based range sensor, which relies on optical spray, sensor movement, and the principal of triangulation to construct a three-dimensional measurement. The scan files are then imported into a CAD program and a text file is generated for subsequent strain analysis.

Figure 26: Handyscan 3D

Definitions

Handyscan – A line of portable handheld three-dimensional laser mapping cameras from Creaform Inc.

VxScan – The software that is used to acquire the model during scanning.

PolyWorks – Three dimensional, inspection software used to manipulate, measure, and compare data. It is used after that data has been scanned by VxScan.

Positioning Targets – Also known as Positioning Features or Dots, small circular identification points used by the software to locate the scanner and its orientation in three dimensional spaces.

Facets – Object includes the scanned surface profile information.

Bounding Box – Also known as Volume, the area in space over which curves will be recorded in VxScan. The size of the bounding box is directly proportional to the resolution.

IMInspect – A module in PolyWorks in which the analysis is carried out.

IMEdit – A module in PolyWorks in which the adjustment on scanned surface is carried out.

Polygonal Model – A type of data that is imported into PolyWorks such as the VxScan data.

Feature – A type of specific geometric definition, such as cylinder, circle…

IGES – A format used to create reference objects in PolyWorks.

Reference – The origin point and axes that define direction and the coordinate system.

NACE 3 – A surface preparation level where all foreign matter has been removed except for slight shadows, streaks, and discolorations. Wire wheeled and sand blasted surfaces are acceptable.

MOP – Maximum Operating Pressure as assigned by pipeline owner or operator. Typically, it's the pressure that has been maintained in the pipeline for the past 60 days.

Figure 27 Components of Handyscan 3D

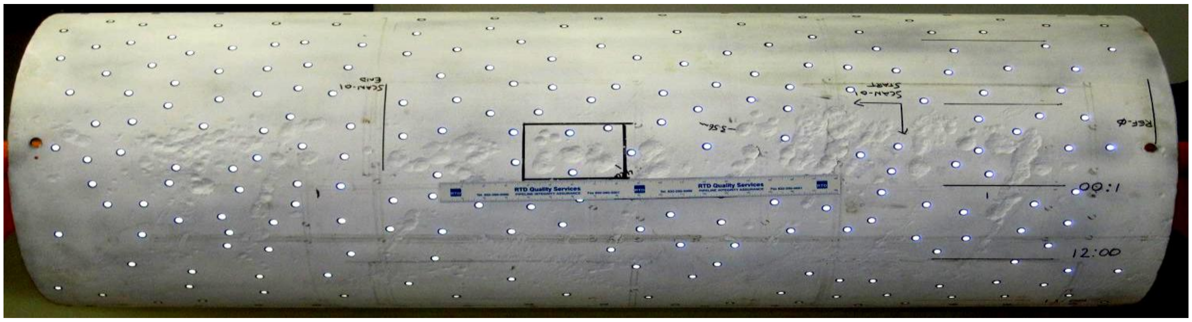


Figure 28: Preparation of Pipe surface for using Handyscan 3D [Dots (Positioning Targets) are placed on pipe surface that serves as reference points for building a 3D plane]

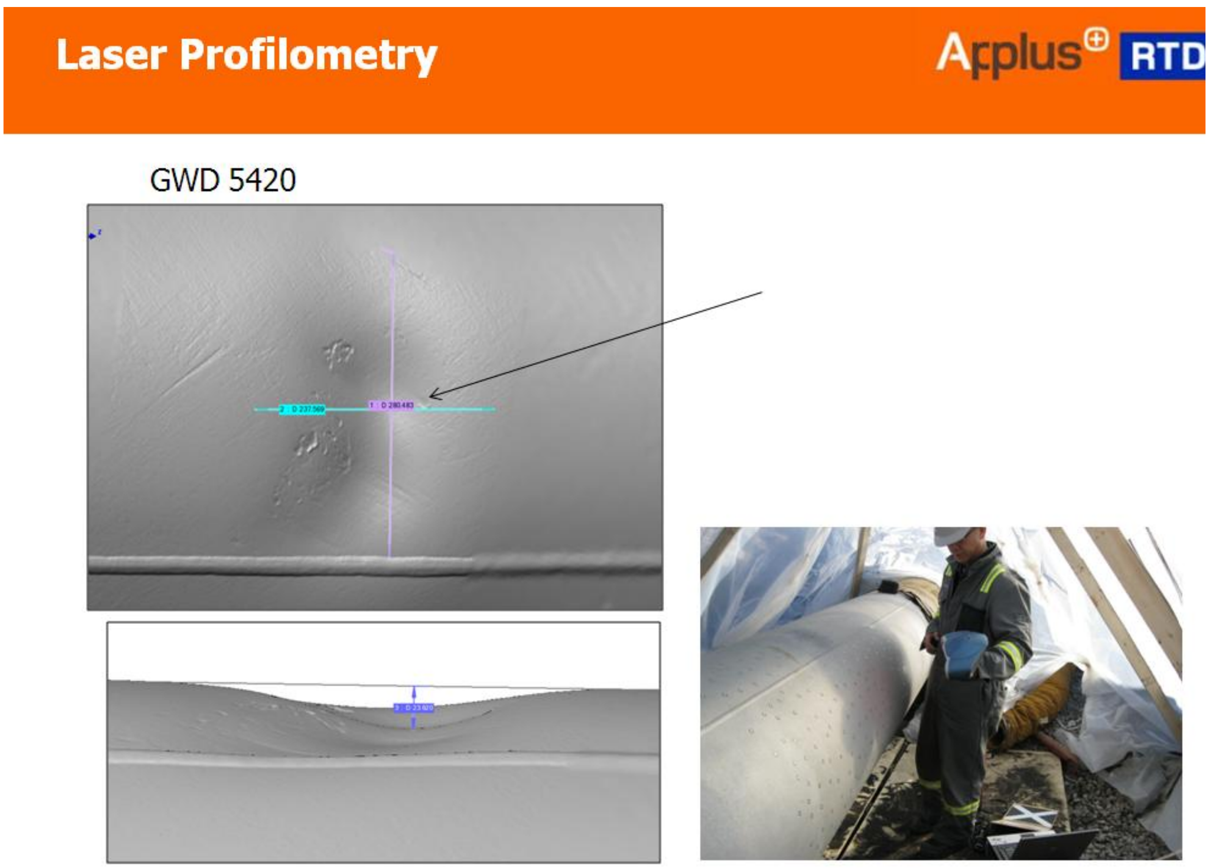


Figure 29: Inspection using Handyscan 3D

Attachment 2

MWM-Array Sensors

Measurement Grids

JENTEK uses precomputed databases of sensor responses, called Measurement Grids, to represent the MWM field interactions with the pipe (or other materials under test). For example, Figure 25 shows a measurement grid for a two-unknown permeability/lift-off measurement. The measurement grid is generated using the model of the MWM field interactions with the neighboring material. The grid is generated once (off-line) and stored as a precomputed database for access by the GridStation® software environment. To generate the grid, all combinations of lift-off and magnetic permeability over the range of interest are input into the MWM models to compute the corresponding grid points. The visualization in Figure 25 includes lines of constant lift-off, h, (green in the figure, also called permeability lines) and lines of constant magnetic permeability, μ, (brown in the figure, also called lift-off lines).

To perform a permeability/lift-off measurement, first the real and imaginary parts of the complex trans inductance (VS/jωID, where ID is the drive winding current and VS is the sense winding voltage) are measured, at an instant in time, using a parallel architecture impedance instrument with 37 parallel channels. Then, the GridStation software performs a nonlinear search through the two dimensional database (Measurement Grid) to provide simultaneous estimates of the lift-off and magnetic permeability.

In Figure 25, the data shown in blue is a series of measurements taken with the sensor held in the air. In the measurement grid, this point, called the Air Point. JENTEK uses the air point for calibration, eliminating the need for reference standards.

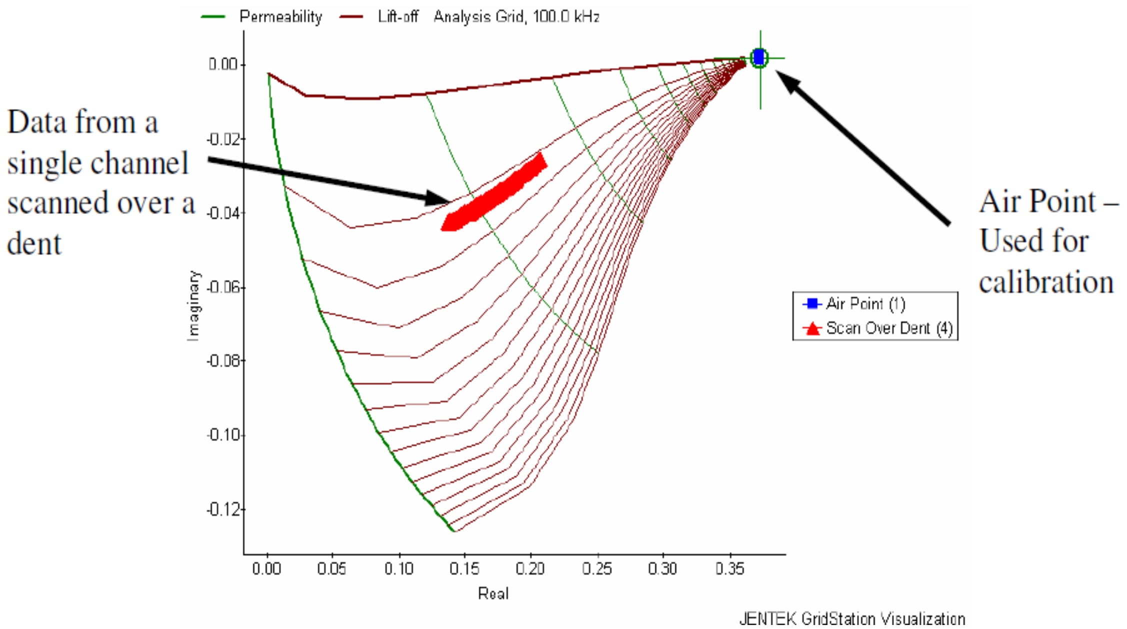


Figure 30: Data from the VWA001 plotted on a measurement grid. The data in blue was taken with the sensor in air, illustration JENTEK's use of air calibration. The data in red was taken during a scan over a dent and shows how the data follows a liftoff line

Figure 31: Set-up of the GridStation system.

MWM array sensors developed by Jentek are eddy current sensors. Jentek uses its VW A001 MWM-Array to investigate the dent profile and the FA24 MWM-Array to investigate the magnetic permeability variation.

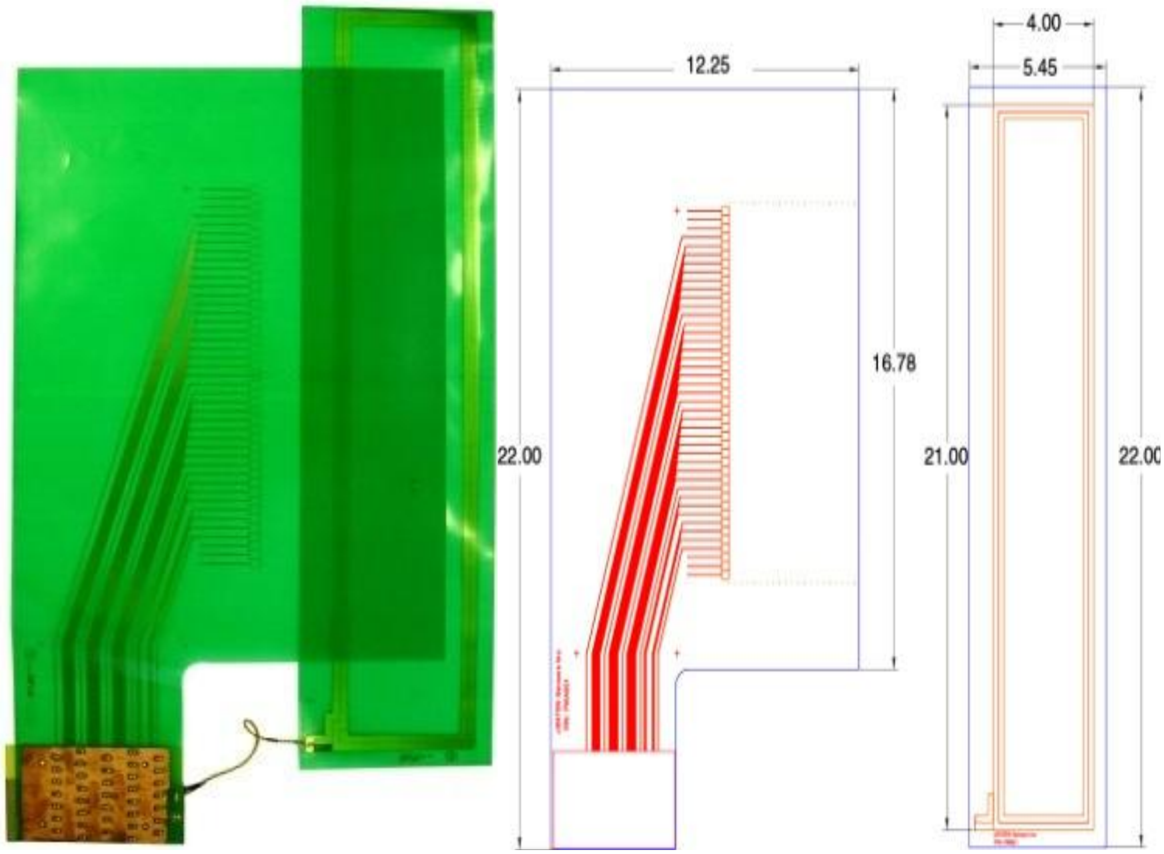


Figure: 32: The VWA001 MWM-Array

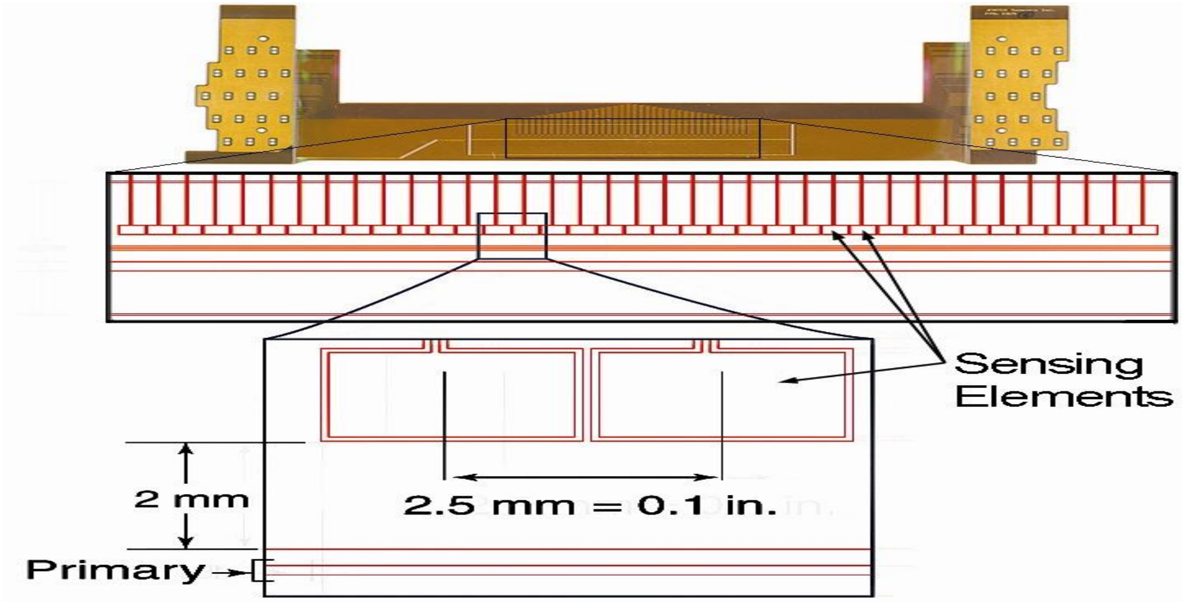


Figure 33: The FA24 MWM-Array

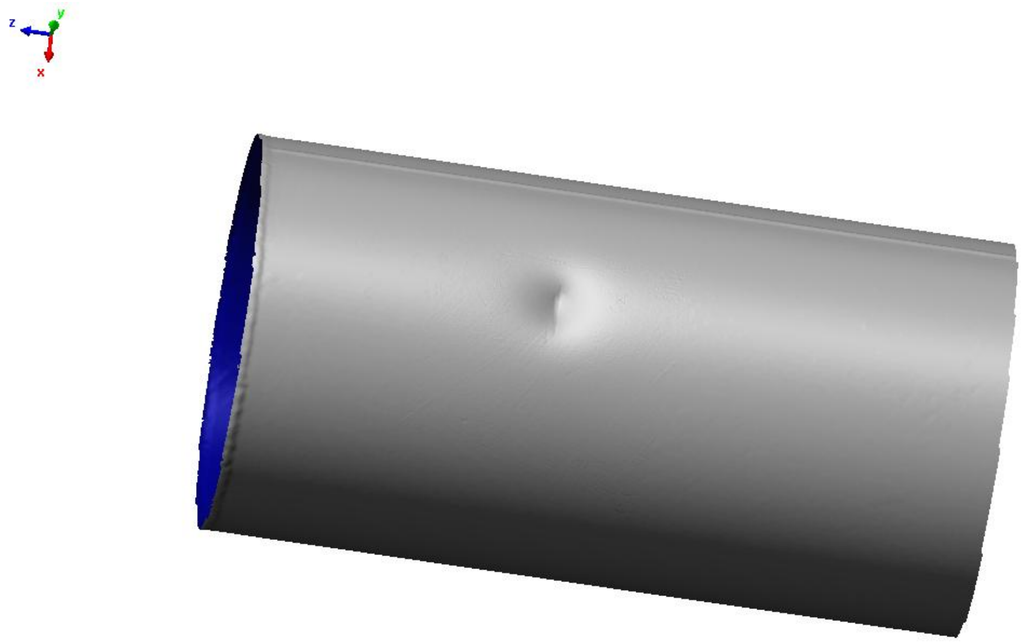
Figure 34: Scanning using the VWA001 MWM-Array over the dented area

Figure 35: Scanning using the VWA001 FA24 MWM Array

Attachment 3

HANDYSCAN 3D REPORTS (ApplusRTD)

HANDYSCAN – MD



Client	
Line	
Site Name	GWD7510
Field Inspector	D. Yu
Report Author	D. Yu
Inspection Date	
Report Date	1/26/2011

Inspection Area

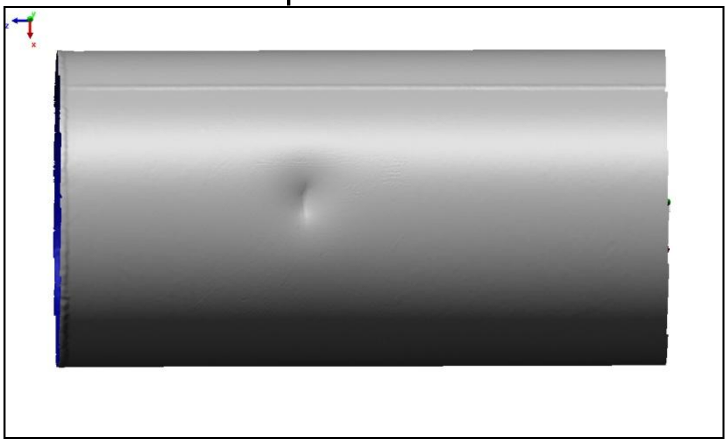


Figure 1: Inspection Coverage

The pipe was mapped for a length of 1.4 meters, full circumference.

Color Gradients

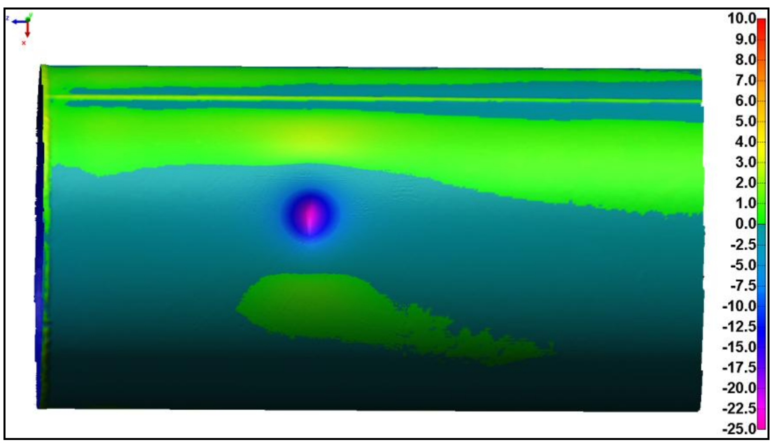


Figure 2: Color Gradient Map

The above images show the difference between the actual pipe body and a best-fit cylinder. The scale on the right (in millimeters) defines positive values as those areas that were larger than the best-fit cylinder, and negative values as those areas that were less than the best-fit cylinder. The minimum value on the scale is NOT the maximum deflection of the pipe as the best-fit cylinder is an ideal cylinder and not a true representation of the original pipe surface prior to deformation.

Measurements

Measurement	Index	Millimeters	Inches
Dent Length	1	444.17	17.49
Dent Width	2	221.39	8.72
Total Depth	3	22.87	0.900
Gouge Length	5	24.76	0.97
Gouge Width	6	83.83	3.30
Gouge Depth	7	0.67	0.026

Length is measured parallel to the axis of the pipe and through the deepest point of the dent. The ends are chosen where pipe profile no longer shows any deflection.

Width is measured perpendicular to the axis of the pipe and through the deepest point of the dent. This dimension does not account for the curvature of the pipe but it the absolute distance between two points in space. (Figure 6)

Depth is the distance from the original pipe profile, or the highest points if bulging occurred, to the deepest point in the dent and gouge. (Figure 5)

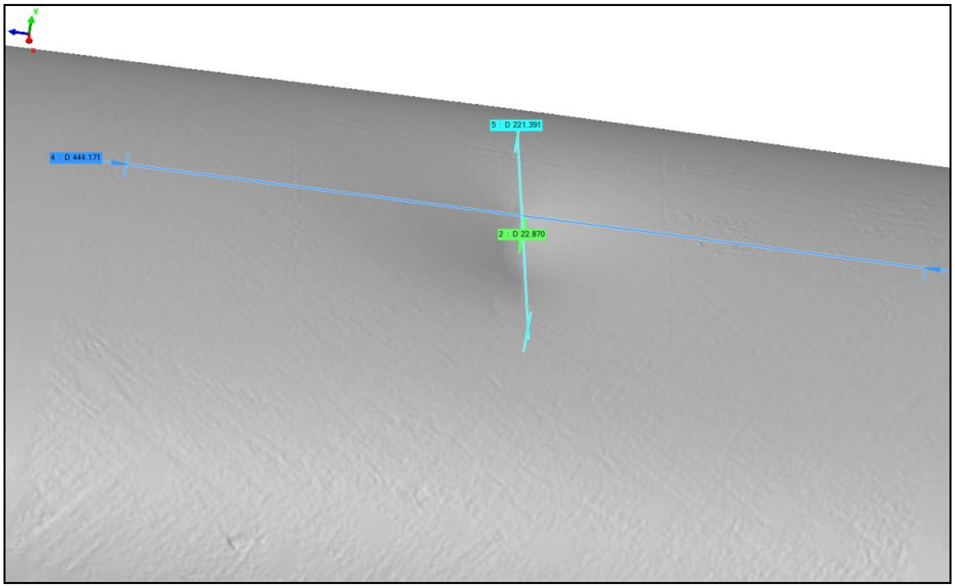


Figure 3: Isometric View of Length, Width, and Depth

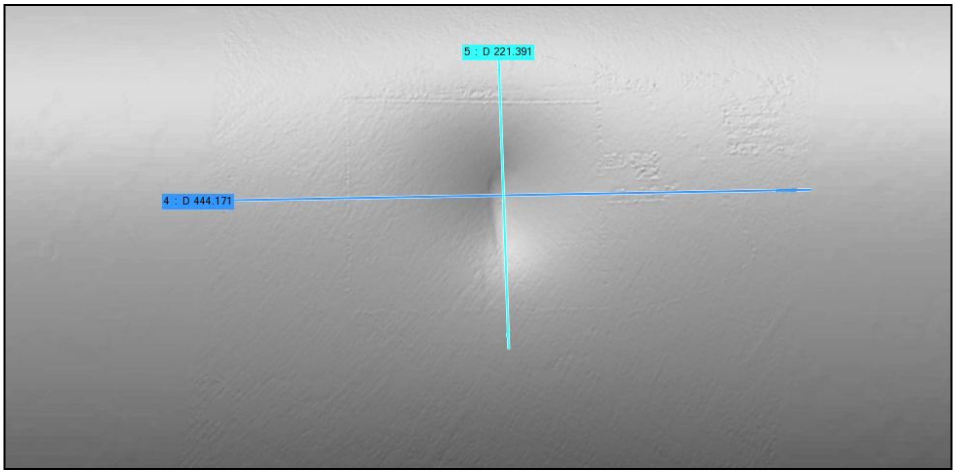


Figure 4: Axial View of Length and Width

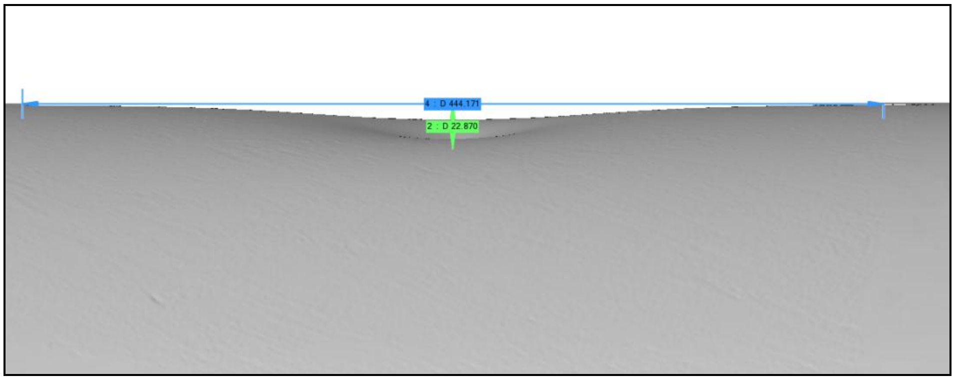


Figure 5: Length and Depth View

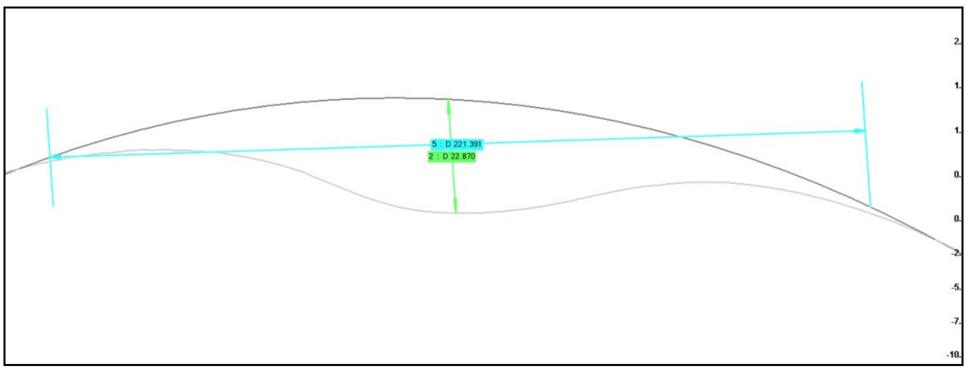


Figure 6: Width and Depth View

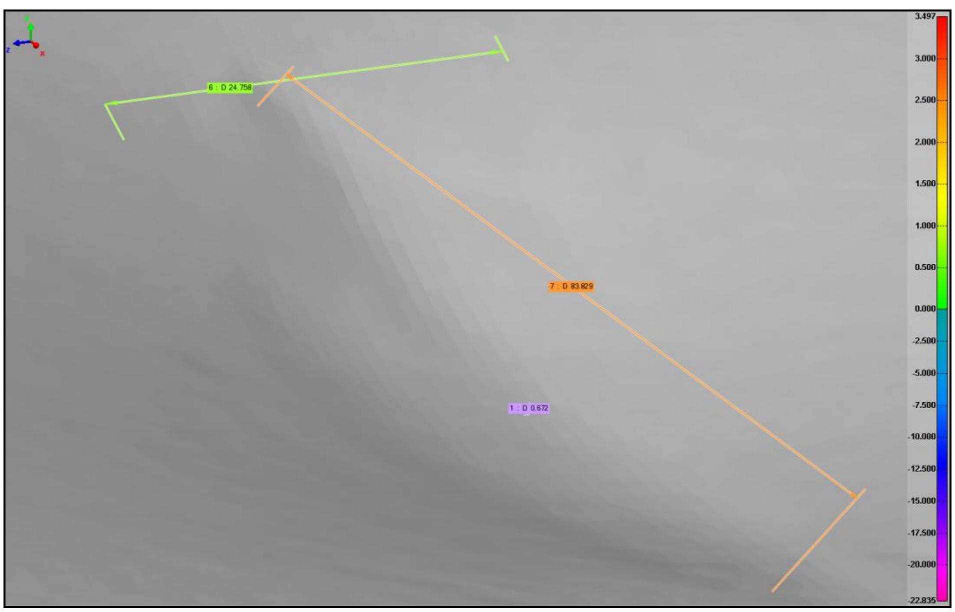


Figure 7: Isometric View of Gouge

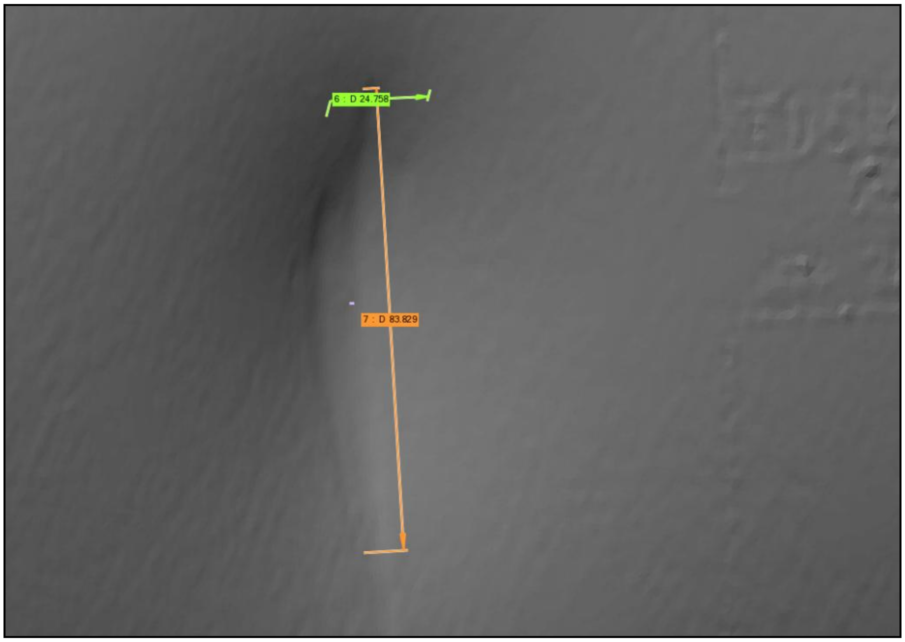
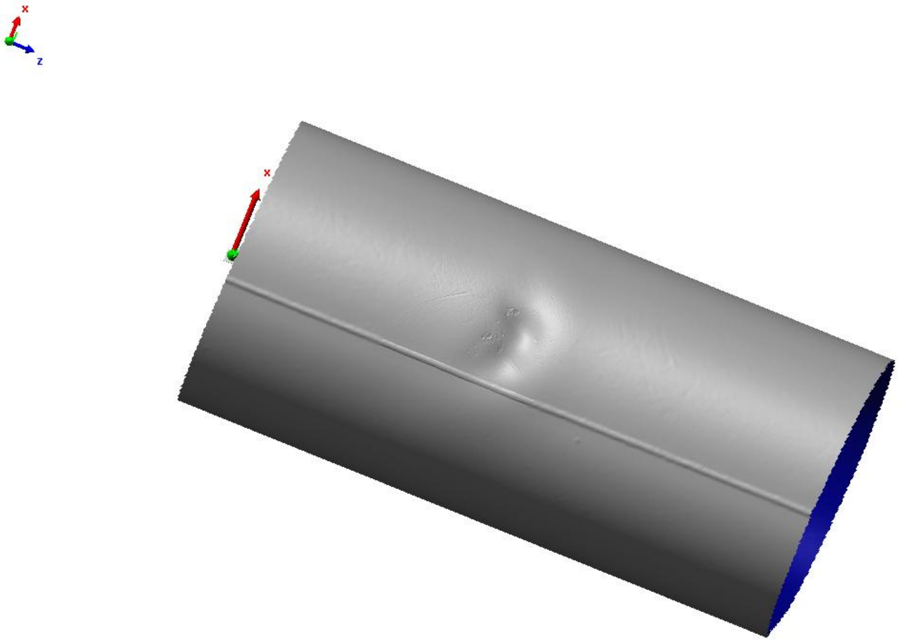


Figure 8: Axial View of Gouge

HANDYSCAN – MD



Client	
Line	
Site Name	GWD5420
Field Inspector	D. Yu
Report Author	D. Yu
Inspection Date	
Report Date	1/30/2011

Inspection Area

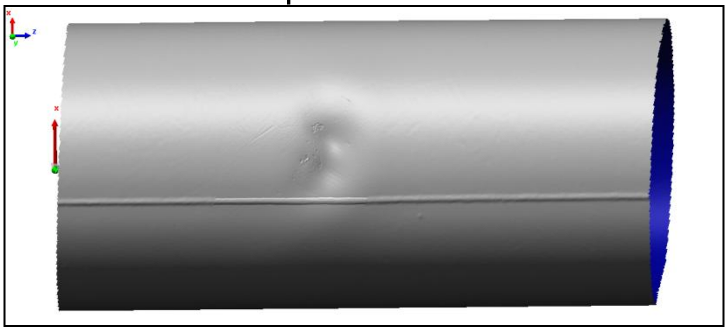


Figure 7: Inspection Coverage

The pipe was mapped for a length of 1.5 meters, full circumference.

Color Gradients

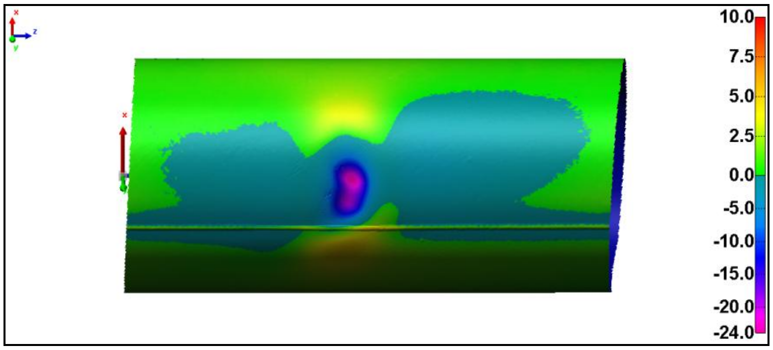


Figure 8: Color Gradient Map

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Measurements

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Depth is the distance from the original pipe profile, or the highest points if bulging occurred, to the deepest point in the dent. (Figure 5)

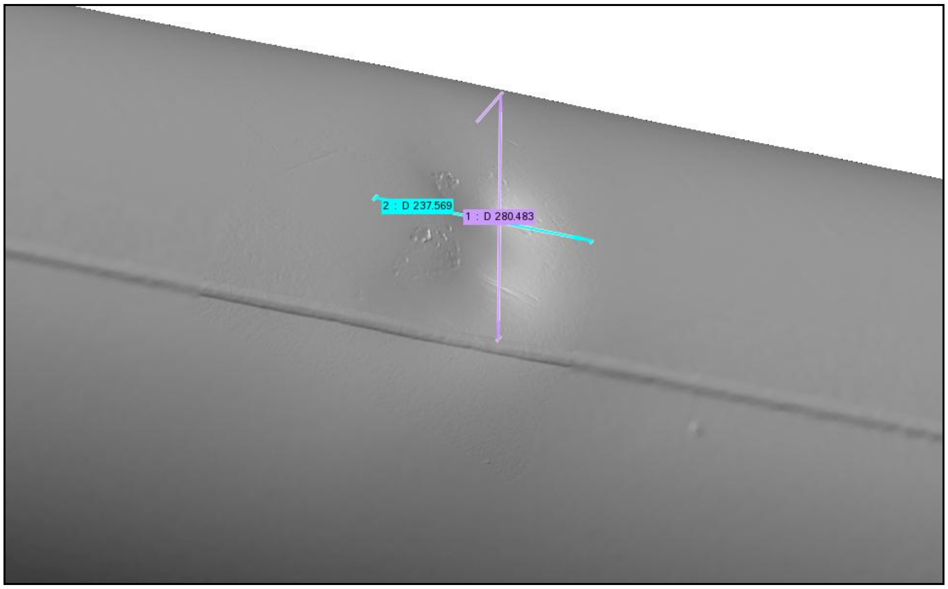

Figure 9: Isometric View of Length, Width, and Depth

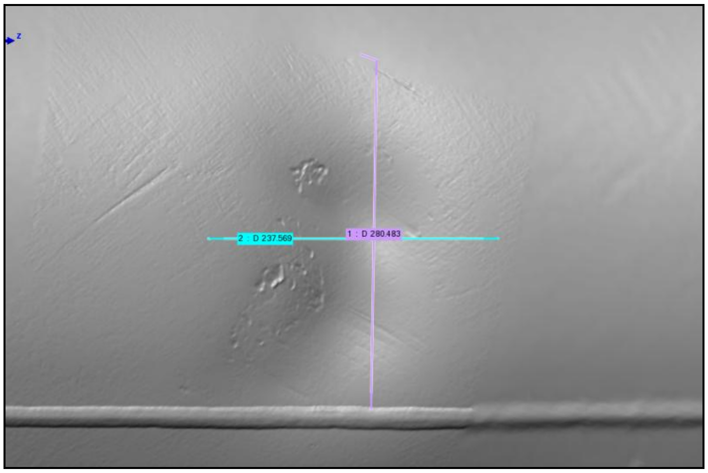

Figure 10: Axial View of Length and Width

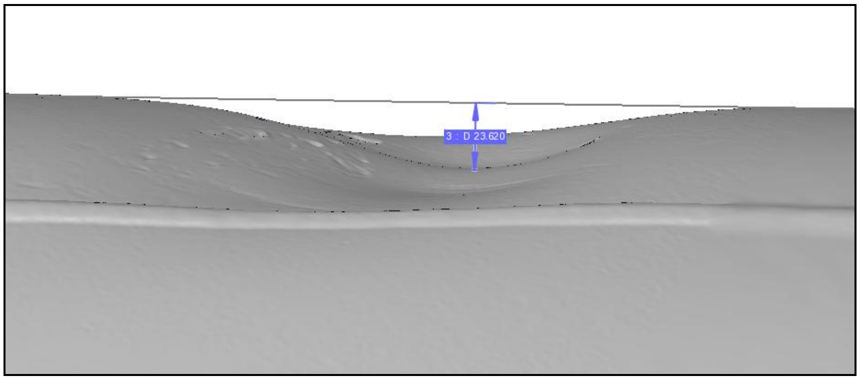

Figure 11: Length and Depth View

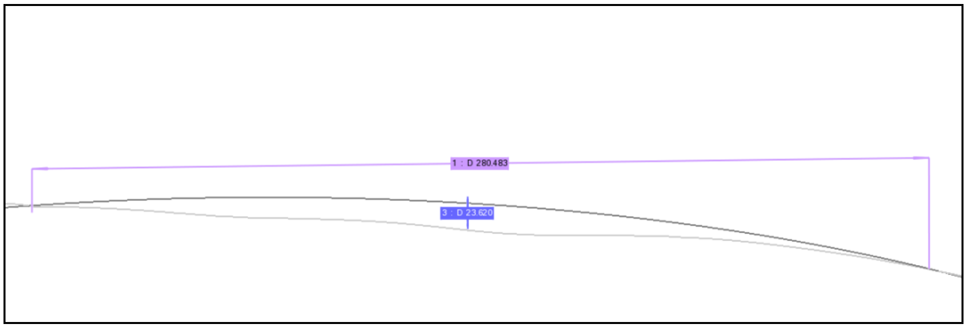

Figure 12: Width and Depth View