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## TESTING OF A DUAL FIELD MAGNETIC FLUX LEAKAGE (MFL) INSPECTION TOOL FOR DETECTING AND CHARACTERIZING MECHANICAL DAMAGE FEATURES

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### ABSTRACT

Battelle has developed dual field magnetic flux leakage (MFL) technology for the detection and characterization of mechanical damage to pipelines. The basic principle involves the use of a high magnetic field between 140 and 180 Oersted (11.1 to 14.3 kA/m) and the use of a low magnetic field between 50 and 70 Oersted (4 to 5.6 kA/m). At high magnetic field levels, the flux leakage signal is primarily influenced by changes in the geometry of a pipe wall. At low magnetic field levels, the MFL signal is due to residual stresses and metallurgical changes as well as geometry changes to the pipe caused by mechanical damage and wall thinning. A decoupling signal processing method developed by Battelle is used to isolate the portion of the mechanical damage signals due to metallurgical damage and residual stresses, which allows the characteristics of a dent-gouge feature to be more clearly differentiated. The decoupling method involves first scaling down the high field signal to the level of the low field signal, and then subtracting it from the low field signal. This produces a decoupled signal that is primarily influenced by the residual stresses and metallurgical changes caused by mechanical damage.

Rosen has developed a tool to test the dual field technology and is evaluating tool performance by running the tool in a 30 inch diameter pipeline segment. The tool itself is composed of three separate modules coupled together: a high field unit downstream of a low field unit which is downstream of a caliper arm unit that is used to detect and characterize reductions in the internal diameter. The general and magnetic design of the tool, along with the scaling algorithm is

discussed. Results from a pull test in a pipe section with dents whose geometry has been independently characterized are also discussed.

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### INTRODUCTION

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 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 [1], 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.

It is possible to detect mechanical damage with Magnetic Flux Leakage (MFL) based inspection tools due to the fact that MFL is sensitive to geometric changes in the pipe wall as well as local residual stress and metallurgical damage.

Geometric changes can take the form of a change in the shape of the pipe wall, which affects the sensor orientation relative to the local pipe wall and changes the measurement of the vector flux field, and hence MFL signal. Additionally

geometric changes in the pipe wall can take the form of wall thinning, and removed metal from the pipe wall that can affect the amount of flux leakage

Metallurgical damage and residual stress have a more complex effect on a MFL signal than pipe wall geometry; residual stress can create magnetic anisotropy in steel thus altering the pattern of flux around a dent. This is a separate effect of mechanical damage on the MFL signal, different from that caused by the change in the orientation of the sensor relative to the pipe wall due to dent geometry.

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.

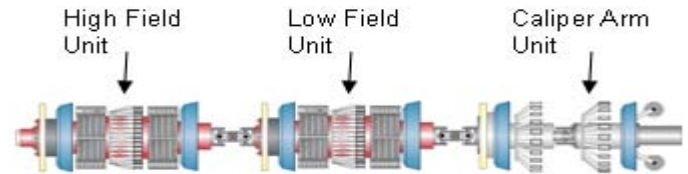
This will allow for more accurate detection, identification and characterization of features that are accompanied by residual stresses such as dents that have under gone pressure cycling or that have re-rounded due to a pipes internal pressure.

A dual field tool was created which is composed of a high field unit at the front of the tool, downstream of a low field unit, and lastly a caliper arm unit that is upstream of both the high and low field units. The high and low field units create a predominantly axially oriented field in the pipe wall. According to the specifications for the project, the optimum 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), as determined by taking the average of the axial component of the field around the entire circumference as the tool travels through a pipe. This field should be achieved over a pipe wall thickness range of 0.281 to 0.314 inches (7.14 to 7.98 mm).

The signals from ten plain dents, obtained during a pull test performed at 0.5 m/s (1.6 ft/s), were examined in order to explore the effects of dent geometry, dent depth and pressure cycling on the decoupled signal. The decoupled signal from a gouge was also investigated. The pull test also included a separate joint taken from the pipe the inline inspection is to be carried out on, which contains a dent that was formed in service.

## MECHANICAL DESIGN

As described in the introduction the dual field tool consists of a high field unit downstream of a low field unit, and a caliper arm unit (RoGeoXt) upstream of both the high and low field units. The tool is 4.98 m (16.34 ft) in length, is designed for a 30" 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.



**FIGURE 1: COMPLETE DUAL MAGNETIZATION TOOL, CONSISTING OF TWO MAGNETIZER UNITS AND A CALIPER ARM UNIT. THE HIGH FIELD UNIT IS DOWNSTREAM OF THE LOW FIELD UNIT AND A CALIPER ARM UNIT IS AT THE REAR OF THE TOOL. MODULAR CORROSION DETECTION PIG (CDP) AND RoGeoXt UNITS ARE USED FOR THE MAGNETIZER AND CALIPER ARM UNITS RESPECTIVELY.**

The caliper arm unit 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.

## MAGNETIZER DESIGN

The magnetizer design is a four pole design consisting of separate low field and high field units, with the high field unit downstream of the low field unit.

The magnetizer units are arranged to help avoid the magnetic field created by each of the high and low field units from interfering with each other. To reduce magnetic coupling between the magnetizer units 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 exist in the pipe due to previous MFL inspections, it is important to have the low field unit upstream of the high field unit. By placing the high field unit downstream of the low field unit, 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. If the low field unit were downstream of the high field unit, the unknown remnant magnetization would affect the induced low field, making it unpredictable.

The high field unit is designed to achieve a field strength within the range of that used by standard MFL tools, so its design 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 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 specified wall thickness range of 0.281-0.314 inches (7.14 to 7.98 mm) was to reduce the effective strength of the magnet packages by removing some of the magnets.

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 can lead to discrepancies between predicted field levels and pull test and inspection results.

## DECOUPLING ALGORITHM

The decoupling algorithm[2], developed by Battelle, scales the high field signal down to the level of the low field signal and subtracts it from the low field signal. Since both the low and high field signals are influenced by mechanical damage geometry, but only the low field signal is influenced by residual stresses this procedure is intended to decouple the part of the signal influenced by residual stress from the part of the signal influenced by geometry as shown in equation 1, where  $H_{low}$  is the low field magnitude and  $H_{high}$  is the high field magnitude:

$$\Delta H = H_{low} - S \cdot H_{high} \quad (1)$$

## PULL TESTS

Pull tests were performed at a speed of 0.5 m/s (1.6 ft/s) on a section of pipe with a nominal diameter of 30" and single dent that was removed from an operating pipeline and also on a three meter long section of pipe that was dented in a manner similar to that used by Battelle in the development of this technology. The naturally dented section, which was supplied by Enbridge, has a dent 1.7 % of the nominal diameter, which had re-rounded 1% from the measured pre-excavation dent depth of 2.7%, which is based on in-line inspection geometry data supplied by Enbridge. The three meter section of pipe was welded between two five meter long sections; all three sections were cut from the same pipe. The dented section of pipe supplied by Enbridge was welded onto the end of one of the five meter long sections. The pipe section placement was made 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 section of pipe supplied by Enbridge 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 unit were in contact with the pipe steel as the magnetizer traversed the dent and not beyond the pipe in the air. The pipe layout is shown in figure 2(a).

The defects in figure 2(b) 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.

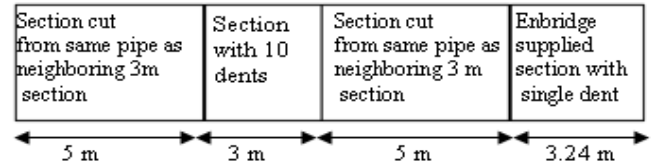
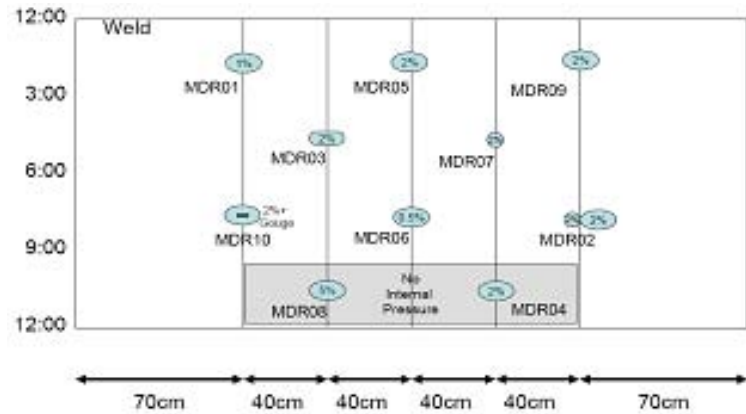


FIGURE 2(A): PULL TEST PIPE LAYOUT.



spherical



cylindrical



wedge

FIGURE 2(B): 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

Dent number 5 has the same geometry and nominal depth as a dent that Battelle has previously obtained MFL signals from with its own prototype dual field tool. This allows a comparison between the low and high field MFL signals Battelle has obtained with a prototype dual field tool and the signals obtained during the current pull tests. The Battelle signals [2] used in this comparison are displayed in figure 3, and the signals obtained during the current pull tests are displayed in figures 4 and 5. MFL signals from dents previously obtained by the lead author during graduate research [3] and used for comparison are displayed in figures 6 and 7.

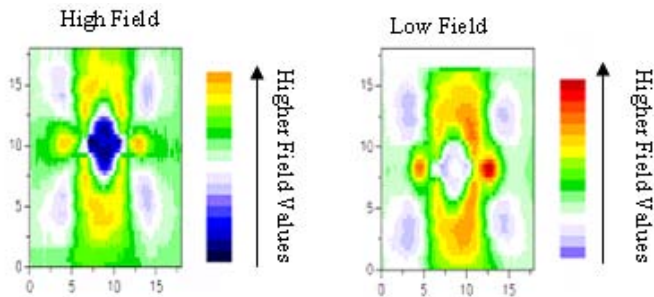
The method used for background subtraction in figures 6 and 7 assumes a linear background in the y and x

directions. For each y coordinate, a separate linear fit is applied to estimate the background and for each x coordinate a separate linear fit is applied to estimate the background. Each linear fit is then subtracted along the coordinate it was created. The background subtraction method used in figures 4 and 5 subtracts the background from the decoupled signal by calculating a median using a moving window. Although different background subtraction methods were used for each signal, the signals are comparable as each method effectively removes the background signal that is present even in the absence of a defect, and on which the defect signal is imposed. While there is no background subtraction in figure 3, the signal patterns are clearly visible above the background level.

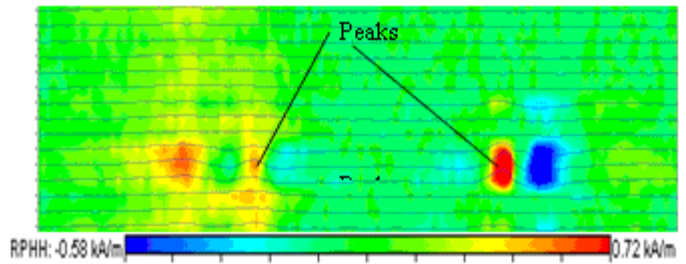
Certain signal patterns are common to all three sets of data, and are also representative of past Rosen experience. Comparing the signals in figures 3 to 7 along the axial centerline (moving in the x axis direction at a central y coordinate), where the dents reach their maximum depth it can be seen that 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.

The difference between the current 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 pigs and the lower speed of the Battelle pull tests (0.1 m/s or 0.3 ft/s).

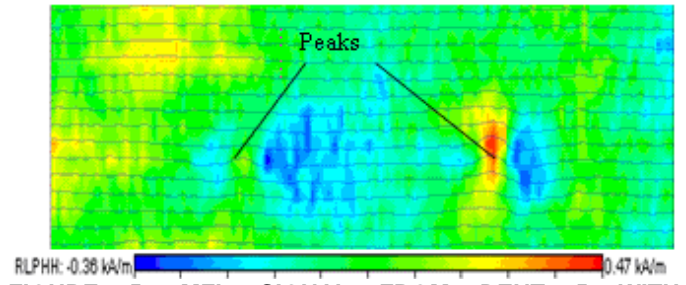
However based on the fact that signal patterns similar to the signals from both the prior Battelle pull tests and the current pull tests were previously obtained during independent research, both signals are valid examples of signals from dents and their differences can likely be attributed to one or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



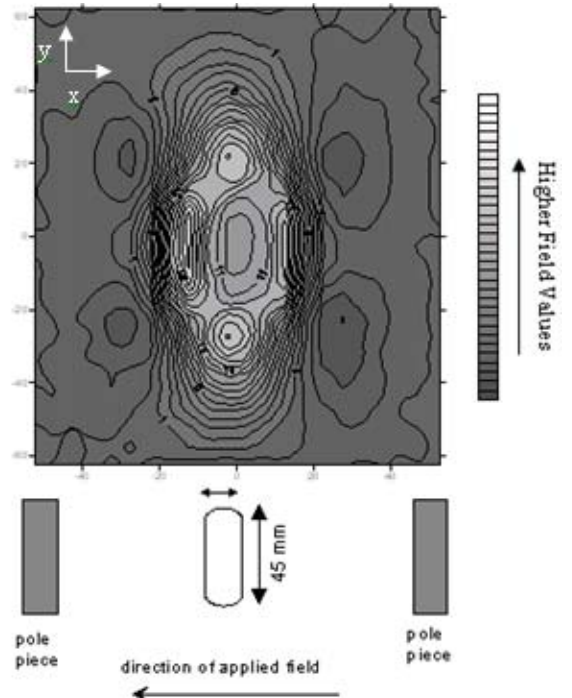
**FIGURE 3: BATTLE HIGH AND LOW FIELD MFL SIGNALS [2] AT APPLIED FIELDS OF APPROXIMATELY 150 AND 75 Oe (11.9 AND 5.9 kA/m) RESPECTIVELY FROM A DENT WITH THE SAME DEPTH AND GEOMETRY AS DENT 5 IN FIGURE 2**



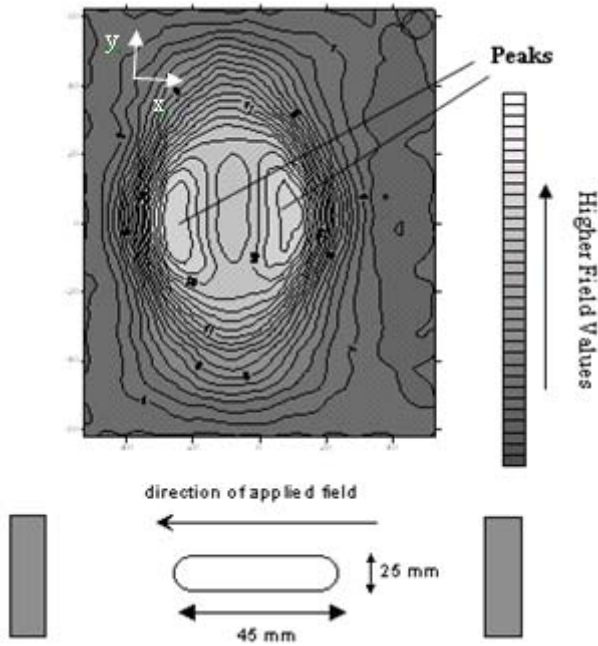
**FIGURE 4: MFL SIGNAL FROM DENT 5 WITH BACKGROUND SUBTRACTED AT AN APPLIED FIELD OF 170 Oe (13.5 kA/m). OBTAINED DURING CURRENT PULL TESTS. INDICATED PEAKS WITH DIP BETWEEN THEM ARE CHARACTERISTIC OF ROSEN MFL SIGNALS FROM SMOOTH, DEEP, DENTS.**



**FIGURE 5: MFL SIGNAL FROM DENT 5 WITH BACKGROUND SUBTRACTED AT AN APPLIED FIELD OF 73 Oe (5.8 kA/m). OBTAINED DURING CURRENT PULL TESTS. INDICATED PEAKS WITH DIP BETWEEN THEM ARE CHARACTERISTIC OF ROSEN MFL SIGNALS FROM SMOOTH, DEEP, DENTS**



**FIGURE 6: MFL SIGNAL FROM A PLAIN DENT WITH BACKGROUND SUBTRACTED. THIS SIGNAL IS FROM INDEPENDENT RESEARCH BY THE LEAD AUTHOR [3] AND CONTAINS THE SAME SIGNAL PATTERNS AS THE MFL SIGNALS OBTAINED BY BATTLE IN FIGURE 3. THIS INDICATES THAT THE BATTLE SIGNALS ARE VALID EXAMPLES OF MFL SIGNALS FROM DENTS.**



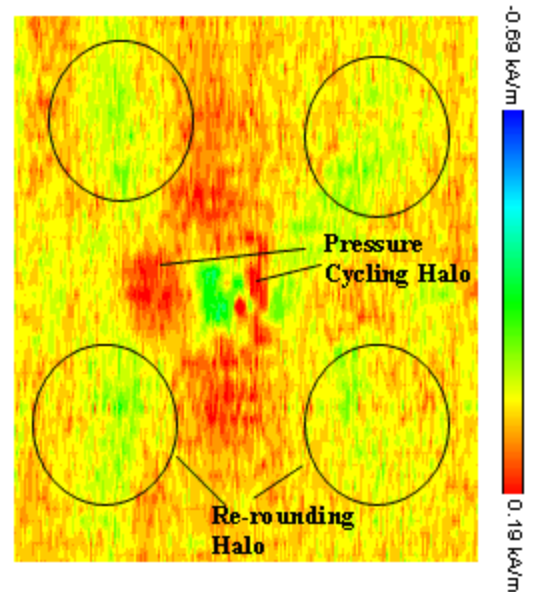
**FIGURE 7: MFL SIGNAL FROM A PLAIN DENT WITH BACKGROUND SUBTRACTED. THIS SIGNAL IS FROM INDEPENDENT RESEARCH BY THE LEAD AUTHOR [3] AND CONTAINS THE SAME SIGNAL PATTERNS AS THE MFL SIGNALS IN FIGURE 4, NOTE THE PEAKS. THIS INDICATES THAT THE SIGNALS IN FIGURE 4 ARE VALID EXAMPLES OF MFL SIGNALS FROM DENTS TOO.**

By comparing the decoupled signal from the dent in the Enbridge supplied section of pipe, shown in figure 8 with a decoupled signal obtained by Battelle, shown in figure 9, as part of a separate research program certain decoupled signal patterns can be identified.

In particular the re-rounding and pressure cycling signal patterns are identified in figure 8, due to their position relative to the other signal patterns, their polarity and their shape. These signal patterns are present in both figures 8 and 9, but are better defined in figure 9, which may be due to different dents and different pipe material, or the fact that different tools were used to obtain the signals.

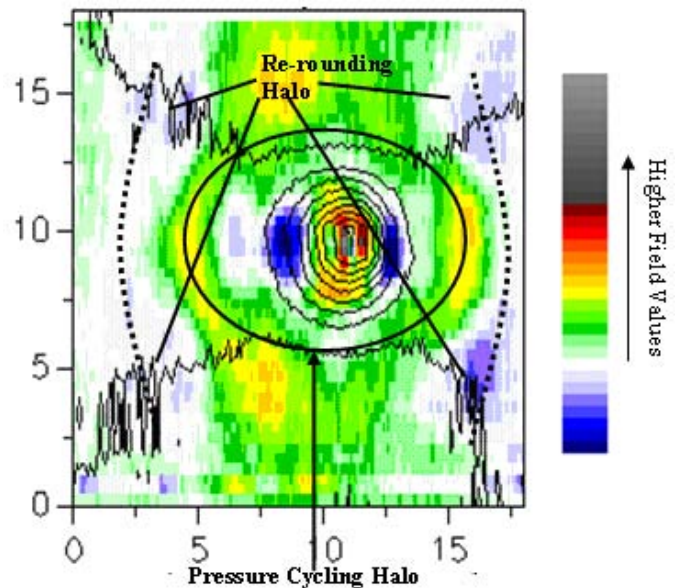
The re-rounding signal pattern has been identified by Battelle as being indicative of a dent that has re-rounded. It consists of a halo signal at the outer edge of the maximum dent extent, which has negative amplitude with respect to the background, and is due to residual stresses which arise from a dent re-rounding [2].

The pressure cycling halo is a decoupled signal pattern that has been identified by Battelle as being indicative of a dent that has been exposed to pressure cycles, or internal pressure increases and decreases over time. It consists of a halo whose amplitude is positive with respect to the background and is located inside the re-rounding halo [2].



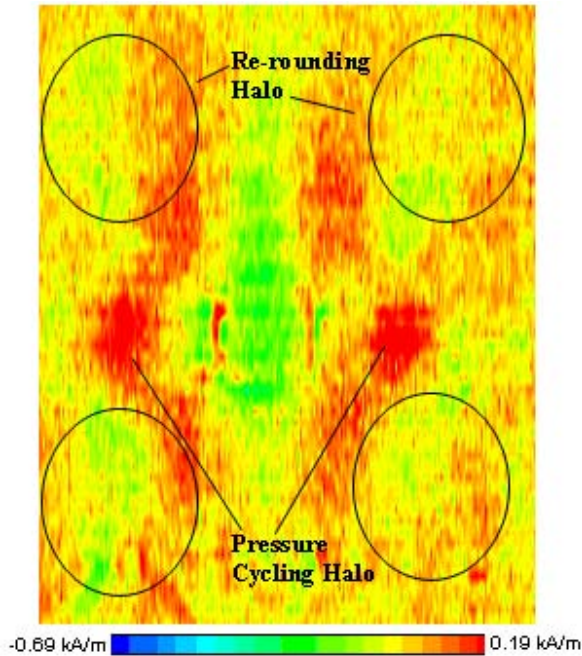
**FIGURE 8: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION FROM PIPE SECTION WITH A NATURAL DENT SUPPLIED BY ENBRIDGE. APPLIED HIGH AND LOW FIELDS ARE 188 Oe AND 80 Oe (15 kA/m AND 6.4 kA/m) RESPECTIVELY. THE RE-ROUNDING HALO IS COMPOSED OF THE FOUR CIRCLED AREAS.**

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.

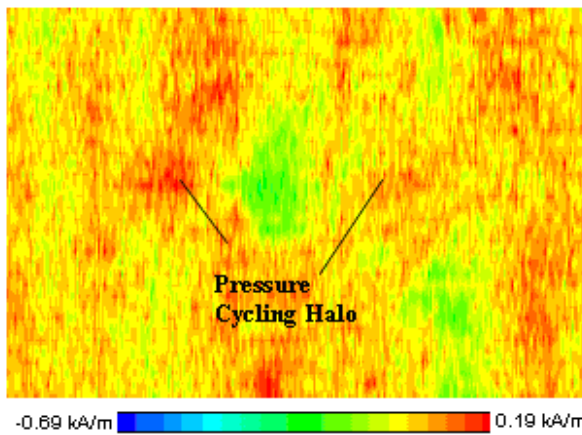


**FIGURE 9: INDEPENDENTLY OBTAINED DECOUPLED SIGNAL FROM A PLAIN DENT [2] IS SHOWN FOR COMPARISON TO FIGURE 8. THE PRESSURE CYCLING AND RE-ROUNDING HALO SIGNAL PATTERNS CAN BE IDENTIFIED IN BOTH FIGURES. THE BLUE PRESSURE CYCLING HALO IS NEGATIVE WITH RESPECT TO THE BACKGROUND**

Dent 9 in figure 10 can be compared to dent 4 in figure 11 to see what the effects of internal pressure and pressure cycling are on the decoupled signal, as both 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.



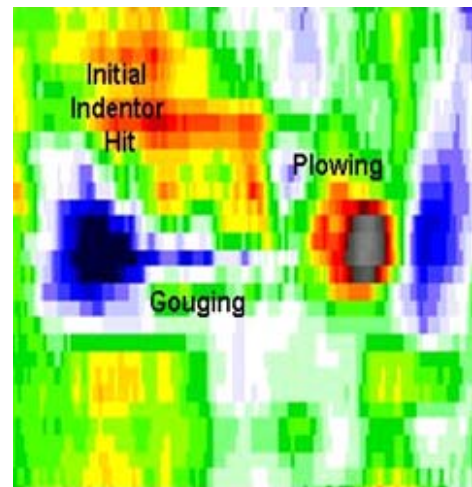
**FIGURE 10: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION CORRESPONDING TO DENT 9 IN FIGURE 2 AND TABLE 1. APPLIED HIGH AND LOW FIELDS ARE 170 Oe AND 73 Oe (13.5 kA/m AND 5.8 kA/m) RESPECTIVELY. THE PRESSURE CYCLING AND RE-ROUNDING HALO SIGNAL PATTERNS ARE IDENTIFIED. THE RE-ROUNDING HALO IS COMPOSED OF THE FOUR CIRCLED AREAS.**



**FIGURE 11: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION CORRESPONDING TO DENT 4 IN FIGURE 2 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 8 based on its position with respect to the pressure cycling halo and polarity (compare to the signal in figure 9). 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 8 other than near the dent. This supports the conclusion that this signal pattern is indeed the re-rounding halo and not noise.

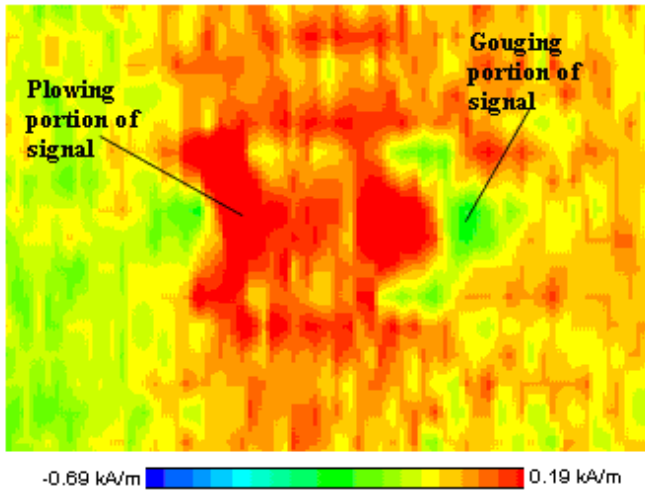
In figures 12-14 the signal from the gouge is compared to a typical decoupled mechanical damage gouge signal obtained by Battelle [2]. The gouge created for the pull test was made with a chisel and hammer and has several gouging and plowing portions, since it was chiseled in several steps, and not in 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 12: DECOUPLED SIGNAL FROM A GOUGE OBTAINED BY BATTELLE [2]**



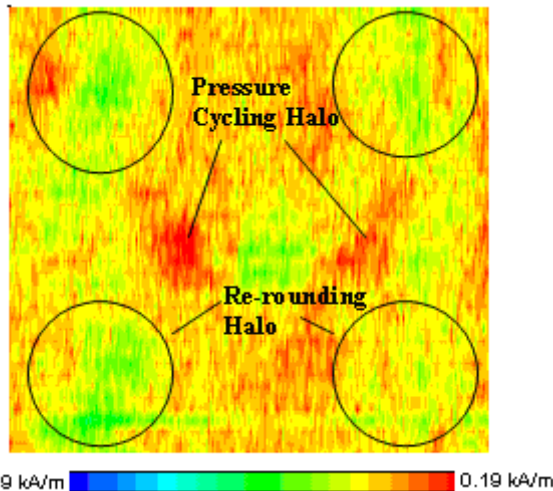
**FIGURE 13: PHOTOGRAPH OF GOUGE USED IN CURRENT PULL TESTS.**



**FIGURE 14: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION FROM GOUGE SHOWN IN FIGURE 13 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 12 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:

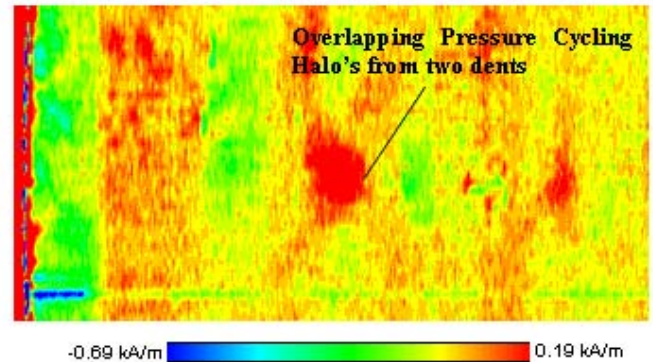
- The shallowest dent in figure 2, dent 6 (0.5%), did in fact produce a decoupled signal with the re-rounding and pressure cycling halos present as shown in figure 15. This indicates that dents as shallow as 0.5% will be detectable in the decoupled inspection.



**FIGURE 15: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION CORRESPONDING TO DENT 6 (0.5%) IN FIGURE 2 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 16 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. 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 16: DECOUPLED PULL TEST RESULTS WITH BACKGROUND SUBTRACTION CORRESPONDING TO DENT 2 IN FIGURE 2 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 HALO'S FROM NEIGHBORING DENTS OVERLAP IS IDENTIFIED.**

## SUMMARY

A dual field tool designed to produce a decoupled MFL signal primarily influenced by residual stress and metallurgical damage caused by mechanical damage has been built and tested through a pull test in preparation for use in 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.

## REFERENCES

[1] Leis B., Forte T., and Zhu X., "Integrity Analysis for Dents in Pipelines," Proc. of IPC'04, IPC04-0061, Oct 2004.  
 [2] Massopust P., Torres C., Dean A., "Improving In-Line Inspection for Mechanical Damage in Natural Gas Pipelines", GRI Contract No. 5096-270-3698, Prepared for the Corrosion and Inspection Technical Committee of Pipeline Research Council International, Inc.  
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