Advances in Feature Identification using Tri-Axial MFL Sensor Technology

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ABSTRACT

Pipeline operators have been using intelligent in-line inspection (ILI) tools as part of their pipeline integrity management systems for several decades now. A wide variety of ILI tools have been developed to serve a multitude of uses. Most notable is the detection, locating, and sizing of metal loss corrosion. Magnetic Flux Leakage Technology (MFL) was developed for that exact purpose, however over the years technology and innovation has vastly improved the capabilities of MFL tools.

This paper contains a comparison of historical and current pipeline feature identification/classification capabilities for axial magnetizing MFL tools with Tri-Axial sensor technology. The pipeline features discussed include corrosion, mechanical defects, structural pipeline components, as well as the physical and magnetic parameters that affect accurate identification, location, and/or sizing. Some of these features have never been detected, identified, or reported in the past, and now constitute a significant portion of the training and testing procedure that occurs in the certification of a new MFL data analyst.

INTRODUCTION

Magnetic Flux Leakage (MFL) technology has been used for the in-line inspection of pipelines for over 40 years. It was developed to provide a cost-effective, non-destructive alternative to hydrostatic testing, for pipeline integrity assessment.

Magnetic Flux Leakage (MFL) inspection tools were developed to detect metal loss resulting from corrosion. In the early days of MFL inspection, these tools could only detect large areas of corrosion, or corrosion clusters. Advancements in tool design, sensors, electronics, among other factors, have resulted in a greater ability to detect smaller defects, as well as, predicting their size to a much greater accuracy. With these improvements, combined with years of industry use in a variety of pipeline environments, MFL tools can identify and sometimes size, many types of pipeline defects and features. The discussion will be focused on axial magnetizing MFL tools with Tri-Axial sensor technology and therefore, will not be valid for all MFL tools. A brief introduction to the identification and sizing of metal loss defects will be given. Then, identification of basic pipeline structural features using MFL data is discussed, along with many other more non-traditional features that are being detected and identified today. This paper is intended as a good introduction to somebody new to MFL technology, and a good reference for people that have had experience with MFL technology.

MFL Tool Advancements

By today's standards, the MFL tools of the 1970's, and early eighties were of low resolution and weak in magnetic strength. Advances in technology enabled pipeline inspection companies to vastly improve in many ways.

The number of magnetic field sensors that could be placed around the tool has increased dramatically over the years. The first MFL tools, and most low resolution tools, measure the magnetic flux leakage field in only a single direction, where as most of the modern high resolution tools have sensors in 2, or all 3 orthogonal directions.

The sampling rate, or number of data samples collected per specified distance or time interval, has also greatly improved. Historically, high data acquisition rates were not possible due to problems of limited data storage, high sensor power consumption, and slow processor speeds. Magnetic tape drives have been replaced with solid state hard drives, battery energy densities and capacities have increased while their size has decreased, and electronic processors have increased speed and become more power efficient.

The principle of Magnetic Flux Leakage centers on the idea of magnetizing the pipe wall to the point of magnetic saturation. Saturation is reached when the amount of magnetic flux in the pipe has reached a point where a further large increase in the applied magnetic field, will not significantly increase the flux density in the pipe wall. If the pipe wall is not saturated then the data from the flux leakage sensors is considerably compromised and potentially useless, depending on the magnitude of flux density. There are two main factors that affect saturation. Pipe wall thickness has generally the largest affect on the saturation, as the thicker the pipe the more difficult it is to saturate. Saturation is also dependent with inspection tool velocity, the faster the pig moves through the pipe the more difficult it is to saturate the pipe wall. It wasn't until the mid eighties when rare-earth material magnets (neodymium-iron boron) became available. The magnetic energy density of these magnets, are several times that of the early ferrite magnets, making it much easier to saturate the pipe wall. Thus the ranges of pipe wall thickness and pig velocity suitable for inspection have widened.

Corrosion Identification and Sizing

MFL tools were designed to locate, identify, and estimate the size and depth of metal loss resulting from corrosion. The first inspection tools developed had large, simple sensors, which were arranged with a relatively low sensor density, and with only a single sensor orientation. These tools could only identify the larger defects and wide areas of corrosion.

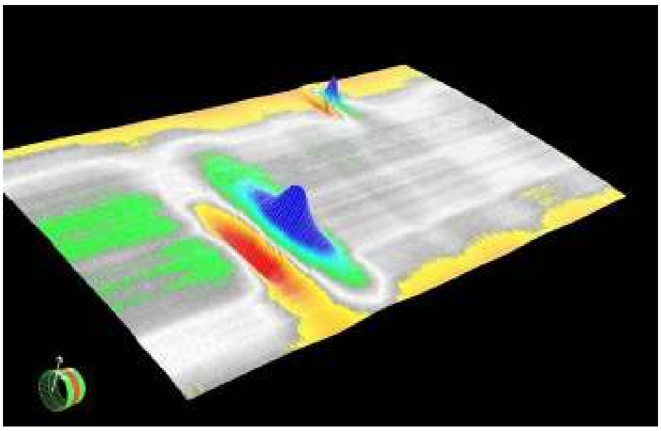


Figure 1: MFL data of the radial oriented sensor of two defects with different signal amplitudes

Figure 1 is a 3D visualization of MFL data from radial oriented sensors. This shows two defects resulting from metal loss. One can see that the two signals cover differing amounts of area, and have differing amplitudes. The defects are quantified, to define the signal, and then passed to a previously created model called a sizing algorithm that predicts the length, width, and depth of the defect. Consider Figure 1, it would be logical to assume that the larger signal would correspond to a larger physical defect, as its amplitude is almost twice that of the smaller signal. As it turns out the defect corresponding to the smaller signal is actually marginally deeper than the defect for the larger signal. This unintuitive nature of the signals, and how they correspond to actual defect length, width, and depth, demonstrates the importance of the sizing algorithm or sizing model. No matter how well an inspection tool is engineered both mechanically and electrically, if a flawed sizing model is used, the data analysis can possibly give unacceptable results.

The purpose of MFL tools is to size metal loss features according to the specifications set by the vendor. An example is shown in Table 1 for Depth, Length, and Width. In summary, it says an MFL tool can identify features greater than 10% in depth and/or greater than 1 by 1 cm in size. A defect that is predicted to be 55% by a MFL tool will be between 45% and 65% with a prediction confidence of 8 times out of 10.

	Minimum	Accuracy	Confidence
Depth	10%	± 10 %	80%
Length	1cm	± 1cm	80%
Width	1cm	± 1cm	80%

Table 1: Sizing Specification

Corrosion Identification

In a Tri-Axial sensor there are three separate sensors orientated perpendicular to each other, an axial sensor that records the magnetic field parallel to the pipe, a radial sensor which records the field perpendicular to the pipe, and a circumferential sensor which records the field directed around the pipe. A fourth sensor, referred to as the eddy sensor, is used for internal external discrimination, but also assists in the identification and classification of features. Many of the following plots display sensor data from all or some of the four sensor types. If a sensor is not shown it generally means the feature in question does not show prominently in that sensor type. Often the circumferential sensor is not shown, however it is extremely useful in the identification of specific features and will be discussed later.

Metal Gains and Metal Losses

The principal use of MFL tools is to identify metal loss resulting from corrosion. Identification and isolation of corrosion from other possible features can be difficult. One of the most important steps in beginning feature identification is the differentiation between metal gains and metal losses. Most often metal gain signals are actually metal objects on the outside pipe surface, or a metal object in close proximity of the pipe. Metal losses are most often corrosion. The differentiation is most noticeable in the radial sensor. A metal gain signal from a radial sensor shows up as a blue then red peak, shown in Figure 2, a metal loss is a red then blue peak, shown in Figure 3. Though the red and blue designations are arbitrary, metal gain signals are always opposite in polarity to metal loss signals.

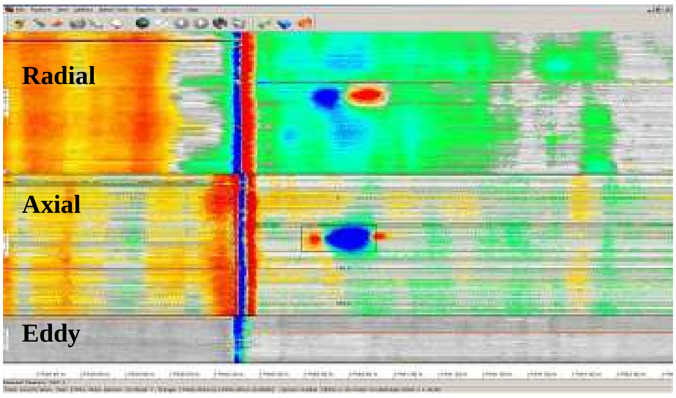


Figure 2: MFL data of a metal gain, most likely a metal object

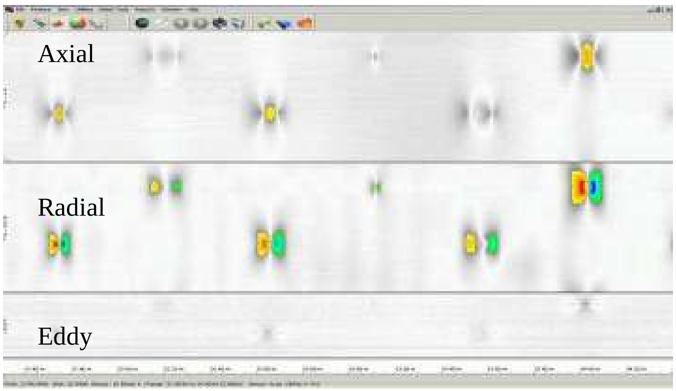


Figure 3: MFL data of 6 separate metal loss features

Complex Corrosion

Simple pitting can be easy to visualize from the MFL signal, however, more complex corrosion is difficult to visualize. An example is shown in Figure 4, showing a large, highly corroded area. The signals show clearly that corrosion is present, but the actual geometry of the corrosion is much less obvious. Figure 5 is a photo of the corresponding corrosion, it shows a band of a varying degree of metal loss going around the pipe.

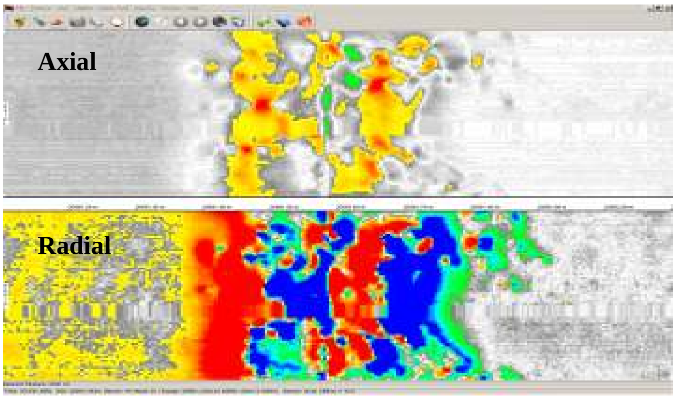


Figure 4: MFL data of a highly corroded complex area

Figure 5: Photo of corresponding complex corrosion

Complex Corrosion (Running Man)

Another example of relating complex MFL signals to actual defect geometry is shown in Figure 6. The corrosion circled was nicknamed the “running man”. The corresponding photo of the corrosion is shown in Figure 7. From the photo one can see that the general shape of the corrosion on the pipe corresponds to the 2D MFL signal shape on the paper print out. The head and body of the running man appear larger in the data because the corrosion in those areas is deeper than the others.

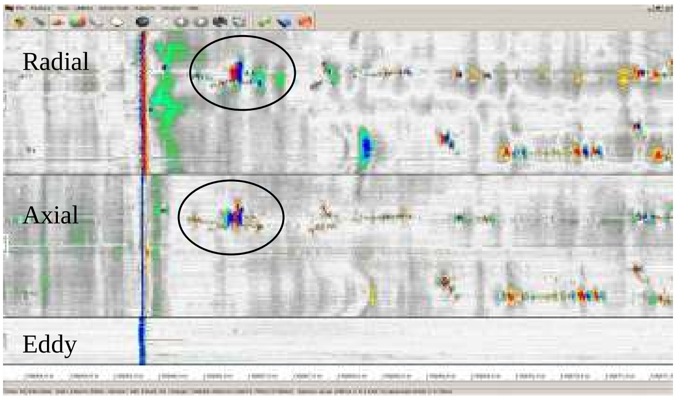


Figure 6: MFL data of an area containing complex corrosion

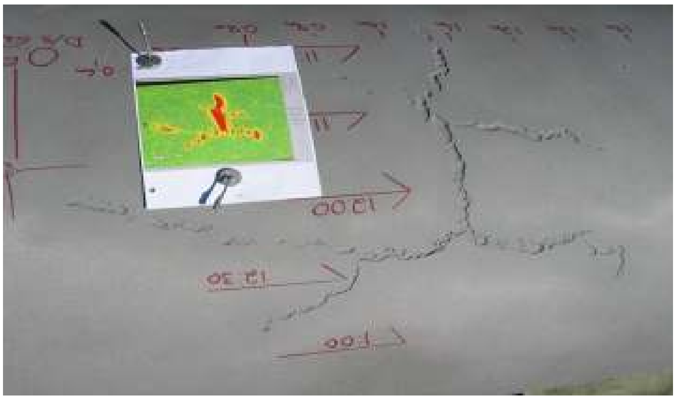


Figure 7: Photo of corresponding complex corrosion

Elongated Axial Defect and the Circumferential Sensor

The circumferential sensor is not as useful as the other sensors for the detection and identification of some defect types, however it does have significant advantages. One of the benefits is the identification of axially elongated defects. Figure 8, shows three separate defects, two rounded defects and one axially elongated (circled). By judging from the axial data alone (left), the circled defect could actually be two separate defects. The addition of the circumferential sensor data Figure 8 (right) gives added confidence that it is an elongated defect and not two defects. The circumferential sensor also assists in the identification of a wide variety of other features including dents and wrinkles.

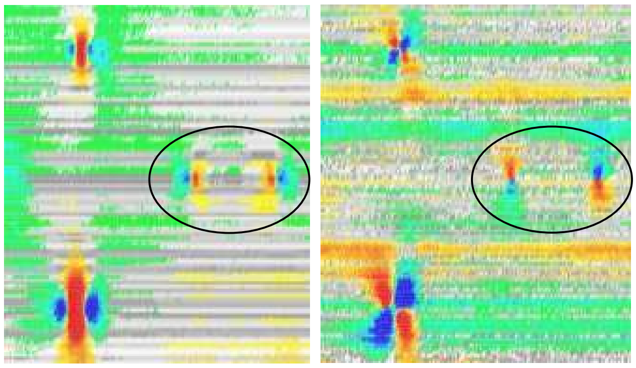


Figure 8: Axial and Circumferential sensor data of three defects.

Another major benefit of having a circumferential sensor is that it completes the triad of sensors along with radial, and axial. The three sensors capture the complete magnetic field leakage vector. These sensors can be combined within the software to create a new virtual sensor that graphically represents the total flux leakage. It is this sensor that analysts quite often use for feature identification and is arbitrarily called the differential sensor.

Figure 6 shows the “running man” corrosion in the radial and axial sensors. Figure 9 shows the same corrosion in the radial and differential sensors. It is obvious that the defect not only shows most clearly in the differential sensor, but also most resembles the photo imagery. In Figure 7 the paper print out is a display of the differential sensor.

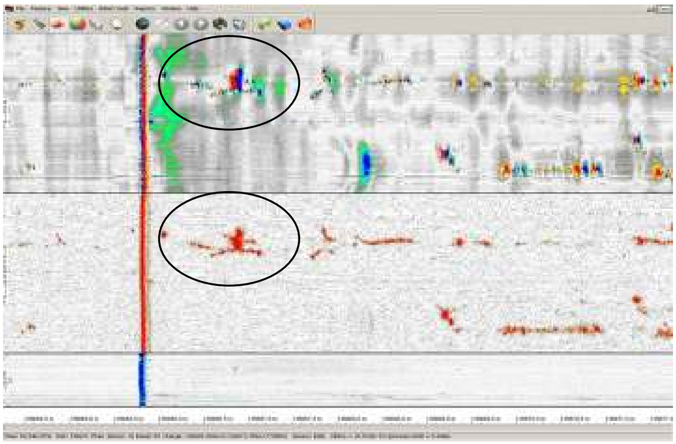


Figure 9: Demonstration of the differential sensor

Structural Feature Identification

As previously mentioned MFL tools were designed to identify metal loss resulting from corrosion, but can also identify many other pipeline features. These features include structural pipeline components, such as valves, ports, tees, girth and seam welds. A variety of such features will be shown, but should not be viewed as a comprehensive list of all identifiable structural features.

Valves

Figure 10 shows MFL data of three types of pipeline valves, with broken borders surrounding the areas of interest in the data. In order starting at the top is, a ball valve, swing/check valve, and gate valve. Valves show prominently in all sensors, simply due to their large structural differences from normal pipe. There are usually other structural components both upstream and downstream of valves.

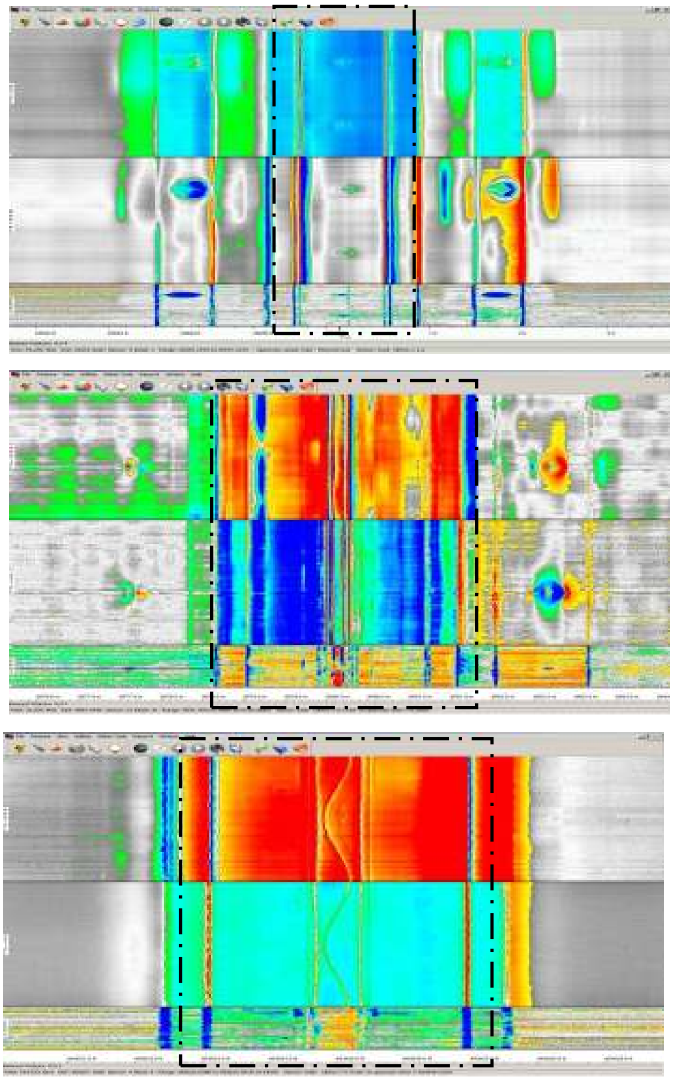


Figure 10: MFL data of three different valve types
Ball Valve (top), Swing/Check (middle), Gate (bottom)

Ports and Tees

Ports and tees also show up clearly in all sensors, and have virtually identical data signals, except tees are typically much larger than ports. Figure 11 shows data from both a tee (left) and a port (right). These pipeline features are easily differentiated by their size and position on the pipe.

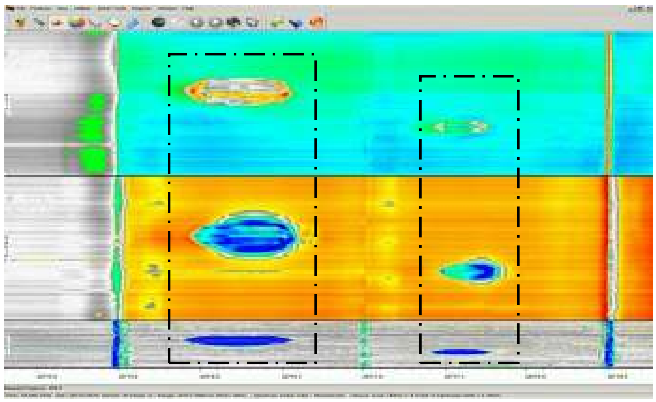


Figure 11: MFL data of a Tee (left) and port (right)

Flanges

Flanges show up clearly in all sensors but are most easily identified in the eddy by a grouping of three vertical lines, as can be seen in Figure 12. The middle line being the actual seal of the flange, connecting the two pipe pieces together.

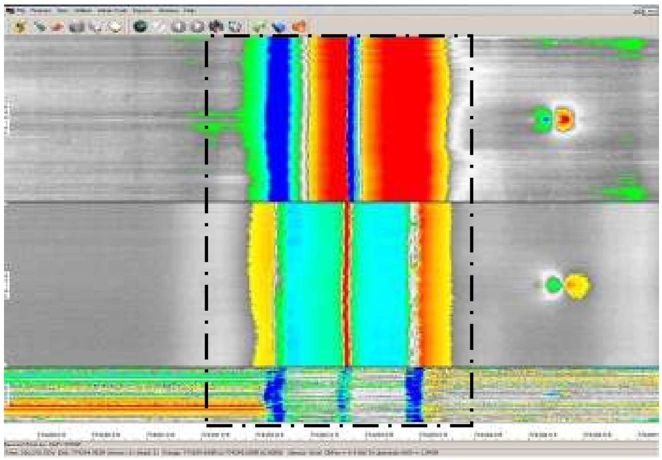


Figure 12: MFL data of a Flange

Wall Thickness Transitions

Wall thickness transitions show almost exclusively in axial with some indication in radial, and little indication in circumferential and eddy. This may be the reason that many of the early MFL tools only had axial oriented sensors. The vertical line in the middle of the screen capture below, Figure 13, is a girth weld that connects two pipe joints of differing wall thickness together. The colour change from orange to grey on either side of the girth weld in the axial sensor, represents a difference in the magnitude of the recorded magnetic leakage field in the axial direction for those pipe sections.

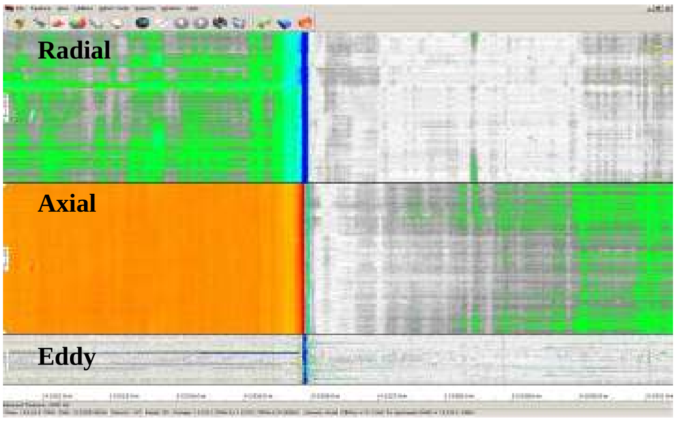


Figure 13: MFL data of a wall thickness change

Long Seam Weld and Spiral Welded Pipe

The obvious difference in long seam and spiral weld pipe is clearly shown in Figure 14. The difference shows up most evidently in the eddy sensor.

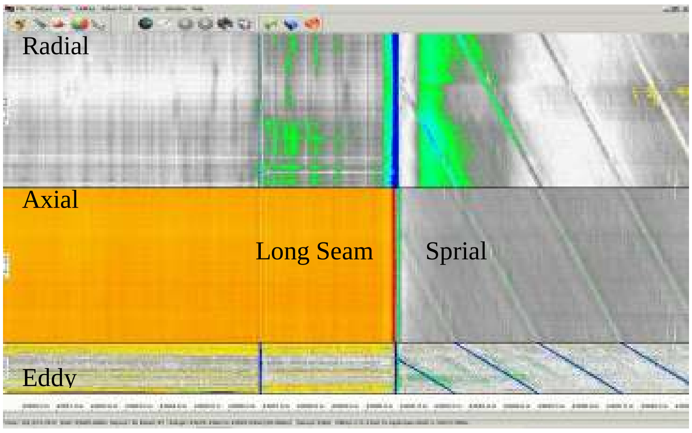


Figure 14: MFL data of Long Seam vs. Spiral Weld

Sleeves and Casings

Sleeves and casings show up equally well in both axial and radial sensors. A sleeve, Figure 15, and casing, Figure 16, look like short discrete wall thickness transitions in the axial and radial data, but does not show as prominently in the eddy sensor as a girth weld. In addition they always start and end in the middle of a pipe. Another significant difference is their length. Sleeves are much shorter and are usually limited to 3 ft unless multiple sleeves are used, as in Figure 15. Sleeves are used as an integrity management solution to mitigate the risk of an existing pipeline defect. In Figure 15 one can still observe the corrosion beside and under the sleeve in the data.

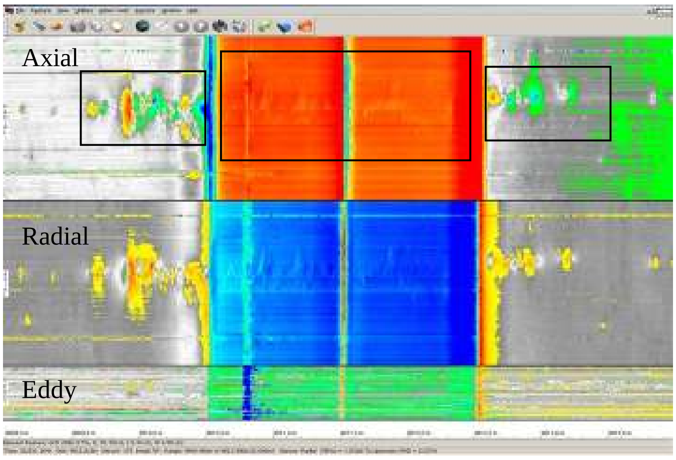


Figure 15: MFL data of a sleeve

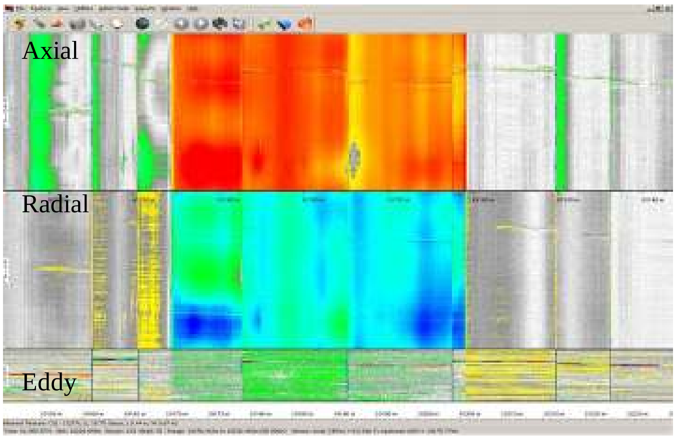


Figure 16: MFL data of a casing

Anchors and Supports

Anchors, Figure 17 (top), and supports Figure 17 (bottom) show up equally well in radial and axial sensor data. An anchor can be identified by a metal gain feature located at the top of a pipe. A support also shows up as a metal gain but goes completely around the pipe. A support looks like a sleeve but are generally equally spaced down the length of the pipe.

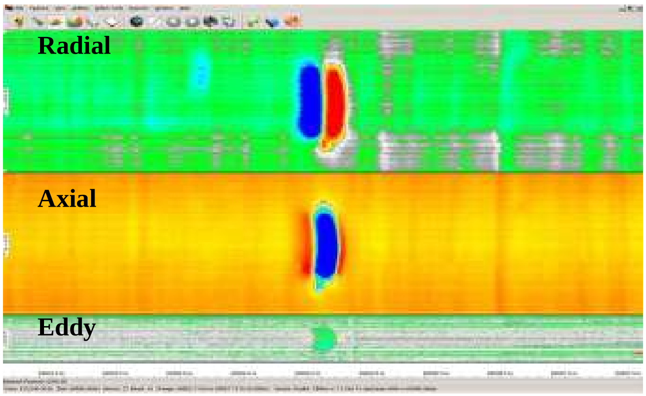
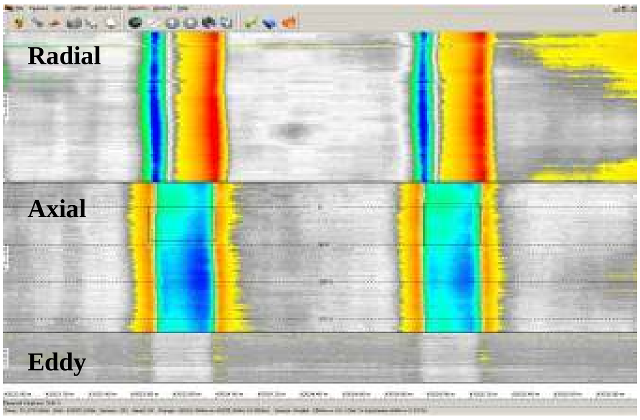


Figure 17: MFL data of a anchor (above) and a support (below)



Mitre Bend

Figure 18 (below) is a data screen capture of a mitre bend. It is comprised of a series of short bend sections welded together. Figure 18 (top right) shows the graphical display of the inertial data, with the welds of the bend sections highlighted in blue.

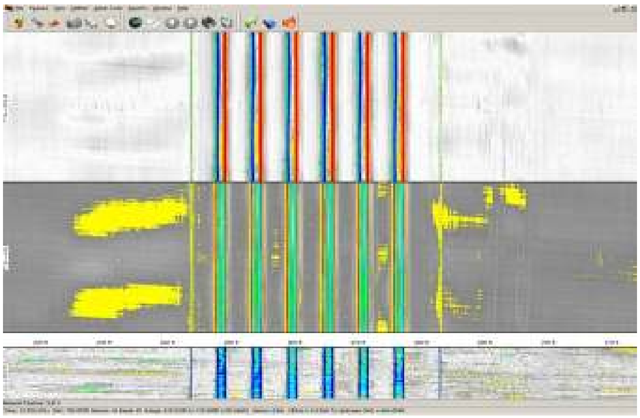
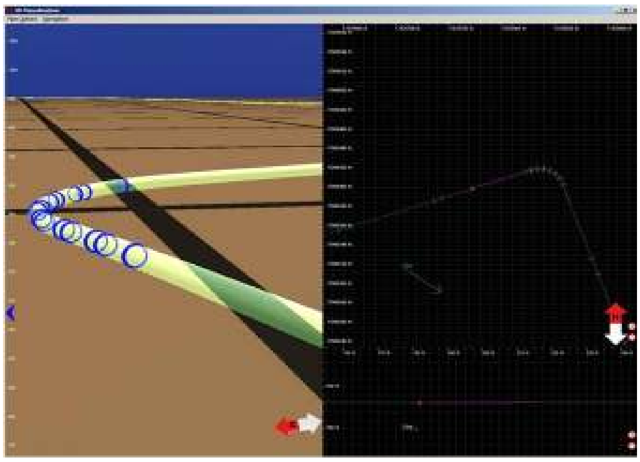


Figure 18: MFL data of a mitre bend (above), and graphical display of the inertial data (below)



Low Quality Field Bends

The quality of older field bends are not always adequate, or up to today's standards. Figure 19 shows, what was initially thought to be dense corrosion in vertical stripes. The observed anomalies were a result of the bending process where the steel, on the outer side of the bend, was stretched and the nominal wall thickness had been greatly reduced in those specific locations. Figure 20 is a 3D rendering of the pipeline, showing the bend and the defects.

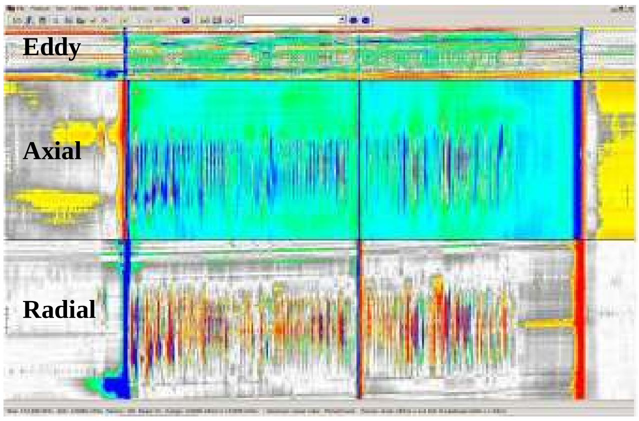


Figure 19: MFL data old field bend

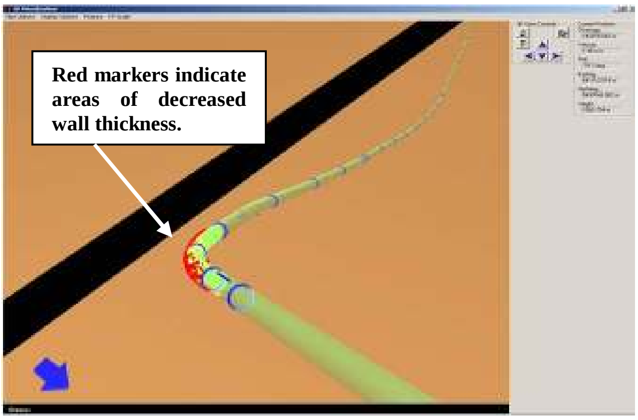


Figure 20: Graphical display of the inertial data

Advanced Feature Identification

Up to this point the defects and features discussed have been those that are commonly accepted for MFL inspection tools to identify. The following are features or defects that pipeline operators are now more frequently asking inspection companies to identify. These features include, but are not limited to, manufacturing/construction damage, hot taps, possible dents and wrinkles, and unusual metal gain and metal loss features.

Ladder on Pipe

Figure 22 shows the MFL data of peculiar feature that was not identified until it was investigated in the field. The photo, Figure 21, clearly shows the stairway directly on top of the pipe. Even though the stairs may not be in direct contact with the pipeline, they are clearly visible in the MFL data.

Figure 21: Photo of a steel stairway next to a pipeline

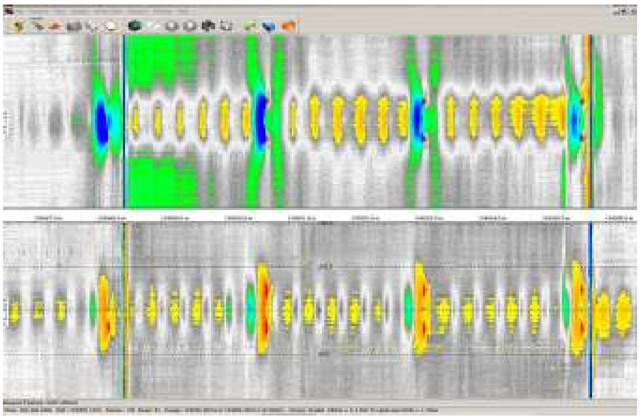


Figure 22: MFL Data of the steel stairway

Manufacturing Damage

Usually a significant defect or damage, caused by the manufacturing process, is detected in the installation and hydro-testing of a new pipeline. Some of these features, however, go undetected until an in-line inspection. Figure 23 shows the radial data of such a feature. Utilizing the data from all three sensors it was deduced, before the excavation of the area, that the feature was not simply a metal loss due to corrosion. The subsequent excavation determined the defect to be manufacturing related, as is shown in Figure 24.

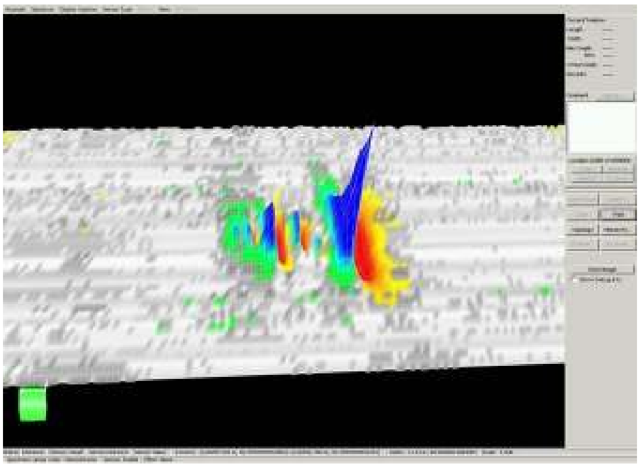


Figure 23: MFL data of a defect

Figure 24: Photo of the corresponding defect

Construction Damage

Sometimes the construction process can cause unintended flaws in the pipeline. In this case, a steel bolt was accidentally in contact with the pipe during the pipe bending process, and an imprint of it was left on the steel surface. Figure 25 is a screen capture of the radial, and circumferential sensor data, and Figure 26 is a photo of the metal loss defect.

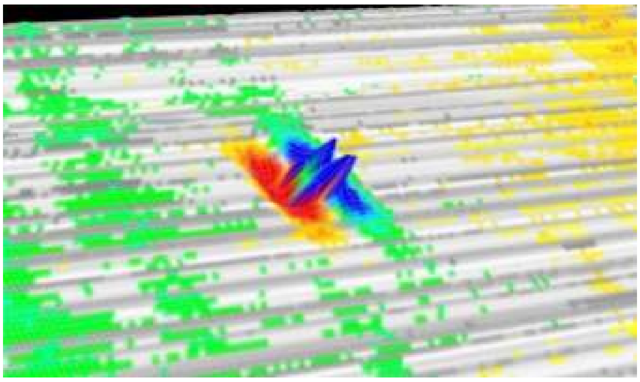
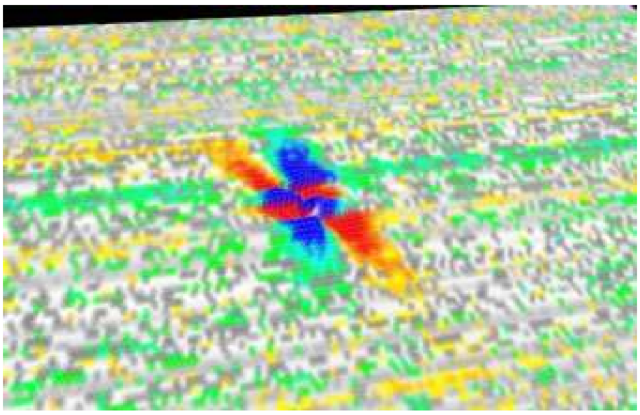


Figure 25: Radial (above) and circumferential (below) MFL data of construction damage



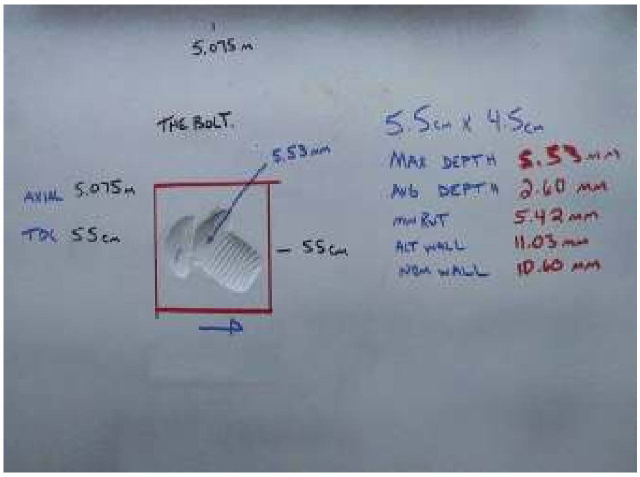


Figure 26: Photo of a metal loss from a steel bolt imprint

Hot taps

Hot taps are small ports which are made while the pipeline is in operation. They can be illegal in nature and in some countries can be a large problem for pipeline operators. Figure 27a shows a hot tap feature in differential and radial data, and Figure 27b shows the 3D data representation.

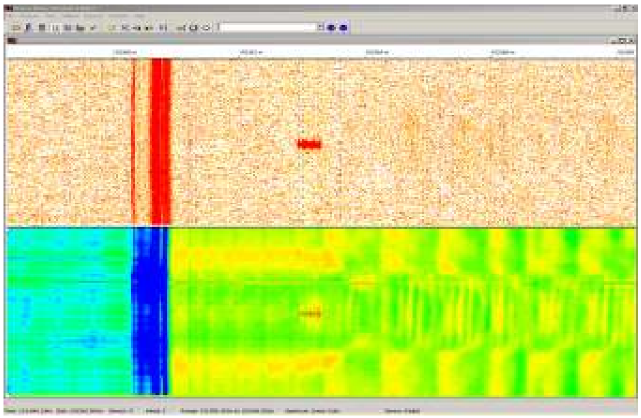


Figure 27a: Radial MFL data of a hot tap

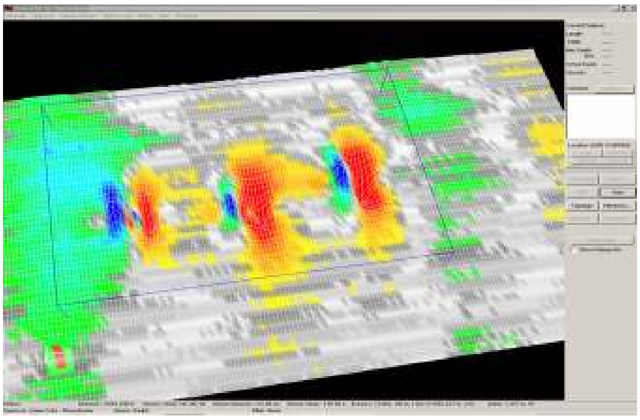


Figure 27b: Radial MFL data of a hot tap

Seam Weld Flaw (Volumetric Inclusion)

Even though they are not metal loss in the traditional sense, seam weld flaws can be identified if they are of a sufficient size. Figure 28 shows radial data (top) of a seam weld and an apparent corrosion on that seam weld. Figure 28 (bottom) shows the corresponding area in axial data.

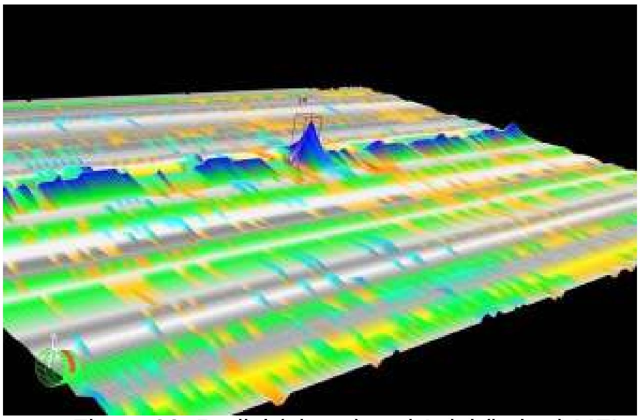
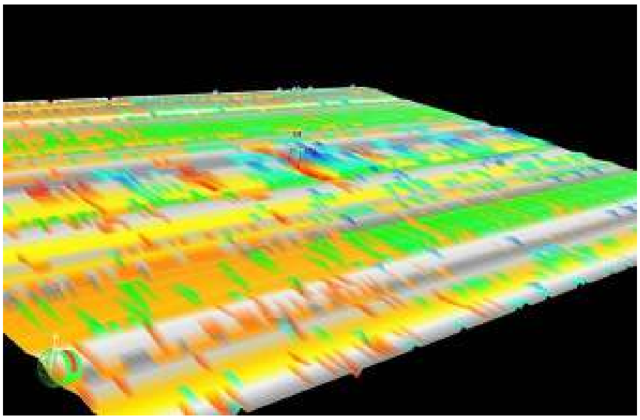


Figure 28: Radial (above) and Axial (below) MFL data of apparent corrosion on a seam weld



During the excavation the apparent metal loss defect could not be found on the seam weld, as shown in Figure 29. The whole area was examined with a ultrasonic wall thickness probe. It was determined that there was a defect within the seam weld, or more accurately, a volumetric void. The area was lightly ground down, exposing the seam weld flaw, as shown in Figure 30.

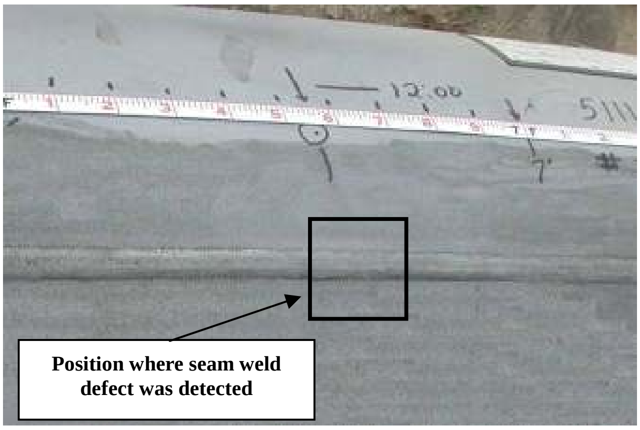


Figure 29: Photo of an apparent corrosion on a seam weld

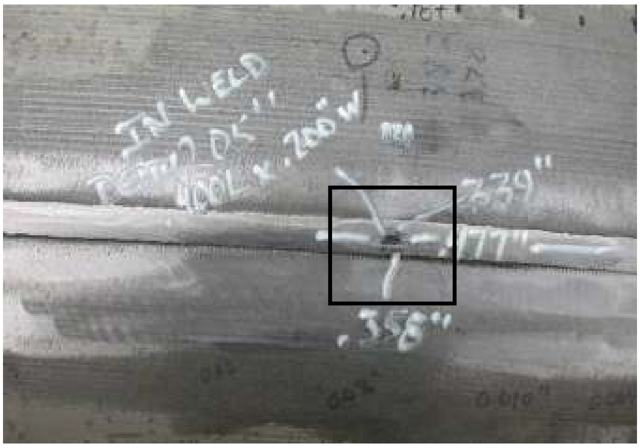


Figure 30: Photo of a seam weld flaw

Dents

Dents were not always thought to be reliably identified by MFL data. This is mostly due to the insensitivity of axially orientated magnetic field sensors. Figure 31 depicts a screen capture of axial sensor data of a girth weld where a dent has formed. The dent is virtually undetectable in the axial data alone. The radial and circumferential oriented sensors, as shown in Figure 32, clearly show a dent on the girth weld and a smaller dent close by (circled). Dent identification demonstrates one of the major benefits of the circumferential sensor.

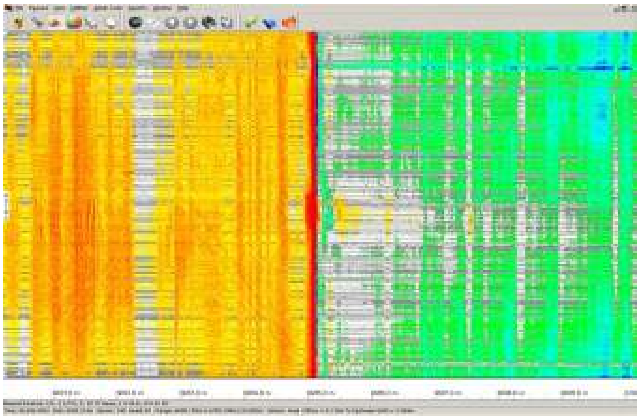


Figure 31: Axial only MFL data of a dent

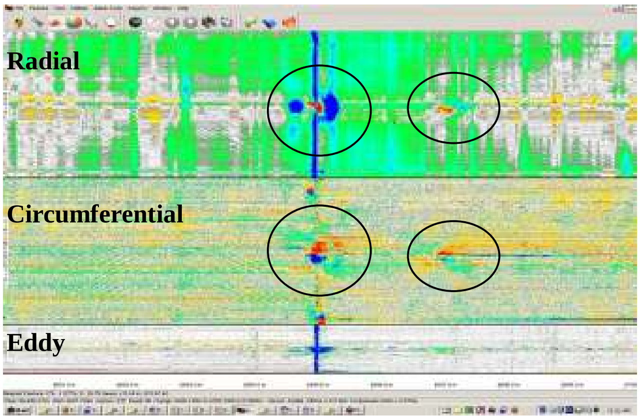


Figure 32: Radial, Circumferential and Eddy MFL data of a dent

Wrinkles & Buckles

Wrinkles, which have similar plastic deformation to dents, can also be easily identified with Tri-Axial MFL inspection tools. Figure 33 shows a buckle, and since it is relatively localized, it resembles a dent. However, the signal is more vertically elongated than a dent. Figure 34 is a photo of that wrinkle.

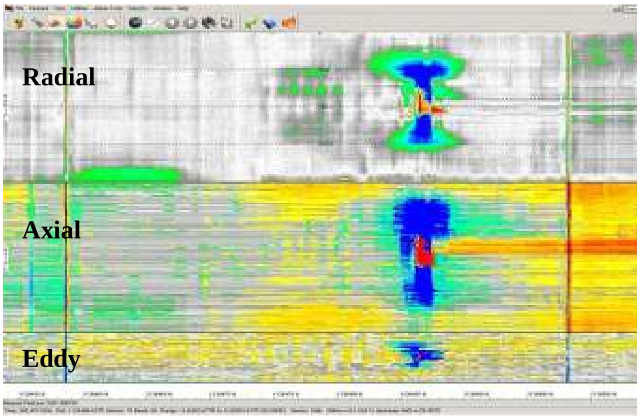


Figure 33: Winkle in MFL data

Figure 34: Photo of corresponding wrinkle

Gouging Without a Dent

A gouge, by itself, is usually metal loss caused by third party damage, and is generally associated with significant strain at that area. Gouging is a very unique metal loss feature with a complex data signal. Figure 35 shows a gouge for three sensor types. The gouging shows up exceptionally well in the radial and circumferential sensor. Figure 36 shows the corresponding photo of the area.

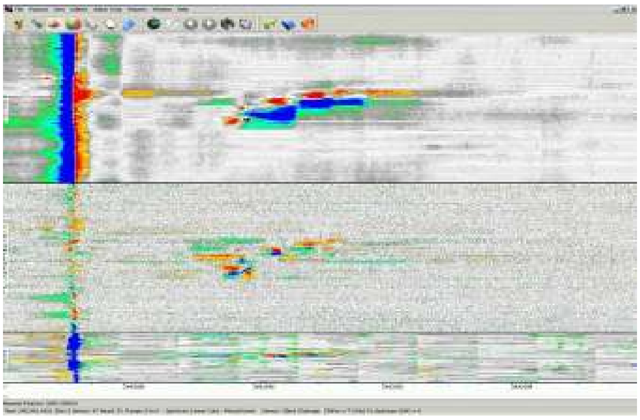


Figure 35: MFL Data of a gouging without denting

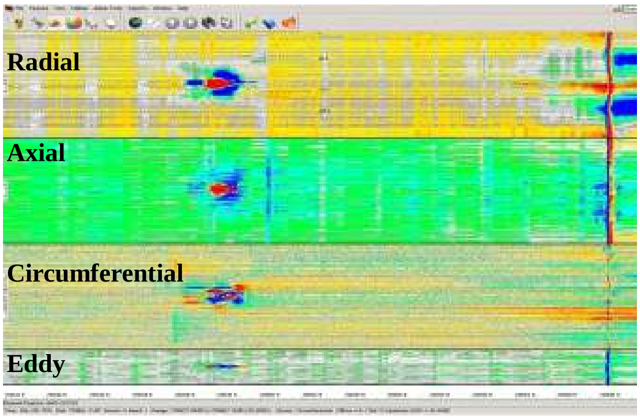


Figure 37: MFL data of a dent with a crack at its center

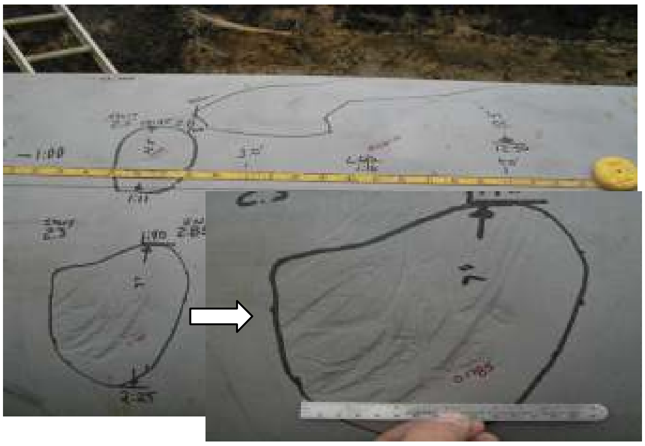


Figure 36: Photo of a Gouging without Denting

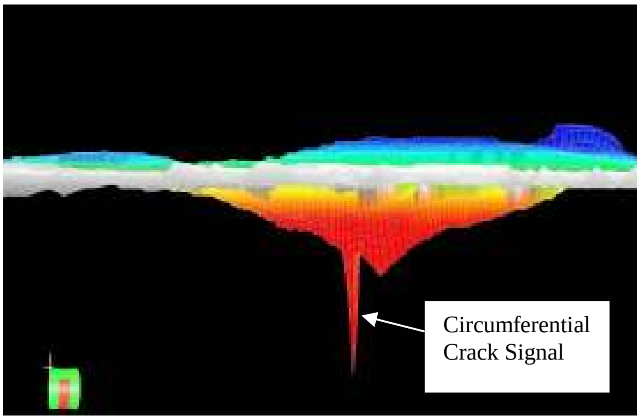


Figure 38: Radial oriented MFL data of a crack in a dent

Circumferentially Oriented Cracks

It has been found that modern Tri-Axial MFL tools can identify significantly wide and deep, circumferentially oriented cracks. Figure 37 shows a large dent and close examination of the data shows a very sharp spike at the center of the feature. That spike feature is a large circumferentially orientated crack at its center, as shown in Figure 38. Figure 39 is a photo of the crack taken in the excavation ditch.

Figure 39: Photo of a large crack inside a dent identified by an MFL Inspection tool

VI Conclusion

Today's pipeline operators are faced with expanding pipeline networks, and using aging pipelines beyond original design life to meet petroleum demands. This, in combination with increasing government regulation, has forced pipeline transmission companies to develop extensive pipeline integrity programs. The use of in-line inspection using intelligent pigs, including MFL tools, has become an important part of these integrity programs. As the demands on the pipeline operators to keep up production, without sacrificing pipeline or public safety, continue to grow, so have the demands of pipeline operators on inspection companies. Timely and successful inspection runs, along with accurate and reliable corrosion data have always been expected, but now further analysis of non-corrosion features is being requested. Pipeline defects such as dents, and wrinkles, which traditionally have not been identified in MFL data reports, are now being requested, especially if they are in conjunction with corrosion. Requests for the re-evaluation and analysis of old MFL data are occurring more frequently, looking for either specific pipeline deficiencies, or just re-classifying all features historically reported as unknowns. The requested minimum depth for reporting corrosion features has also decreased significantly in the last few years.

It is the challenge of today's pipeline inspection companies to meet these new demands and squeeze out more information from MFL technology than ever has been done before.

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