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In-Line Inspection Technologies for Mechanical Damage and SCC in Pipelines - Final Report

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16. Abstract (Limit 200 Words)

This report summarizes work conducted under a contract entitled "In-Line Inspection Technologies for Mechanical Damage and SCC in Pipelines." This project evaluated and developed inspection technologies for mechanical damage and cracks in pipelines.

Most of the project examined MFL for mechanical damage defects. Included were evaluations of existing analysis methods to establish a baseline from which today's tools can be evaluated and tomorrow's advances measured. In addition, improvements were developed and verified through pull rig and flow loop testing. Finally, an experience base and defect sets were built.

- Several techniques were developed for analyzing MFL signals for detection and characterization of mechanical damage. These techniques are valid over a range of defect geometries, but none is valid all the time. Consequently, a combination of techniques will be needed for commercial application.
- Initial commercial applications will seek to detect and determine the relative severity of mechanical damage. Later applications will extend the results so absolute severities can be estimated.
- Follow-on work is needed on methods of predicting defect features and severity.

A smaller portion of the project evaluated inspection technologies for cracks. The focus was on electromagnetic techniques. These techniques are still in the early stages of development.

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In-Line Inspection Technologies for Mechanical Damage and SCC in Pipelines - Final Report

June 2000

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Introduction

This report describes the work conducted for the U. S. Department of Transportation Office of Pipeline Safety under a research and development contract entitled "In-Line Inspection Technologies for Mechanical Damage and SCC (Stress-Corrosion Cracking) in Pipelines." This project evaluated and developed in-line inspection technologies for detecting mechanical damage and cracking in natural gas transmission and hazardous liquid pipelines.

The work conducted under this program consisted of three major tasks. Task 1 covered inspection methods for mechanical damage. Task 2 covered methods of detecting stress-corrosion cracks. Task 3 covered verification testing and improvements in the analysis methods. The work began in July 1996 and continued through the end of 1999, after which the report was written.

- B Link to Task 1 Workplan
- ☐ Link to Task 2 Workplan
- ☐ Link to Task 3 Workplan

This report was originally issued in December 1998, at which time it covered work done in the first two years of the program. In April 2000, the report was reissued in its present state. (Portions *of* the report that significantly changed between the first and second edition are shown in italics in the Table *of* Contents.) It now covers all of the work and the conclusions drawn in the program. The intended audience is government representatives, pipeline companies, and inspection vendors.

The ultimate benefit of the project should be more efficient and cost-effective operation, maintenance, and safety of transmission pipelines. Pipeline companies are benefiting by having access to inspection technologies for detecting critical mechanical damage and cracks, and inspection vendors are benefiting by understanding where improvements to their systems are beneficial and needed and how to make those improvements. These benefits, and others, support the Office of Pipeline Safety's long-range objective of ensuring the safety and reliability of the pipeline infrastructure.

Project Team

The work conducted under this program was a joint effort of three organizations. Battelle acted as the prime contractor and was responsible for ensuring that the overall goals of the program were met. Southwest Research Institute was heavily involved in work to determine the effects of stresses and strains on the magnetic properties of pipeline steels, work on nonlinear harmonic sensors, and work on stress-corrosion cracking. Iowa State University was responsible for the work on neural networks, other advanced analysis techniques, and stress-corrosion cracking. Battelle was responsible for the remaining technical tasks.

Report Organization

This report is written in an interactive or Web format. The body of the report (this document) is an Executive Summary with links to additional details. This format was chosen to let readers quickly access more detailed information of interest to them. The Table of Contents lists the main sections of the report. Within each section, there are links to background and more detailed information on various topics, and many examples of data and technical analyses are given through links. This report is being distributed as a printed copy of the body of the report along with a compact disk containing the entire report and all of its links. Many of the links and the glossary can be printed for easy reference.

Links are identified with a basic document icon (B), a more advanced document icon (A), a data icon (D), a figure icon ( ), a video icon ( ), an underline, or a button. Typically, document links open in place of the current document (which can be accessed again by pressing the back key); figure and video links open in a separate window; and underlined links (without an icon) redirect the user to another location on the same page or to an external Internet link. The text on a button will identify its use; buttons can redirect the user, open windows, allow the reader to download a video clip, or launch an external program. In addition, there is an on-line glossary. Words listed in italics are included in the glossary.

This report has three main sections: (1) Mechanical Damage, (2) Cracking, and (3) Conclusions. The first section, " Mechanical Damage," contains the following sections:

- "Results from Prior Work" describes the basic components of inspection signals from mechanical damage, identifies key signal parameters and features, and summarizes conclusions from prior work.
- "Data Collection" describes the defect fabrication process and the test equipment used to record inspection signals, summarizes the data taken, and summarizes the conclusions drawn about the basic magnetic properties of common pipeline steels.
- "Analysis Methodologies" describes *feature-based* analysis methods, *neural network* analysis methods, and the use of *nonlinear harmonic systems* to detect and characterize mechanical damage. Each subsection gives conclusions drawn.

The second section, " Cracking," contains the following sections:

- "External Techniques for Sizing Cracks" summarizes work done here on a method of sizing tight cracks from the outer pipeline surface.
- "Velocity Induced Eddy Currents" summarizes work to date on inspections via eddy currents that are generated near magnetic flux leakage (MFL) magnetizers.
- "Remote Field Eddy Currents" summarizes work on defining the effect of magnetic saturation on remote field inspection techniques.

"Conclusions" summarizes the important findings from this program.

Mechanical Damage Detection and Characterization

Magnetic flux leakage, or MFL, is the most commonly used in-line inspection method for the detection of corrosion in pipelines. [Bubenik92] Extending this technology for mechanical damage would simplify deployment and have many practical and economic benefits. MFL inspection tools locate pipeline defects by applying a magnetic field in the pipe wall and sensing a local change in this applied field with sensors near the pipe wall. These changes depend on the type of defect (metal loss or changes in material or magnetic properties).

🅱 Background material on MFL

MFL has been shown to be capable of detecting some mechanical damage. [Davis96, Davis97] Part of the signal generated at mechanical damage is due to geometric changes - for example, a reduction in wall thickness due to metal loss causes an increase in measured flux and sensor/pipe separation (liftoff). Other parts of the signal are due primarily to changes in magnetic properties that result from stresses, strains, or damage to the microstructure of the steel.

☐ Background material on magnetic properties
☐ Background material on magnetic property changes with stress and strain
🅱 Description of typical mechanical-damage features

Goals of this work were to develop methods of using MFL to detect mechanical damage, differentiate it from other defects, and if practical, determine its severity.

Results from Prior Work

MFL signals for metal loss, dents, cold work (defined here as damage to the microstructure), residual stresses, and *plastic strains* are fundamentally different. These differences create the potential to identify, decouple, and analyze different signal components as a means of assessing the severity of mechanical damage defects.

🅱 Comparison of centerline MFL signals for metal loss, dents, and cold work

MFL inspection tools that are designed to detect metal-loss corrosion are not optimized for detecting mechanical damage. These tools use high magnetic fields to suppress noise sources, such as stresses and microstructural damage, which diminish sizing accuracy for corrosion. However, a mechanical-damage tool needs to detect stresses and microstructural damage because they are important characteristics of mechanical damage.

The results of previous studies show that the optimum field level for detecting stress and cold work (microstructural damage) in mechanical damage is low and high field levels can mask or erase important components of the signal. Unfortunately, the noise sources that are avoided by high magnetizing fields become a part of the signal at low magnetization levels, making *detection* and *characterization* more difficult.

Basic effects of various parameters on MFL signals were measured in an earlier project. [Davis96] The prior results showed:

- Cold working typically increases the average magnetic *permeability* in the defect area, causing a decrease in the magnetic flux at the sensor.
- The optimum magnetization point for detecting cold working (along with residual stresses and strains) is near the *knee of the magnetization (B-H) curve.* Conversely, the optimum magnetization point for corrosion detection is well above the knee into saturation.

Data Collection

Several different types of data have been taken in this program: magnetic and mechanical material properties, inspection signals, and defect characteristics.

Early in the program, magnetic and mechanical properties of typical pipe steels were measured. These measurements were made to ensure that later findings would be applicable to a wide variety of steels. Material property data were taken from 36 pipes that had been removed from service and from new pipe material.

MFL data were taken from fabricated and natural defects. Fabricated mechanical-damage defects were installed in flat plates, pipe sections, and full pipe pieces. In addition, a rubber-tired backhoe was used to damage several sections of pipe, and a limited number of pipe samples with defects were collected from the field. The MFL signals were collected in the Gas Research Institute (GRI home page) Pipeline Simulation Facility (PSF) linear test rig, [Nestleroth95] pull rig, [Bubenik95a] . and flow loop [Bubenik99]

Defect characteristics were measured after installation, after each repressurization, and after testing to failure. In a limited number of cases, defects were cross sectioned to allow additional measurements.

Material Properties

Magnetic, mechanical, metallurgical, and chemical property data have been taken in this program. The magnetic properties of pipeline steels are variable and a function of fabrication process, alloying agents, and microstructure. Stress and strain play major roles in defining a steel's magnetic properties. Since stress and strain are important parts of mechanical damage, understanding their effects was a key part of this project.

Magnetic and mechanical properties of 36 different pipe steels were measured.[Nestleroth98] Measurements were made on a subset of the samples under tensile and compressive loading. Additional measurements were made around a full pipe-circumference to ensure the findings would be apply to full pipe sections.

- ☐ Description of basic material property testing
- B Description of material property stress tests
- B Description of full pipe tests
- D Table of measured material property variations
- ☐ Database of material properties

This evaluation reached two main conclusions. First, because there is no clear correlation between magnetic properties and commonly measured mechanical properties, the change in magnetic properties due to mechanical damage must be outside the range of typical magnetic properties in order for the damage to be easily detected. Alternatively, when assessment of mechanical damage defect signals requires data on actual magnetic properties, they must be measured because they cannot be estimated easily from the more commonly known mechanical properties.

The second conclusion is that compressive stresses or strains in the same direction as the magnetizing field are easier to see than tensile stresses or strains. Changes in magnetic properties due to compressive stresses or strains are large enough to fall outside the typical scatter band of magnetic properties. So, detecting compressive stresses and strains should be possible without measuring the magnetic properties of a pipeline steel. The same cannot be said of tensile stresses. Tension causes more subtle property changes. So, detecting tensile stresses and strains would require measurements of magnetic properties in order to determine whether changes had occurred.

Based on the measurements made in this program, a database on the magnetic properties of steel, along with previously measured mechanical properties and chemical compositions, was compiled.[Nestleroth98] (The majority of the data from this database are included in ☐ Database of material properties , which is referenced above.) Metallurgical data includes information on grain size, grain distortion, inclusion size, density, and distribution. The database can be used as a basis for further developing MFL techniques and other inspection technologies to nondestructively determine a pipe's mechanical and magnetic properties.

Defect Data

Defect Sets

Data were taken from three types of defects in the pull rig and flow loop. Two of these defect types were fabricated with an indenting machine on pressurized pipe samples, and one was made by hitting pressurized pipe with a backhoe. The first type of fabricated defect was made with a spherical indentor that housed a small protruding tooth. The second type was made with a more realistic indentor that was shaped like a backhoe tooth. The third type of defect was made with a small rubber-tired John Deere backhoe.

- Details on Defect Installation
- Effects of Defect Installation Procedures

The defect sets were made in six pipe samples. Detailed descriptions and photographs of the defects are given in the following links. In all cases, dent depth refers to the maximum depth of a dent during installation (not the final or rerounded dent depth) and length refers to the travel distance along the pipe axis for the indentor:

- Defect Set 1 - Descriptions and Photographs
- Defect Set 2 - Descriptions and Phofographs
- Defect Set 3 - Backhoe Defects: Descriptions and Photographs
- Defect Set 4 - Practice Defects: Photographs and *MPI* Results
- Defect Set 5 - Pull Rig Defects: Photographs and *MPI* Results
- Defect Set 6 - Flow Loop Defects: Photographs and *MPI* Results

The defect set number reflects the order in which the defect sets were prepared. The first five defect sets were used in the pull rig, and the last set was used in the flow loop.

Defect Sets 1 and 2 were made with the spherical indentor and included dent depths up to 6 percent of the pipe diameter. Gouge depths ranged from nearly zero to 25 percent of the wall thickness, and gouge lengths ranged from nearly zero to 6 inches.

Defect Set 3 was made with the rubber-tired backhoe. These defects were made with pipe in the ground at pressures of 150 and 250 psi. A series of hits were made along and across the pipe, as well as at an angle. In general, these mechanical damage zones contain short or long gouges with little or no denting. In places, the gouge depths are substantial, approaching 25 percent of the wall thickness.

Defect Sets 4, 5, and 6 were made with a combination of spherical and tooth-like indentors. Typically, dent depths were 1 to 3 percent, and gouge lengths were up to 8 inches. Gouge depth was not controlled directly. These defects, and those made by backhoe, most closely represent defects seen in the field.

Analysis Methodology

The approach to developing analysis methodologies in this program was largely empirical. Numerical results were used to expand and strengthen the conclusions reached from measured data. To correlate MFL signals with defect parameters, it was necessary to understand the relative severity of the defects being tested.

To provide insight into defect severity, a number of measurements were made on the defects - during and after installation, pressure testing, and repressurization. Load and deflection data were taken for about half of the defects during their installation. Wet fluorescent magnetic particle inspections were made of each defect, as was a measurement of residual dent depth. In selected cases, the wall thickness of the pipe in and around the defect was measured with an ultrasonic thickness gauge from the inside pipe diameter.

A subset of the mechanical-damage defects was destructively tested by cross sectioning to establish a set of severity indices. These indices were based on metallographic assessments and measurements. For example, the assessments included measurements of hardness, cold work geometry, degree of grain elongation, and amount of metal removal. In addition, more detailed analyses were conducted on two defects that failed during repressurization.

Load Deflection Data

Load-time-deflection measurements were made during the installation of many of the defects. Vertical (radial) forces were measured, as were horizontal (axial) forces. As expected, the maximum forces were a function of defect geometry, indentor size and shape, and pipe pressure.

- ☐ Load-time-deflection measurements

The following links include the load-deflection and load-time curves for Defect Sets 4, 5, and 6:

- ☐ Defect Set 4 - Practice Defects: Load-Time-Deflection Plots
- ☐ Defect Set 5 - Pull Rig Defects: Load-Time-Deflection Plots
- ☐ Defect Set 6 - Flow Loop Defects: Load-Time-Deflection *Plots*

Failure Analyses

Some *of* the defect sets used in this program were repressurized to change the stress and strain conditions around the defects and, possibly, introduce or extend cracking. In two cases, a defect failed during repressurization. After failure, the damaged sections were cut out and a patch welded in place. Then, additional sets of MFL measurements were taken. The failed sections were subjected to detailed failure analyses to provide insight into defect parameters that may be important to detect or characterize during in-line inspections.

The analyses indicated the failures had three distinct phases: initiation, stable tearing, and final fracture. Initiation refers to the formation of a shear-like crack in response to the mechanical damage process. Stable tearing refers to the transition of the shear-like crack to a perpendicular crack and its continued growth by void nucleation and coalescence through the wall thickness. Finally, if the through-wall crack is sufficiently long, unstable crack extension (fracture) will follow.

From an inspection perspective, the conditions that led to initiation of a shear-like crack are most important. The shear-like cracks themselves would be difficult to see, but the cracking was accompanied by two important features: microstructural changes and wall thinning. The shear-like cracks formed when the microstructure was changed by the mechanical damage and rerounding created conditions that exceeded the initiation resistance of the material. Since MFL can be sensitive to changes in stresses and strains, techniques that are sensitive to changes in microstructure and high stresses may help identify defects as significant. Additional details on the failure analyses can be found in the following link.

Failure Analyses

Cross Sections

Selected defects were cross sectioned and examined after they had been used for collecting inspection data. The maximum pressure that these defects could sustain was not destructively determined, but a number of severity indices were identified and measured.

Cross-Sectional Data

Inspection Data

Linear Test Rig Data

Linear test rig measurements were made on several dozen defects at velocities under about 3 miles per hour. At this velocity, velocity has a negligible effect on the signals. Typically, data were taken at 10 Oersted intervals, ranging from as low as 10 Oersted to as high as 150 Oersted. In addition, remanent measurements were taken using no applied field.

Three types of defects were investigated in the linear test rig: defects made under pressure, natural dent defects in pipe removed from service, and simple mechanical damage defects made in flat plates. The defects consisted of plain dents, cold worked regions, dents with cold worked regions, and cold worked regions with removed metal. The linear test rig defects were made in two pipe steels: the flow loop material and a generic X52 material. The materials used were the same as those used for the pull rig defects, discussed below.

☐ Additional details on linear test rig experiments and defect sets

Pull Rig and Flow Loop Data

Test Bed Vehicle Upgrades. The linear test rig experiments showed that multiple magnetization levels provide additional information for detection and characterization of mechanical damage defects. However, the flux leakage levels needed are smaller for these defects than for metal loss. These results indicated that changes were required in the accuracy with which data were taken with the MFL test bed vehicle. [Nestleroth96] To meet the data collection needs, the magnetizer and sensors were modified and the electronics module was replaced. Other components, such as the battery system and the sensor wiring collar, were not changed. Mechanical components such as tow links, cups, and pressure vessels, were used as originally designed.

☐ Description of the MFL test bed vehicle
A Additional details on the test bed vehicle modifications

MFL Inspection Signals. MFL inspection signals were recorded in the pull rig and flow loop under a variety of conditions. The following links provide details on the test sequences and summarize the data taken:

☐ Test Details
☐ Defect Set **4** - Practice Defects: *MFL Data*
☐ Defect Set 5 - Pull Rig Defects: *MFL Data*
D Defect Set 6 - Flow Loop Defects: *MFL Data*
☐ Magnetic Noise Measurements
☐ Comparisons Between Fabricated and Backhoe Defects

Analysis Methodologies

Feature-Based Analysis Methods

Feature-based analysis methods make use of discrete signal parameters, such as peak amplitude or peak-to-peak amplitude. Peak amplitude is the maximum recorded value in an inspection signal, and peak-to-peak amplitude is the difference between the maximum and minimum recorded values in an inspection signal.

Feature-based analysis methods are commonly used by inspection vendors today. These methods typically preprocess data to determine the input to various algorithms that are used, for example, to determine the depth of a corrosion defect. Some feature-based analysis methods make adjustments to the overall defect signal, but these adjustments are generally a function of discrete signal features.

To improve the ability to reliably detect, classify, and size mechanical damage defects, Battelle developed a multiple magnetization approach. [Davis99] The approach requires two magnetizing levels: a high level for detecting geometric changes and a low level for detecting both magnetic and geometric changes. Classifying and determining the severity of the damage requires additional signal processing. A process called decoupling was developed to extract unique signals due to geometric and magnetic changes. Using the geometric and magnetic signals, different types of damage become apparent.

Decoupling

The decoupling method developed under this project works in the following manner. The MFL signal taken at a low magnetization level contains information on both the magnetic and geometric changes. At a high magnetization level, the MFL signal contains information on the geometric changes only. The geometric or high-magnetization level signal is "scaled" to the lower magnetization level. This scaled signal is then subtracted from the low level signal. The result is a signal that reflects the magnetic changes only. This signal is referred to as the decoupled signal.

- Flowchart of decoupling procedure
- Additional details on decoupling
- Graph of optimum low magnetization level
- Defect Set **4** - Practice Defects: *Decoupled Data*
- Defect Set 5 - Pull Rig Defects: *Decoupled Data*
- Defect Set *6* - Flow Loop Defects: *Decoupled Data*

The optimum low magnetization level was found to be between 50 and 70 Oersteds, depending on pipe material and residual stress amplitudes. Data from this program indicate that the effects of most magnetic changes disappear above 150 Oersteds. So, a *high magnetization level* of 150 Oersteds was used.

The decoupling method has worked well on most defects studied. It provides a signal that can be used to reveal cold working where cold work has occurred and no cold work where there is none. Some defects, such as surface scratches, where signal amplitudes are small (e.g., under 5 gauss), have problems due to noise, as discussed later. Magnetic noise found in most pipe is on the order of 2 to 3 gauss, making classification and decoupling difficult.

A Example - Decoupling with External Metal

Determining the Severity of Mechanical Damage Defects

In an ideal situation, once an MFL signal has been decoupled into its geometric and magnetic components, the signal would be further analyzed to determine the severity of the damage. Such a process is a goal on any inspection methodology. But determining the severity of a mechanical damage defect is a complicated and controversial topic, and there is no clear cut methodology of doing so. Consequently, this program evaluated the ability to measure various defect features that may be related to mechanical damage severity. If these features can be predicted from MFL signals, integrity experts may be able to assess actual severities.

The parameters used to calculate the structural integrity of a pipe with mechanical damage are a subject of ongoing research. In most analysis methods, information on both geometric changes (*residual dent depth* , amount of wall thinning) and mechanical changes (residual stresses, plastic deformation and cold working) are important. Prior research has been done on determining the geometric shape of a defect based on high magnetization MFL signals. The methods developed in the prior work allow the metal-loss geometry to be determined from the geometric signal found by the decoupling process.

Predicted Defect Features

The following features were selected to demonstrate the ability to predict defect features from the magnetic component of MFL signals:

- Maximum indentor load
- Presence and degree of dent *rerounding*
- The energy absorbed by the pipe when the damage was inflicted.
- The amount of cold work in terms of length, width, depth, and severity

None of the methods of estimating these indices was found to be reliable 100 percent of the time. Instead, the methods were successful in different situations or for defects with different characteristics. So, combinations of methodologies for estimating different defect indices will be needed in assessing whether mechanical damage is likely to be severe. In addition, additional work will be necessary to develop and calibrate methods of predicting defect features once their utility in assessing defect severity has been established.

Maximum Indentor Load. The maximum indentor load is the maximum force applied to the pipeline by the object causing the damage. A relationship between the maximum indentor load and the peak-to-peak amplitude of the decoupled signal was derived. Accurate estimates of maximum indentor load were found to be possible if the yield strength of the material is known. The minimum detectable load is about 10 ksi.

A Details on predicting maximum indentor loads

Rerounding. After denting, a pipeline will reround due to internal pressure. During the denting process, a *maximum dent depth* is reached, and when the load is removed, the dent rerounds due to internal pipeline pressure. During the tests conducted in this program, rerounding as high as 80 percent occurred. The maximum dent depth can be estimated from a "halo" signal around a defect. The halo signal is a ring of magnetic changes that surrounds defects that have been rerounded from internal pipe pressure.

A Details on rerounding and predicting the maximum dent depth

Absorbed Energy. Finally, a method was developed to estimate the energy absorbed during the mechanical damage process. This method is based on a recreation of the load-deflection curve for the damage process. Once the load deflection curve has been recreated, it is a simple process to estimate the energy absorbed during the damage process. The absorbed energy is the area under the initial load deflection curve (the applied energy) minus the area under the unloading portion of the curve (the released energy).

A Details on recreating the load-deflection curve and predicting the absorbed energy

Other Defect Parameters. The parameters discussed above are not the only factors that affect the severity of mechanical damage. Other parameters, such as the volume of material damaged by cold working or the size and shape of removed metal, are also important. These and other defect characteristics were investigated in this program.

For example, the true extent of the cold-worked region around a gouge often lies outside the immediate area of the geometric changes. Wherever the pipe has been damaged, however, there will be magnetic changes even in the absence of geometric changes. The decoupled signal contains information on these changes. Procedures to evaluate this information were developed in this program.

Effects of Installation Variables, Pressure, and Operational Parameters

An important aspect of mechanical-damage inspection will be the effects of natural variations in defect, material, and pipeline media and flow characteristics. During the last phase of this program, many defects were investigated to verify the analysis methodologies with typical variations in defect installation, pipe materials, pressure, and operational parameters. The data used in this investigation are summarized above for Defect Sets **4,** 5, and 6. Basic effects are summarized below, followed by conclusions regarding variations.

Basic Effects

Dent Depth. Dent depth refers to the maximum depth of a dent during installation, which as expected, has a strong impact on MFL signals. High- and low-magnetization level signals appear **at** dent depths as low as one percent. The defect halos used to determine the effects of rerounding begin to become prominent at dent depths around three percent and become stronger as dent depth increases.

B Effects of Dent Depth

Dent Length. Dent length refers to the axial travel distance of the indentor along the pipe. Dent length also has a strong impact on the signals. For short mechanical-damage defects, signal features overlap. For defects over several inches long, a series of peaks and valleys in the high, low, and decoupled MFL signals becomes apparent.

B Effects of Dent Length

Variations

Indentor Shape. Indentor shape and footprint affects the normal and shearing forces applied to a pipe. Consequently, they should affect the degree of cold working. Several indentors were used to determine how changes in indentor shape and cold working affected the MFL signals. Some differences in signals could be seen as a result of using more narrow indentors, but there was not a significant correlation between tooth geometry and signal features. Nonetheless, the basic signal features used to identify rerounding and the presence of **a** gouge were preserved.

☐ Effects of Indentor Shape

Sharpness. Dent or gouge sharpness refers to the angle at which an indentor moves into the pipe. Defects with a high incident angle have widely spaced signals features, while those made more gradual entry and exit have signal features that tend to smear and overlap. For deeper defects, these features are more apparent and the ability to analyze the features to determine defect sharpness appears likely.

B Effects of Ramp In and Ramp Out

Other Variations. Pressure and velocity variations were also evaluated in this program. Pressure had a small effect on the high, low, and decoupled MFL signals, while the effects of velocity were similar to those for metal loss.

Areas for Future Work

Near the end of this program, an additional signal feature was identified that is related to the presence and severity of a gouge. This feature is a magnetic dipole that appears to be a function of the direction in which the defect is magnetized. This dipole is superimposed on the defect signal, which makes interpretation of the decoupled signal more difficult. However, preliminary comparisons between the dipole strength and the gouge depth are promising. If a method can be developed to easily identify and extract the dipole, a direct measure of the severity of the gouge and cold work may be possible.

A Magnetic Dipoles

Conclusions on Feature-Based Analysis Methods

The goal of the work on feature-based methods has been to obtain signals that increase the probability of obtaining a *measurable* signal from significant mechanical damage and properly differentiate these signals from other "anomalous" signals. The primary reason for decoupling the MFL signal is to reveal the presence of cold working. A defect with a cold worked area yields a distinct signature in the magnetic component of the MFL signal. This signature is often overshadowed by the defect's geometric component, and so, a decoupling method was developed to make the signature more distinguishable.

Decoupling allows further analysis of the signal components for help in assessing the severity of the defect. To date, procedures have been developed for estimating (1) the maximum radial load used to create the damage, (2) the amount of dent rerounding and maximum dent depth, (3) and the load-displacement curve. These procedures appear valid over a range of defect geometries, but none is reliable 100 percent of the time. So, combinations of methodologies for estimating different defect indices will be needed in assessing whether mechanical damage is likely to be severe.

Additional work is needed to develop and calibrate methods of predicting defect features once their utility in assessing severity has been established. In this sense, inspection for mechanical damage is much like early inspections for corrosion: detection is likely and characterization possible. Initial commercial applications are likely to be based on detecting and determining the relative severity of defects. Later, commercial attempts will extend the initial applications to allow the absolute severity of mechanical damage to be estimated.

Finally, the ability to extract and use a magnetic dipole signal feature should be further investigated. Of all the signal features investigated, this feature shows a relationship with the presence and severity of cold work. Cold work and damage to the microstructure beneath a gouge are critical factors in determining defect severity. So, information from the magnetic dipole may provide a needed link in estimating absolute defect severity.

Nonlinear Harmonic Methodologies

Two other methods of assessing mechanical damage were investigated in this program. The first, nonlinear harmonics, seeks to measure the residual stresses and plastic deformation around a damaged region. The second, neural networks, is an alternative method of identifying and characterizing damaged zones.

The nonlinear harmonic method is an electro-magnetic technique that is sensitive to the state of applied stress and plastic deformation in steel. [Kwun86, Kwun87, Burkhardt88] A sinusoidal magnetic field is applied at a fixed frequency. Odd-numbered harmonics of that frequency (typically the third harmonic) are generated because of the non-linear magnetic characteristics (hysteresis curve) of ferromagnetic materials. By detecting and measuring the harmonic signal, changes in magnetic properties can be inferred.

- **B** Overview of nonlinear harmonic method
- **A** Details on nonlinear harmonic measurements

Work done prior to this project indicated that the nonlinear harmonic output changes with changes in magnetic permeability. So, the nonlinear harmonic output was expected to be an indicator of applied stress and plastic deformation. Under this project, laboratory experiments demonstrated that capability. In addition, specimens with plastic strain were tested. Results showed that the nonlinear harmonic method could be used to detect the stressed area around a mechanical damage defect.

Two additional studies were conducted to investigate questions associated with using nonlinear harmonic sensors on an in-line inspection tool. In the first, the effects of liftoff were measured. In the second, the potential for making quantitative damage measurements was assessed. The following links provide details on the results.

- **A** Evaluation of liftoff effects
- **D** Details on quantitative damage measurements

Conclusions

Work under this program evaluated the use of nonlinear harmonic inspection methodologies for detection and characterization of mechanical damage. The effects of filtering, bias magnetic fields, pipe grade, excitation frequencies, lift off, and speed were evaluated.

The results show that there is good detection of defects but that there is not a clear indication of the severity of the defect in the nonlinear harmonic signal amplitude. Consequently, nonlinear harmonics may be best used as a complement to other inspection methodologies rather than as a stand-alone technique.

Neural Network Analysis Methods [Haykin99]

Background

A neural network analysis method uses a large number of relatively simple calculations to make a prediction. As an example, a neural network might be designed to predict the shape of a corrosion defect or classify a possible defect based on information contained in the MFL signal. Although the calculations are simple, the large number of computations allows neural networks to perform sophisticated tasks.

- Introduction to Neural Networks

The basic form of a neural network is very general, and several different types of networks are in use. The network is usually designed to transform a set of measurements or data (MFL signal) into another set of data (geometric profile of the defect). The nature of the transformation is dictated by the form of the neural network and the choice of the different parameters associated with the network. A proper choice of parameters allows the MFL signal to be transformed **by** the network to a representation of the shape and size of the defect.

In work done in this project, several types of neural networks were evaluated. In developing classification networks, *multilevel perceptrons* [Lippman] were used with sigmoid nodal functions. For the more complicated problem of predicting defect geometry, *radial basis functions* [Broomhead88] were first employed. Several radial basis functions were considered including Gaussian, logarithmic, and a multiquadric. A third set of networks, using *wavelet functions* [Bakshi93, Mallat89], was also investigated. Wavelet functions are similar to radial basis functions, but they generally offer better approximation properties both locally and globally.

Based on the results from the individual neural networks, an improved defect characterization scheme was developed using feedback neural networks. The scheme uses a closed loop design and provides an estimate of the error. Initial results indicate that the technique is capable of predicting metal-loss defect profiles reasonably well.

Classification of Mechanical Damage Signals [Ivanov98] [Afzal199, Ivanov97]

In order to evaluate mechanical damage defects in pipelines, the signals from mechanical damage must be detected and distinguished from other types of signals. In developing classification neural networks, multilevel perceptrons were used with sigmoid nodal functions.

For *training* , MFL signals from defect sets of the two types were obtained from the Pipeline Simulation Facility. The data consisted of 6 to 10 features from the MFL signal (e.g., peak amplitude) of fabricated mechanical damage and corrosion defects studied on an earlier project. An input data set of 30 defect signatures was selected after preprocessing the experimental signals.

☐ Overview of training for perceptron neural networks

A multilevel perceptron network using a back-propagation algorithm was trained to classify the defects into two categories. The architecture of the neural network (a single *hidden layer* multilevel perceptron) is shown in Graphical representation of classification network . Also shown in the figure are typical training data (MFL signals). The network has two output *nodes* , which correspond to two classes: mechanical damage (including dents and gouges) and metal loss. The nodes generate binary values, 0 or 1, depending on the class of signal encountered at the input.

The multilevel perceptron was tested using a different data set. A classification accuracy of 93 percent (28 correct calls out of 30) was obtained. The two defects that were misclassified were identified as gouges rather than metal-loss defects.

Defect Characterization [Hwang97, Hwang96, Xie97, Mandayam96]

After a signal has been classified as coming from a mechanical damage defect, the defect must be characterized. As discussed earlier, characterizing the severity of mechanical damage is a subject of ongoing research and development. Consequently, methodologies for estimating various defect parameters were investigated.

Prediction of Two-Dimensional Stress Fields [Ivanov98]

A separate neural network for predicting stress fields was developed and trained using finite-element stress predictions and experimental residual MFL signals.

Initially, two-dimensional fields were estimated. Later, three-dimensional fields were considered.

For the two-dimensional stress fields, two sets of defects were made: metal loss and pressed-in gouges. Results showed nearly identical signatures from the pressed-in gouges and the metal loss at saturation. However, a large difference in the residual field signals was observed.

Finite-element modeling involved two steps. A structural analysis was carried out first in order to obtain the distribution of stresses resulting from known loading conditions. The stress distribution was then used to develop a magnetic finite-element model.

☐ Additional details on the prediction of two-dimensional stress fields

Mapping from the MFL signal to the stress profile was accomplished using a radial basis function neural network. The input to the network was the residual MFL signal. The network was tested with MFL signals that were not part *of* the training set and the predicted stress profiles were compared with those generated by the mechanical damage finite-element model. The agreement between the predicted and desired profiles indicates that this method shows promise.

A Windows (r) -based implementation of this two-dimensional algorithm was prepared and transferred to Battelle for verification and testing. The software can be used for the prediction of stress distribution around a defect for the characterization of mechanical damage in gas pipelines.

Prediction of Three-Dimensional Stress Fields[Ivanov99]

A technique for predicting three-dimensional residual stress profiles was also investigated. This technique is an extension of the two-dimensional approach described above. The approach for predicting the three-dimensional residual stress distribution involves solution of a two-step problem, namely:

- Establishing a relationship between magnetic properties (e.g., coercivity) of the pipe material and residual stress due to mechanical damage.
- Determining the inverse relation between the residual MFL signal and the residual stress distribution in pipelines.

Coercivity is related to residual stress resulting from plastic deformation in steel [Atherton86a, Atherton86b]. Similarly, other parameters can also be linked to residual stress, for example: remanence, hysteresis loss, and the angle of the B-H curve. Therefore, it was postulated that estimating residual stress distributions may be possible by measuring these hysteretic properties of the material close to the surface.

To verify this hypothesis, experiments were carried out to observe the distribution of residual stress resulting from the test samples discussed above. The resulting sets of data were processed and compared with the stress distribution patterns obtained from a structural finite-element model. The results suggest that the residual stress can be linked to magnetic parameters such as coercivity, remanence, and hysteresis loss. The studies show that remanence is more sensitive than coercivity, while hysteresis loss is most sensitive.

A Details on hysteretic property measurements

Prediction of Metal-Loss Profiles [Yan97, Hoole91, Hwang97, Haykin94]

Both radial basis and wavelet functions were used to perform three-dimensional defect characterization from the MFL signals. The networks were used to predict the shape of the metal-loss portion of the defect (either corrosion or mechanical damage) using 6 to 10 features from the MFL signal as input. (The original radial basis function networks were developed under an earlier project for GRI.) The wavelet network architecture is similar to that of the radial basis network; however, it uses wavelets for functional approximation. The use of wavelets provides a simplified training procedure and a trade-off between computational complexity and prediction accuracy in defect characterization.

A Additional details on defect characterization using radial basis and wavelet functions

A Improved characterization using feedback neural networks

Conclusions on Neural Network Methods

A feedback neural network scheme was investigated for characterizing defect geometry. This scheme uses a closed loop design and, consequently, provides an estimate of the error during the test phase. Initial results on MFL data indicate that the technique is capable of predicting the defect profiles reasonably well.

The results presented above are based on data obtained from finite-element methods. Follow-on work should concentrate on correlating experimental data with the finite-element data. Furthermore, the robustness of the system with respect to noise should be tested. The use of feedback in the algorithm should improve the sensitivity of the system to noise. Finally, the feedback system needs to be tested for the reconstruction of three-dimensional flaws.

Crack Detection

Stress-corrosion cracking (SCC) is a complex phenomenon associated with several in-service and hydrostatic retest failures on gas and liquid pipelines. SCC occurs at isolated locations and when a limited set of conditions are met. The exact mechanisms that lead to SCC and the field and operating conditions that affect cracking are the subject of ongoing research.

B Background on stress-corrosion cracking

Inspection systems for SCC will need to consider tight, irregular, branching cracks. [Bubenik95b, Crouch941 Inspections for both high- and low-pH stress-corrosion cracks will be more difficult than those for fatigue cracks or artificial cracks, which are generally smooth, planar, and open. Also, inspection systems will need to discriminate between cracks and other pipeline features, such as inclusions and segregation bands.

Years of pipeline operating experience have demonstrated that small *imperfections* (for example, small regions of corrosion metal loss) cause only a small reduction in failure pressure. Stress-corrosion cracks cannot be considered independently, though, because their ultimate failure may involve *coalescence* of several cracks. As a result, the coalescence of several cracks that could each survive a high-pressure hydrotest could result in a single crack that would be on the verge of failure at typical operating pressure. Accounting for the likelihood of coalescence increases the emphasis on shorter, deep cracks in setting inspection requirements

B Additional impacts of cracks on inspection requirements

External Techniques for Sizing Cracks

Reference samples with stress-corrosion cracks are needed to evaluate technologies for detecting and sizing SCC. Ideally, the cracks in the reference samples should have known depths and be reproducible so that comparisons can be made on different pipe materials. Sizing SCC is difficult, though, even from the outside of the pipe. This subtask evaluated methods of creating artificial cracks in the laboratory and techniques for sizing SCC from the outside of the pipe to ensure test samples are well characterized before use.

Intergranular SCC usually occurs in colonies, where the cracks are often branched and irregular at their tips. As a result, using ultrasonic techniques to measure crack-tip signals for sizing is difficult. The difficulty is compounded by the presence of background signals from ultrasonic energy that are scattered by the crack face, reflected off the nearby pipe surface, and converted from one mode to another at interfaces.

Crack Fabrication

SwRI produced a set of fabricated cracks to be used as possible calibration samples for actual stress-corrosion cracks. [Watson96, Gruber95] The cracks were created by excavating a small notch in the pipe, then filling the excavation with weld metal using a tungsten inert gas welding technique. An addition was made to the weld metal to induce cracking as the material cools. The depth and length of the cracks are controlled by the depth and length of the initial notch.

Prior studies show that the cracks are contained in the capsule of weld metal. Since the welding process is relatively low heat input, the heat affected zone of the weld has reasonably good properties.

Inspection Techniques

There are a number of problems associated with sizing near-surface axial cracks from the outside surface of a pipe. A primary difficulty is the inability of conventional ultrasonic procedures, such as shear-wave and amplitude-based techniques, to locate the end points of the flaw in both the axial and through-wall directions. To address this difficulty, SwRI developed several transducer techniques for near-surface flaw applications. Two of these techniques were evaluated in this program.

The SwRI techniques are termed SLIC, which refers to the simultaneous use of shear and longitudinal waves to inspect and characterize flaws. [Gruber84, Gruber86, Gruber87] The techniques were developed in the 1980s and early 1990s.

B Details on the SLIC systems

Evaluation

SwRI evaluated two SLIC transducers: the SLIC-30 and the SLIC-50. The SLIC-30 is a multi-beam technique, and the SLIC-50 is a multi-mode technique. The systems were evaluated using 18 weld solidification cracks fabricated using the method described above.

Four techniques using the SLIC systems were evaluated for sizing cracks: amplitude-drop, phase-comparison, peak-echo, and satellite-pulse. [Gruber, Smilie90] Each technique was calibrated against four electro-discharge machined (EDM) axial notches placed in one of the test specimens. The amplitude drop technique was used for estimating the crack lengths. The phase-comparison technique in conjunction with the peak-echo and satellite-pull techniques were used for depth. The crack measurements were generally within 5 percent of their design values. Hence, the techniques permit reliable and accurate measurement capabilities of the fabricated cracks.

Velocity-Induced Remote-Field Effects

One of the reasons that many cracks cannot be effectively detected and characterized by current MFL tools is that the *applied magnetic field* has an orientation parallel to axial cracks, such as SCC. However, some electromagnetic phenomena inherent in conventional tools, such as *velocity-induced remote-field* effects and current perturbations, have strong components that are oriented preferentially for detecting axial cracks. The purpose of this subtask was to evaluate the sensitivity of velocity-induced phenomena and the ease with which these can be incorporated into existing pipeline inspection tools. This work was conducted by Iowa State University.

A General theory of velocity-induced remote fields

As an MFL tool passes any point in the pipe wall, velocity-induced currents are generated, first in one direction and then in the opposite direction. Such currents constitute one cycle of an alternating current waveform, which along with any defect-induced currents set up a remote-field effect. The velocity effects tend to distort and weaken MFL signals from corrosion and mechanical damage, and they are often viewed as a detriment rather than as a potential crack detection mechanism. The pipe wall currents have a strong component that is oriented orthogonal to axial cracks, though. So, an appropriately positioned Hall-effect sensor could be sensitive to perturbations in the currents due to the presence of cracks.

In order to investigate the feasibility of the technique, a three-dimensional finite-element model for simulating the velocity-induced fields in the remote region and the effect of cracks on these fields was developed. This model demonstrated that individual cracks produced measurable signals.

Finite-Element Modeling [Sun94, Mergelas96, Katragadda96]

Modeling of the interaction between axial cracks and circumferential currents is a significant challenge in terms of both the computation time and memory requirements. The challenges arise due to nonlinearity of material properties, the size of tight cracks relative to that of the magnetizer, and the time stepping involved in modeling velocity effects. A three-step approach for surmounting these difficulties was developed in this project:

- **Step 1:** Calculate velocity induced currents in a pipe wall due to axial motion of the magnetizer inside a defect-free pipe.
- **Step 2:** Model an axial crack by applying a current at the nodes that define the crack, and compute total perturbation current.
- **Step 3:** Use results obtained in Step 2 to solve for the perturbation fields that can then be measured with an induction coil.

A Details on finite-element modeling of velocity-induced remote fields [Yang98]

The results of the finite-element study demonstrated the technical feasibility of the proposed approach. If practical feasibility can also be demonstrated, the approach could be implemented with minimal modification to existing tools. Additional evaluation of the technique is continuing outside of this program, with experimental validation of the inspection process yet to be done.

Remote-Field Eddy Currents with Magnetic Saturation

Like velocity-induced remote-field techniques, *remofe-fieldeddy-current* techniques are sensitive to axial crack-like defects. The fundamental difference between this technique and the one discussed above is in the generation of the source electromagnetic field. The remote-field eddy-current technique uses a sinusoidal current flowing in an exciter coil to induce currents in the pipe, while the velocity-induced remote-field technique uses the permanent magnets on the inspection tool.

- ☐ Overview of remote-field eddy-current techniques

Since the remote-field eddy-current technique relies on signals of known frequencies, sharp filters can be used to detect defect signals while eliminating other sources of electromagnetic noise. Detection of defects can be accomplished by observing a change in either the magnitude or the phase angle of the received signal. Along with detecting SCC, the potential exists for remote-field eddy-current techniques to detect cracks associated with mechanical damage and to provide additional information for characterizing the severity of the damaged region.

Methods to improve the sensitivity of the remote-field eddy-current technique and to increase inspection speed were investigated in this project. The technique used is referred to as magnetic saturation, where a sufficiently strong magnetic field reduces the relative permeability of the pipe material.

Frequency, conductivity, and permeability all affect the amplitude or phase angle of the eddy currents, and hence, they all affect inspection performance. The conductivity of a pipe material is a fixed quantity, though, while the magnetic permeability can be changed by a strong static magnetic field, similar to the field applied by MFL magnetizers. A sufficiently strong magnetic field can theoretically drive the relative permeability of the pipe material from a value of 80 to 1, greatly increasing the inspection performance. Increasing the magnetic level should allow the use of higher frequency exciters and increase the range of possible inspection speeds.

Complete saturation may not be optimal, and a complete reduction of the magnetic permeability to the value of air is not practical in pipelines. Other research indicates that driving the relative permeability to between 5 and 15 is better for detection of stress-corrosion cracks than complete saturation.

Experiments

Three critical experiments were performed to evaluate the improvements made to remote-field eddy-current results using magnetic saturation. They were used to

- Determine the placement of remote-field eddy-current exciter coil
- Detect stress corrosion cracks using exciter coil saturation
- Demonstrate noise reduction with magnetic saturation.

These results show that the relative permeability of the pipe can be reduced by a factor of approximately 6.5 using magnetic saturation. This means the signal amplitude at the receiver or the inspection frequency should be 6.5 times greater with saturation than without. Either benefit shows that magnetic saturation could help overcome implementation difficulties associated with the use of remote-field eddy currents.

A Details on the remote-field eddy-current experiments

Conclusions on Magnetic Saturation

Magnetic saturation could help overcome some of the difficulties associated with the implementation of remote-field eddy-current techniques in pipelines. Saturation helps in two ways. First, experiments show that with saturation at the exciter coil, cracks and other defects can be detected at signal frequencies of 100 Hertz, a five-fold increase in frequency. Second, saturation helps in the reduction of noise. If the saturating magnetic field is uniformly applied, the noise levels are significantly lower as compared to non-uniform magnetization.

Conclusions

This report summarizes work done for the U. S. Department of Transportation Office of Pipeline Safety under a research and development contract entitled "In-Line Inspection Technologies for Mechanical Damage and SCC (Stress-Corrosion Cracking) in Pipelines." This project has evaluated in-line inspection technologies for detecting mechanical damage and cracking in transmission pipelines.

A significant portion of this project examined MFL for detecting mechanical damage defects. Included were evaluations of existing signal generation and analysis methods to establish a baseline from which today's tools can be evaluated and tomorrow's advances measured. In addition, improvements to signal analysis methods were developed and verified through pull rig and flow loop testing. Finally, an experience base and defect sets were built to generalize the results.

Important mechanical-damage results from the project include:

Feature-Based Analysis Methods:

- Several techniques were developed for decoupling and analyzing MFL signal components so that mechanical damage can be better detected and characterized. These techniques are valid over a range of defect geometries, but none is valid all the time. Consequently, a combination of techniques will be needed for detecting and assessing mechanical damage.
- Initial commercial applications are likely to be based on detecting and determining the relative severity of mechanical damage defects. Later, commercial attempts will extend the initial applications to allow the absolute severities to be estimated.
- Follow-on work can be used to further develop and calibrate methods of predicting defect features and severity.
- The ability to extract and use a magnetic dipole signal feature should be further investigated. The magnetic dipole may provide a needed link in estimating absolute defect severity.

Nonlinear Harmonics:

- An inspection technique called nonlinear harmonics has promise for detecting mechanical damage defects. There is not a clear indication of the severity of the defect in the signal amplitude. So, nonlinear harmonics may be best used as a complement to other inspection methodologies.

Neural Networks:

- Feedback neural networks are promising for characterizing defects. Initial results based on characterizing the size and shape of metal loss have been promising. Further developments will need to be extended and tested for more complex mechanical damage defects.

A smaller portion of this project evaluated inspection technologies for detecting cracks. The focus was on electromagnetic techniques that have been developed in recent years and that could be used on or as a modification to existing MFL tools. While these techniques are still in the early stages of development, the project showed:

- Tight crack samples can be made in the laboratory and used as calibration samples. These cracks have a morphology that is similar to stress corrosion cracking.
- Velocity-induced remote field techniques are technically feasible for detecting tight cracks, such as stress corrosion. Additional work will be necessary before this technique can be applied in the field.
- Magnetic saturation increases signal strength and allowable inspection speeds for remote-field eddy current inspection methods. These results indicate that higher inspection speeds are possible.

Future Designs of Inspection Tools and Field Applications

MFL tools for mechanical damage will need to contain multiple types of sensors and inspection systems. At least two different magnetization levels are needed to separate signal components due to geometric changes and magnetic changes near the damage. By decoupling signal components, detection and sizing algorithms can concentrate on damage components that are most related to defect severity. In addition, important defect information can be obtained through still other systems, such as detailed measurements of the shape of the inner pipe surface. Combining results from different types of sensors should allow much more robust inspection capabilities.

Analyzing inspection field data will initially require analysis packages that look for several indicators of severity. For example, the analysis methods could look for the thin layer of cold work immediately below severe gouges, evidence of rerounding, wall thinning, high residual stresses, and plastic distortions. Combinations of these conditions would indicate more severe defects.

To date, none of the inspection methods can reliably detect any of these damage components all the time. So, field applications must consider the confidence level with which critical defects are found. Increasing the confidence level will increase the number of false calls. The number of false calls will increase until more robust techniques are developed for determining which mechanical damage defects are candidates for delayed failure and which are not.

Development of more robust techniques for characterizing mechanical damage requires field experience and close coordination between further development of inspection methodologies and research into the conditions that make defects critical.

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* END OF REPORT *

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Mechanical Damage Glossary

Applied magnetic field. The strength of the magnetization field that is produced in a pipe wall by a magnetizing system in an inspection tool.

Backward propagation. A process used in the training of a neural network. In backward propagation, derivatives *of* error functions are calculated and used to minimize the resultant error. The term backward propagation is used to suggest that the errors are corrected back through the network using the derivatives or gradient of the error function.

B-H curve. See magnetization curve.

Characterization. The process of quantifying the size, shape, orientation, and location of a defect after it has been detected. There are many degrees to which characterization can be successful. For example, one type *of* characterization of mechanical damage may be to determine whether the defect contains a cold worked region (severe) or not (less severe).

Coalescence. The linking or growing together of two or more cracks.

Cold working. Distortion of the grains in the vicinity of a gouge. Cold working often occurs immediately under the visible gouge and can significantly reduce the mechanical properties of a pipe steel.

Crack-tip diffraction. Creation of ultrasonic waves at a crack tip as an ultrasonic wave passes by the crack.

Decoupling. The process of estimating a hypothetical MFL signal that is due to magnetic property changes and independent of geometry and moved or removed metal.

Defect. An anomaly in a pipeline that would not survive a hydrotest to 100 percent of the pipe's yield stress.

Dent. A deformation in the cylindrical shape of a pipe.

Detection. The process of obtaining an inspection signal that is recognized as coming from a defect or anomaly. An inspection system can detect only those defects that produce signals that are both measurable and recognizable. Not all defects are detectable with all inspection systems.

Detection limit. The largest defect that could be missed (not the smallest defect that could be found) by an inspection system.

Diffraction. The scattering of an ultrasonic wave as it passes by a defect, such as a crack.

Feature-based analysis method. Analysis method that makes use of discrete signal parameters, such as peak amplitude or peak-to-peak amplitude.

Feedback. Feedback in a neural network implies that the calculation sequence can loop back upon itself.

Feedforward. Feedforward refers to the direction of the calculations in a neural network. Calculations are made on the input data, which are then acted on by the basis functions in the nodes, eventually leading to an output or prediction. The calculations continue in the same direction, forward from the input toward the output.

Forward propagation. See feedforward.

Gouge. Local damage that occurs in the immediate vicinity of and below an indentor.

Gouging. The process of creating a zone of mechanical damage that includes cold working, residual stresses, plastic distortion, and (generally) moved or removed metal.

Hidden layer. A layer between the input and output layer of a neural network. Using hidden layers allows highly nonlinear transformations to be implemented and increases the power of a neural network.

High magnetization level. A magnetization level at which the effects of magnetic distortion become negligible and the measurable MFL signal is nearly the same as that which would be produced by the mechanical distortion only.

Identification. The process of differentiating a signal caused by one type of defect from signals caused by other types of defects or pipeline features. Identification is particularly important for mechanical damage defects because their signals are so small that they can be mistaken as due to benign conditions. Mechanical-damage signals are also small compared to signals from metal loss and features such as valves.

Imperfection. An anomaly in a pipeline that would fail a hydrotest to 100 percent of the pipe's yield stress.

Knee of the magnetization curve. The region of a magnetization curve where the permeability of the pipe material reaches a maximum.

Layer. The description of a set of calculations made in a neural network. **A** set of vertical nodes and the connections to its right constitute a layer. The first layer is called the input layer. The final layer is called the output layer (whose output represents the corrosion depth at various points along the pipe).

Learning. A repetitive process used in a neural network to estimate various weighting factors. Typically, at the start of this process, random values are assigned to the weighting factors, after which the network learns via an iterative process that seeks to minimize the error in the resultant predictions. See training.

Magnetization curve. A representation (plot) of the magnetic flux in a pipe wall as a function of the applied magnetic field. **A** magnetization curve is typically nonlinear and is also referred to as a B-H curve.

Magnetic distortion. Changes in the magnetic properties of a pipe steel in the vicinity of mechanical damage. Magnetic distortion, as used here, is due to active stresses, residual stresses, plastic strains, and/or cold working.

Magnetic flux. A measure of the amount of magnetization carried by a material.

Magnetic flux leakage. An inspection technique in which a magnetic field is applied to a pipe section and measurements are taken of the magnetic flux density at the pipe surface. Changes in measured flux density indicate the presence of a possible defect. Also called MFL.

Magnetic saturation. Presence of a magnetizing level in a pipe wall that is above the knee of the magnetization curve.

Maximum dent depth. The maximum depth to which an indentor has pressed into a pipe. Maximum dent depth does not take into account rerounding due to pressure.

Measured dent depth. See residual dent depth.

Measurable. Producing an inspection signal that is above the noise level inherently present in the pipe.

Mechanical distortion. Changes in wall thickness or changes in the cylindrical shape of a pipe. A gouge, because it includes cold working, residual stresses, plastic strains, and moved or removed metal, contains both mechanical and magnetic distortion.

MFL. An inspection technique in which a magnetic field is applied to a pipe section and measurements are taken of the magnetic flux density at the pipe surface. Changes in measured flux density indicate the presence of a possible defect. Also called magnetic flux leakage.

Multilevel perceptron. A type of neural network that has hidden layers and is made by combining or cascading individual perceptrons.

Network structure. The set of rules that control when and which calculations are made in a neural network. Many structures are possible, and the network's structure must be chosen to fit the problem. The key is to select a structure that allows the network to learn which constants to use to make good predictions.

Neural network. An analysis method that uses a large number of relatively simple calculations to make a prediction. As an example, a neural network might be designed to predict the shape of a corrosion defect or classify an indication based on information contained in the MFL signal. Although the calculations are simple, the large number of computations performed in concert allows neural networks to perform fairly sophisticated tasks.

Nonlinear harmonics system. A magnetic inspection technique that is sensitive to the state of applied stress and plastic deformation in steel.

Node. A place in a neural network at which input parameters are weighted and acted upon by various nodal functions.

Over-fitting. Difficulties in neural networks that occur when the network's output data are forced to match the target output data. Forcing the fit to exactly match the data is possible, but usually produces poor results - errors can be introduced when the neural network attempts to predict random noise. Over-fitting is possible when the amount of training data is limited, and is to be avoided.

Parallel processor. A description of a neural network. Parallel processing is used to indicate that many calculations can be performed simultaneously because the input of each calculation is independent of the output of the other calculations.

Perceptron. The simplest type of neural network. A single perceptron has no hidden layers and typically uses a step function at the node (e.g., if the sum of the inputs is less than a prescribed threshold level, the output is zero, and if the sum is greater than or equal to the threshold value, the output is one). The name perceptron dates to the 1950s and was chosen to reflect that the network could perceive or learn from exposure to different input and output pairs of data.

Permeability. A measure of the ability of a material to carry magnetic flux.

Plastic strains. Strains beyond the elastic limit of a material due to mechanical damage. Plastic strains and cold working are related, but not the same.

Radial basis functions. One of several types of nodal functions used in neural networks.

Recognizable. Producing a signal that can be identified as coming from a particular type of defect, e.g., mechanical damage.

Reflection. Creation of an echo when an ultrasonic wave impinges upon a defect.

Remote-field eddy currents. Currents that are induced after the passage of a magnetizing inspection tool. In this report, these fields are produced by an exciting system and are generally restricted to those that occur one or more diameters beyond the end of the magnetizer.

Rerounding. The process of changing the dent depth and shape by internal pressure in the pipe. Generally, dents due to third-party contact will reround, while dents due to rocks will not unless the rock causing the dent is removed.

Residual dent depth. The dent depth measured under a particular set of conditions, e.g., in unpressurized pipe used in the pull rig or in pressurized pipe in a pipeline. While maximum dent depth does not change, the residual or measured dent depth changes with pressure and loading history. Also referred to as the measured dent depth.

Residual stresses. Elastic stresses that were not present within the pipe wall before mechanical damage but that are present after the damage has occurred.

SCC. Stress-corrosion cracking. Environmentally assisted cracking that can result when the combined action of stress, an electrochemical cracking environment, and temperature causes cracks to initiate and grow in a susceptible line-pipe steel.

Shear and longitudinal waves to inspect and characterize. An inspection technique pioneered by Southwest Research Institute for detecting and sizing cracks.

Sizing. See Characterization.

SLIC. Use of shear and longitudinal waves to inspect and characterize a material.

Stress-corrosion cracking. Environmentally assisted cracking that can result when the combined action of stress, an electrochemical cracking environment, and temperature causes cracks to initiate and grow in a susceptible line-pipe steel.

Synaptic weighting. See weighting.

Training. The process of estimating the weighting factors associated with a neural network. Training is accomplished by applying signals (called training signals or data) from well-characterized defects to the network. The predicted output (for example, the geometrical profile of the defect) is then compared with the true or desired output. The prediction error is utilized to iteratively adjust the weighting factors until some measure of the prediction error drops below a preset threshold.

As in statistical methods, the training process seeks to minimize some measure of the error in the predictions. Different error functions can be used to emphasize different parts of the error. For example, when minimizing a function such as spending, you might decide to spend more effort on the big ticket items than on smaller outlays. When minimizing functions related to corrosion profiles, more effort might be placed on deeper rather than shallow depths.

Velocity-induced fields. Currents and magnetic fields that are introduced by the passage of a magnetizing inspection tool in a pipeline. In this report, these fields are generally restricted to those near the magnetizing element.

Wavelet basis functions. One of several types of nodal functions used in neural networks.

Weighting. The action taken on the input to a node in a neural network. Weighting can be as simple as scaling (multiplying each input by a different constant). Also called synaptic weighting because similar actions are thought to take place in the synapses of the brain.