PNNL-15184

Characterization of Plastic Strain in Pipelines
05 FE-63576.000
Project 42623

Report to the National Energy Technology Laboratory
October 1, 2000 through October 2004

Submitted by
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August 2005

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Abstract

This report summarizes the progress towards developing ultrasonic nondestructive methodologies to determine the integrity in natural gas pipelines. This work has been performed by the Pacific Northwest National Laboratory (PNNL), under the Natural Gas Infrastructure Reliability Program run by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). The Pacific Gas and Electric Company (PG&E) has been an industrial sponsor during this work.

Of particular importance to the Nation's natural gas infrastructure is the accurate prediction of the lifetime of damaged pipelines due to outside force. In order to accurately predict the remaining life it is essential to accurately determine the stress and strain in the damaged region. Currently there is a significant technological gap inhibiting accurate diagnostics and prognostics for pipeline life assessment. Specifically, there is a limited empirical connection between nondestructive measurements and the state of stress and strain in a damaged region. The focus of this project has been to fill this technology gap.

The main goal is to provide an in-situ measurement from inside a pipe to avoid the cost of replacing sound pipes due to benign defects. The long term objective is to provide utility companies and pipeline operators with a nondestructive method to determine the reliability of an existing pipeline by coupling the output of the ultrasonic measurements determining with computational mechanics models to provide a max operating pressure of a damaged pipeline. To begin to meet these goals we have performed a series of systematic laboratory measurements to determine the relationship between ultrasonic measurements and stress and strain. In addition, measurements on dented specimens in the laboratory were studied. The work in FY04 culminated in a successful blind field test where we accurately classified hidden dents in an unknown section of pipe. The current scope is to develop a generic sensor platform that can be integrated with robots and other inline inspection devices to measure pipeline integrity due to dents and bends

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1.0 EXECUTIVE SUMMARY

This report summarizes the progress towards developing ultrasonic nondestructive methodologies to determine the integrity in natural gas pipelines. This work has been performed by the Pacific Northwest National Laboratory (PNNL), under the Natural Gas Infrastructure Reliability Program run by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). This program was established to provide research and technology development to ensure safe and efficient operational reliability of the Nation's natural gas transmission and distribution network. Maintaining the highest levels of integrity and reliability regarding design, construction and operation of the Nation's natural gas infrastructure is of primary importance.

Of particular importance to the Nation's natural gas infrastructure is the accurate prediction of the lifetime of damaged pipelines due to outside force. In order to accurately predict the remaining life it is essential to accurately determine the stress and strain in the damaged region. Currently there is a significant technological gap inhibiting accurate diagnostics and prognostics for pipeline life assessment. Specifically, there is a limited empirical connection between nondestructive measurements and the state of stress and strain in a damaged region. The focus of this project has been to fill this technology gap.

This project is focused on measuring the stress and strain due to third party contact and bending due to landslides and earth movement. The main goal is to provide an in-situ measurement from inside a pipe to avoid the cost of replacing sound pipes due to benign defects. The long term objective is to provide utility companies and pipeline operators with a nondestructive method to determine the reliability of an existing pipeline by coupling the output of the ultrasonic measurements with computational mechanics models to provide a max operating pressure of a damaged pipeline. To begin to meet these goals we have performed a series of systematic laboratory measurements to determine the relationship between ultrasonic measurements and stress and strain. In addition, measurements on dented specimens in the laboratory were studied. The work in FY04 culminated in a successful blind field test where we accurately classified hidden dents in an unknown section of pipe. The current scope is to develop a generic sensor platform that can be integrated with robots and other inline inspection devices to measure pipeline integrity due to dents and bends.

There are several categories of outside force incidents that can lead to the failure of otherwise sound pipe. These include: 1) third-party mechanical damage, usually caused by construction damage; 2) secondary loads imposed on a pipeline, usually due to soil movement; and 3) dents due to the pipe resting on rocks. Third-party damage, sometimes referred to as "dig-in's" by the industry, accounts for the vast majority of outside force incidents in pipelines. Either immediate or delayed failure can occur due to mechanical damage. Immediate failure occurs when construction equipment punctures the pipe and produces a leak at the time of damage. However, mechanical damage more frequently provides an initiation site for crack formation and eventual failure. Unreported damage

can result in delayed failure due to either slow crack growth through the thickness or hydrogen-stress cracking of the cold worked and strain-aged steel. Recent failures in Edison, New Jersey and Bellingham, Washington serve as examples of damage to pipelines that resulted in delayed catastrophic failure. Often these delayed failures are caused by fatigue cracks which grow due to cyclic stressing at damaged locations.

At the present time In Line Inspection (ILI) tools are the most commonly used technique to detect mechanical damage. In Line Inspection tools (or smart pigs) are instrumented pigs that are placed in the pipeline and moved from one location to another along the line by traveling with the product in the pipe. Almost any type of instrumentation can be mounted on a pig. The most common techniques for pipeline integrity assessment are electromagnetic, ultrasonic or dimension measurements. Magnetic Flux Leakage (MFL) is commonly used to detect mechanical damage mechanical damage. Caliper tools measure the pipe radius at multiple locations around the circumference and have been used to detect dents and estimate their geometry [1]

Some pigs use a ring of acoustic sensors to measure the inside profile of the pipeline in liquid filled lines. Ultrasonic methods have also been used to detect dents and cracks; however, implementation on pigs is complicated because of the need to couple the sound to the pipe. Therefore, measurements which utilize alternate forms of transduction are attractive such as, gas coupling or the use of Electromagnetic Acoustic Transducers (EMATs), which require no coupling [2].

One of the most important outputs from in-situ damage characterization is to provide the capability to distinguish between damage that can result in either delayed failure or no failure. When inspecting for damage of pipelines, there are two steps, the first is detecting and locating the damage and the second is classifying it as a dent or a bend. Currently MFL and caliper tool can detect damage, however, characterizing the degree of stress and strain in dents and bent regions is a particularly challenging task because the damage creates spatial and through thickness stress and strain gradients. Figure 1 shows examples of damage found in the field.

Currently U.S. Regulation CFR 192 requires the removal of dents in transmission pipelines operating at pressure that results in a hoop stress of 20 percent or more of the specified minimum yield strength if the dent contains a stress concentrator such as a scratch, gouge, groove, or arc burn, or affects a weld [3,4]. The CFR requirements only take the dent depth into consideration and in some cases these regulations can be very general and inaccurate, and in most cases the pipe has rerounded due to the internal pressure of the gas and this criteria is not conservative, especially if an axial gouge is present. In other cases where the pipe has not rerounded, the criteria may be very conservative. While these regulatory mechanisms are adequate in some cases there is a need to have a more quantitative measure of the degree of damage to the pipeline in order to predict the remaining life.

Figure 1. Damage to natural gas pipelines seen in the field including a bent section on left figure and dents in the right figures. Photos courtesy of PG&E.

The detection and analysis of mechanical damage has been an ongoing interest for the pipeline industry for many years. This report provides an indication of the present state of research in the area, to identify gaps in the application of NDE techniques to characterize damaged pipelines and indicate how current research by the authors advances the understanding and implementation of mechanical damage characterization.

In the remainder of this document, we will summarize our empirical experimental results that correlate specific ultrasonic parameters with the degree of stress and strain in pipeline steels. We will then describe results showing comparisons with accepted ultrasonic theories. This document will conclude with a discussion of recent data collected on dented pipelines at PNNL and during the field test at Battelle in Columbus, Ohio.

2.0 EXPERIEMENTAL

To understand the accomplishments from this work it is useful to first consider the different types of ultrasonic waves that can be generated in metals and their relation to the important material parameters affected by damage. The key material properties that need to be determined for effective damage characterization are the residual stress and the plastic strain. From a nondestructive perspective, one common method utilized is the measurement of the ultrasonic velocity because of its sensitivity to these properties. The ultrasonic velocity is defined as the ratio between the thickness of the pipe wall and the time it takes the ultrasonic wave to traverse the thickness.

One common ultrasonic wave is a Longitudinal Wave (L-Wave) which has a particle displacement parallel to the direction of propagation as illustrated in Figure 2. The relationship between the speed of sound of L-Waves is given in equation 1 below. Here the velocity is written as V with the first subscript designates the direction of propagation and the second subscript designating the direction of polarization of the displacement of the atoms, ρ is the density, B and G are the bulk and shear moduli respectively, C_0 is the texture free single crystal elastic constants of the material, W_{klm} is the texture parameter which describes the orientation of the crystallites in the metal microstructure, sigma is the stress (applied or residual) and K_I is the acoustoelastic constant which describes the change in the velocity as a function of stress. One other common wave is the shear waves shown in Figure 2 with the equations 2 and 3 below. Of particular importance is the polarization of the displacement of the atoms in the shear waves. Specifically, the V31 and the V32 waves are propagating in the same direction, the 3 direction, with polarization in directions perpendicular to each other (the 1 and 2 directions)

$$\rho \quad \mathrm{V}_{33}^2 = C_{33} = B + \frac{4G}{3} + 4.786 C_0 \mathbf{W_{400}} + K_1 \sigma \tag{1}$$

$$\rho\, \mathrm{V}_{31}^2 = C_{31} = G - 6.381 C_0 \mathbf{W_{400}} + 10.089 C_0 \mathbf{W_{420}} + K_2 \sigma \tag{2}$$

$$\rho\, \mathrm{V}_{32}^2 = C_{32} = G - 6.381 C_0 \mathbf{W_{400}} - 10.089 C_0 \mathbf{W_{420}} + K_3 \sigma \tag{3}$$

$$\rho\, \mathrm{V}_{12}^2 = C_{66} = G + 1.595 C_0 \mathbf{W_{400}} - 13.348 C_0 \mathbf{W_{440}} + K_4 \sigma \tag{4}$$

$$\rho\, \mathrm{V}_{21}^2 = C_{66} = G + 1.595 C_0 \mathbf{W_{400}} - 13.348 C_0 \mathbf{W_{440}} + K_5 \sigma \tag{5}$$

$$\rho\left(\mathrm{V}_{12}^2 - \mathrm{V}_{21}^2\right) = \left(K_4 - K_5\right)\sigma \tag{6}$$

$$Shear_Birefringence = \frac{V_{31} - V_{32}}{\left(V_{31} + V_{32}\right)/2} \tag{7}$$

Of particular importance is the dependence on crystallographic orientation or texture parameters and moduli. These texture parameters arise during manufacturing and will vary along the length of any given pipe or plate due to chemical changes, and thermo-mechanical treatment such as rolling, heating and welding. It is critically important that methodologies which utilize ultrasonic measurements to characterize damage account for the effects of manufacturing on the ultrasonic velocity. Our approach has been to include several additional ultrasonic modes in order to isolate the effects of the stress, the strain and the manufacturing variations. Specifically, we have utilized Shear Horizontal (SH) waves to aid in the separation of the stress from the texture terms. This can be accomplished by taking a difference of the two polarizations of SH waves as shown in equation 6. A schematic of the SH wave is shown in Figure 2.

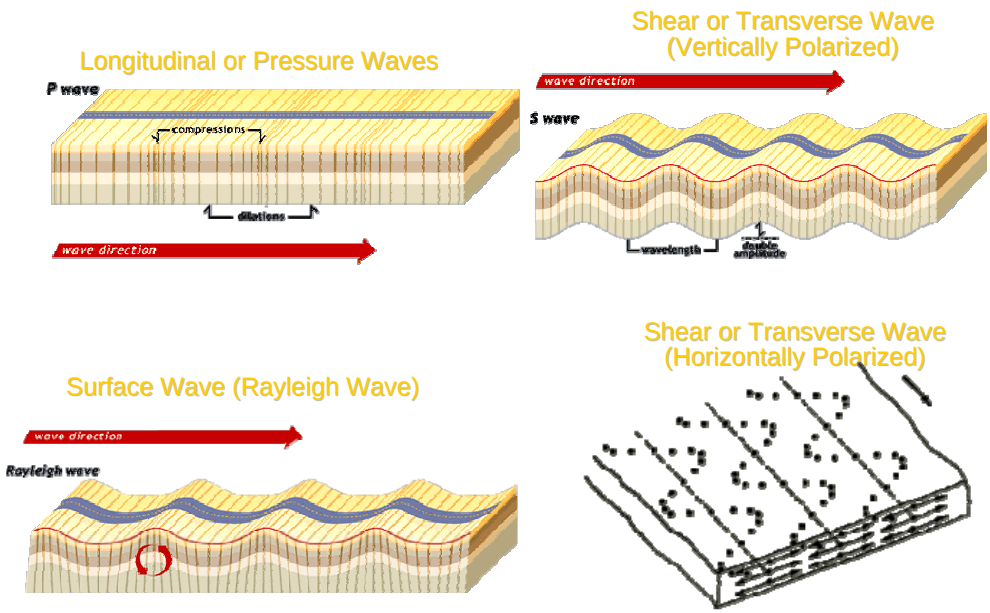


Figure 2. Schematics of ultrasonic waves showing the direction of propagation and motion of the particles.

In addition, to the axial and circumferential variations in the texture parameters due to processing, denting pipes creates variations in the radial direction of the pipe. To address this depth dependence we have utilize ultrasonic Rayleigh waves which travel along the surface of the metal. The penetration depth of the Rayleigh waves can be controlled by altering the frequency of the wave, with the lower frequency waves penetrating more deeply into the pipe.

When performing ultrasonic measurements, it is critical to ensure consistent coupling between the ultrasonic transducer and the part under inspection. To ensure consistent coupling, this project has relied heavily on Electromagnetic Acoustic Transducers

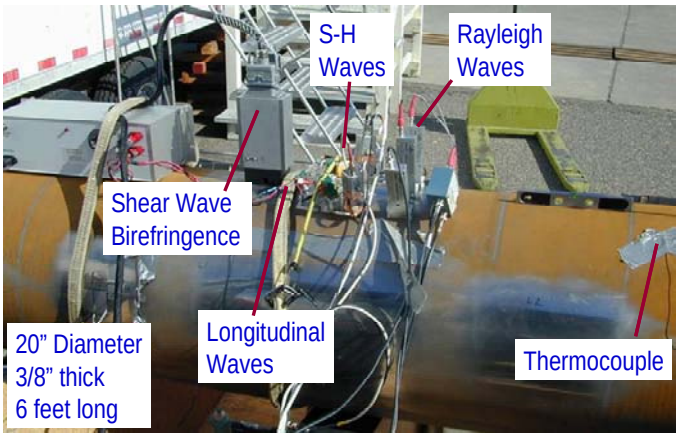


Figure 3. Photo of pressurized pipe with EMATs in place for measurements.

(EMATs) [2,5]. An EMAT consists of a coil of wire and a permanent magnet arranged in a specific geometry. The ultrasonic wave is produced by the interaction of a surface current on the metal part and the magnetic field from the permanent magnet. The type of wave and the direction of propagation are governed by the Lorentz force between the magnetic and electric fields and the orientation and configuration of the coil with respect to the magnet. EMATs have been chosen because they can easily generate several types of waves and are not affected by rust or scale on the surface of the pipes. In addition, there is no need for coupling gel or water to be carried onboard inspection devices inside pipes.

3.0 RESULTS AND DISCUSSION

3.1 Stationary Laboratory Measurements

The ultrasonic velocity measurements have been performed on several specimens in various states of deformation, including uniaxial and biaxial elastic deformation and uniaxial plastic deformation. In addition we have performed measurements on dented regions which have both triaxial elastic and plastic deformation. Measurements in the elastic region were performed on a gas pipe that was pressurized with water (see Figure 3). Results shown in Figure 4 in the elastic region show a direct relationship between the shear wave birefringence, the Rayleigh wave velocity and the L- wave velocity and applied stress. The resultant relationships were in agreement with published values [6]. These results are useful for understanding the effects of elastic deformation on the ultrasonic velocities, however, dented and bent portions of pipe are deformed plastically.

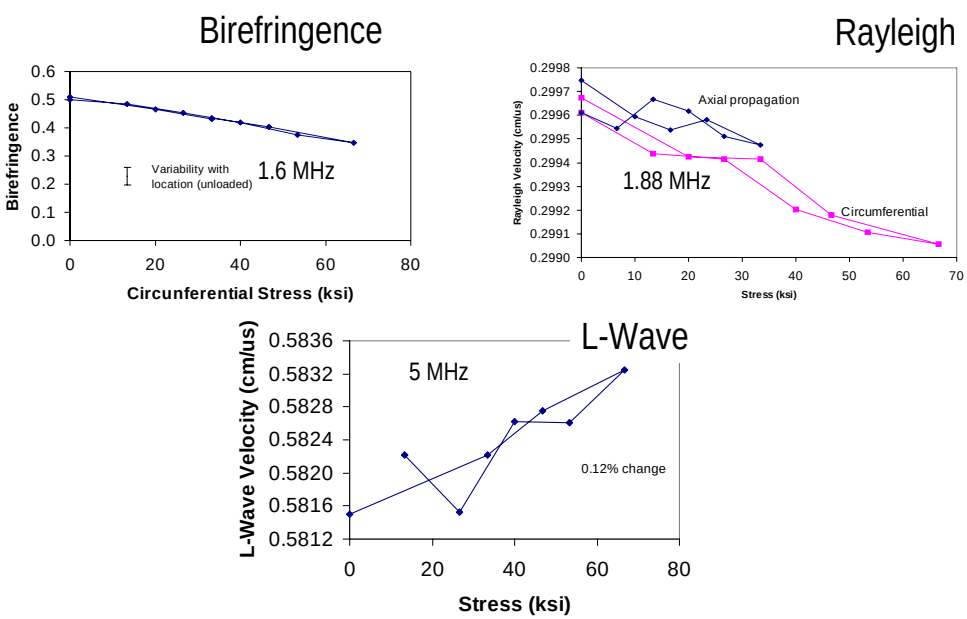


Figure 4. Ultrasonic results from pressurized pipe in elastic region.

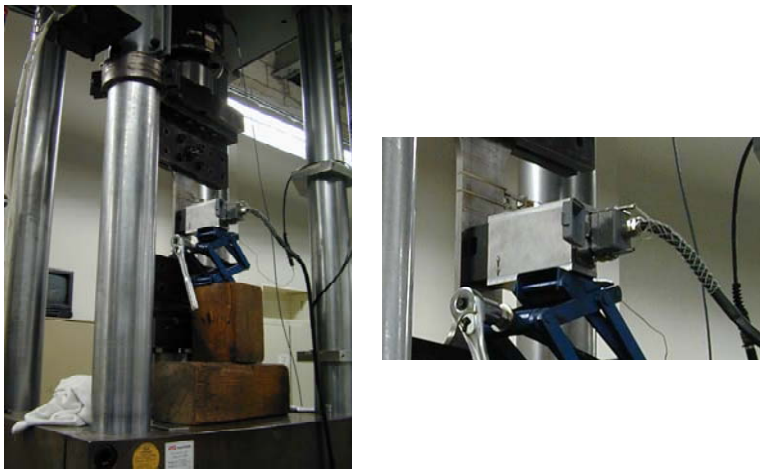


Figure 5. Photographs of samples in tensile test machine with EMAT sensor in place.

Tensile specimens (dogbones) were cut from a ½" thick flat plate of ferritic steel and deformed in a standard tensile test machine as shown in Figure 5. The dog bones measured 3 feet in length with a gage width of 3 inches. The tensile tests were performed in a standard MTS testing machine at room temperature under load control in the elastic regions and displacement control in the plastic regions. Ultrasonic data was collected at the center of the dogbone approximately one minute after each stress level was obtained. Figure 6 shows the speed of sound of two shear waves with polarizations parallel and perpendicular to the applied stress on a flat dogbone. As the load increased in the elastic region, the speeds approached one another, followed by a large drop in speed with plastic deformation. The unloading process caused the velocities to move apart from one another as the stress was decreased. The bottom right schematic in Figure 6 shows the loading history in the stress strain diagram. These results show that the ultrasonic velocity is very sensitive to both elastic and plastic deformations and can potentially be utilized to measure the residual stress and plastic strain in materials.

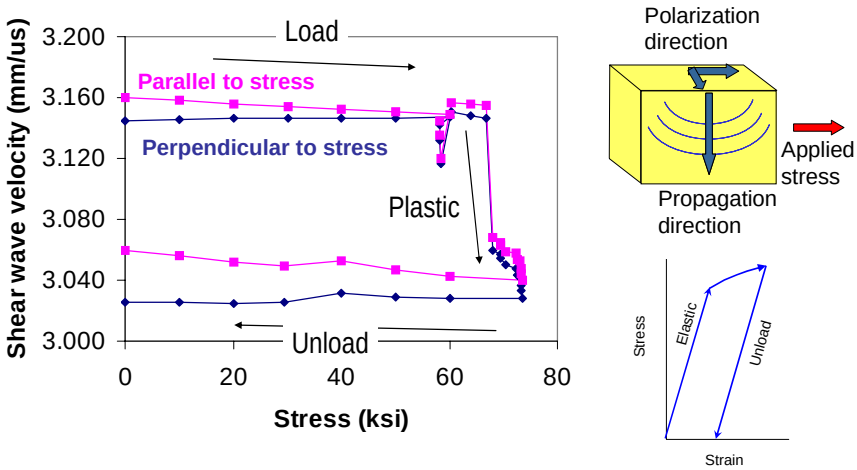


Figure 6. Shear wave velocity as a function of stress for polarizations perpendicular and parallel to the applied stress.

While the shear wave velocity is a useful quantity for lab measurements, in the field, deformation causes the thickness of the pipe to change thus the thickness is needed to calculate the velocity. When a pipe undergoes deformation the wall becomes thinner, thus changing the transit time of the ultrasonic wave. To accurately measure the velocity, one also needs to know the thickness of the wall; a measurement that is not trivial in the field with enough accuracy. To overcome the need to measure the wall thickness we have utilized various combinations of ultrasonic wave velocities that are independent of thickness. Specifically, we have combined the velocities of shear waves with two different polarizations to calculate the birefringence (see equation above). The important aspect of this parameter is that it is independent of thickness, and thus a measure of the material property changes without the effects of the thickness change.

The result of the birefringence as a function of stress are shown in Figure 7 a b, and c, for deformation of 2.5%, 5% and 11% respectively on a dogbone cut from a 24" diameter pipe. The birefringence dropped dramatically as the load increased in the elastic region due to the shear wave velocities approaching one another. The birefringence then increased as a function of plastic deformation and continued to increase as the load was removed. The results were very reproducible as can be seen by the birefringence while reloading in the elastic region tracking along the unloading path. Figure 8 shows the birefringence as a function of plastic strain after the load was removed, showing a direct dependence on plastic strain for three different pipeline steels.

These empirical results are very encouraging, however, they are limited to the laboratory and the deformation is well controlled with no stress after unloading. In addition these measurements were performed with the sensor stationary. Measurements performed while the sensor was in motion are in a later section. Comparisons with existing theories [7] are shown in Figure 9 for deformations up to 15%. Kobayashi accounts for the plastic deformation by including terms that are dependant on the plastic strain. The theoretical predictions and experimental results are in excellent agreement, demonstrating the feasibility of providing a quantitative estimate between the plastic deformation and the ultrasonic shear wave birefringence. While these results are encouraging, they represent excellent progress in a controlled experiment, on flat plates under a uniaxial load with no resultant residual stress. Dents and bends in pipelines are significantly more complicated and further analysis and interpretation is needed as will be shown in subsequent sections.

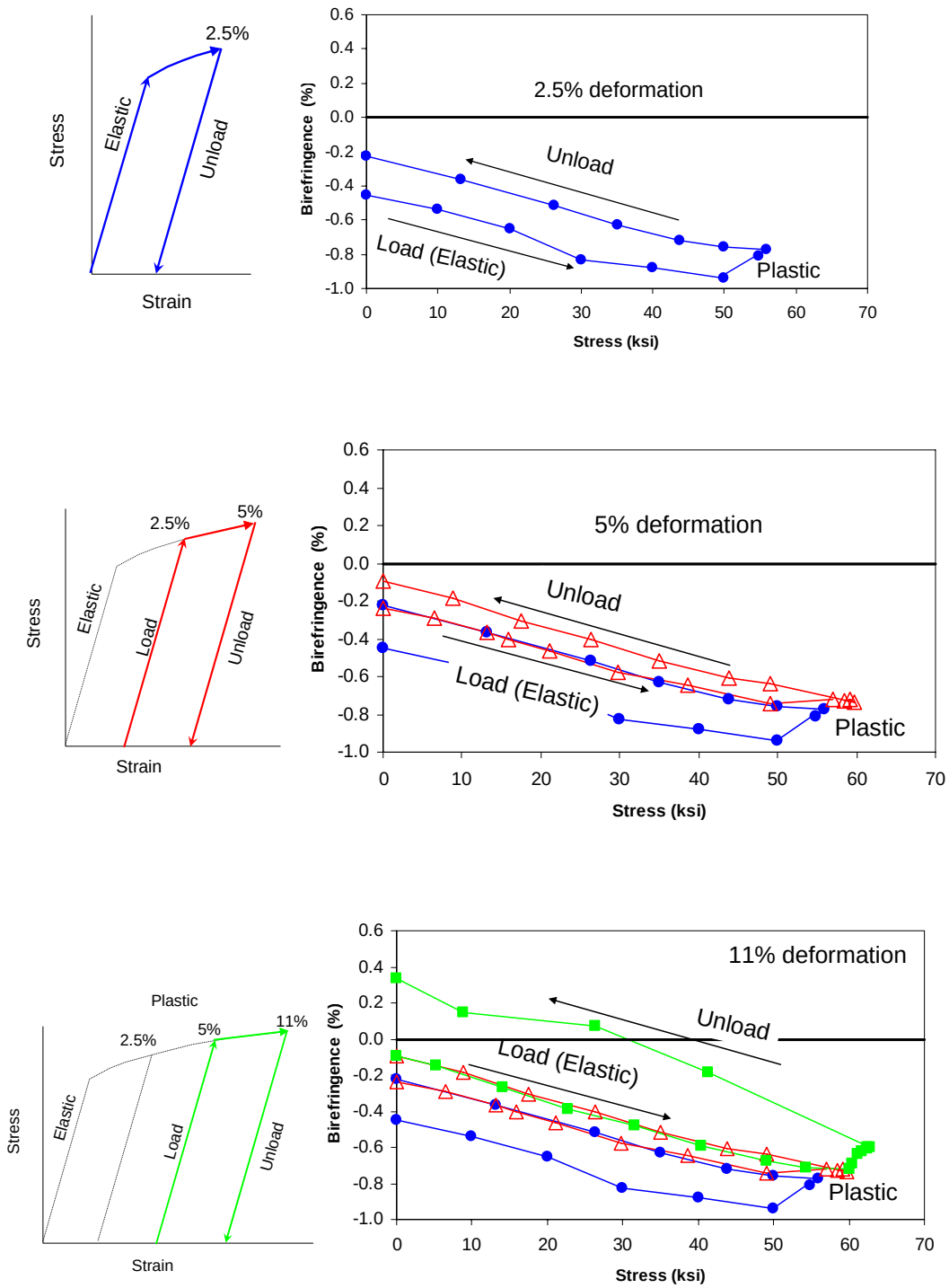


Figure 7. Shear wave birefringence as a function of stress on one specimen loaded and unloaded through several cycles (top) 2.5%, (middle) 5%, and (bottom) 11%. The specimen was cut from a 24 inch diameter pipe with dimensions approximately 3 feet long (along the axis of the pipe) with a gage width of 3 inches.

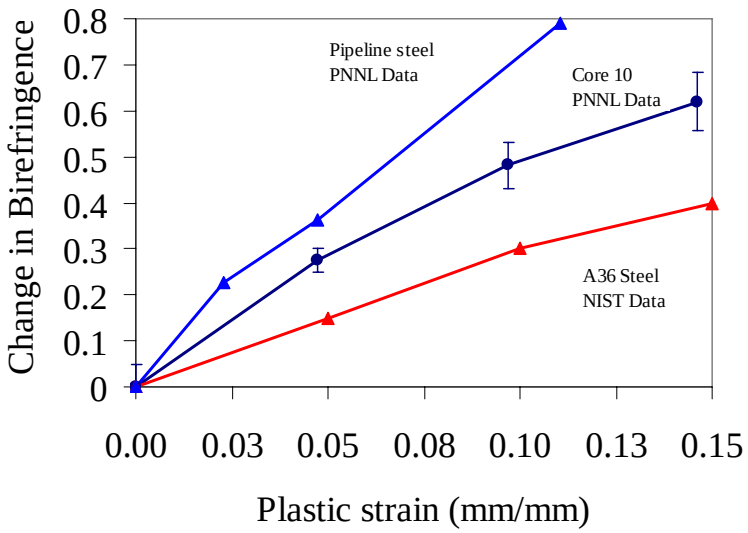


Figure 8. The change in the birefringence as a function of plastic strain after unloading for several dogbones.

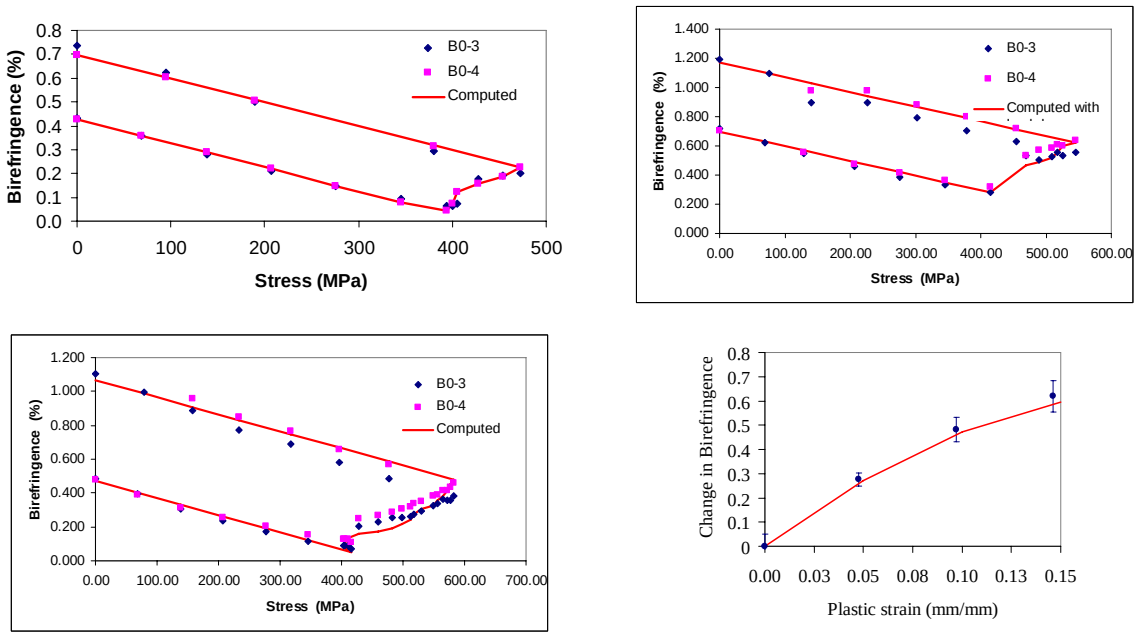


Figure 9. Comparisons between theoretical predictions (lines) and experimental measurements (points) from flat plate dogbones presented in Figure 7.

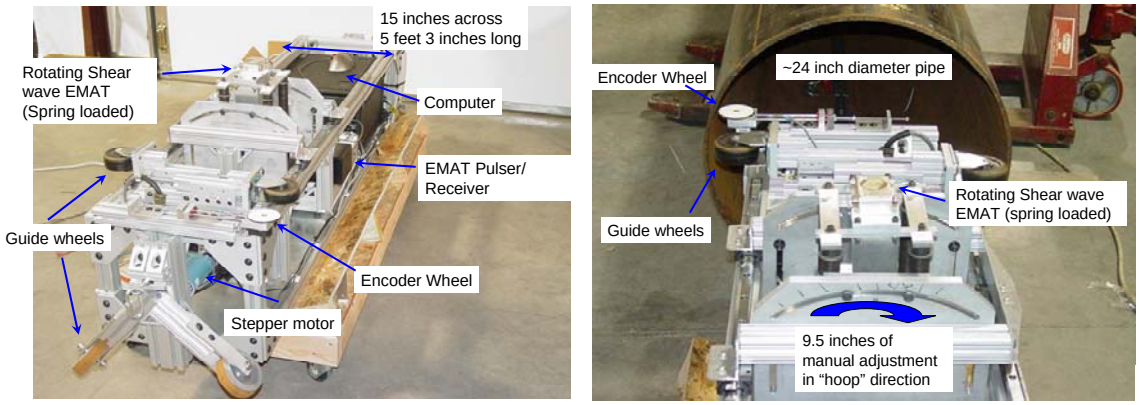


Figure 10. Photos of cart to carry EMAT sensor, electronics, and computer.

3.2 Dented pipelines at PNNL

To perform measurements on pipelines while moving the sensor along the inside of the pipe, a rudimentary cart was constructed as shown in Figure 10. The cart was designed to hold the sensor, all the electronics, and the computer to control the system. This cart was utilized to map the damage in pipelines at speeds over 2 inches per second with data collected in real time every 0.1 seconds, every 0.2 inches along the axis of the pipe. The pipe and a layout of the dents is shown in Figure 11 at PNNL's facility. The pipe was dented at the Battelle Pipeline simulation Facility. The pipe was oriented with the dents at the top dead center (TDC) of the pipe. Figure 12 shows the shear wave birefringence as a function position along the axis of the pipe. The sensor was scanned along lines that were 4.5 inches on either side of the dents. The red squares show the actual location of the dents. There is a clear relationship between the dent location and the change in the

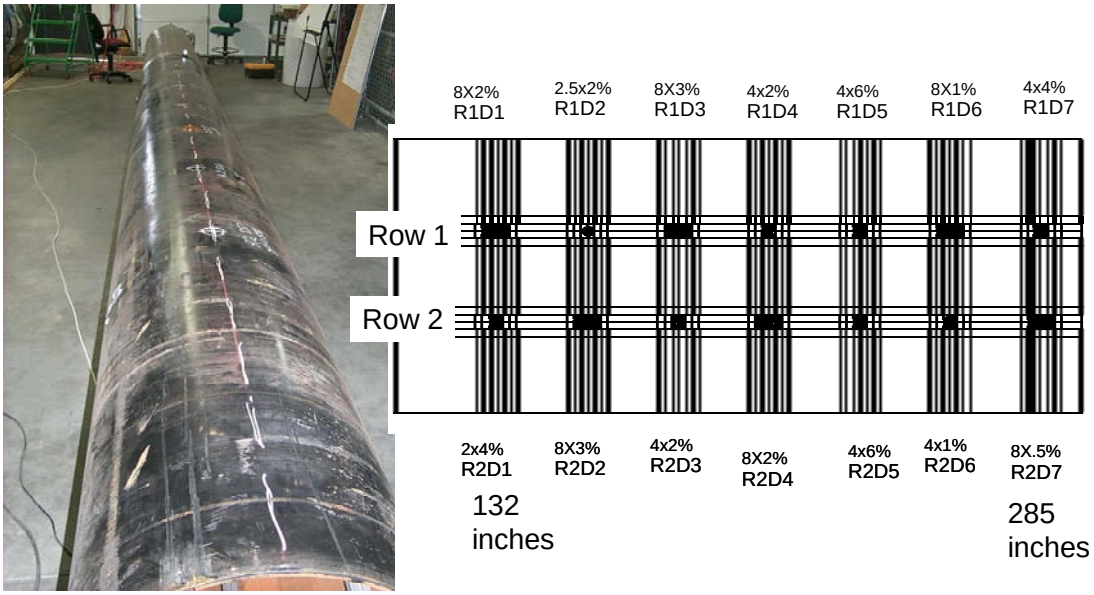


Figure 11. The dented pipeline and schematic of dent layout on pipe for testing at PNNL.

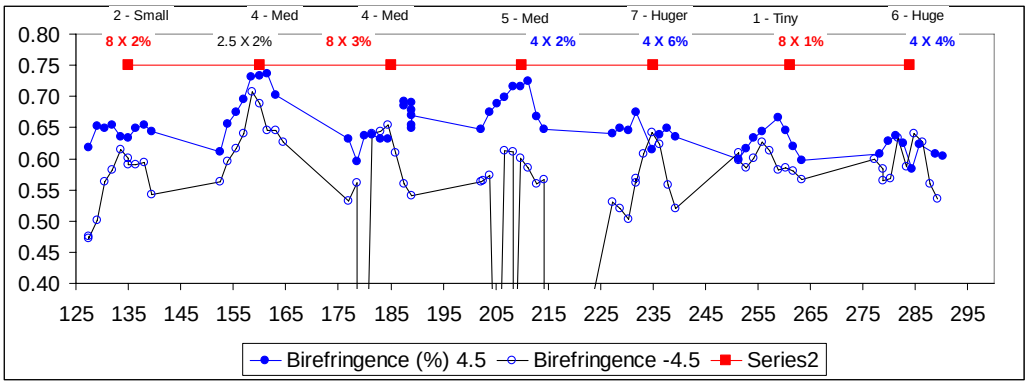


Figure 12. The shear wave birefringence as a function of axial position along the pipe axis.

birefringence with the large dents causing the birefringence to change over a larger axial distance. The deviation from the baseline is also related to the degree of deformation similar to Figure 8.

3.3 Blind Field on Dented Pipeline

The same test apparatus was transported to Battelle in Columbus, Ohio for a field test September 13-17, 2004. This blind test was performed without knowledge of the location or severity of the dents. The results were excellent for classifying the degree of deformation in the supplied pipes as will be shown below.

Two pipes were tested at Battelle's Pipeline Simulation Facility in Columbus Ohio. The results from pipe 2 are especially encouraging. The pipes were scanned along the axis from the interior utilizing the same non-contact Electromagnetic Acoustic Transducer (EMAT). The EMAT generated a wave which traveled through the thickness of the pipe continuously as the sensor was moved along the pipe at speeds greater than 2" per second. Data was collected every 0.2" along the axis. Figure 13 shows the amplitude of the ultrasonic wave as a function of position along the axis of pipe 2 with the sensor

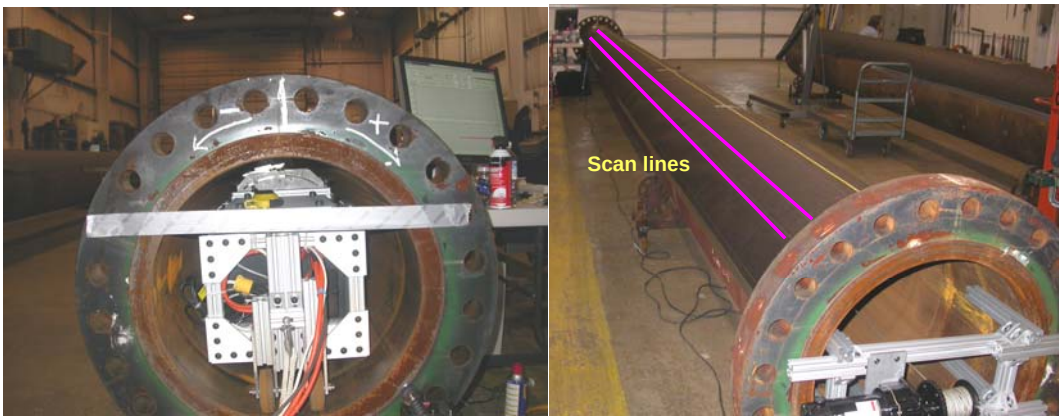
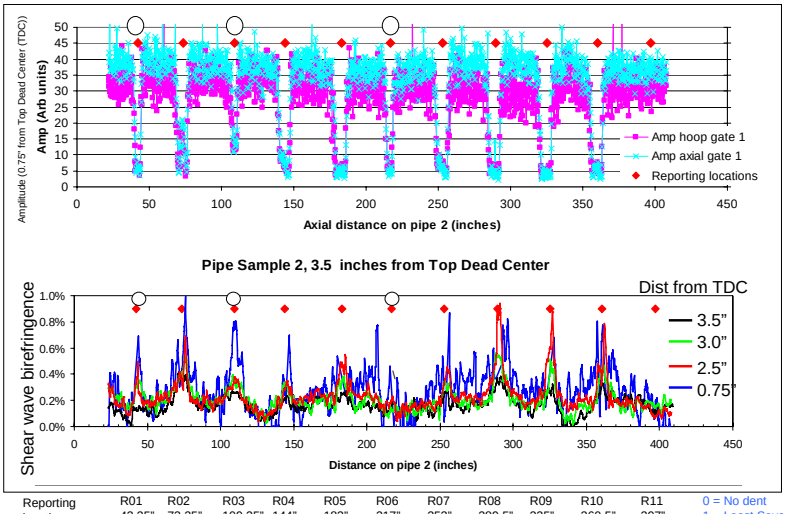


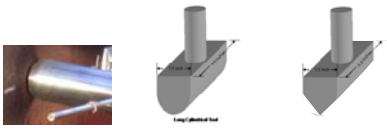
Figure 13. Photos of pipe specimen 2 at the field test.



Reporting locations	R01 42.25"	R02 73.25"	R03 109.25"	R04 144"	R05 183"	R06 217"	R07 253"	R08 289.5"	R09 325"	R10 360.5"	R11 397"
PNNL Ranking	1	2	1	2	3	1	2	3	2.5	3	0
Benchmark	1	2	1	3	2	1	2	3	2	3	0

Calibration ← → Blind

0 = No dent
1 = Least Severe
2 = Moderate Severity
3 = Most Severe

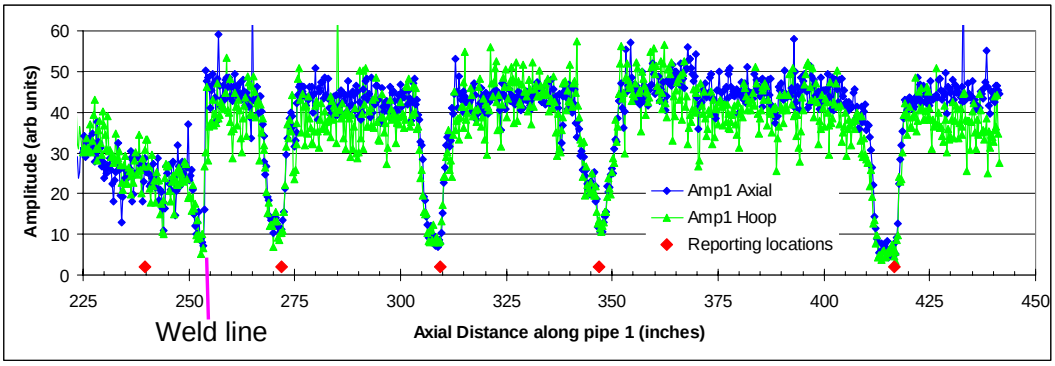


(1) Spherical (2) Cylindrical (3) V-shaped

Figure 14. The amplitude of the ultrasonic signal as a function of axial distance on pipe 2 (top) and the shear wave birefringence as a function of axial distance on pipe 2. The red diamonds are the reporting locations.

located 0.75" along the hoop direction from top dead center. Figure 14 shows the shear wave birefringence with our classification and ranking of the dent severity is in the bottom figure below. We correctly assessed the degree of deformation on 8 out of the 9 reporting locations. Our assessment for locations R04 and R05 was reversed and our assessment for R09 should have been 2 rather than 2.5. The reason for the deviation for R09 was due to the fact the damage from the indenter at locations R08 and R10 was severe and extended over a large region, causing additional damage near location R09.

Our assessment of pipe 1 was complicated due to the complex processing history of the pipe. After denting Pipe 1, it was ruptured during a pressure test, releasing some of the residual stress in the region of the calibration defects. In addition, the pipe was cut; relaxing some of the residual stress, and a portion was rotated to align defects, then welded back together. The result was a set of calibration defects that existed in a section that was different than the reporting locations. Even with these complications our assessment was reasonably accurate, with our ranking for Q4 and Q5 correlating nicely with the degree of damage. Figure 2 shows the amplitude of the ultrasonic signal along the axis of pipe 2 for two different polarization of the shear wave. The location of the dents is clearly visible as is the difference in the material properties as the EMAT moved across the weld line of the pipes at ~250 inches. The results from further analysis of this data will be reported in subsequent reports and publications.



Reporting locations	Q6 239.5"	Q5 272"	Q4 309.5"	Q3 347"	Q1 416.5
PNNL Ranking	none	1.5	2	1	3
Benchmark	0	1-	2	3-	1

0 = No dent
1 = Least Severe
2 = Moderate Severity
3 = Most Severe

Figure 15. The amplitude of the ultrasonic signal as a function of axial distance on pipe 1. The red diamonds are the reporting locations.

4.0 CONCLUSIONS

These results show a direct empirical and quantitative correlation between the speed of ultrasonic waves and the degree of stress and strain in metal. In addition, we have shown the feasibility for the ultrasonic shear wave birefringence to accurately determine the severity of damage in dented pipelines. These results show that the non-contact ultrasonic methods can be utilized in real time on the inside of pipelines to map the severity of dents. These results are very encouraging and show that our ultrasonic measurements can accurately asses the damage in dented pipelines. The ultrasonic measurements are sensitive to stress and strain in the specimens and can be applied to bent sections as well as dented regions. In addition, these EMAT sensors can be configured for small pipes (~4" diameter) and have been attached to PIGs and robots for remote testing.

5.0 RECOMMENDATIONS FOR FUTURE WORK

To fully realize the ability to nondestructively determine the severity of damage in natural gas pipelines and predict the maximum operating pressure, the following path forward is recommended. First, the ability to discriminate between dents and bends is critical to sustaining the nation's natural gas supply. This path entails utilizing the methods developed in this program to develop a sensor system that will be compatible with various robotic and PIG platforms. This sensor platform will utilize several ultrasonic wave types and scan along the inside of the pipelines. This system will be tested to identify necessary enhancements for the final prototype system. In addition, a parallel path is recommended to determine the maximum operating pressure in a damaged pipeline. This approach will offer a complete characterization and life

prediction methodology from detecting and identifying damage and determining the severity of the damage to predicting the maximum operating pressure.

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