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VALIDATION AND ENHANCEMENT OF LONG RANGE GUIDED WAVE ULTRASONIC TESTING

A KEY TECHNOLOGY FOR DIRECT ASSESSMENT OF BURIED PIPELINES

Public Version of Final Report

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Executive Summary

This project is part of a consolidated R & D program by NYSEARCH/NGA to address the technical challenge that is presented by a significant population of LDC-owned transmission lines in HCAs; un-piggable pipelines and lines that are difficult to inspect because they are hard-to-reach areas such as pipes that are in casings at highways, river crossings, railroad crossings, etc.

The overall aim of the completed project on guided wave inspection that is reported here was to develop and further validate long range inspection techniques that can be used as a screening tool to detect external and internal corrosion and coating defects in gas pipes (with diameters from 2" to 60"). The objectives were to: 1) improve detection performance of long range guided ultrasonics in coated and cased pipe by focusing methods, 2) reduce the effects of coatings on test performance, and, 3) demonstrate performance in field trials.

Propagation characteristics of guided waves are dependent on both the frequency and the thickness of the component under study. Changes in thickness cause a disruption to the wave and produce both reflections and changes to the transmitted wave. This method is therefore sensitive to loss of thickness and it is highly suited to the detection of corrosion and other metal loss defects. Where a guided wave test is carried out over a long distance, of tens or even hundreds of feet, the possible sensitivity and resolution will not be as good as where the test is examining the area directly underneath the sensor, as for a thickness measurement. There is consequently a compromise between the ability of the guided wave technique to examine a large volume of material from a remote location and the level of detail which may be obtained about any given defect. In a pipe using the traditional axi-symmetric scanning technique, the wave travels as a circular pulse with energy uniformly distributed around the circumference. As it interacts with a defect, it may be envisioned that the strength of the interaction is proportional to the size of the defect related to of the cross-section of the pipe wall. A consequence of this is that the signal detected by the guided wave system is related to the area of the defect presented to the advancing wave, i.e. it depends on both the circumferential length and the depth, and there is no direct measurement of wall loss, or of remaining wall thickness.

With the new technique advanced under this project, known as focusing, there is a concentration of energy on a small proportion of the circumference. Focusing both increases sensitivity and provides positional information around the circumference. Techniques were developed early in this project for thorough coverage so that the focal "spot" is electronically scanned around the pipe and covers the whole of the pipe wall.

Mathematical modeling was carried out to accomplish the following: 1) Predict the behavior of the focused guided wave ultrasonic system, 2) Provide parameters for optimum practical operation of the test system and to highlight areas for study in the experimental trials, and, 3) Study (model or define) the effect of pipeline coatings on the propagation of low frequency guided waves.

Experimental trials consisted of two tasks. The first was an assessment of the improvement in response level and the accuracy of the focus in locating a defect. This was demonstrated using both artificial defects (notches) and real corrosion from pipes that were retired from service. The second was an assessment of the effects of different amounts of coating on the attenuation of guided waves.

Modeling and the experimental tests showed that the focusing technique improved both the signal amplitude and the signal to noise ratio of responses from defects, hence increasing the sensitivity to smaller defects. In light of the findings from the experimental tests and the early field tests, the procedure used for the traditional application of the guided wave tests using the Teletest™ system was reviewed and revised. About halfway through the project, a revised operational procedure document was released to project sponsors and to the commercial outlet for the Teletest™ tool, Plant Integrity.

The first series of field trials included several iterations of controlled tests at the NYSEARCH/NGA test bed as well as live field tests in the second and third quarter of 2006 at PECO and National Grid/NMPC. For the live jobs, in addition to coordinating schedules, multiple discussions were held to determine what sites to test at, what to prepare for and how to insure that data could be collected. The second series of field trials were held in September 2006 at PECO and Enbridge and November 2006 at live jobs at Keyspan. Utility support for the five different live field tests included extensive in-house coordination with utility crews to identify, excavate, monitor, provide traffic control, validate and restore the sites used for testing.

Through the project, considerable laboratory evidence is provided to show that focusing the ultrasound can offset some of the attenuating effects of the coatings. Similarly, in not all cases, field test results have evidence of improvements using focusing. Examples are available to project funders from the controlled tests at the test bed to show that focusing improves defect detection (compared to axi-symmetric scanning with the same tool) and it can be used to provide a basis for exact positioning and sizing of the defects. In addition to the enhancements provided through the focusing technique, another procedure that was used to improve overall detection was the use of multiple wave modes. This approach, known as "Multi-mode™ incorporates transducers to excite both longitudinal and torsional wave modes.

As a result of the findings from the controlled tests and some of the field tests, TWI is now working with Plant Integrity to adopt a second revision to the Operating procedure. The additional use of guided waves focused at the defect, which is unique and essential feature of the Teletest™ system, allows more information to be collected which is specifically related to size and shape of the defect.

As a result of this work, a methodology and field usable techniques for determining the effect of coatings has been established. However, this revised approach has only been assessed for a small number of cases. It is recommended that an additional systematic study is performed on coatings that are used in the field and using these new techniques, more work be done to establish advances in how to optimize field setting and test results.

Throughout the work, oversight was provided by NYSEARCH/NGA Staff and the utility sponsors. Input and in-kind services were provided in areas such as feedback on pipeline operator requirements, definition of varying levels of defect sizes and their severity, contribution of test pipes and selection, preparation, access, restoration and validation regarding controlled and live field tests sites.

1. Introduction

To meet DOT/OPS Pipeline Integrity rules, gas operators must go through a process (defined in the regulations) to identify their gas transmission lines that are in “High Consequence Areas” or HCAs. Lines in HCAs are subjected to a rigorous integrity program that includes conducting “baseline assessments” and then follow up “reassessments”. The assessment of coated, buried and, in some cases, cased pipelines presents considerable challenges, in that there may be many miles of such pipe in high consequence areas and there is the potential for in-service degradation to have occurred at any point along the length of the line.

This project is part of a consolidated R & D program by NYSEARCH/NGA to address the technical challenge that is presented by a significant population of LDC-owned transmission lines in HCAs; un-piggable pipelines and lines that are difficult to inspect because they are in hard-to-reach areas such as pipes that are in casings at highways, river crossings, railroad crossings, etc. For these lines, access costs are likely to be high for external examinations and there are cases, for example where a casing is present, where the possibility to apply inspection techniques is limited.

Specifically, this project addressed the potential of low frequency long range guided wave ultrasonic testing (LRUT) to meet requirements set by a steering committee of representatives from the gas industry for the detection and evaluation of defects in gas pipelines. Of major concern is the inaccessibility of pipe sections which are cased, for example at road/rail crossings. In such areas follow up visual examinations are difficult. Therefore the findings of remote inspections such as by guided waves must be reliable if pipe integrity is to be assured for continued operation.

The work was carried out by TWI Ltd, Cambridge, UK and FBS Inc. State College PA, with oversight and controlled and field test evaluation by NYSEARCH/NGA.

2. Objectives

The overall aim of the project was to further validate and to develop long range inspection techniques that can be used as a screening tool to detect external and internal corrosion and coating defects in gas pipes (with diameters from 2” to 60”). The objectives were:

- To improve detection performance of long range guided wave ultrasonics in coated and cased pipe by focusing methods
- To reduce the effect of coatings on test performance
- To demonstrate performance in field trials

The principal deliverables for the project were:

1. Laboratory and field validated procedures for application of enhanced techniques using long range guided ultrasonic waves as part of direct assessment procedures for transmission pipelines,
2. Validation data to enable pipeline operators to make engineering judgments based on test findings,
3. Theoretically and experimentally based procedures for improving the test performance of guided waves on coated and buried pipelines,
4. Field performance data and corresponding field test reports, and,
5. Guidance documentation for pipeline operators and inspection service providers to enable best practice application of guided ultrasonic waves.

3. Technical Approach using Guided Waves

Ultrasonic testing is an established technology for industrial material thickness measurement and weld examination. The ultrasound consists of elastic waves (of very small amplitudes, imperceptible to the naked eye), typically in the 1 to 10 MHz frequency range, which are transmitted through the material under test. These waves are usually generated and detected by piezo-electric sensors, although electromagnetic and laser sensors may be used. The waves interact with discontinuities and this interaction allows material thickness to be determined and defects to be detected. In most cases longitudinal and transverse so-called 'bulk' waves are generated which propagate in the body of a material as well-defined beams of energy. These waves typically propagate for a distance of several inches and allow a local examination adjacent to the sensor. The wavelength of the ultrasound is usually much smaller than the thickness of the material under test.

If the transmitting sensor introduces the ultrasound at an oblique angle to the surface (beyond the second critical angle), Surface (also called Rayleigh) waves are introduced by refraction. These follow the contour of the surface. Surface waves are a type of guided wave in that their propagation is governed by the presence of the material surface where they were generated. Again, these occur when the wavelength of the ultrasound is much smaller than the material thickness. The depth of penetration of the energy into the material is approximately one wavelength.

If a flat plate is considered, when ultrasound is generated at a frequency where the wavelength is greater than the material thickness, then the wave interacts with both the top and bottom surfaces and the whole plate is vibrated, see Figure A. In such cases, the plate acts as a wave guide along which the wave propagates, hence the term guided waves. It may be seen that, for engineering components, to achieve the condition where the wavelength is large compared to the thickness, the frequency must be considerably lower than for conventional ultrasonic testing. For guided wave tests, the frequency range of interest is typically from the upper audible (around 10kHz) to around 100kHz.

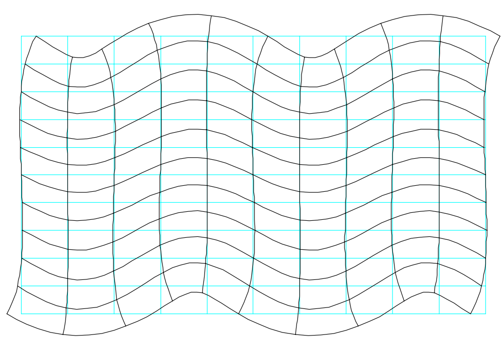


Figure A Vibration pattern of an asymmetric mode (A_0) in a plate

These 'low frequency' guided waves have a number of properties which make them useful for large area monitoring:

- They can be propagated in a variety of material shapes: plates, pipes, rods, I-sections and rails,
- They vibrate the whole thickness of the material so 100% of the section is interrogated,
- They can propagate over long distances with minimal attenuation (see also below) so examination of long lengths of components is possible.
- The propagation characteristics of these waves are dependent on both the frequency and the thickness of the component. Changes in thickness cause a disruption to the wave and produce both reflections and changes to the

transmitted wave. The method is therefore sensitive to loss of thickness and it is highly suited to the detection of corrosion and other metal loss defects.

However, there are other characteristics which must be understood and considered when using these guided waves:

- Many different wave modes can exist under most circumstances, so that the test conditions must be chosen either to eliminate unwanted modes, or to recognize that they exist and enable the resulting waveforms to be interpreted,
- Most wave modes exhibit dispersive behavior (where the wave velocity is dependent on frequency) in some frequency ranges. These regions are best avoided but, if they cannot, the effects need to be accounted for in the signal processing and analysis,
- Where energy is able to leak out of the wave guide and be lost, for example where a pipe wall has a thick layer of tar-like protective coating, the energy transmitted along the component will constantly diminish (i.e. the attenuation rate will increase), so that the achievable test range will be reduced,
- Where a test is carried out over a long distance, of tens or even hundreds of feet, the possible sensitivity and resolution will inevitably not be as good as where the test is examining the area directly underneath the sensor, as for a thickness measurement. There is consequently a compromise between the ability of the guided wave technique to examine a large volume of material from a remote location and the level of detail which may be obtained about any given defect.
- In a pipe, the wave travels as a circular pulse with energy uniformly distributed around the circumference. As it interacts with a defect, it may be envisioned that the strength of the interaction is proportional to the size of the defect related to of the cross-section of the pipe wall. A consequence of this is that the signal detected by the LRUT system is related to the area of the defect presented to the advancing wave, i.e. it depends on both the circumferential length and the depth, and there is no direct measurement of wall loss, or of remaining wall thickness. This is illustrated in Figure B.

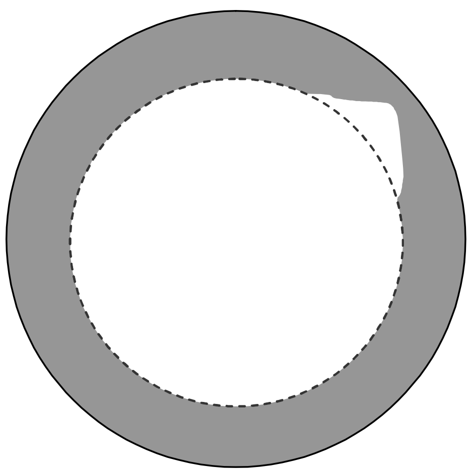


Figure B Defect detection is related to the cross-sectional area loss

4. State of readiness of the technology

In the last decade, there has been a large amount of development work done in the field of application of guided waves for examination of industrial components. Test regimes have been developed which address the above considerations and there are a number of commercial systems on the market.

This work was carried out using laboratory apparatus and the Teletest® system. The hardware and software employed for the field work used the Mk 2 Teletest® ‘Multimode’™ system with Version 1.32 software and the addition of the focusing capability.

An important element of this work was to assess the extent to which the available techniques meet the needs of the pipeline operators and to demonstrate the improvements which can be achieved by enhancing the test equipment, techniques and procedures. To be acceptable to both the pipeline operators and the regulatory authorities, an inspection technique has to satisfy certain criteria:

- Technology is based on sound physical principles,
- Technology should be capable of revealing the types of defect likely to occur in the components tested,
- This capability is backed up by evidence for performance based on controlled and field test data,
- Techniques can be applied consistently and reliably in the field by qualified personnel with an appropriate level of education, training and certification for the pipeline industry.

LRUT has the advantage that it inspects 100% of the pipe wall and is sensitive to both external and internal flaws. It has a potential range of 50 - 100 feet in each direction so that 100-200 feet of pipe can be inspected from a single access point. For many pipes, it is particularly valuable for inspecting road crossings and other HCAs. Some pipes with thicker coating are difficult to fully address. This condition will be discussed later in the report. Currently LRUT is used as a screening or search tool. (Note that to date, LRUT has not been used for sizing defects and cannot determine quantity of wall loss. However, the work that was funded as part of this program is part of a range of on-going studies to expand this potentially versatile technology.) If a flaw is located, it is necessary to investigate it in more detail using conventional NDE techniques.

While LRUT using guided waves has been widely and successfully used in process plant applications, for example for the detection of corrosion under insulation (CUI), there has been, up to now, little evidence to support its performance for the examination of areas such as cased crossings. This is partly owing to the fact that validation of indications found by LRUT on insulated pipe is relatively easy, whereas there is limited scope for physical assessment of the condition of a cased crossing unless the operator has a need to pull the pipe for other reasons. Consequently, there is only very limited evidence for its performance for this application. The other main factor is that cased crossings contain features, e.g. centering spacer belts, which are not generally present on insulated pipes. It was considered that such factors may have an effect on the performance of the technique, possibly masking the occurrence of responses from defects or producing false positive calls. So, a major advantage of concentrating this work on cased pipe was also the ability to gather data and validate what pipe conditions could be diagnosed within cased crossings.

5. Work Performed

5.1 NYSEARCH Oversight, Utility Input and Reporting

NYSEARCH Staff had very active involvement in the project from the planning and initiation stages as well as throughout the entire project. One role of the Staff was to oversee all work by the sub-contractors and to insure that there was regular input by the (8) NYSEARCH sponsoring members as well as by DOT/PHMSA. NYSEARCH's model is to have daily to weekly participation by an engineer who is named as project manager and is a full-time person on Staff at NYSEARCH. In this case, the project manager is also the NYSEARCH program lead, Daphne D'Zurko.

Utility input started with the discussions that took place prior to DOT/PHMSA involvement including previous field demonstrations and a Question & Answer period that started in April 2004 when the project proposal was first brought to NYSEARCH through to when DOT/PHMSA joined the program in November 2004. Utility input also consisted of defect detection definitions that were provided by utility operators through this project and multiple reviews of the progress of the technology. Utility input continued in the second year of the project with in-person participation at the controlled and live field tests. In addition, utility operators from NYSEARCH member companies were actively involved in the planning and design of the controlled tests at the test bed, the (5) field tests held at live jobs in member company territories and in the Collaborative Technology demonstration that was held in July 2006.

5.2 Mathematical modeling

The guided wave system is complex and a thorough physical understanding of the propagation characteristics of the various modes is essential if improvements are to be made in the performance of the tests in the field. Modeling was carried out in several areas:

- To predict the behavior of the focused guided wave ultrasonic system,
- To provide parameters for optimum practical operation of the test system and to highlight areas for study in the experimental trials, and,
- To study (model or define) the effect of pipeline coatings on the propagation of the low frequency guided waves to be studied.

5.3 Procedure Optimization

The main emphases for this task were to fully implement the focusing function to concentrate the ultrasound at pre-determined points in the pipe and to provide a protocol for frequency selection. Software was produced which allowed the focus parameters to be entered into the test schedule efficiently. This new software also allowed the use of a frequency sweep and the 'Quick Look Scan' to assess the frequency dependence of responses from features and defects.

5.4 Procedure Validation

The aim of this work was to demonstrate the performance achieved by using the optimized procedures on controlled specimens. These were 6" schedule 40 (0.28" wall) un-coated pipes containing deliberately introduced corroded areas which had been physically measured previously. A total of (26) defects were available. This allowed the performance of the procedure to be assessed. The corroded areas were considered to be representative of real defects. An example is shown in Figure C.

Figure C Corroded area on a 6" schedule 40 pipe used for procedure validation work

Performance was judged against a set of requirements provided by NYSEARCH/NGA members.
The results were assessed in terms of the probability of detection (PoD) which is a widely recognized method of determining the performance of non-destructive test methods.

5.5 Experimental trials

This task consisted of two main activities. The first was an assessment of the improvement in response level and the accuracy of the focus in locating a defect. This was demonstrated using both artificial defects (notches) and real corrosion from specimens retired from service. The second was an assessment of the effects of different amounts of coating on the attenuation of the guided waves.

Following on from the issues determined during the procedure optimization studies, there was a requirement to develop a method of normalizing the transducers. The focusing routine makes the assumption that all segments of the tool make an equal contribution to the transmitted signal and have the same sensitivity to the incoming waves on reception. Key to the success of such a normalization method is the availability of a consistent signal so that the relative efficiencies of each segment may be compared and accounted for. Various approaches were tested, including the use of a metal strap tightened around the pipe and an innovative use of signals transmitted around the pipe from one segment to another to achieve the normalization.

Assessment of Affects of Different Amounts of Coating

The effect of the presence of attenuating coatings was studied using different lengths of wax tape wound on to a pipe. Table 1 shows the experimental conditions. The purpose was to assess both the attenuating effect of the coating and its effect on the ability of the system to detect the defects. As may be seen from the Table, three different shaped defects were studied.

Table 1 Experimental matrix for the wax coating tests

	Corrosion	**Through-wall hole**	**Saw Cut**
Defect location from sensor	11ft	15ft 6in	19ft 4in
	Wax length in front of defect		
Test 1 (bare pipe)	No wax	No wax	No wax
Test 2	No wax	No wax	1ft wax to defect
Test 3	No wax	1ft 2in wax to defect	5ft wax to defect
Test 4	1ft 4in wax to defect	5ft 10in wax to defect	9ft 8in wax to defect
Test 5	7ft 7in wax to defect	12ft wax to defect	16ft wax to defect

The effect of casing spacers was also studied to determine the nature of the responses from these features so that rules for discrimination between these and defects could be established.

5.6 NYSEARCH Planning, Preparation and Participation - First Series of Field Tests

The first series of field tests included several iterations of tests at the NYSEARCH/NGA test bed as well as tests through July 2006 at PECO and National Grid/NMPC. The controlled tests were held at the test bed in September 2005 and May, September and November 2006. The live field tests in the first series were held at PECO in June 2006 and at National Grid/NMPC in July 2006.

NYSEARCH Staff and utility sponsors spent a great deal of time preparing the NYSEARCH/NGA test bed for the capability to test on two above-ground (one coated, one bare) and one below-ground cased pipe at the test bed. Considerable in-kind funding was provided for the design and implementation of these cased pipes with external and internal defects and other appurtenances.

For the live jobs, in addition to coordinating schedules, multiple discussions were held to determine what sites to test at, what to prepare for and how to insure that data could be collected. NYSEARCH staff coordinated this effort and traveled to participate at the jobs in Pottstown, Pa. and Syracuse, NY. Probably the most time consuming effort in this task was preparing and monitoring multiple tests at the NYSEARCH/NGA test bed and then taking numerous hours to compare predictions made by TWI/FBS to the actual machined defect locations for the numerous defects that were imparted into the test bed pipes. This documentation process took months of planning and CAD drawing implementation and the results from this project were the first to be compared to actual circumferential and axial locations of defects on the cased pipes at the test bed.

5.7 First Set of Field Trials

A number of field trials were carried out to assess the performance of the guided wave technique in the field. An important part of this exercise was the use of the NYSEARCH/NGA test facility at Johnson City NY, where there were (3) sections simulating cased crossings which contained deliberately introduced defects. These were:

- 20” uncoated - above ground,
- 16” coated with a coal tar enamel - above ground,
- 12” coal tar epoxy coated - below ground with access vaults

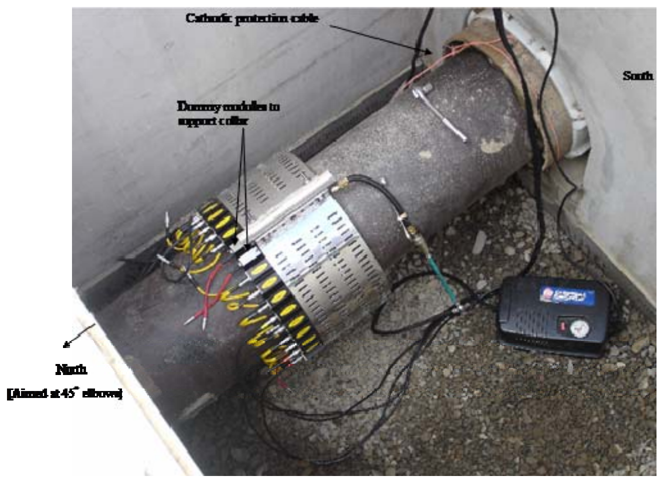
Figure D shows overall views of the Johnson City site. In each section, the length of the cased section was approximately 80 feet.

Tests were all carried out using the multi-mode approach, utilizing both longitudinal and torsional waves and included focusing of the ultrasound on suspect areas in addition to the ‘standard’ axi-symmetric tests to determine more closely the position and nature of the defects.

(a)

Overall layout of the 12” pipe

(b)



TeleTest on 12” coated, cased, and buried pipe [Vault #1]

(c)

Figure D Setup Illustrations at the Johnson City test site. a) the Teletest tool on the 16” coal tar enamel coated specimen. The 20” pipe may be seen in the background, b) the location of the 12” buried cased section, showing the access vaults at each end, c) the Teletest tool mounted on the 12” pipe.

Site field tests were also carried out at the following locations:

- 8” Trenton wax coated pipe with cured-in-place composite liner under a bridge, extending into a cased section, at Pottstown PA, for PECO Energy (Figure E)
- 12” Polyurethane coated cased road crossing at Baldwinsville NY, for National Grid (Niagara Mohawk), Figure F.

An additional visit was made to the Johnson City test site in July 2006 to demonstrate the technology to DoT personnel and their constituents as part of a collaborative demonstration. [1]

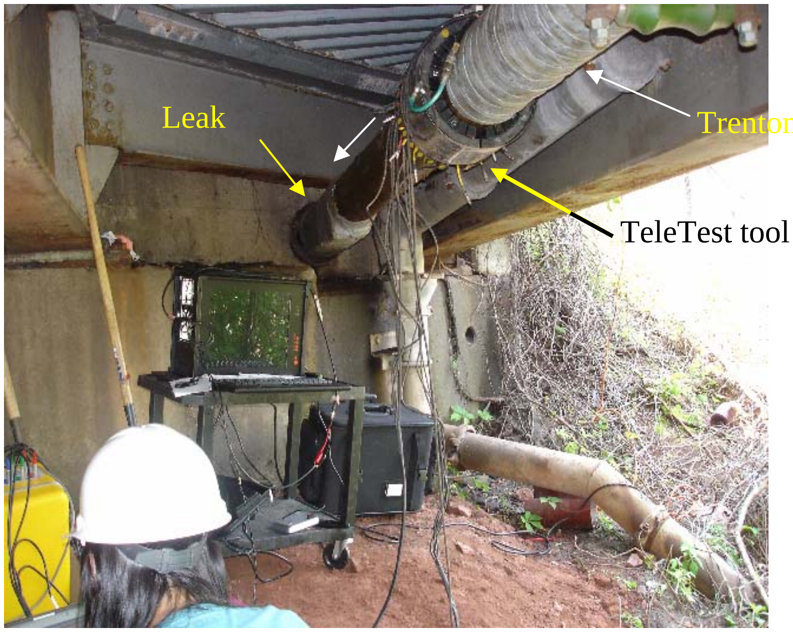


Figure E Test location under bridge for PECO Energy at Pottstown PA

5.8 Procedure revision

In the light of the findings from the experimental tests and the field work, the procedure used for the application of the guided wave tests using the Teletest system was reviewed and revised. This revised document was originally provided in 2nd Quarter. This original document was considered to be an interim version of the test procedure and was the subject of further revision following the second set of field trials.

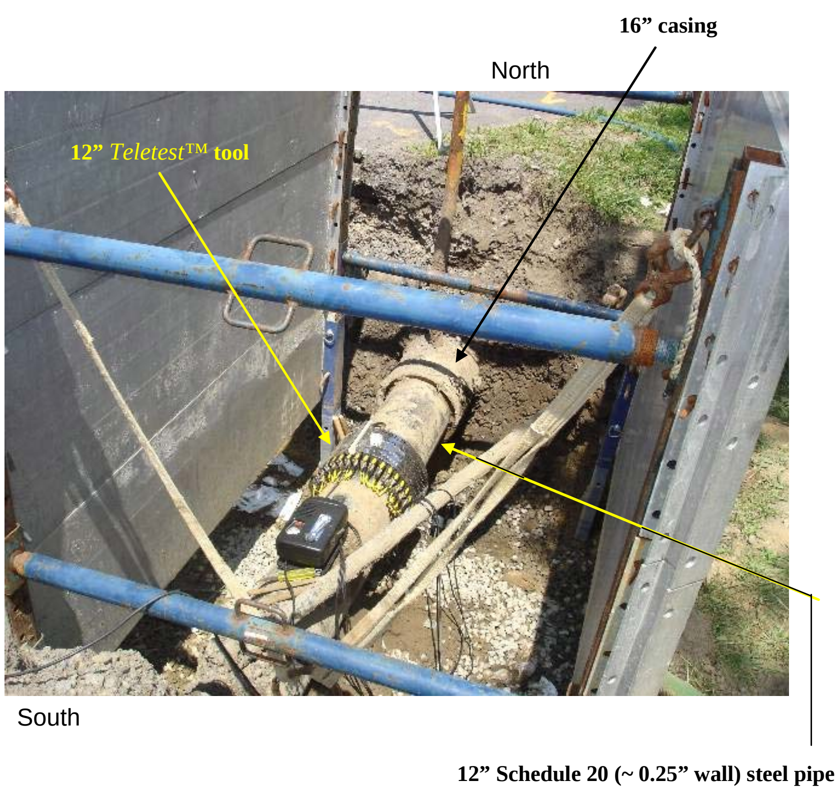


Figure F Test for National Grid at Baldwinsville NY

5.9 NYSEARCH Milestone Meetings

Two milestone review meetings were planned in this project for all sponsors. The first was planned towards the completion of the first year of modeling and experimental trial work. It was held in September 2005 in Albany, NY and attending were representatives from the NYSEARCH sponsoring utilities, the TWI co-sponsors (BP), DOT/PHMSA and TWI and FBS. While there were several other reviews held with NYSEARCH sponsors and discussions held with DOT/PHMSA, the second milestone meeting was held in Washington, D.C. in November 2006 with NYSEARCH Staff and DOT/PHSMA representatives present.

5.10 NYSEARCH Planning, Preparation and Participation – Second Series of Field Tests

The second series of field tests were held with Enbridge, PECO and Keyspan. The Enbridge and PECO tests were held in September 2006 (using advances made in focusing and other lessons learned from previous tests) and the Keyspan tests were held in November 2006. There are separate test reports for all these tests (details provided in the Quarterly reports).

NYSEARCH planning, preparation and participation again consisted of time to coordinate schedules, communicate site specifics and data collection needs and to participate in all tests. There was an unusual additional amount of planning for the second PECO site (which was under a live highway) and for the Keyspan site which was in a dense area of Long Island with multiple sub-structures and massive excavation and shoring tasks required. Several conference calls and discussions were held to plan these tests and documentation was collected and discussed. In the case of the Keyspan tests, discussions started two months before the actual tests.

5.11 Utility Support

The (8) utility sponsors of this project as well as the (13) NYSEARCH sponsors of the design, construction and implementation of the NYSEARCH/NGA test bed provided utility support in several ways to this project. In addition to the input by the (8) sponsors regarding the program targets and progress in over (6) meetings held on this project, many people played a role and spent time and resources providing materials for laboratory testing as well as identifying and preparing sites for live testing.

Utility support for field tests included extensive in-house coordination with utility crews to identify, excavate, monitor, provide traffic control, validate and restore the sites used for testing. In-kind expenses for excavating and examining casings can be extensive and expensive. All field test participants agreed to take extra measures to validate the predictions from the TWI/FBS tests. These participants included several parties from PECO Energy, National Grid/NMPC, Enbridge and Keyspan Energy Delivery.

During the Collaborative Demonstration held as part of this project for multiple guided wave vendors, in addition to high participation by DOT/PHMSA representatives, there was participation by Con Edison of NY, Enbridge, Keyspan, NFG, National Grid/NMPC and RG & E.

5.12 Second Set of Field Trials

Further field tests were carried out to gather more information on the performance achievable in operational conditions. These were:

- 8” Trenton wax coated pipe with possible cured-in-place composite liner under a bridge over I95, extending into a casing at Levittown PA, for PECO Energy (Figure G)
- 8” bitumen coated buried line and 12” Tape coated cased line for Enbridge Gas, Ottawa (Figure H)
- 30” coal tar coated case railroad crossing and adjacent 8” electrical conduit at Garden City NY, for Keyspan Energy (Figure I)

5.13 Collaborative Technology Demonstration

In June 2006, a task was added to this project to conduct a collaborative demonstration for multiple vendors on the same cased pipes at the NYSEARCH/NGA test bed. With input by DOT/PHMA, NYSEARCH Staff coordinated discussions by a DOT Steering Committee and developed a test plan for the tests. Three vendors agreed to participate in the tests and multiple discussions were held with all participants regarding the test conditions as well as a draft list of "guidelines" that DOT/PHMSA was looking for feedback on as far as what information should be communicated between regulators, operators and guided wave service providers.

The tests were held in July 2006 for two days at the test bed. Following that effort, where there was participation by over (13) people, data was collected and analyzed. Given the amount of data and the documentation that needed to be completed, test information was released to the Steering Committee in late October and conference call discussions led to requests for additional analysis by the guided wave vendors. Submittal of additional information to NYSEARCH Staff in November led to a draft report that was issued in late November 2006. Comments from both the vendors and Steering Committee members led to revisions on that report and a second revision issued in December. In total, after the second revision, five reports were issued on the Collaborative demonstration. They consisted of: 1) Steering Committee report with Confidential information and data from all three vendors, 2) (3) vendor-specific reports which did not include Confidential data from the other two vendors, and, 3) a public version of the report with NO Confidential data. Those reports are considered separate deliverables to this project.

In part due to the discussion started as part of this Collaborative Technology demonstration and due to other un-related ongoing PHMSA discussions related to a July 2005 Federal Register notice on means for applying to use Guided Wave Ultrasonics as an alternative to hydrotesting for Direct Assessment of High Consequence Areas, PHMSA issued a revised guided wave "checklist" in March 2007. A sub-contractor to this program, TWI, has issued some reaction to that revised checklist in the context of their participation in the Collaborative Demonstration as well as the results of this larger body of work.

5.14 Production of Operational Guidelines
The lessons learned from the field tests on the controlled and operational pipes were studied and as one of the deliverables at the end of this phase of work, a best practice document was developed. This document is intended to provide information to both suppliers of test services and operators of pipelines about the optimum application of LRUT.

6. Research Findings and Discoveries

6.1.1 Reducing the effects of coatings
Coatings affect the propagation of guided waves in a complex manner and can cause severe attenuation and scattering. The influence of coatings is the biggest area of uncertainty in the prediction of guided wave performance and has a major effect on the ability of the technique to provide good inspection data in the field. Furthermore, the variability from one coating to another makes generalized rules for mitigating the effects difficult to establish. In this project, a considerable amount of work was done to characterize the properties of individual coatings and to assess their effect on the guided wave test. To assist this process, a tool has been developed under the SBIR program (the 'Vector™') which allows in-situ property measurements on coatings which can then be used to assess the influence of that particular coating via the physical models available. The device is shown in Figure J.

Coatings have a dramatic effect on the propagation of the guided waves. These effects are manifested as distortions to the displacement patterns of the waves. They are dependent on the mode shape (determined by the displacement patterns and hence on the mode being transmitted) and the frequency. Further, the attenuation of the longitudinal wave is not significantly frequency dependent, whereas there is a strong effect of frequency on the attenuation of the torsional wave. This provides further evidence that, for a specific circumstance, one wave mode may have better properties than another and that by using more than one mode the chances of being able to perform a satisfactory test are increased. As may be evident, the length of coating will affect the total amount of attenuation in the system.

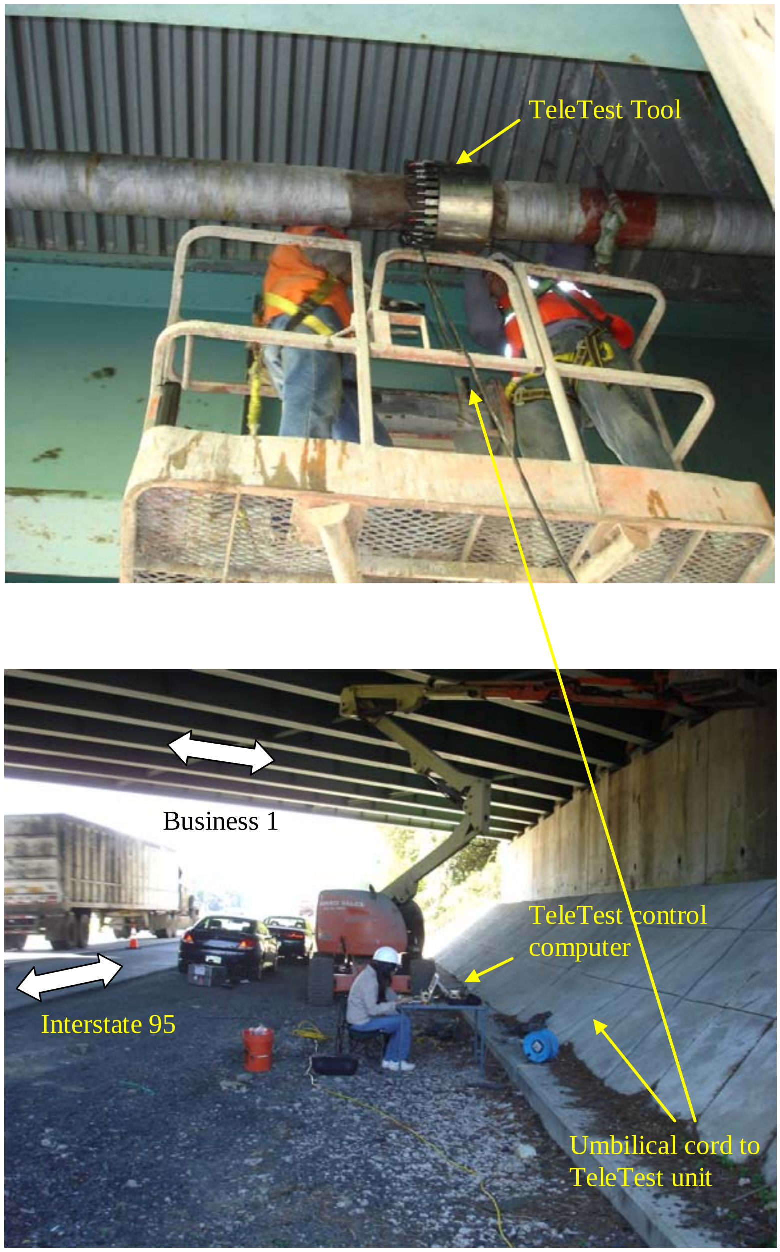


Figure G Test on 8” pipe on bridge over I95, for PECO Energy

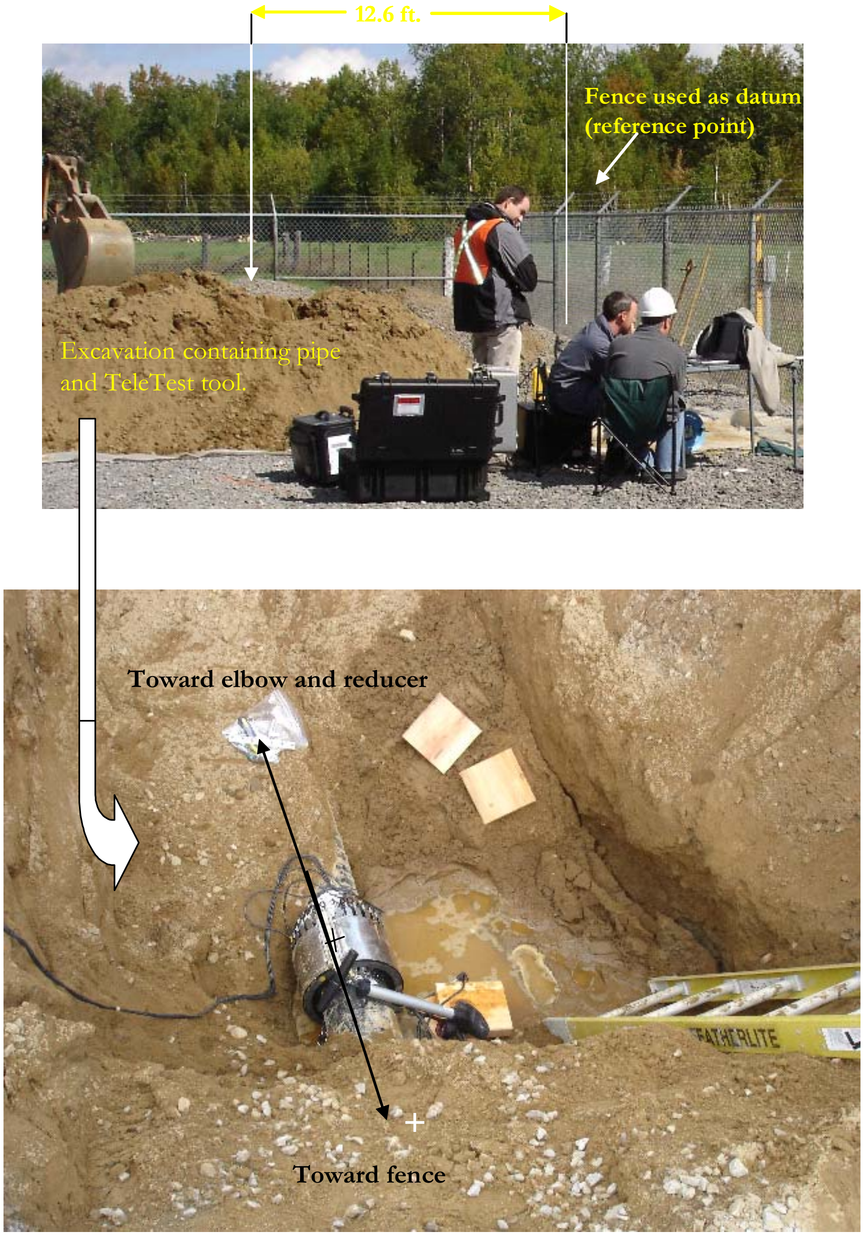


Figure H 8" buried line being examined at Enbridge Gas, Ottawa

Figure I 30" tape coated gas line at Garden City NY. The 8" electrical cable conduit in the foreground was also examined

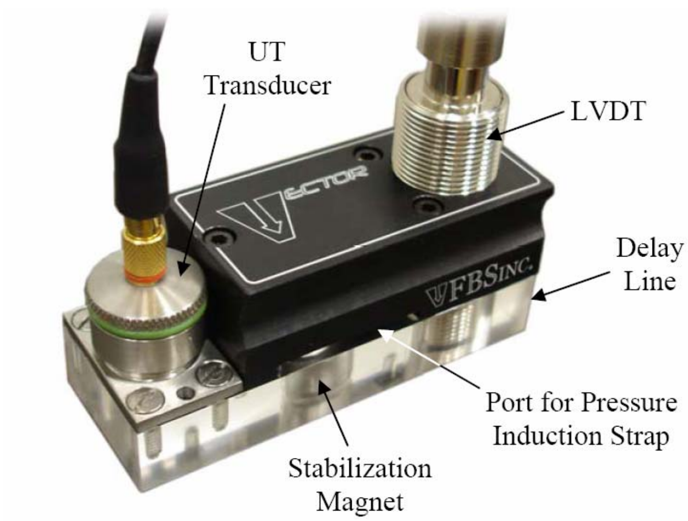


Figure J   The 'Vector' tool for in-situ determination of coating properties

Another example is the effect of different coating types on the attenuation characteristics of the coated pipes. Table 2 shows the relationships between coating type, frequency and attenuation, and the effective test range if a loss of 50dB can be tolerated along the test length.

Table 2 Effect of 3mm (0.120”) thick coatings on attenuation with frequency

Material	Frequency	Attenuation constant α	Attenuation (dB/m)	Propagation Distance with 50 dB attenuation, m (ft)
Mereco 303 Epoxy	30 kHz	0.008	0.07	714 (2,342)
	50 kHz	0.0794	0.69	72.5 (238)
	100 kHz	0.144	1.25	40.0 (131)
Bitumastic 50 Coating	30 kHz	0.118	1.03	48.0 (157)
	50 kHz	0.739	6.42	7.9 (62)
	100 kHz	0.511	4.44	11.3 (37)

It is evident from the table that frequency is a vital parameter in determining the test range possible.

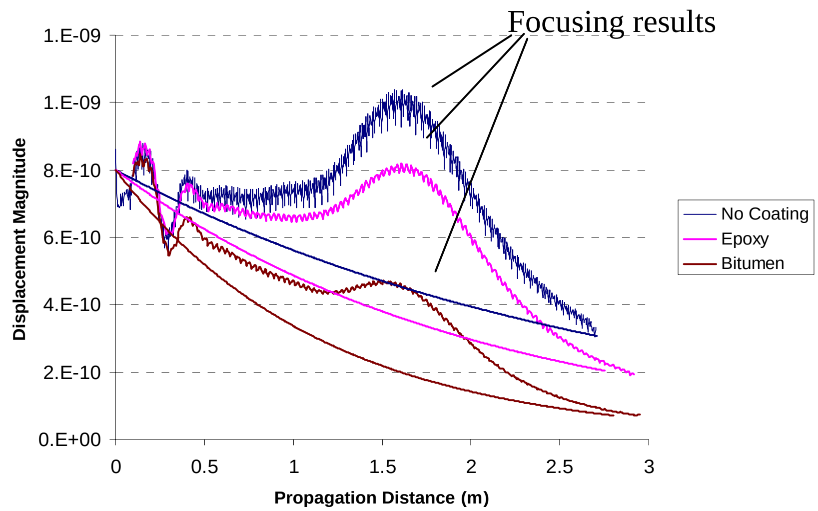


Figure K Angular profile for the 100 kHz L(0, 2) wave with axisymmetric and phased array loading, for no coating, 3 mm epoxy and 3 mm bitumen. Note that focusing increase the magnitude significantly at the focal point.

There is considerable laboratory evidence that focusing the ultrasound can offset some of the attenuating effects of the coatings. Figure K shows the effect of focusing the ultrasound on the decrease in signal amplitude with distance and how a local focus can increase the amplitude.

These examples seek to show the general nature of the effects of coatings on the tests. Specific cases will differ from one another and it is necessary to assess each case on its merits. Tools such as the Vector™ are important in determining local coating properties in order to assess the influence on the test.

6.1.2.1 FBS Modeling of Coatings and Parametric Studies

Models of coatings representative of those on the chart in Figure L were developed. These models were used to parametrically study the effects of coating properties on guided wave propagation and on guided wave focusing.

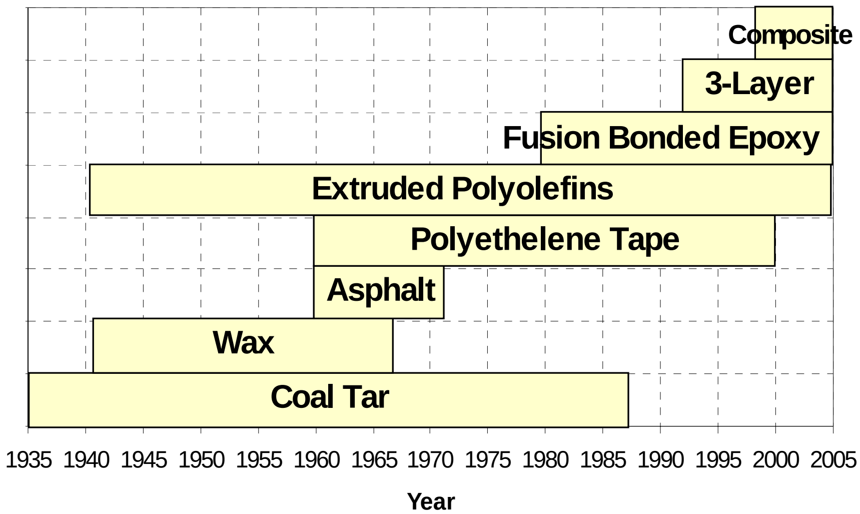


Figure L
Coating usage history of pipeline industry in North America ([2] Papavinasam and Revie)

Mereco 303 Epoxy and Bitumastic 50 were the two coatings that were modeled.

Finite-Element Modeling of Coatings

Figure M shows the finite-element model that was used. The commercial finite-element program ABACUS was the used for the modeling. The thickness was 3 mm for each. Three modes L [0, 1], L [0, 2] and T [0, 1] were evaluated at three frequencies 30 kHz, 50 kHz, and 100 kHz. Coating density, longitudinal attenuation constants, shear attenuation constants, and wave velocity were the parameters that were varied.

Table 2 (above) shows the attenuation results and projected penetration distances (meters) as a function of frequency for the two materials. The 50 dB figure indicates the noise floor and at that level, the signal is no longer useful.

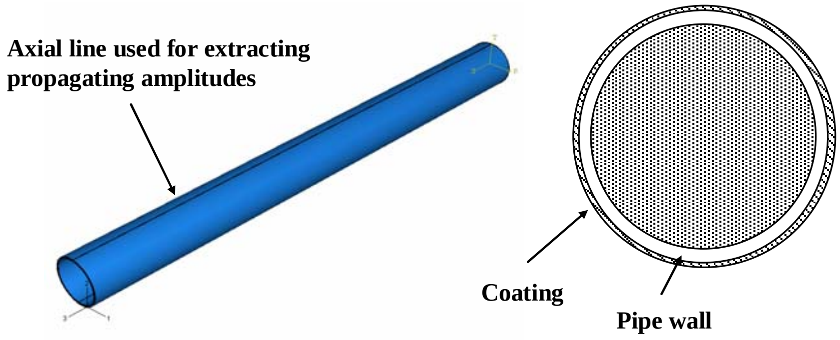
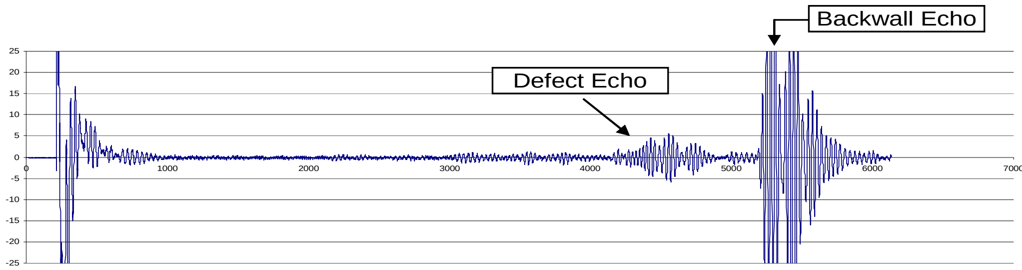


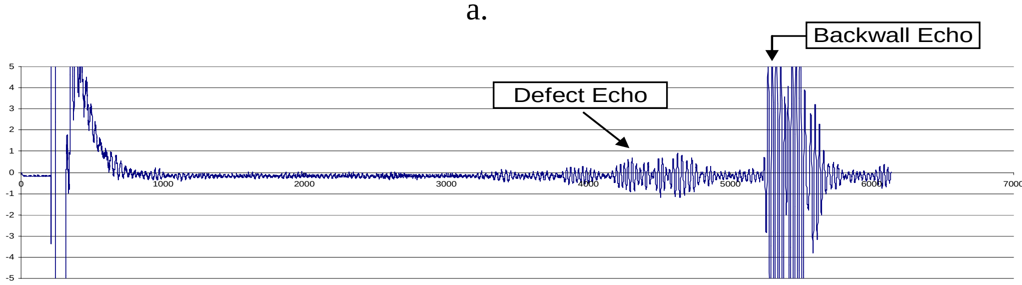
Figure M
Finite-element model used to evaluate coating influences on guided wave propagation and focusing.

For pipes coated with viscoelastic materials, it is important to investigate how a coating effects focusing. Therefore, a finite-element modeling study of phased array focusing was performed for no coating, a 3 mm epoxy coating and a 3 mm bitumen coating. The axi-symmetric profiles are also plotted for comparison purpose. It is interesting to note that focusing was realized quite well at the expected distance and that the signal magnitudes were increased. As an example, at the focal point, the focused wave amplitude for the pipe coated with bitumen was even higher than the wave amplitude in the bare pipe. About 8 dB of gain (or a factor of approximately 2) can be attributed to focusing.

Experiments were performed on two 16” schedule 30 carbon steel pipes, one coated, the other not. The purpose of the experiments provided verification that focusing can be used with coated pipes. Figure N shows that the focusing in the coated pipe is quite similar to that of the bare pipe.



a.



b.

Figure N
Focusing experiments on (a) a bare pipe and (b) a tar-coated pipe with a 6mm deep, 3.26% CSA, 63% through-wall saw cut in both.

Conclusions from Coating Modeling and Parametric Study

Wave scattering from defects in a pipe was studied with a 3-D finite element model. The results showed that phased array focusing enhances the ability to find non-planar defects as compared to axi-symmetric methods. A two layer 3-D finite element model was also developed to study coating effects on guided wave propagation and on focusing in a coated pipe. The model used measured coating acoustic properties as inputs.

- It is shown that a viscoelastic coating has no effect on focusing capability, although there is an amplitude loss which is dependent on the coating viscosity and frequency.
- Phased array focusing with longitudinal waves often increases the signal energy by 16 dB, indicating a much longer propagation distance and improved defect detection sensitivity.
- Longitudinal waves are recommended over torsional waves when considering the effects of coatings on attenuation

6.2.2 Tests on Operating Pipelines

6.2.2.2 Overall Summary of Field Test Performance

Correlation of the results from the tests on operating pipelines are more difficult to assess, because there is limited scope in most cases for the pipe to be examined by other means to verify the results. However, in all the cases examined the pipeline operator carried out some follow up verification and for each test at least one defect was found where the guided wave tests had reported an indication.

The test for PECO at Pottstown PA reported defects in the cased section. These were proved up by a CCTV inspection inside the casing.

The test for National Grid at Baldwinsville NY identified a defective weld. This was confirmed as the source of a leak in the pipe when it was subsequently extracted from the casing.

The test for PECO at Levittown PA again reported a defect in the cased section, which was found on follow-up.

Initial prove-up by excavation of the 12” line tested at Enbridge Gas, Ottawa did not reveal any indications at the reported location. However, a discrepancy was found in the positioning of the datum points for distance measurement. Once this was corrected, the reported defect was found (Figure O).

Figure O Defect detected by Teletest examination at Enbridge, Ottawa

The test on the 8” electrical cable conduit at Keyspan Energy, Garden City NY identified a defect just inside the casing. This casing was cut back and a defect revealed at the location specified. The test on the 30” high pressure gas pipe proved that the predicted defect area was correct axially to within 1” and the angular orientation (circumferential prediction) was off by 180°.

In the case of the Enbridge tests, validation was made by removing the casing and a direct examination. In the case of the Keyspan test, validation was made using other video inspection techniques and comparing to recent (but previous) inspection pig results. After the initial validation using these tools, since the problem areas were close to the end of the casing, Keyspan also cut back the casing to expose the predicted areas.

While a thorough prove-up of field results on operating pipelines is difficult, the project partners put a great deal of effort into checking out the results obtained within this project and have found a good correlation with defects reported. This, backed up by the performance data from the laboratory and the controlled tests, provides a considerable measure of confidence in the suitability of the technique to meet the needs of the pipeline operators.

7. Review of Findings

The findings of the project may be summarized as follows:

Coatings

The project has:

- Developed visco-elastic coating modeling and analysis procedures,
- Demonstrated that an assessment of coating properties can help in determining optimum test conditions,
- Demonstrated that focusing the ultrasound improves penetration power compared with an axi-symmetric test,

Focusing of Ultrasound

- The characteristics of the focal spot of the ultrasound have been determined and the procedures for implementing them optimized,
- Phased array focusing has been implemented in field equipment and procedures,
- Displays have been improved for presentation of data and ease of user interpretation

Defect Detection

- Detection studies have demonstrated performance in the laboratory and in the field,
- Focusing improves signal to noise ratio, increasing the probability of detection of small defects and decreasing the false alarm rate,
- Circumferential location information allows the development of sizing techniques
- Use of multi-mode procedures, using both longitudinal and torsional waves, increases test performance

To address these factors and to incorporate the above evaluation method, an operational guidelines document has been produced, which gives best practice advice for field testing. The key improvements are:

- The removal of a threshold for reporting indications. Any indication observed must be dealt with within the evaluation process,
- The inclusion of multi-wave mode testing at an increased number of frequencies, which allows better corroboration of the presence of defect indications,
- The requirement to focus the sound energy at the locations where indications have been identified, which both increases the local sensitivity. If there is a defect present, the signal amplitude will increase. This allows the gathering of the important directionality information to give a value for the 'sharpness' of the defect,
- The increase in the training and qualification requirements for testing personnel. With this document, a higher level interpretation training syllabus is being introduced and independent comparisons to ISO 9712 are being established.

The training has been divided into Level 1 and Level 2, the former concentrating on data collection and the latter on interpretation. A pre-requisite for this certification is at least a Level 1 UT certificate from a recognized body.

The Level 1 course enables the candidate to:

- Appreciate the essential characteristics of guided waves and their properties for pipe inspection,
- Operate the *Teletest*® system, including setting up the tool on pipes and using the software,
- Set up appropriate test conditions and collect data in accordance with written procedures,
- Assess the adequacy of the data collected for subsequent interpretation by a level 2 operator,
- Store the test data securely and record essential details of the tests performed,
- Maintain the system in an operational condition,
- Trouble-shoot problems arising in the field,

The Level 2 course enables the candidate to:

- Understand the basic properties of ultrasonic guided waves and their use for non-destructive testing,

– Expand the level of understanding of the practical application of guided wave tests above that in Level 1,
– Use this knowledge to develop techniques for testing specific components,
– Understand the factors affecting the performance of guided wave tests,
– Understand the factors affecting the interpretation of the guided wave signals
– Be able to interpret and report the results of guided wave tests

For both levels, the candidates are examined by a combination of theoretical and practical exercises, including off-line interpretation of data for the Level 2 candidates.

8. Concluding Remarks

The new phased array focusing technology along with frequency scanning has been effectively demonstrated and points toward future successes in long range ultrasonic guided wave inspections of cased pipes.

Major accomplishments are as follows:

1. Improvement in penetration power by a factor of 2 to 4, as compared to axisymmetric scanning, when using focusing

2. Improvement in defect detection of 6 dB or more, as compared to axisymmetric, when using focusing

3. Ability to detect defects completely missed by axisymmetric methods

4. Improvement in defect axial location

5. A bonus capability to estimate the circumferential location of a defect

6. A method for distinguishing spacer belts from welds, defects, and pipe artifacts such as relief valves, instrument lines, etc.

7. Improvement in identifying serious weld defects

8. The capability, in most cases, to test a pipe without removing the coating

9. The special development of a FBS, Inc. tool "VECTOR" to assess a pipe coating and predict inspectability (yes/no) and with (yes), expected penetration

10. Ability to insect a pipe with both exterior and interior coatings

11. Capability to use both longitudinal and torsional modes which can exploit defect and coating sensitivities to mode type

9. Additional Work

While this project has made considerable progress in understanding factors, such as coatings, and their influence on guided wave tests, improving guided wave test capability by using enhanced procedures such as focusing and demonstrating the performance achieved in the field in order to gain the confidence of the pipeline industry in the application of the technique, there remains some critical areas which have not yet been established.

A methodology and field usable techniques for determining the effect of coatings has been established but it has only been assessed for a small number of cases. There needs to be a systematic study of coatings used in the field to establish a predictive method of optimizing the tests.

The spatial information provided by the focusing technique will allow the development of a sizing procedure which will provide pipeline operators with the means of determining pipeline condition required by the relevant codes.

A major issue for the success of guided wave tests is the skill of the test operators, both for gathering good quality data and for the interpretation and reporting of the results. A vital area, now being addressed, is the development of independently assessed training and certification schemes, which will ensure that the test technicians possess the necessary skills and experience to carry out satisfactory tests.

10. References

1. D'Zurko, D., 'Report to DOT/PHMSA Steering Committee on collaborative demonstration of guided wave ultrasonics: Controlled tests and data analysis', NYSEARCH, November 2006.
2. S. Papavinasam and R.W. Revie, "Standards for Pipeline Coatings", Workshop on Advanced Coatings for R&D for Pipelines and Related Facilities, National Institute of Standards and Technology, Garithersburg, MD, June 9-10, 2005.