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Field Demonstration of Innovative Condition Assessment Technologies for Water Mains: Leak Detection and Location

SCIENCE

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FIELD DEMONSTRATION OF INNOVATIVE CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS: LEAK DETECTION AND LOCATION

by

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ABSTRACT

Three leak detection/location technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This activity was part of a series of field demonstrations of innovative leak detection/location and condition assessment technologies sponsored by the U.S. Environmental Protection Agency (EPA). The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research-support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

Leak detection was one part of a comprehensive water pipeline condition assessment demonstration where six inspection companies operated 12 technologies that were at various stages of development and provided different types and levels of leak and/or structural condition data. Technologies were included for wall-thickness screening (i.e., average wall loss over many tens of feet), for detailed mapping of wall thickness, and for leak detection. Both in-line and external inspection technologies were demonstrated. The inspection technologies used visual, mechanical, acoustic, ultrasonic, and electromagnetic methods for acquiring leak and pipe condition data. The inspection results for each technology were compared to the leak rates or dimensions of introduced and naturally occurring anomalies, as well as their location along the pipeline.

This report presents the results from three leak detection technologies: Pressure Pipe Inspection Company's (PPIC's) Sahara®, Pure's SmartBall™, and Echologics' LeakfinderRT. Simulated leaks using calibrated orifices in combination with natural leaks that already existed in the test pipe were used to evaluate the performance of each leak detection system. The natural leaks were used to assess detection and location capabilities, while the calibrated orifices were used to evaluate the leak rate assessment capabilities for each technology. The combination of natural leaks and simulated leaks provided an assessment of the capability of each leak detection system to detect, locate, and prioritize leak rates. Each company provided a written report on the location and general size of natural leaks detected in the test pipe, as well as leak rate estimates for the simulated leaks. Additional results from the acoustic pipe wall assessment, internal inspection and external inspection technologies will also be made available in a companion report.

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EXECUTIVE SUMMARY

The state of the art in condition assessment technologies for water mains is still developing and water utilities are interested in third-party, independent sources of information on the capabilities of innovative inspection technologies. Technology demonstrations with a range of real-life defects and conditions are particularly valuable to water utilities and can play a vital role in accelerating the adoption of appropriate, innovative condition assessment technologies. A field demonstration program was conducted to evaluate condition assessment technologies applicable to the inspection of cast iron water mains. It is critical that utilities have the capability to undertake reliable condition assessment of cast iron pipelines in order to prevent failures and/or premature rehabilitation or replacement.

The main goal of the demonstration program was to acquire a snapshot of the current performance capability and cost of applicable inspection technologies under real-world pipeline conditions so that technology developers, technology vendors, research organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies. As part of this research effort, several emerging and innovative inspection technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This report presents the results from three leak detection technologies including the Pressure Pipe Inspection Company's (PPIC's) Sahara®, Pure's SmartBall™, and Echologics' LeakfinderRT. A companion report discusses the results of the acoustic pipe wall assessment and internal/external inspection demonstrations.

The three leak detection technologies were demonstrated to assess their capabilities to detect, locate, and size leaks on a straight, cement-lined, 24-in. cast iron water main. The test pipe had a burial depth between 3.5 and 6.0 ft and wall thicknesses ranging from 0.68 to 0.78-in., as measured periodically during routine maintenance activities. The test pipe historically operated at pressures between 45 and 50 pounds per square inch (psi), while transmitting 4 to 6 million gallons per day (MGD) of flow. Under the Louisville Water Company's (LWC) Main Replacement and Rehabilitation Program, a portion of 24-in. diameter cast iron transmission water main along Westport Road was scheduled for replacement. LWC agreed to make this portion of the pipe available for field demonstration, as well as provide necessary on-site assistance.

Many aspects of the leak detection technologies were observed and documented over the course of the demonstration. This included documenting the logistical and operational requirements encountered during the demonstration, which are summarized in the report including the number of technicians needed, any need for operator intervention, the number and spacing of pipe contact points, access requirements, and more. This information will help utilities to gauge the feasibility of using these technologies at their site. Sahara® and SmartBall™ require internal pipe access, but are non-disruptive in nature and can be performed while the pipeline is in service. LeakfinderRT does not require internal pipe access, is non-disruptive, and can be performed on a live main with or without flow. While each technology used some form of acoustic listening device, the implementations were quite different:

- PPIC's Sahara® mounted a hydrophone sensor at the end of a cable tether. The hydrophone, which was inserted and pulled through the pipeline using the water flow, provided real-time assessment of leaks. The hydrophone sensor was tracked by an operator from ground level.
- The Pure SmartBall™ sensor and data-recording device were placed within a foam ball. The sensor and ball were inserted in the pipeline and propelled by the water through the pipeline to a downstream extraction point where a net inserted into the pipe caught and removed the unit.

- Echologics LeakfinderRT demonstrated two types of sensors. Pairs of accelerometers were mounted on the outside of the pipe at discrete locations to detect and locate unknown leaks. Then pairs of hydrophones in contact with the water at discrete locations were used to estimate simulated leak rates.

A combination of simulated leaks and natural leaks were used to provide an assessment of the capability of each leak detection system to detect, locate, and quantify leaks.

Simulated leaks were chosen to assess the leak sizing capability of each technology. By using artificial leaks, changes in leak rate could be made by changing one variable (e.g., the leak diameter) enabling the direct correlation of reported leak rates to actual leak rates. The restriction ports used for the simulated leaks ranged in size from 0.25-in. down to a 0.02-in. diameter hole. The simulated leak rates ranged from 0.06 to 8.2 gpm. The test-pipe pressure was monitored and recorded during the demonstration and used in combination with leak calibration curves to estimate the actual leak rate. The results for each technology were compared with the pre-determined leak rates under each test condition to evaluate the vendor reported leak rates.

Sahara® and SmartBall™ were able to detect the smallest single, simulated leaks, which were 0.06 gpm. LeakfinderRT was only capable of locating leaks with a flow rate greater than 0.6 gpm. None of technologies could discern two separate leaks in close proximity (less than 2.7 ft apart) for any of the simulated leak clusters and appear only to report the larger leak rate for the cluster of leaks. The ability to identify whether a signal is from an isolated leak or multiple leaks in close proximity is helpful in judging the general condition of a pipeline. However, it is also important to accurately identify the location and size of the largest leaks for repair purposes. Leaks within a foot or two of each other will likely both be excavated if they are large enough to merit remediation. For this demonstration, the technology was considered to be successful if it detected at least one leak in a cluster of leaks because of their close proximity (with spacing from 0.6 to 2.7 ft).

For the simulated leaks, Sahara® , SmartBall™, and LeakfinderRT were able to find all of the leak clusters and estimate the approximate magnitude of the largest leaks for over half of the leak clusters. The results are summarized as follows:

- Sahara® reported 11 of 19 total simulated leaks, but reported 11 of 11 leak clusters. Within each leak cluster, Sahara® accurately characterized the leak range for 6 of the 11 clusters. For leak sizes that were not accurately characterized, four were off by one size category, while one leak was off by two size categories as defined by the vendor.
- SmartBall™ reported 11 of 19 total simulated leaks, but reported 11 of 11 leak clusters. Within each leak cluster, SmartBall™ accurately characterized the leak range for 7 of the 11 clusters. All four of the leaks not accurately characterized were off by one size category as defined by the vendor.
- LeakfinderRT reported 11 of 19 total simulated leaks and reported 11 of 11 leak clusters. LeakfinderRT accurately characterized the leak range for 8 of the 11 clusters. Three of these eight leak rates were reported as "negligible," meaning either close to, or less than, the 0.6 gpm detection threshold defined during calibration. The three leak rate ranges not accurately characterized differed from the simulated leak rates by approximately one to four gpm.

The natural leaks were used to assess detection and location capabilities. Eight potential leak locations identified by the technology vendors were excavated and examined. During the excavation, the soil was examined for excessive moisture and erosion. When each leak site was fully uncovered, visual assessment was used to determine whether the leak was from a bell-and-spigot joint or the body of the pipe at an anomaly such as corrosion or a crack. After the potential leak sites were uncovered, the pipe was pressurized to qualitatively assess the leak sizes by examining the amount of water leaching/spraying from the pipe. During this process, EPA's contractor was able to definitively confirm naturally occurring leaks in four of the eight locations that were excavated; all occurred at the bell-and-spigot joint. The other four excavation locations could not be examined under pressure because of field conditions, but soil moisture in the vicinity of the reported leak was visually assessed during pipe removal as a possible indication that the test pipe had been leaking.

For the natural leaks, Sahara®, SmartBall™, and LeakfinderRT reported 6, 12, and 3 natural leaks, respectively. Each was able to detect the two largest natural leaks. SmartBall™ reported the most natural leaks, many of which were categorized by them as small (approximately 0.1 to 5.5 gpm), but not all were verified due to time and budget constraints. The results are summarized as follows:

- Sahara® reported six natural leaks in real time. Except for one very small leak at 1,696 ft that was not excavated and therefore could not be verified, the remaining five leaks were directly (leak pinpointed) or indirectly (wet soil in the general vicinity) verified based on visual evidence. However, Sahara® initially missed a small leak at one location. After the leak was verified by EPA's contractor and reported to the vendors, PPIC performed additional post-processing and subsequently reported that they were able to detect this leak.
- For the 12 natural leaks reported by SmartBall™, six were excavated and directly or indirectly verified based on visual evidence; two other reported leaks were excavated, but the existence of small leaks were not conclusive. The remaining four locations were not excavated.
- LeakfinderRT reported the largest verified natural leak at 341.5 ft and another two leaks near 1,912 ft and 1,930 ft, which were also found by Sahara® and SmartBall™. However, it failed to identify natural leaks at bell-and-spigot joints near 53 ft, 195 ft, 556 ft and 640 ft, which were confirmed to exist. It is not clear whether LeakfinderRT would have found these leaks had the larger leaks been repaired and their noise signatures removed.

The cost of inspection is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and number of services requested (some vendors offer multi-service discounts). Based on vendor quotes for inspecting 10,000 ft of 24-in. diameter cast iron pipe along the same route as the demonstration site in Louisville, KY, the cost for a leak detection survey ranges from $2 to $5/ft. The three leak detection platforms that were demonstrated can also be used for pipe wall thickness screening surveys; the cost for both leak detection and pipe wall thickness survey ranges from $2.7 to $9/ft. Cost savings can be achieved when combining the leak detection with pipe wall thickness survey to reduce time, labor, and equipment costs for inspection.

The inspection costs presented above do not include the cost for the water utilities to prepare the line and provide traffic control and other logistical support. This site preparation cost for line modification and field support is highly site-specific. It will depend upon regional costs for construction labor, along with factors such as the access requirements, availability and condition of existing hydrants/valves, length of deployment, days on site, and more. Based on typical construction costs (RSMeans, 2011), it is estimated that the site preparation costs for a leak detection inspection of 10,000 ft, 24-in. diameter cast iron pipe may range in magnitude from $0.12/ft (for traffic control only with use of existing taps) to $0.43/ft (including traffic control, pit excavation, tapping, backfill, and surface restoration).

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APPENDICES

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

ANSI	American National Standards Institute
EPA	United States Environmental Protection Agency
gpm	gallons per minute
GPS	global positioning system
LWC	Louisville Water Company
MGD	million gallons per day
MJ	mechanical joint
MRRP	Main Replacement and Rehabilitation Program
NDT	non-destructive testing
NPT	National Pipe Thread
NRC	National Research Council
NRMRL	National Risk Management Research Laboratory
PPIC	Pressure Pipe Inspection Company
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RF	radio frequency
SBR	SmartBall™ receiver
SOTR	State of the Technology Review
TO	Task Order
WERF	Water Environment Research Foundation

1.0: INTRODUCTION

Three leak detection/location technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. cast iron water main in Louisville, KY. This activity was part of a series of field demonstrations of innovative leak detection/location and condition assessment technologies sponsored by the U.S. Environmental Protection Agency (EPA) from July through September 2009. The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research-support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

Leak detection was one part of a comprehensive water pipeline condition assessment demonstration where six inspection companies operated 12 technologies that were at various stages of development and provided different types and levels of leak and/or structural condition data. Technologies were included for wall-thickness screening (i.e., average wall loss over many tens of feet), for detailed mapping of wall thickness, and for leak detection. Both in-line and external inspection technologies were demonstrated. The inspection technologies used visual, mechanical, acoustic, ultrasonic, and electromagnetic methods for acquiring leak and pipe condition data. The inspection results for each technology were compared to the leak rates or dimensions of introduced and naturally occurring anomalies, as well as their location along the pipeline.

This report presents the results from three leak detection technologies, i.e., Pressure Pipe Inspection Company's (PPIC's) Sahara®, Pure's SmartBall™, and Echologics' LeakfinderRT[1]. For all of the technologies evaluated in this demonstration, the leak detection methods are the most mature and therefore are somewhat less novel in their approach than the newer condition assessment techniques (e.g., pipe wall metal loss). However, each of the leak detection/location technology platforms presented in this report is also being explored as a screening tool for detection of pipe wall metal loss. These technology implementations were also demonstrated, but are discussed in a separate report.

1.1 Background

To gain a better understanding of the available technologies for condition assessment of water mains, a Technology Forum was held on September 9 and 10, 2008, in Edison, NJ under Task Order (TO) 62. The Forum indicated that the state of the art in condition assessment technologies is still developing and that water utilities could benefit from third-party, independent sources of information on the capabilities of innovative inspection technologies. Technology demonstrations on real systems are particularly valued by water utilities and can play a vital role in accelerating the adoption of appropriate, innovative condition assessment technologies. A range of real-life defects and conditions should be present when undertaking these types of demonstrations to maximize the benefit to utilities.

After participating in the Forum, the Louisville Water Company (LWC) offered an approximately 2,500-ft-long, 24-in. diameter, cement-lined, cast iron pipe for field demonstrations of water main inspection technologies. LWC treats 135 million gallons per day (MGD) of water and transmits water to 270,000 service taps through 3,500 miles of water main ranging from 1 to 60-in. in diameter. Under its Main Replacement and Rehabilitation Program (MRRP), the company annually replaces over 35 miles of water mains to maintain the water transmission system. As part of this program, the 2,500-ft portion of 24-in. diameter cast iron transmission water main along Westport Road was scheduled for replacement in

[1] Since the time of the demonstration in July 2009, the Pressure Pipe Inspection Company (PPIC) was acquired by Pure Technologies Ltd., and Echologics Engineering, Inc. was acquired by Mueller Water Products.

September 2009. LWC agreed to make this portion of the pipe available for field demonstration, as well as provide necessary on-site assistance.

The field demonstration occurred between July 6 and September 4, 2009. This field demonstration program presented an opportunity to (1) apply inspection technologies under nearly normal operating conditions; (2) thoroughly compare measurements of parameters via non-destructive testing (NDT) with direct measurements of those same parameters; and (3) remove sections of the pipe for comparative testing at a later date with other technologies.

Cast iron pipe is the oldest and largest part of the water network. It is critical that utilities have the capability to undertake reliable condition assessment of cast iron pipes to prevent failures and premature rehabilitation or replacement. Innovative technologies are available for condition assessment of cast iron mains, but only limited third-party performance and cost data are available, which inhibits their effective consideration by the user community.

The suite of technologies considered for demonstration was based on a state of the technology review report prepared under TO 62 on inspection technologies of water mains for ferrous pipes (Thomson and Wang, 2009) and Forum input. Consistent with the focus of the state of the technology review and the Forum, only leak detection/location and structural condition assessment technologies for ferrous pipes were considered for the field demonstrations. Six vendors providing 12 different technologies including leak detection/location and condition assessment technologies (both internal and external) agreed to participate in the field demonstration program with substantial in-kind support.

The EPA contractor, in coordination with the leak detection technology vendors and the LWC, was responsible for the planning, coordination, oversight, and execution of this field demonstration project. The major tasks associated with the field demonstration project are described below:

- ***Task 6.1: Pre-Demonstration Activities***. Pre-demonstration activities included planning and coordination of project activities among EPA, LWC, and participating technology vendors; preparation of a Quality Assurance Project Plan (QAPP); development of test protocols (with vendor input); and communication of project schedules and testing requirements to all project participants.
- ***Task 6.2: Field Demonstration***. EPA's contractor coordinated with the participating vendors and LWC for all on-site demonstration activities, communicated safety requirements, planned/adjusted test schedules, monitored test progress, and documented field observations. In performing the field demonstration, the technical and quality assurance/quality control (QA/QC) procedures were followed as specified in the EPA-endorsed QAPP.
- ***Task 6.3: Post-Demonstration Evaluation and Reporting***. This task included the preparation of technical reports and photo documentation in order to summarize the results of the field demonstration.

1.2 Project Objectives

The main goal of the demonstrations was to acquire a snapshot of the current performance capability and cost of these innovative technologies under real-world pipeline conditions so that technology developers, technology vendors, research-support organizations, and the user community can make more informed decisions about the strengths, weaknesses, and need for further advancement of these technologies.

The ultimate desired outcome from these demonstrations is to detect problems in large diameter, cast iron water mains prior to their failure, as well as to reduce premature replacement of sound buried water infrastructure. These outcomes are expected to arise from improved decision making regarding location, time, and types of water main inspection, maintenance, and renewal activities. Improved asset management decision making is expected to occur due to expanded and accelerated acceptance and use of effective condition assessment devices, systems, and procedures and better decisions regarding development and use of innovative condition assessment devices, systems, and procedures. This field demonstration program directly supports the goals of EPA's Sustainable Water Infrastructure Initiative and National Risk Management Research Laboratory's (NRMRL's) Aging Water Infrastructure Research Program.

1.3 Organization of Reports

This report is divided into four main sections that include introductory material (Section 1.0), summary and conclusions from the results of the field demonstration (Section 2.0), description of the materials and methods used to manage the field demonstration (Section 3.0), and discussion of results provided by each technology vendor (Section 4.0). This report covers leak detection and location. A companion report discusses the results of the acoustic pipe wall assessment and internal/external inspection demonstrations.

2.0: SUMMARY AND CONCLUSIONS

The PPIC Sahara®, Pure SmartBall™, and Echologics LeakfinderRT leak detection, location, and sizing technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a straight, cement-lined, 24-in. diameter cast iron water main in Louisville, KY. The test pipe had a burial depth between 3.5 and 6.0 ft and wall thicknesses ranging from 0.68 to 0.78-in., as measured periodically during routine maintenance activities. The test pipe typically operated at pressures between 45 and 50 pounds per square inch (psi) while transmitting 4 to 6 MGD of flow. A closed-circuit television video inspection of the entire test pipe indicated that the cement liner was uniform and no through-wall anomalies were detected in the pipe wall.

While each technology used some form of acoustic listening device, the implementations were quite different:

- PPIC's Sahara® mounted a hydrophone sensor at the end of a cable tether. The hydrophone, which was inserted and pulled through the pipeline using the water flow, provided real-time assessment of leaks. The hydrophone sensor was also tracked by an operator from ground level and leaks were marked on the pavement.
- The Pure SmartBall™ sensor and data-recording device were placed within a foam ball. The sensor and ball were inserted in the pipeline and propelled by the water through the pipeline to a downstream extraction point where a net inserted into the pipe caught and removed the unit.
- Echologics LeakfinderRT demonstrated two types of sensors. Pairs of accelerometers were mounted on the outside of the pipe at discrete locations to detect and locate unknown leaks. Then pairs of hydrophones in contact with the water at discrete locations were used to estimate simulated leak rates.

All leak detection systems on the market have the ability to listen for leaks; however, quantifying the leak rate is not as straightforward or as broadly applied. The leak detection technologies selected for the demonstration are all developing innovative, proprietary methods for not only detecting the leak, but also interpreting the acoustic signals to quantify the leak rate.

Quantifying the leak rate in the pipe's natural condition is challenging because the acoustic signal generated by the leak can be greatly affected by the leak size and geometry, internal pipeline pressure, and backpressure created by soil or water outside the pipe. Nature rarely provides a sufficient range of conditions that span the performance parameters to be tested. Furthermore, because excavation would disturb the natural conditions, accurate verification of the leak rate cannot be performed for natural leaks. Therefore, for practical reasons, artificial leaks were chosen to assess the leak sizing capability of each technology. By using artificial leaks, changes in leak rate could be made by changing one variable, the leak diameter, enabling the direct correlation of reported leak rates to actual leak rates. Quantification of artificial leak rates is just one measure of the performance of each leak detection technology. Detection of natural leaks still provides valuable information on a technology's capability to detect and locate leaks as well as its ability to qualitatively assess the leak rate.

Many aspects of the technologies were observed over the course of the demonstration. Table 2-1 provides comparison data for the logistical and operational variables encountered during the demonstration. On-site preliminary reports were provided by all, some instantaneously, with the longest delivery time being the next morning. Preliminary reports were requested within 1 week and final reports within 5 weeks of the demonstration. These vendor reports are an important source of data presented in this summary report and are provided in Appendix A (Sahara®), Appendix B (SmartBall™), and

Appendix C (LeakfinderRT). Users of this report can refer to these Appendices to review the original format and organization of the inspection data as issued by the individual vendors.

Since this demonstration was a snapshot in time, new developments may have taken place since completion of the demonstration. Therefore, the findings in this report may not be wholly representative of the current operational capabilities of the demonstrated technologies. For this reason, the vendors were asked to provide formal comments on the final leak detection report to highlight advancements since completion of the demonstration and/or clarification on what was reported. These comment letters are contained in Appendix D.

Table 2-1. Comparison Data for the Logistical and Operational Variables Associated with the Field Demonstration

Logistical/Operational Variables	PPIC Sahara®	Pure SmartBall™	Echologics LeakfinderRT
Equipment logistics	Dedicated truck	Overnight shipping company	Operator transported two cases
Requires internal pipe access?	Yes	Yes	No (accelerometers) Yes (hydrophones)
Utility preparation	Requires one access point and a controlled flow rate	Requires two access points and a controlled flow rate. Large off takes on the pipe must be closed	Requires two access points, but can be accomplished with hydrants or common pipeline appurtenances
Number of technicians needed for operation	2-3	2	1
Pipe contact points	One; Supplied equipment for LWC could inspect up to 2,500 ft; Sahara® has a 6,000 ft maximum cable length.	Two; Distance depends on flow rate	Two per test; Every 1,000 ft for leak rate; Every 300-400 ft for location/detection and condition assessment [(b)]
Sterilization	Yes	Yes	Yes
Real-time data display	Yes	No	Yes
Leak positioning	Leak position directly known; technician marks leaks at ground level	Post analysis used to locate leaks	Leak position determined analytically
Onsite report	Verbal as leaks were found	Verbal, overnight	Written within 1 hour of test completion
Quick-look report	10 days after left site	7 days after left site	19 days after left site
Final report[(a)]	12 weeks after left site	1 week after left site	7 weeks after left site
Operator intervention	When leak detected, operator moved device back and forth to locate leak	No operator tasks after ball is launched until it is received	Manual setting of filters; automatic detection and location

(a) PPIC provided one combined report for leak detection and condition assessment technologies; Pure provided an individual report for their leak detection technology and one for their pipe wall assessment technology; Echologics provided one combined report for leak detection and wall thickness assessment technologies.

(b) The sensor spacing for locating and detecting leaks was shorter than what is typically used by Echologics so that they could collect data for leak location/detection and pipe condition at the same time. The 300-400 ft spacing was needed to demonstrate their condition assessment technology, which is not part of this report; see Appendix D for additional information.

Simulated leaks using calibrated orifices in combination with natural leaks that already existed in the test pipe were used to evaluate the performance of each leak detection system. The natural leaks were used to assess detection and location capabilities, while the calibrated orifices were used to evaluate the leak rate assessment capabilities for each technology. The combination of natural leaks and simulated leaks provided an assessment of the capability of each leak detection system to detect, locate, and quantify leaks.

Simulated Leaks

A summary of the simulated leak results are provided in Table 2-2. The results for each technology were compared with the pre-determined leak rates under each test condition to evaluate the accuracy of the vendor reported leak rates and locations. The simulated leak rates ranged from 0.06 to 8.2 gpm.

Table 2-2. Summary of Simulated Leak Detection Results by PPIC Sahara®, Pure SmartBall™, and Echologics LeakfinderRT[2]

Demo No.	Pit ID[a]	Corp Valve ID	Dist. (ft)	Simulated Leak Rate (gpm)[e]	Sahara® Leak Rate (gpm)[b]	Sahara® Dist. (ft)[c]	SmartBall™ Leak Rate (gpm)[f]	SmartBall™ Dist. (ft)	LeakfinderRT Leak Rate (gpm)	LeakfinderRT Dist. (ft)
1	Pit 4	CV1	577.4	0.59	Very Small (0 to 1.8)	Pit 4	0.57	579	Negligible	-
	Pit 2	CV3	1,082.2	8.2	Small (1.8 to 18)	Pit 2	8.0	1,080	8.0	1,077.1
2	Pit 4	CV2	578.4	0.06	Very Small (0 to 1.8)	Pit 4	0.3	579	Negligible	-
	Pit 2	CV4	1,082.8	0.15	Very Small (0 to 1.8)	Pit 2	2.8	1,080	Negligible	-
		CV6	1,084.9	0.59						
	Pit 5	CV7	1,583.0	1.1	Large (75 to 128)	Pit 5	15	1,580	5.0 to 8.0	1,580.2
		CV8	1,585.7	8.2						
3	Pit 4	CV1	577.4	1.0	Small (1.8 to 18)	Pit 4	1.8	579	2.0 to 5.0	577.6
		CV2	578.4	2.0						
	Pit 2	CV3	1,082.2	0.14	Small (1.8 to 18)	Pit 2	7.2	1,080	5.0 to 8.0	1,082.2
		CV4	1,082.8	0.57						
		CV6	1,084.9	4.6						
	Pit 5	CV7	1,583.0	7.9	Medium (18 to 75)	Pit 5	30	1,580	5.0 to 8.0	1,578.2
		CV8	1,585.7	0.57						
4	Pit 4	CV1	577.4	0.06	Very Small (0 to 1.8)	Pit 4	4.5	579	0 to 1.0	560.7
		CV2	578.4	4.6						
	Pit 2	CV5	1,084.1	1.0	Small (1.8 to 18)	Pit 2	0.1	1,080	2.5 to 5.0	1,092.6
	Pit 5	CV7	1,583.0	7.9[d]	Medium (18 to 75)	Pit 5	40	1,580	Negligible[d]	-
		CV8	1,585.7	2.0						

(a) See Figure 3-11 for the location of the simulated leak pits along the test pipe.
(b) Sahara® only reported qualitative leak rates. In subsequent correspondence Sahara® provided additional details on the approximate quantitative leak rate which is presented in Table 4-1 of this report. The values in parentheses represent the leak rate range for the specific leak classification defined by Sahara®.
(c) The general procedure for a Sahara® inspection is to track the device with an aboveground sensor and mark the leak location on the pavement. For the demonstration, Sahara® reported the simulated leak location as a pit number marked on the pavement rather than the actual distance.
(d) CV7 was closed for LeakfinderRT demo.

[2] In Table 2-2 the text with a red background signifies leak rate estimates that are off by one or more categories as defined by each individual vendor.

(e) The leak rate values represent the average rate over the entire demonstration. The pipe pressure varied from 50 psi to 58 psi which will slightly impact these leak rates.
(f) The leak size categories defined by SmartBall™ are small (0 to 2 gpm), medium (2 to 10 gpm) and large (>10 gpm). If the predicted leak rate by SmartBall™ was in the same leak category as the actual leak rate they were given credit as accurately sizing the leak cluster.

During each demonstration, the leaks were turned on or off using the corp valve and the leak rate was controlled by the size of the orifice installed in the corp valve. Simulated leaks were placed in three pits (4, 2, and 5). Pit 4 was first, followed by Pits 2 and 5 approximately 500 ft and 1,000 ft downstream of Pit 4, respectively. Within the pits there were two to four corp valve-orifice assemblies for simulating leaks, and these assemblies were axially spaced along the pipeline anywhere from 0.6 to 2.7 ft apart.

In Demo 1, the simulated leak rate was provided to the vendors to use as a calibration point, while the remaining demos were blind, in that the technology had to report both the location and the approximate size of the leaks. LeakfinderRT was able to establish a detection limit of 0.6 gallons per minute (gpm) at a sensor spacing of 1,081 ft in Demo 1. Detection limits were not determined for Sahara® and SmartBall™ , but they were each able to detect the smallest simulated leaks, which had a rate of 0.06 gpm. Each technology conducted four demos following the same test metrics. With extra time available, additional demos were conducted upon vendor's request to gather additional data for technology advancement. These additional tests are not part of the demonstration results evaluation – they were only provided as a courtesy to the vendors.

In general, Sahara® and SmartBall™ were able to find the general location of all simulated leak clusters[3]. Sahara® and SmartBall™ were able to detect the smallest single, simulated leaks, which were 0.06 gpm. LeakfinderRT located and estimated flow rates for simulated leaks with a flow rate greater than 0.6 gpm; leaks with flow rates <0.6 gpm were reported as "negligible."

- Sahara® reported 11 of 19 total simulated leaks, but reported 11 of 11 leak clusters. Within each leak cluster, Sahara® accurately characterized the leak range for 6 of the 11 clusters. For leak sizes that were not accurately characterized, 4 of 5 were off by one size category, while the leak in Demo 2, Pit 5 was off by two size categories. The location accuracy could not be evaluated as Sahara® only reported the pit number in which they found the leak.
- SmartBall™ reported 11 of 19 total simulated leaks, but reported 11 of 11 leak clusters. Within each leak cluster, SmartBall™ accurately characterized the leak rate range for 7 of the 11 clusters. All four of the leak rates not accurately characterized were off by one size category. The location accuracy could not be evaluated as SmartBall™ only reported the location of the pit and not where the actual leaks were located.
- LeakfinderRT reported 11 of 19 total simulated leaks and reported 11 of 11 leak clusters. Within each leak cluster, LeakfinderRT accurately characterized the leak range for 8 of the 11 clusters. Three of these eight leak rates were reported as "negligible," meaning either close to, or less than, the 0.6 gpm detectdion threshold defined by LeakfinderRT during calibration. The other three leak rates not accurately characterized differed from the simulated leak rates by approximately 1 to 4 gpm. The location accuracy was within 0 to 5 ft of the actual leak location except for Demo 4 where the distances were off by a maximum of 17 ft.

[3] A cluster of leaks is defined as 1 to 3 leaks within the same demonstration pit (less than 2.7 ft apart).

None of the technologies was able to discern two separate leaks in close proximity (less than 2.7 ft apart) for any of the simulated leak clusters and appear only to report the larger leak rate for the cluster of leaks. The ability to identify whether a signal is from an isolated leak or multiple leaks in close proximity is helpful in judging the general condition of a pipeline. However, it is also important to accurately identify the location and size of the largest leaks for repair purposes. Leaks within a foot or two of each other will likely both be excavated if they are large enough to merit remediation. For this demonstration, we considered the technology to be successful if it detected at least one leak in a cluster of leaks because of their close proximity and the likelihood that the larger leaks masked detection of the smaller leaks. Sometimes the process calls for making the repair of the leak found (usually the larger) and then returning to sound again in hopes that no leaks are missed. This was not done as part of the test protocol, but could be an area for future research to improve leak discrimination capabilities.

Natural Leaks

Over a dozen naturally occurring leaks were reported by the leak detection technologies and were marked as L1 to L13 on the surface for excavation to verify the leaks (see Table 2-3). Eight of the 13 locations were excavated and examined between August 19 and 24, 2009 for indications of a leak. Upon observation of wet soils at L3, L4, L6, and L7, the pipe was pressurized to visually verify the leak locations and qualitatively estimate the leak rates by examining the amount of water leaching/spraying from the pipe. Leaks L4, L6, and L7 all occurred at the bell-and-spigot joints; leak L3 appeared to originate from a bell-and-spigot joint, but could not be directly pinpointed. It should be noted that none of the reported natural leaks occurred within the regions where the simulated leaks were generated.

The other four excavation locations, i.e., L1, L10, L11, and L12, could not be examined under pressure because the water supply valve broke in the closed position and could not be repaired within the time and budget constraints. As an alternative, soil moisture in the vicinity of the reported leak was visually assessed during pipe removal as a possible indication that the test pipe had been leaking. For L1 and L12, the soil was definitely wetter in the area excavated; however, the actual leak location could not be identified. For L10 and L11, the soil was relatively dry, but could not be used to exclude the possible existence of a very small leak.

- Sahara® reported six natural leaks in real time. Except for one very small leak at 1,696 ft which was not excavated and therefore could not be verified, the remaining five leaks were directly (leak pinpointed) or indirectly (wet soil in the general vicinity) verified based on visual evidence. However, Sahara® initially missed a small leak at L6. After the leak was verified by EPA's contractor and reported to the vendors, PPIC performed additional post-processing and subsequently reported that they were able to detect this leak.
- For the 12 natural leaks reported by SmartBall™, six were excavated and directly or indirectly verified based on visual evidence; two other reported leaks (L10 and L11) were excavated but the existence of small leaks were not conclusive. The remaining four locations were not excavated due to time and budget constraints and therefore could not be verified.
- LeakfinderRT reported the largest verified natural leak at L4 (341.5 ft) and another two leaks near 1,912 ft (L12) and 1,930 ft (L12), which were also found by Sahara® and SmartBall™. However, it failed to identify natural leaks at bell-and-spigot joints near 53 ft, 195 ft, 556 ft and 640 ft (i.e., L1, L3, L6 and L7), which were confirmed to exist. It is not clear whether LeakfinderRT would have found these leaks had the larger leaks been repaired and their noise signatures removed.

Additional measurements were taken for the one natural leak found in Pit L to understand what may have caused the leak. The joint rotation was measured — that is, the angle between the two pipe joints where the leak was found. Researchers at the National Research Council (NRC) of Canada suggested measuring the joint rotation to test a hypothesis that an angle of more than 2° would cause a joint leak and that an angle of more than 5° would crack the bell. While the test pipe was generally level, this leak occurred near a storm sewer. The angle measured was approximately 1.5°, indicating that the bell would not be cracked (as was verified visually) or leaking due to joint rotation. Therefore, the large leak was most likely due to degradation in the leadite seal for the bell-and-spigot joint rather than joint rotation.

Table 2-3. Summary of Natural Leak Detection Results by PPIC Sahara®, Pure SmartBall™, and Echologics LeakfinderRT[4,5]

Location ID	PPIC Sahara®			Pure SmartBall™			Echologics LeakfinderRT			
	ID#	Distance (ft)	Description [(a)]	ID#	Distance (ft)	Description	ID#	Distance (ft)	Description	Visual Verification
L1	1	50	Very small leak (0-1.8 gpm)	1	53	Small leak (~0.15 gpm)	Did not report leak			Verification attempted; soil was wet, but there was a nearby storm sewer at 52 ft; leak not pinpointed, but elevated moisture indicative of leak.
L2	Did not report leak			2	125	Small leak (~0.1 gpm)	Did not report leak			No verification attempted
L3	2	194	Very small leak (0-1.8 gpm)	3	199	Small leak (~0.8 gpm)	Did not report leak			Verification attempted; water in pit near bell-and-spigot joint at ~195 ft; did not pinpoint leak
L4	3	338	Large leak (75-128 gpm)	4	341	Medium leak (~15 gpm)	2a	341.5	~2.5-5.0 gpm	Verification attempted; leak at bell-and-spigot joint ~339 ft
L5	Did not report leak			5	414	Small leak (~0.2 gpm)	Did not report leak			No verification attempted
L6	Initially did not report leak, but found after verification results were provided to PPIC. The leak was masked by an artificial leak at 578 ft.			6	556	Small leak (~1.0 gpm)	Did not report leak			Verification attempted; leak at bell-and-spigot joint at ~556 ft
L7	4	638	Small leak (1.8-18 gpm)	7	641	Small leak (~2.0 gpm)	Did not report leak			Verification attempted; leak at bell-and-spigot joint ~640 ft
L8	Did not report leak			8	966	Small leak (~0.1 gpm)	Did not report leak			No verification attempted (at intersection with St. Matthews)
L9	Did not report leak			9	1,210	Small leak (~1.0 gpm)	Did not report leak			No verification attempted
L13	5	1,696	Very small leak (0-1.8 gpm)	Did not report leak			Did not report leak			No verification attempted
L10	Did not report leak			10	1,724	Small leak (~1.5 gpm)	Did not report leak			Verification attempted, but no wet soil was found at ~1,724 ft; inconclusive[6]
L11	Did not report leak			11	1,809	Small leak (~2.0 gpm)	Did not report leak			Verification attempted, but no wet soil was found at ~1,809 ft; inconclusive[6]
L12	6	1,906	Small leak (1.8-18 gpm)	12	1,930	Small leak (~5.5 gpm)	7c	1,912 1,930	~1.0-2.5 gpm ~1.0-2.5 gpm	Verification attempted; soil was moist at ~1,906 ft or 1,930 ft; leak not pinpointed, but elevated moisture indicative of leak.

(a) Sahara® only reported qualitative leak rates. In subsequent correspondence, Sahara® provided additional details on the approximate quantitative leak rate, which is presented in Table 4-1 of this report. The values in parentheses represent the leak range for the specific leak classification.

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[4] Sahara® also found a large air pocket at 900-ft; this finding is not included in the results as detection of air pockets was not requested or verified.

[5] In Table 2-3, the gray background signifies natural leaks that were verified in the field (by pinpointing leak or elevated moisture), the yellow background signifies leaks that we attempted to verify but could not find any evidence of a leak; the red background signifies false negatives, and the white background signifies leaks found by one or more leak detection technologies, but were not verified in the field.

[6] Inconclusive because the pipe could not be pressurized at the time of excavation (see Section 3.6).

Acoustic Interference

In their most basic form, leak detection technologies work by detecting and analyzing acoustic signals. Unfortunately, there are numerous other causes of acoustic signals that can create problems when interpreting the data for leaks. Pipeline flow conditions, road conditions and traffic, and construction are a few of the sources of unwanted acoustic signals or noise that can affect the results. The propagation of these numerous noise sources in the pipeline is a function of the pipeline geometry. For this demonstration, factors that could have affected the acoustic signal from a leak include:

- Water was diverted to a sanitary sewer though a 12-in. line to create flow during the demonstrations. While the noise was clearly audible, it is not known how much of this noise could be detected in the main pipe.
- One lane of traffic was blocked for the demonstration, but through traffic was still permitted in the other lane.
- Air pockets were observed in the pipeline even though efforts were made to eliminate air from the line.
- Train tracks paralleled the pipe with several trains passing by the demonstration site each day.
- Excavation equipment was being used to lay new water pipe within a mile of the demonstration site.

In addition, the acoustic signal produced by larger leaks could mask the sound generated by the smaller leaks located nearby. In this demonstration, two or more leaks were often in close proximity, which can influence a technology's ability to distinguish separate leaks.

Demonstration Summary

PPIC, Pure, and Echologics demonstrated their technologies to detect, locate, and size leaks on a straight, cement-lined, 24-in. cast iron water main operating nominally at 50 to 58 psig. The capabilities of each technology were demonstrated, with many aspects of the technologies observed over the course of the demonstration. For the simulated leaks, Sahara® and SmartBall™ were able to find all of the leak clusters and estimate the approximate magnitude of the largest leaks for over half of the leak clusters. LeakfinderRT was also able to find all of the simulated leak clusters, but four leak rates were designated as negligible, i.e., less than the detection limit of 0.6 gpm determined during calibration. However, none of the technologies were able to discriminate individual smaller leaks within a leak cluster when the spacing between leaks was anywhere from 0.6 to 2.7 ft. For the natural leaks, Sahara®, SmartBall™, and LeakfinderRT reported 6, 12, and 3 natural leaks, respectively. Each was able to detect the two largest natural leaks. SmartBall™ reported the most natural leaks, many of which were categorized by them as small (approximately 0.1 to 5.5 gpm), but not all were verified due to time and budget constraints.

Each vendor uses different terminology for leak sizes, which makes it difficult to directly compare the results. The demonstration program was set-up to simulate what utilities consider typical leak rates that might warrant inspection yet not so large that they would be found without the need for inspection. Currently, there are no industry guidelines that define what is considered a small, medium, or large leak.

Each technology has its own advantages and limitations, providing utilities with options to choose one that best fits their needs and expectations. Sahara® and SmartBall™ require internal pipe access, but are non-disruptive in nature and can be performed while the pipeline is in service. LeakfinderRT does not require internal pipe access, is non-disruptive, and can be performed on a live main with or without flow (LeakfinderRT was operated under no-flow conditions for this demonstration).

The cost of inspection is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and number of services requested (some vendors offer multi-service discounts). Based on vendor quotes for inspecting 10,000 ft of 24-in. diameter cast iron pipe along the same route as the demonstration site in Louisville, KY, the cost for a leak detection survey ranges from $2 to $5/ft. The three leak detection platforms that were demonstrated can also be used for pipe wall thickness screening surveys; the cost for both leak detection and pipe wall thickness survey ranges from $2.7 to $9/ft. Cost savings can be achieved when combining the leak detection with pipe wall thickness survey to reduce time, labor, and equipment costs for inspection.

The inspection costs presented above do not include the cost for the water utilities to prepare the line and provide traffic control and other logistical support. This site preparation cost for line modification and field support is highly site-specific. It will depend upon regional costs for construction labor, along with factors such as the access requirements, availability and condition of existing hydrants/valves, length of deployment, days on site, and more. Based on typical construction costs (RSMeans, 2011), it is estimated that the site preparation costs for a leak detection inspection of 10,000 ft, 24-in. diameter cast iron pipe may range in magnitude from $0.12/ft (for traffic control only with use of existing taps) to $0.43/ft (including traffic control, pit excavation, tapping, backfill, and surface restoration).

3.0: MATERIALS AND METHODS

3.1 Site Description

3.1.1 Site Location. Louisville is located in the north-central portion of Kentucky, immediately south of Indiana along the Ohio River. Its climate can be described as humid sub-tropical with yearly temperatures ranging from 0°C in January to 25°C in July. The city's estimated population, as of 2006, was just fewer than 600,000; the Louisville Metropolitan Area's population was approximately 1,250,000. Supplied by the Ohio River, the source water is treated and transmitted to service taps by LWC, which was granted a charter from the Kentucky Legislature in 1854. Under this charter, water was first provided to the citizens of Louisville by LWC in 1860. Currently, LWC treats and transmits 135 MGD of water to 270,000 service taps through 3,500 miles of water mains, ranging in diameter from 1 to 60-in. Under its MRRP, the company replaces over 35 miles of pipe every year as either a preventive or reactionary effort to maintain the water transmission and distribution system.

As part of LWC's pipe replacement and rehabilitation program, a 2,500-ft length (2,057-ft were used for the leak detection technologies) of 24-in. diameter pipe that was scheduled for replacement was made available for the demonstrations of inspection and condition assessment technologies. The pipeline right-of-way is in the north lane of Westport Road, from the intersection of Westport Road and Chenoweth Lane, to the intersection of Ridgeway Avenue and Westport Road (see Figure 3-1). At Ridgeway Avenue, the 24-in. diameter line goes under a set of CSX railroad tracks.

3.1.2 Test Pipe Condition. The portion of the 24-in. diameter transmission main along Westport Road between Chenoweth Lane and Ridgeway Avenue was made available for the field demonstration project (referred to herein as "the test pipe"). The test pipe is Class 150 deLavaud spun cast iron that is lined with a factory-installed cement mortar and represents approximately 2,500 ft of transmission line. The test pipe was installed in September 1933 and had a burial depth between 3.5 and 6.0 ft. Wall thicknesses of the pipe range from 0.68 to 0.73-in., as measured periodically during routine maintenance and inspections or during repairs. During a site visit in May 2009, wall thicknesses of pipe samples removed during the installation of a 24-in. by 12-in. tee were measured and ranged from 0.76 to 0.78-in. The test pipe typically operates at pressures between 45 and 50 pounds per square inch (psi) while transmitting 4 to 6 MGD of flow. Table 3-1 summarizes the historical, operational, and environmental characteristics of the test pipe.

In preparation for the new installation and prior to the demonstration, all taps and off takes on the 24-in. diameter test pipe were removed. The test pipe was bypassed and taken offline, but could be filled or drained as needed for each demonstration. During the demonstration, traffic was restricted to a single lane and traffic flow was sporadic. The amount of traffic during a demonstration was not separately measured or recorded.

3.1.3 Leak History. Seven joint leaks and one pipe break have been reported along the test pipe from May 1973 to August 2008; however, no information exists regarding the test pipe leak history prior to 1973. Figure 3-2 shows the location and date of the recorded leaks and breaks: two near the intersection of Ridgeway Avenue and Westport Road on May 22, 1973 and March 2, 1977; three near the intersection of St. Matthews Avenue and Westport Road on December 14, 1995, August 23, 2001, and February 17, 2002; and two near the intersection of Sherrin Avenue and Westport Road on November 18, 1985 and December 27, 2003. All of the seven joint leaks occurred at leadite joints.

Since no evidence of wall loss was noted at the time of the repairs, most of these joint leaks are assumed to have been induced by settling/consolidation of underlying fill material or natural soils or as a result of the freeze/thaw cycle causing differential movement of pipe segments attached to the common joint. The exception to this was the December 14, 1995 joint leak at the intersection of St. Matthews Avenue and Westport Road in which evidence of corrosion was observed.

Table 3-1. Summary of Historical, Operational, and Environmental Characteristics of Test Pipe

Historical	
Pipe Material	Cast iron
Installation Date	09/1933
Pipe Segment Length (ft)	12
Pipe Inner Diameter (in.)	24
Pipe Class	deLavaud Spun Cast; Cement lined; Class 150
Pipe Thickness (in.)	0.68 – 0.78
Approximate Total Pipe Length (ft)	2,000
Burial Depth (ft)	3.5 – 6.0
Pipe Lining	Factory Applied Cement Mortar
Pipe Lining Thickness (in.)	Variable, on the order of 0.25
External Coating	Bitumen paint
Type of Joints	Leadite
Land Use over Main	Residential traffic; bituminous paving
Leak History (recorded)	Eight leaks since 1973 (see Figure 3-2)
Date of First Joint Break (recorded)	05/22/1973
Date of First Pipe Break (recorded)	08/29/2008 (not within 2,057-ft test pipe)
Operational	
Typical Operating Flow (MGD)	4 – 6 • Flow throttled due to concerns of main breaks • Available flow for inspection ranging from 1,400 to 2,800 gpm (or 1 to 2 ft/sec) due to sewer restrictions
Typical Operating Pressure (psi)	45 – 50
Water pH (S.U.)	8.2
Environmental	
Soil Parameters (moisture, pH, resistivity, redox potential, etc.)	No historical data[(a)]
Average Monthly Temperature (°C)	January through December: 0, 2, 8, 14, 19, 23, 25, 24, 21, 14, 8, 3 Minimum – 0 (January) Maximum – 25 (July)

(a) Soil characterization was performed during the demonstration project.

The only recorded pipe break occurred on August 29, 2008, approximately 12 ft north of the centerline of Ridgeway Avenue and 40 ft east of the centerline of Westport Road. The break appears to have occurred near a joint and propagated longitudinally along the pipe (see Figure 3-3), resulting in complete failure. The pipe break was caused by an attempt to operate the line at its full capacity, which indicated that the pipe might have lost part of its original structural integrity due to aging. It should be noted that the location of the pipe break is outside the test area (that is, not strictly part of the test pipe). However, it is noteworthy because of the nature of the break and because it occurred just a few days before the EPA Forum, which prompted LWC to offer the pipe for this demonstration.

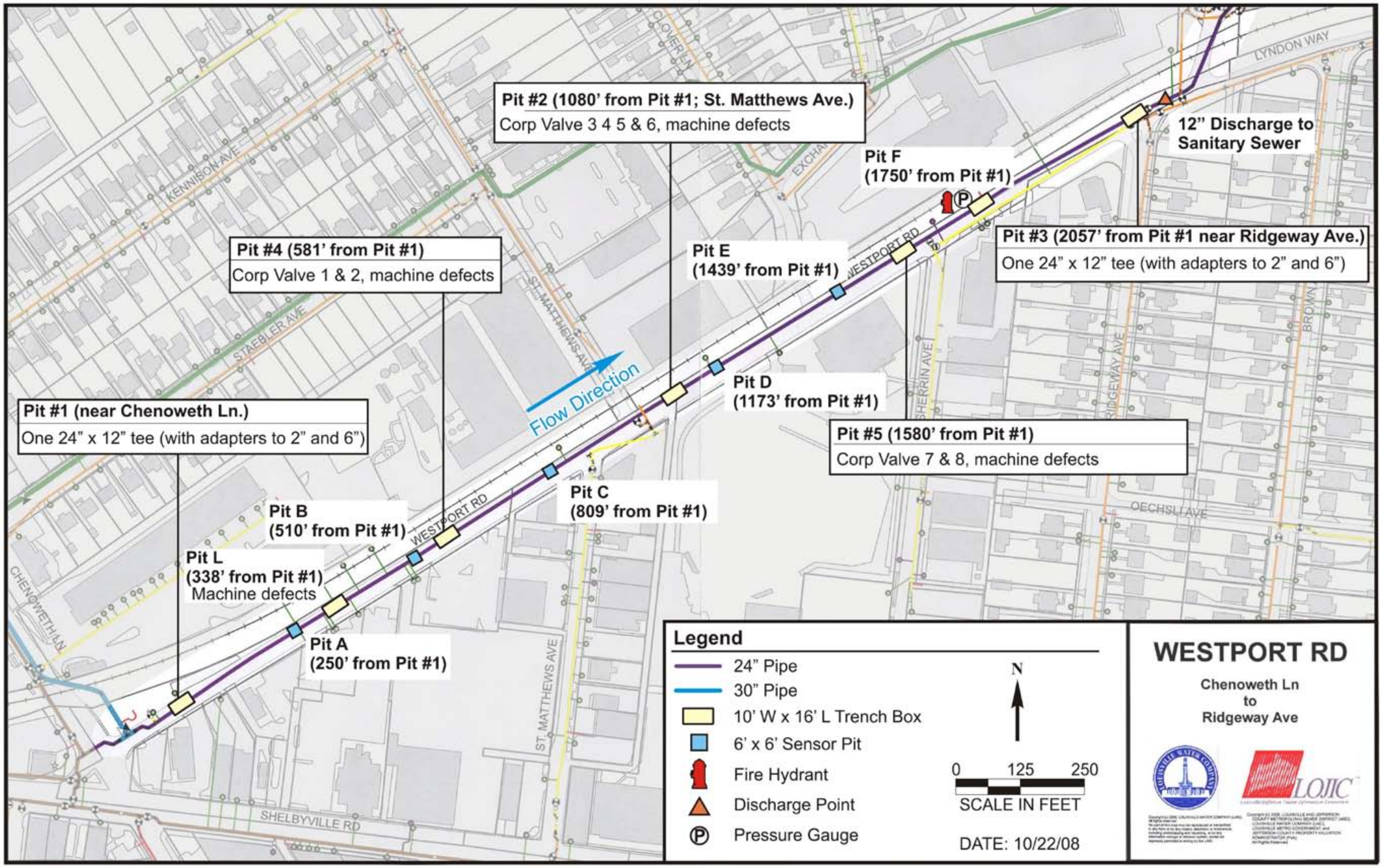

Figure 3-1. Location Map of Westport Road Transmission Main Replacement Project

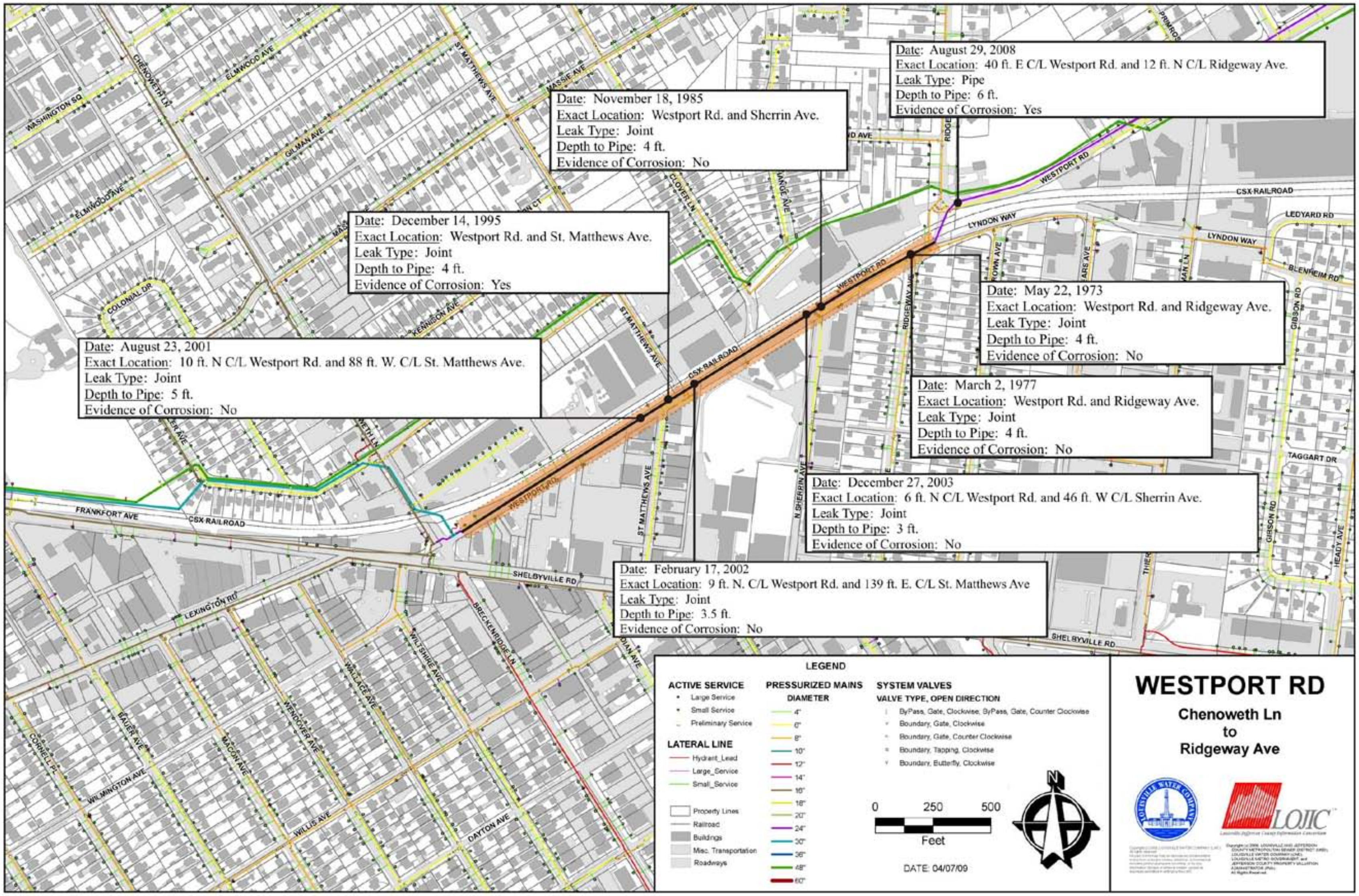

Figure 3-2. Locations and Details of Pipe and Joint Breaks and Leaks

Note: arrow pointing to longitudinal propagation of crack

Figure 3-3. Pipe Break along Westport Road Adjacent to Test Area in August 2008

3.2 Technology/Vendor Selection

The TO 62 State of the Technology Review (SOTR) report (Thomson and Wang, 2009) provides an overview of the state of inspection technologies for ferrous pipes. The technologies selected for demonstration at Louisville, KY were based on the TO 62 SOTR report, feedback from the Technology Forum, and an additional literature search on relevant reports prepared by organizations such as Water Research Foundation (formerly American Water Works Association Research Foundation), Water Environment Research Foundation (WERF), and EPA, as well as vendors' web sites. A list of potential candidate technologies was compiled, which included acoustic-, magnetic-, electromagnetic-, and ultrasonic-based technologies. Technologies that require the removal of coatings and preparation of the pipe surface (such as ultrasonic tools for wall thickness measurement) are well established and were not considered in this field demonstration. Innovative and emerging ultrasonic tools can be demonstrated offsite after the pipe is exhumed.

The candidate technologies were further screened based on (1) suitability of the technologies for the test pipe diameter and material, (2) readiness of the technologies within the field demonstration timeline, and (3) potential to yield useful data for interested utilities. It is also important that the technologies considered not only represent those that are commercially available, but also those that are in the stage of development that could be demonstrated in the field. An added benefit of this demonstration project is to bring new technologies to the forefront of condition assessment research and allow utilities to become familiar with these technologies.

After the technology screening, an e-mail transmittal was sent to prospective vendors in February 2009 to solicit expression of interest. Most vendors responded promptly and expressed their keen interest in participating in the demonstration. Several vendors were eliminated from further consideration due to either lack of interest or financial constraints. Six vendors agreed to participate in and provide partial in-kind contributions to the field demonstration project.

3.3 Technology Description

Various methods are available for detecting and locating leaks within water mains. These methods typically involve acoustic leak detection equipment that 'listens' for the noise created by water escaping a pipe. These devices can include individual fixed listening devices (such as accelerometers) in contact with the pipe, valves and/or hydrants, or mobile/fixed listening devices in the water column (such as hydrophones).

Several factors affect the loudness and frequency range of sounds made by water main leaks, including leak size and shape, pipeline pressure, backpressure at the leak, distance from the noise source or pipe discharge, pipe material and diameter, soil type and compaction, and ground cover. The pipeline diameter was the main factor that limited the number of technologies available for this demonstration. While many fixed leak detection systems are available for small-diameter pipes, only one fixed system and two mobile systems specified functionality for a 24-in. diameter pipeline.

Technology developers are also advancing leak detection technologies to quantify leak rates. The rate at which water leaks from a pipeline depends on the leak size, internal pipeline pressure, and backpressure created by soil or water outside the pipe. All of these factors affect the acoustic signal that is produced by the leak and what is ultimately detected by the leak detection technologies. The leak detection technologies selected for the demonstration are all developing innovative methods for not only detecting the leak, but also interpreting the acoustic signals to quantify the leak rate. The following sections detail the leak detection technologies that were demonstrated at LWC.

3.3.1 PPIC Sahara® Leak Detection. Sahara® is a platform for several inspection techniques that were demonstrated, such as Sahara® Video, Sahara® Leak Detection, and Sahara® Condition Assessment. The Sahara® Leak Detection system is a technology that identifies the location and estimates the magnitude of leaks in large diameter, 12-in. and above, water transmission mains of all material types. This technology works on the principle that leaks cause pressure differential, which makes noise that can be detected. This passive form of leak detection/location uses a 1-in. diameter piezoelectric hydrophone (frequency range of 1 Hz to 170 kHz) tethered to a calibrated umbilical cable (see Figure 3-4). The system is then inserted into a live main through a standard 2-in. tap. The insertion mechanism combines a glanding arrangement to form a seal around the cable, and a retractable guide to protect the cable from damage as it passes into the pipe. A winch and cable drum control the deployment and retrieval of the umbilical, which ensures that the leak sensor can be reliably and consistently removed from the pipeline.

Once inserted, a drogue (parachute) attached in front of the hydrophone captures water flow to control the inspection speed and guide the tool through the pipeline. As the sensor head travels along the pipeline, leak sounds within the pipe are identified and confirmed in real time by the hydrophone in the sensor head and then transmitted through the cable to the processing equipment for interpretation.

During operation, an operator stands by at the controller station to control hydrophone deployment, listen to the hydrophone signal for leaks, and visually monitor the signal using specialized spectrogram software. The initial indication of a leak is audibly detected by the operator and then verified by the spectrogram. Once a leak is detected, the hydrophone can pass over the leak multiple times to classify and pinpoint the leak. At the same time, a second operator travels the pipeline above ground using a tool to detect the exact location of the sensor. When a leak is detected this operator will make a mark on the ground identifying the location and record a global positioning system (GPS) point for reference.

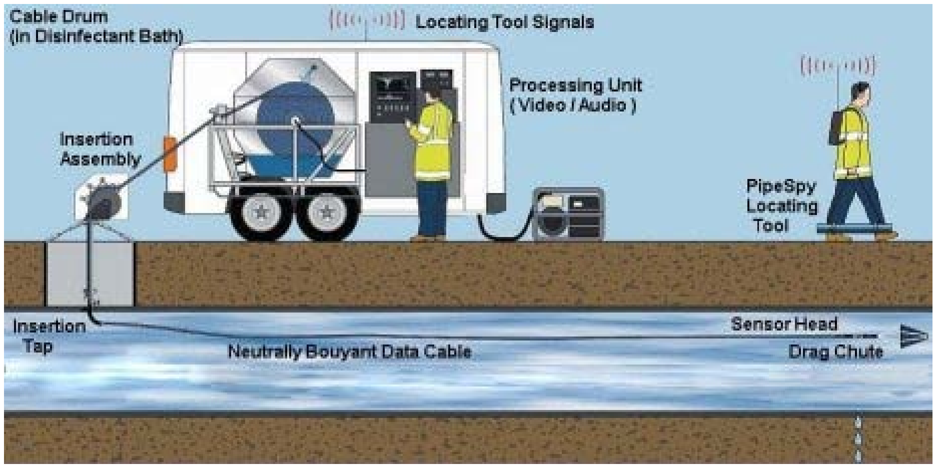

Figure 3-4. Sahara® Inspection System (courtesy of PPIC)

The Sahara® system can provide information on the location and qualitative size estimates of leaks in real time. An electronic processing unit with audio and visual output is used for data analysis. The distinctive acoustic signal produced by a leak is recorded by the sensor and processed into a visual signal. The visual signal is then analyzed, along with the audio signal, to quantify the leak. In no-flow situations, a second tethering line (mule tape) can be used to pull the hydrophone through a pipeline.

The Sahara® survey distance is not only affected by the amount of available cable (usually 1.2 miles [2 km]), but also by factors like the flow velocity, the number and degree of pipeline bends, pipeline diameter, and internal pipe conditions (e.g., butterfly valves). In 2009, the specifications provided for the Sahara® system indicated allowable operating pressures from 7 to 230 psi and flow velocities from 1 to 5 ft/s. In 2010, after the field demonstration, PPIC reported that the Sahara® specification was for an operating pressure range from 5 to 200 psi and a flow rate range from 1 to 12 ft/s (Appendix D). Since the demonstration, PPIC has configured Sahara® to operate from 5 to 200 psi and 1 to 12 ft/s (Appendix D). A typical pressure insertion requires a minimum water flow of 1 ft/s to propel the sensor head and drag the drogue through the pipe. Pipeline pressures above 200 psi may cause deployment difficulties. The Sahara® system is claimed to be capable of locating a leak to less than 1 meter in pipelines that are less than 30-ft deep.

Calibration is performed by testing each hydrophone and comparing it to a standard frequency response. The Sahara® hydrophone has sensitivity to leaks as small as 0.005 gpm (located in 72-in. PCCP at 87 psi). Data are interpreted and analyzed in real time by on-screen spectrogram and audio listening. The Sahara® hydrophone uses dual analysis methods to distinguish leaks from ambient noise. Factors such as low water pressure, electrical noise, air pockets, and external ambient noise can all affect the real-time analysis of the sensor signal. During the demonstration, some leaks were masked by external factors and required post-analysis to detect them. Post analysis methods include filtering noise to improve leak detection.

3.3.2 Pure Technologies SmartBall™. SmartBall™ is an autonomous in-line system that uses acoustic technology to detect and locate leaks and gas pockets in a pipeline. SmartBall™ consists of two primary components: an aluminum alloy core and lightweight foam outer shell. The core is 2.5-in. in diameter and houses the acoustic acquisition device, tracking equipment, data storage equipment, and power supply. The aluminum core is placed within the foam shell (see Figure 3-5) that can vary in diameter depending on the size, operation, and configuration of the pipeline to be surveyed (usually less than one third of the diameter of the pipe). The SmartBall™ system is claimed to be operable for up to 12 hr and is applicable for pipes greater than 4-in. in diameter. While not tested in this demonstration, significant flow in a path different from that heading towards the net can be a problem; off takes with sizes and flows should be reported to field personnel. The potential for the SmartBall™ to be lost exists if the direction of flow suddenly changes or another activity (e.g., high customer use or hydrant flow) diverts the sensor from the planned inspection path.

Figure 3-5. Aluminum Case and Foam Housing for SmartBall™ Acoustic Acquisition Device, Data Storage, and Power Supply

During an inspection, SmartBall™ is inserted into the pipeline through hydrants and any valve configuration with clearance 4-in. diameter or greater using a specialized insertion tube that can be bolted to the appurtenance (see Figure 3-6). Once in the pipeline, the foam shell absorbs water to allow acoustic activity to penetrate the foam for recording by the core. SmartBall™ has negative buoyancy in water which allows the ball to settle on the bottom of the pipe and traverse the pipe by rolling with the flow. As it travels through the pipe, sound from leaks is measured by hydrophone and position data magnetometers feedback position data, which is stored in the ball. Sound pulses transmitted between the ball and external devices (SmartBall™ receiver [SBR]) on the pipe are used to determine the position of the ball. Absolute position reference points obtained from the SBR are applied to time-stamped data to generate a position-versus-time relationship for the entire length of inspection. After the survey, data are downloaded from the ball and analyzed to generate the acoustic information relative to the distance the ball had traveled. SmartBall™ is then retrieved through another 4-in. diameter or greater valve using an extraction tube bolted to the valve, which contains a specialized net that captures the SmartBall™, compresses the foam shell, and removes it from the pipeline (see Figure 3-6).

3.3.3 Echologics LeakfinderRT. Echologics' proprietary leak detection system, LeakfinderRT, uses a patented, cross-correlation technology to passively listen for noise created by a leak in large diameter metal and plastic pipes. The system hardware consists of leak sensors, a wireless signal transmission system, and a personal computer. The system places sensors on two water system fittings -- such as valves, hydrants, or exposed pipe-- that are separated by some distance and that bracket the leak. If a leak is present, the software then uses the difference in leak signal arrival times at the two sensors; the distance between the two sensors; and, the sound velocity in the pipe to identify the leak location. Two types of sensors were used:

- Echologics' proprietary hydrophones for direct measurement of the water column (see Figure 3-7)
- Echologics' piezoelectric accelerometers, with a sensitivity of 1 V/g.

Each sensor has its own specific attributes that make it preferable in certain situations. Echologics reports that the hydrophone is particularly well-suited to measuring asbestos cement and medium- to large-diameter mains (12-in. and larger), since leaks on these pipes generally are dominated by lower-frequency noise (200 Hz and below).

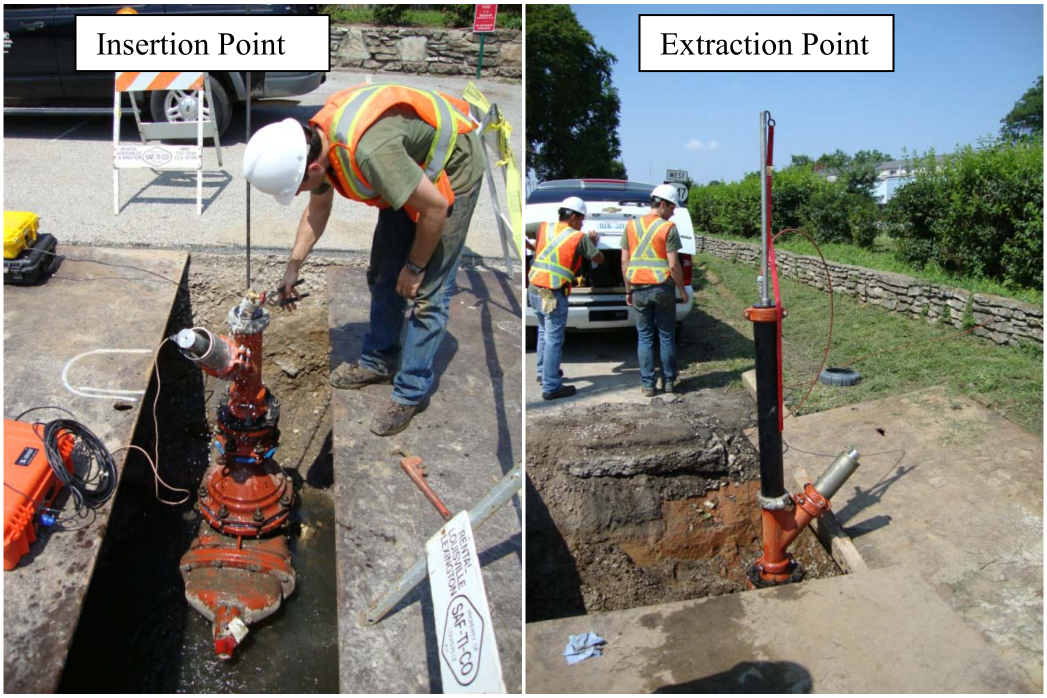

Figure 3-6. SmartBall™ Insertion and Extraction Tubes

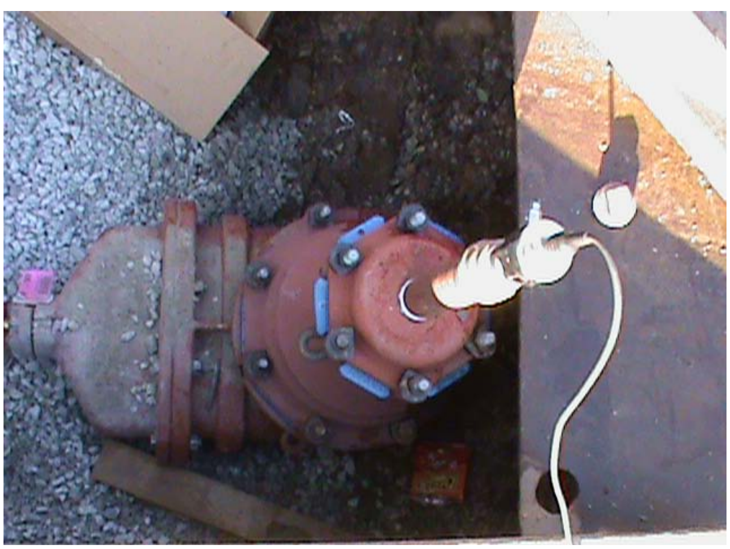

Figure 3-7. Echologics Proprietary Hydrophone Technology

The accelerometers are used to sense leak-induced vibration while hydrophones are used for sensing leak-induced sound. The personal computer calculates the cross-correlation function of the two leak signals to determine the time lag, $\tau_{max,}$ between the two sensors. Then the location of the leak can be derived from Equation 3-1 below:

$$L_1 = \frac{D - c \cdot \tau_{max}}{2} \text{ and } L_2 = D - L_1 \qquad \text{(Equation 3-1)}$$

L_1 and L_2 are the positions of the leak relative to sensors 1 and 2, respectively. *c* is the propagation velocity of sound in the pipe. *D* is the distance between location 1 and 2. Propagation velocity needs to be determined experimentally or is estimated based on the type and size of the pipe.

The LeakfinderRT enhanced cross-correlation function is calculated indirectly in the frequency domain using the inverse Fourier transform of the cross-spectral density function rather than using the shift-and-multiply method in the time domain (Hunaidi et al., 2004). The enhanced correlation function provides improved resolution for narrow-band leak signals. This is very helpful for plastic pipes (low frequency sound emission), small leaks, multiple leaks and situations with high background noise. Moreover, a major advantage of the enhanced function is that it does not require the usual filtering of leak signals to remove interfering noises (Hunaidi et al., 2004). The enhanced correlation function allows for improved detection of leaks over traditional leak detection technologies.

For this demonstration, the hydrophone sensors for detecting and quantifying the simulated leaks were placed about 1,000 ft apart, while the accelerometer sensors for detecting any naturally occurring leaks were placed about 300 ft apart. The signals emitted by the sensors were detected by wireless transmitters (460 MHz or 433 MHz analogue units manufactured by Echologics, as shown in Figure 3-8), which send the signal to a computer to record the data. According to Echologics, the wireless transmitters should be at least 1 ft above ground to eliminate radio frequency (RF) signal interference. The LeakfinderRT software requires pipe material, pipe diameter, and sensor spacing as key input variables. Leak sounds are recorded and correlated by LeakfinderRT for a period of time determined in the field. The cross-correlation results are displayed on screen and continuously updated in real time while leak signals are being recorded.

Any potential leaks will appear as a spike in the cross-correlation plot. The position of the spike on the x-axis corresponds to the time difference it takes for the signal to arrive at the two sensor locations. The position relative to either of the sensors can be computed using the wave velocity for the material under inspection and time difference. Figure 3-9 provides an example of a cross-correlation plot and spike indicating a leak. LeakfinderRT also incorporates an enhanced correlation function, which allows narrow-band leak noise to have more well-defined peaks. This is important when multiple leaks occur, when leak sensors are placed in close proximity to each other, and/or the pipe contains very small leaks.

3.4 Site/Test Preparation

Several activities were necessary prior to, during, and after the field demonstration to accommodate the various technology vendors/visitors and to verify the inspection conditions (leaks). The following sections detail specific measures taken in order to conduct the field demonstration.

Figure 3-8. Wireless Transmitter

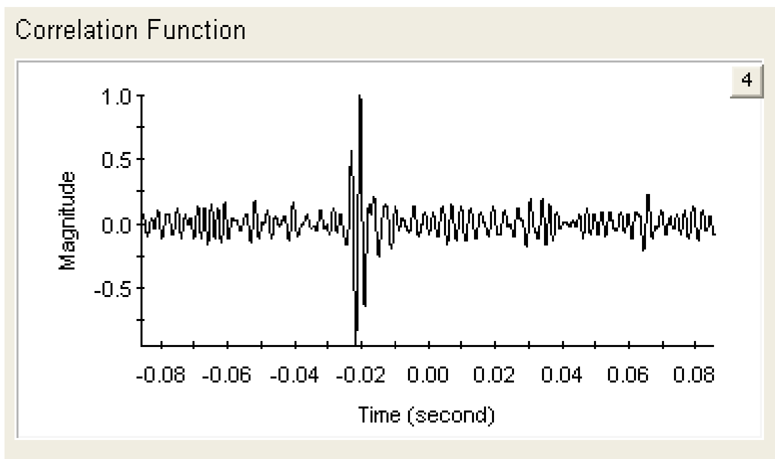

Figure 3-9. Example Cross-Correlation Plot with Spike Indicating a Leak (courtesy of Echologics)

To assess the performance of the leak detection systems, leaks of a known location and size were required. As such, EPA's contractor developed a plan to create simulated leaks, using calibrated orifices in combination with any natural leaks that might already exist in the test pipe. The natural leaks were used for detection and location assessment; however, they could not be used for leak rate assessment, because the leak rate could not be accurately determined once excavated. The combination of natural leaks and simulated leaks enabled an assessment of the capability of each leak detection system to detect, locate, and estimate the flow rate of leaks.

Although it was intended to keep the locations of the simulated leaks hidden, this could not be reasonably accomplished during the demonstration. As discussed in more detail below, large excavations were necessary to install leak taps for 1-in. corporation (commonly referred to as corps or corp valves) valves that would contain the calibrated leak orifices. In addition, each excavation pit had to be open for access during the demonstration to turn the simulated leaks 'on" or 'off." It was not possible to completely hide the location of the simulated leaks because one of the leak detection technology vendors used aboveground tracking devices to mark the location of the leak during the inspection, while the other two vendors routinely walked the length of the test pipe during the demonstration.

Prior to the actual demonstration, the condition of the test pipe was relatively unknown, aside from basic pipeline location data and information obtained during previous leak investigations. In June, the valves at both ends of the 2,057-ft test pipe were closed to evaluate if there was any significant pressure drop in the system. This assessment showed that the line maintained a nominally constant pressure for a full day, so it was quite possible that there were no large natural leaks in the test pipe.

3.4.1 Access Requirements. The internal leak detection/location inspection technologies required only the installation of relatively small taps (2 to 4-in. in diameter) for insertion and extraction. For the in-line inspection technology demonstration, a 12-in. diameter tap and gate valve with a mechanical joint (MJ) fitting were installed at each end of the test pipe for insertion and retrieval of equipment (see companion report on internal inspection tools). Reducers were used to match the leak detection equipment requirements to the 12-in. MJ fitting for launching and receiving the leak detection technologies. For the Sahara® and LeakfinderRT hydrophone technologies, a 12-in. MJ to 6-in. MJ reducer and a 6-in. MJ cap with a 2-in. National Pipe Thread (NPT) tap were used. Echologics supplied an additional 2-in. to 1.5-in. reducer for its equipment. SmartBall™ required either a 4-in. or 6-in. American National Standards Institute (ANSI) flange for a gate valve to launch its equipment. To achieve this setup, a 12-in. MJ to 6-in. MJ reducer and a 6-in. MJ to 6-in. ANSI flange were used because this equipment could be easily provided by LWC. LWC supplied all pipe fittings for the demonstration. Video inspection methods confirmed the pipe did not have any internal obstructions such as tuberculation which may have impeded the application of internal inspection technologies.

Echologics' LeakfinderRT technology uses two sensor types: hydrophones that require direct contact with the water column and accelerometers that are glued to the outside of the pipe. Therefore, two demonstration configurations were needed: (1) direct access to the water in the pipe for placement of hydrophones at approximately 1,000-ft intervals by the access method described in the previous paragraph, and (2) direct access to the pipe exterior for placement of accelerometers at approximately 300-ft intervals. The 300-ft intervals were achieved through five large excavation sites and six smaller excavated holes. A summary of all access requirements is provided in Table 3-2.

3.4.2 Safety, Logistics, Excavation, and Tapping

Safety and Logistics

During the demonstration, MAC Construction (LWC's contractor) was responsible for traffic rerouting and control. All technology demonstrations occurred on weekdays during normal business hours. While the demonstration was ongoing, portions of Westport Road were closed to through traffic, with some access allowed for local businesses. At the end of each day, MAC Construction plated all open excavations to help avoid accidents during the evenings and weekends and reopened both lanes of traffic on Westport Road.

A construction trailer (see Figure 3-10) equipped with electrical power provided a work space for the inspection technology vendors, as well as equipment storage during the demonstration. At least one EPA contractor was onsite each day of the demonstration and coordinated the dissemination of safety and contact information to the technology vendors and visitors. All logistical and operational questions were handled by the EPA contractor in charge. The EPA contractor also coordinated daily activities with the technology vendors, MAC Construction foreman, and LWC inspectors to ensure that the demonstration ran efficiently and effectively.

Several visitors, including representatives of the EPA and utility companies, came to the site during the demonstration. Visitors were instructed to pre-register via e-mail and sign in with the EPA contractor at the construction trailer before going onsite. Safety gear including hard hats, steel-toed shoes and safety vests was required before visitors could gain access to the demonstration site.

Table 3-2. Summary of Test Pipe Access Requirements for LWC Demonstration

Vendor	Type of Inspection	Technology/ Product	Flow Requirements/ Pipeline Constraints	Pipe Access Requirements
The Pressure Pipe Inspection Company (PPIC)	Internal; tethered	Sahara® Leak Detection/Location System	Flow must be >1 ft/s for single 2-in. diameter tap; Mule tape is required in no-flow situations or when flow is insufficient. At lower flows, the parachute is unable to overcome the drag of the cable for a given distance.	One per inspection interval (every 2,500 ft for LWC demonstration; up to 6,000 ft based on Sahara® maximum cable length). A 2-in-diameter (or larger) tap with female NPT thread reducer located at upstream to the section to be inspected; ~10 ft clearance to mount insertion equipment.
Pure Technologies	Internal	SmartBall™ Leak and Gas Pocket Location	Requires appurtenances along pipeline to place receivers Flow range reported at time of demonstration was > ~0.8 ft/s, but < ~1.5 ft/s; Note: Pure reports in Appendix D inspections as low as 0.5 ft/s and as high as 7 ft/s.	Two per inspection interval (at beginning and end of inspection). 4-in. or 6-in. diameter clear bore gate valve. > 8 ft vertical clearance at launch tap and > 12 ft vertical clearance at retrieval tap. Both taps at 12 o'clock position
Echologics Engineering	External	LeakfinderRT	Requires appurtenances and/or pipe access to place sensors Requires air to be removed from the line; no flow requirements (tests conducted without flow)	Two per inspection interval. Hydrophones require direct contact with the water. Accelerometers require solid contact with the pipe exterior. Pipe access every 300 to 2,500 ft

Figure 3-10. Construction Trailer for Equipment Storage and Work Space

Excavation

Five large excavations were provided for the leak detection technologies during the demonstration; these included Pits 1 through 5 as shown in Figure 3-11 and described in Table 3-3. These sites were selected based solely on location along the test pipe. Since the condition of the pipe was initially unknown, EPA's contractor installed eight 1-in. taps in Pit 2 (4 taps), Pit 4 (2 taps), and Pit 5 (2 taps) to ensure that leaks were available for calibration and inspection during the demonstration. An additional six small excavations, identified as Pits A, B, C, D, E, and F in Figure 3-11, were used to demonstrate one leak detection system and several other condition assessment technologies. Pictures of locations for Pits 1, 2, and 3 are shown in Figures 3-12 through 3-14.

Tapping

Several taps were provided for the demonstration, either to facilitate operation of internal assessment tools or to simulate leaks. Pits 1 and 3 each contained a 12-in. diameter tap to install a gate valve for insertion and extraction of internal inspection tools. Several reducers for the 12-in. gate valve were provided to launch PPIC's Sahara® technologies (12-in. × 2-in. reducer), Pure's SmartBall™ system (12-in. × 6-in. reducer), and Echologics' LeakfinderRT (12-in. × 2-in. reducer).

Pits 2, 4, and 5 contained taps into which corp valves were installed to simulate pipeline leaks (see Figure 3-15). Corp valves are 1-in. diameter valves with a ¾-in. internal threaded outlet port. Pit 2 contained four corp valves (labeled CV3, CV4, CV5, and CV6), while Pit 4 and Pit 5 contained two corp valves each (labeled CV1 and CV2; CV7 and CV8, respectively).

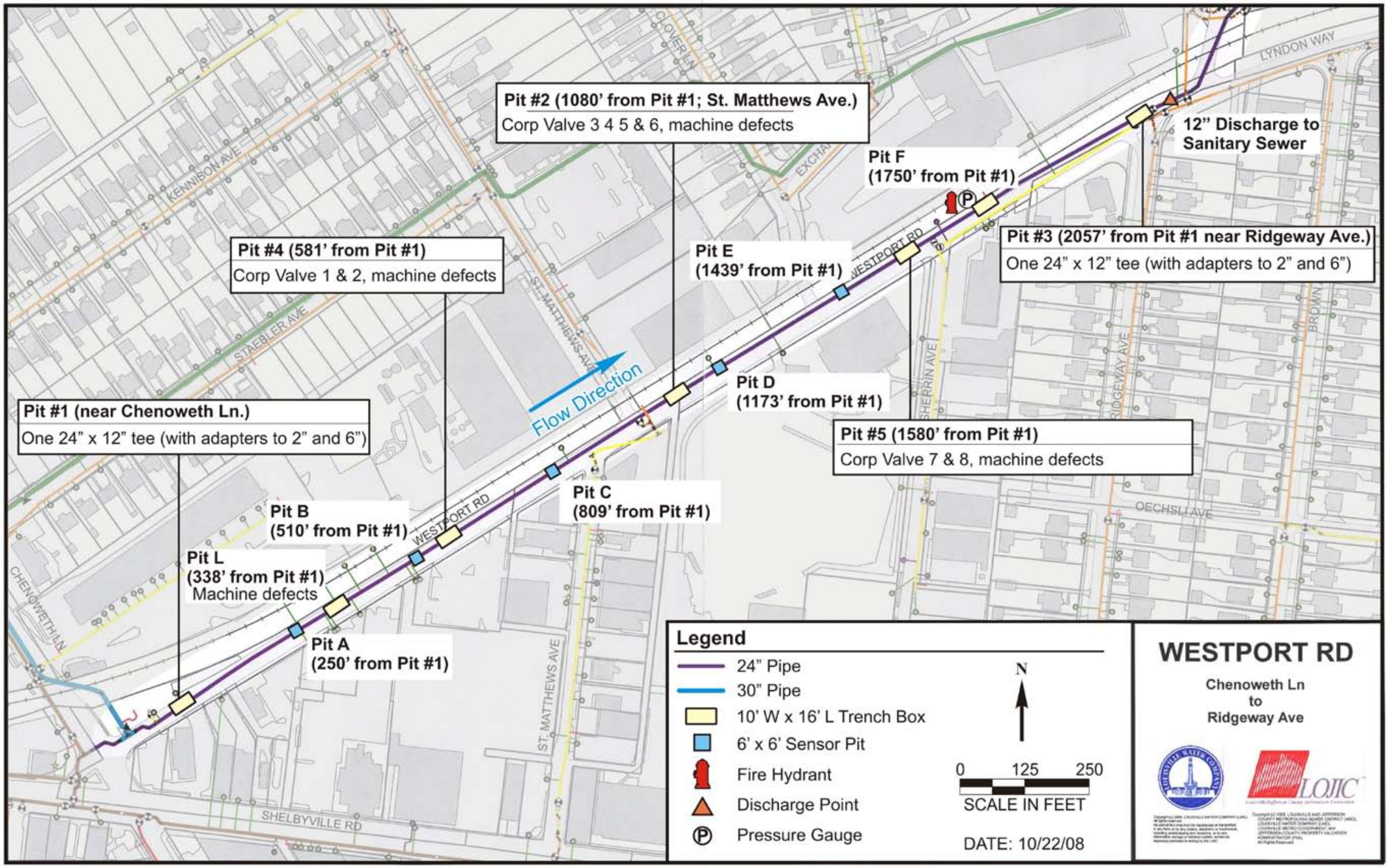

Figure 3-11. Location of Pits for Demonstration

Table 3-3. Summary of Access Pits – Description and Purpose

Pit ID	Description	Purpose
Pit 1	• Near Chenoweth Lane at location of first 24-in. × 12-in. tee • 8 ft of pipe exposed • Reference point – 0 ft	• Launch internal inspection technologies • Install 12-in. service tap (May 2009); attach 12-in. × 2-in. and 12-in. × 6-in. reducers to allow access for internal tools
Pit 2	• Intersection of Westport Road and St. Matthews Avenue • ~1,080 ft from first 24-in. × 12-in. tee in Pit #1 • ~8 ft of pipe exposed; ~2-ft circumferential clearance	• Install four 1-in. service taps for leak simulations • Install two calibration metal loss defects* • Install nine additional metal loss defects for condition assessment*
Pit 3	• Near Ridgeway Ave. at location of second 24-in. × 12-in. tee • ~2,057 ft from first 24-in. × 12-in. tee • 8 ft of pipe exposed	• Retrieve internal inspection technologies • Install 12-in. service tap (May 2009); attach 12-in. × 2-in. and 12-in. × 6-in. reducers to receive internal tools • Install 12-in. tee to divert flow to storm/sanitary sewer
Pit 4	• ~581 ft from first 24-in. × 12-in. tee • 3 ft of pipe exposed; top half only	• Install two, 1-in. service taps for leak simulations • Install pit-like metal-loss defects for condition assessment*
Pit 5	• ~1,580-ft from first 24-in. × 12-in. tee • 3 ft of pipe exposed; top half only	• Install two, 1-in. service taps for leak simulations • Install pit-like metal-loss defects for condition assessment*
Pit A	• ~250 ft from first 24-in. × 12-in. tee in Pit #1 • ~3 ft of pipe exposed; top portion only	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling*
Pit B	• ~510 ft from first 24-in. × 12-in. tee in Pit #1 • ~3 ft of pipe exposed; top portion only	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling*
Pit C	• ~809 ft from first 24-in. × 12-in. tee in Pit #1 • ~3 ft of pipe exposed; top portion only	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling*
Pit D	• ~1,173 ft from first 24-in. × 12-in. tee in Pit #1 • ~3 ft of pipe exposed; top portion only	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling*
Pit E	• ~1,439 ft from first 24-in. × 12-in. tee in Pit #1 • ~3 ft of pipe exposed; top portion only	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling*
Pit F	• ~1,750 ft from first 24-in. × 12-in. tee in Pit #1 • ~20 ft of pipe exposed; ~2-ft circumferential clearance	• Small excavation for LeakfinderRT, keyhole condition assessment technologies and soil sampling; significant graphitization was found when excavated* • Install one large calibration defect (metal-loss defect ~ 6 1/8 in long; 0.28 to 0.45 in depth)*

* These pits were created for demonstration of condition assessment technologies, but were also used to demonstrate the external leak detection technology (LeakfinderRT).

Figure 3-12. Location of Pit 1 – Near Chenoweth Lane

Figure 3-13. Location of Pit 2 – Near St. Matthews Ave.

Figure 3-14. Approximate Location of Pit 3 – Near Ridgeway Ave.

Figure 3-15. 1-in. Corporation Valve with ¾-in Threaded Plug with Leak Orifice

The positioning of the corp valves was based on access restrictions within each pit (location of bell-and-spigot joints for longitudinal placement and trench boxes for clock position). The manner in which the trench boxes were placed in Pit 2 and Pit 4 to avoid a parallel fiber optic communication conduit and other buried utilities only allowed taps for the corp valves to be drilled on one side of the pipe. In addition, the length of the arm on the mechanical tap did not allow for a majority of the taps to be installed at 270°, which was originally planned. Therefore, the orientation of the corp valves was placed as close to 270° as practically possible. In Pit 5, it was possible to install one tap on each side of the pipe at orientations of 45° and 315° from the top of the pipe. The location and orientation of the corp valves in each pit is provided in Table 3-4.

Table 3-4. Summary of Corp Valve Locations and Orientations

Corp Valve ID	Pit ID	Distance (ft)	Approx. Orientation (degrees)*
CV1	Pit 4	577.4	315
CV2		578.4	315
CV3	Pit 2	1,082.2	315
CV4		1,082.8	270
CV5		1,084.1	315
CV6		1,084.9	320
CV7	Pit 5	1,583.0	45
CV8		1,585.7	315

* Counter-clockwise from the direction of flow.

The corp valves in all three pits were used in conjunction with various ¾-in. restriction ports, with drilled holes of various sizes inserted into the valve outlet to simulate a range of leak sizes during the demonstration (see Section 3.4.3 for details). The corp valve locations for the leak simulations are shown in Figures 3-16 through 3-18.

The two 12-in. taps for launching and receiving the internal inspection technologies were installed in May 2009. The 1-in. corp valves were installed in June 2009 prior to commencement of the field demonstration. The restriction ports were also fabricated and tested several weeks prior to the field demonstration.

Generating Flow

While some of the inspection technologies require flow to detect and locate leaks, the test pipe was no longer supplying water to customers in anticipation of the pending replacement project. Therefore, to create flow during the demonstration, water was supplied to the test pipe through a valve near Chenoweth Lane connected to a 30-in. diameter line with a pumping station within a mile. At the end of the test pipe, the flow was diverted to the sanitary sewer through a 12-in. gate valve and polyvinyl chloride (PVC) line located downstream of Pit 3 (see Figure 3-19).

There were two drawbacks to this arrangement. First, the discharge was essentially a very large leak that created noise during the demonstration and interfered with the acoustic sensors; the effects of which became more pronounced as technologies neared the discharge point. Second, because the discharge was diverted to the storm sewer, it could not be used immediately after heavy rainfall to prevent sewers from overflowing. Rain delayed several of the demonstrations with a record rainfall of 6.5-in. on August 4, 2009, causing a 2 ½-day delay.

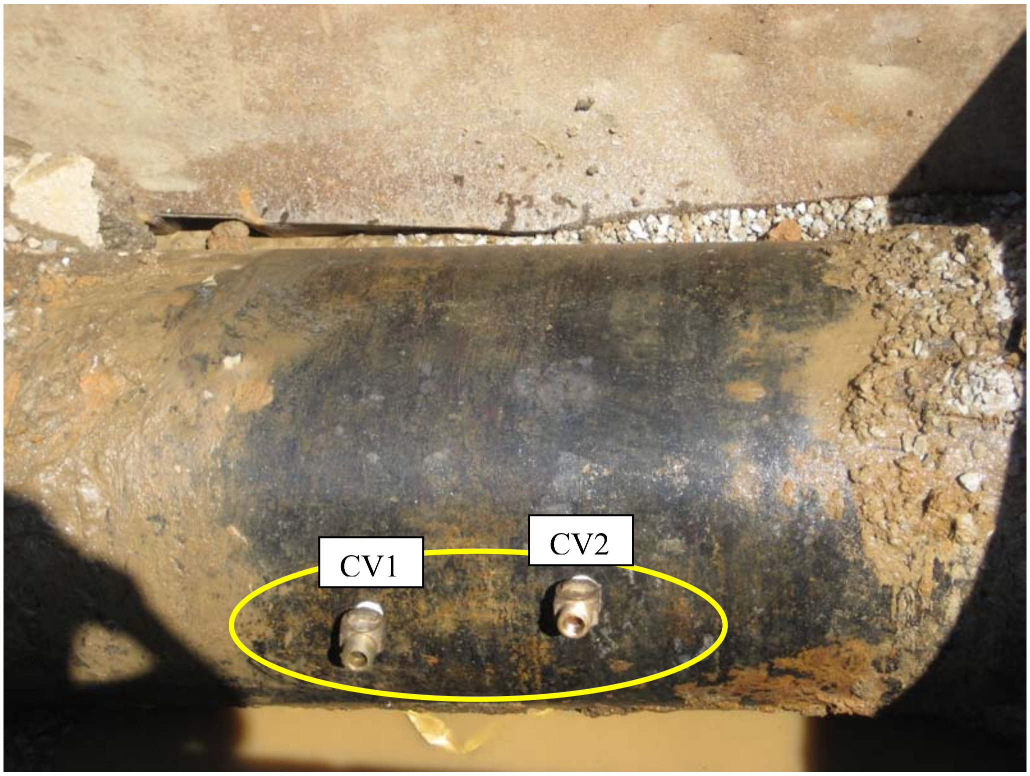

Figure 3-16. Tap Locations in Pit 4

Figure 3-17. Tap Locations in Pit 2

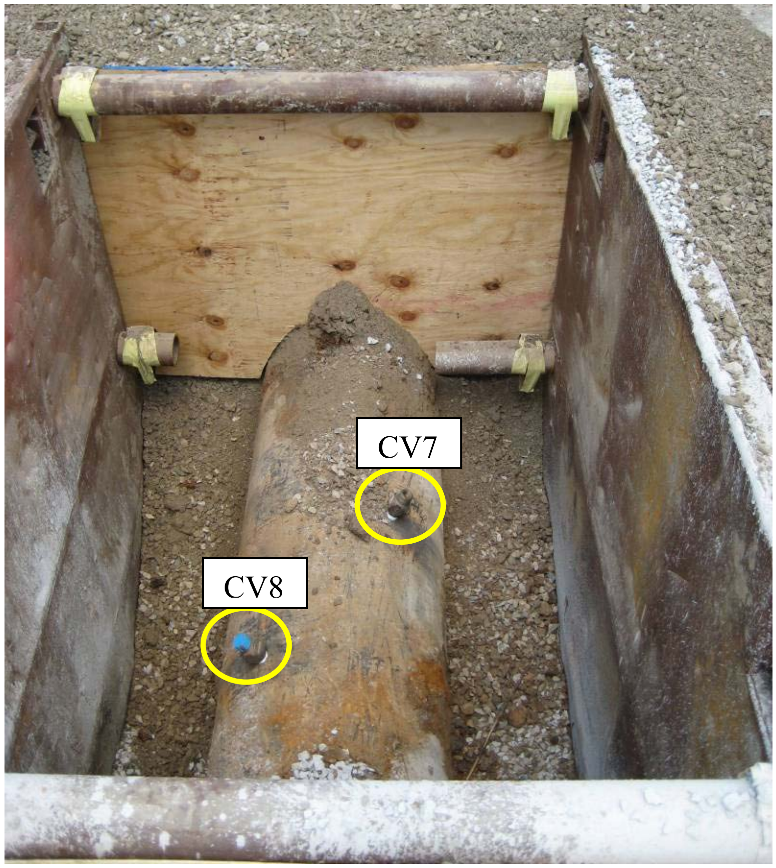

Figure 3-18. Tap Locations in Pit 5

Figure 3-19. Test Pipe Discharge to Storm Sewer Configuration

3.4.3 Simulated Leaks. The goal of a leak simulation demonstration is to determine the capabilities of different technologies at detecting and locating leaks of sizes that are a concern to water utilities. Ideally, the demonstration should test both tool sensitivity for discerning leak rates and location accuracy. As such, the demonstration was designed to identify capabilities for detecting/locating various sizes of leaks, as well as multiple leaks in close proximity. In addition, and per vendor recommendations, the simulated leaks were discharged close to the pipeline surface (rather than piped away) to generate a similar acoustic signature to actual pipeline leaks.

The criticality of a leak can vary, depending on the pipeline operational needs and location of the leak. Leaks that initially appear benign from a lost revenue standpoint may still be critical for water utilities to detect and repair to avoid further consequences like icing on roadways or contamination of natural waterways. However, if this same leak is in a non-critical location, it may only be an indication of potential future pipeline condition issues and not critical for immediate repair.

The various leak rates were selected based on correspondence with EPA and the LWC. Leak rates less than 1 gpm were selected to demonstrate technology potential as an early detection warning method. Leak rates between 1 and 5 gpm were selected based on the potential for the leak to be economical to repair. Leaks greater than 10 gpm are typically detected without the need for inspection and therefore were not included as part of the demonstration.

The 1-in. taps in Pits 2, 4, and 5 were used to create leaks within a range of sizes from as low as 3 gallons per hour up to 8 gpm. Removable restriction ports (Table 3-5) in each tap were used to create the various sizes of leaks. The restriction ports ranged in size from 0.25-in. down to a 0.02-in. diameter hole. A narrow saw-cut restriction port was also used to simulate a leaking crack in demos 2 through 4; in demos 2 and 3 it was combined with a larger leak orifice nearby while in demo 4 it was isolated. Since different pipeline pressures give different flow results from each orifice, the pipeline pressure was monitored and recorded during the leak inspections (see Figure 3-20). The typical line pressure during the demonstration was between 52 and 55 psi, with the highest pressure attained in the morning and a gradual drop in pressure during the day.

To keep water from filling the pits and changing the leak noise level, a slotted vertical standpipe containing a sump pump was placed in the corner of each excavation (see Figure 3-21). Each pit was backfilled with gravel to a level slightly above the leak taps to prevent flow from spraying out of the pit. The goal was to provide a consistent signal level and mimic acoustic signals similar to leaks covered by backfill. During each demonstration, the water level in the pits was monitored to ensure it did not raise above the outlet of the corp valves. Between demonstrations, the slotted standpipe was pumped down as necessary. Input from the leak detection vendors was requested, and the simulated leak design was adapted from their supplied procedures and phone conversations. The leak simulation approach was accepted by the leak detection companies at a meeting prior to installation of the corp valves.

Since Echologics' LeakfinderRT technology did not require flow to operate, the discharge valve downstream of Pit 3 was kept in the closed position during the demonstration while the supply valve at Chenoweth Lane was partially opened to pressurize the pipe and to maintain constant leak rates during the LeakfinderRT demonstration.

Table 3-5. Orifices Used to Simulate Various Leak Sizes During the Demonstration

Orifice Size (in.)	Leak Rate (gpm) at 30 psi	Leak Rate (gpm) at 50 psi	Photo
0.250	5.9	7.5	
0.187	3.3	4.3	
0.125	1.4	1.8	
0.062	0.43	0.54	
0.032	0.11	0.14	
0.020	0.05	0.06	
Crack 0.09 wide 0.375 long	0.72	0.97	

Figure 3-20. Monitoring Pipeline Pressure

Figure 3-21. Sump Pump System for Simulated Leak Locations

3.5 Test Configuration

Three vendors participated in the water main inspection demonstration for leak detection technologies on the following dates:

- Echologics LeakfinderRT leak detection/location with surface-mounted sensors and hydrophones. Onsite from July 6, 2009, through July 8, 2009, and again August 10, 2009, through August 12, 2009[7]
- PPIC Sahara® leak detection/location. Onsite from July 13, 2009, through July 17, 2009
- Pure SmartBall™ leak and gas pocket detection/location. Onsite from August 3, 2009, through August 7, 2009[8]

The activities conducted each day are provided in Table 3-6.

3.5.1 PPIC Sahara® Leak Detection. Five Sahara® insertions were performed from July 13 to July 17 for three different inspection technologies (leak detection, video, and condition assessment) that used the same tether, insertion equipment, and tracking method as the leak detection technology. The equipment arrived by a custom vehicle on the morning of the inspection. The vehicle contained the sensors, cable deployment system, support electronics, and electrical power for conducting video, leak, and condition assessment surveys. The Sahara® video inspection was performed first, on July 13, to inspect the inside of the pipeline. This inspection identified potential obstacles for other internal inspections, as well as internal corrosion and air pockets. The Sahara® video head was inserted into Pit 1 and traversed the line using the pipeline flow. In its initial launch, the Sahara® video parachute caught during insertion and failed to deploy; it was replaced rather than repaired (as noted by the EPA contractor's field observations). Once re-inserted, the Sahara® video head traveled the length of the test pipe. After reaching Pit 3, the video head was then retracted and taken out of Pit 1.

Sahara® Leak Detection's activities were performed on July 14, 15, and 17, 2009. Three full surveys of the pipeline were performed to test different arrangements of simulated leaks. Like the Sahara® Video head, the Sahara® Leak Detection sensor head was inserted and retracted out of Pit 1 to conduct the leak survey. With the proper fittings being installed prior to the inspection, setup required about 2 hours and teardown required about 1 hour. Setup and tear down were faster on subsequent days of the demonstration. All fittings that touched the water were sprayed with a chlorine solution for sterilization. On July 15, a thunderstorm required that flow in the pipeline be stopped due to reduced storm sewer capacity, so the survey ended before completion. Also, during several inspections, at the request of the operator, the pipeline flow rate was increased to maintain the inspection rate.

After the initial inspections, the Sahara® hydrophone was tested onsite and found to have technical problems and as such did not detect some of the small, simulated leaks. Subsequently, that particular hydrophone was replaced on the last day of the demonstration with an alternate hydrophone confirmed to pass QA/QC tests. Two of the very small leaks were re-simulated and were detected onsite using the new

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[7] Because a significant amount of air was in the line during their first visit to the demonstration site, Echologics was unable to get accurate data from their LeakfinderRT technology. The test pipe was dewatered and cut a few weeks prior to the demonstration to install tees at both ends of the test pipe. While the test pipe was filled and flushed for a few hours upon completion of the tee installation, a video assessment showed that air pockets remained throughout the pipeline. Attempts were made by LWC to remove air from the line and Echologics was permitted to return at a later date to complete their demonstration.
[8] Heavy rain fall occurred on August 4, 2009, preventing LWC from discharging to the storm sewer for 2-1/2 days. As such, Pure was unable to access the pipeline for leak assessment until August 6, 2009.

Table 3-6. Daily Activities for Each Leak Detection Technology Vendor

Date	Daily Activities
Echologics LeakfinderRT – One operator	
July 6	• Checked-in at demonstration site and set-up equipment • Unable to complete noise test; background levels appeared low
July 7	• Installed sensors (accelerometers) in Pits 1 and 3 with receiver in Pit C • Assessed background noise; added filters • Reconfigured to 1,000 ft • Pipe pressure at 53 psi • Suspected that the pipe had air pockets because could not get a clear signal; tried to swap RF transmitters
July 8	• Still unable to get a good signal; prior experience by the vendor suggested that the cause of the poor signal may have been air in the line. • Opened fire hydrant to purge air from line. Milky water observed. • Did not get any data; arranged to come back at a later date
Aug. 10	• Checked-in at demonstration site and setup equipment
Aug. 11	• Condition assessment for pipe from Pits 1, 2, and 3 using accelerometers • Found one large leak and one or two smaller leaks
Aug. 12	• Hydrophones placed in various pits to conduct leak detection • Pipe pressure between 52 and 54 psi • Road traffic over pits caused noise interference increasing inspection time • Packaged equipment for shipping
PPIC Sahara® – 2-3 operators[9]	
July 13	• Checked-in at demonstration site and setup Sahara® Video equipment • Pipe pressure at 56 psi; flow rate ~ 2.6 ft/s with three valve turns • Launched Sahara® Video; parachute failed to deploy and was replaced • Started video inspection; increased flow to keep camera from bouncing (~2-2-½ hours) • Retrieved Sahara® Video equipment (~45 minutes)
July 14	• Launched Sahara® leak detection equipment for calibration survey; natural leaks and simulated leaks detected during all surveys • Conducted second leak detection survey • Pipe pressure at ~58 psi
July 15	• Launched Sahara® leak detection equipment for third and fourth leak surveys
July 16	• Installed accelerometers for condition assessment • Launched Sahara® condition assessment equipment - hydrophone • Pipe pressure at ~55 psi
July 17	• Finished condition assessment • Pipe pressure at ~55 psi • Conducted leak detection survey with new hydrophones • Prepared for PPIC PipeDiver inspection • Packaged equipment for shipping
Pure SmartBall™ – Two operators	
Aug. 3	• Check-in at demonstration site and set up equipment
Aug. 4	• Significant rainfall; demonstration canceled
Aug. 5	• Significant rainfall; demonstration canceled

[9] More were onsite for the demonstration. PPIC used the demonstration to train new operators.

Table 3-6. Daily Activities for Each Leak Detection Technology Vendor (Continued)

Date	Daily Activities
Aug. 6	• Installed sensors in Pits 1, C, and 3 • Installed insertion and extraction tubes • Launched SmartBall™ (~45 minutes) • Conducted second SmartBall™ run (~50 minutes) • Dismantled insertion and extraction tubes
Aug. 7	• Installed insertion and extraction tubes • Conducted first SmartBall™ run (~75 minutes) • Conducted second SmartBall™ run (~53 minutes) • Conducted third SmartBall™ run (~44 minutes) • Dismantled insertion and extraction tubes • Packaged equipment for shipping

hydrophone. As a precaution, now all Sahara® hydrophones are reported to be tested following standard QA/QC procedures and an on-site test protocol is implemented prior to inspection. The conclusion from the last day was that the hydrophone used on the first three days had lower sensitivity to small leaks.

Sahara® Leak Detection verbally reported leaks as they were detected during the survey. As the hydrophone transited the test pipe, the operator listened for leaks and stopped the hydrophone to isolate the location of the leak. The hydrophone would periodically be moved back and forth to better assess whether a leak was found and its potential size. When a leak was confirmed, an aboveground tracker would locate the exact position of the tool and mark where the leak was found.[10] Throughout the demonstration, observers could listen to the hydrophone output, watch data on computer screens, and speak with analysts about the real-time results. A preliminary report of leak detection was provided to EPA's contractor on July 27, 2009. A final report with the leak detection and structural integrity demonstration results was submitted to EPA's contractor. This document in Appendix A was resubmitted on October 14, 2009 after leak verification information was released by EPA's contractor. Information was added by PPIC on a 7th leak in close proximity to a calibration leak, which was claimed to mask the natural leak signal. The rest of the report was not changed including the cover page and original submission date of July 2009.

3.5.2 Pure Technologies SmartBall™. Five SmartBall™ insertions were performed from August 6 to August 7, 2009, for leak detection and pipe-wall thickness assessment. Seven cases of equipment, five suitcase-sized and two long, thin boxes arrived by common overnight delivery service the week prior to the demonstration.

SmartBall™ leak detection was performed by launching the equipment in Pit 1, allowing the SmartBall™ to travel with the water flow to conduct the inspection, and then extracting the equipment using an extraction tube in Pit 3. LWC provided a 6-in. ANSI flange on the top of the gate valve in Pits 1 and 3 to which Pure mounted its 4-in. diameter insertion and extraction tubes. Prior to the insertion, Pure verified that adequate flow was available to carry the SmartBall™ the full length of the test pipe in a reasonable amount of time. Flow rates between 1 and 2 ft/s were maintained, resulting in inspection times between 45 minutes and 1 hour.[11] The inspection procedure involved first placing the extraction net in the pipeline, then inserting the SmartBall™. With the proper fittings being installed prior to the inspection, the setup and tear down process for SmartBall™ required about an hour each. All fittings that touched the water were sprayed with a chlorine solution for sterilization.

[10] The typical PPIC procedure is to mark the road above the pipeline with marking paint at the exact position of the leak; however, this was not done during the demonstration to avoid giving away results to subsequent vendors conducting leak assessment surveys.
[11] The SmartBall™ typically travels at about 90 percent of the flow rate.

Knowing the position of the SmartBall™ within the pipeline is critical for locating important pipeline features, such as leaks, and multiple locating methods are used by SmartBall™. Distance profiles are generated to give a rough estimate of the SmartBall™ position over time. Data obtained from the accelerometers and magnetometers on board the SmartBall™ are used to obtain a velocity profile for tracking the tool. Also, absolute position reference points obtained from the SBR are applied to the time-stamped data to track the position of the SmartBall™. Individual SBRs tracked the ball's progress through the pipeline for over 850 ft; the distance and location of these SBRs were based on information provided to Pure by EPA's contractor. The result of the rotation profile and SBR tracking is a position-versus-time relationship for the entire run of the tool. The exact location of where each SBR was placed along the test pipe during each run is detailed in Table 3-7.

Figure 3-22 shows an example of the position data recorded for each run. The position of the SmartBall™ indicated by the red line was fixed by fitting the position profile to known locations along the pipeline. The slope of the red line indicates the instantaneous velocity of the tool. An example of the velocity of the SmartBall™ as it travels through the pipeline is shown in Figure 3-23. Figure 3-24 shows an example of the ball's position as it was tracked in real time by the SBRs. The combined use of travel time (a coarse measure of position), velocity, and SBR position tracking (data can be noisy) provides an acceptable solution for determining the SmartBall™ position.

Once the ball was launched, observers and technicians waited for the ball to be received at Pit 3. The vendor verbally reported on leaks to EPA's contractor the day after each inspection. There were no ongoing activities for the operators to perform as the SmartBall™ traveled through the pipeline. A final report of leak detection results was provided on August 14, 2009.

To quantify the approximate leak rate documented during the inspection, Pure compared the leak indication power of a detected leak with that of a known leak rate. The previously established calibration curve[12] used by SmartBall™ is shown in Figure 3-25. Additional calibration leaks (Demo 1) were provided by EPA's contractor during the demonstration (shown in green in Figure 3-25) to help Pure size and locate blind leaks during subsequent runs.

Pure noted that because the simulated leaks are controlled and released through a threaded outlet, the comparison to actual field-condition leaks may vary. This is because the acoustic frequency and power indication of any leak will vary with many factors, including pressure, pipe diameter, anomaly size, and anomaly configuration (pin-hole, rolled gasket, split pipe, etc.). However, the leak calibration curve provides a useful tool to approximate leak rates for identified leaks. The reported leaks detected during the inspection are shown as red circles in Figure 3-25.

Pure reports actual leak rates, but also provided classification of their leak sizes as follows:

- 0 to 2 gpm (0-7.5 liters per minute) = small,
- 2 to 10 gpm (7.5 to 37.5 liters per minute) = medium,
- > 10 gpm (37.5 liters per minute) = large.

Subsequent results only show the actual leak rates as provided by Pure.

[12] The calibration curve was developed by Pure outside of this demonstration using a ½-in valve attached to the extraction stack and a calibrated bucket to measure the leak rates. Further details are provided in their report included in Appendix B.

Table 3-7. SmartBall™ Receiver (SBR) Locations

Location ID	Distance from Launch (ft)
Insertion	0.0
Midpoint	809.0
Extraction	2,057.0

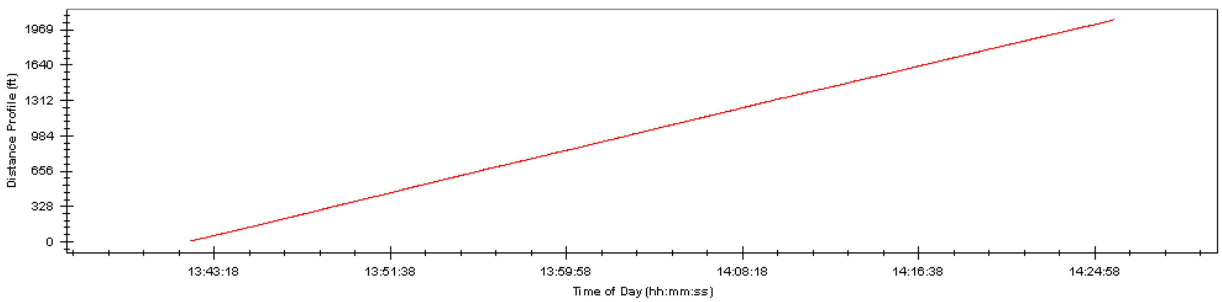

Figure 3-22. Example Position Profile of the SmartBall™ vs. Time of Day from Run #1 on August 6 (courtesy of Pure)

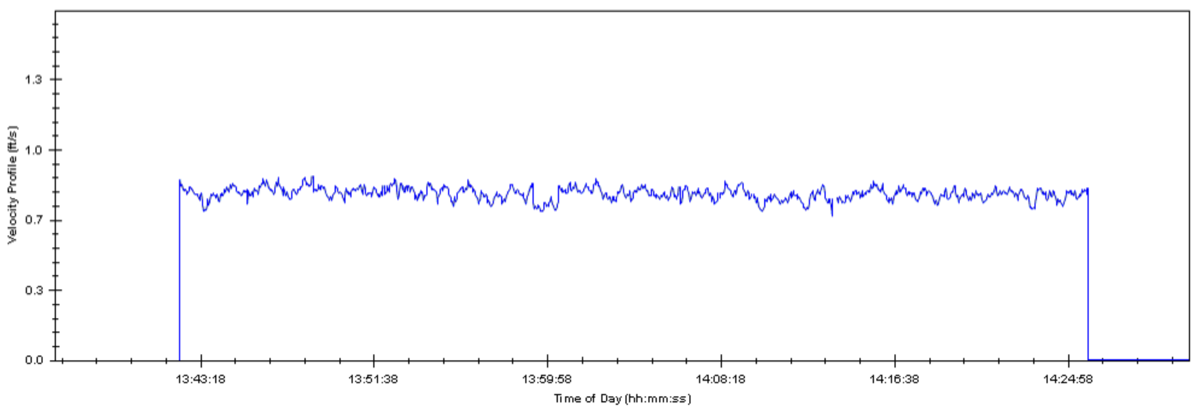

Figure 3-23. Example Velocity Profile of the SmartBall™ vs. Time of Day from Run #5 on August 7 (courtesy of Pure)

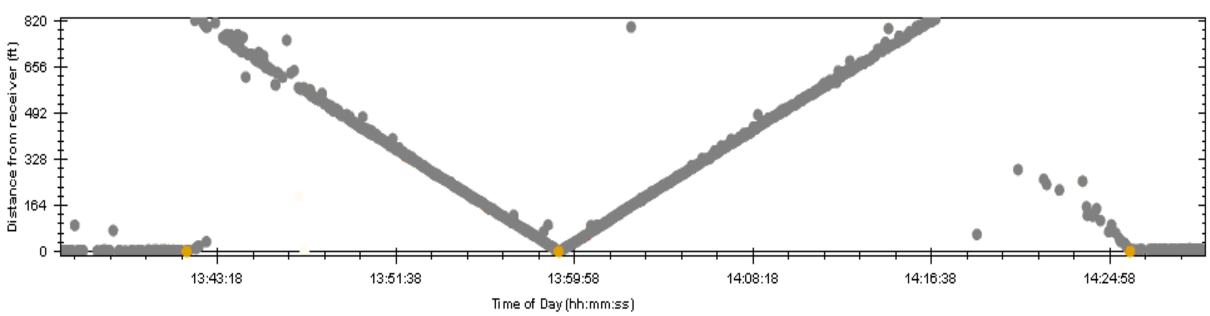

Figure 3-24. Example SmartBall™ Receiver Tracking Points vs. Time of Day from Run #2 on August 6 (courtesy of Pure)

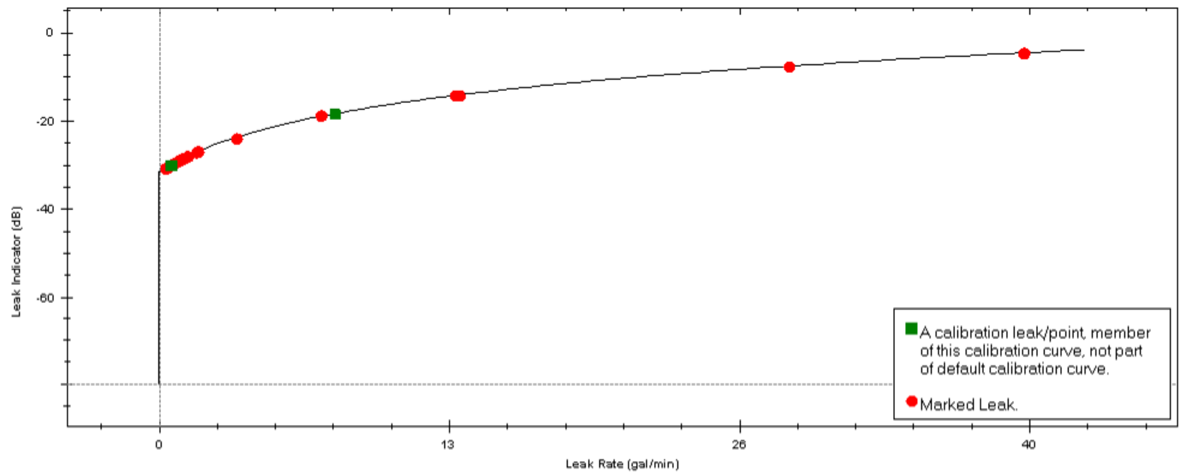

Figure 3-25. Example Leak Calibration Curve Used to Size Leaks (courtesy of Pure)

3.5.3 Echologics LeakfinderRT. From July 6 through 8, 2009, Echologics was onsite to demonstrate its ThicknessFinder and LeakfinderRT technologies. These initial inspections were unsuccessful.[13] Echologics was allowed to return August 10 through 12 to have a second chance at demonstrating these technologies. The leak assessment was conducted on August 11 and 12. One Echologics technician arrived the day of the inspection with two cases of equipment the size of a common suitcase in the back of a small rented vehicle. This report describes the LeakfinderRT demonstration. The ThicknessFinder demonstration will be reported in a subsequent report.

LeakfinderRT used two types of sensors: (1) hydrophones (1.5-in. NPT threads) that required contact with the water column, and (2) accelerometers that were glued to the outside of the pipe. The distance between sensors is a function of many variables, including local noise considerations. The simplest configuration would have been to examine the entire distance from Pit 1 to Pit 3, using the 12-in. taps as the sensor locations. However, initial tests showed that this configuration was not feasible due to excessive noise levels. Instead, taps installed for the simulated leaks in Pit 2 were made available to shorten the hydrophone distance intervals for assessing the simulated leaks to 1,000-ft. For detection of natural leaks, accelerometers were used to record and correlate data between neighboring sensors spaced 300 ft apart using all the access pits (Pits 1 through 5 and Pits A through F).

Echologics initially performed background measurements with LeakfinderRT accelerometers over the shorter test pipe lengths of 300 ft in order to find any natural leaks and to collect pipe wall thickness data at the same time (using ThicknessFinder, which is discussed in a companion report). This was followed by the simulated leak assessment using LeakfinderRT hydrophones over the larger distance intervals (e.g., 1,000 ft). The assessment lengths were a field decision made by Echologics based on the test pipe configuration.

Echologics presents the need for using the two sensor types in its report (see Appendix C). They state that, in general, it is more challenging for a leak noise correlator to survey for water main leaks than it is

[13] Because a significant amount of air was in the line during their first visit to the demonstration site, Echologics was unable to get accurate data from their LeakfinderRT technology. The line was dewatered and cut a few weeks prior to the demonstration to install tees at both ends of the test pipe. While the line was filled and flushed for a few hours upon completion of the tee installation, a subsequent video assessment showed that air pockets remained throughout the pipeline.

to locate a known leak, since there will be a high incidence of negative (no leak) results. When many negative results are encountered, the surveyor may begin to question the operation of the equipment or his procedures. Therefore, one of the main issues with testing pipes where there is no known leak is the need to take steps to ensure that the results are properly analyzed so that the presence (or lack) of a leak may be definitively decided. Based on Echologics' previous experience with leak detection surveys and their familiarity with acoustic technology, procedures were implemented onsite, and follow-up analyses were performed to make a definitive decision on whether a leak was present. They performed the following activities:

- Hydrophones were attached on valves or hydrants available at each site. Where measurements were performed on valves, the sensors were placed on the tops of valve keys that had been lowered onto the valves or placed directly on the valve nut when possible (if the valve chamber was clear of debris).
- After placement of the sensors on the appropriate valve or hydrant, the fitting was tapped and listened to at the radio receiver to ensure that the sensor was functioning and that the radio signal was reaching the receiver properly. This is called a scratch test.
- Sensor spacing was measured using a calibrated measuring wheel.
- A correlation measurement was performed, and the signal was saved to the computer, so that further analysis could be performed later in the office, and so that the client could have a permanent record of the raw noise file, if needed.
- Where a positive signal was detected (a correlation peak with good signal coherence), the location was immediately checked to determine if it corresponded to a service line or other notable draws from the pipe. If this was the case, several more correlations were conducted to see if the "usage" stopped.
- Where negative results were obtained (no clear correlation peak was obtained), a series of checks was completed, including a review of coherence and of the two communication frequency spectra, to detect the presence of a PVC repair or some other anomaly in the test section. Such checks are part of Echologics' protocol for leak detection surveys.

Echologics also presents several possible sources of error in its demonstration results documentation (see Appendix C). These include inaccurate measurement of distances along the test pipe and errors in manufacturing wall-thickness tolerances. A much smaller source of errors from electronic hardware and digital processing is also identified by Echologics in Appendix C.

Once the acoustic sensors (either hydrophones or accelerometers) were set up, a few minutes of data were recorded. Observers of the demonstration could watch the real-time data analysis and discuss the findings with the LeakfinderRT technician. A preliminary field-written leak report was provided within an hour of the inspection. With the proper fittings being installed prior to the inspection, setup and tear down required about ½ hour each. All equipment that touched the water column was wiped with a chlorine solution for sterilization. A detailed preliminary report was provided on August 31, 2009, and a final report was provided on September 30, 2009, with minor revisions submitted on November 4, 2009 and again on November 13, 2009.

3.6 Post-Demonstration Leak Confirmation

Simulated Leaks

The leak rates for each restriction port discussed in Section 3.4.3 were established prior to the demonstration. EPA's contractor quantified the leak rates at pipeline pressures ranging from 20 to 50 psi for the various restriction port sizes, using laboratory facilities in West Jefferson, OH. A large pipe was filled with water, and then pressurized to the various levels. Each restriction port was placed on a valve attached to the pipe, and the leak rate was calculated based on the weight of water released over a specific period of time. Figure 3-26 provides these leak calibration curves for each restriction port. Given the orifice sizes in Figure 3-26, the calibration curves were nominally linear over the range of pressures used. The conditions at the exit of the orifice can increase or decrease the flow rate. Water at the exit can decrease flow rate by creating back pressure; the stone backfill and sump system installed was used to reduce this effect. However, the stone can potentially increase the flow rate. The flow through an orifice naturally contracts, referred to as the vena contracta; backpressure and cavitation caused by the backfill can increase the effective orifice size. Testing was performed under controlled conditions; the variation with water and backfill could increase or decrease the flow 2 to 10%. Because measuring the leak rate during the demonstration may change the acoustic properties of the leak, the exact leak rate during each live inspection run was not measured. Instead, the test-pipe pressure was monitored and recorded during the demonstration and used in combination with the leak calibration curves (see Figure 3-26) to estimate the actual leak rate. Since testing pressures were up to 8psi above the expected maximum pressure of 50 psi, the flowrates were determined by extrapolating the nominally linear curves in Figure 3-26.

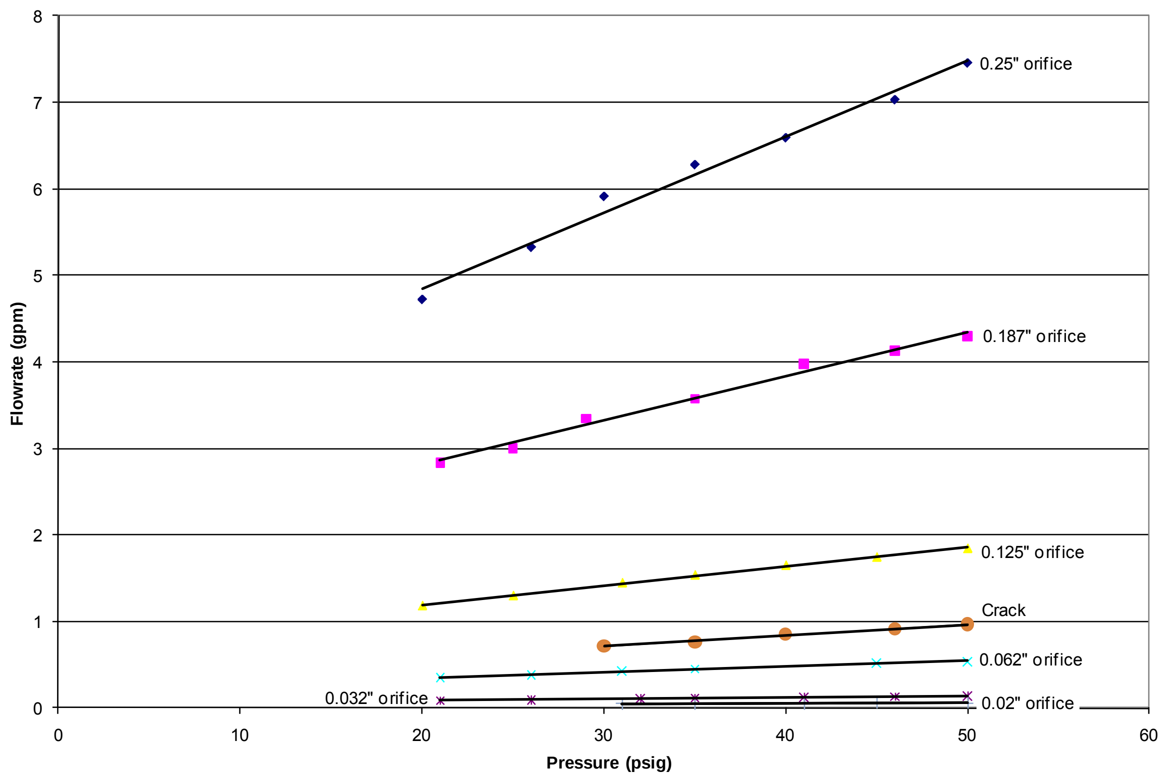

Figure 3-26. Calibration Curves for Restriction Ports

The leak matrix used for the demonstration is provided in Table 3-8 for the PPIC Sahara® and Pure SmartBall™ technologies. Upon completion of the leak test matrix, both vendors had extra time available to conduct additional simulated leak runs to help in advancing their technologies. SmartBall™ conducted one additional run (called Demo 5) with a 0.25-in. orifice in CV1 and a 0.063-in. orifice in CV3. Sahara® conducted three additional runs (called Demo 5, Demo 6, and Demo 7) with a 0.187-in., 0.062-in., and 0.032-in. orifice in CV2.

Table 3-8. Leak Test Matrix for PPIC Sahara® and Pure SmartBall™

Pit #	Corp Valve ID	Leak Configuration							
		Demo 1 (Calibration)		Demo 2		Demo 3		Demo 4	
		Orifice Size (in)	Leak Rate[(a)] (gpm)	Orifice Size (in)	Leak Rate[(a)] (gpm)	Orifice Size (in)	Leak Rate[(a)] (gpm)	Orifice Size (in)	Leak Rate[(a)] (gpm)
Pit 4	CV1	0.063	0.57	--	--	Crack	1.0	0.02	0.06
	CV2	--	--	0.02	0.06	0.125	1.9	0.188	4.6
Pit 2	CV3	0.250	7.8	--	--	0.032	0.14	--	--
	CV4	--	--	0.032	0.14	0.063	0.57	--	--
	CV5	--	--	--	--	--	--	Crack	1.0
	CV6	--	--	0.063	0.57	0.188	4.6	--	--
Pit 5	CV7	--	--	Crack	1.0	0.25	7.8	0.25	7.8
	CV8	--	--	0.25	7.8	0.063	0.57	0.125	1.9

(a) Leak rate is for a pressure of 54 psi. The pipeline pressure, and consequently the leak rates, varied during testing from approximately 50 psi to 58 psi.

The test matrix is slightly different for LeakfinderRT due to the methods used to collect the data. Rather than inspecting the entire length of pipe in one run, LeakfinderRT used two hydrophones placed approximately 1,000 ft apart to assess the line for leaks. As such, the simulated leak demonstration had to be conducted in three stages to cover the entire test pipe length. The first set of four leak scenarios was established using CV1 and CV2 in Pit 4; the two hydrophones that bracketed Pit 4 were in Pits 1 and 2. The second set of four leak scenarios was established using CV7 and CV8 in Pit 5; the two hydrophones that bracketed Pit 5 were in Pits 2 and 3. The third set of four leak scenarios was established using CV3, CV4, CV5, and CV6; the two hydrophones that bracketed Pit 2 were in Pits 4 and 5. The LeakfinderRT test matrix is presented in Table 3-9.

For each simulated leak demonstration, a cluster of leaks was used to determine the leak detection, location, and sizing capabilities for each technology. A leak cluster is defined as anywhere from one to three leaks within the same pit that are axially spaced anywhere from 0.6 to 2.7 ft. In some of the demonstrations, only one leak orifice was opened within a pit while other pits may have had two or three orifices open. The demonstration was designed to identify capabilities for detecting/locating various sizes of leaks, as well as multiple leaks in close proximity.

Table 3-9. Leak Test Matrix for Echologics LeakfinderRT

Demo #	Pit #	Corp Valve ID	Leak Configuration	
			Orifice Size (in.)	Leak Rate[a] (gpm)
Demo 1 (Calibration)	Pit 4	CV1 CV2	0.063 --	0.57 --
Demo 2	Pit 4	CV1 CV2	-- 0.02	-- 0.06
Demo 3	Pit 4	CV1 CV2	Crack 0.125	1.0 1.9
Demo 4	Pit 4	CV1 CV2	0.02 0.188	0.06 4.6
Demo 1 (Calibration)	Pit 5	CV7 CV8	-- --	-- --
Demo 2	Pit 5	CV7 CV8	Crack 0.25	1.0 7.8
Demo 3	Pit 5	CV7 CV8	0.25 0.063	7.8 0.57
Demo 4	Pit 5	CV7 CV8	0.25 0.125	7.8 1.9
Demo 1 (Calibration)	Pit 2	CV3 CV4 CV5 CV6	0.25 -- -- --	7.8 -- -- --
Demo 2	Pit 2	CV3 CV4 CV5 CV6	-- 0.032 -- 0.063	-- 0.14 -- 0.57
Demo 3	Pit 2	CV3 CV4 CV5 CV6	0.032 0.063 -- 0.188	0.14 0.57 -- 4.6
Demo 4	Pit 2	CV3 CV4 CV5 CV6	-- -- Crack --	-- -- 1.0 --

(a) Leak rate is for a pressure of 54 psi. The pipeline pressure varied during testing from approximately 50 psi to 58 psi. The mean pressure was used to determine the flow rate from the pressure-flow rate graph.

Naturally Occurring Leaks

The leak rates and locations for the simulated leaks were recorded by EPA's contractor for later comparison to the reports provided by the individual vendors. In addition, the leak detection/location capabilities for the various technologies were qualitatively verified through focused excavations of the pipeline to find naturally occurring leaks.[14] Eight identified leak locations were excavated and examined.

During the excavation, with the assistance of MAC Construction, the soil was examined for excessive moisture and erosion. When each leak site was fully uncovered, visual assessment was used to determine whether the leak was from a bell-and spigot joint or the body of the pipe at an anomaly such as corrosion or a crack. After the potential leak sites were uncovered, the pipe was pressurized to qualitatively assess the leak sizes by examining the amount of water leaching/spraying from the pipe.

During verification, EPA's contractor was able to definitively confirm naturally occurring leaks in four of the eight locations that were excavated; all occurred at the bell-and-spigot joint (see Table 3-10 and Figure 3-27). This does not mean that the other four leaks that could not be verified did not exist. For two of the unverified leaks, the soil was definitely wetter in the area excavated; however, EPA's contractor was unable to pinpoint the leak location. For the other two unverified leaks, where the soil was relatively dry, it is quite possible that the reported locations used to determine the excavation location were off by several feet so that EPA's contractor could not find evidence of a leak.

Additional measurements were taken for the one natural leak found in Pit L to understand what may have caused the leak. The joint rotation was measured — that is, the angle between the two pipe joints where the leak was found. Researchers at the NRC of Canada suggested measuring the joint rotation to test a hypothesis that an angle of more than 2° would cause a joint leak and that an angle of more than 5° would crack the bell. While the test pipe was generally level, this leak occurred near a storm sewer. The angle measured was approximately 1.5°, indicating that the bell would not be cracked (as was verified visually) or leaking due to joint rotation. Therefore, the large leak was most likely due to degradation in the leadite seal for the bell-and-spigot joint rather than joint rotation.

Table 3-10. Natural Leak Verification Results[14]

Leak ID#	Leak Excavation Location (ft)	Location Where Leak Found (ft)	Description
L1	50-53	52	Soil was wet, but there was a nearby storm sewer at 52 ft; leak not pinpointed, but elevated moisture considered as an indirect indication of potential leak.
L3	194-199	195	A lot of water in pit near bell-and-spigot joint; did not pinpoint leak
L4	338-341	339	Large leak at bell-and-spigot joint
L6	556	556	Small leak at bell-and-spigot joint
L7	638-641	640	Small leak at bell-and-spigot joint
L10	1,724	--	No wet soil found at this location; inconclusive
L11	1,809	--	No wet soil found at this location; inconclusive
L12	1,906-1,933	1,909	Soil was moist at ~1,906 ft or 1,930 ft; leak not pinpointed, but elevated moisture considered as an indirect indication of a potential leak.

[14] EPA's contractor was only able to pressurize the line to witness four of the leaks (L3, L4, L6, and L7). Shortly after verifying these leaks, the stem broke on the control valve near Chenoweth Lane, prohibiting the line from being pressurized for remaining leak verification. As such, other external cues, such as wet soil and possibly odor from leaching leadite in joints, were used to indirectly decide if a leak could have been present in the line.

Figure 3-27. Leak ID L7 – Small Leak at Bell-and-Spigot Joint

4.0: RESULTS AND DISCUSSION

PPIC Sahara®, Pure SmartBall™, and Echologics LeakfinderRT leak detection, location and sizing technologies were demonstrated on a 76-year-old, 2,057-ft-long portion of a cement-lined, 24-in. diameter cast iron water main in Louisville, KY. While each technology used some form of acoustic listening device, the implementations were quite different:

- PPIC's Sahara® mounted a hydrophone sensor at the end of a cable tether. The hydrophone, which was inserted and pulled through the pipeline using the water flow, provided real-time assessment of leaks. The hydrophone sensor was also tracked by an operator from ground level and leaks were marked on the pavement.
- The Pure SmartBall™ sensor and data-recording device were placed within a foam ball. The sensor and ball were inserted in the pipeline and propelled by the water through the pipeline to a downstream extraction point where a net inserted into the pipe caught and removed the unit.
- Echologics LeakfinderRT demonstrated two types of sensors. Pairs of accelerometers were mounted on the outside of the pipe at discrete locations to detect and locate unknown leaks. Then pairs of hydrophones in contact with the water at discrete locations were used to estimate simulated leak rates.

After the demonstration was complete, a closed-circuit television video inspection of the entire test pipe length was performed. The inspection report indicated that the cement liner was uniform and no through-wall anomalies were detected in the pipe wall. The joints at the reported natural leak locations were closely examined as well as the joints before and after these leak locations and no significant differences (such as larger gaps) were observed.

The implementation of the leak detection/location technology demonstration could not have been accomplished without the significant efforts of LWC, MAC Construction, and the technology vendors PPIC, Pure, and Echologics. Each vendor participated by mobilizing their technology and crews onsite, setting up the equipment, operating the technology, collecting data, and providing the requested inspection reports. Detailed results for all three leak detection technologies are discussed in the subsequent sections with a summary of the results provided in Section 2. The individual leak inspection reports provided by each vendor are included in Appendix A (Sahara®), Appendix B (SmartBall™), and Appendix C (LeakfinderRT).

Since this demonstration was a snapshot in time, new developments may have taken place since completion of the demonstration. Therefore, the findings in this report may not be wholly representative of the current operational capabilities of the demonstrated technologies. For this reason, the vendors were asked to provide formal comments on the final leak detection report to highlight advancements since completion of the demonstration and/or clarification on what was reported. These comment letters are contained in Appendix D.

4.1 PPIC Sahara® Systems

PPIC presented two sets of leak detection/location results: (1) for naturally occurring pipeline leaks; and (2) for simulated leaks. All results provide a qualitative evaluation of the pipe condition and leak sizes (very small, small, medium, and large). As with the other technologies, the location accuracy of the anomalies is dependent on the accuracy of the pipe distance as measured on the surface and lay information as the pipe may not precisely follow the road surface.

4.1.1 Summary of Results. For Sahara® Leak Detection, PPIC has defined their leak rate classification scheme based mainly on the distance away from a leak that the leak can first be detected. Table 4-1 shows the leak rate classification scheme developed by PPIC based upon their own data for pipes ranging from 24-in. to 60-in. in diameter.

Table 4-1. Sahara® Leak Classification Table for 24-in. to 60-in. Diameter Pipe

Classification	Distance Detected [m]	Approximate Measured Leak Size					
		Min [m^3/hr]	Max [m^3/hr]	Median [m^3/hr]	Min [gpm]	Max [gpm]	Median [gpm]
Very Small	0-2	0	0.4	0.2	0	1.8	0.88
Small	2-5	0.4	4	2	1.8	18	8.8
Medium	5-15	4	17	10	18	75	44
Large	15-50	17	29	23	75	128	101
Very Large	50+	29	42	35	128	185	154

The Sahara® Leak Detection inspection identified six natural leaks in real time and 11 simulated leak clusters[15]. A seventh natural leak was reported after verification results were sent to PPIC by EPA's contractor; the additional leak signal was reported to be masked by a larger artificial leak 22 ft away. Details of the natural leaks are presented in Table 4-2 with specific information on the direction, distance from the insertion point, and estimated leak rate. Details of the detected simulated leaks are presented in Table 4-3, specifically the corp valve ID and estimated leak rate for each simulated leak.

Table 4-2. Natural Leaks Detected by Sahara® Leak Detection

Sahara® ID#	Distance from Start (ft)	Description as Provided by Vendor	Direction from Insertion Point
1	50	Very small leak	Downstream
2	194	Very small leak	Downstream
3	338	Large leak	Downstream
4	638	Small leak	Downstream
5	1,696	Very small leak	Downstream
6	1,906	Small leak	Downstream
Post[(a)]	558	Very Small	Downstream

(a) Initially, PPIC did not report a leak at this location, but later identified a signal after receipt of the verification data. PPIC reported that the signal was initially masked by an artificial leak at 578 ft.

[15] With extra time available, additional demos were conducted upon the vendor's request. These additional demos are not included in the simulated leak verification numbers as they were done as a common courtesy to allow the vendors to gather more data for technology development.

Table 4-3. Simulated Leaks Detected by Sahara® Leak Detection

Pit #	Corp Valve ID	Estimated Leak Rates (gpm)				
		Demo 1 (calibration)	Demo 2	Demo 3	Demo 4	Demos 5, 6, and 7[b]
Pit 4	CV1 CV2	Very small[a]	Very small[a]	Small	Very small[a]	Small Very small Very small
Pit 2	CV3 CV4 CV5 CV6	Small	Very small	Small	Medium Small	--
Pit 5	CV7 CV8	--	Large	Medium	--	--

(a) While larger leaks were orally reported during the demonstration, the detection of these very small leaks required post-operation analysis.

(b) Demos 5, 6, and 7 were only conducted for Sahara® Leak Detection. Demo 5 (0.187-in. orifice), Demo 6 (0.062-in. orifice), and Demo 7 (0.032-in. orifice) leaks originated from CV2. As time permitted, vendors were extended the courtesy of conducting additional tests for improving their technology.

4.1.2 Leak Evaluation. Sahara® reported six natural leaks (L1, L3, L4, L7, L13, and L12) in real time, and a seventh (L6) after verification results were provided to PPIC by EPA's contractor. The additional leak signal was reported to be masked by an artificial leak 22 ft away. Except for one very small leak at 1,696 ft, which was not excavated and therefore could not be verified, the remaining five leaks were directly or indirectly verified based on visual evidence and other vendor leak reports (leak pinpointed, wet soil in the general vicinity, or another vendor reported a leak in the same vicinity).

Sahara® Leak Detection also detected and qualitatively estimated the leak rate for 11 of 19 simulated leaks and 11 of 11 leak clusters. Each simulated leak cluster was a combination of one to three consecutive leaks, from orifices of different sizes, arranged 0.6 to 2.7 ft apart. Within each leak cluster, Sahara® accurately characterized the leak range for 6 of the 11 clusters. For leaks that were not accurately characterized, 4 out of 5 were off by one size category, while the leak in Demo 2, Pit 5 was off by two size categories. The location accuracy could not be evaluated as Sahara® only reported the pit number in which they found the leak.

Sahara® was not able to discern two separate leaks in close proximity (less than 2.7 ft apart) for all of the simulated leaks. Identifying whether a signal is from an isolated leak or multiple leaks in close proximity is helpful in judging the general condition of a pipeline. However, it is also important to accurately identify the location and size of the largest leak(s). As reported by PPIC, when individual leaks are at close proximity, the leak signatures combine and are difficult to differentiate.

Details of the detected natural leaks and subsequent visual verification are presented in Table 4-4. The detected simulated leaks vs. the actual test conditions are presented in Table 4-5.

Table 4-4. Evaluation of Natural Leaks Detected by Sahara® Leak Detection[16]

Leak ID#	Sahara ID#	Distance from Start (ft)	Description as Provided by Vendor	Visually Verified by EPA Contractor?
L1	1	50	Very small leak	Verification attempted; soil was wet, but there was a nearby storm sewer at 52 ft; leak not pinpointed, but elevated moisture indicative of leak.
L3	2	194	Very small leak	Verification attempted; a lot of water in pit near bell-and-spigot joint at ~195 ft; did not pinpoint leak
L4	3	338	Large leak	Verification attempted; leak at bell-and-spigot joint at ~339 ft
L6	Post	558	Very small leak	Verification attempted; leak at bell-and-spigot joint at ~556 ft
	Initially, did not report a leak, but found after verification results were provided to PPIC. The leak signal was reported to be masked by an artificial leak at 578 ft.			
L7	4	638	Small leak	Verification attempted; leak at bell-and-spigot joint at ~640 ft
L13	5	1,696	Very small leak	No verification attempted
L12	6	1,906	Small leak	Verification attempted; soil was moist at ~1,906 ft; leak not pinpointed, but elevated moisture indicative of leak.

Table 4-5. Evaluation of Simulated Leaks Detected by Sahara® Leak Detection[17]

Corp Valve ID	Distance to Leak (ft)		Estimated Leak Rates (gpm)[(a)]									
			Demo 1 (calibration)		Demo 2		Demo 3		Demo 4		Demo 5, 6, 7	
	A	S	A	S	A	S	A	S	A	S	A	S
CV1	577.4	Pit 4	0.59	Very small (0-1.8)	--	Very small (0-1.8)	1.0	Small (1.8-18)	0.06	Very small (0-1.8)[18]	--	Small (1.8-18) Very small Very small (0-1.8)
CV2	578.4		--		0.06		2.0		4.6		4.6 0.57 0.14	
CV3	1,082.2	Pit 2	8.2	Small (1.8-18)	--	Very small (0-1.8)	0.14	Small (1.8-18)	--	Small (1.8-18)	--	--
CV4	1,082.8		--		0.15		0.57		--		--	
CV5	1,084.1		--		--		--		1.0		--	
CV6	1,084.9		--		0.59		4.6		--		--	
CV7	1,583	Pit 5	--	--	1.1	Large (75-128)	7.9	Medium (18-75)	7.9	Medium (18-75)	--	--
CV8	1,585.7		--		8.2		0.57		2.0		--	

(a) Pipeline pressure was 58 psi for Demos 1 and 2; unknown for Demos 3 and 4 (assumed 55 psi); and 55 psi for Demos 5, 6, and 7.
A = actual, S = Sahara®

[16] The gray background signifies natural leaks that were verified in the field (by pinpointing leak or elevated moisture); the red background signifies false negatives; and the white background signifies leaks found by one or more leak detection technologies, but were not verified in the field.
[17] The text with a red background signifies leak rate estimates that are off by one or more categories as defined by each individual vendor.
[18] After rates were disclosed, PPIC reported a natural air pocket near the leak and reported that this may have masked the leak, thus minimizing its signature.

4.2 Pure Technologies SmartBall™

SmartBall™ presented two sets of leak detection/location results: (1) for naturally occurring pipeline leaks; and (2) for simulated leaks. Both sets of results provide a qualitative evaluation of the leak size (small, medium, large), as well as an estimated leak rate. As with the other technologies, the location accuracy of the anomalies is dependent on the accuracy of the pipe distance as measured on the surface and lay information (as the pipe may not precisely follow the road surface).

4.2.1 Summary of Results. For SmartBall™, the leak rate classifications as defined by Pure are shown in Table 4-6.

Table 4-6. SmartBall™ Leak Classification Table

Classification	Approximate Leak Size		
	Min [gpm]	Max [gpm]	Median [gpm]
Small	0	2	1
Medium	2	10	6
Large	>10		

The SmartBall™ inspection reported 12 natural leaks and 11 simulated leak clusters[19]. Details of the natural leaks are presented in Table 4-7 with specific information on the distance from the insertion point, leak description, and estimated leak rate. Details of the detected simulated leaks are presented in Table 4-8, specifically the corp valve ID, distance, and estimated leak rate for each simulated leak.

Table 4-7. Natural Leaks Detected by SmartBall™

Leak ID#	Distance from Start (ft)	Description as Provided by Vendor	Approx. Size (gpm)
1	53	Small leak	0.15
2	125	Small leak	0.1
3	199	Small leak	0.8
4	341	Medium leak[(a)]	15
5	414	Small leak	0.2
6	556	Small leak	1.0
7	641	Small leak	2.0
8	966	Small leak	0.1
9	1,210	Small leak	1.0
10	1,724	Small leak	1.5
11	1,809	Small leak	2.0
12	1,930	Small leak[(a)]	5.5

(a) According to Table 4-6 these leaks would be classified as large and medium, respectively; however, the description in Table 4-7 is what was reported in Pure's inspection report as included in Appendix B.

[19] With extra time available, one additional demo (i.e., demo 5) was conducted upon the vendor's request. The additional demo is not included in the simulated leak verification numbers as they were done as a common courtesy to allow the vendors to gather more data for technology development.

Table 4-8. Simulated Leaks Detected by SmartBall™

Pit #	Corp Valve ID	Distance to Leak (ft)[1]	Estimated Leak Rates (gpm)				
			Demo 1 (calibration)	Demo 2	Demo 3	Demo 4	Demo 5
Pit 4	CV1	579	0.57 (small)	0.3 (small)	1.8 (small)	4.5 (medium)	8 (medium)
	CV2						
Pit 2	CV3	1,080	8 (medium)	2.8 (medium)	7.2 (medium)	0.1 (small)	0.57 (small)
	CV4						
	CV5						
	CV6						
Pit 5	CV7	1,580	0 (small)	15 (large)	30 (large)	40 (large)	0 (small)
	CV8						

Note: 1) One location was reported for all of the simulated leaks associated with a specific pit.

4.2.2 Leak Evaluation. SmartBall™ reported 12 natural leaks (L1 through L12) within the inspected area. For the 12 natural leaks reported by SmartBall™, six were excavated and directly or indirectly verified (L1, L3, L4, L6, L7, and L12) based on visual evidence (leak pinpointed, wet soil in the general vicinity, or another vendor reported a leak in the same vicinity); two other reported leaks (L10 and L11) were excavated, but the existence of small leaks were not conclusive. The remaining four locations were not excavated due to time and budget constraints and therefore could not be verified.

SmartBall™ reported 11 of 19 total simulated leaks but reported 11 of 11 leak clusters. Each simulated leak was a combination of one to three consecutive leaks, from orifices of different sizes, arranged 0.6 to 2.7 ft apart. Within each leak cluster, SmartBall™ accurately characterized the leak range for 7 of the 11 clusters. All four of the leaks not accurately characterized were off by one size category. The location accuracy could not be evaluated as SmartBall™ only reported the location of the pit and not where the actual leaks were located.

SmartBall™ was not able to discern two separate leaks in close proximity (less than 2.7 ft apart) for any of the simulated leaks. The locations of the leaks in Pits 4, 2 and 5 were reported at only one point in the excavation regardless of which leak orifice was open, not where the actual leak occurred.

The findings of the pipeline inspection are summarized in Table 4-9, along with the field verification results for the naturally occurring leaks. Table 4-10 summarizes the simulated leak results as compared to the actual leak rate based on the orifice size and pipeline pressure at the time of the inspection.

Table 4-9. Evaluation of Natural Leaks Detected by SmartBall™[20]

Leak ID#	SmartBall™ Results: SmartBall™ Leak ID#	Distance from Start (ft)	Description	Approx. Size (gpm)	Visually Verified by EPA Contractor?
L1	1	53	Small leak	0.15	Verification attempted; soil was wet, but nearby storm sewer at 52 ft; leak not pinpointed, but elevated moisture indicative of leak.
L2	2	125	Small leak	0.1	No verification attempted
L3	3	199	Small leak	0.8	Verification attempted; water in pit near bell-and-spigot joint at ~195 ft; did not pinpoint leak
L4	4	341	Medium leak	15	Verification attempted; leak at bell-and-spigot joint ~339 ft
L5	5	414	Small leak	0.2	No verification attempted
L6	6	556	Small leak	1.0	Verification attempted; leak at bell-and-spigot joint at ~556 ft
L7	7	641	Small leak	2.0	Verification attempted; leak at bell-and-spigot joint ~640 ft
L8	8	966	Small leak	0.1	No verification attempted
L9	9	1,210	Small leak	1.0	No verification attempted
L10	10	1,724	Small leak	1.5	Verification attempted, but no wet soil was found at ~1,724 ft; inconclusive
L11	11	1,809	Small leak	2.0	Verification attempted, but no wet soil was found at ~1,809 ft; inconclusive
L12	12	1,930	Small leak	5.5	Verification attempted; soil was moist at ~1,930 ft; leak not pinpointed, but elevated moisture indicative of leak.

Table 4-10. Evaluation of Simulated Leaks Detected by SmartBall™[21]

Corp Valve ID	Distance to Leak (ft)		Estimated Leak Rates (gpm)									
			Demo 1 (calibration)		Demo 2		Demo 3		Demo 4		Demo 5	
	Actual	SB[(b)]	Actual[(a)]	SB	Actual[(a)]	SB	Actual[(a)]	SB	Actual[(a)]	SB	Actual[(a)]	SB
CV1	577.4	579	0.57	0.57	--	0.3	1.0	1.8	0.06	4.5	7.8	8
CV2	578.4		--		0.06		1.9		4.6		--	
CV3	1,082.2	1,080	7.8	8	--	2.8	0.14	7.2	--	0.1	0.57	0.57
CV4	1,082.8		--		0.14		0.57		--		--	
CV5	1,084.1		--		--		--		1.0		--	
CV6	1,084.9		--		0.57		4.6		--		--	
CV7	1,583	1,580	--	0	1.0	15	7.8	30	7.8	40	--	0
CV8	1,585.7		--		7.8		0.57		1.9		--	

(a) Actual leak rates assume a pipeline pressure of 54 psi as representative of the operating pressures.
(b) SB stands for SmartBall™; One location was reported for all simulated leaks associated with a specific pit.

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[20] The gray background signifies natural leaks that were verified in the field (by pinpointing leak or elevated moisture); the yellow background signifies leaks that we attempted to verify, but could not find any evidence of a leak; and the white background signifies leaks found by one or more leak detection technologies, but were not verified in the field.
[21] The text with a red background signifies leak rate estimates that are off by one or more categories as defined by each individual vendor.

4.3 Echologics LeakfinderRT

LeakfinderRT presented two sets of leak detection/location results: (1) for the simulated leaks, including an estimated leak rate; and (2) for naturally occurring pipeline leaks.. Leakfinder RT first attempted to use hydrophones in Pit 1 and Pit 3, which are located near each end of the test pipe, to assess the simulated leaks in Pits 2, 4, and 5. However, detection of the relatively small calibration leak (0.6 gpm) over the 2,057 ft pipe length was not possible due to ambient noise masking the signal. Instead, LeakfinderRT placed the hydrophones at approximately 1,000 ft intervals and collected leak rate data on three sections of the test pipe (see Table 4-11). The three sections were chosen so that a pit containing simulated leaks would be bracketed by the two hydrophone sensors. As shown in Table 4-12, LeakfinderRT used a second configuration which involved placing accelerometers at much shorter distances to detect natural leaks. The accelerometers were installed, with distances between sensors of approximately 250 ft to 361 ft, in Pits 1 through 3 and Pits A through F.

Table 4-11. Hydrophone-to-Hydrophone Distances for Detection of Simulated Leaks

Location of Leak (Pit #)	Location of Hydrophones	Sensor-to-Sensor Spacing (ft)
Pit 4	Pit 1 & Pit 2	1,080.7
Pit 5	Pit 2 & Pit 3	979.3
Pit 2	Pit 4 & Pit 5	1,001.6

Table 4-12. Accelerometer-to-Accelerometer Distances for Detection of Natural Leaks

Location of Leak (ft)	Location of Accelerometers	Sensor-to-Sensor Spacing (ft)
0-250	Pit 1 & Pit A	250
250-510	Pit A & Pit B	260
510-809	Pit B & Pit C	299
809-1,080	Pit C & Pit 2	271
1,080-1,439	Pit 2 & Pit E	361
1,439-1,750	Pit E & Pit F	295
1,750-2,057	Pit F & Pit 3	313

4.3.1 Summary of Results. LeakfinderRT reported three natural leaks and 7 simulated leak clusters. Details of the natural leaks reported by LeakfinderRT (with accelerometers) are presented in Table 4-13 with specific information on the distance from the contact point and estimated leak rate. Details of the detected simulated leaks are presented in Table 4-14, specifically the corp valve ID and leak rate reported by LeakfinderRT (with hydrophones) for each simulated leak.

Table 4-13. Natural Leaks Detected by LeakfinderRT with Accelerometers

Location of Accelerometers	Upstream Accelerometer Location (ft)	Downstream Accelerometer Location (ft)	Distance (ft)	Leak Location (ft)	Estimated Leak Rate (gpm)
Pit A & Pit B	250	510	260	341.5	2.5-5.0
Pit F & Pit 3	1,750	2,057	307	1,912	1.0-2.5
Pit F & Pit 3	1,750	2,057	307	1,930	1.0-2.5

Table 4-14. Simulated Leaks Detected by LeakfinderRT with Hydrophones

Pit #	Corp Valve ID	Est. Leak Rates (gpm)	Dist. to Leak (ft)	Est. Leak Rates (gpm)	Dist. to Leak (ft)	Est. Leak Rates (gpm)	Dist. to Leak (ft)	Est. Leak Rates (gpm)	Dist. to Leak (ft)
		Demo 1 (calibration)		Demo 2		Demo 3		Demo 4	
Pit 4	CV1 CV2	Negligible	--	Negligible	--	2.0 to 5.0	577.6	0 to 1.0	560.7
Pit 2	CV3 CV4 CV5 CV6	8.0	1077.1	Negligible	--	5.0 to 8.0	1082.2	2.5 to 5.0	1,092.6
Pit 5	CV7 CV8	--	--	5.0 to 8.0	1580.2	5.0 to 8.0	1578.2	Negligible	--

4.3.2 Leak Evaluation. LeakfinderRT (with accelerometers) reported three natural leaks within the inspected area. LeakfinderRT (with accelerometers) reported the largest natural leak at L4 (341.5 ft) and another two leaks near 1,912 ft (L12) and 1,930 ft (L12), which were also found by Sahara® and SmartBall™. However, it failed to identify natural leaks at bell-and-spigot joints near 53 ft, 195 ft, 556 ft and 640 ft (i.e., L1, L3, L6 and L7), which were confirmed to exist. It is not clear whether LeakfinderRT would have found these leaks had the larger leaks been repaired and their noise signatures removed.

LeakfinderRT (with hydrophones) reported 7 of 19 total simulated leaks and reported 7 of 11 leak clusters. The simulated leaks were placed in clusters of one to three consecutive leaks, from orifices of different sizes, arranged 0.6 to 2.7 ft apart. Within each leak cluster, LeakfinderRT accurately characterized the leak range for 5 of the 11 clusters. For leak clusters not accurately characterized, 3 of 6 were below the 0.6 gpm threshold defined by LeakfinderRT during the demonstration. The other three leaks not accurately characterized were off by approximately one size range. The location accuracy was within 0 to 5 ft of the actual leak location, except for Demo 4 where the distances were off by a maximum of 17 ft. As with the other technologies, LeakfinderRT was not able to discern two or three individual leaks in close proximity (less than 2.7 ft apart) for any of the simulated leaks.

With a leak rate of 0.6 gpm and a sensor spacing of 1,080.7 ft or greater in the calibration run, LeakfinderRT (with hydrophones) was unable to detect the leak during the correlation test. Although the LeakfinderRT(with hydrophones) was unable to detect the small calibration leak, Echologics still considered the calibration run to be successful, since it defined a boundary of leak rate-hydrophone spacing beyond which leaks in the test pipe cannot be correlated with the existing equipment.

Table 4-15 summarizes the findings of the LeakfinderRT (with accelerometers) assessment of naturally occurring leaks compared with the field verification results. Table 4-16 presents a summary of the simulated leak results reported by LeakfinderRT (with hydrophones) compared with the actual leak rate based on the orifice size and pipeline pressure at the time the inspection was conducted.

Table 4-15. Evaluation of Natural Leaks Detected by LeakfinderRT with Accelerometers[22]

EPA Contractor Leak ID	Location of Sensors	Leak Location (ft)	Estimated Leak Rate (gpm)	Visually Verified by EPA Contractor?
L1	Pit 1 (0 ft) and Pit A (250 ft)	No leak detected		Verification attempted; soil was wet, but there was a nearby storm sewer at 52 ft; leak not pinpointed, but elevated moisture indicative of leak.
L3	Pit 1 (0 ft) and Pit A (250 ft)	No leak detected		Verification attempted; water in pit near bell-and-spigot joint at ~195 ft; did not pinpoint leak.
L4	Pit A (250 ft) and Pit B (510 ft)	341.5	2.5-5.0	Verification attempted; leak at bell-and-spigot joint ~339 ft
L6	Pit B (510 ft) and Pit C (809 ft)	No leak detected		Verification attempted; leak at bell-and-spigot joint at ~556 ft
L7	Pit B (510 ft) and Pit C (809 ft)	No leak detected		Verification attempted; leak at bell-and-spigot joint ~640 ft
L12	Pit F (1,750 ft) & Pit 3 (2,057 ft)	1,912	1.0-2.5	Verification attempted; soil was moist in this area but could not locate the leak at ~1,912 ft; inconclusive
L12	Pit F (1,750 ft) & Pit 3 (2,057 ft)	1,930	1.0-2.5	Verification attempted; soil moist at ~1,906 ft; leak not pinpointed; elevated moisture indicative of leak.

Table 4-16. Evaluation of Simulated Leaks Detected by LeakfinderRT with Hydrophones[23]

Demo No.	Pit ID	Corp Valve ID	Actual Dist. (ft)	Actual Leak Rate (gpm)[(a)]	LeakfinderRT Leak Rate (gpm)	LeakfinderRT Dist. (ft)
1	Pit 4	CV1	577.4	0.57	Negligible	-
	Pit 2	CV3	1,082.2	7.8	8.0	1,077.1
2	Pit 4	CV2	578.4	0.06	Negligible	-
	Pit 2	CV4	1,082.8	0.14	Negligible	-
		CV6	1,084.9	0.57		
	Pit 5	CV7	1,583.0	1.0	5.0 to 8.0	1,580.2
		CV8	1,585.7	7.8		
3	Pit 4	CV1	577.4	1.0	2.0 to 5.0	577.6
		CV2	578.4	1.9		
	Pit 2	CV3	1,082.2	0.14	5.0 to 8.0	1,082.2
		CV4	1,082.8	0.57		
		CV6	1,084.9	4.6		
	Pit 5	CV7	1,583.0	7.8	5.0 to 8.0	1,578.2
		CV8	1,585.7	0.57		
4	Pit 4	CV1	577.4	0.06	0 to 1.0	560.7
		CV2	578.4	4.6		
	Pit 2	CV5	1,084.1	1.0	2.5 to 5.0	1,092.6
	Pit 5	CV7	1,583.0	--[(b)]	Negligible	-
		CV8	1,585.7	1.9		

(a) Pressure assumed to be 54 psi for actual leak rate calculations.
(b) CV7 was closed for LeakfinderRT demo.

[22] The gray background signifies natural leaks that were verified in the field (by pinpointing leak or elevated moisture) and the red background signifies false negatives.
[23] The text with a red background signifies leak rate estimates that are off by one or more categories as defined by each individual vendor.

4.4 Cost of Leak Detection/Location

The cost of leak detection/location has two main components: (1) the cost of the leak detection/location service provided by the inspection vendor; and (2) the cost for the water company to prepare the line and support the leak detection/location vendor, which is often more difficult to quantify.

4.4.1 Leak Detection/Location Services. The leak detection/location vendor's cost to conduct a leak detection/location survey is dependent on a number of variables including the length and diameter of pipe to be inspected, pipe accessibility, and types of services requested (some vendors offer volume discounts for leak detection and condition assessment services). Costs usually include mobilization/demobilization, inspection (per ft or mile), tap installation (if required), travel, and data analysis and reporting. Inspection service providers will readily provide cost proposals for specific lines to be inspected, however, it is rare that a water company will only inspect a short segment of pipe such as the one used for this demonstration.

To supplement the cost information gathered for the demonstration, EPA's contractor also requested that the vendors provide a cost estimate for inspecting 10,000 feet of 24-in. cast iron pipe along the same route as the demonstration in Louisville, KY. They were asked to include in their cost estimates:

- The cost of conducting a leak survey alone
- The cost of conducting a pipe wall thickness assessment alone
- The cost of conducting both (leak and pipe wall thickness survey) at the same time.

Each vendor was given drawings of the 30-in. diameter pipeline that replaced the test pipe used for the demonstration. The vendors were instructed that the pipeline for the cost estimate would follow the route of the 30-in. line, but to assume that the line is 24-in. diameter and 10,000 ft in length.

To the extent possible, the vendors were asked to supply with their cost estimates:

- Costs for line modifications to perform the inspection (and who is responsible for the modifications)
- Mobilization/demobilization costs
- Inspection costs (including data analysis and reporting)
- Factors that can affect pricing, such as diameter, length, risers, valves, bends, tees, insertions, etc. and how these factors might impact the cost

Since some details regarding the pipeline and its location were not well defined, the vendor was informed that a range of costs was acceptable.

PPIC Sahara®

For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a Sahara® leak and/or pipe wall thickness inspections are provided in Table 4-17. Costs were not broken out by individual activity (e.g., data acquisition, data analysis, reporting, etc.). Charges for mobilization/demobilization are $4,000 while data analysis and reporting are included in the price of the survey.

As reported by PPIC, each site inspection has different factors that may result in modification costs for either the client or inspection vendor. Pipeline and operational parameters, such as pipeline length, access preparation, features, flow condition, etc. can affect pricing. Proper pre-inspection preparation (drawings, access preparation, flow rate control, etc.) by the client can significantly increase productivity while reducing the overall cost of the inspection. Inspecting longer lengths of pipe at the same time can benefit from long-term program pricing discounts.

Table 4-17. PPIC Sahara® Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline

Type of Survey	Cost Estimate[24]
Leak and gas pocket survey (includes data acquisition, data analysis, and final report)	$22,000
Pipe wall thickness survey (includes data acquisition, data analysis, and final report)	$33,000
Leak and gas pocket AND pipe wall thickness survey (includes data acquisition, data analysis, and final report)	$44,000

Pure SmartBall™

Pure provided a range of costs to conduct three types of surveys: (1) a leak and gas pocket survey, (2) a pipe wall thickness survey, and (3) both leak and pipe wall thickness surveys on one mobilization. Line modifications would be required of the client to install two 4-in. taps, one at the beginning and one at the end of the survey length. Pipeline flow would also need to be maintained between 1.5 and 2 ft/s and pipeline pressure above 10 psi. Pure stated that it was possible to conduct a leak survey at lower pipeline pressures, but the accuracy of the results could sometimes be compromised. Pure also stated that these prices were to be used as a guideline and not as fact for inspection projects of this size.

For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a SmartBall™ inspection are provided in Table 4-18. Costs were not broken out by individual activity (e.g., mobilization, data acquisition, reporting, etc.). Charges for mobilization, demobilization, data acquisition, data analysis, and final report run between $25,000 and $40,000 per inspection depending on which technology is used. Technology charges run between $12,000 and $20,000 per mile of survey, again depending on which technology is used.

Table 4-18. Pure SmartBall™ Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline

Type of Survey	Cost Estimate[24]
Leak and gas pocket survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report)	$40,000 to $50,000
Pipe wall thickness survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report)[25]	$55,000 to $65,000
Leak and gas pocket AND pipe wall thickness survey (includes mob/demob, data acquisition, data analysis, technology charges, and final report)	$80,000 to $90,000

[24] The Sahara®, SmartBall™, and LeakfinderRT cost estimates do not include utility preparation and support costs.
[25] Pure requires feedback on the pipe wall assessment results from the Louisville demonstration before they are comfortable quoting more specific cost estimates.

This type of survey would require two days onsite, one to do a site review with the client and an actual day of work with the tool in the pipeline. Pure can produce an on-site interim report and the final report within two weeks of completing the survey. The interim report generated just after the survey, while the field crew is still onsite would cost an additional $3,000 to $5,000.

Echologics LeakfinderRT

Echologics provided a fairly detailed cost proposal describing the work to be done for executing leak and condition assessment surveys for a 24-in. diameter, 10,000 ft long cast iron pipeline. Preparation work would be required by the client before the arrival of Echologics field technicians and includes:

- Assess traffic management requirements and prepare a traffic management plan.
- Identify confined space entry locations and provide a confined space entry plan and necessary equipment.
- Identify all fittings to be used for the inspection and mark with blue spray paint or the equivalent.
- All fittings should be in working order with no leaking seals or joints when under pressure. Any leaking fittings must be repaired before the inspection. Failure to do so prevents accurate data from being acquired in this location.
- Any valves installed on the pipe to be surveyed should be operated, if possible, to make sure they are fully open. Any boundary/closed valves should be acoustic sounded to make sure the valve is not passing water.
- Valve boxes, chambers, and vaults are to be cleared of debris prior to the inspection. Failure to meet this requirement will prompt the need for an on-call VAC truck for the duration of the project.
- Provide detailed maps, plans, and as-built drawings, if possible, showing all pipe fittings and any other essential distribution information to establish a data acquisition plan.
- Provide all repairs and rehabilitation history, if possible, on the section of pipe to be surveyed.
- Air must not be present in the main and all air relief valves must be in good working order and inspected prior to the start of the survey. If air is present, flushing must be undertaken to eliminate any trapped air.
- Pipe pressure must be maintained at a minimum working pressure of 25 psi with a maximum pressure of 150 psi. Anything outside of these limits will require special consideration.

Echologics also requires the provision of an experienced water operator with a fully equipped truck for the duration of the project. These requirements are necessary to accomplish the project within the proposed timeline and budget.

For the leak detection survey, Echologics will mount hydrophones on air valves, pitot taps, or wash outs, as available. The hydrophones require a 1.5-in. NPT male nipple for installation. Echologics can supply all fittings if they are provided with the thread sizes. The sensor-to-sensor spacing shall not exceed 1,000 ft (305 m).

For the condition assessment survey, Echologics requires access to the pipe every 300 to 500 ft through the use of vacuum excavated potholes. The potholes should measure 6 to 8-in. in diameter and provide access to the top of the pipe. Data acquisition will be performed using magnetic surface mounted sensors attached to available fittings or the pipe surface. Fire hydrants will need to be flushed to take the water temperature at each measurement site. Pipeline installation date and site-specific pipe manufacturer data must be provided prior to field work.

Echologics provided cost estimates for mobilization, data acquisition, data analysis, and final reporting. Mobilization includes all of the preparation work required by Echologics field technicians along with travel and shipping expenses. Data acquisition will take approximately 3 to 5 days with two field technicians. Generally, it is possible to cover between 2,500 ft and 5,000 ft of pipe per day. If any leaks are discovered during the data acquisition process it will be the decision of the client as to whether or not a detailed investigation will be performed to pinpoint the location of the leak. Data analysis includes the time required to analyze the acoustic recordings upon completion of data acquisition using proprietary processes. The analysis time will depend on the pipe size and total length of pipe surveyed. The final report will summarize all of the results and include background, methodology, sources of error, data interpretation methods, analysis, results, and final recommendations. A draft report will be submitted to the client prior to its finalization.

For a 24-in. diameter, 10,000 ft long cast iron pipe, the cost estimates for a LeakfinderRT inspection are provided in Table 4-19.

Table 4-19. Echologics LeakfinderRT Cost Estimates for Inspection of a 24-in. Diameter, 10,000 ft Long Cast Iron Pipeline

Type of Survey	Rate	Units	Cost Estimate[26]
Leak detection survey			
Mobilization	$3,000	flat	$3,000
Data Acquisition	$1.25	ft	$12,500
Data Analysis	$0.25	ft	$2,500
Reporting	$165	hrs	$2,310
Total			**$20,310**
Condition assessment and leak detection[26]			
Mobilization	$3,500	flat	$3,500
Data Acquisition	$1.50	ft	$15,000
Data Analysis	$0.50	ft	$5,000
Reporting	$165	hrs	$3,630
Total			**$27,130**

For a leak detection survey only, Echologics estimated a total of three to four days onsite and an additional 14 hours of data analysis and final report preparation. The rate proposed is based on a 10 hour workday. If overtime is needed the client will be invoiced accordingly. A standby rate of $1,500 per person per day is incurred if Echologics field technicians are delayed for reasons out of their control (not including weather).

For a condition assessment and leak detection survey, Echologics estimated a total of four to five days onsite and an additional 22 hours of data analysis and final report preparation.

[26] Leak detection is automatically performed during the condition assessment process.

4.4.2 Site Preparation. The inspection costs presented above do not include the cost for the water utilities to prepare the line and provide traffic control and other logistical support. This site preparation cost for line modification and field support is highly site-specific. It will depend upon regional costs for construction labor, along with factors such as the access requirements, availability and condition of existing hydrants/valves, length of deployment, days on site, and more. Based on typical construction costs (RSMeans, 2011), it is estimated that the site preparation costs for a leak detection inspection of 10,000 ft of 24-in. diameter cast iron pipe may range in magnitude from $0.12/ft (for traffic control only with use of existing taps) to $0.43/ft (including traffic control, pit excavation, tapping, backfill, and surface restoration).

During an inspection, SmartBall™ can be inserted into the pipeline through existing hydrants or any valve configuration with greater than 4-in. diameter clearance. SmartBall™ is then retrieved through another 4-in. or greater valve. For purposes of this cost estimate, it is assumed that the two required access points must be installed for a 10,000 ft pipe inspection (e.g., no existing hydrants or valves are used). Table 4-20 estimates the site preparation costs as approximately $4,290 based upon 2 access pits and installation of two 4" taps for a SmartBall™ inspection (with pits located at 0 ft and 10,000 ft).

Table 4-20. Estimated Site Preparation Costs for SmartBall™ Inspection of 10,000 ft pipe

Cost Item	Setup Costs	Quantity	Unit Cost	Unit	Total Cost
1	2 – Rented 6 ft x 8 ft trench boxes	2 boxes x 2 days = 4 days	$93.00	4	$372.00
2	4-in. taps w/ valve and 150 lb standard flange with extension tube	2 taps	$525.00	2	$1,050.00
3	1 CY of stone backfill	1 CY	$46.50	1	$46.50
4	Traffic control	1 person x 2 days x 8 hrs/day = 16 hrs	$50.00	16	$800.00
5	3 Persons - Labor (excavate, install taps, backfill, restoration)	3 persons x 1 day x 8 hrs/day = 24 hrs	$52.70	24	$1,264.80
6	1 Person – Equipment Operator (excavate, remove plates, backfill)	1 person x 1 day x 8 hrs/day = 8 hrs	$67.75	8	$542.00
7	1 – 5/8 CY Wheel Mounted Backhoe	1 day	$215.00	1	$215.00
				Total	**$4,290.30**

During a Sahara® inspection, a 1-in. diameter hydrophone is inserted into a live main through a 2-in. tap. The maximum length of inspection is 6,000 ft based on the umbilical cable length. For purposes of this cost estimate, it is assumed that two required access points must be installed for a 10,000 ft pipe inspection (e.g., no existing taps are used). Table 4-21 estimates the site preparation costs as approximately $3,933 based upon 2 access pits and the installation of two 2-in. taps for a Sahara® inspection (with pits located at 0 ft and 6,000 ft).

Table 4-21. Estimated Site Preparation Costs for Sahara® Inspection of 10,000 ft pipe

Cost Item	Setup Costs	Quantity	Unit Cost	Unit	Total Cost
1	2 – Rented 6 ft x 8 ft trench boxes	2 boxes x 2 days = 4 days	$93.00	4	$372.00
2	2-in. taps w/ valve and 150 lb standard flange with extension tube	2 taps	$346.23	2	$692.46
3	1 CY of stone backfill	1 CY	$46.50	1	$46.50
4	Traffic control	1 person x 2 days x 8 hrs/day = 16 hrs	$50.00	16	$800.00
5	3 Persons - Labor (excavate, install taps, backfill, restoration)	3 persons x 1 day x 8 hrs/day = 24 hrs	$52.70	24	$1,264.80
6	1 Person – Equipment Operator (excavate, remove plates, backfill)	1 person x 1 day x 8 hrs/day = 8 hrs	$67.75	8	$542.00
7	1 – 5/8 CY Wheel Mounted Backhoe	1 day	$215.00	1	$215.00
				Total	**$3,932.76**

Echologics mounts hydrophones on hydrants, air valves, pitot taps, wash outs, or other fittings as available. The hydrophones require a 1.5-in. NPT male nipple for installation. The sensor-to-sensor spacing for the hydrophones was 1,000 ft (305 m) for the Louisville, KY demonstration, so 11 contact points with direct access to the water in the pipe would be needed in a 10,000 ft span. Fire hydrants are typically located at spacings of 500 to 1,000 ft apart, so it is assumed that in a typical application where Echologics was selected as an appropriate option that no excavation would be required and existing fittings could be used. Traffic control for a 3-day inspection would be approximately $1,200.

5.0: REFERENCES

Hunaidi, O., A. Wang, M. Bracken, T. Gambino, and C. Fricke. 2004. *Acoustic Methods for Locating Leaks in Municipal Water Pipe Networks*. International Conference on Water Demand Management, Dead Sea, Jordan, 1-14.

RSMeans. 2011. *CostWorks® Cost Books Online*. http://meanscostworks.com/. Norcross, GA: Reed Construction Data.

Thomson, J. and Wang, L. 2009. *Condition Assessment of Ferrous Water Transmission and Distribution Systems: State of the Technology Review Report*. EPA/600/R-09/055, prepared for U.S. EPA, Office of Research and Development, National Risk Management Research Laboratory. http://www.epa.gov/nrmrl/pubs/600r09055/600r09055.pdf

APPENDIX A

THE PRESSURE PIPE INSPECTION COMPANY SAHARA® LEAK DETECTION* REPORT
(See Appendix A, pp. 4 to 7; 10 to14; and 29 to 36)

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1. EXECUTIVE SUMMARY

Over the course of July 13th to 29th, 2009, the Pressure Pipe Inspection Company (PPIC) performed non-destructive condition assessment of a cast iron main using two non-disruptive inspection platforms, Sahara and PipeDiver. The assessment was conducted on a 2057 foot long, 24 inch diameter, cast iron section of the Westport Rd. Transmission Main between Pit 1 (Launch/Insertion Pit) and Pit 3 (Receive/Extraction Pit).

PPIC used its patented Sahara Technology, including Sahara Leak Detection, Sahara Video, and Sahara Wall Thickness Testing. In addition, PPIC conducted a Remote Field Eddy Current (RFEC) pilot test for metallic pipe wall condition assessment using the PipeDiver inspection platform. Both technologies are non-disruptive and allow the pipeline to remain in service during the inspection. PPIC's inspections are part of a study conducted by the U.S. Environment Protection Agency (EPA).

Sahara Leak Detection identified six natural leaks and an air pocket within the inspected area and detected all simulated leaks. Sahara Video identified several corrosion spots, outlets, and air pockets within the pipeline. Analysis of the Sahara Wall Thickness Testing data revealed several areas of suspected wall thickness loss. PipeDiver RFEC testing was performed over the full scope (2057 ft) under live conditions and identified 41 pipe sections with anomalous data signals. Verification and further calibration are recommended to confirm the exact nature of these anomalies and help in further refinement of the PipeDiver analysis procedures. Each individual technology provides a particular service but their combined results provide a complete overall condition assessment of the pipeline.

2. PROJECT BACKGROUND

2.1 Project Background

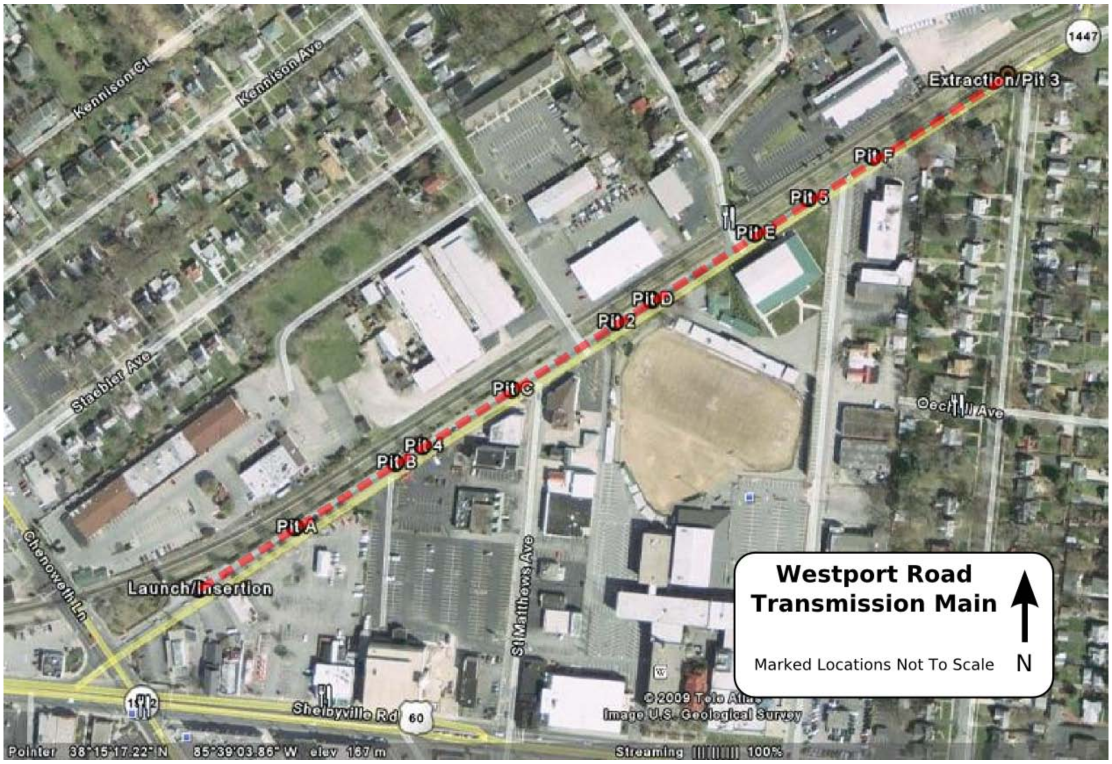
The U.S. Environmental Protection Agency (EPA) contracted the Battelle Memorial Institute (BMI) to demonstrate selected innovative leak detection/location and structural condition assessment technologies. This study emphasizes the need for non-invasive, non-destructive, "inexpensive" techniques to help utilities assess the condition of their lines to allow them to make good decisions regarding capital replacements, rehabilitation or monitoring of their pipe infrastructure.

The Pressure Pipe Inspection Company (PPIC) is one of the several companies contracted by BMI to demonstrate their non-destructive condition assessment techniques of metallic pipes. These include PPIC's patented Sahara Leak Detection, Sahara Video, Sahara Wall Thickness Testing and PipeDiver RFEC Testing. All these technologies are invasive, requiring internal pipe access, but are non-disruptive in nature and are performed while the pipeline is in service. Each technology has its own set of advantages and limitations which allows utilities an option on which inspection technique best fits their needs and expectations. Additionally, multiple techniques can be applied to a single pipeline to provide successive levels of detail about the pipe condition.

The condition assessment technologies deployed by PPIC are at various stages of commercial deployment. The Sahara leak detection system, for example, has been successfully used commercially worldwide for over 10 years. While PipeDiver has been successfully used in PCCP for live condition assessment, PipeDiver RFEC for metallic pipes is still undergoing development and in the process of becoming a commercially available service.

The Westport Rd. Transmission Main is a 24 inch diameter cast iron pipe that has been taken out of service. EPA has acquired this pipeline for a non-destructive condition assessment study, which PPIC is a part of. A map showing the approximate location of the inspected pipeline is shown in Figure 2.1.

Figure 2.1 Pipeline Plan



Additional features were created along the inspection scope for various test procedures. These features are listed in Table 2.1 (distances provided by the Battelle Memorial Institute).

Table 2.1 Feature List

Feature	Distance from Pit 1 (ft)	STA
Pit 1 (Launch/Insertion Pit)	0	160+55
Pit A	250	163+05
Pit B	510	165+65
Pit 4	581	166+36
Pit C	809	168+64
Pit 2	1080	171+35
Pit D	1173	172+28
Pit E	1439	174+94
Pit 5	1580	176+35
Pit F	1750	178+05*
Pit 3 (Receive/Extraction Pit)	2057	181+12

*Approximate STAs are in relation to fire hydrant STA of 178+05 (hydrant listed in same location as Pit F from Battelle chart).

2.2 Purpose of Inspection

The purpose of this inspection is to demonstrate PPIC's various non-destructive condition assessment services on metallic pipe which, together, provide an overall condition assessment of the pipeline. These services include:

- A visual inspection of the inside of the pipeline
- Identifying and quantifying the presence of leaks
- A pipe wall assessment including wall thickness loss and irregularities

All services are performed using PPIC's patented Sahara technology platform and the PipeDiver platform, both of which are live inspection platforms that operate while the pipeline is in service.

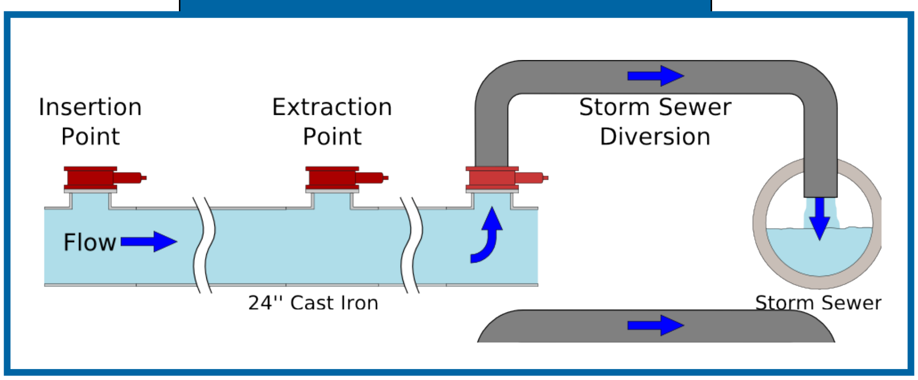
2.3 Test Pipe Line Description

The non-destructive condition assessment inspections of the Westport Rd. Transmission Main were conducted from July 13th to 29th, 2009. The test details are summarized in Table 2.2.

Table 2.2 Test Summary	
Pipeline	Westport Rd. Transmission Main
Inspection Dates	July 13th to 29th, 2009
Total Distance	2057 feet

In order to produce sufficient flow in the pipeline for inspection purposes a 12 inch tee past the extraction point was used to temporarily create flow by diverting water into a nearby storm drain.

Figure 2.2 Pipeline Flow Setup



The flow amount and duration was limited by the capacity of the storm sewer. In the event of rain, the storm sewer's capacity would be reduced or eliminated entirely which, in turn, would likewise affect the flow available in the 24 inch cast iron line.

3. SAHARA TECHNOLOGY

3.1 Background and Theory

3.1.1 Sahara Platform

The first tool designed for live inspection of large diameter water mains, the Sahara Pipeline Inspection System, is capable of detecting leaks, pockets of trapped gas, and structural defects in large mains. Sahara is a critical component of condition assessment and water loss management programs for utilities around the world. The unique Sahara platform allows adaption of multiple technologies such as leak detection, video inspection, and wall thickness assessment.

Advantages to the Sahara inspection system include:

- No disruption to pipeline service
- Use existing 2 inch (50 mm) taps
- A tethered system allows complete control of the sensor's position along the pipe and ensures no lost sensors
- Accurate surface tracking to map pipelines and leak locations
- Usable in mains of all material types, as small as 4 inches in diameter, and with pressures up to 200 PSI

3.1.2 Sahara Leak Detection

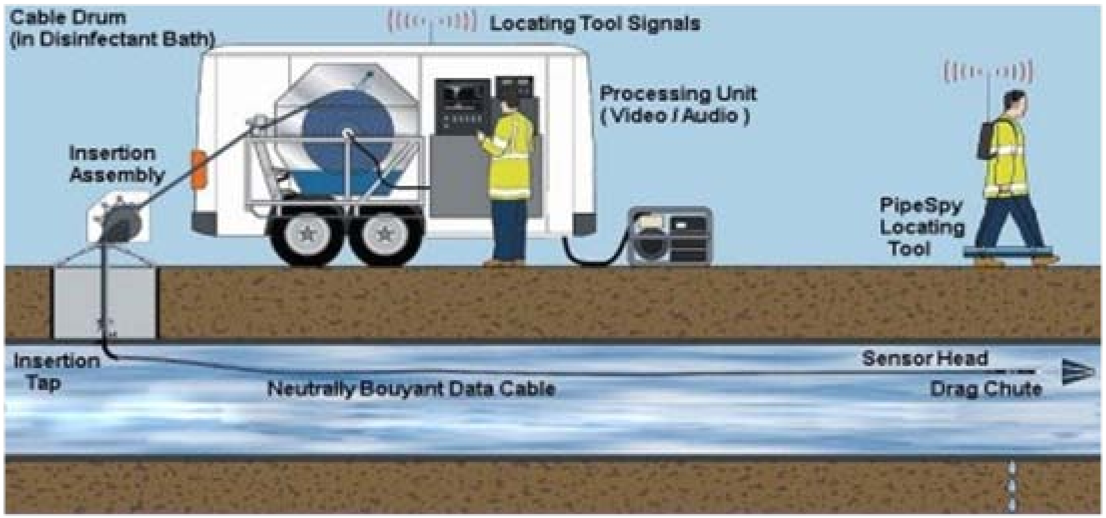
The Sahara system is a non-destructive condition assessment technology that pinpoints the location and estimates the magnitude of leaks in large diameter, 12 inch and above, water transmission mains of all construction types. With over 1,000 miles (1,600 km) of inspections Sahara Leak Detection has proven sensitive to leaks as small as 0.005 gal/min (located in 72" PCCP at 87 psi). Leaks are located above ground in real-time and marked to within 1 foot of accuracy.

In operation, the system is inserted into a live pipeline through any tap that is at least 2 inches in diameter. Carried by the flow of water, the tethered sensor head can then travel through the pipe for distances up to 6,000 feet per survey detecting each leak as it is found. The leak's position is then located and marked on the above ground surface facilitating subsequent repairs.

An electronics processing unit with audio and visual output is used for data analysis. A leak produces a distinctive acoustic signal which is recorded by the sensor and processed into a visual signal. The visual signal is then analyzed along with the audio signal to quantify the leak.

In no flow situations a second tethering line (mule tape) can be used to pull the hydrophone through a pipeline.

Figure 3.1 Sahara Inspection System

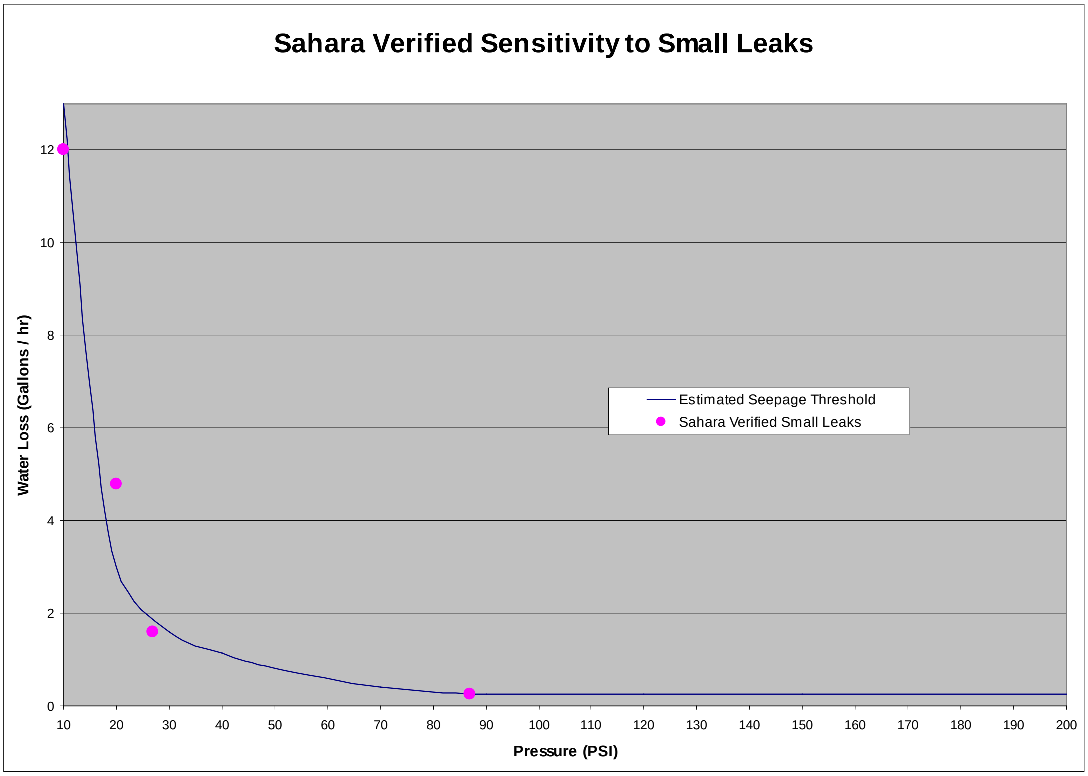


An operator stands by at the controller station to control hydrophone deployment and listen to the hydrophone signal for leaks in real time. Once a leak is detected the hydrophone can pass over the leak multiple times to classify and pinpoint the leak. A second operator travels the pipeline above ground using a tool to detect the exact location of the sensor. When a leak is detected this operator will make a mark on the ground identifying the location and record a GPS point for reference.

The capable survey length of the Sahara system is limited not only by the amount of available cable, usually 1.2 miles (2 km), but also by the pipeline geometry (horizontal/vertical elbows and bends), the pipeline flow rate, and the internal pipe conditions.

Sahara Leak Detection is a proven technique in identifying the smallest leaks in pipelines. Figure 3.2 below depicts some verified leaks and the corresponding pressures the leaks were detected at.

Figure 3.2 Sahara Verified Leaks



Calibration is performed by testing each hydrophone and comparing it to a standard frequency response. The Sahara hydrophone has sensitivity to leaks as small as 0.005 gal/min (detected on 48" PCCP pipeline at 87 psi).

Data is interpreted and analyzed in real time by on screen spectrogram and audio listening. Using dual analysis methods provides high accuracy and can clearly distinguish leaks from ambient noise.

Factors such as low water pressure, electrical noise, air pockets, and external ambient noise can all affect the real time analysis of the sensor signal. During the inspection, some leaks were masked by external factors and required post analysis to detect the leaks.

3.1.3 Sahara Video Description

Sahara Video provides real time, in-service CCTV inspection through a 2 inch or larger tap. Real-time video inspection enables visual inspection of features including:

- Cement and other liners
- Internal corrosion and tuberculation assessments
- Valve location and inspection
- Debris and blockages

Figure 3.3 Sahara Video Head

The Sahara video system utilizes the same control system and tethered cable as the Sahara Leak Detection system but the hydrophone sensor head is switched to a video camera head that traverses a pipeline after begin inserted through a standard 2 inch tap. A drogue (parachute) is attached just behind the camera which captures water flow and carries the camera and cable down the pipeline.

An operator stands by at the controller station to control camera deployment and views the video output in real time. A second operator traverses the pipeline above ground using a tool to detect the exact location of the camera. When an item of interest is seen the second operator will make a mark on the ground identifying the location and record a GPS point for reference.

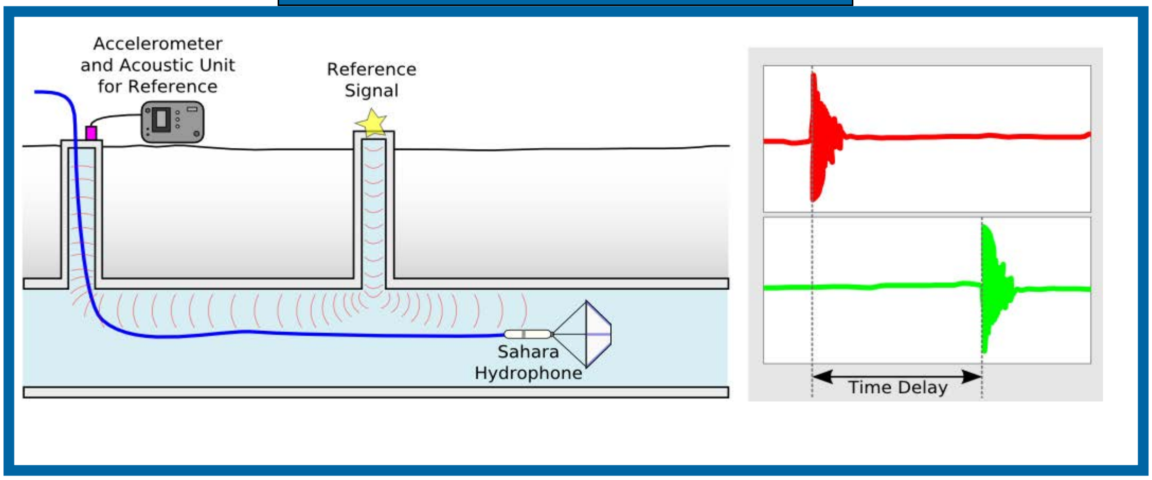
Like the Sahara leak detection, the Sahara video system has a limited survey length from the pipeline configuration and available flow rate. One circumstance or factor affecting accuracy is video clarity. Video image becomes less clear in larger diameter pipes, due to diffuse lighting and reduced field of view, and unclear water. To calibrate the video system, each video camera is tested and compared to a standard frequency response. Video is interpreted and analyzed in real time, but also recorded for future examination.

3.1.4 Sahara Wall Thickness Testing

Sahara Wall Thickness Testing can be performed in conjunction with a Sahara Leak Detection inspection. Testing requires a secondary acoustic sensor, either an external accelerometer attached to the pipe surface or an additional internal hydrophone. Reference signals (e.g., test strikes at access points or sounds produced by a speaker) are generated within the pipe for testing.

The sound waves propagate through the pipeline in a specific manner bouncing repeatedly off of the pipe walls. As the sound wave travels in this manner they gather information about the pipe wall. By measuring the speed of sound multiple times in a section of pipe the average wall thickness can be deduced. By using multiple acoustic sensors separated by a known distance time of arrival data from the reference signal can be used to calculate the speed of sound within the pipe and thus the average wall thickness.

Figure 3.4 Sahara Wall Thickness



The tethered control of the Sahara system allows the hydrophone to stop at precise locations for each interval. Time of arrival data is then used to calculate the average wall thickness over each interval. Since the wall thickness average intervals are defined by hydrophone location there are infinite interval possibilities limited only by the amount of time and resources available for the inspection.

Sahara wall thickness has the same limitations on survey as the leak detection system. Also like the leak detection, air pockets can significantly interfere with the wall thickness measurements as they affect the acoustic signal propagation. It is important to note that the wall thickness measurements resulting from this technique are only an average thickness over a range of pipes

Average wall thickness results need detailed pipe information and fluid parameters for calculations. Current testing procedure requires an access (i.e. hydrant, flange, or exposed pipe surface) a minimum of every 400 feet to generate reference acoustic signals.

Some factors affecting wall thickness accuracy include:

- Distance of a given section (the shorter, the more uncertain)
- Distance readings of the sections
- Accuracy of the pipeline and fluid parameters
- Unknown pipe features
- Rehabilitation, or large stationary air pockets

However, many pipeline related factors can be eliminated through a repeat inspection.

Before each Sahara Wall Thickness test adequate calibration and preparation is performed to ensure high quality. This includes:

- Calibration of Sahara sensor's sensitivity and distance reading
- Calibration of reference acoustic sensor for synchronization with Sahara
- Repeatability tests

A relative result is obtained based on all calculated results in every 30 foot interval. A nominal pipe wall thickness would be calculated from a group of intervals that shows similar wall thickness results (< 2% difference from the mean), and the result of other portions would show the wall thickness change ratio to this nominal value. This relative result is provided instead of calculated wall thickness to eliminate and minimize possible uncertainties introduced by composite pipe material and alterable fluid parameters.

3.2 Sahara Tests

3.2.1 Sahara Test Schedule

A total of five Sahara insertions were performed from July 13th to July 17th for all the different inspection technologies. The Sahara video inspection was performed first, on July 13th, to inspect the inside of the pipeline. This inspection identifies potential obstacles for other internal inspections as well as internal corrosion and air pockets. The Sahara video head was inserted into Pit 1 and traversed the line using the pipeline flow. After reaching Pit 3 the video head was then retracted and taken out of Pit 1.

Sahara Leak Detection was performed on July 14th, 15th, and 17th. Three full surveys of the pipeline were performed to test different arrangements of simulated leaks and perform a repeatability survey under varying conditions. Like the Sahara video head, the Sahara sensor head was inserted and retracted out of Pit 1. The leak detection survey was conducted during the deployment and retrieval of the sensor through the pipeline. On July 15th a thunderstorm required that flow in the pipeline be stopped due to reduced storm sewer capacity and the survey ended before completion.

Sahara Wall Thickness Testing was performed on July 15th and 16th in conjunction with Sahara Leak Detection. The Sahara sensor head was inserted into Pit 1 and secondary external sensors were installed at Pits A, C, E, and 3.

Multiple test reference signals were generated at each of the pits to conduct the wall thickness measurements.

Table 3.1 Insertion Details					
Date	**Insertion Point**	**End Point**	**Survey Length (ft)**	**Flow Direction**	**Description**
July 13th	Pit 1	Pit 3	2057	East	Video
July 14th	Pit 1	Pit 3	2050	East	Leak Detection & Leak Simulations
July 15th	Pit 1	After Pit F	1797	East	Leak Simulations
July 16th	Pit 1	Before Pit 3	1984	East	Wall Thickness
July 17th	Pit 1	Pit 3	2050	East	Repeat Leak Detection, Simulations & Wall Thickness

3.3 Sahara Results

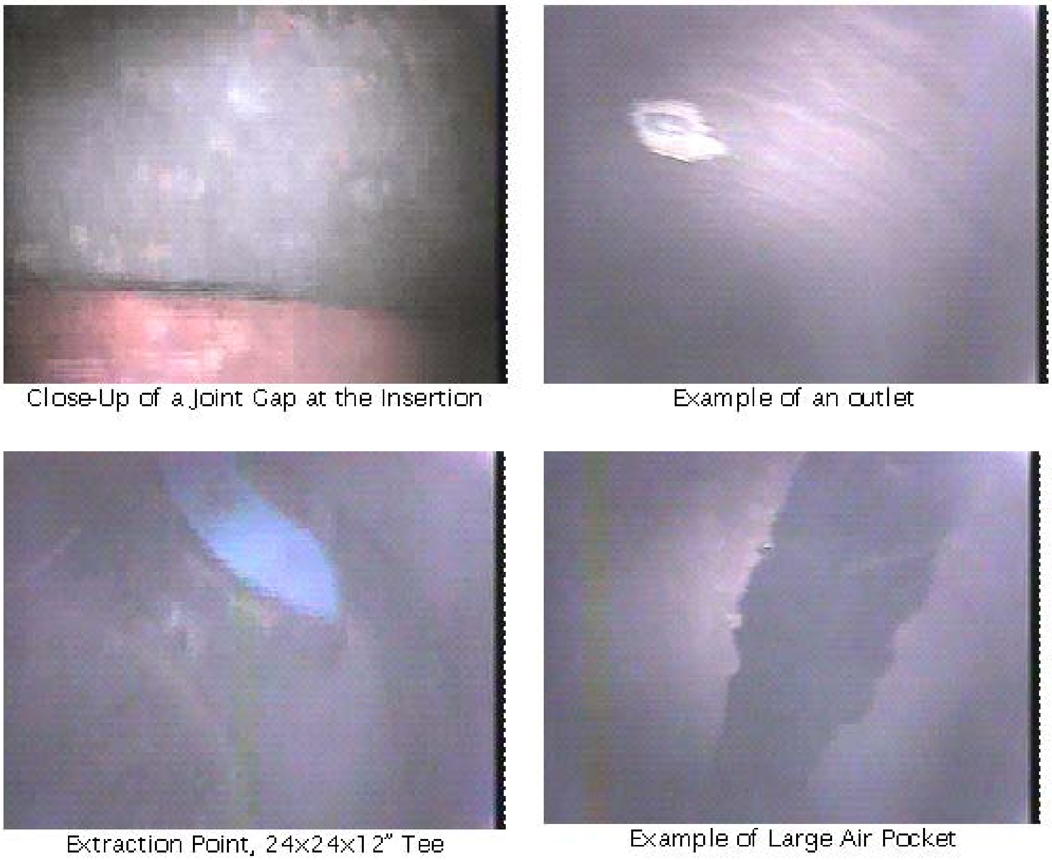
3.3.1 Sahara Video Survey Results

The Sahara Video inspection of Westport Rd. Transmission Main successfully identified several significant observations. Details of the observations are presented in Table 3.2, specifically the direction and distance the observation was found from the insertion point (Pit 1).

Table 3.2 Observation Details				
#	**Description**	**Estimated Distance from Pit 1 (ft)**	**Direction from Insertion**	**Potential Correlated Pipe Feature**
1	Outlet	154	Downstream	
2	Outlet	677	Downstream	
3	Air pocket	886	Downstream	
4	Large air pocket	1024	Downstream	
5	Outlet	1061	Downstream	Pit 2 (1080 ft)
6	Large air pocket	1237	Downstream	
7	Outlet	1552	Downstream	Pit 5 (1580 ft)
8	Corrosion	1565	Downstream	
9	Outlet	1628	Downstream	
10	Large area of corrosion	1637	Downstream	
11	Outlet	1755	Downstream	Pit F (1750 ft)
12	Outlet	1946	Downstream	

Many additional air pockets, ranging from small to large in size, were discovered during the video inspection. Both air pockets and wall corrosion could be clearly distinguished in the video inspection.

Figure 3.5 Sahara Video Examples



Close-Up of a Joint Gap at the Insertion

Example of an outlet

Extraction Point, 24x24x12" Tee

Example of Large Air Pocket

3.3.2 Sahara Leak Detection Results

The Sahara Leak Detection of Westport Rd. Transmission Main successfully identified 6 natural leaks and 14 simulated leaks. Details of the natural leaks are presented in Table 3.3, specifically the direction and distance the leak was found from the insertion point. The most accurate method to locate a leak is from the mark created above ground by the inspection team during the survey.

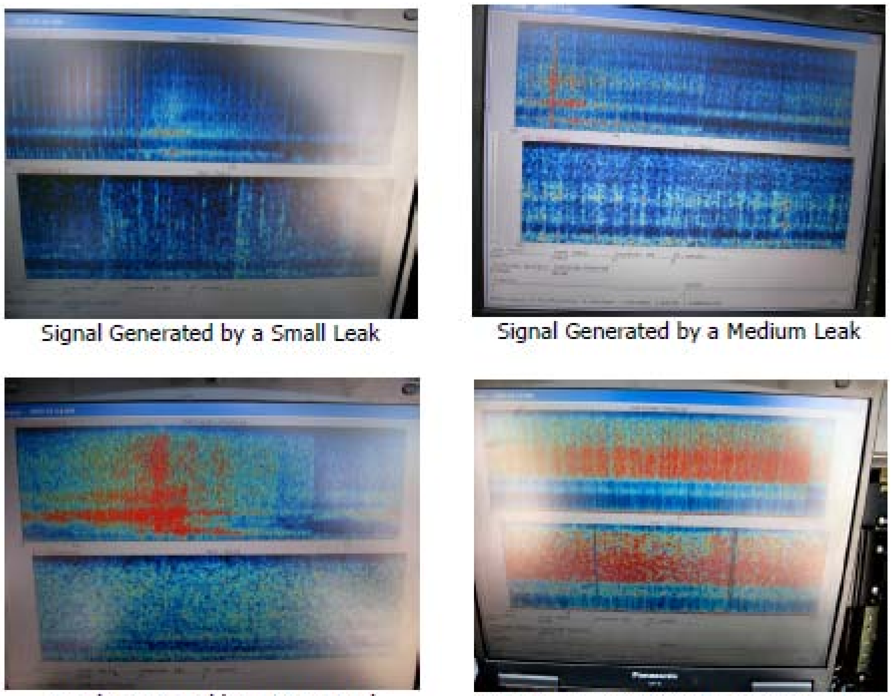
Table 3.3 Natural Leak and Air Pocket Details			
Leak #	**Feature**	**Distance from Pit 1 (ft)**	**Direction from Insertion Point**
1	Very Small Leak	50	Downstream
2	Very Small Leak	194	Downstream
3	Large Leak	338	Downstream
4	Very Small	558	Downstream
5	Small Leak	638	Downstream
-	Large Air Pocket	900	Downstream
6	Very Small Leak	1696	Downstream
7	Small Leak	1906	Downstream

Simulated leaks were rearranged several times. Details of the detected simulated Leaks are presented in Table 3.4, specifically the arrangement number, direction, and location.

Table 3.4 Simulated Leak Details			
Arrangement #	**Date**	**Leak Classification**	**Location**
1*	July 14th	Very small	Pit 4
1	July 14th	Small	Pit 2
2	July 14th	Large	Pit 5
2	July 14th	Very small	Pit 2
2*	July 14th	Very small	Pit 4
3	July 15th	Small	Pit 4
3	July 15th	Small	Pit 2
3	July 15th	Medium	Pit 5
4	July 15th	Medium	Pit 5
4	July 15th	Small	Pit 2
4*	July 15th	Very small	Pit 4
5	July 17th	Small	Pit 4
6	July 17th	Very small	Pit 4
7	July 17th	Very small	Pit 4

*These leaks required post analysis. Leak signal could be masked by air pockets, water discharge, and/or electrical issues.

Figure 3.6 Examples of Sahara Leak Signals



Signal Generated by a Small Leak

Signal Generated by a Medium Leak

Signal Generated by a Large Leak

Signal Generated by the Discharge Line

3.3.3 Sahara Wall Thickness Results

The Sahara Wall Thickness Assessment of Westport Rd. Transmission Main successfully identified specific areas of wall thickness loss. Details of the wall thickness loss are presented in Table 3.5, specifically the pipeline interval and average result over that interval.

Table 3.5 Wall Thickness Details

Distance from Pit 1 (ft)	Average Wall Thickness Loss Ratio (%)
0-17	N/A
17-33	< 15%
33-66	Nominal
66-98	< 15%
98-131	Nominal
131-164	Nominal
164-197	Nominal

197-230	15 - 30%
230-295	N/A
295-328	> 30%
328-361	> 30%
361-394	> 30%
394-426	Nominal
426-459	< 15%
459-492	15 - 30%
492-525	< 15%
525-558	< 15%
558-590	< 15%
590-623	Nominal
623-656	< 15%
656-689	Nominal
689-722	15 - 30%
722-754	15 - 30%
754-787	Nominal
787-1640	N/A
1640-1673	Nominal
1673-1706	Nominal
1706-1738	< 15%
1738-1771	< 15%
1771-1804	< 15%
1804-1837	< 15%
1837-1870	Nominal
1870-1902	Nominal
1902-1935	15 - 30%
1935-2057	N/A

Pipeline intervals with an average wall thickness loss of less than 2% are listed as nominal. The average wall thickness loss ratio is in relation to the nominal mean value.

The section from 295 to 328 feet shows the highest wall thickness loss.

Increased error margin in the section from 230 to 295 feet is due to the close proximity of internal and external sensors. Subsequently, a wall thickness loss ratio cannot be calculated for this interval. From 787 to 1640 feet a wall thickness ratio cannot be calculated due to presence of large air pockets and/or the proximity of sensors. The pipeline discharge masked acoustic activity after 1935 feet.

4. PIPEDIVER TECHNOLOGY

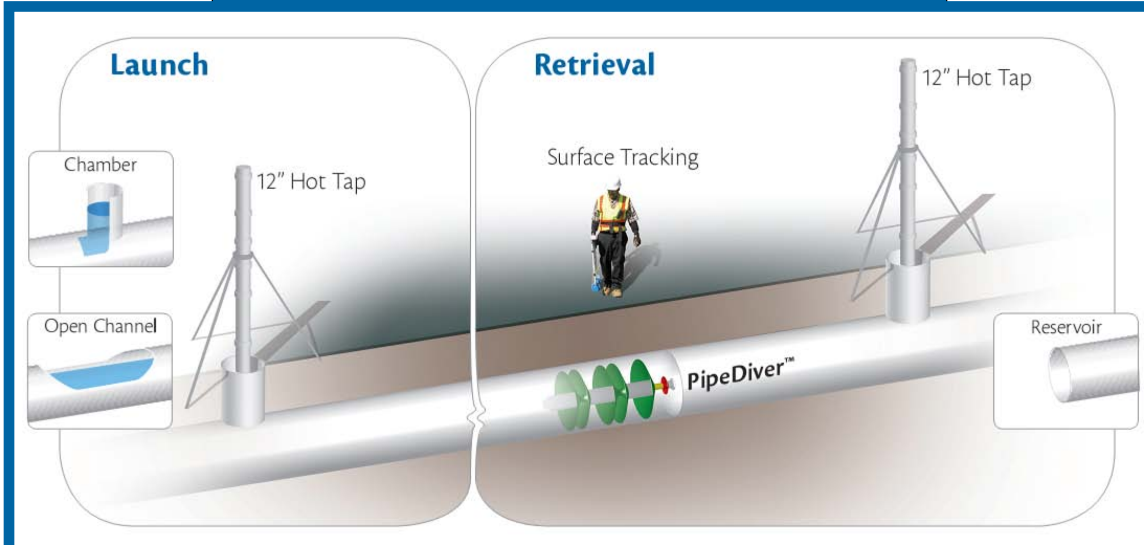
4.1 PipeDiver Background and Theory

4.1.1 PipeDiver Platform

The PipeDiver system has been specifically designed for use in pipelines that are live or can not be taken out of service due to lack of redundancy or operational constraints. PipeDiver provides accurate condition assessment of critical infrastructure, specifically detecting prestressing wire breaks in Prestressed Concrete Cylinder Pipe (PCCP). This solution offers significant cost savings as the pipeline remains in service eliminating the need for service shutdown and dewatering. The system has been proven effective for the inspection of live PCCP lines from the verification of its pilot inspection of 30 inch diameter pipe in Halifax in 2007.

PipeDiver is a non-tethered, free swimming inspection platform for in-service water mains. The inspection vehicle allows inspection of pipelines from 24 inch in diameter and larger through two 12 inch diameter taps installed on the pipeline, one at each end of the inspection region. Alternatively, reservoirs or open channels can be used as insertion and extraction points.

Figure 4.1 The PipeDiver Inspection System

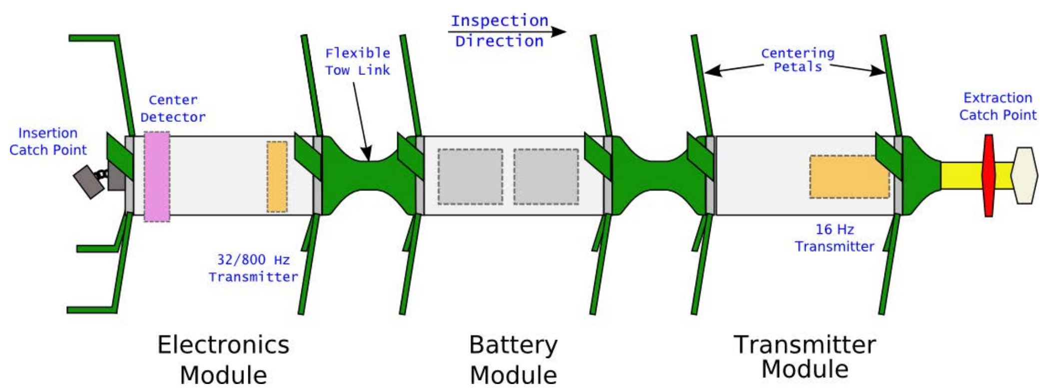


For a standard launch the insertion tube containing the PipeDiver vehicle is attached to the 12 inch tap before being filled with water, pressure equalized, and opened to the pipeline. The internal insertion piston pushes the PipeDiver vehicle into the pipe and, once fully in the pipe, the vehicle is released and begins to travel with the flow. For a standard retrieval, once the PipeDiver vehicle reaches the extraction side, a robotic claw and net which blocks the entire pipe diameter grabs the front of the vehicle and secures it before pulling up out of the pipe and into the retrieval tube.

The PipeDiver vehicle travels at approximately 90% of the pipeline's flow rate, the neutrally buoyant inspection vehicle can run for up to 30 hours in a single insertion. Flexible fins are used to center the tool within the pipe and provide propulsion. Its flexible design ensures that PipeDiver can navigate through most butterfly valves and bends in the pipeline while travelling long distances.

Figure 4.2 PipeDiver Retrieval Arm

Figure 4.3 The PipeDiver Inspection System



The PipeDiver inspection tool is inserted into a live main through a 12" tap directly on top of the main, then retrieved using a robotic arm inside a similar chamber at the end of each inspection run. The modular system includes an electronics module, battery module, and transmitter module for above ground tracking.

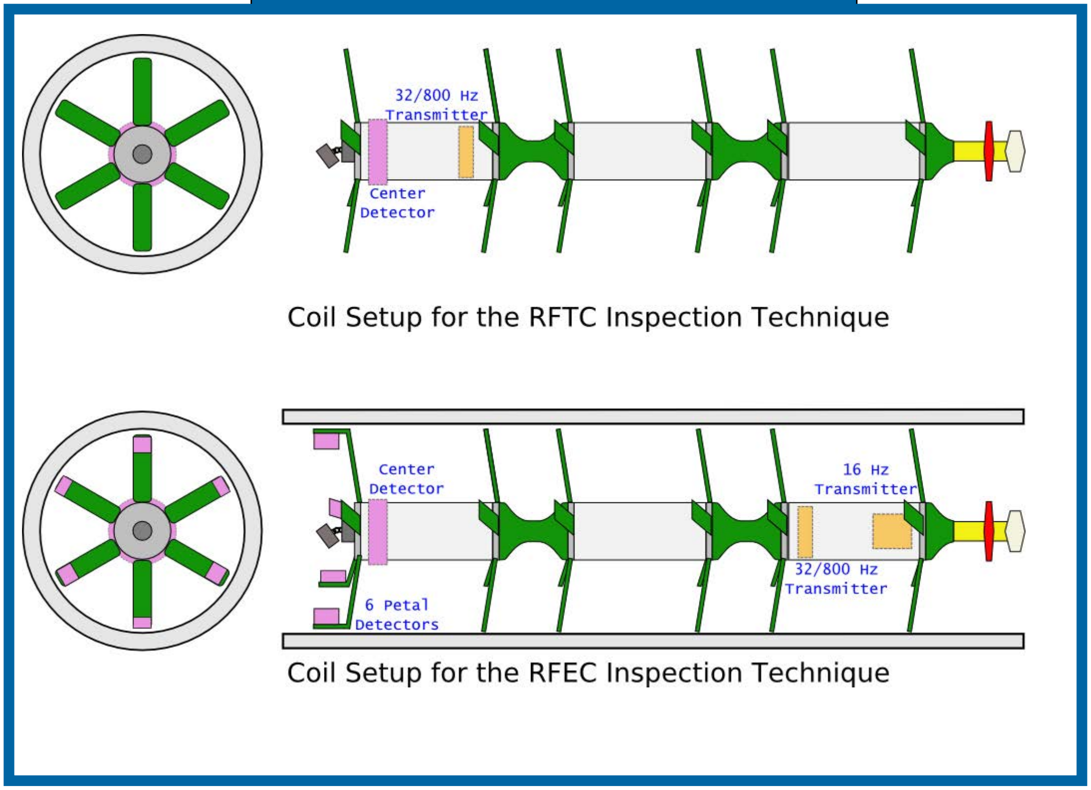
4.1.2 PipeDiver RFEC Testing Description

The Remote Field Eddy Current (RFEC) is a proven technique for non-destructive inspection of metallic pipelines. The PipeDiver is similarly a proven platform for insertion into live pipelines and inspection using the RFTC technique. While the RFTC and RFEC techniques are similar in nature there are several challenges involved in modifying the PipeDiver platform to support RFEC technology:

- Detectors have to be closer to the wall
- More detectors are required
- Signal levels are significantly lower than RFTC
- Exciter to detector axial separation is much larger

To modify the PipeDiver for a RFEC inspection the exciter coil was moved from the rear body near the center detector into the first body to achieve the minimum 1.5-2 pipe diameters required for the RFEC technique. Six additional detector coils were added to petals at the rear of the vehicle to provide increased sensitivity to wall thickness loss while still permitting the the vehicle to be inserted and extracted through a 12 inch diameter opening.

Figure 4.4 PipeDiver Coil Locations



The future challenges for PipeDiver RFEC development will be to increase the number of detectors close to the pipe wall, especially for larger diameter pipes, to increase the resolution and accuracy of the wall thickness measurements.

Common factors affecting accuracy for any RFEC system include the pipeline design and composition (i.e. metallic variations), inspection tool calibration, inspection tool riding quality, the type and position of the defect. Calibration details include running standard RFEC tests (with various coil separation/frequency setups) on pipes with a set of defects (size and shape) to achieve the best detection and sensitivity.

4.2 PipeDiver Testing

4.2.1 PipeDiver Inspections

PipeDiver RFEC Testing and trials were performed from July 21st to July 29th and four successful runs were completed. This was a pilot inspection using the RFEC technique in metallic pipe to obtain additional field data for analysis.

Table 4.1 shows the details of actual inspections, specifically the survey length and description of the inspection.

Table 4.1 Insertion Details

Date	Insertion Point	End Point	Survey Length (ft)	Flow Direction and Speed	Description
July 23rd	Pit 1	Pit 3	2057	East, 1ft/sec	PipeDiver RFEC
July 24th	Pit 1	Pit 3	2057	East, 0.5 ft/sec	PipeDiver RFEC
July 27th	Pit 1	Pit 3	2057	East, 1ft/sec	PipeDiver RFEC
July 28th	Pit 1	Pit 3	2057	East, 1ft/sec	PipeDiver RFEC

4.2.2 PipeDiver Insertion Issue

On July 21st, the first insertion attempt, the PipeDiver vehicle became stuck during the insertion process and that day's inspection had to be stopped and the vehicle retrieved from the pipe. An investigation of the issue with the help of Sahara video (Figure 4.5 and 4.6) led to the conclusion that the front of the PipeDiver has become stuck in a large, unfilled gap estimated to be 3 to 4 inches in width between joints just downstream of the insertion point.

Figure 4.5 Sahara Video of the Joint Gap

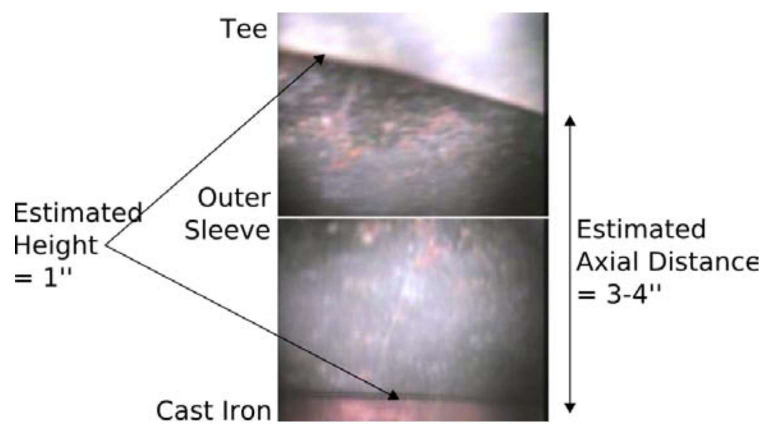
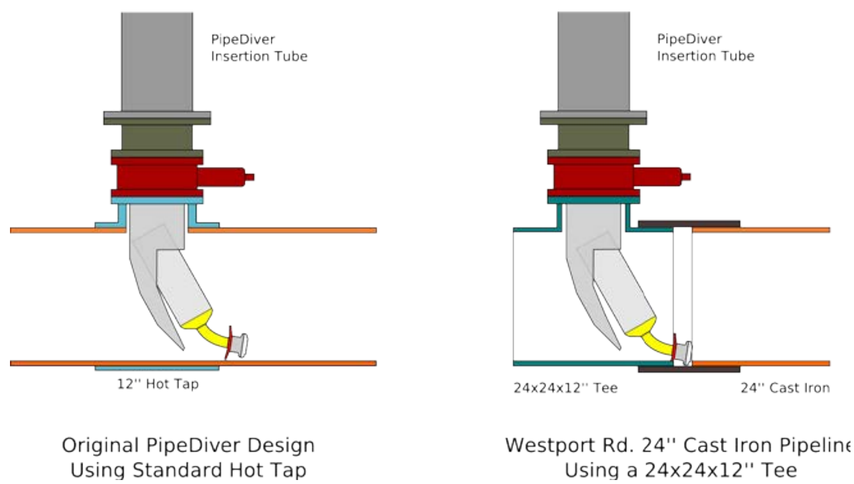


Figure 4.6 PipeDiver Insertion Schematic



An alternate insertion process was designed and implemented and the following four insertions were successful.

PipeDiver is designed for live inspections using standard accesses including 12 inch diameter hot taps, tees with minimum joint gaps, or similar features. For certain accesses such as tees with large unfilled joint gaps or accesses with unknown internal conditions Sahara Video is recommended to identify the exact layout of the insertion point. The insertion design and process can then be modified for a successful insertion if required.

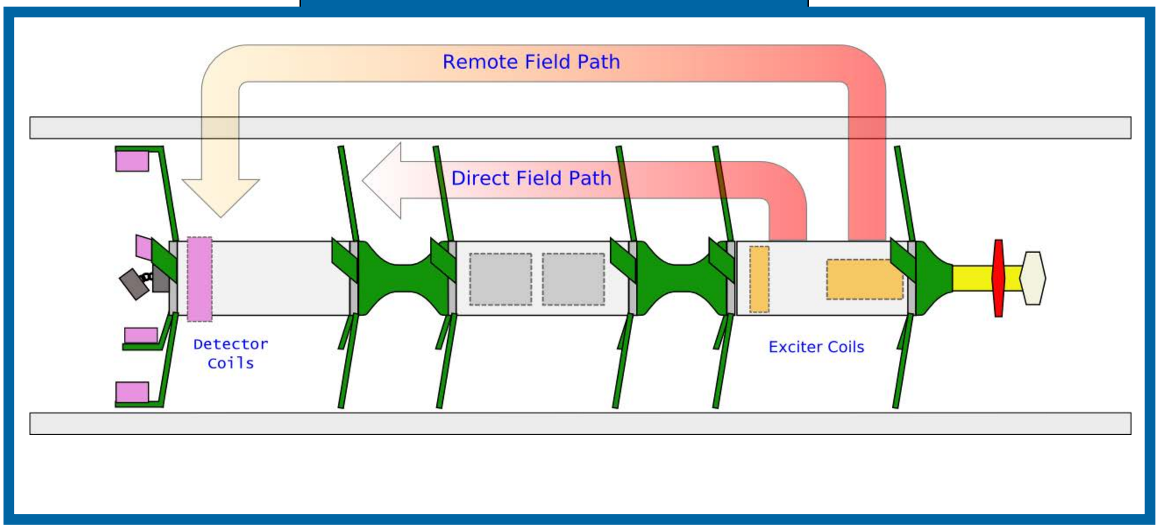
4.3 PipeDiver Results

4.3.1 PipeDiver RFEC Result Description

PipeDiver RFEC Testing was conducted as a pilot project to obtain field data for analysis. Data was analyzed and characterized based on basic pattern recognition from simple models of wall thickness variations.

Remote Field Eddy Current works on the basic theory that when a time harmonic magnetic field is generated inside a metallic pipe it has two paths from the exciter to detector coils (see Figure 4.7).

Figure 4.7 RFEC Signal Paths



The direct path remains inside the pipe and couples the coils directly while the remote path remains outside of the pipe as long as possible. When the exciter-detector coil separation exceeds 1.5 pipe diameters the signal from the remote field significantly dominates the total signal received at the detector. Since the remote field path has passed twice through the pipe wall any variation in magnetic wall properties including wall thickness, conductivity, and magnetic permeability will result in a change in the detector signal.

4.3.2 PipeDiver RFEC Results Overview

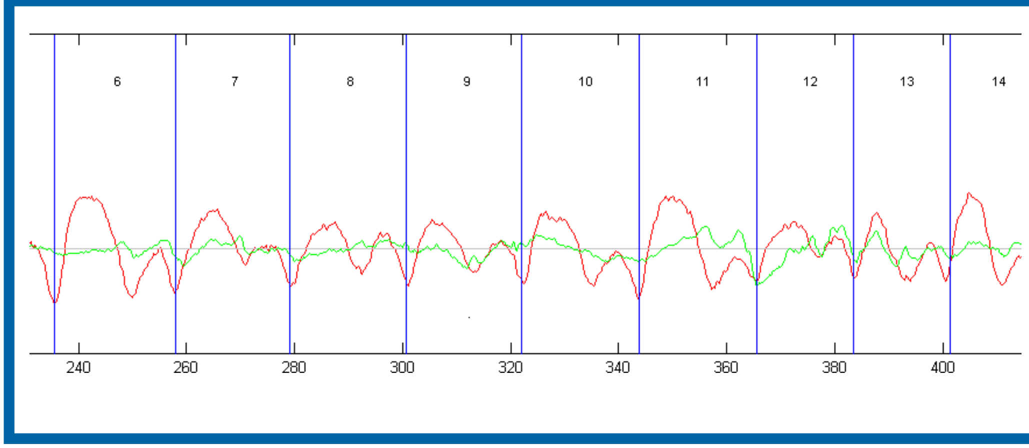
Table 4.2 lists the location of pipe sections PipeDiver data characterized as anomalous and their distance from Pit 1.

Table 4.2 PipeDiver Anomalous Pipes	
Distance from Pit 1 (ft)	
Start	End
216	228
264	276
276	288
324	336
360	372
384	396
444	456
504	516
516	528
576	588
612	624
864	876
936	948
948	960
1044	1056
1056	1068
1176	1188
1212	1224
1284	1296
1308	1320
1332	1344
1356	1368
1368	1380
1416	1428
1452	1464
1512	1524
1584	1596
1608	1620
1620	1632
1644	1656
1656	1668
1704	1716
1740	1752
1752	1764
1788	1800
1812	1824
1860	1872
1872	1884
1908	1920
1956	1968
1992	2004

4.3.3 PipeDiver RFEC Pipe Signals

Figure 4.8 below shows the center detector signal amplitude (red) and phase (green) from the July 23rd inspection of a section of pipeline which is classified as containing normal pipes.

Figure 4.8 PipeDiver RFEC Nominal Pipes



Each joint is composed of a double signal due to the remote field effect. One signal is from the exciter passing the joint and one from the detector passing. The first signal in a joint is generally higher and longer due to the relative lengths of the pipe and axial exciter-detector coil separation, 12 and 5.5 ft respectively (Figure 4.9).

Figure 4.9 PipeDiver RFEC Joint Detection

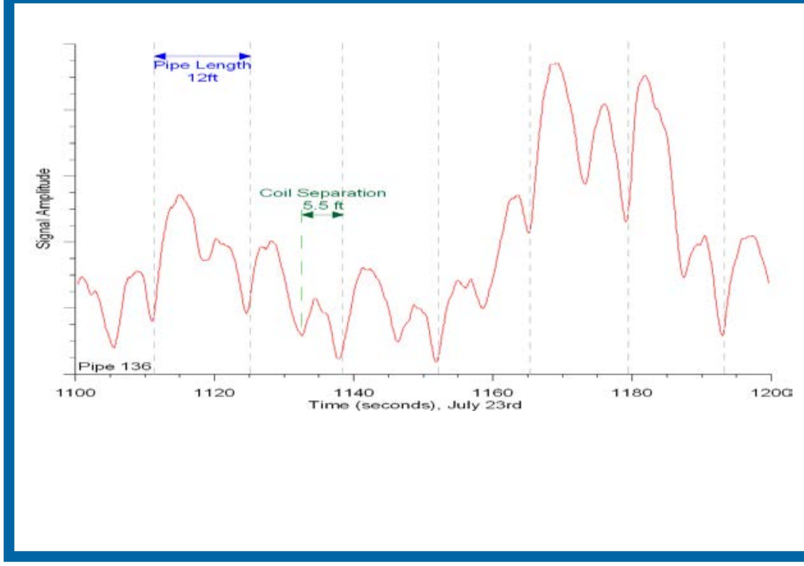
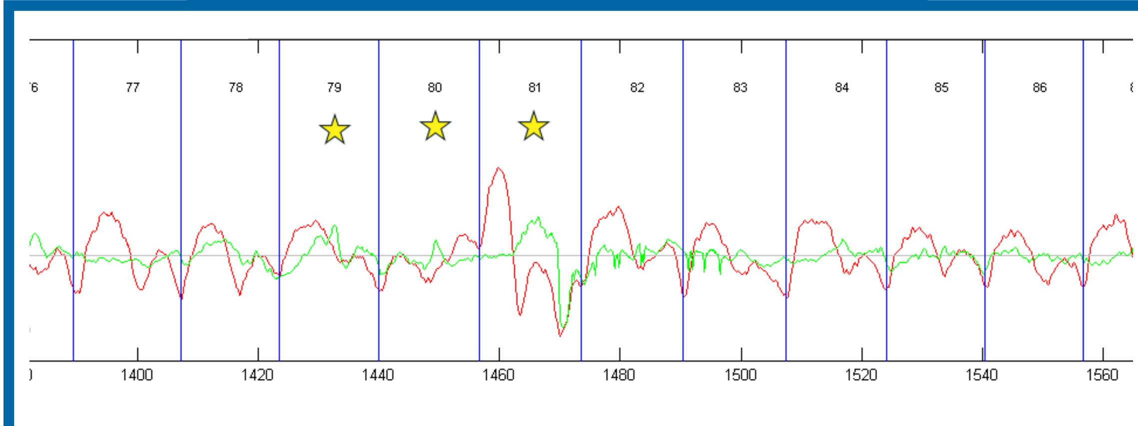


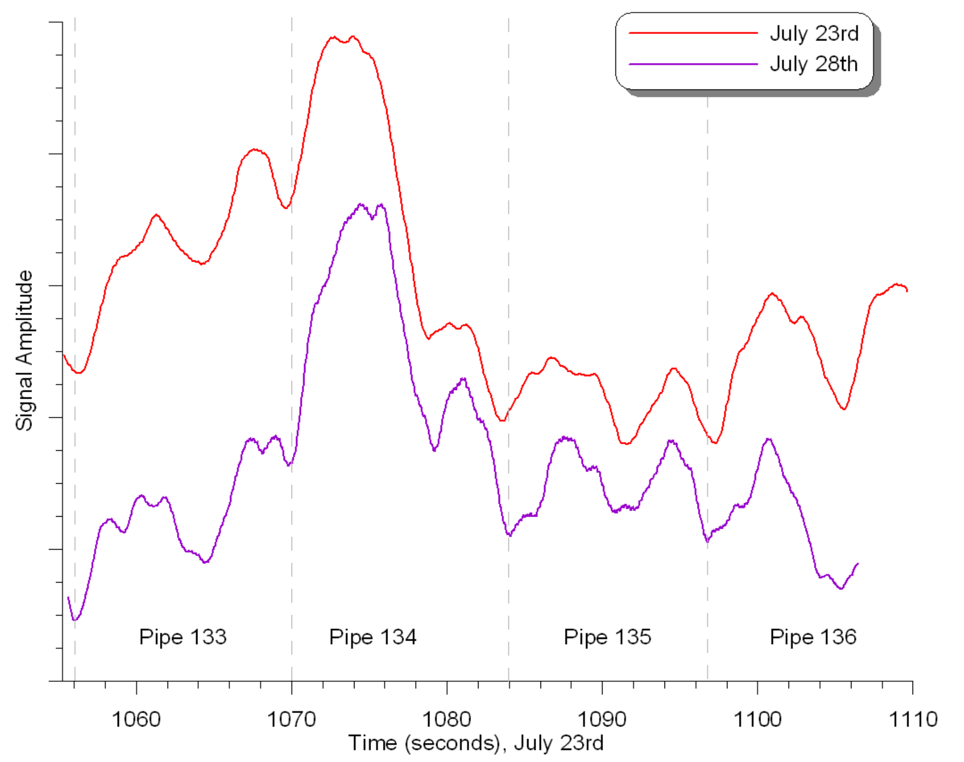
Figure 4.10 below shows an example of several pipes classified as anomalous from their RFEC signal. The second half of pipe 79 and the first half of pipe 80 show an anomalous signal which could be due to a wall thickness loss from pipe 80. The entire signal in pipe 81 differs largely from the nominal pipe signal and could be due to wall thickness loss or from an unidentified pipe feature.

Figure 4.10 PipeDiver RFEC Anomalous Pipes



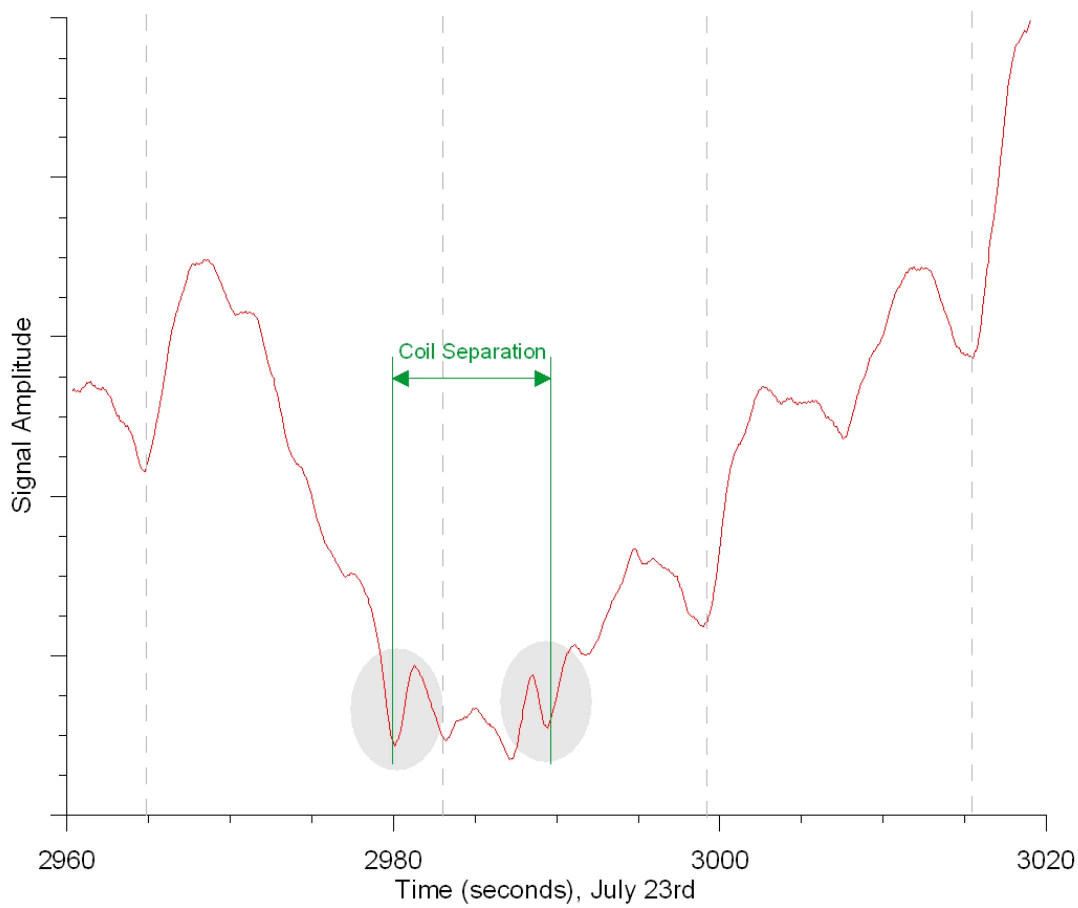
The PipeDiver configuration used on the July 23rd and 28th inspections were almost identical which allows a direct comparison of the signals. Figure 4.11 below shows a comparison for a section of four pipes from the center detector. One of the objectives of this inspection was to verify the validity of the PipeDiver RFEC technology by performing such repeatability tests. The results from the multiple PipeDiver scans show good repeatability.

Figure 4.11 RFEC Repeatability



A known feature from the pipeline that is readily seen in the PipeDiver RFEC data is the hydrant outlet that is located near Pit F (Figure 4.12). While the signal is relatively small as compared to the joint signal it can be distinguished by having a double signal occurring the exact distance as the PipeDiver's detector-exciter coil separation distance.

Figure 4.12 PipeDiver RFEC Hydrant Signal



Four new defects were machined into Pit F on July 28th (Figure 4.13). By comparing the RFEC signals from the data before and after the defects were created we have the best possible chance of seeing this relatively small amount of wall thickness loss in the data (Figure 4.14).

Figure 4.13 New Pit F Defects

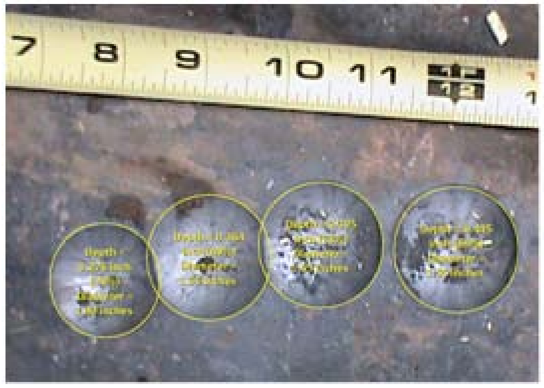
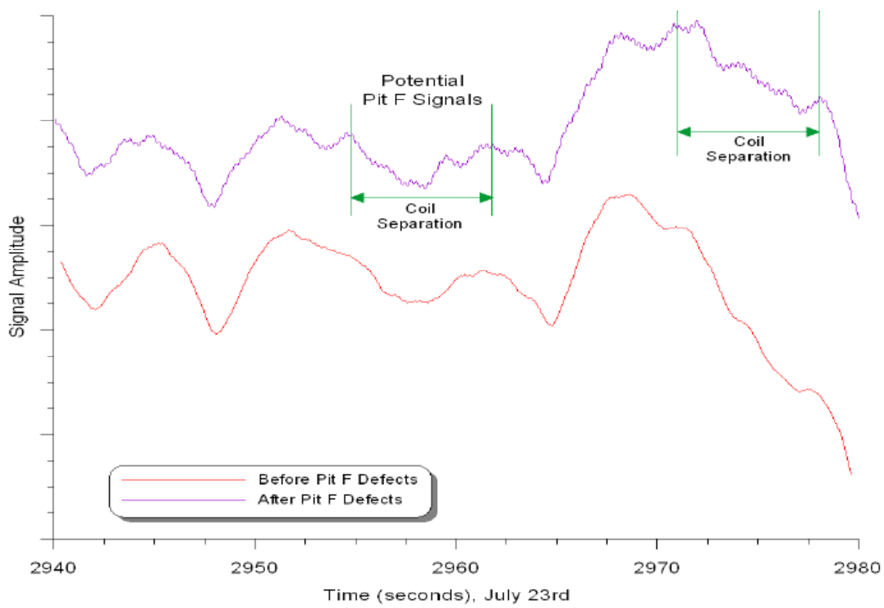


Figure 4.14 Comparing RFEC Data Before and After Defects



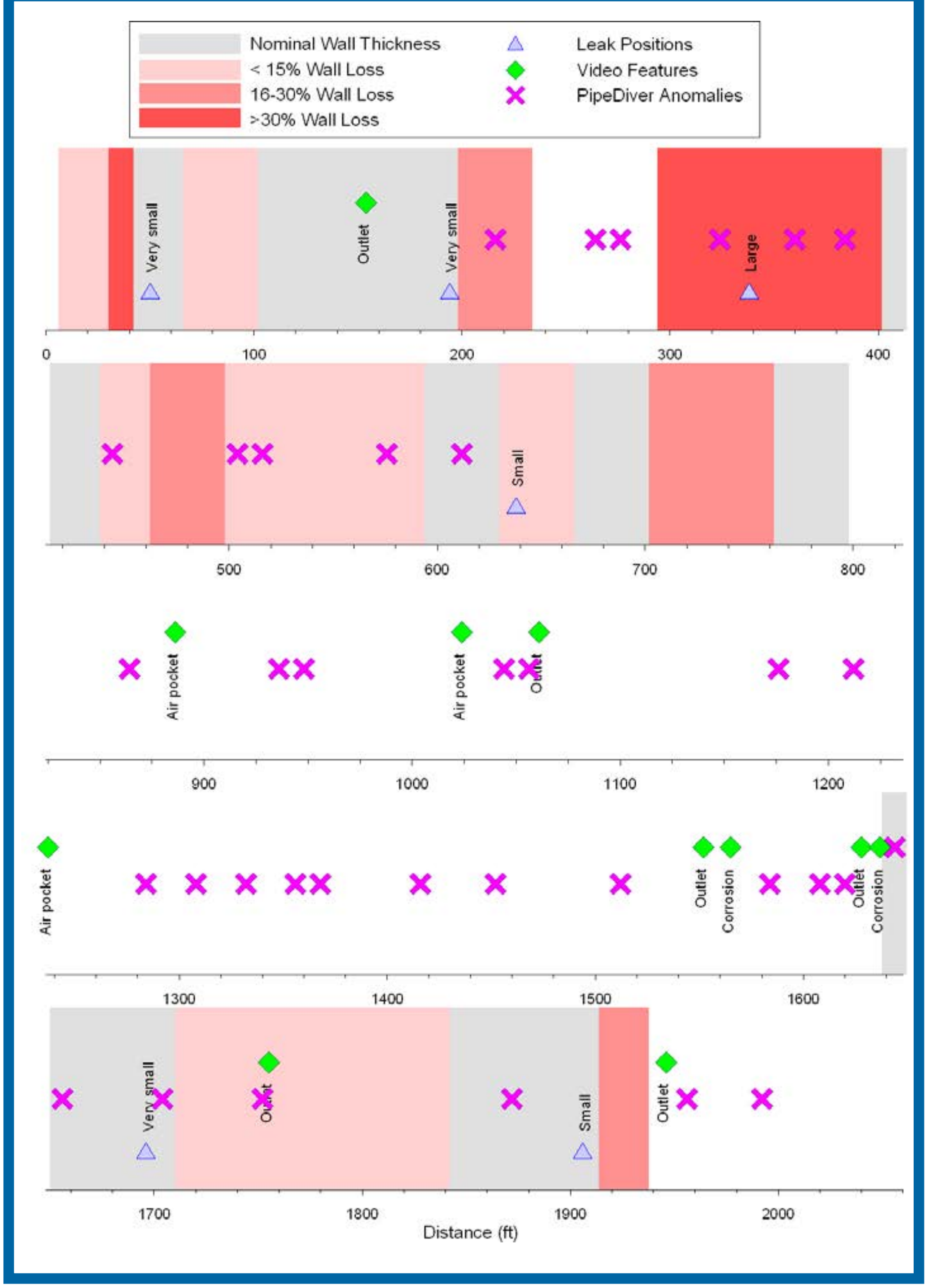
The PipeDiver RFEC results show good repeatability between multiple scans using the same configuration which validate it as a non-destructive inspection technique. The RFEC data clearly shows joint signals, known features and anomalous signals which may be potentially due to wall thickness loss. Further verification and calibration is needed to confirm the nature of these anomalous signals.

5. SUMMARY

5.1 Combined Test Results

The following figure 5.1 combines all results including Sahara Leak Detection, Sahara Video, Sahara Wall Thickness, and PipeDiver RFEC, showing their relative locations along the pipeline.

Figure 5.1 Combined Results



The combined results make it easier to identify potential areas of interest within the pipe. For example, the section between 300 to 400 ft contains a large leak, several PipeDiver RFEC anomalies and has a high average wall thickness loss and is one of the areas recommended for further verification and calibration. Similarly, the area between 1560 to 1640 ft contains several identified corrosion spots and PipeDiver RFEC anomalies.

5.2 Inspection Conclusions

PPIC's evaluation of the Westport Rd. Transmission Main between Pit 1 and Pit 3 (2057 foot section) provided an overall condition assessment of the metallic pipeline.

The Sahara platform was used to provide three critical non-destructive condition assessment services, including:

- Internal video inspection
- Leak detection
- Sahara and PipeDiver wall thickness assessment

All Sahara services were successfully inserted using a 2 inch tap in live conditions not requiring the line to be shut down. The tethered system allowed the sensor to be stopped at precise locations which enabled operators to make accurate and repeatable identifications regarding pipeline condition discoveries.

Sahara Leak Detection detected six unidentified leaks and one air pocket, recorded and marked their above ground position, and estimated the leak size all in real time. Several simulated leaks were also detected in real time, and post analysis was able to identify all leaks that had been masked by external noise factors such as the pipeline discharge.

Sahara Video's tethered CCTV inspection was also successfully deployed using a 2 inch tap. Real time analysis of the video provided insight into the internal condition of the pipeline and clearly distinguished two areas of corrosion. Air pockets and outlets were also clearly identifiable from the real time inspection. The second purpose of a video inspection, to discover possible obstacles for a PipeDiver inspection, showed that PipeDiver could be used with no risk from unidentified obstacles. Video recordings were used for post analysis and helped identify a previously unknown risk: a joint gap just downstream of the insertion point. These video results can now be used to improve and change aspects of the PipeDiver system.

Sahara Wall Thickness was performed in conjunction with leak detection thus minimizing extra resources and time. Analysis of the results uncovered specific intervals of the pipeline showing higher wall thickness loss than others. By utilizing the tethered Sahara system and being able to stop the hydrophone at precise locations, consistent and multiple pipe intervals could be set to calculate average wall thickness readings.

The PipeDiver platform is poised to becoming the industry standard for in-service pipeline inspections. The technology can be modified for different services and eliminates the need to take pipelines out of service during inspections. PipeDiver was successfully inserted and retrieved via two 12 inch Tees installed into the live main. Results obtained form the Westport Rd. Transmission main inspection have identified anomalous signals and processes that will allow PPIC to further improve the PipeDiver system, specifically RFEC Testing.

5.3 Advantages and Limitations

The significant advantage to the overall Sahara inspection technologies is that its tethered cable design brings the sensor as close as possible to the leak and allows unlimited control of the sensor position. For Sahara Leak Detection this means that the farthest the hydrophone sensor will be from a leak is the pipe diameter, or more realistically the pipe radius, which permits very small leaks to be detected. Leaks are detected in real time and immediately accurately located and marked above ground.

The primary limitation of the Sahara system is the same as its main advantage: its tethered cable design. The inspection length possible from an insertion point is limited by the amount of available cable as well as the amount of flow in the pipe line and how far this flow can carry the hydrophone and cable through the pipe before friction stops it.

Sahara Video permits a real time video inspection of a live pipeline and only requires a 2 inch access although it has the same cable and inspection limitation and the video quality is reduced in larger diameter pipes.

The Sahara Wall Thickness technique allows flexible distance and better interval resolution from the cable control but can only indicate the average wall thickness in a section and not specific defects.

PipeDiver is a proven platform designed for live inspection of PCCP using the RFTC technology but has been adapted to use the RFEC technique to provide wall thickness loss in metallic pipelines. The detection sensitivity is limited by the number of sensor channels but since the significant challenge of non-disruptive inspection has been overcome future development can focus on increasing the number of available detectors.

The Sahara and PipeDiver techniques are complementary technologies that offer a spectrum of solutions to utilities. By detecting very small leaks and accurately pinpointing the leak position, Sahara leak can provide pinhole corrosion in pipe wall and joint problems, which are a good indication of pipe condition. For wall thickness issues, including graphite, wall thinning, but not yet leaking, Sahara Wall Thickness can provide average sectional wall thickness info during the same time with Sahara leak and PipeDiver RFEC will be able to provide more detailed information. Also, Sahara Video provides internal line condition and visual corrosion information. All are live inspections that take place while the pipeline remains in service.

5.4 Future Developments

Sahara Leak Detection is a mature technology used successfully for many years and future development of the technique will focus on making it even easier to use. The main challenge with Sahara Video is to improve its video and lighting quality in larger diameter pipes and to possibly combine the video and leak techniques into a single sensor head which would reduce the amount of insertions required and make the overall inspection more efficient. The Sahara Wall Thickness technique will continue to fine tune its field and analysis procedure in addition to more verification and calibration.

PipeDiver is a proven platform for entering a pipe through a standard access in live conditions and for inspection of PCCP. Using the data and experience obtained from this first PipeDiver RFEC inspection pilot PPIC will be able to further improve the PipeDiver system for metallic pipeline inspections. Technical components will be reviewed for possible advancements including improved detectors and detector placement. As well, the analysis process will be reviewed for new analysis techniques and improved software. Specifications and implementations of standard accesses will be reviewed to prevent future insertion and retrieval issues. Results need to be compared to actual pipe calibration and verification from the Westport Rd. Transmission Main in order to review and improve the current analysis techniques.

6. PHOTOGRAPHS

Sahara insertion site with valve and tap in Pit 1.

Sahara control center (truck) and Sahara insertion setup at Pit 1.

Valve creating a simulated leak in Pit 4.

Pits were constantly flooded due to ground water and rain storms.

PipeSpy locating a simulated leak at Pit 4

Orifice used to create simulated leaks

The Sahara Video sensor head and drogue.

Technicians inserting the Sahara hydrophone into the pipe in live conditions.

The Sahara insertion tube setup in Pit 1.

Acoustic unit recording reference sound signals at the insertion point.

Accelerometer acoustic sensor attached to the Sahara insertion tube.

Carrying the PipeDiver tool ready to be installed into the insertion tube.

Preparing the PipeDiver insertion and retrieval tubes.

PipeDiver insertion tube setup at the launch site.

Attaching the PipeDiver extraction tube on the gate valve.

Setting up the PipeDiver extraction tube.

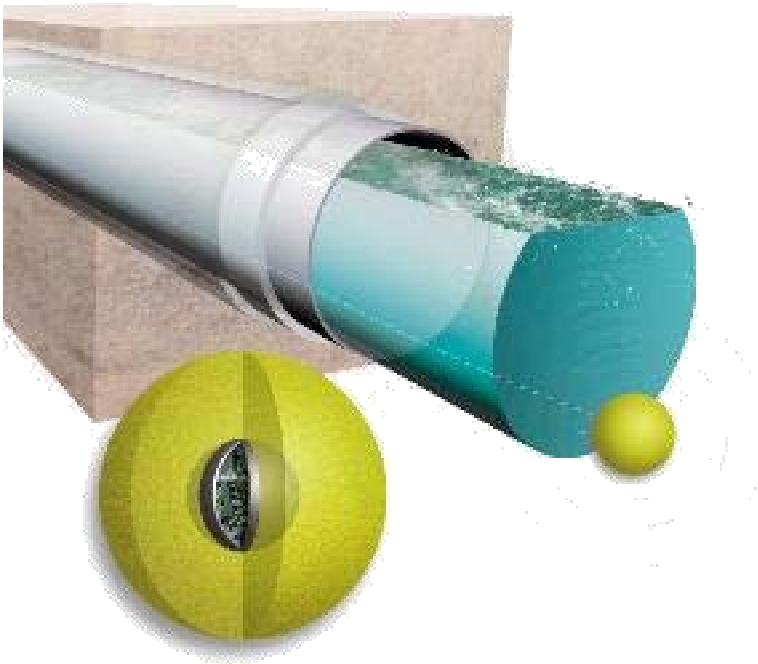
Technicians locating the PipeDiver vehicle from above ground.

APPENDIX B

PURE SMARTBALL^{TM} LEAK DETECTION REPORT

SmartBall® Leak Detection Survey
August 6 & 7, 2009

Prepared For the Environmental Protection Agency



Prepared By:

Pure Technologies Ltd

August 14, 2009

Jeff Kler

1 Executive Summary

The SmartBall was deployed to inspect the24 inch cast iron mortar lined pipeline on Thursday August 6th and Friday August 7th, 2009. The SmartBall was run through the pipe and was able to detect acoustic anomalies likely caused by leaks at 15 locations. The identified leaks have been summarized below.

Summary of Pipeline Details

Total Length of Pipe Surveyed: Type of Pipe: Diameter of Pipe:	2057.0 ft Cast Iron Mortar Lined 24 inch
Number of Leak Locations	12
Number of Simulated Leak Locations	3
Total Number of Leak Locations	15

2 Pipeline Summary

The approximate layout of the 24 inch cast iron Water pipeline inspected starting at the intersection of Chenoweth Lane and Westport Road, to the intersection of Ridgeway Avenue and Westport Road. The approximate line location is displayed on the aerial photograph below in Figure 2.1.

Figure 2.1: General layout of the pipeline inspected.

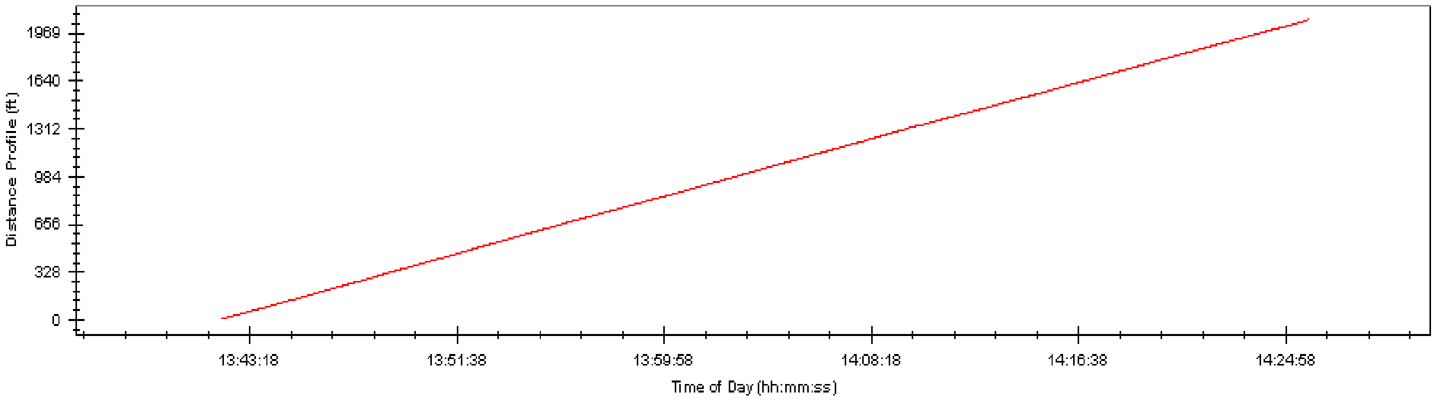
Sensor Locations () of the pipe inspected

3 Tracking the Position of the SmartBall

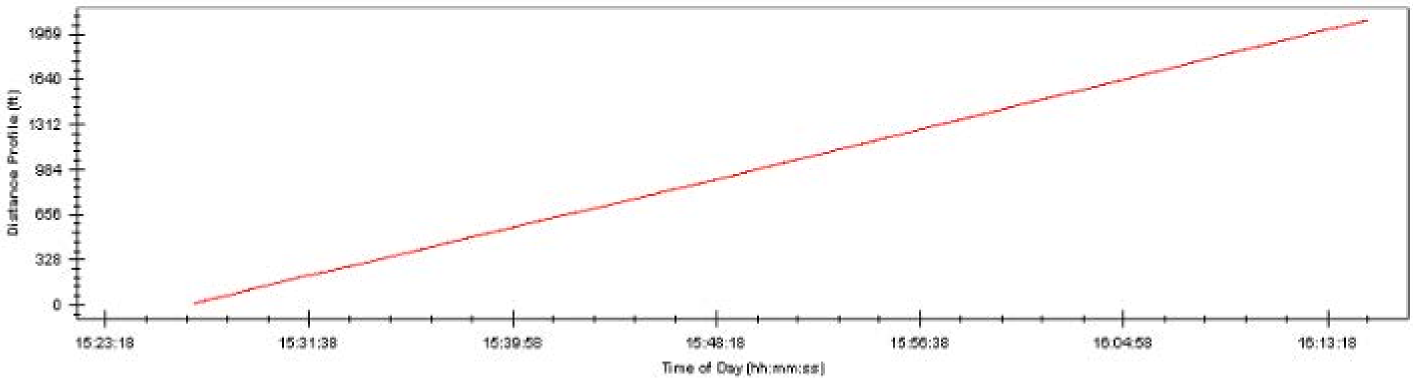
The position of the SmartBall within the pipeline is critical for locating important features, such as leaks. The methodology used to track the tool involves obtaining a velocity profile using data obtained from the accelerometers and magnetometers on board the SmartBall. Then, absolute position reference points obtained from the SmartBall Receiver (SBR) are applied to time stamped data. Individual SBR's were able to track the ball's progress through the pipeline for over 850 feet and the distance and location of these SBR's were based on the information provided to Pure by Battelle. The result of the rotation profile and SBR tracking is a position versus time relationship for the entire run of the tool. The exact location of where each SBR was placed along the pipeline during the run is detailed in Appendix A.

Figure 3.1 shows the position data for the runs. The position of the SmartBall indicated by the red line was fixed by fitting the position profile to known locations along the pipeline. The slope of the blue line indicates the instantaneous velocity of the tool. The velocity of the ball as it travelled through the pipeline is shown in Figure 3.2. Figure 3.3 displays the position of the ball as it was tracked in real time on site by the SBR's.

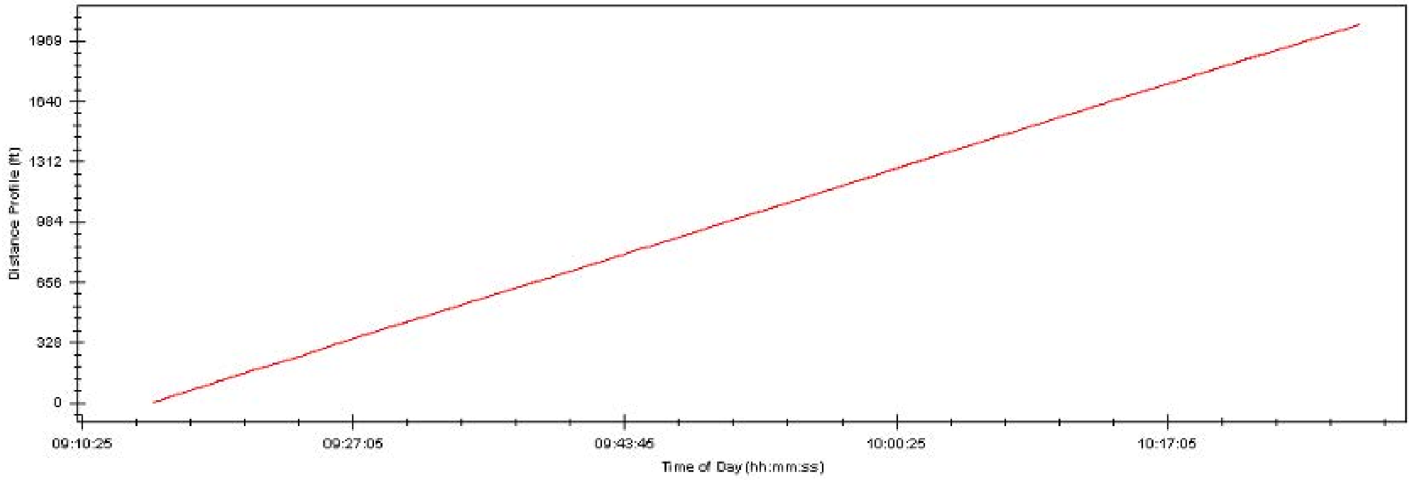
Run #1 (Aug 6):



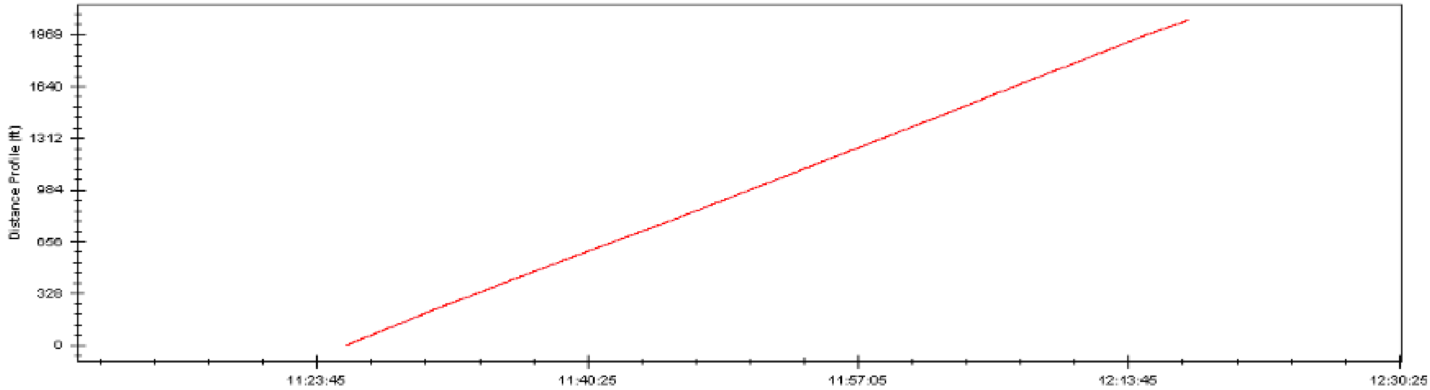
Run #2 (Aug 6):



Run #3 (Aug 7):



Run #4 (Aug 7):



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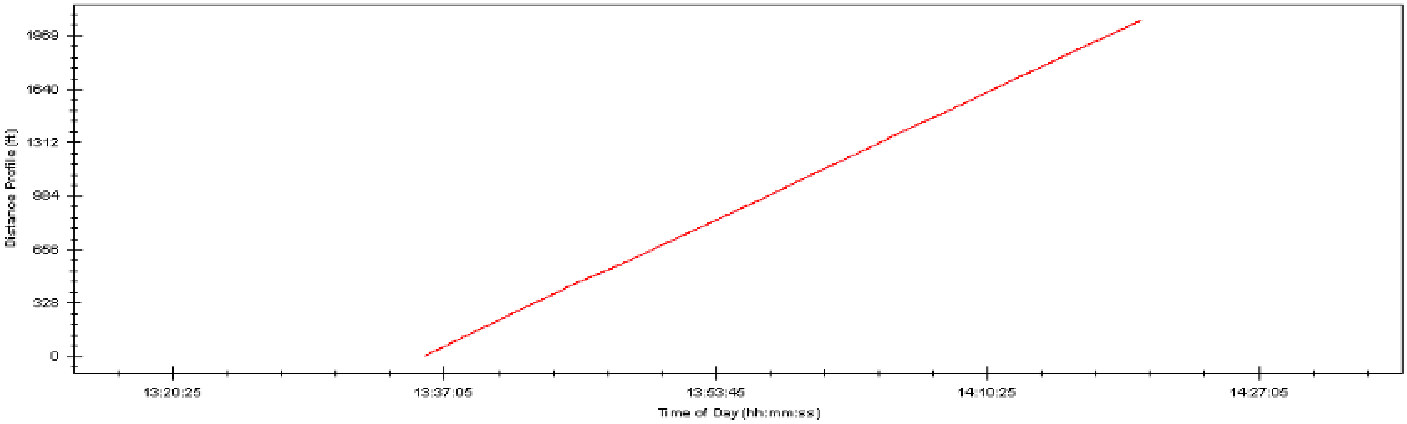
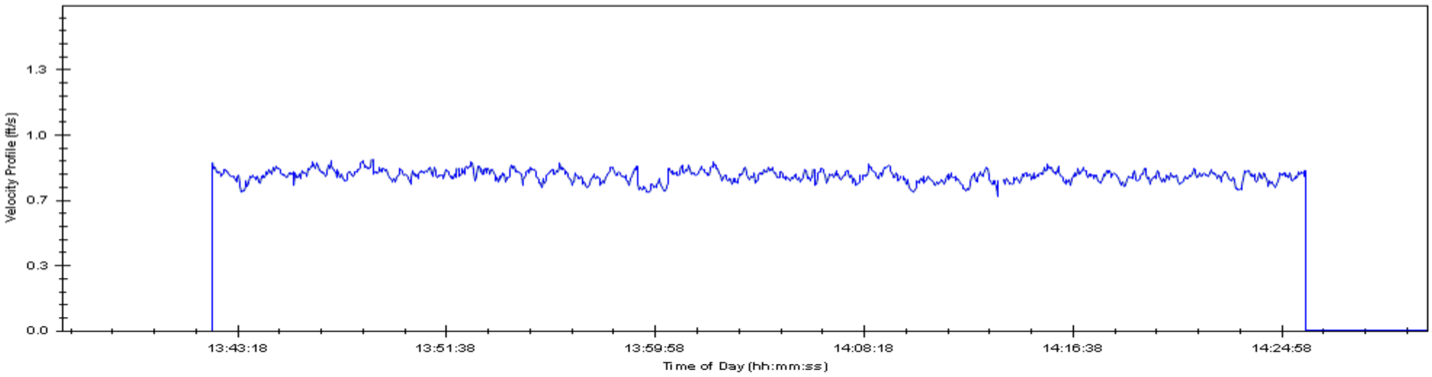


Figure 3.1: Position Profile of the SmartBall vs. Time of Day for the August 6th, and 7th, 2009 inspections

Run #1 (Aug 6):



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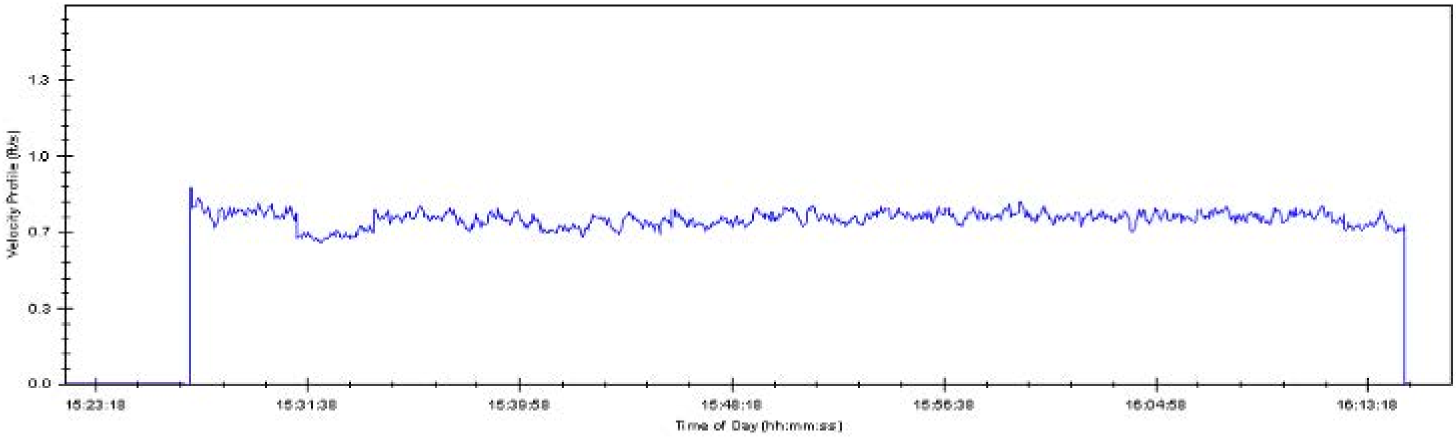

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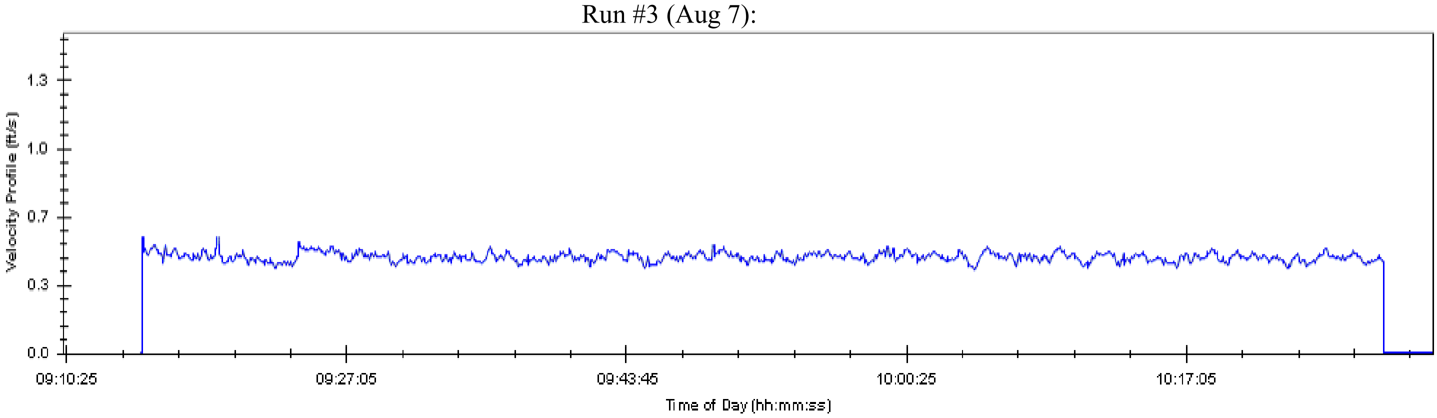
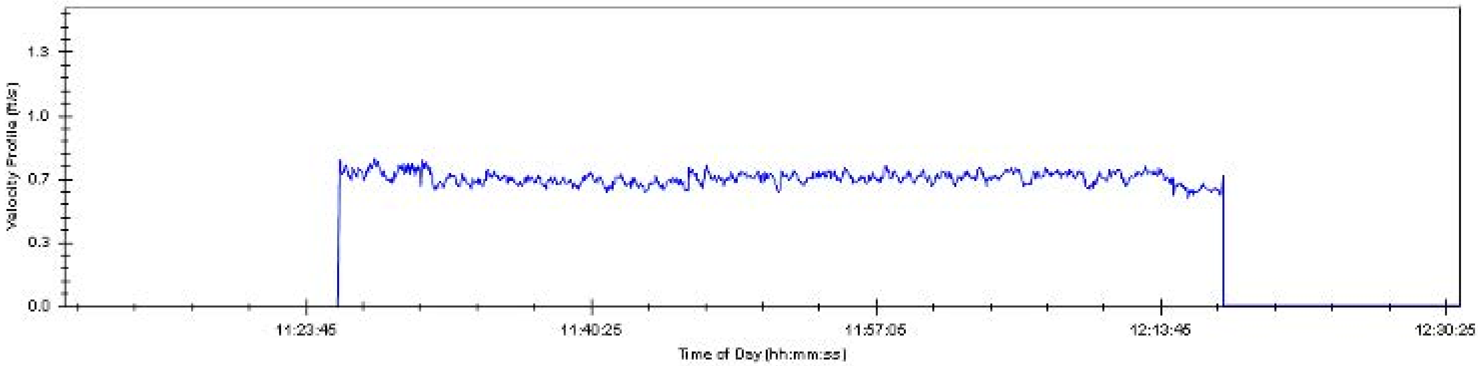


Run #4 (Aug 7):



Run #5 (Aug 7):

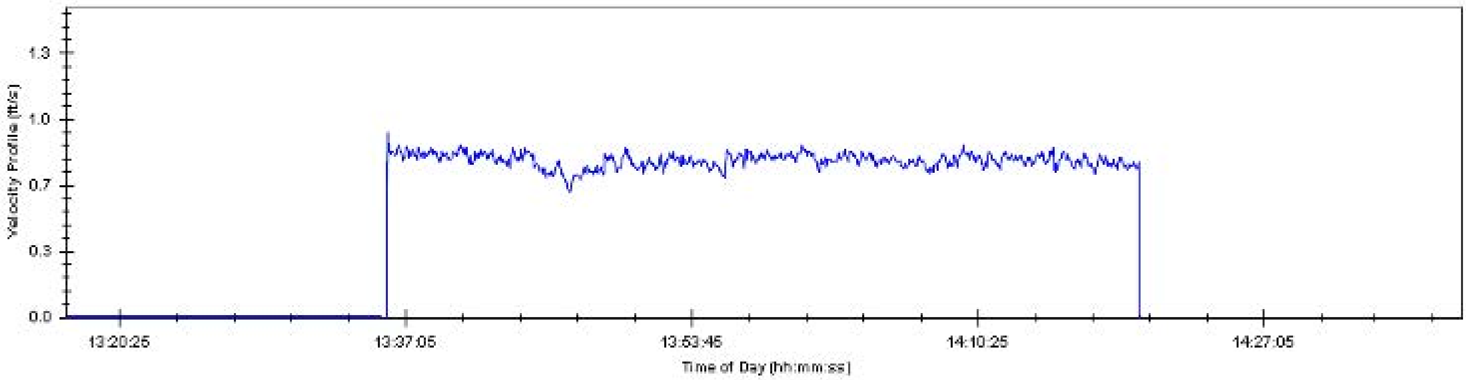
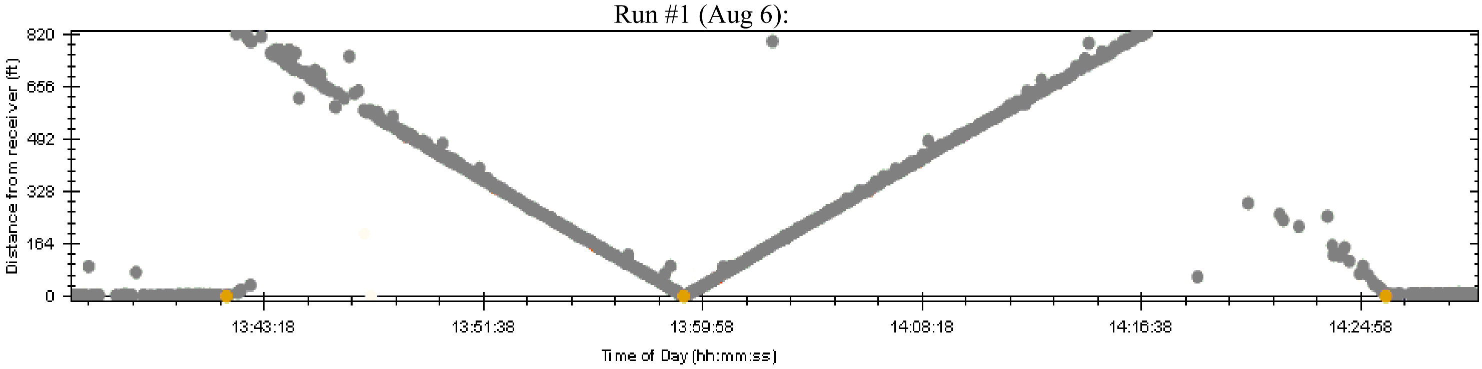


Figure 3.2: Velocity Profile of the SmartBall vs. Time of Day for the August 6th, and 7th, 2009 inspections

Run #1 (Aug 6):



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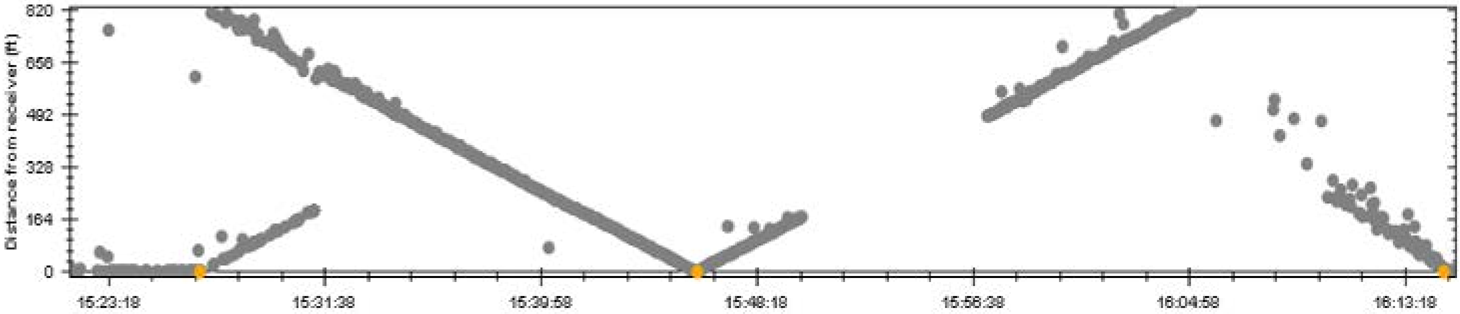

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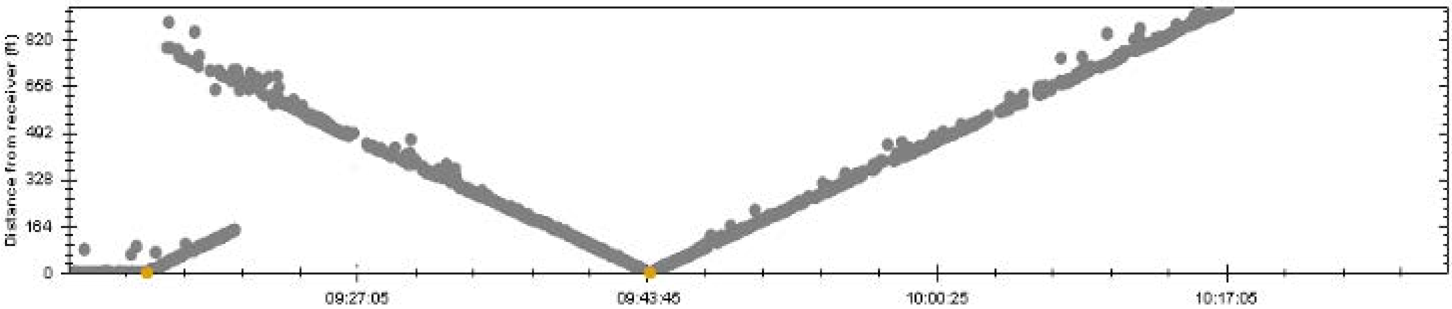
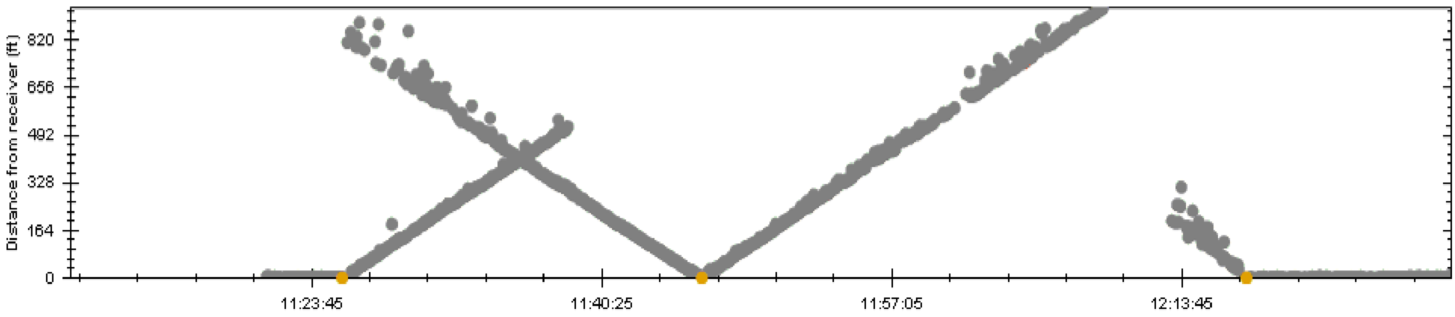


Run #4 (Aug 7):



Run #5 (Aug 7):

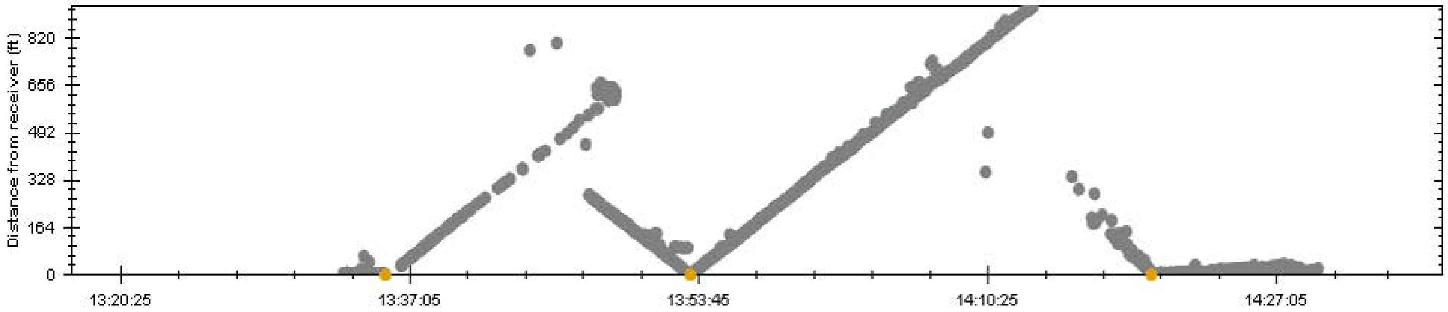


Figure 3.3: SBR Tracking Points vs. Time of Day for the August 6th, and 7th, 2009 inspections

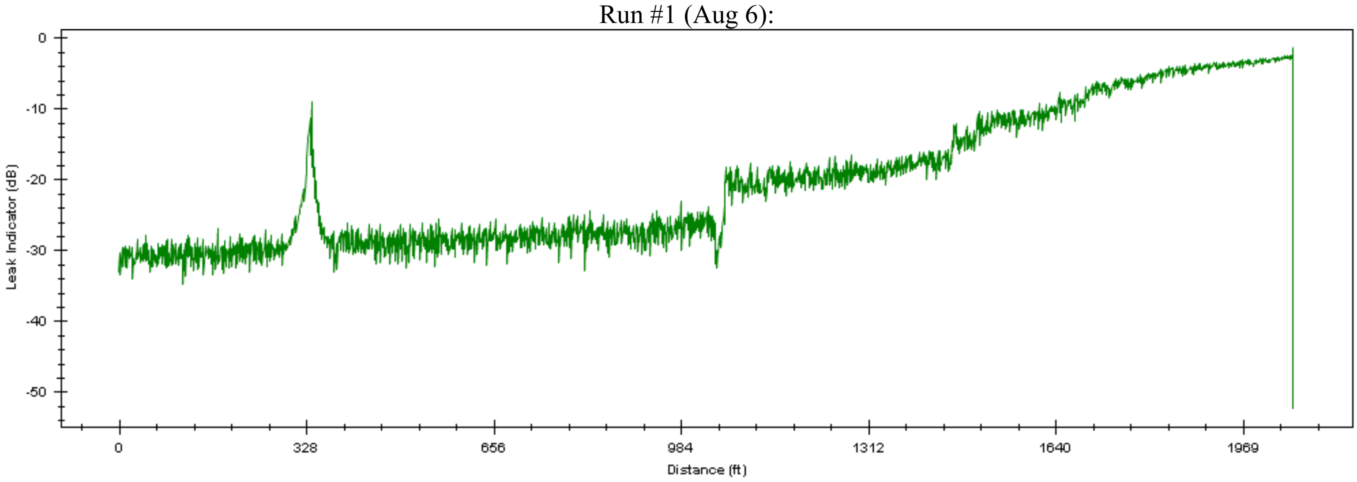
4 Results

Upon retrieval of the tool, the acoustic data recorded by the SmartBall was analyzed and cross-referenced with the position data from the SBR to determine location. A summary of the leaks found in the runs is detailed below. The location accuracy of the anomalies is dependant on the accuracy of the pipe distance and lay information provided to Pure.

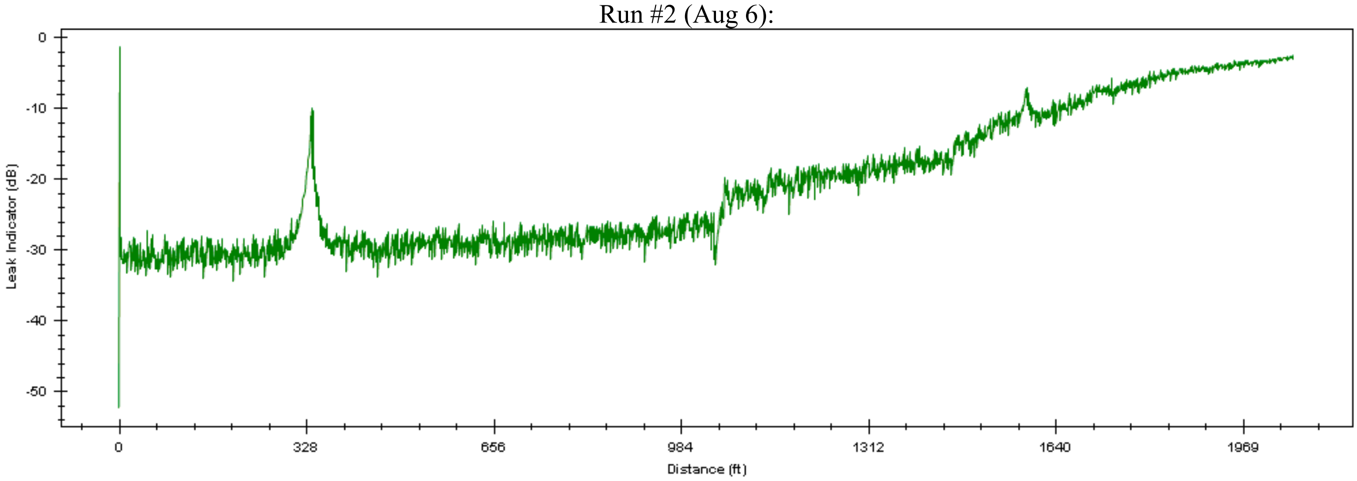
4.1 Summary of Results

Figure 4.1 shows the value of the leak indication power as detected by the SmartBall with respect to the position of the SmartBall along the pipeline. The severity of any leaks found can be estimated by correlating the value of the leak signal (a calculated parameter) with calibrations performed by the SmartBall and are detailed in section 4.2 titled Leak Calibration Curve. The general upward slope toward the right side of each graph has resulted from a large amount of flow noise generated by the water pressure relief valve and disposal at the downstream end of the run.

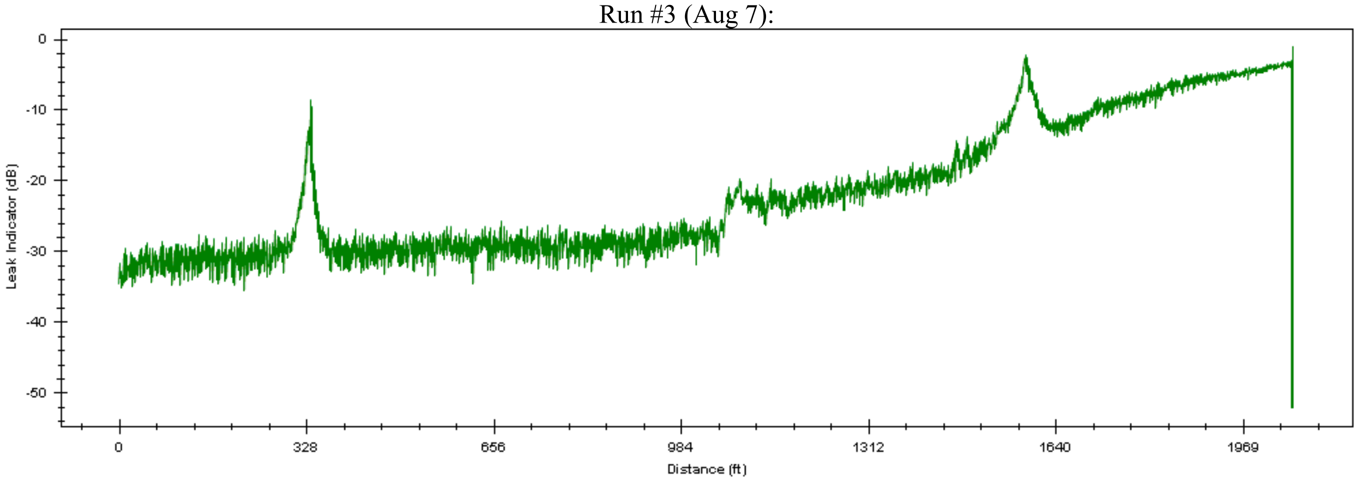
Run #1 (Aug 6):



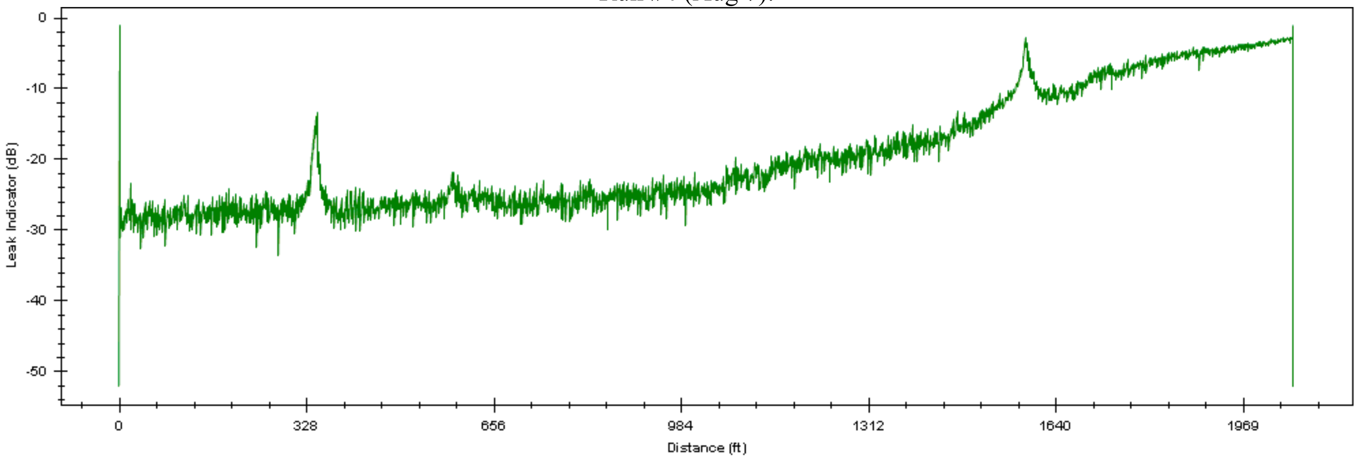
Run #2 (Aug 6):



Run #3 (Aug 7):



Run #4 (Aug 7):



Run #5 (Aug 7):

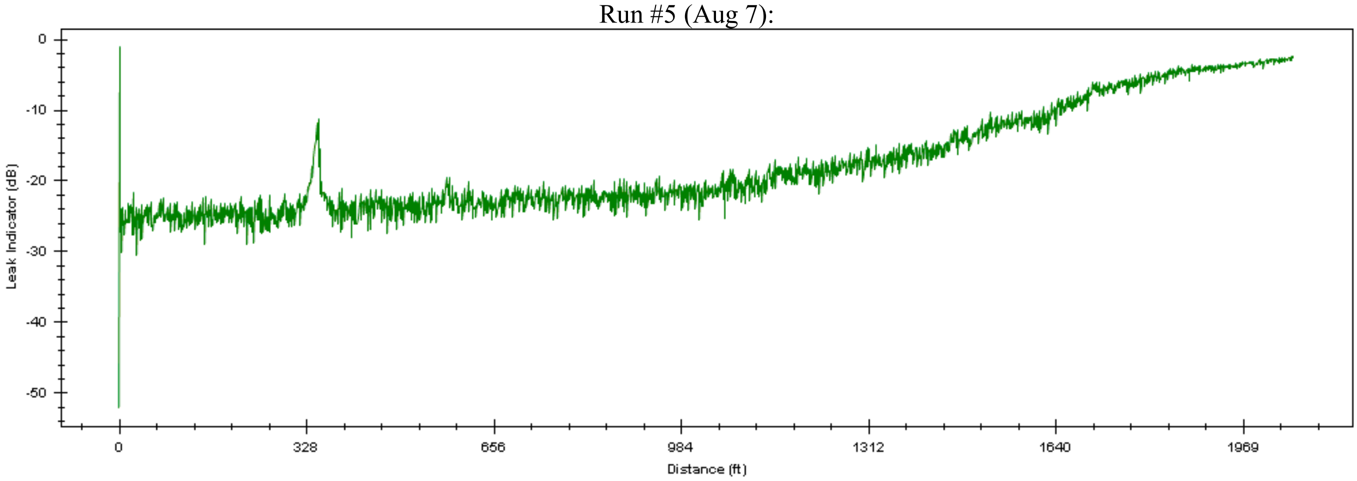


Figure 4.1: Acoustic Profile of the SmartBall vs. Time of Day for the August 6th, 7th, 2009 inspections

The critical findings of the pipeline inspection are summarized in table 4.1.

Table 4.1 – Summary of Acoustic Anomalies Resembling Leaks That Are Not Simulated

Leak ID #	Distance from Start	Description	Approximate Size (US gpm)
1	53ft	Leak (Small)	0.15
2	125ft	Leak (Small)	0.1
3	199ft	Leak (Small)	0.8
4	341ft	Leak (Medium)	15
5	414ft	Leak (Small)	0.2
6	556ft	Leak (Small)	1.0
	579ft	*Simulated Leak Site*	*Varying*
7	641ft	Leak (Small)	2.0
8	966ft	Leak (Small)	0.1
	1080ft	*Simulated Leak Site*	*Varying*
9	1210ft	Leak (Small)	1.0
	1580ft	*Simulated Leak Site*	*Varying*
10	1724ft	Leak (Small)	1.5
11	1809ft	Leak (Small)	2.0
12	1930	Leak (Small)	5.5

Table 4.2 – Simulated Leaks Detected by the SmartBall

Distance from Start	Inspection 1 Estimated Leak Rate (US gpm)	Inspection 2 Estimated Leak Rate (US gpm)	Inspection 3 Estimated Leak Rate (US gpm)	Inspection 4 Estimated Leak Rate (US gpm)	Inspection 5 Estimated Leak Rate (US gpm)
579ft	0.57	0.3	1.8	4.5	8
1080ft	8	2.8	7.2	0.1	0.57
1580ft	0	15	30	40	0

4.2 Leak Rate Calibration

To assist in identifying the approximate leak rate of any identified leak for the inspection performed on Thursday Aug. 6th and 7th, 2009, Pure Technologies Ltd has compared the leak indication power of a detected leak with that of a known leak rate. The calibration curve applied to gauge the size of the leaks detected on this inspection is shown in Figure 4.2. Known leak rates and their leak indication power (in dB) are usually developed by holding the SmartBall in the extraction net at the end of surveyed runs. For these inspections leaks were created for the SmartBall while it passed through the pipe (shown in green in Figure 4.2 below). The leak indication power is the single most important indicator of a leak's size and presence. In order to confirm that an acoustic anomaly is actually a leak, a frequency analysis tool is used and is shown with each identified leak in Section 5.

Leaks of varying rates are produced using a 1/2 inch ball valve attached to the extraction stack and a graduated bucket was used to collect and measure the water created by each of the leaks over a measured period. Because the simulated leaks are controlled and released through a threaded outlet, the comparison to actual field condition leaks may vary. This is because the acoustic frequency and power indication of any leak will vary with many factors, including pressure, pipe diameter, size and configuration (pin-hole, rolled gasket, split pipe, etc.). However, the leak calibration curve provides a useful tool in approximating leak rates for identified leaks. These calibration leaks are shown in the below graph as green squares. The actual leaks detected during the inspection are shown as red circles.

As an approximation, the leaks in the range of 0-2 US Gallons per Minute (0-7.5 Liters per Minute) have been classified as small, 2-10 US Gallons per Minute (7.5 to 37.5 Liters per Minute) have been classified as medium, and above 10 US Gallons per Minute (37.5 Liters per Minute) have been classified as large.

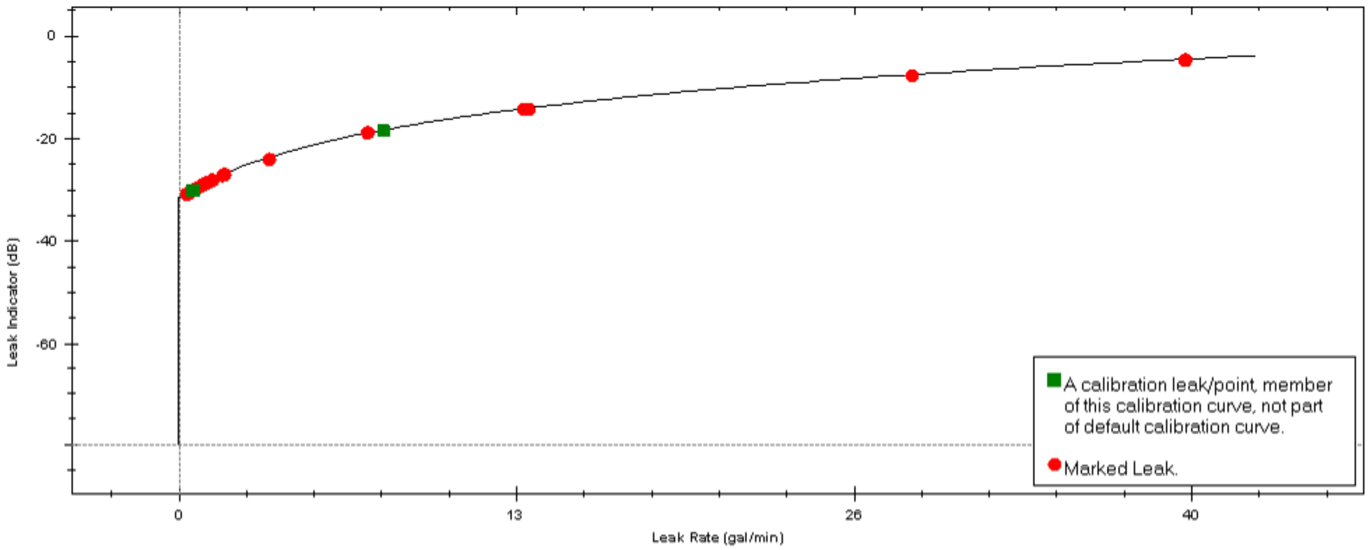


Figure 4.2: Leak Calibration Curve used to size the leaks on the Thursday Aug. 6, 2009 inspection

5 Sites of Interest - Details

Leak #1

Distance from Insertion Point:	53 ft
Distance to Nearest Sensor:	53 ft after Insertion
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	0.15

Leak Indicator

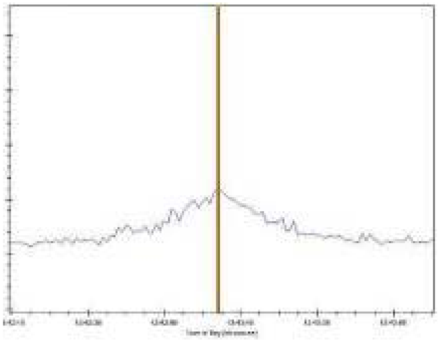


Figure 5.1a: Leak Indication Power of Leak

Frequency Spectrum

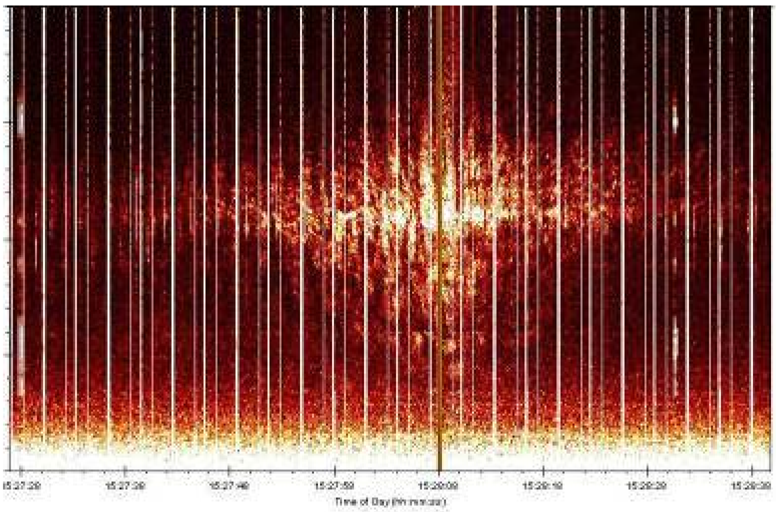


Figure 5.1b: Frequency Spectrum of Leak

Location

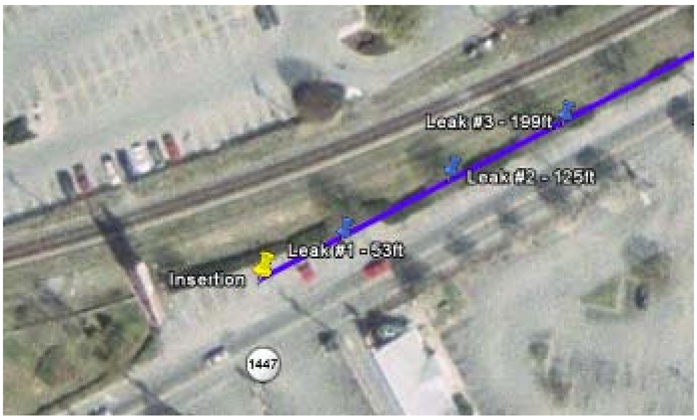


Figure 5.1c: Approximate Location of Leak

Leak #2

Distance from Insertion Point:	125 ft
Distance to Nearest Sensor:	125 ft after Insertion
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	0.1

Leak Indicator

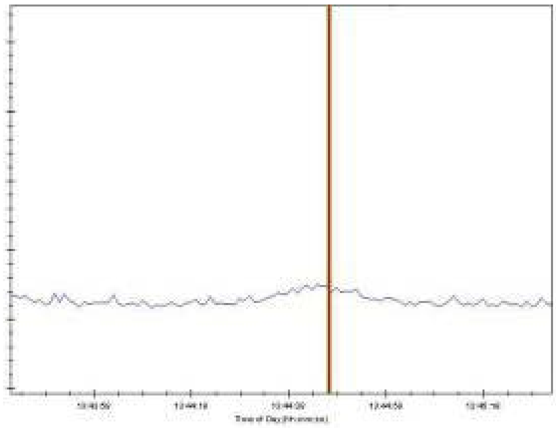


Figure 5.2a: Leak Indication Power of Leak

Frequency Spectrum

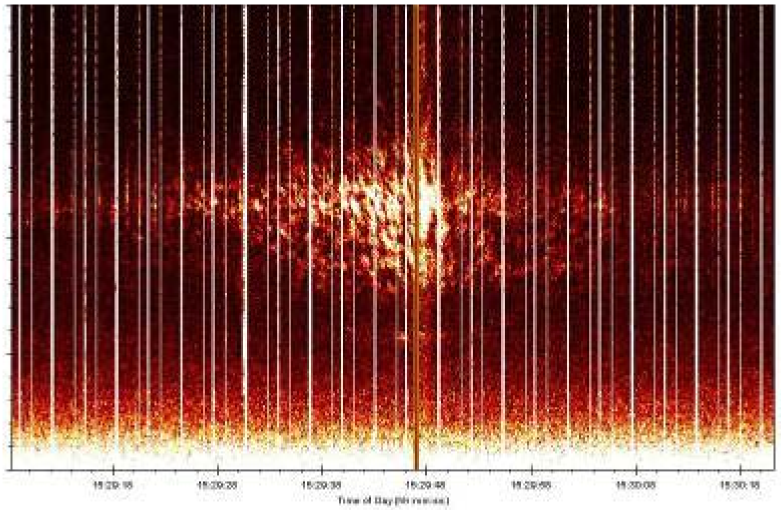


Figure 5.2b: Frequency Spectrum of Leak

Location

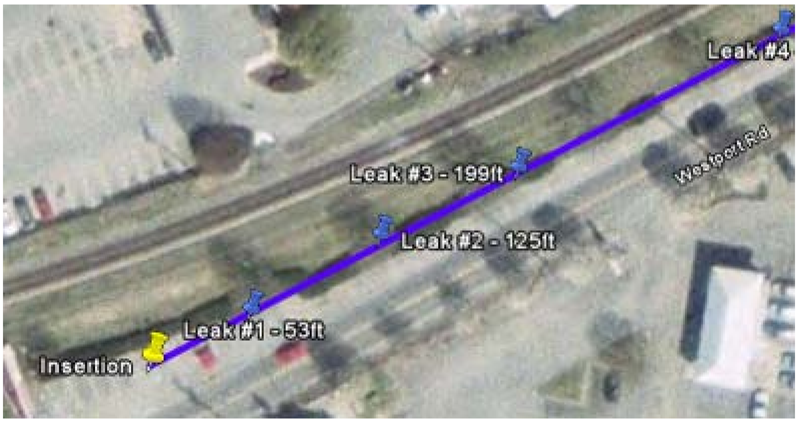


Figure 5.2c: Approximate Location of Leak

Leak #3

Distance from Insertion Point:	199 ft
Distance to Nearest Sensor:	199 ft after Insertion
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	0.8

Leak Indicator

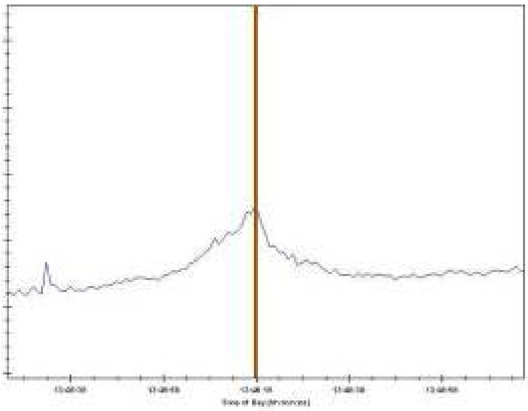


Figure 5.3a: Leak Indication Power of Leak

Frequency Spectrum

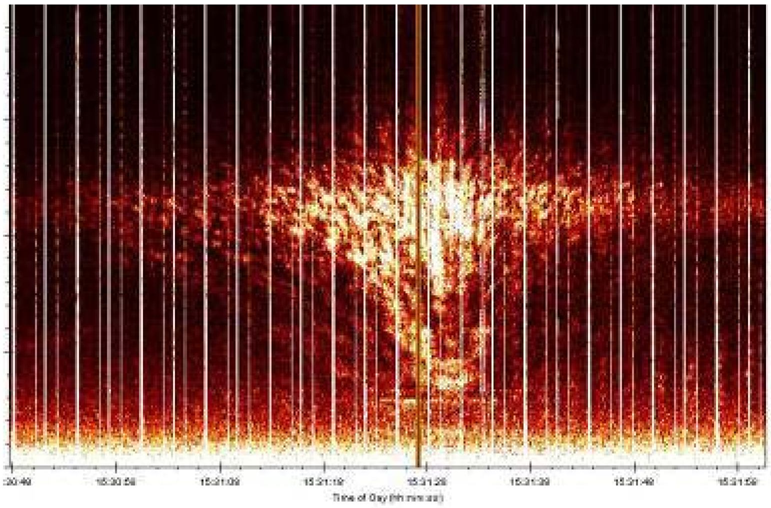


Figure 5.3b: Frequency Spectrum of Leak

Location

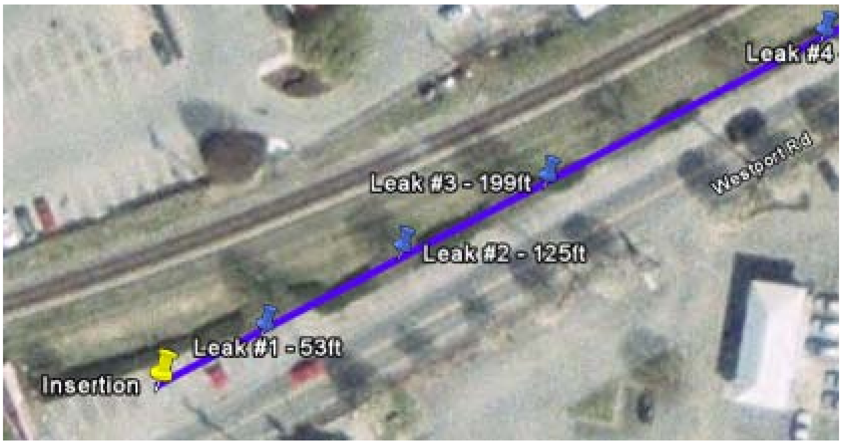


Figure 5.3c: Approximate Location of Leak

Leak #4

Distance from Insertion Point:	341 ft
Distance to Nearest Sensor:	341 ft after Insertion
Estimated Size of Leak (small/med/large):	Medium
Estimated Size of Leak (US gpm)	15

Leak Indicator

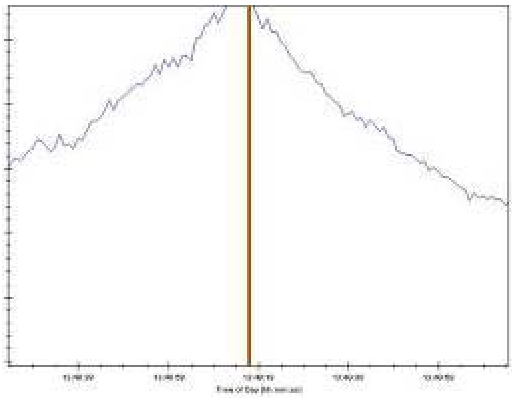


Figure 5.4a: Leak Indication Power of Leak

Frequency Spectrum

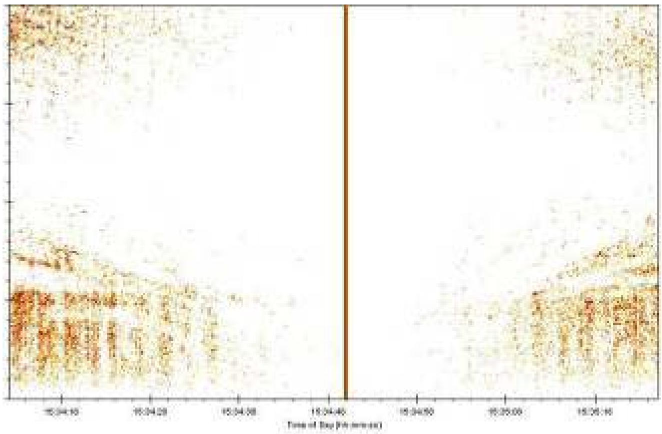


Figure 5.4b: Frequency Spectrum of Leak

Location

Figure 5.4c: Approximate Location of Leak

Leak #5

Distance from Insertion Point:	414 ft
Distance to Nearest Sensor:	395 ft before Mid-Point Sensor
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	0.5

Leak Indicator

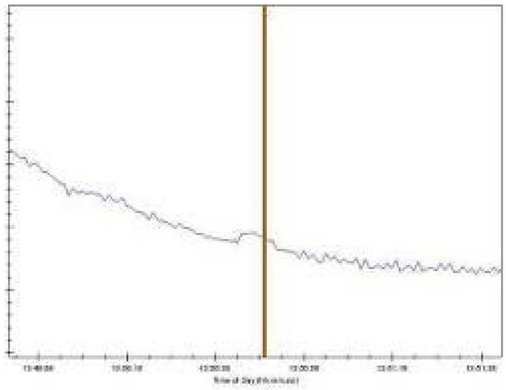


Figure 5.5a: Leak Indication Power of Leak

Frequency Spectrum

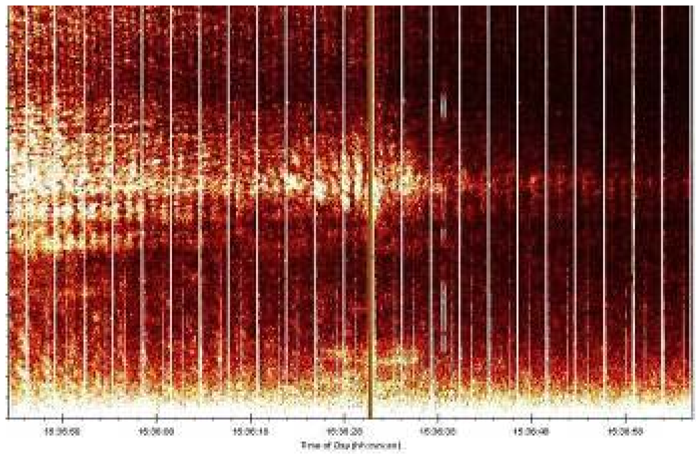


Figure 5.5b: Frequency Spectrum of Leak

Location

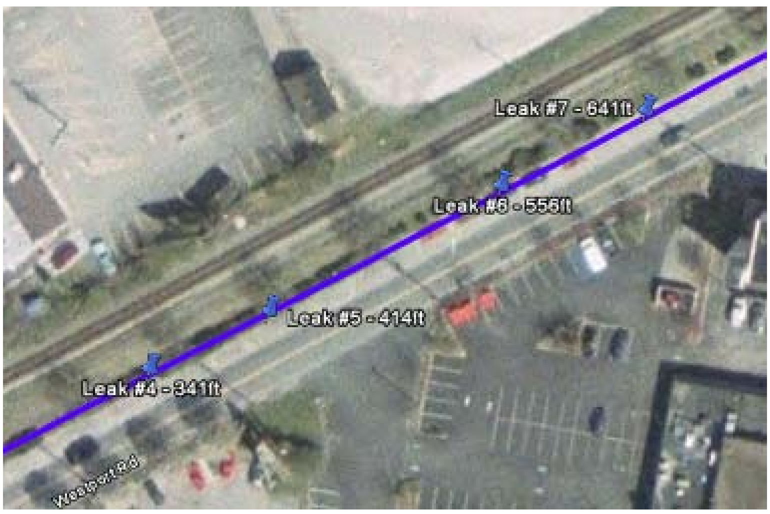


Figure 5.5c: Approximate Location of Leak

Leak #6

Distance from Insertion Point:	556 ft
Distance to Nearest Sensor:	253 ft before Mid-Point Sensor
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	1.0

Leak Indicator

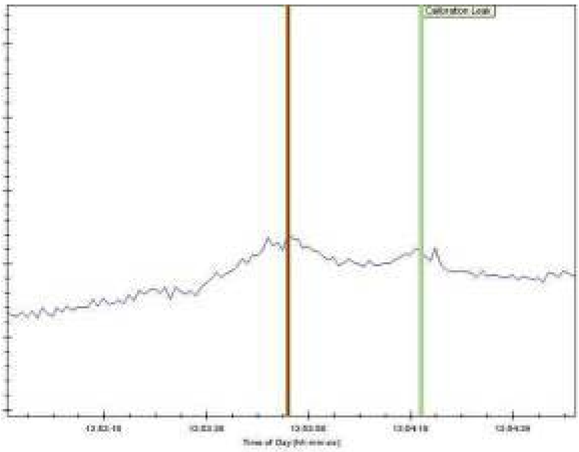


Figure 5.6a: Leak Indication Power of Leak

Frequency Spectrum

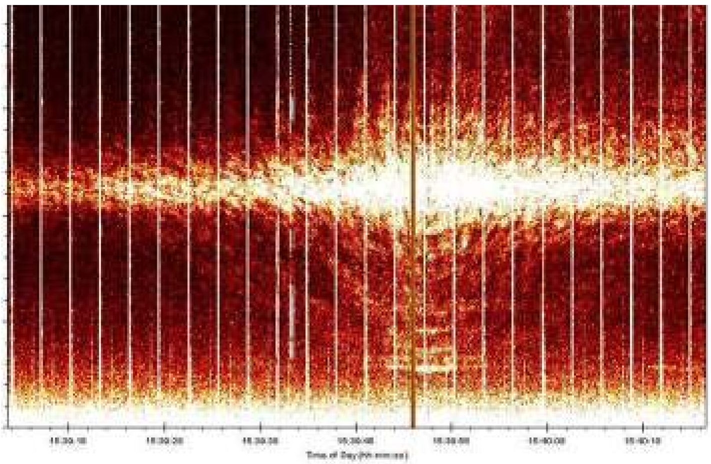


Figure 5.6b: Frequency Spectrum of Leak

Location

Figure 5.6c: Approximate Location of Leak

Leak #7

Distance from Insertion Point:	641 ft
Distance to Nearest Sensor:	168 ft before Mid-Point Sensor
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	2.0

Leak Indicator

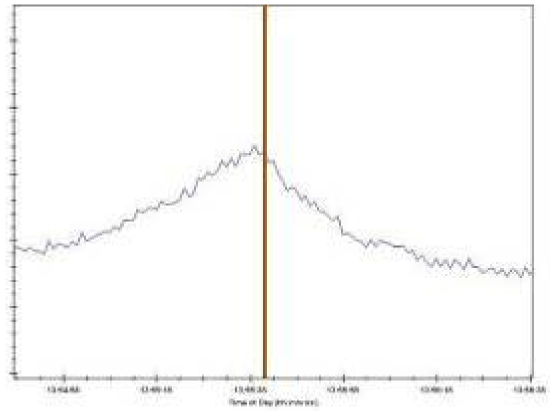


Figure 5.7a: Leak Indication Power of Leak

Frequency Spectrum

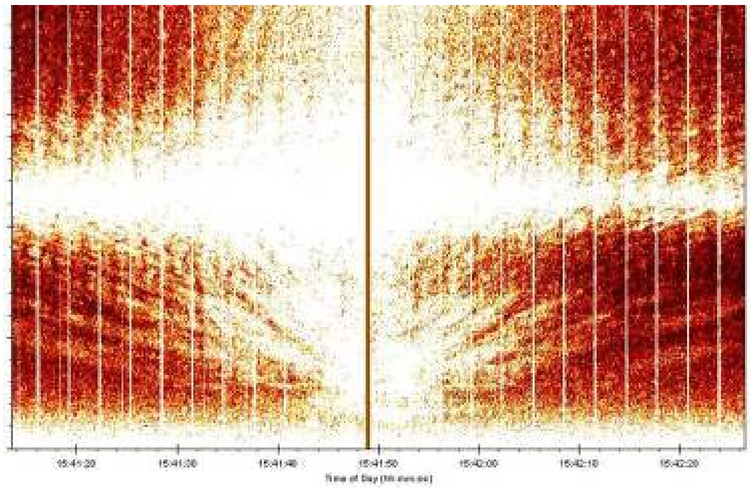


Figure 5.7b: Frequency Spectrum of Leak

Location

Figure 5.7c: Approximate Location of Leak

Leak #8

Distance from Insertion Point:	966 ft
Distance to Nearest Sensor:	157 ft after Mid-Point Sensor
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	0.1

Leak Indicator

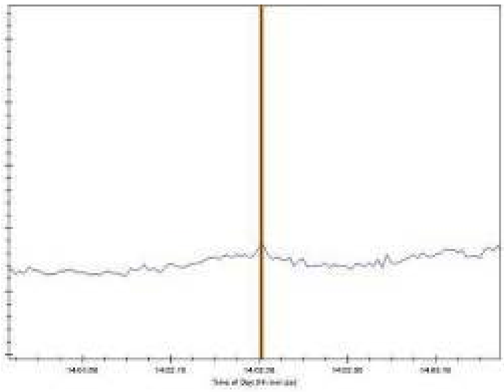


Figure 5.8a: Leak Indication Power of Leak

Frequency Spectrum

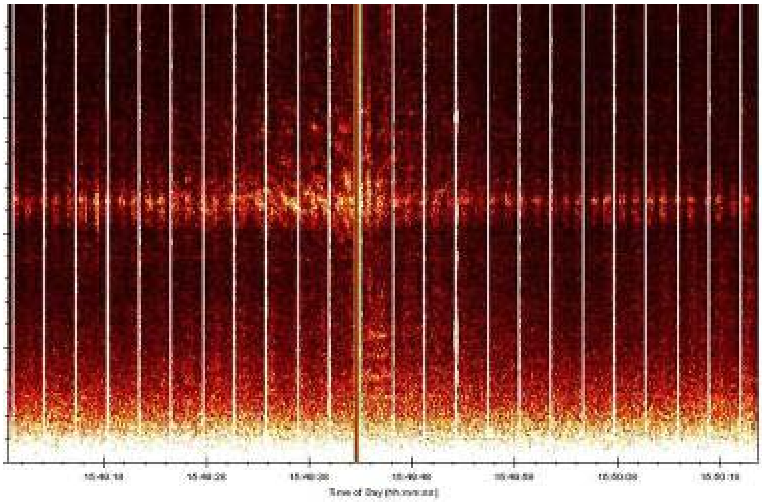


Figure 5.8b: Frequency Spectrum of Leak

Location

Figure 5.8c: Approximate Location of Leak

Leak #9

Distance from Insertion Point:	1,210 ft
Distance to Nearest Sensor:	401 ft after Mid-Point Sensor
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	1

Leak Indicator

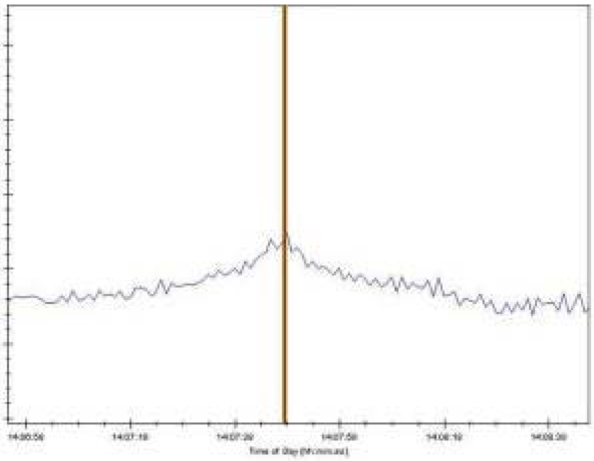


Figure 5.9a: Leak Indication Power of Leak

Frequency Spectrum

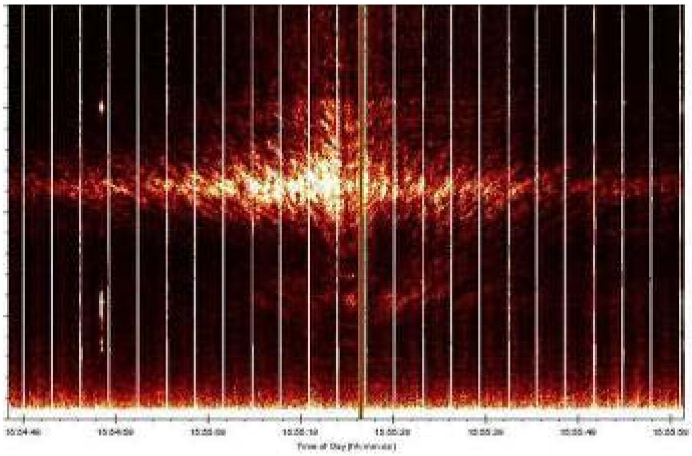


Figure 5.9b: Frequency Spectrum of Leak

Location

Figure 5.9c: Approximate Location of Leak

Leak #10

Distance from Insertion Point:	1,724 ft
Distance to Nearest Sensor:	333 ft before Extraction
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	1.0

Leak Indicator

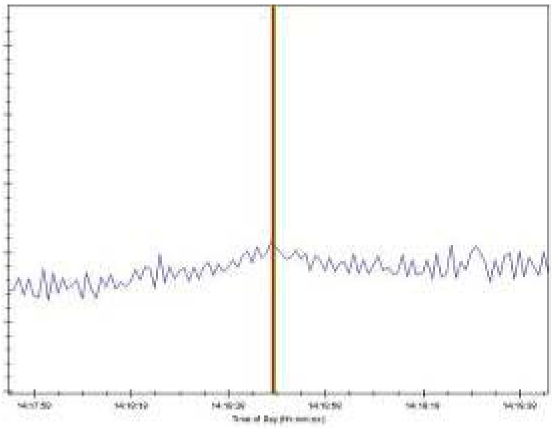


Figure 5.10a: Leak Indication Power of Leak

Frequency Spectrum

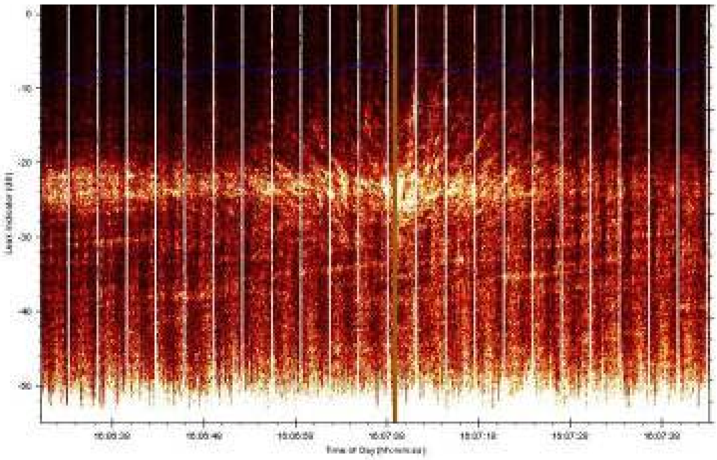


Figure 5.10b: Frequency Spectrum of Leak

Location

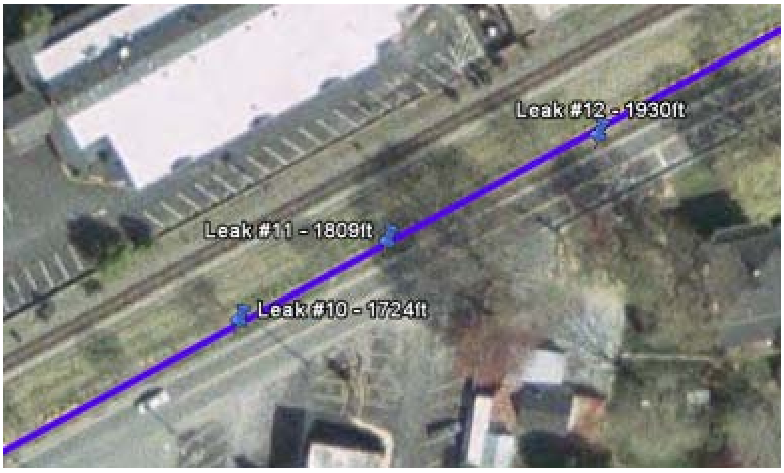


Figure 5.10c: Approximate Location of Leak

Leak #11

Distance from Insertion Point:	1,809 ft
Distance to Nearest Sensor:	248 ft before Extraction
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	2.0

Leak Indicator

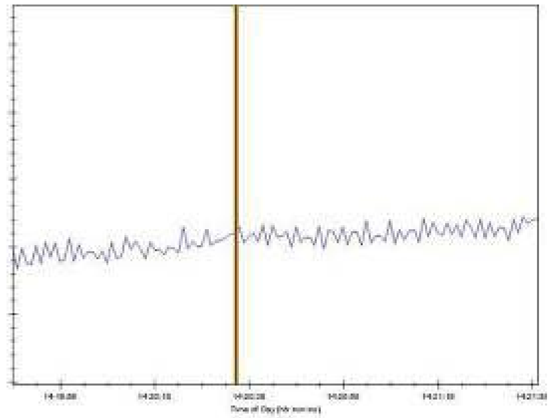


Figure 5.11a: Leak Indication Power of Leak

Frequency Spectrum

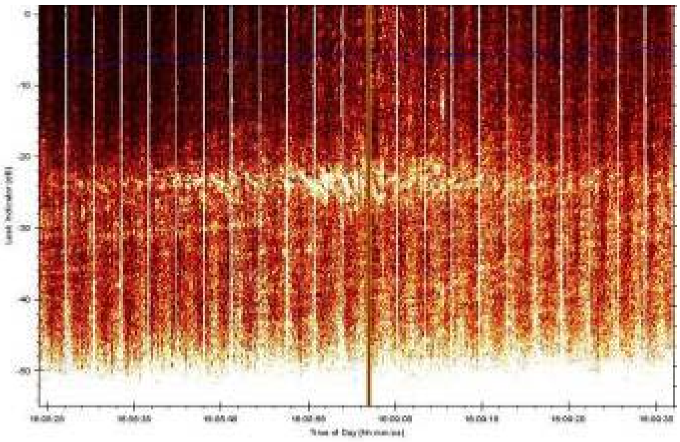


Figure 5.11b: Frequency Spectrum of Leak

Location

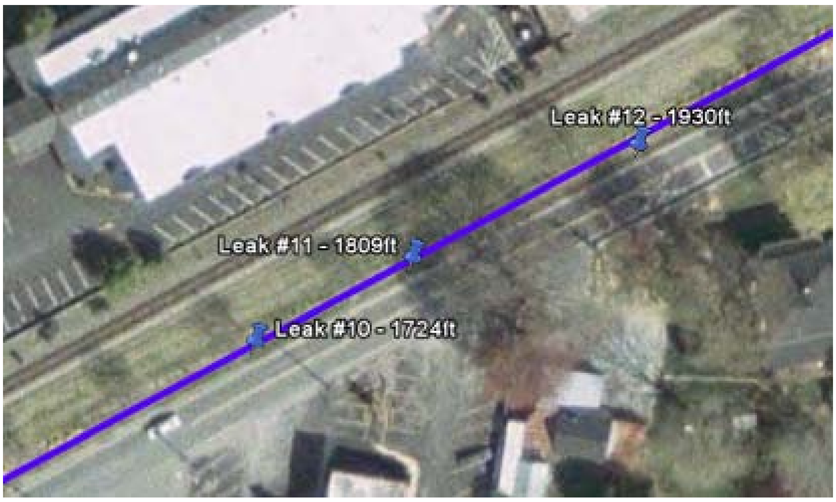


Figure 5.11c: Approximate Location of Leak

Leak #12

Distance from Insertion Point:	1,930 ft
Distance to Nearest Sensor:	127 ft before Extraction
Estimated Size of Leak (small/med/large):	Small
Estimated Size of Leak (US gpm)	5.5

Leak Indicator

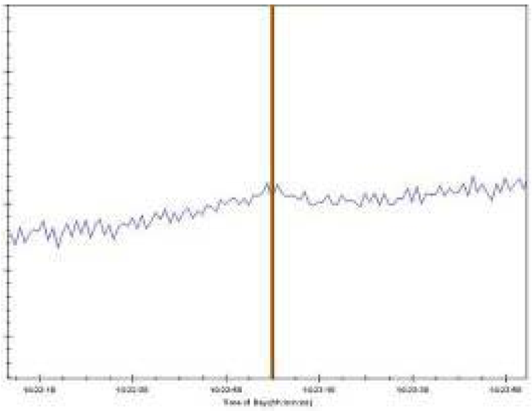


Figure 5.12a: Leak Indication Power of Leak

Frequency Spectrum

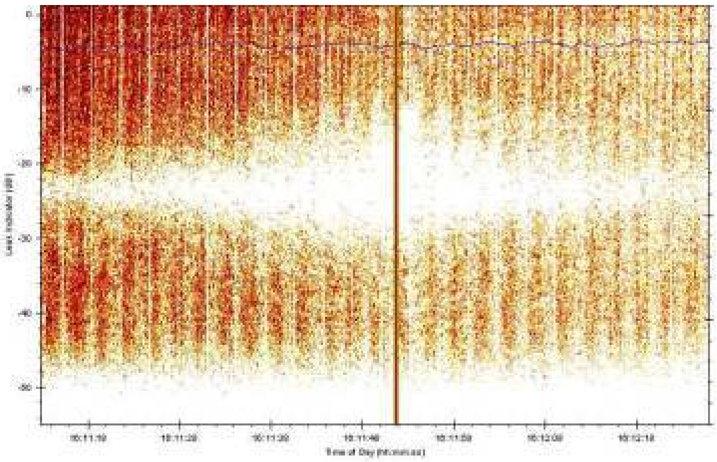


Figure 5.12b: Frequency Spectrum of Leak

Location

Figure 5.12c: Approximate Location of Leak

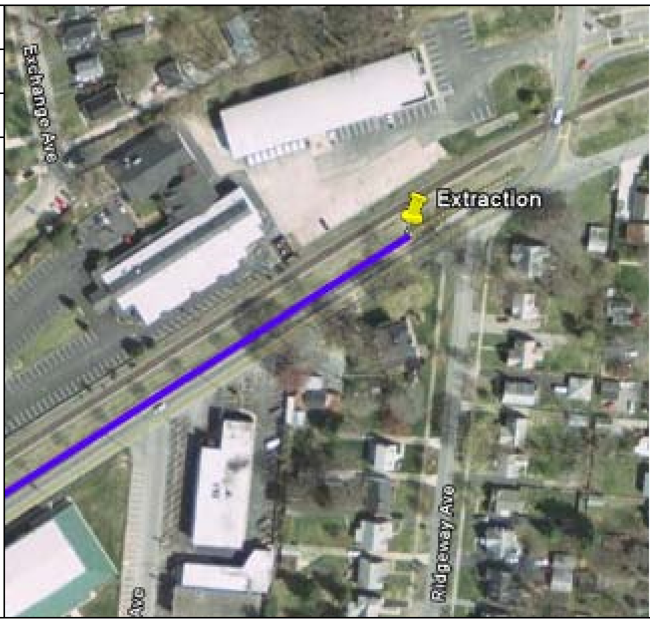
Appendix A: Ball Tracking Sensor Locations

Sensor Locations for August 6th and 7th, 2009 Inspections

AGM Location ID	Insertion
Latitude	38.2536
Longitude	-85.6549
Distance from Launch	0.0 ft

AGM Location ID	Midpoint Sensor
Latitude	38.2547
Longitude	-85.6525
Distance from Launch	809.0 ft

AGM Location ID	Extraction
Latitude	38.2566
Longitude	-85.6489
Distance from Launch	2057.0 ft



APPENDIX C

ECHOLOGICS LEAKFINDER LEAK DETECTION* REPORT
(*See pp. 1,2,3, 10, 15, 16, 17, 18, 19, 20, 21, 22, and 23)

Condition Assessment Field Demonstration

Echologics Engineering Inc.

This report outlines the results of non-destructive condition assessment testing performed on 24-inch concrete-lined cast iron cylinder pipe in Louisville, Kentucky.

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Summary

The purpose of this study is to assess the performance of Echologics proprietary non-destructive acoustic condition assessment technology for leak detection and condition assessment on cast iron pipes. Data acquisition was performed on a 24-inch cast iron pipe that runs beneath Westport Rd in Louisville Kentucky on August 11th and 12th 2009. This report summarizes the results of the data acquisition and the corresponding analysis.

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Keith Coombs – Program Manager

Revisions

0.1	Sept 7, 2009	Dave Johnston – Draft Report
0.2	Sept 18, 2009	Ellen Turner – Draft Report Revision
0.3	Sept 25, 2009	Marc Bracken – Draft Review
0.4	Sept 30, 2009	Dave Johnston – Draft Submittal to Client
1.0	Nov 4, 2009	Dave Johnston – Final Revision
1.1	Nov 13, 2009	Dave Johnston - Update

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Contents

Figures

Tables

1. Introduction

Echologics Engineering was invited to conduct a pilot study on selected cast iron pipes in Louisville, Kentucky. The intent of the study is to test the feasibility of Echologics proprietary non-destructive condition assessment technology both for condition assessment and leak detection on a 24-inch cast iron pipe along Westport Rd.

Data acquisition was performed on several sections of the 24-inch main. There are three sets of results presented in this report. First, the results of the background leak detection results will be discussed. Locations of any already existing leaks will be presented in this section. Second, The results of the leak detection demonstration will be presented. This will include whether or not the demonstration leak was discovered and what the estimated flow rate is. Finally, the results of the condition assessment will be presented.

Background measurements were performed in section lengths between 250-feet and 360-feet in length. The background measurements were performed with the purpose of finding any already existing leaks and performing the condition assessment measurements. Typically, the same methods are used when Echologics is performing commercial assessment services.

The demonstration measurements were performed using different sensors (hydrophones) and longer section lengths, approximately 1000-feet. Again, this arrangement was chosen because it would be typical for commercial leak detection projects.

As a warning to the reader, it should be noted at the outset that for completeness, we have included fairly extensive technical information, some of which will be beyond the technical knowledge base of some of the readers of this report. It is not our intent to educate readers in signal processing theory, although we have provided some layman's explanation of the background theory.

2. Background

2.1. Signal Processing

Time differences are measured using fast Fourier transforms (FFTs) and advanced cross-correlation algorithms. There are also a number of other acoustic tools that aid in data analysis processes. For the purposes of understanding this report, there are several signal processing functions that should be understood:

Coherence Function: The coherence function is a measure of how similar the vibration signals are on a frequency basis. When two signals are perfectly similar at a given frequency (for example, two sine waves), the coherence function value is 1 at that frequency. Good coherence would be considered anything at 0.5 and above.

Transfer function: The transfer function is a frequency based plot of the relative strength of the two measurement channels. This function shows the relative vibration level of the blue and white stations, and can be given in log or linear format. Many vibration engineers prefer to see both formats, as a log plot is easier on initial read, however a linear plot will show more detail.

Frequency plot (FFT): The frequency plots given in this report are fast Fourier transforms of the raw level vs. time signals. Very simply, these plots show the frequency content of the vibration signals measured. It is often possible to pick out leak noise on the frequency plots, and these can be used to analyze the leak detection signals. For example an FFT from the blue station may show a spectrum consistent with leak noise with significant higher frequency vibration, while the white station signal may show no high frequency content indicating a possible PVC repair (the PVC repair may filter out high frequency content).

Correlation Function: The correlation function is the level vs. time function that will indicate a leak, and in the case of condition assessment measurements will show the out-of-bracket peak or time difference. Ideally a good correlation peak should be very sharp, and very prominent. The LeakfinderRT software will present a warning for an out-of-bracket signal when the time delay of the signal approaches the total time delay of the entire measurement distance (i.e when t⇒d/v).

2.2. Leak Detection

The leak detection methodology used is the cross correlation method. A correlator listens passively for noise created by a leak. Two sensors are mounted on fire hydrants, exposed pipe, or valves in such a way that the leak lies between them, or is 'bracketed' by the sensors. A leak that lies outside the area spanned by the sensors is known as an 'out-of-bracket' leak. Any active leaks or draws or other sources of noise on the pipe will vibrate the pipe and detected by the sensors.

The signals will be recorded and the cross-correlation plot will be analyzed. Any potential leaks will appear as a spike in the cross-correlation plot. The position of the spoke on the x-axis corresponds to the time difference it takes for the signal to arrive at the Blue and White stations. The wave velocity is known and therefore the position relative to either of the stations can be computed.

2.3. Non-Destructive Condition Assessment

An acoustic signal induced in the pipe may be used to determine the acoustic wave velocity in a section of pipe, which can in turn be used to back calculate the average wall thickness of the pipe. Knowing the distance between two sensors mounted some distance apart on valves or fire hydrants, the acoustic wave velocity will be given by v = d/t, where d is the distance between the sensors, and t is the time taken for the acoustical signal to propagate between the two sensors. If an accurate measurement of the acoustic wave velocity is made, it is possible to back-calculate the remaining average thickness of the pipe between the two sensors.

The wall thickness measured represents an average between the two sensors. Typically the length of the pipe section over which the acoustic velocity is measured 100 to 300 metres *(300'-1000')*, however this distance can be decreased to anywhere between 30-100 m to increase the resolution.

Echologics proprietary leak noise correlator, LeakfindeRT was used to determine the acoustic velocity. An acoustic source outside the area spanned by the sensors (an 'out-of-bracket' source) was used to induce an acoustic wave in the pipe, and the time delay difference was measured. At each site the noise source to induce the acoustic wave; was either operation of a fire hydrant, or a valve or hydrant was impacted.

The average wall thickness of the pipe section between the acoustic sensors is then back calculated from a theoretical model. As the pipe wall thickness decreases over time, the acoustical wave velocity decreases. From an intuitive perspective, this is akin to trying to run on a trampoline versus solid ground; as the bounding layer becomes more flexible the propagation velocity decreases. The acoustical wave velocity is given in Equation 1: Wave Velocity - Thickness Model *below.* It should be noted that there are other factors that affect the propagation velocity such as water temperature and pipe wall inertia. These factors are not shown here but have been accounted for in the final results.

$$v = v_o \sqrt{\frac{1}{[1 + (D/e)(K_{water}/E_{pipe})]}}$$

where

v: Propagation velocity of leak noise in pipe
v_o: Propagation velocity of sound in an infinite body of water
D: Internal diameter of pipe
e: Thickness of pipe wall
K_{water}: Bulk modulus of elasticity of water
E_{pipe}: Young's modulus of elasticity of pipe material

Equation 1: Wave Velocity - Thickness Model

The acoustic propagation wave (the water hammer mode) propagates as a compression wave in the fluid, and a dilatational wave in the pipe. Therefore the *pipe will breathe on a microscopic level, and therefore the pipe will go into stress*. There are two key implications to this:

1. Only the structural part of the pipe that can carry load will contribute to the structural stiffness of the pipe, therefore deposits on the pipe wall such as tuberculation or graphite will not be included in the average wall thickness measurement.

2. We will measure the minimum structural thickness of the pipe, as the level of strain of the pipe will be dependent on the minimum wall thickness at any point around the circumference the pipe.

As noted, the pipe wall thickness calculated from these measurements represents an average value for the pipe section over which the acoustic velocity is measured. At first glance, this may appear to be a limitation of the technology, as the question could be reasonably asked as to whether the method can find pockets of corrosion. In practice this has not been the case. The technology has been applied to generally much greater sample lengths *of pipe than could be done with random sampling or electro-magnetic technologies. Therefore when surveying long lengths of type, the operators begin to look for anomalies in the measurements that could indicate degraded sections of pipe. When these are seen, the* distance between the sensors may be *decreased and more resolution* obtained. Generally, pipes will have a more-or-less uniform thickness profile with isolated pockets of corrosion over significant lengths, say 50 to 100 meters, as soil and bedding conditions are unlikely to change significantly over such distances. Also, average wall thickness values are *suitable to evaluate the residual life of pipes for the purpose of long-term planning of rehab and replacement needs.* The use of techniques such as evaluation of stray currents, and soil corrosivity studies and main break history may be used in conjunction with our data to evaluate overall pipe condition.

2.4. Metallic Pipe

The primary degradation mechanism in buried metallic pipes is corrosion. Corrosion occurs in many different forms and can be accelerated or inhibited based on soil properties, water properties and characteristics of the pipes surroundings.

Two main forms of corrosion occur in buried pipelines: uniform corrosion and pitting corrosion. Uniform corrosion occurs when general, constant corrosion occurs on all surfaces of the pipeline. This can occur from the inside out and is caused by the properties of the water that the pipe is carrying. Or it can occur from the outside in if the pipe is in submerged or semi-submerged conditions.

Pitting corrosion occurs on the inside and outside surfaces of the pipe. This is when small areas corrode preferentially leading to cavities or pits, and the bulk of the surface remains unaffected. Pitting corrosion can be accelerated under stagnant conditions, which is why it is generally more severe on the outside surface of the pipe.

Other forms of corrosion can occur including: galvanic (dissimilar metals), De-Alloying (graphite), inter-granular and erosion corrosion. All of these can contribute to the overall degradation of the pipe but they are considered to be relatively insignificant compared to the impact of uniform and pitting corrosion.

2.5. Concrete Lining

The wave propagation velocity is a function of the thickness of the pipe wall and the corresponding material elastic modulus. Therefore, if a pipe is concrete lined the structural stiffness of the pipe is increased via the addition strength of the concrete. The wave velocity then becomes a function of the structural stiffness of the metal and the concrete lining.

In order to account for this, it is necessary to calculate the nominal thickness of the pipe as if it was not lined with concrete i.e. the equivalent structural thickness of a metallic pipe without the concrete lining. This will be referred to as the equivalent thickness and generally it is 2–3mm thicker than the thickness of the base metal. This value can also be considered as the ‘effective’ or the ‘structural’ thickness of the pipe.

The measurement will then be compared to this value, the equivalent thickness rather than the thickness of the metal alone.

2.6. Nominal Data

Battelle provided original specifications for both diameters of pipe. The details are presented below in Table 1: Nominal Dimensions. There is also an image of the cross-section of the pipe shown in Figure 6: Pipe Wall Cross-Section. It closely matches the values presented here.

YOI	Type	Dia (inch)	Dia (mm)	Cast Iron Thickness (inch)	Cast Iron Thickness (mm)	Lining Thickness (inch)	Lining Thickness (mm)
1932	Pit Cast Iron	24	610	0.75	19.05	0.25	6.35
	Equivalent Thickness of Cast Iron without Concrete Lining						
		=	22.2	mm			
		=	0.874	inch			

Table 1: Nominal Dimensions

2.7. Sensitivity Analysis

Echologics has committed a substantial amount of effort to reduce sources of error in our assessments. However there are still variables that strongly affect the final result. They are as follows:

Distance Measurement

A calibrated wheel is used for obtaining our distances, and distance measurements were repeated 3-4 times for each location to ensure the best possible accuracy. For example, on a total distance of 150m, an error of +2.5m resulting in a measured distance of 152.5m will cause a positive error in the final result of approximately 17.5%. An accurate distance measurement is therefore crucial to an accurate assessment. For this reason, our preference is always to use line valves, as these provide the most accurate distance measure, as it is a point-to-point measurement. If the pipe has multiple bends and elevation changes between the sensor connection points, error in the distance measurement increases, as it is not always easy to identify where the bends occur. As a result, if a situation existed where the pipe location was in question, it was requested that Bristol Water re-measure the distance after a pipe location was performed. In some cases this improved the measurement result.

Pipe Manufacturing Tolerances

The pipe laid will have small differences in thickness and due to manufacturer and tolerances. This factor is usually 5-10% dependent on the manufacturer and the material. This may lead to a pipe growing by a small percentage (5-10%) compared to the nominal thickness used. This is particularly true of the older vintages of pipe measured in this study. Generally, the materials data used for the calculation is chosen using conservative estimates. The purpose of this is to provide a worst-case scenario to the client i.e. assume that the pipe is manufactured to the better side of the tolerances and calculate the remaining thickness based on this. This is not considered to be error because the presented result actually represents the current condition of the pipe.

Variation in internal diameter of the pipe can also affect the final result. If the manufacturing tolerances for the diameter are approximately 5-10% the corresponding results on the calculated value will also vary by approximately 5-10%. This is considered to be relatively insignificant if, in fact, the information provided by the client is correct. This is not always the case and it will be discussed later in this section.

Repair Clamps on Previous Leaks

A small number of repair clamps should have an insignificant effect on the test results, since the acoustic wave is primarily water borne and will bypass the clamps. It should be noted that although the acoustic wave is primarily water-borne, it is a coupled wave that moves simultaneously in the pipe (in an axi-symmetrical breathing mode), and in the water as a compression wave. Thus the wave will generally skip across discontinuities such as clamps, and reestablish itself in the pipe material beyond.

Variation on Young’s Modulus

In general, a change in elastic modulus of 10% will cause a change in the calculated thickness by approximately 10%. Therefore it is necessary to account for this variation. The elastic modulus is known for common materials used in the manufacturing of pressure pipe but this value can vary from manufacturer to manufacturer. This depends on the manufacturing process and the quality of the material.

Replacement of short Pipe Sections for Leak Repairs

The effect of short pipe replacements will depend on the material used. For example, a new 6-metre long ductile iron repair in a 100-metre long / 152 mm-diameter cast iron pipe section of average condition, will produce a small error of +3.5% in predicted wall thickness. However, the same repair made with PVC pipe would produce an unacceptable error of -41%. Preferably, pipe sections selected for testing should be free of repaired segments. However, if this condition does not exist, the effect of new pipe segments can be accounted for provided that accurate information is available for the location, length, material type and class of new pipe segments.

Inaccurate Records

In some cases the possibility exists that inaccurate information was provided by the client, specifically referring to the pipe diameter and the pipe material. As described above, small manufacturing variations in elastic modulus and internal diameter only affect the final result by 5-10% but if the information supplied by the client is incorrect, it is flawed by much greater magnitudes. For example, a common error would be to mistake a 200mm pipe for a 250mm pipe. When the calculation is performed using an internal diameter of 250mm, the remaining thickness may be 12.5mm. If the same calculation is performed using an internal diameter of 200mm, the remaining thickness is reduced to 9.3mm, a change of 3.2mm! In this case, the error caused a 35% over estimation of the pipe wall thickness.

Another common problem arises when improper pipe material information is provided. For example, if a pipe was thought to be spun cast iron when, in fact, it is ductile iron. When the calculation is performed using the elastic modulus for spun cast iron (131Gpa), the remaining thickness may be 11.6mm. If the same calculation is performed for a ductile iron pipe (169Gpa), the remaining thickness drops to 8.9mm, a change of 2.7mm! The error caused a 30% over estimation of pipe wall thickness.

It becomes obvious that accurate records from the client are an essential requirement for providing accurate condition assessment results.

2.8. Sources of Error

The results of the sensitivity analysis provide insight into how the various material properties and pipe dimensions can affect the final result. If one ignores error introduced by manufacturing tolerances and inaccurate nominal information, the main source of error is cause by improper sensor-to-senor distance measurements.

The average section of pipe tested during this project was 150m. If one assumes that the sensor-to-sensor spacing can be measured accurately to within 1m, the resulting error in the thickness calculation is approximately 5%. If however, there are multiple bends in the pipe or significant elevation changes, the error in the distance measurement may increase. For example, one bend in the pipe may introduce an additional error of 1m. With a total distance error of 2m, the resulting error in the final calculation is approximately 10%.

2.9. Negative Correlation Signals

There were several locations where correlation signals could not be acquired, or they were of poor quality. This can happen for a number of reasons, and we typically find that this occurs on a percentage of all of our projects. Although we have never had the opportunity to fully explore the reasons for this, the following are some of the conditions that we have encountered that have affected our measurements:

1. The presence of plastic repairs in metallic pipes can cause poor correlation signals, and will also cause inaccurate thickness

2. Loose or worn components in fittings used for the measurements, such as valve or hydrant stems.

3. Heavily tuberculated pipe, particularly old cast iron or unlined ductile iron may attenuate the acoustic signals to such an extent that a correlation is of very low quality.

2.10. Condition Assessment Data Interpretation

The condition of a pipe may be assessed based by judging it based on other pipes that we have measured and then exhumed to determine the condition. For a full condition assessment, it is recommended that our data be used in conjunction with soils information, any ground potential measurements done, along with any pipe samples exhumed during leak repairs. Acoustic non-destructive condition assessment cannot pinpoint the source of degradation. For example, a reading of -20% pipe wall could mean that the pipe is generally degraded along it's entire length, or the pipe could have significant degradation at only one or two locations.

In the absence of other parameters, we have provided a gradation scale based on our previous project experience and pilot studies. Based on our previous experience, we have provided background on typical results found during the course of our condition assessment surveys. Please note that the sample photos shown in the following section are from a previously performed pilot study. They are to be used only to demonstrate the typical levels of degradation found from previous testing. This is meant to act only as a guideline in assessing the results of this study.

The images presented below show four pictures in each. The top left picture shows the as-found condition of the pipe. The top right image shows an overview shot. The bottom left shows a close up of the surface after it was sandblasted. The bottom right shows the internal surface after it was sandblasted.

The descriptions below described results measured by Echologics, given by an averaged measured loss in percent. The physical results given are the average measured value at either end of the pipe, the average pit depth on the outside surface / inside surface and the qualitative condition on the outside surface / inside surface.

2.11. Results of Pipe with 5% degradation

A section of pipe where 4.7% measured loss is shown in Figure 1. The nominal thickness of this pipe was 12mm (0.47in), whereas the lab measured physical thickness at either end of the sample was 11.4+/-2.7mm (0.45in +/-0.1in). The average pit depth was 1.5mm / 1.9mm. The pipe was qualitatively described as very good / very good.

This again is an indication that the acoustic wave velocity from the acoustic mode of the pipe that we are measuring is based on the average minimum structural thickness, not the average physical thickness.

The sample was taken from an area with corrosive clay based soil. The figures indicate that although there are local areas of corrosion, the pipe wall is generally in good condition. Based on this type of result, a pipe at this level of degradation may have occasional failures from corrosion holes but it is structurally sound.

2.12. Results of Pipe with 9% degradation

Figure 2 shows photographs of a section of pipe measured at 8.9% average loss. The physical thickness of this pipe was measured at 8.8+/-0.8mm (0.35in +/-0.03in)(nominal was 9mm), with average pit depth at 2.5mm / 3.0mm. The condition of the pipe was rated as very good / moderate. The corrosion of this pipe was primarily localized internally on the bottom of the pipe as can be seen in the right photo. The corrosion appeared in this case more continuous perhaps due to sediment build up at the bottom of the pipe. Overall the structural integrity of the pipe is good.

2.13. Results of Pipe with 47% degradation

Figure 3 provides photographs of a pipe with a measured 47.3% average loss of pipe wall thickness (11.0mm, 0.43in nominal). In the lab the average physical thickness was measured as 11.6+/-3.3mm (0.456in, +/-0.13in) and an average pit depth of 3.8mm / 2.5mm. The physical condition of the pipe was described as very poor / poor. Note that there were also numerous through holes in the pipe evident after sand blasting. It is interesting to note that the pipe was not leaking when measured, probably due to the build up of tuberculation.

Figure 1: Photos of pipe with 4.2% measured loss

Figure 2: Photos of pipe with 8.9% measured loss

Figure 3: Photos of pipe with 47.3% measured loss

Guidelines for Interpretation of Results

Based on the results, we recommend the following guidelines for the interpretation of our data:

- 10% or less: The pipe is in very good condition, but may still have minor levels of uniform corrosion. Some localized areas of pitting corrosion may exist but it is expected that the areas are isolated.
- 10-20%: Pipe is in good condition, there may be some moderate uniform surface or internal corrosion, or more localized areas of pitting corrosion.
- 20-35%: Pipe may have significant localized areas of pitting corrosion, or moderate uniform corrosion throughout.
- >35%: Pipe is in poor condition and may have numerous areas of pitting corrosion, including significant uniform thinning of the pipe.

3. Methodology

3.1. Leak Detection

In general, it is more challenging to survey for water main leaks with a leak noise correlator than using it to pinpoint a leak, which is known to exist, as there will be a high incidence of negative (no leak) results. When many negative results are encountered, the surveyor may begin to question the operation of the equipment, or his procedures. Therefore, one of the main issues with testing pipes where there is no known leak is to ensure that the proper steps are taken to ensure that the results are properly analyzed so that the presence (or lack of) a leak may be definitively decided. Based on our previous experience with leak detection surveys, and our familiarity with acoustic technology, procedures were implemented for both on site, and follow-up analyses were performed in order to make a definitive decision on whether or not a leak was present.

1. Sensors were attached on valves or hydrants as available at each site. Where measurements were performed on valves, the sensors were placed on the tops of valve keys that had been lowered onto the valves or placed directly on the valve nut when possible (if the valve chamber was clear of debris).

2. The LeakfinderRT radio channels are color-coded blue and white, where blue is always the right audio channel and white the left. For all measurements, the locations of the blue and white channel were noted.

3. In general, all leak detection measurements were taken on the same segments of pipe where the condition assessments were performed.

4. After placement of the sensors on the appropriate valve or hydrant, the fitting was tapped, and listened to at the radio receiver to ensure that the sensor was functioning, and that the radio signal was arriving properly at the receiver. This is called a scratch test.

5. Where possible, sensor spacing was accurately measured using a calibrated measuring wheel.

6. A correlation measurement was performed, and the signal was saved to the computer, so that further analysis could be performed later in the office, and so that the client could have a permanent record of the raw noise file if needed.

7. Where a positive signal was detected (a correlation peak with good signal coherence), the location was immediately checked to determine if it corresponded to a service line or other notable draws from the pipe. If this was the case, several more correlations were conducted to see if the ‘usage’ stopped.

8. Where negative results were obtained (no clear correlation peak was obtained), a series of checks was completed, including a review of coherence and of the blue and white frequency spectra, to detect the presence of a PVC repair or some other anomaly in the test section. Such checks have become part of our protocol for leak detection surveys.

3.2. Condition Assessment

The following survey methodology was used:

1. For each location surveyed, the distance between the sensors was measured. A very accurate measurement of the distance between sensors is required. Although less important for leak detection measurements, an error in measurement of even 3 feet over a 300 foot distance can lead to errors of 15% in wall thickness estimation. The margin of error acceptable will be dependent on the pipe type and the distance between sensors. Typically, for a cast iron pipe, we have not found it difficult to obtain this measurement accuracy. There were some cases where accurate pipe geometry was not available. For example, elevation changes and curves in the road may create discrepancies between our distance measurement along the surface and the physical distance of the pipe underground. Any locations that presented this difficulty were noted and will be discussed in the final results.

2. Sensors were placed on the fittings, either hot taps that were previously installed or in potholes on the surface of the pipe, and a noise source was created, typically at a location out-of-bracket (beyond one of the sensors). The noise sources were either a running well, light impacting on valves or use of the shaker. Some sites permitted the use of all 3, others were limited to 1 based on space restrictions

3. The temperature of the water was recorded, generally at the time of testing, for each of the test sites.

4. The data was stored as a raw wave file for further analysis and confirmation in our offices. Data was reanalyzed and filtered to obtain an optimum correlation peak.

3.3. Instrumentation

The leak detection was completed using Echologics' proprietary leak detection system, LeakfinderRT. The system works by placing sensors on two water system fittings such as valves or hydrants bracketing the leak. If a leak is present, the software then uses the time difference it takes the leak noise to reach the two sensors to pinpoint the leak location. The sensors used for the purposes of this project were surface mounted, either on hydrant flanges, hydrant secondary valves or line valves. There were two types of sensors used in this study:

- Echologics’ proprietary Hydrophones for direct measurement of the water column
- Echologics’ piezoelectric accelerometers, with a sensitivity of 1 V/g

Each sensor has its own specific attributes that make it preferable in certain situations. The Hydrophone is particularly well suited to measuring asbestos cement and medium to large diameter mains (12in and larger), as leaks on these pipes generally are dominated by lower frequency content (200Hz and below). The standard piezoelectric accelerometer has a slightly higher noise floor, and has better high frequency response, making them more suitable for some measurements on smaller diameter (10in and lower) metallic pipes that typically have higher frequency content (200 Hz and higher). Radios used were 460 MHz or 433 MHz analogue units manufactured by Echologics.

4. Results and Discussion

First, general information regarding the site location and the pipe will be discussed. Following this, the results of the demonstration will be presented first, followed by the results of the background measurements and the corresponding condition assessment. A map showing the site location and the general layout can be found in Figure 7: Site Layout.

Table 2: Excavation Locations presents a list with the locations of the excavation pits. It shows the approximate distance between pits and a corresponding description of the type of excavation. The distances presented were not the same distances used when performing data analysis.

For the Leak Detection Demonstration, the pipe was broken up into three longer sections. For the Background and Condition Assessment measurements the pipe was broken up into seven sections. More sections were chosen for the assessment measurements in order to provide a better representation of the pipe condition.

Pipe excavation locations

EPA technology Demonstration

ID	Distance Feet	Name	Type
1	0	Lauch Pit	6x8 with trenchbox, 12" T, Reducer
A	250	Sensor Pit A	3x3 to top of pipe
B	510	Sensor Pit B	3x3 to top of pipe
4	581	Corp Valve **1 &2**	6x8 with trenchbox, stone backfill
C	809	Sensor Pit C	3x3 to top of pipe
2	1080	Corp Valve **3 4 5 & 6**	6x8 with trenchbox, stone backfill
D	1173	Sensor Pit D	3x3 to top of pipe
E	1439	Sensor Pit E	3x3 to top of pipe
5	1580	Corp Valve **7 & 8**	6x8 with trenchbox, stone backfill
F	1750	Sensor Pit F	3x3 to top of pipe
		Fire Hydrant	Pressure gage
3	2057	Receive Pit	6x8 with trenchbox, 12 inch T, Reducer
	2100	12" Discharge	

Table 2: Excavation Locations

Location	Sensor-to-Sensor Spacing (ft)
Pit1 to Pit2	1080.7
Pit2 to Pit3	979.3
Pit4 to Pit5	1001.6
Pit1 to PitA	250.7
PitA to PitB	260.5
PitB to PitC	298.6
PitC to Pit2	271
Pit2 to PitE	360.9
PitE to PitF	294.6
PitF to Pit3	312.7

Table 3: Sensor-to-Sensor Distances

4.1. Demonstration Results

The results of the demonstration tests are presented below in Table 4: Demonstration Results. The column titled File # corresponds to the WAV file number in the name of the file when it was recorded. It can be cross-referenced with the screenshots presented in the Appendix. The column titled Type corresponds to the type of test that was provided by Battelle. At each location there was four demonstrations the first of which, Demo1 Cal, was a calibration test where the induced flow rate was known. The column titled Location presents where the sensors were attached to the pipe. The column titled Flowrate (GPM) presents either the known flow rate for calibration tests or the estimated flow rate for the others. The column titled Result presents the outcome of the correlation measurement, either negative or positive.

File #	Type	Location	Flowrate (GPM)	Result
1d	Demo1 Cal	Pit1 to Pit2	0.6	Negative
1f	Demo2	Pit1 to Pit2	Negligible	Negative
1g	Demo3	Pit1 to Pit2	2.0 to 5.0	Positive - 577.6ft from Pit1
1h	Demo4	Pit1 to Pit2	0 to 1.0	Positive - 560.7ft from Pit1
2b	Demo1 Cal	Pit2 to Pit3	None	Negative
2c	Demo2	Pit2 to Pit3	5.0 to 8.0	Positive - 476.8ft from Pit3
2d	Demo3	Pit2 to Pit3	5.0 to 8.0	Positive - 478.8ft from Pit3
2e	Demo4	Pit2 to Pit3	Negligible	Negative
3b	Demo1 Cal	Pit4 to Pit5	8.0	Positive - 502.9ft from Pit5
3c	Demo2	Pit4 to Pit5	Negligible	Negative
3d	Demo3	Pit4 to Pit5	5.0 to 8.0	Positive - 497.8ft from Pit5
3e	Demo4	Pit4 to Pit5	2.5 to 5.0	Positive - 487.4ft from Pit5

Table 4: Demonstration Results

Section 1: Pit#1 to Pit#2, Demonstration in Pit#4

The calibration test, Demo 1, was performed with a known flow rate of 0.6Gpm. The resulting correlation test presented a negative result. This suggests that a flow rate of 0.6Gpm or less cannot be detected with hydrophones at a sensor spacing of 1080.7ft or greater. Although the final result was negative this is still considered to be a successful calibration test as it has defined a range that cannot be successfully correlated.

The flow rates in Demo 2, 3, and 4 were unknown. Demo 2 presented a negative correlation test. This suggests that the flow rate is negligible and most likely to be close to or below the calibration value, 0.6Gpm. Demo 3 presented a positive result at a distance of 577.6ft from Pit #1. The character of the noise sources suggested a moderate sized flow rate in the range of 2.0 to 5.0Gpm. Demo 3 presented a positive result at a distance of 560.7ft from Pit #1. The coherence was very low and the correlation peak was weak suggesting that the flow rate was low. It is estimated that this flow rate is between 0 and 1.0Gpm but probably closer to 1.0Gpm as it is known that 0.6Gpm yielded a negative correlation.

Section 2: Pit#2 to Pit#3, Demonstration in Pit #5

The calibration test, Demo 1, presented a negative result with no flow out of the test valves. This is as expected. Demo 2 and Demo 3 presented very similar results. The correlated distances were within two feet of each other, 476.8ft and 478.8ft from Pit#3 respectively. Also, the character of the recordings was very similar suggesting that the flow rates are almost the same. It is estimated that the flow rates are both between 5.0 and 8.0Gpm but the similarity in the signals suggests that it may be flowing from the same orifice. Demo 4 presented a negative correlation result meaning that the flow rate is close to or below 0.6Gpm.

Section 3: Pit#4 to Pit#5, Demonstration in Pit#2

The calibration test, Demo 1, was performed with a known flow rate of 8.0Gpm. The corresponding correlated distance was 502.9ft from Pit#5. The coherence was very strong and the correlation peak was prominent. Overall this test presented the loudest of all file recorded suggesting that it is the highest flow rate of all the demonstrations. Demo 2 presented a negative correlation result meaning that the flow rate is close to or below 0.6Gpm. Demo 3 presented a positive correlation result at a distance of 497.8ft from Pit#5. The recording had good coherence and a good correlation peak suggesting that there was a high flow rate. It is estimated that the flow rate for Demo 3 was between 5.0 and 8.0Gpm. Demo 4 presented a positive correlation result at a distance of 487.4ft from Pit#5. The coherence was lower than the previous test but the correlation peak was strong. It is estimated that the flow rate was between 2.5 and 5.0Gpm for Demo 4.

General Comments

In some cases distance discrepancies between 2ft and 17ft is seen when the simulated leak is being generated in the same excavation pit. It is known that there is more than one valve in each of the demonstration pits but the distance between valves in the pit is unknown. It is assumed that the discrepancies are mainly due to the fact the valves are approximately 5ft apart, thus accounting for the difference. However, some of the difference may actually be due to signal processing error, which can get worse as the signal-to-noise ratio decreases. This may be the case for Demo 4, in Section 1: Pit#1 to Pit#2, Demonstration in Pit#4.

4.2. Leak Detection Results

There were two positive leak locations discovered over the duration of the testing.

File #2a – Pit A to Pit B

File 2a was recorded with the Blue station on the pipe in Pit B and the White station in Pit A with sensor spacing of 260.5ft. The correlation function shown for this file indicates a leak at a position was 91.5ft from the White sensor. A sharp correlation peak and moderate levels of coherence indicates a flow rate of 2.5 – 5.0 Gpm for this leak.

The evidence presented here strongly indicates the presence of a leak and if this pipe were to remain in service, it would be suggested to perform remedial action.

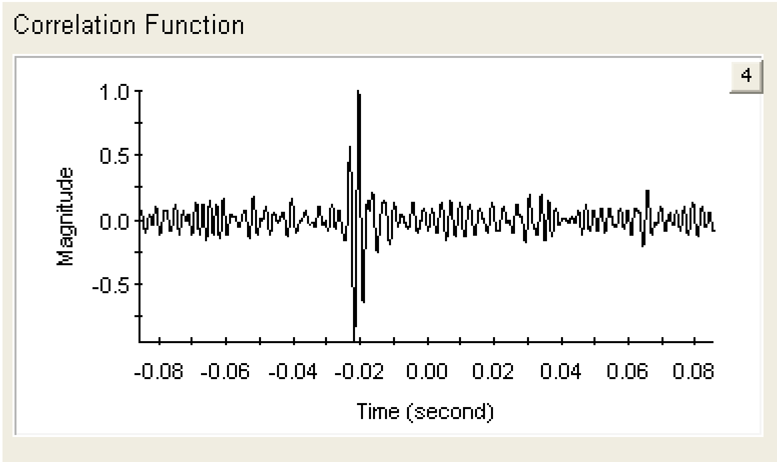

Figure 4: Correlation result for File #2

File #7c – Pit F to Pit 3

The correlation function shown for File 7c was recorded with the Blue station mounted to the pipe in Pit F and the White station mounted to the pipe in Pit #3 with a sensor-to-sensor spacing of 312.7ft. The character of the signal suggests that there may be two leaks at this location at a distance of 126.6ft and 144.6ft from the White station. The weaker signal and wider correlation peak indicates a small leak, which sets the estimated flow rate at 1.0 – 2.5 Gpm for each leak.

The evidence presented here is not entirely conclusive because the correlation peak is not defined. If this pipe were to remain in service, it would be suggested to perform further investigation by either using a ground-microphone to confirm a noise source or potholing to confirm the presence of water.

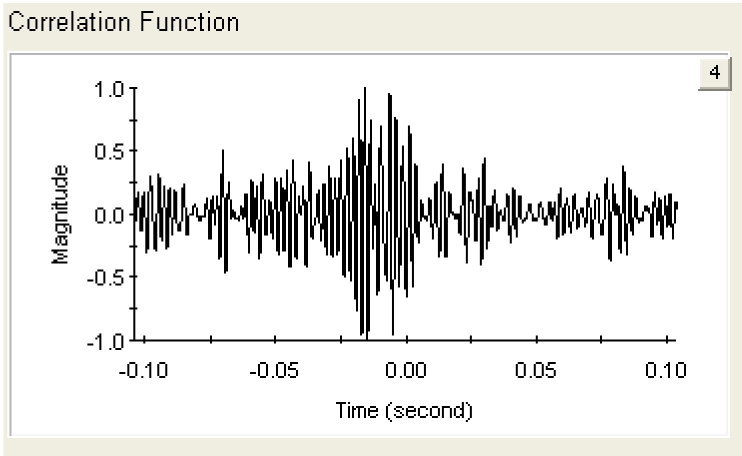

Figure 5: Correlation Result for File #7

4.3. Condition Assessment Results

The results of the condition assessment measurements are presented in Table 5: Condition Assessment Results. Starting from Pit #1, three sections in a row presented remaining equivalent thickness greater than 0.875-inches. This suggests that there is minimal deterioration in these sections and the pipe is in good structural condition. Of the remaining four sections of pipe between Pit C and Pit #3, three of them presented remaining thickness below 0.875-inches. These are marked with an asterisks in the table. This suggests that these sections of pipe have experienced slightly higher corrosion rates although the pipe is still in good structural condition. The section showing the highest losses is between Pit F and Pit #3. It presented a remaining equivalent thickness of 0.85-inches.

It should be noted that none of the sections tested presented results significantly below the nominal values. This suggests that, overall; the pipe is still in good condition.

File #	Location	Sensor-to-Sensor Spacing (ft)	Measured Average Thickness (inch)	Condition
1a	Pit1 to PitA	250.7	0.89	Good
2c	PitA to PitB	260.5	0.91	Good
3c	PitB to PitC	298.6	0.91	Good
4b	PitC to Pit2	271	0.87	Good*
5d	Pit2 to PitE	360.9	0.87	Good*
6c	PitE to PitF	294.6	0.88	Good
7b	PitF to Pit3	312.7	0.85	Good*

Table 5: Condition Assessment Results

5. Concluding Remarks

We thank you again for the opportunity to test the technology and we trust that this is acceptable. Please do not hesitate to contact us if there are any questions regarding the study.

Sincerely,

Echologics Engineering Inc.

Marc Bracken, M.A.Sc., P.Eng.

Dave Johnston, B.Eng. Materials Engineering

6. Appendix

Figure 6: Pipe Wall Cross-Section

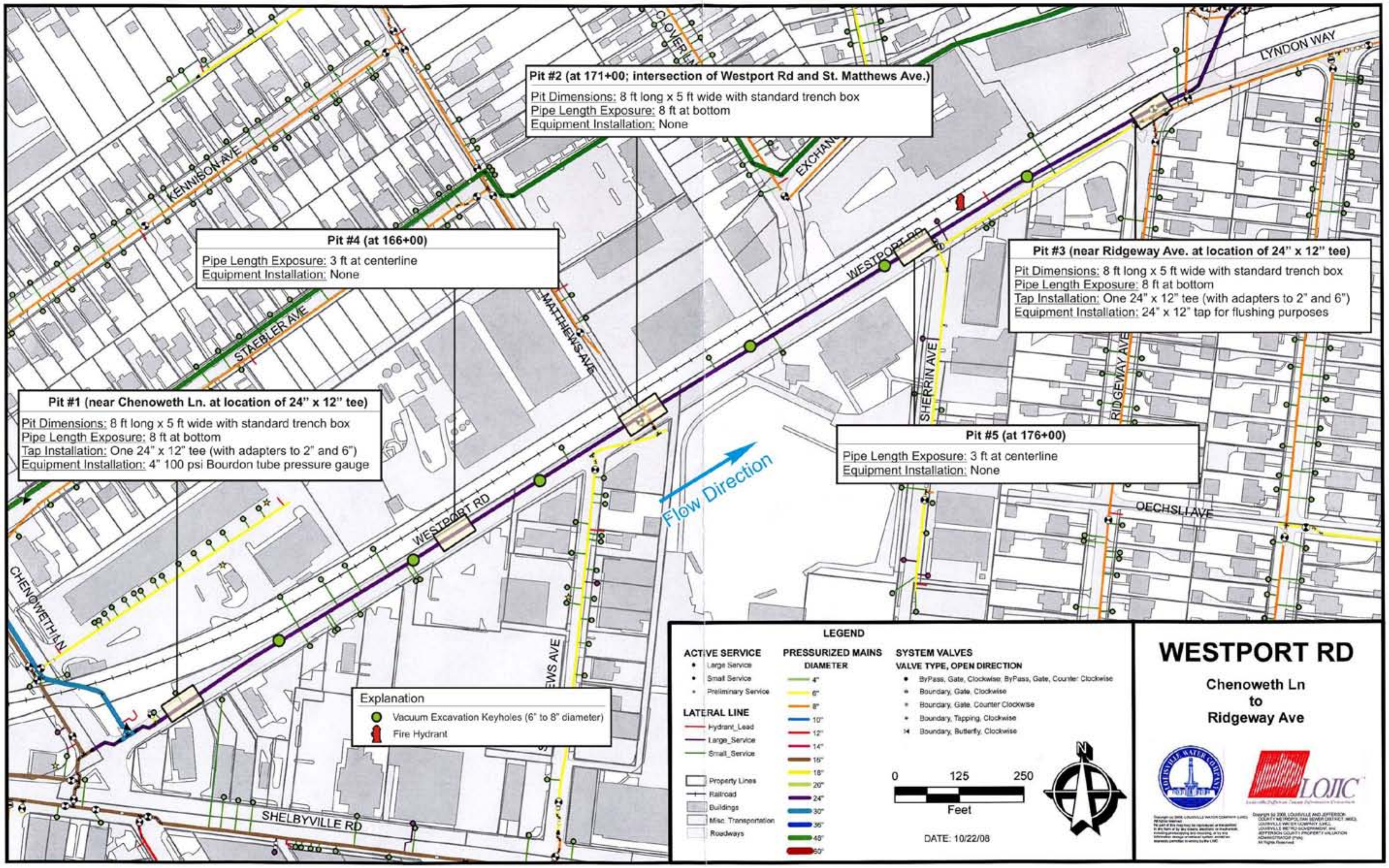

Figure 7: Site Layout

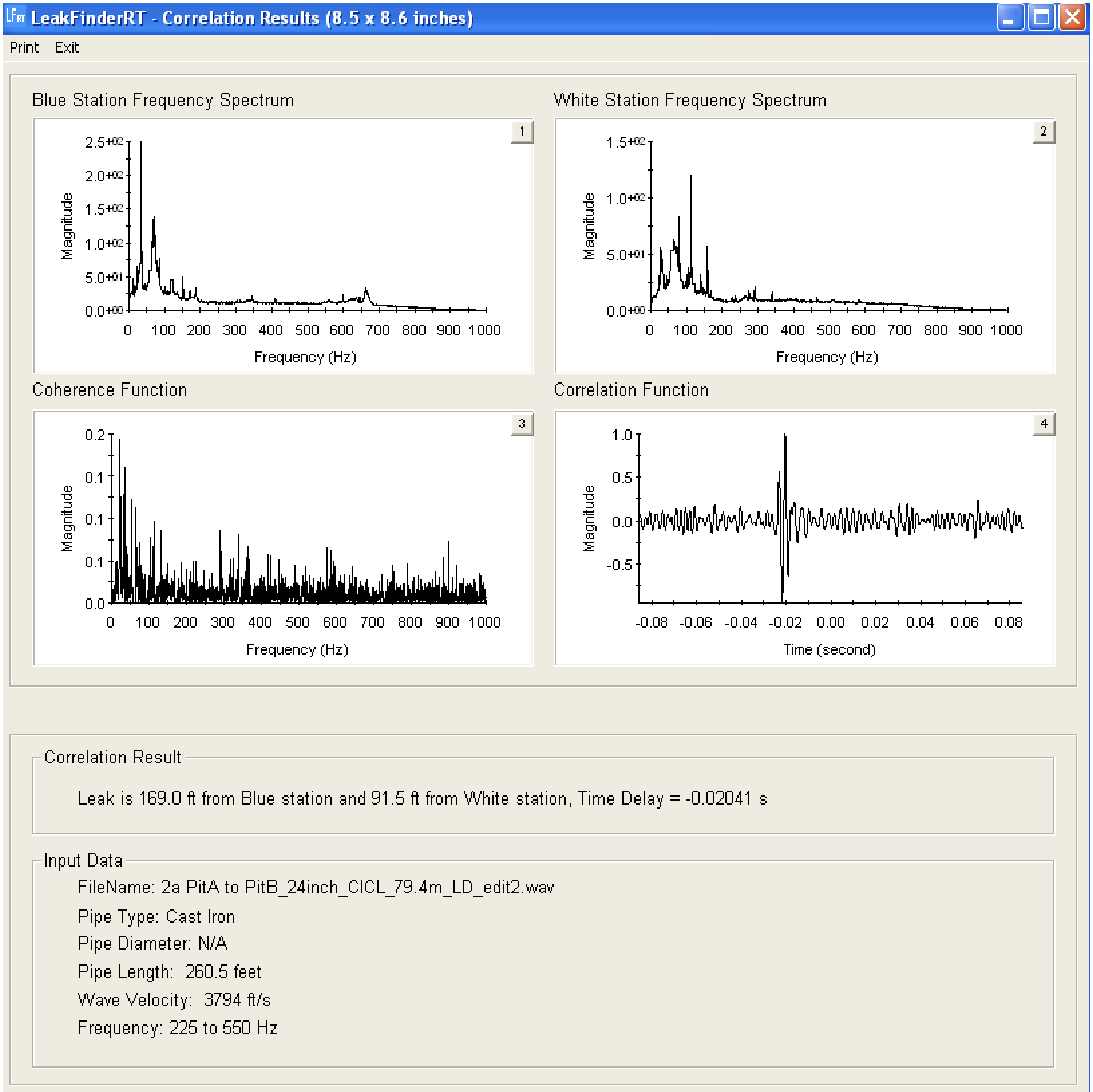

Figure 8: Correlation Report for File #2a - PitA to PitB

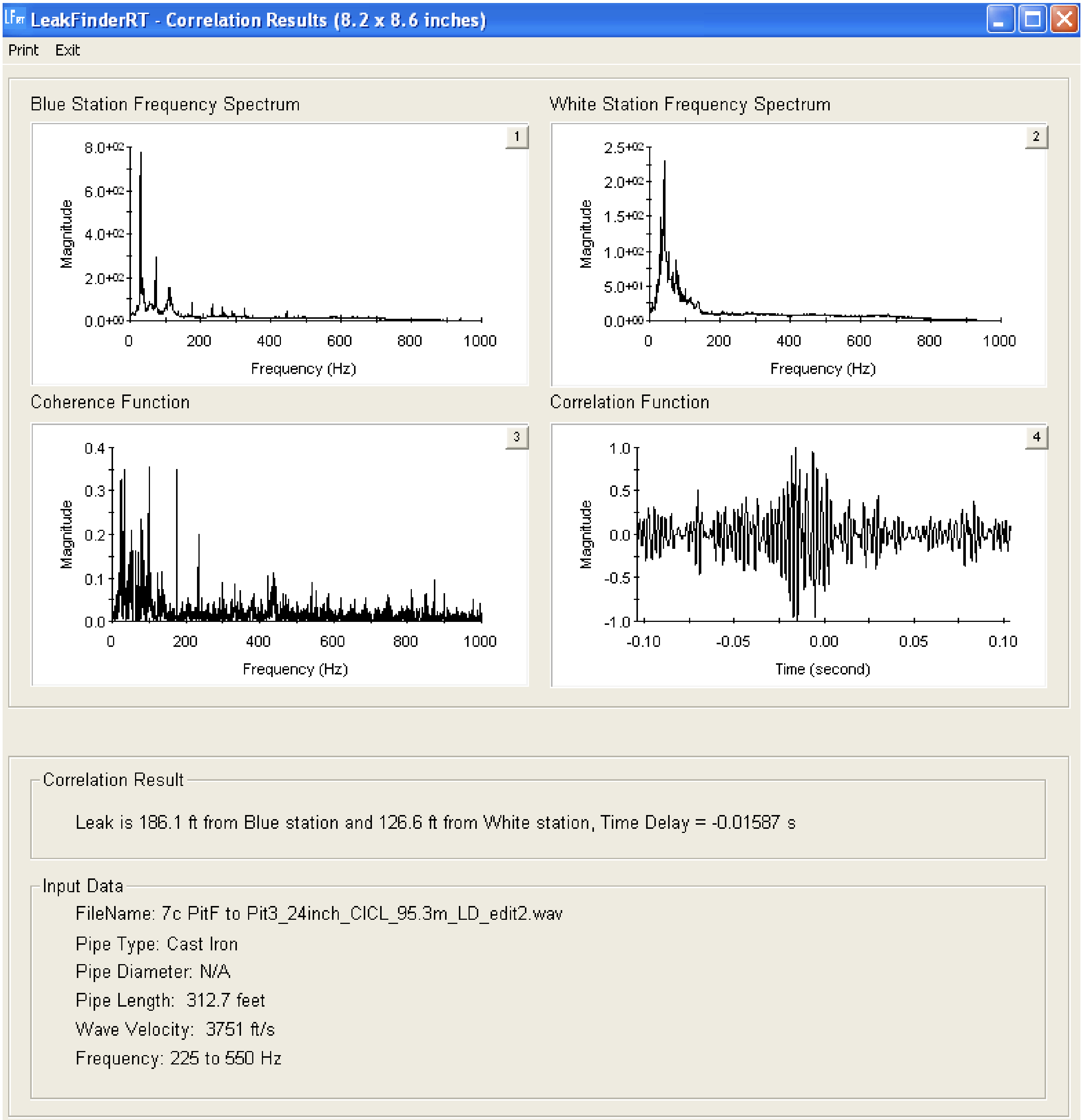

Figure 9: Correlation Report for File #7c - PitF to Pit3

APPENDIX D

INSPECTION VENDORS COMMENTS TO FINAL REPORT

Lessons learned from the demonstration:

After passing over simulated leaks, the Sahara hydrophone was tested on-site and found to have technical problems. Subsequently, that particular hydrophone was replaced with an alternate hydrophone confirmed to pass quality control/assurance tests. Two of the very small leaks were re-simulated and were detected on-site using the new hydrophone. As a precaution, all Sahara hydrophones are tested onsite following standard QC/QA procedures prior to inspection.

Improvement to the equipment used for leak detection since demonstration:

Sahara Leak Detection is a mature technology used successfully for many years and future development of the technique will focus on making it even easier to use. The main challenge with Sahara Video is to improve its video and lighting quality in larger diameter pipes and to possibly combine the video and leak techniques into a single sensor head which would reduce the amount of insertions required and make the overall inspection more efficient.

Pure Technologies' Comments on Report
to_62-final_report_part1_leak_detection_rev1_09152010-final.pdf

This document outlines the comments Pure Technologies Ltd would like to see acknowledge regarding the report issued by Battelle/Alsatech for the US Environmental Protection Agency regarding the SmartBall® technology titled "*to_62-final_report_part1_leak_detection_rev1_09152010-final.pdf".*

Section 3.3.2

The report states that "The potential for the SmartBall® to be lost exists if the direction of flow suddenly changes or another activity (high customer use or hydrant flow) diverts the sensor from the planned inspection path." Please note that SmatBall® have never been lost due to activities such as hydrant flow or high customer demands.

Table 3-2

The table states that the required flow for SmartBall® is ~0.8ft/s-1.5ft/s. Please note that SmartBall® have done inspections at flow as low as 0.5ft/s and as high as 7ft/s.

Table 3-2

The final column of Table 3-2 describes "Pipe Access Requirements" for each technology. It describes access frequency for LeakfinderRT but does not but not discuss the requirements for SmartBall® or Sahara. Such additional columns might resemble:

Technology	Pipe Appurtenance Required	Frequency of Required Appurtenance.
Sahara	2" diameter or larger full port valve with vertical clearance of 10 feet	Every 2500 ft upstream of the section to be inspected
SmartBall	4" diameter or larger full port valve with vertical orientation and clearance of 12 feet	Twice, one at beginning and one at the end of inspection
Leakfinder RT	(?)	Every 300 to 2500 ft

We continue to reference the data from this test to refine our algorithms and methods, it's a great source since we rarely (if ever) get to run the same line so many times.

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Echologics Comments on the Report:

FIELD DEMONSTRATION OF INNOVATIVE CONDITION ASSESSMENT TECHNOLOGIES FOR WATER MAINS AT LOUISVILLE, KENTUCKY PART 1: LEAK DETECTION AND LOCATION

Below are Echologics's direct comments on the report:

Section 2.0, Paragraph 1, item 3:

The statement: "pairs of hydrophones that contacted the water at discrete locations to estimate simulated leak rates" is not correct. The leak rates can be estimated using either hydrophones or surface mounted sensors. In this case, surface mounted sensors were used to demonstrate leak detection and condition assessment capabilities.

Typically, surface mounted sensors are placed at shorter intervals to increase the resolution of condition assessment results. This also has the added benefit of increasing the sensitivity of the leak detection.

Section 2.0 Table 2-1:

In the pipe contact points row: "Every 1,000 ft for leak rate Every 300-400ft for detection" is incorrect and should read: "typically every 1,000ft for leak detection and rate, every 300-400ft for condition assessment". In this case, surface mounted sensors were used at shorter intervals because condition assessment measurements were already being performed.

Lessons learned from the demonstration:

This demonstration allowed us to confirm several of our hypotheses. Specifically when dealing with large quantities of air pockets. As our technology cannot directly test for air pockets within the pipe, we must test for it indirectly. The demonstration allowed for the confirmation of a long term theory that air pockets are the cause of attenuation of vibrations within the water column. Since the date of the demonstration, this theory has been applied and confirmed at several other project locations, much to the appreciation of our clients.

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Also, in the past, Echologics technology was only used to qualitatively estimate the size of a leak. The demonstration allowed us gain insight into the energy / leak size relationship and create a more accurate model for predicting leakage rate.

Improvement to the equipment used for leak detection since the demonstration:

As Echologics is continuously striving to improve on our leak detection and condition assessment technology and methodology, we have made several improvements since this date, specifically within the realm of passive signal filtering. We have developed new hardware that better allows us to focus only on leak noise and attenuate background noise.

Echologics enjoyed the opportunity to demonstrate our technology and greatly appreciated the efforts the EPA and LWC in organizing this endeavor. We hope to be able to participate alongside our competitors in any future projects of this nature.

Sincerely,

Dave Johnston, B. Eng

September 23rd 2010