ESTCP
Cost and Performance Report

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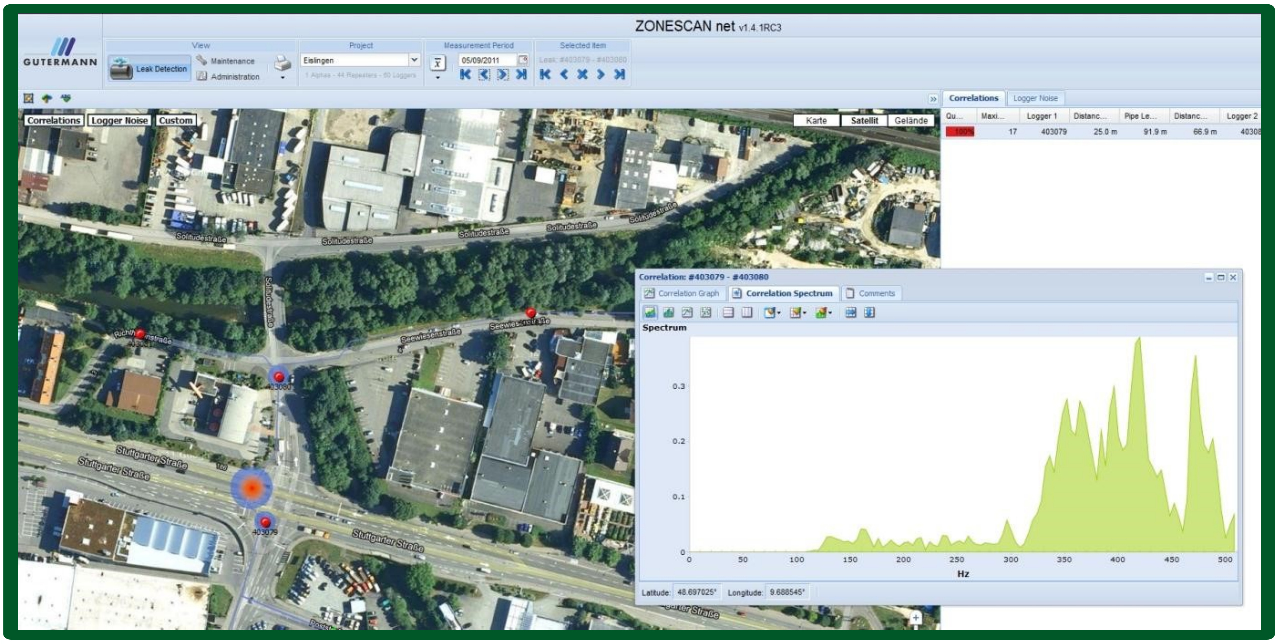

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Innovative Acoustic Sensor Technologies for Leak Detection in Challenging Pipe Types

December 2016

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Reducing water loss at U.S. Department of Defense (DoD) installations is important to preserve potable water needed for essential functions and to limit the drawdown of local water supplies. Implementation of improved leak detection technologies and the timely repair of water mains will support Federal and DoD sustainability goals. This project assessed three innovative acoustic leak detection technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging pipe types, as well as metallic pipes.

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Leak detection; acoustic correlation; water distribution systems

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COST & PERFORMANCE REPORT
Project: EW-201339

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AC	asbestos cement
AMI	advanced metering infrastructure
AWWA	American Water Works Association
CI	cast iron
DI	ductile iron
DoD	Department of Defense
DPW	Department of Public Works
EO	Executive Order
EPA	U.S. Environmental Protection Agency
ERDC	Engineer Research Development Center
ESTCP	Environmental Security Technology Certification Program
EXWC	Engineering and Expeditionary Warfare Center
ft	feet
FY	fiscal year
gpm	gallon per minute
GWI	global water intelligence
hr	hour
HVAC	heating, ventilation, and air condition
ILA	industrial, landscaping, and agricultural
IT	information technology
kgal	kilogallon
kWh	kilowatt hour
NAVFAC	Naval Facilities Engineering Command
NIST	National Institute of Standards and Technology
NPV	net present value
O&M	operations and maintenance
PDA	personal data assistant
PNNL	Pacific Northwest National Laboratory
psi	pounds per square inch
PVC	polyvinyl chloride
rf	radio frequency

SIR	savings-to-investment ratio
TB	Test Bed
UEM	Utility and Energy Management

ACKNOWLEDGEMENTS

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The project team would like to thank the U.S. Army ERDC for hosting both the test bed (TB) and field test demonstrations. We also would like to thank Mr. Tony King of the ERDC Public Works for his role in building the TB and providing operational and testing support throughout the demonstration.

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EXECUTIVE SUMMARY

Reducing water loss at U.S. Department of Defense (DoD) installations is important to preserve potable water needed for essential functions and to limit the drawdown of local water supplies. DoD installations lose significant amounts of water through leaking pipe systems that are near the end of their life cycle. Unfortunately, comprehensive leak detection efforts to identify leaks are not a widespread practice among DoD installations (Pacific Northwest National Laboratory [PNNL], 2013a). However, recent policy from Executive Order (EO) 13693 released in 2015 titled *Planning for Federal Sustainability in the Next Decade* requires installations to take more proactive measures to reduce water loss. Implementation of improved leak detection technologies and the timely repair of water mains supports these Federal and DoD sustainability goals. The DoD Environmental Security Technology Certification Program (ESTCP) supported this project to assess three innovative acoustic leak detection technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging pipe types, as well as metallic pipes found at DoD installations.

Objectives of the Demonstration

The project objective was to demonstrate and validate the performance of three innovative technologies for leak detection by assessing their ability to detect and accurately locate leaks in challenging pipe types such as polyvinyl chloride (PVC), asbestos cement (AC), and mixtures of pipe types typically found on DoD installations. The fundamental questions addressed by this study include: Is implementation of these technologies technically feasible for use by DoD installations to reduce water loss and to help meet water and energy conservation goals of the EO? Are these technologies cost effective?

Technology Description

The demonstration evaluated two types of cross-correlating leak detection technologies: (1) a continuous monitoring network approach, and (2) an inspection approach that used sensors temporarily deployed to test segments of pipe within a water distribution system. Three different product lines were tested: one for continuous monitoring and two for periodic inspection of pipe segments. Each technology was demonstrated for detecting and pinpointing leaks in metallic and challenging non-metallic pipe types. For each of the technologies, accelerometers or hydrophones were used to detect acoustic signatures of leaks, and time offsets between sensor locations were used to derive leak locations.

Evaluations were conducted under controlled conditions at an underground pipeline test bed (TB) that was configured with simulated leaks followed by testing under operating conditions within the U.S. Army Engineer Research Development Center's (ERDC's) water distribution system. The TB included 11 simulated leaks ranging from approximately 1 gallon per minute (gpm) to 8 gpm that could be controlled from above ground. Projected benefits from water and energy savings and estimated costs for leak detection deployment were also estimated. These projections indicate a savings-to-investment ratio (SIR) greater than 1 for installations with average rates of water main breaks within their water distribution systems. Actual cost-benefit performance should be monitored as leak detection systems are deployed on a site-specific basis.

Demonstration Results

For the TB evaluation, only the technology that used an inspection approach and accelerometers met all of the performance criteria. The continuous monitoring technology and the survey technology using both hydrophones and accelerometers did not meet several performance criteria in the TB evaluation. The simulated leak conditions were successfully detected by all of the technologies. However, the location accuracy varied between the technologies. Two of the three technologies passed the performance objective of locating 90% of simulated leaks within ± 4 feet (ft) of the known locations in the TB. The leak location results for PVC pipe ranged from 86% to 100% within ± 4 ft of the known leak locations. False positives were an issue for two out of the three technologies. There is a potential to mitigate false positives in field applications through focused acoustic surveys that are typically conducted at the correlated location prior to marking the leak location. All three technologies were able to detect small leaks at approximately 1 gpm. Challenges were encountered with detecting multiple leaks within a bracketed sensor pair (even though the simulated leaks were spaced more than 5 ft apart) and in spanning mixed pipe materials. Although the capability to detect and locate leaks under these scenarios was claimed, the leak detections were not as accurate compared to the single leak and single pipe material scenarios within the TB.

For the operational water distribution testing, three leaks were detected within the portion of the ERDC water distribution system selected for inspection. The limited number of leaks detected in the field tests did not provide sufficient information for the evaluation of the performance criteria (even though visual indications of one leak were observed during the test). Water, energy, and SIR estimates were developed based upon an industry average water main break frequency and regional water and energy cost data.

Implementation Issues

Leak detection systems that rely on an intermittent inspection approach hold the most promise for implementation at military installations at this time. A widely accepted best management practice with this technology is to cover an entire base every 3 to 5 years (American Water Works Association [AWWA], 2009). Both the LeakFinderRT and Correlux leak detection systems process the leak signature data in the field without any requirement for information technology (IT) security, or connection to government IT assets or the Internet. Leak detection using these systems can be procured as a service via a maintenance or job order contract. In addition, if an installation has the manpower, equipment can be procured for in-house use. Since the Correlux technology met all of the performance thresholds for the TB evaluations, this technology could be considered for additional field testing and deployment in its current state.

Further development and investment would be required for widespread adoption of a continuous monitoring system at military installations. Software compatibility issues and the difficulties of securing IT approval would deter implementation at military installations under the current IT security environment. The primary operating concern to be addressed includes network security for information systems that are being deployed in conjunction with advanced metering infrastructure (AMI) systems.

1.0 INTRODUCTION

The U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) has supported a project to assess leak detection methodologies for water distribution systems at military installations. This study was conducted by the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) in collaboration with the U.S. Army Engineer Research Development Center (ERDC) and Battelle. TB and operating distribution system evaluations were conducted to demonstrate advanced acoustic sensor technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging underground pipe systems. The demonstration was conducted at the ERDC facility in Vicksburg, Mississippi. The demonstration validated two types of cross-correlating leak detection technologies: 1) a continuous monitoring network approach, and 2) an inspection approach that used sensors temporarily deployed to test segments of pipe within a water distribution system (known as “lift and shift”). Three different product lines were tested including one for continuous monitoring and two for periodic inspection of pipe segments. Each methodology was demonstrated for detecting and pinpointing leaks in metallic and challenging non-metallic pipe types. Evaluations were conducted under controlled conditions at an underground pipeline TB configured with simulated leaks followed by validation under operating conditions within ERDC’s existing water distribution system.

The project contributes to the DoD’s water conservation and energy saving initiatives by validating approaches for leak detection in its aging potable water infrastructure. Leaks are commonplace at military bases where pipe distributions systems vary in age, construction, and local site factors (such as stress loading and soil conditions). Some leaks reach the ground surface and can be quickly detected and repaired, while leaks without surface expression may continue undetected for long periods of time, resulting in significant water loss. Advanced leak detection technologies capable of detecting leaks in plastic and metallic pipes can be used to find and repair leaks in a timely manner, potentially saving millions of gallons of water per year.

1.1 BACKGROUND

Water distribution systems at DoD installations were typically installed during initial base construction. Many of these systems are at or near the end of their design life (typically 50 to 75 years). Similar to municipal water distribution systems, these systems are mostly underground, are laid out along streets, roads or in parallel with other utility alignments, and have been expanded over the years. A wide variety of pipe sizes and materials such as ductile iron (DI), cast iron (CI), asbestos cement (AC), and polyvinyl chloride (PVC) have been widely used. Although each installation has a site-specific layout of water meters, pipelines and distribution grids, all share common layout elements. A typical layout is provided in Figure 1.1 showing pipelines leading to administrative buildings, landscaping, and industrial and residential areas. Public Works offices usually have as-built drawings or other historical water utility records that show the relative location of underground pipelines. However, it is important to note that there can be inaccuracies that make it challenging to locate underground water mains, valves, and actual leaks in the field.

The frequency of leaks generally increases with the age of the distribution system, heavy vehicle traffic, and soil settlement. The rate of water main breaks is between 0.21 to 0.27 breaks per mile of pipeline per year according to a recent survey of water utilities (WaterRF, 2015).

Leaks are generally not noticed until water rises to the surface or until significant amounts of water have been lost over extended periods of time (Fanner et al., 2007; King, 2014). Small leaks can result in considerable cumulative losses if allowed to persist over time. For example, at a leak rate of 1 gallon per minute (gpm) an unrepaired leak could result in a loss of over 500,000 gallons per year. Studies from the U.S. Environmental Protection Agency (EPA) show that on average 14 percent of water consumption is lost through leaks, with some water utilities losing more than 60 percent of water input into the system (EPA, 2012).

Figure 1.1. Typical Water Distribution System Layout for a DoD Installation

Leak detection is not currently a widespread practice even among installations featured in the pilot efforts for the Army's Net Zero Water Program. Out of the eight utilities in the pilot demonstration, only Tobyhanna Army Depot was noted as having a comprehensive leak detection program (Pacific Northwest National Laboratory [PNNL], 2013a). Previously, conventional leak detection methodologies were limited primarily to time consuming field surveys using sounders (listening sticks) that relied heavily upon operator skill or noise correlators that were tuned for finding leaks in metallic pipes. The detection of leaks in PVC and AC pipes has been particularly challenging because leak signatures are significantly attenuated in these pipe types compared to metallic pipes (Hunaidi, 2000).

1.2 OBJECTIVE OF THE DEMONSTRATION

The primary project objective was to:

- Demonstrate and validate the performance of three advanced innovative acoustic sensor technologies for leak detection by assessing their ability to detect and accurately locate leaks in PVC, AC, and mixed pipe distribution systems that have been proven challenging for conventional technologies.

Technology benefits were quantified by projecting potential water savings and energy conservation as part of the demonstration project and a return-on-investment was calculated for further consideration of DoD-wide implementation of these leak detection approaches.

A secondary project objective was to:

- Integrate acoustic sensors with advanced metering infrastructure (AMI) networks.

This objective was eventually eliminated from the study due to software compatibility and cybersecurity approval issues.

1.3 REGULATORY DRIVERS

The primary regulatory requirement addressed by this research is Executive Order (EO) 13693 *Planning for Federal Sustainability in the Next Decade*, which recognizes and supports the need for water conservation efforts by Federal agencies. Improved leak detection technologies also support other sustainability initiatives such as the Army's Net Zero Water and Energy Installation Programs. DoD installations located in these states need to adapt to water supply constraints or choose to implement industry best practices to achieve sustainability with respect to water resources, as required by the water conservation goals of the EO. This order requires agencies to improve water use efficiency and management as follows:

- Reducing agency potable water consumption intensity, measured in gallons per gross square foot, by 36% by fiscal year (FY) 2025 through reductions of 2% annually relative to a baseline of the agency's water consumption in FY 2007.
- Installing water meters and collecting and utilizing building and facility water balance data to improve water conservation and management.

- Reducing agency industrial, landscaping, and agricultural (ILA) water consumption by 2% annually through FY 2025 relative to a baseline of the agency's ILA water consumption in FY 2010.
- Installing appropriate green infrastructure features on federally-owned property to improve stormwater and wastewater management.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

All three of the leak detection systems tested in this study are based on acoustic sensor technologies. These systems use one of two types of sensors. The most commonly used sensor is the accelerometer, which measures vibrations in the pipe walls. These vibrations are created by a rapid decrease in water pressure as it passes through the leak opening. These sensors are attached externally to the water line or a fixture such as a valve or hydrant in contact with the water line. The second type of sensor used is a hydrophone, which measures small rapid changes, or pulses, of pressure in the water column passing through the water line. As with the vibrations in the pipe walls, these pulses of water pressure are caused by the water pressure rapidly decreasing as it passes through the leak opening. Hydrophones must be attached to a spigot or hydrant that allows the sensor to be in direct contact with the water in the transmission system.

Determining the location of a leak requires two sensors, one on each side of the leak that can detect the acoustic signature produced by the leak (see Figure 2.1). Each leak produces a relatively constant sound spectrum, characterized by the amplitude of the signal at different frequencies. Both sensors will pick up the same leak signature, but this sound will arrive at each sensor at a slightly different time, due to the varying distances between each sensor and the leak. The difference in time is determined by matching the recorded sound spectrum over time at each sensor. This is accomplished by shifting the spectrum along the time axis until a match is achieved (also referred to as coherence). The time shift and the estimated speed of sound propagation along the pipe wall are used to estimate the difference in distances between each sensor and the leak.

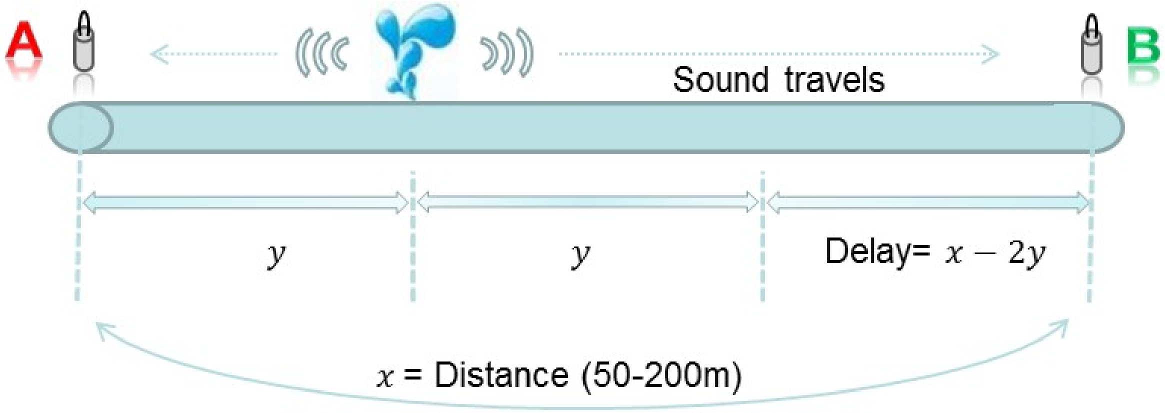


Figure 2.1. Cross-Correlation Methodology

The speed at which acoustic signals travel in a pipe are dependent on both the pipe material and diameter. The effective detection range of a sensor will vary based on acoustic velocity, which is correlated with the pipe material and diameter. In general, hydrophones are reported to have a greater detection range. The accuracy of these systems is dependent on the knowledge of the pipe system to which they are attached, the accuracy of the acoustic velocity in the system, the sensitivity of the sensors, and the capabilities of the analytical software. The representativeness of the acoustic velocity in the system may be improved by direct measurement of the speed of a sound that is artificially induced into the pipe network.

Table 2.1. provides a comparison of the three innovative leak detection technologies to conventional leak management practices. Each technology was demonstrated to evaluate its ability to accurately detect and locate leaks under controlled conditions in a TB configuration and under real-world conditions within the ERDC water distribution system.

Table 2.1. Summary of Innovative Leak Detection Technologies Demonstrated

Method of Leak Detection	Technology/ Current Practice	Frequency of Use	Usage/ Ownership	Equipment	Cost Considerations
Visual Visual report of surfacing water or high water usage	Conventional Practice[1]	Ad hoc	NA	NA	• Loss of water prior to detection • Potential damage to nearby infrastructure
Continuous Monitoring Fixed network monitoring with multiple sensors with cross-correlation	Gutermann ZoneScan Alpha®	Continuous monitoring for leak signatures	Department of Public Works (DPW) or Utility and Energy Management (UEM)	Sensors, Transmitters, Computer, Personal Data Assistant (PDA)	• Capital equipment • Maintenance • DPW operational labor cost • Contractor installation and setup cost • Annual service fee
Periodic Inspection Deployed in a “lift and shift” survey with cross-correlation	Echologics LeakFinderRT™	Field survey of leak signatures. Recommended every 3-5 years	Contractor	Sensors, Transmitter, Laptop	• Water loss between survey events • Survey costs and contractor expenses
	SebaKMT Correlux HL6000X™	Field survey of leak signatures. Recommended every 3-5 years	Contractor (or purchased by DPW for in-house use)	Sensors, Transmitter, Processor	• Water loss between survey events • Survey costs and contractor expenses

NA = not applicable

Many DPWs do not have in-house staff to conduct routine leak audits and pipeline repairs. Instead, many installations rely on service contracts or in-house contractors to conduct routine repairs.

2.1.1 Gutermann ZoneScan Alpha

The ZoneScan Alpha acoustic logger sensor system for continuous monitoring is shown in Figure 2.2. Table 2.2 summarizes the primary components, along with their respective function. System components include: (1) radio repeater modules to send data to a centralized computer processing system; (2) extended antenna (optional to transmit data over longer distances); (3) personal data assistant (PDA) for system setup; (4) communication link for system setup;

(5) ZoneScan acoustic sensors; and (6) ZoneScan Alpha Com Link. The system also relies on data management, processing and display capabilities provided by a personal computer system operated by the user and Gutermann's centralized server that provides data processing capability. The sensors are permanently or temporarily installed on valves or fire hydrants at targeted areas of the potable water distribution system. The sensors are easily attached via a magnet on the bottom of each sensor. The sensors can be connected via radio transmission or they can be integrated into an existing AMI network.

Figure 2.2. ZoneScan Alpha System Components (Courtesy of Gutermann)

Note: See Table 2.2 for definition of system elements

Table 2.2. Primary Components of the ZoneScan Alpha System

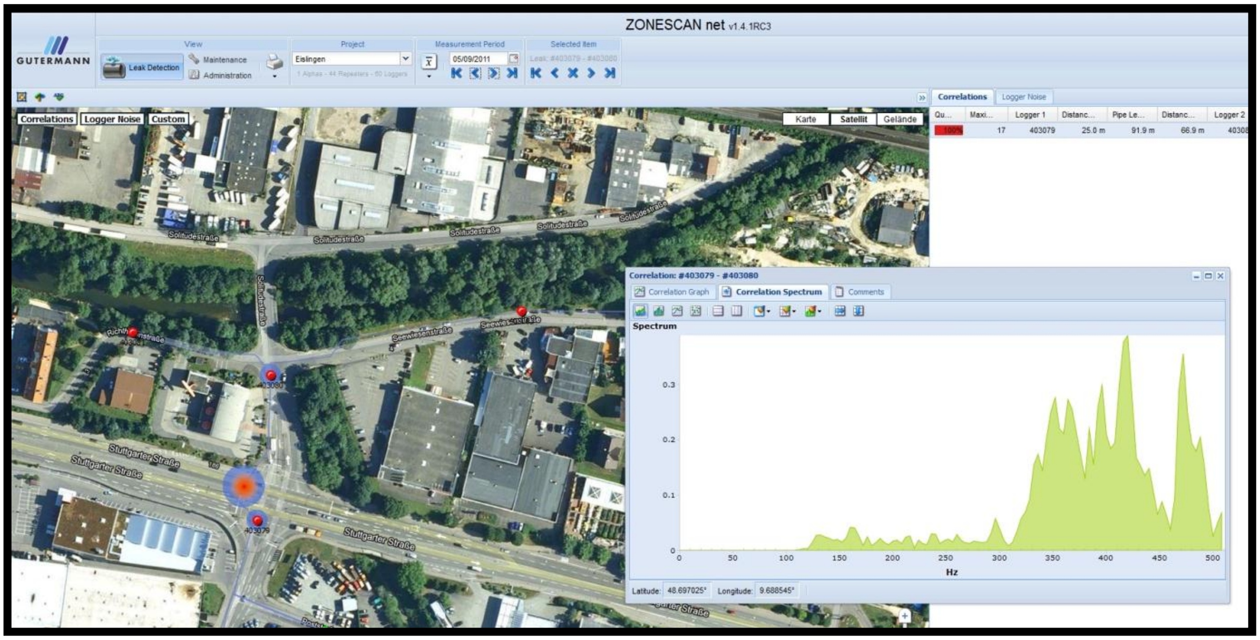
Item/No.	Location	Primary Function
Radio repeater modules (1)	Located near sensor and Alpha Com Link	Relays leak signal data to Alpha unit
Extended antenna (2)	Located on the sensor	Supports data transmission
PDA for system setup (3)	Operator	Used to set global positioning system coordinate and synchronize sensors
Communication link (4)	Operator	Used to communicate with sensors
ZoneScan acoustic noise logger sensors (5)	Water distribution system, valves, hydrants	Acoustic sensors to log leak signal data
Alpha Com Link (6)	Nearby building roof or other high location	Collects all data from loggers and sends to server
Central Processor (not shown)	Cloud-based server	Data processing and display generation
User Computer (not shown)	Users on-station	Provides graphical illustration of piping and displays location of sensors and identified leak locations

Table 2.3 summarizes suggested installation parameters and typical acoustic sensor performance. According to the manufacturer, sensor spacing is not impacted by minor bends, valves, or grid layout as long as sensors are properly positioned at nodes (valves or hydrants). Sensors are typically installed as part of a fixed monitoring network within the water distribution system at the spacing intervals identified in Table 2.3. Once installed, they are synchronized, and their physical coordinates captured for graphical display on the ZoneScan.net website. The sensor locations and distribution system layout are displayed on a map overlay, as shown in Figure 2.3.

Table 2.3. ZoneScan Alpha Sensor Installation and Performance for Leak Detection

Pipe Type	Maximum Sensor Spacing on Straight Pipe	Typical Location Accuracy
PVC	200 to 250 feet (ft)	1 in. per 250 ft
AC	450 to 500 ft	1 in. per 750 ft
Ferrous	500 to 750 ft	1 in. per 1000 ft
Steel	500 to 750 ft	1 in. per 1000 ft

Note: Manufacturer-supplied performance specifications. Gutermann does not specify a minimum detectable leak size.



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100%	17	403079	25.0 m	91.9 m	66.9 m	40308

Latitude: 48.697025° Longitude: 9.688545°

Figure 2.3. Leak Alert Location and Leak Correlation Spectrum Typical for Large Leak

(Courtesy of Gutermann)

The sensors are programmed to activate at night to monitor for acoustic leak signatures when background noise is at a minimum and pipeline water pressure is highest. For example, the default time period is set for 2:00 to 4:00 am local time with data taken every two seconds over the two-hour (hr) interval. After the data collection is complete, the sensors send the data via radio transmission to the data link that connects to the ZoneScan.net server. The sensors are then deactivated to conserve battery life. The server software performs the cross-correlation analysis and generates a display of results when prompted by the end-user. The end-user can graphically display results using the ZoneScan Alpha online software daily or be alerted by e-mail when leak-like conditions are detected. If a leak is not identified, the sensor locations will appear on the display in green to signify normal conditions. When the acoustic signal of a leak is detected, the display will show a red dot over the correlated location of the suspected leak in the pipe network (as shown in Figure 2.3), along with corresponding distances from the adjacent sensors. Processing and filtering capabilities within the software algorithm are designed to reduce false positives caused by background noise such as vehicular traffic or heating, ventilation, and air condition (HVAC) systems.

2.1.2 Echologics LeakFinderRT

The LeakFinderRT system is deployed to conduct field surveys by placing and moving sensors along pipe segments in a "lift and shift" deployment. After each section of pipe is assessed for leaks, the sensor(s) would be removed ("lifted") and relocated ("shifted") to another section of pipeline in the distribution system. The LeakFinderRT system shown in Figure 2.4 is composed of leak sensors (either hydrophone sensors or accelerometers), two transmitters (white/blue), and a central receiver. Technical specifications for the LeakFinderRT system are included in Table 2.4 and sensor types are selected based upon pipe conditions as listed in Table 2.4. The system also includes a wireless radio frequency (rf) signal transmission system and a portable computer. The sensors are attached to two contact points along the targeted pipe section. The location of the contact point differs for each of the two sensor types. The hydrophone sensors are inserted through fire hydrant outlets or other access points that provide direct contact with the water, while the accelerometers are typically placed in direct contact with external components such as fire hydrants, valves or on the pipe wall (via potholes if required to meet sensor spacing requirements).

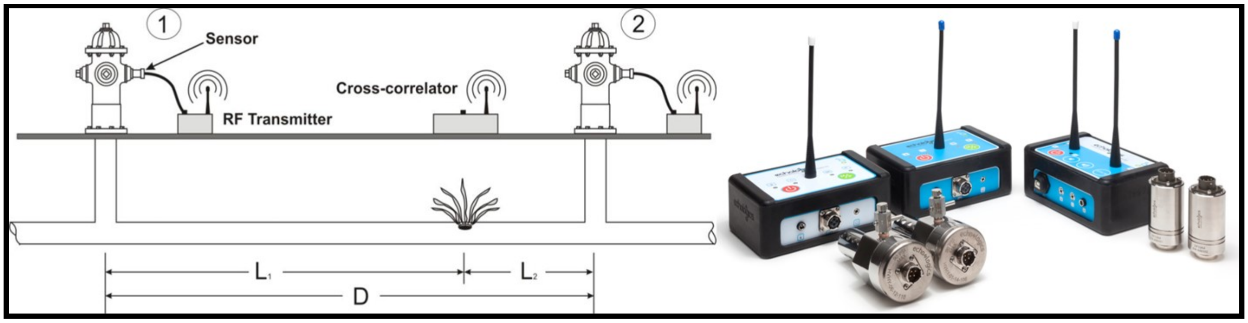

Figure 2.4. LeakFinderRT System (Courtesy of Echologics [now called LeakFinderST])

Table 2.4. Technical Specifications for LeakFinderRT

Operational Variable	LeakFinderRT
Equipment Logistics	Portable Case
Pipe Material	Pit Cast Iron, Spun Cast Iron, Steel, Ductile Iron, Asbestos Cement, Reinforced or Bar-wrapped Concrete, PVC, Polyethylene and other Plastics, as well as lined pipe.
Requires Internal Access	Yes for Hydrophones; No for Accelerometers
Pipe Diameter Range	>12-inch typically use hydrophones; <10-inch typically use accelerometers
Insertion Requirements	1.5-inch Tap or Fitting
Inspection Distance	500 to 2,500 ft

The LeakFinderRT's cross-correlation software runs on a laptop computer. The software was enhanced to provide improved resolution of narrowband leak signals and does not require signal filtering to remove interfering noise. This enhanced cross-correlation method is claimed to provide improved leak detection and location for plastic pipes (low frequency sound emission), small leaks, large diameter pipes (which can attenuate signals), and settings with high background noise (Liu et al., 2012). Table 2.5 summarizes installation parameters and typical acoustic sensor performance specifications for the LeakFinderRT leak detection application.

Table 2.5. LeakFinderRT Sensor Installation and Performance for Leak Detection

Pipe Type	Recommended Sensor Type	Suggested Sensor Spacing	Minimum Detectable Leak Size	Typical Location Accuracy
PVC	Hydrophones	Up to 800 ft	1 to 2 gpm	3 ft
AC	Accelerometers	Over 1,000 ft	1 gpm	3 ft
Ferrous	Accelerometers	Over 1,500 ft	1 gpm	3 ft
Steel	Accelerometers	Over 1,500 ft	1 gpm	3 ft

Note: Manufacturer-supplied performance data.

Sensor data are transferred via rf to a portable computer equipped with the LeakFinderRT software. The location of the leak is derived from the equation below:

$$L_1 = \frac{D - c \cdot \tau_{\max}}{2} \text{ and } L_2 = D - L_1$$

where:

L_1 and L_2 are the distances of the leak relative to sensors 1 and 2
c is the propagation velocity of sound in the pipe
D is the distance between the locations of sensors 1 and 2 and
$\tau_{\max}$ is the time lag between the two sensors.

Default values can be used for the propagation velocity of sound based on the type and size of pipe or propagation velocity can be determined experimentally in the field to improve the accuracy of the location calculations, as previously described above. During the field survey, the operator reviews the initial analysis on the laptop including displays of coherence and correlation plots to determine if the correlator has identified a leak in between the sensors. When a probable leak is identified, the correlator provides the distance from the leak to each sensor. The operator uses a manual, hand-held listening probe to confirm the predicted leak location, and makes any needed adjustment to the location and marks the site with biodegradable paint.

2.1.3 SebaKMT Correlux

The Correlux HL6000X is a correlator system used for automatically pinpointing leaks in water pipes (see Figure 2.5). It consists of two radio transmitters that connect to piezo-ceramic accelerometers (transmitter A and B), the correlator (the user interface device), correlation software, and headphones. The correlator device can be connected to a personal computer for software updates, downloading data, and to printout results. The correlator device has enough memory to record data for up to 10 segments. It is powered by a battery with an operational life of 12 hrs. Each radio transmitter is powered by an internal battery with an operational life of 15 hrs. All devices can also be externally powered using a 12-volt direct current car adapter or 110-volt alternating current power supply.

Figure 2.5. Correlux HL6000X System (Courtsey of Vivax-Metrotech)

The correlator system works by placing the two accelerometers (sensors) at either end of a pipe section (on valves, exposed pipe sections, or hydrants as the local conditions dictates). Table 2.6 shows the recommended sensor spacing based upon pipe type. The sensor spacing must be accurately measured for input into the correlator if a leak is detected. No information was available on a minimum detectable leak size or typical location accuracy of the Correlux system.

The correlator is activated and the sensor outputs are transmitted to the correlator. Once the correlator unit receives the sensor outputs and inputs data into the correlation software for analysis, the user provides the pipe data including the pipe material, pipe diameter, and pipe length. The device then displays the correlation graph, which compares both signals and provides the distance to the leak. For each correlation, the software automatically sets filters depending on the pipe material, and the filter limits can be adjusted by the user. If a leak is detected, the correlator provides the leak location in ft away from each of the two sensors. At that point the operator uses a listening probe to validate the leak location at the calculated distance from the sensors. If no leak is detected in the correlator, a zero reading is displayed and one of the sensors can be placed to evaluate the next pipe segment in the field survey.

Table 2.6. Correlux Sensor Installation Parameters for Leak Detection

Pipe Type	Suggested Sensor Spacing
PVC	300 to 500 ft
AC	1,600 ft
Ferrous	2,500 ft
Steel	2,500 ft

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages and limitations of the three leak detection technologies are summarized in Table 2.7. In general, all of the technologies have capabilities to detect and locate leaks. Some limitations exist for the technologies where monitoring is conducted on distribution system segments that contain mixed pipe materials between monitoring locations. Also, the presence of more than one leak in a monitoring interval generally reduces the reliability of the location estimates. Accessibility to monitoring locations can be an issue for all monitoring technologies, and continuous monitoring could not be implemented during the study by making use of existing information technology (IT) networks at active installations.

Table 2.7. Advantages and Limitations of Leak Detection Technologies

Leak Detection System	Advantages	Limitations
ZoneScan Alpha	• Minimally-intrusive system used to locate leaks • High accuracy in locating PVC leaks for this study • Ability to locate leaks in all types of pipes • Ability to detect leaks down to 1 gpm • Remote pinpointing of leaks, reducing man hrs needed to search for leaks • Continuous monitoring for leaks and daily updates allows for quick discovery and repair of leaks, reducing water loss • Small size of sensors allows for ease of deployment • Automatically filters out background noise • Moderately user-friendly interface	• Overall accuracy of pinpointing leaks did not meet performance objective for this study, although PVC leak location results met the performance objective • Sensor spacing is influenced by both the pipe diameter and material due to the attenuation of the acoustic signal • Access points to install sensors must be available at required sensor spacing, otherwise “potholing” is required to access pipe • Does not provide an indication of leak size • Requires use of proprietary software housed on a non-DoD server • Requires a dedicated frequency for communications
LeakFinderRT	• Minimally-intrusive system used to locate leaks • High accuracy in locating leaks using accelerometer • Leak detect is acquired as a service • Ability to locate leaks in all types of pipes • Ability to detect small leaks down to 1 gpm • Small size of sensors allows for ease of deployment	• Lower accuracy of pinpointing leaks using hydrophone • Sensor spacing is influenced by both the pipe diameter and material due to the attenuation of the acoustic signal • Access points to install sensors must be available at required sensor spacing, otherwise "potholing" is required to access pipe • If hydrophones are used, direct access through hydrants or risers is required • Does not provide indication of leak size • Monitoring duration depends on the quality of the signal
Correlux	• Minimally-intrusive system used to locate leaks • High accuracy in locating leaks using accelerometer • Leak detection can be acquired as a service • Ability to locate leaks in all types of pipes • Ability to detect small leaks down to 1 gpm • Small size of sensors allows for ease of deployment • System components are compact and easy to carry	• Sensor spacing is dependent on the pipe diameter and pipe material due to attenuation of the acoustic signal • Access points to install sensors must be available at required sensor spacing, otherwise “potholing” is required to access pipe • Does not provide indication of leak size

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3.0 PERFORMANCE OBJECTIVES

Table 3.1 summarizes the quantitative and qualitative performance objectives for this field demonstration and their corresponding success criteria used to assess progress towards meeting water conservation and energy goals.

The key performance consideration is the ability to accurately detect and locate leaks. Once the leaks are pinpointed, repairs can be efficiently made to reduce overall water loss. Reduction in water loss equates to energy savings both in reduced pumping and water treatment. Leak detection technologies that can accurately detect and pinpoint leaks within ± 4 ft and produce an acceptable rate of false positives will reduce the overall cost of making repairs. Repair costs are minimized by reducing the area of excavation and surface reconstruction needed to expose the leak and perform the repair.

Because of the limited number of leaks identified within ERDC’s operating water distribution system, only the performance objectives that were applicable to the TB leak simulations could be evaluated as summarized in Table 3.1. Only three potential leaks of interest were identified within the ERDC water distribution system. The DPW only chose to excavate one of these potential leak locations, which did not permit further verification of the leak sizes or locations. Therefore, detailed discussion and assessment of performance objectives associated with the operating water distribution system were not possible. For this reason, estimated water savings, energy savings, and savings-to-investment ratio (SIR) values were calculated as discussed in Section 7.

Table 3.1. Performance Objectives for Leak Detection Testing

Performance Objective	Metric	Data Requirements	Success Criteria	ZoneScan Alpha®	LeakFinderRT (Accelerometer)	LeakFinderRT (Hydrophone)	Correlux HL6000X
Quantitative Performance Objectives (Test Bed [TB] Simulated Leak Testing)							
True positive leak detection	Number of leaks detected	Acoustic signals	90% of known leaks detected	Achieved 100% (14/14)	Achieved 100% (14/14))	Achieved 86% (12/14)	Achieved 100% (14/14)
False positives	Number of false positives	Acoustic signals	≤ 5% of leaks detected were false positives	Not Achieved 25% (2/8)	Not Achieved 33% (3/9)	Not Achieved 22% (2/9)	Achieved 0% (0/9)
Leak location	Distance (ft)	Distance for leak location	Detected leak locations projected within ± 4 ft of the actual leak location	Not Achieved 86% (12/14)	Achieved 100% (14/14)	Not Achieved 50% (7/14)	Achieved 93% (13/14)
Minimum detectable leak size	Flow rate (gpm)	Flow rate for known leaks verified in the field with orifice plates	Ability to detect leaks above 1 gpm	Achieved 1.0 gpm	Achieved 1.0 gpm	Achieved 1.0 gpm	Achieved 1.1 gpm (exceedance by 0.1 gpm not considered significant)
Quantitative Performance Objectives (Water Distribution System Field Leak Testing)							
True positive leak detection	Number of leaks detected	Acoustic signals	80% accuracy	Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information).			
False positives	Number of false positives	Acoustic signals	≤ 20% of leaks detected were false positives	Insufficient field test results located to evaluate performance objectives (see Section 6 for more detailed information).			
Leak location	Distance (ft)	Distance for leak location	Locate within ± 4 ft	Insufficient field test results located to evaluate performance objectives (see Section 6 for more detailed information).			
System availability	Amount of time the system is operational (days)	Downtime/uptime	95% system uptime (after system startup and shakedown)	Achieved 96%	Achieved No significant downtime noted	Achieved No significant downtime noted	Achieved No significant downtime noted
System reliability	Amount of time system performs as designed (days)	Downtime/uptime			Achieved No significant downtime noted	Achieved No significant downtime noted	Achieved No significant downtime noted
Estimated water savings in test area	Water loss in gallons per year	Estimated size of remediated leak based on pipe line pressure	Site-specific calculation to achieve SIR > 1.0	Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7.			

Table 3.1. Performance Objectives for Leak Detection Testing (Continued)

Table 3.1. Performance Objectives for Leak Detection Testing (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria	ZoneScan Alpha®	LeakFinderRT (Accelerometer)	LeakFinderRT (Hydrophone)	Correlux HL6000X
Estimated energy savings in test area	Pumping power (kWh) per year	Calculated based on water savings volume and pumping requirements	Site-specific calculation to achieve SIR > 1.0	Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7.			
Savings-to-Investment Ratio (SIR)	Ratio of water loss cost savings to leak detection and repair costs.	Cost savings based on the value of water pumped, treated, pressurized, and transported) compared to leak detection costs and leak repair costs	SIR > 1.0	Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7.			
Qualitative Performance Objectives							
Ease of use	Ability of installation personnel to use/maintain the technology.	Feedback on ease of use from base personnel compared to current leak detection method; time required for training to use equipment; time required for troubleshooting.	Equal or reduced workload compared to conventional leak detection methodologies (if employed)	Skill Level: Intermediate Sensors: Moderately User-Friendly Desktop Software: Moderately User-Friendly PDA Software: Slightly User-Friendly	Not Applicable (contractor provided service only)	Not Applicable (contractor provided service only)	Skill Level: Advanced Sensors: Very User-Friendly Device: Moderately User-Friendly
Operational efficiency gains	Documentation of any operational changes possible as a result of technology.	Feedback from base personnel on changes to operations and maintenance (O&M) process for target area.	Ability of equipment to provide actionable alerts for earlier detection of leaks or to focus and prioritize repairs	Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information).			

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4.0 SITE DESCRIPTION

The TB and field demonstration site were located at ERDC in Vicksburg, Mississippi. It is a 673-acre site located in west-central Mississippi, approximately 2 miles east of the Mississippi River. ERDC's Environmental Laboratory is dedicated to providing solutions to environmental and water resource challenges through environmental science and engineering research and development. Therefore, this project aligns with ERDC Environmental Laboratory's mission to demonstrate and export technologies throughout the Army, DoD, and the nation.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The ERDC facility was established in the 1930s. The water distribution system varies in age with development of the installation, and has been constructed of several types of materials. The DPW at ERDC manages more than 65,000 linear ft (12+ miles) of distribution system made up of steel, iron, AC, and PVC pipe. More than 42,000 linear ft of the system is aging steel pipe, with steel and PVC repairs located throughout the water distribution system. Figure 4.1 shows the water distribution system layout for the facility. ERDC was selected as the location for the TB, as the distribution system layout allowed for pipes with artificial defects to be connected to the distribution system for simulated leak testing. The TB description, its operation, and site conditions are included in this section.

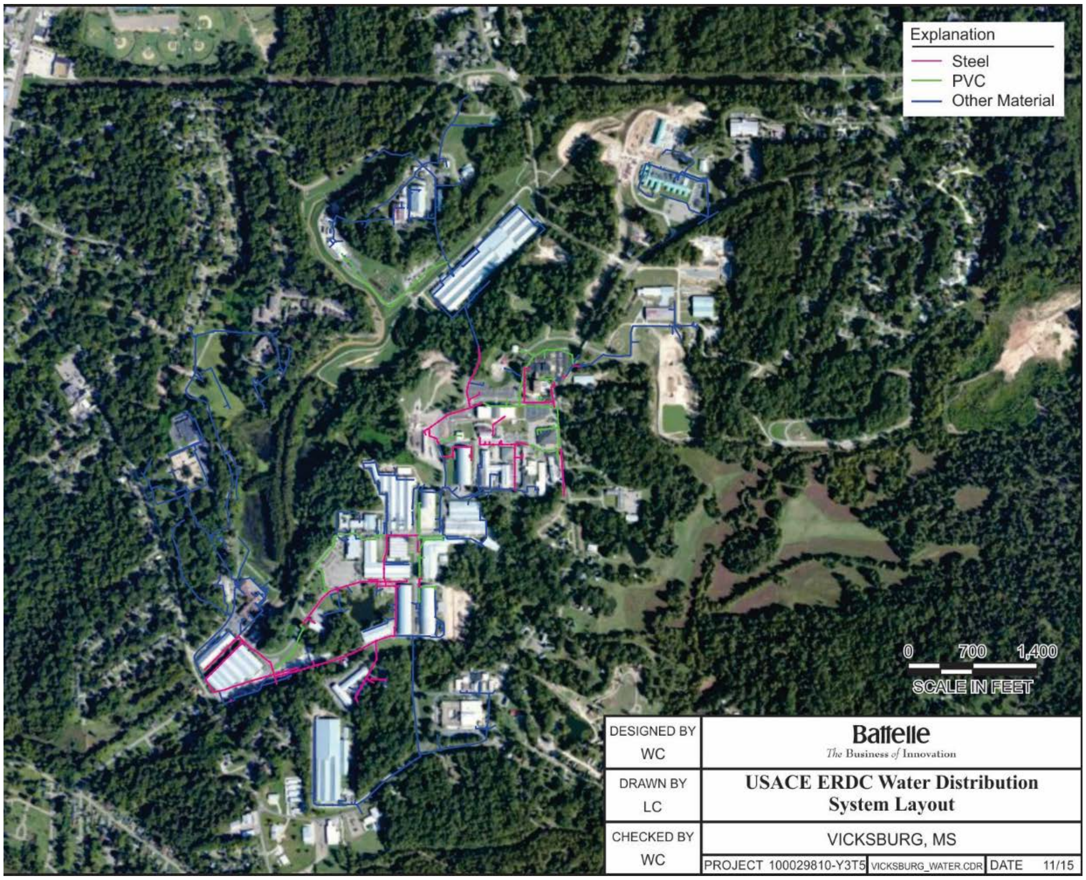

Figure 4.1. USACE ERDC Water Distribution System Layout

A 200-foot TB was constructed for use in the project, which was located in the northeastern corner of the ERDC campus (see Figure 4.2). It was previously used as part of a hydraulic testing facility with a 6-inch PVC water supply line leading to a large surface impoundment. The TB consisted of 90 ft of 6-inch DI pipe and 110 ft of 6-inch PVC pipe. Risers were installed on the test sections to allow for the placement of the acoustic sensors including accelerometers and hydrophones. After TB construction, 10 simulated leak locations were installed on the main line, along with one simulated leak on a nearby PVC lateral line. The 11 total simulated leaks were established using corporation valves and orifice plates with openings of various diameters (as discussed in Section 5.0).

(Source: ESRI, 2015)

Figure 4.2. Test Bed (TB) Site Location

4.2 FACILITY/SITE CONDITIONS

The ERDC Environmental Laboratory facility was selected for the demonstration site due to availability of the test location, similarity of infrastructure to existing military installations, and the on-site presence of the project team to facilitate the leak detection studies. The location was an advantage in that the construction of the TB could occur in any season due to the moderate climate.

Also, as a research facility, the team was able to obtain permission from ERDC Security to utilize the necessary bandwidths for sensor communication and data transmission. ERDC is classified as a consecutive water system, which means that it receives potable water from another entity without further on-site treatment. ERDC's potable water supply is from Vicksburg Water and Gas. ERDC does not have its own water tower or any additional treatment of the water supplied by the utility. The water system distribution pressure at the TB area ranges from 90 to 98 pounds per square inch (psi) and averaged 93 psi during the TB trials. The average cost of potable water is approximately $2.80 per 1,000 gallons, which is the value used in the economic analysis (King, 2015).

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5.0 TEST DESIGN

This section provides a detailed description of the TB design and testing procedures used to evaluate the innovative acoustic leak detection sensors.

5.1 CONCEPTUAL TEST DESIGN

This section provides an overview of key test variables for the controlled TB and the physical layout of the test facility. Figure 5.1 is a schematic of the TB, which was 200 ft in overall length and consisted of 6-inch diameter PVC and 6-inch diameter DI pipe.

- **Independent variables**: The independent variables for the controlled TB included the simulated leak flow rate and the simulated leak location. The simulated leak flow rate was varied through the use of orifice plates of varying sizes installed in the TB. Several leak locations were installed in the TB to assess the accuracy of the cross-correlation methods in pinpointing the leak locations.

- **Dependent variables**: The dependent variables included the acoustic signature generated by each leak and the projected leak location as determined by the technologies.

- **Controlled variables**: The controlled variables included the pipeline pressure, the pipe material, the pipe diameter, and the distance between the sensors. The pipeline pressure at ERDC averaged 93 psi as maintained by the water utility. The pipe material was 6-inch diameter PVC and 6-inch diameter DI pipe.

- **Hypothesis**: The hypothesis was that the cross-correlating acoustic sensors could detect and locate leaks within the given performance objectives in a controlled test environment. The controlled TB provided the setting to determine how accurately each technology could detect and locate leaks.

The TB provided 11 total simulated leaks installed at known locations. These included five simulated leaks on the 6-inch diameter PVC pipe and five simulated leaks on the 6-inch diameter DI pipe. In addition, one leak was installed on a lateral “T” off of the TB. To simulate pipeline leaks, corporation valves were installed with a ¾-inch internal threaded outlet port and a handle affixed to turn the valve on/off from the surface (see Figure 5.2). As shown in Table 5.1, the corporation valves were then fitted with ¾-inch brass orifice plates with drilled holes of various sizes to simulate a range of leak sizes. The estimated flow rate was calculated based on the pipeline pressure and Greeley's formula (American Water Works Association [AWWA], 2009). The flow rates ranged from approximately 1 to 8 gpm based on the average 93 psi pipeline pressure at ERDC. Calibration of the leakage rates was conducted in the field.

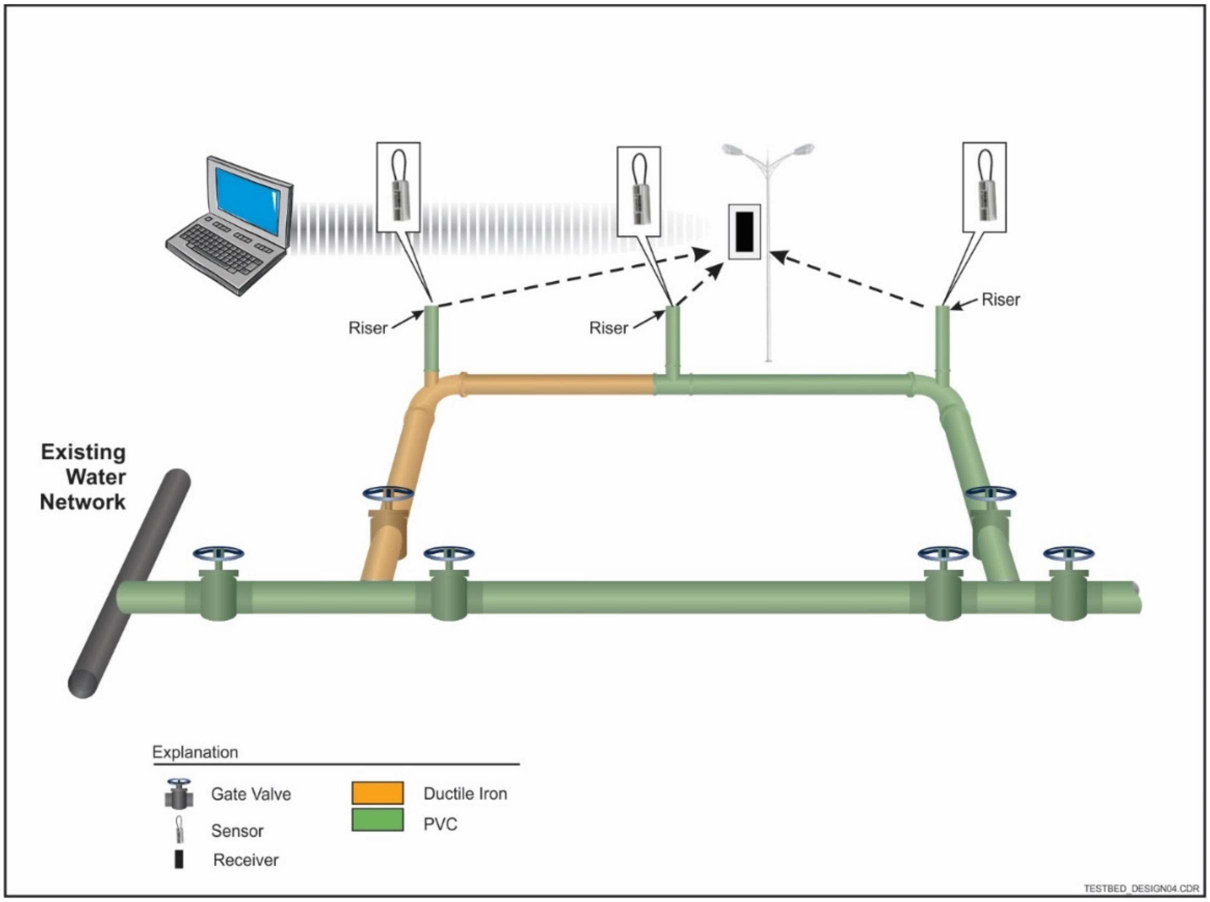

Figure 5.1. TB Schematic

Figure 5.2. Simulated Leak Configuration Using Corporation Valves

Table 5.1. Orifice Sizes Used to Simulate Various Leak Sizes during the Demonstration

Orifice Size (in.)	Leak Rate (gpm) at 90 psi	Leak Rate (gpm) at 93 psi	Leak Rate (gpm) at 98 psi	Photo
0.187	7.9	8.0	8.3	
0.154	5.4	5.5	5.6	
0.125	3.5	3.6	3.7	
0.0935	2.0	2.0	2.1	
0.067	1.0	1.0	1.1	

Note: the 0.032 orifice size was installed, but ultimately not included in the demonstration program because the calculated flow rate of 0.23 gpm (at 90 psi) was below the significance threshold for leak size selected for the performance criteria (see Section 3.0).

5.2 BASELINE CHARACTERIZATION

Baseline characterization included the collection of water distribution system information; the collection of water, energy, and labor costs; and TB operational parameters. The pipe type and location information was collected from the ERDC DPW as shown in Figure 4.1.

Discussions were held with ERDC about the optimal location for the TB and locations to place the acoustic leak sensors out in the water distribution system for field testing, based on considerations such as pipe type, pipe size, and a history of known or suspected water leakage. The following baseline information was collected to support the technology assessment:

- Water Distribution System Parameters (Pipe Type, Sizes): Figure 4.1
- Water Pressure (Minimum, Maximum, and Average): 90 to 98 psi (average 93 psi)
- Unit Water Costs for the ERDC Installation: $2.80 per 1,000 gallons[1]
- Unit Electrical Costs for the ERDC Installation: $0.08 per kWh (blended or average rate)[2]
- Personnel labor rates: $20.06/hr Davis Bacon Wage Rate Plus Fringe for Plumber (contractor rate)[3]
- As-Built TB Specifications and Operational Parameters: Leak locations were documented upon TB construction, along with other operational data including pressure testing, TB flow rate measurements, orifice size measurements, orifice flow rate verification, and water temperature. The TB pressure, flow rates, and water temperature were within expected guidelines. The orifice sizes were confirmed to be accurate and initial flow rate verification tests concluded that the relative percent differences between the theoretical and measured flows ranged from 12% to 28% with the measured flow rates tending to be slightly lower than the theoretical calculation would estimate. Additional underground flow verification results indicated that the average of the flow verification results was within 15% of the theoretical calculation.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

This section provides a description of the major technology components for the three innovative leak detection systems. The configurations of the three leak detection systems are similar as they each use similar types of components to detect leaks including: pre-positioned acoustic sensors, transmitters, and software to analyze data and pinpoint leaks using a cross-correlation methodology. However, there are some notable differences in how the technologies are deployed as summarized below.

5.3.1 System Design

The ZoneScan Alpha system is installed as a fixed long-term monitoring network to be operated by local DPW personnel, while the LeakFinderRT and Correlux systems are installed on a temporary “lift and shift” basis during a one-time leak detection survey performed as a contracted service. The primary advantage of a fixed monitoring network design would be the continuous monitoring from a central location. This could potentially reduce the required labor hrs to search for leaks and provide real-time leak notification on a daily basis as leaks emerge.

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[1] T. King personal communication, 2015

[2] http://www.electricitylocal.com/states/mississippi/vicksburg/

[3] http://www.wdol.gov and $20.06/hr based on the Davis-Bacon Wage Rate and Fringe for Warren County, Mississippi as of January 2016.

The LeakFinderRT and Correlux technologies are generally deployed via a periodic service contract rather than procured and used by DPW personnel. This approach would be more advantageous for DPWs that do not have local expertise in leak detection or prefer to contract out the service. The leak detection survey frequency would need to be determined by the DPW in placing contracts for the service. This section provides a description of how the technologies were installed and deployed in the field.

ZoneScan Alpha: Figure 5.3 shows a schematic and photos of the key components of the ZoneScan Alpha system. The primary components include the ZoneScan acoustic noise logger, radio repeater modules, and Alpha units. The acoustic noise logger was installed on the operating nut of water valves or on fire hydrants via a magnet on the bottom of the sensor. No potholes were made to install the sensors directly on the pipe, although this is a possible configuration. The acoustic sensors analyzed noise on the water lines at scheduled times to pinpoint the location of leaks. The repeaters and Alpha units were then used to transmit the real-time acoustical data to the ZoneScan.net data server.

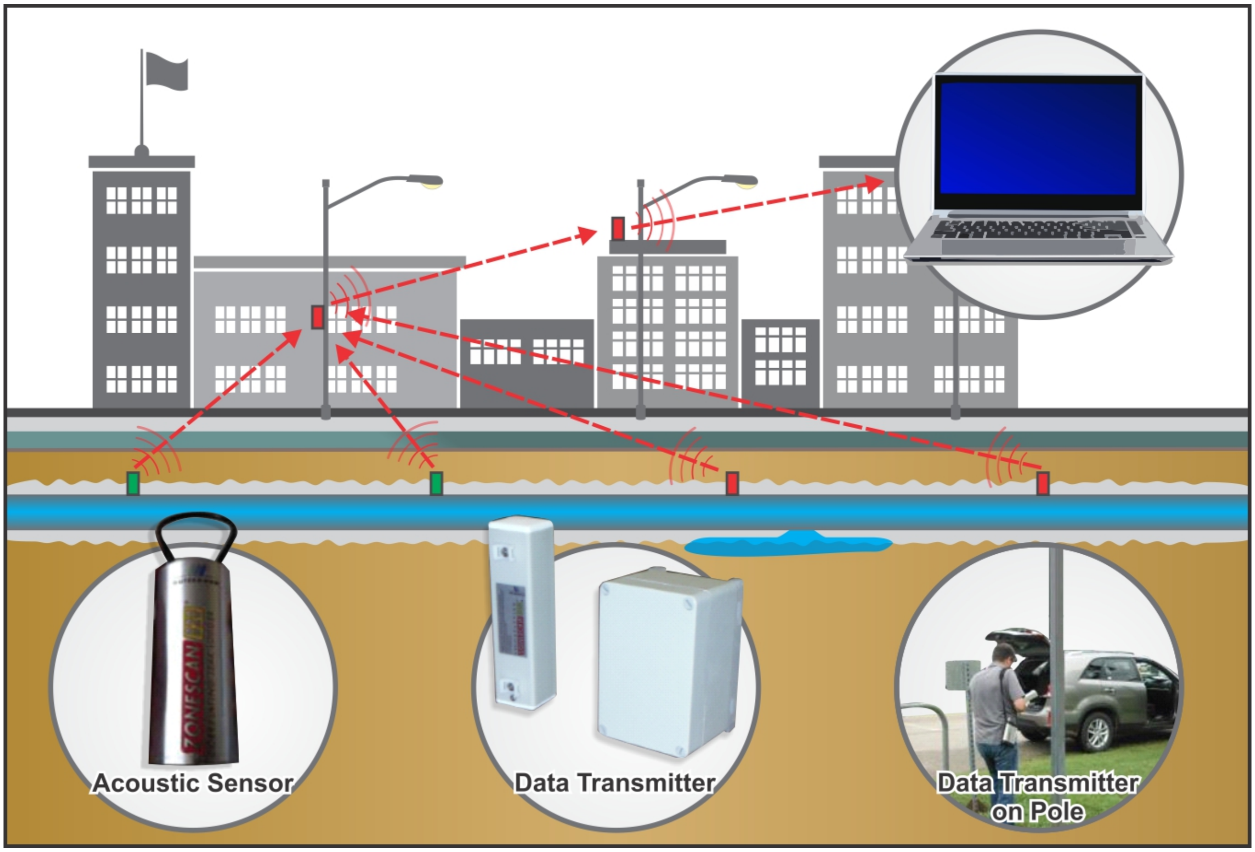

Figure 5.3. ZoneScan Alpha Installation and Components

LeakFinderRT: As shown in Figure 5.4, the LeakFinderRT system is composed of leak sensors, a wireless signal transmission system, and a personal computer equipped with cross-correlation software. Two acoustic sensors are mounted on water valves, fire hydrants, or exposed pipe in such a way that the pipe interval of interest is located between the sensors. Any active leaks will vibrate the pipe and be detected by the acoustic sensors. The acoustic signals are recorded and a cross-correlation plot generated on a personal computer to pinpoint the location of the leak.

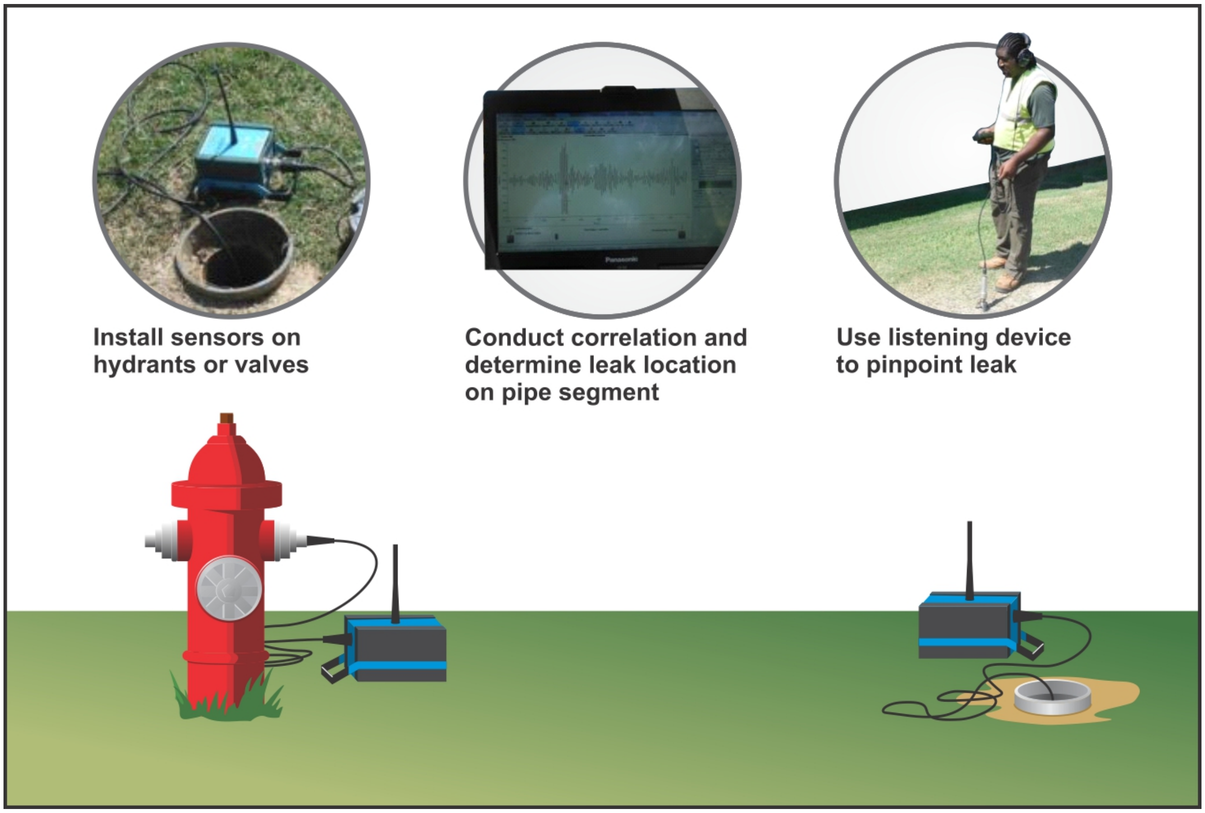

Figure 5.4. LeakFinderRT Installation and Components

Correlux: As shown in Figure 5.5, the Correlux system is composed of two leak sensors, a wireless signal transmission system, and a correlating device. Two acoustic sensors are mounted on water valves, fire hydrants, or exposed pipe in such a way that the pipe interval of interest is located between the sensors. Any active leaks will vibrate the pipe and be detected by the acoustic sensors. The acoustic signals are recorded and a cross-correlation plot is generated to pinpoint the location of the leak.

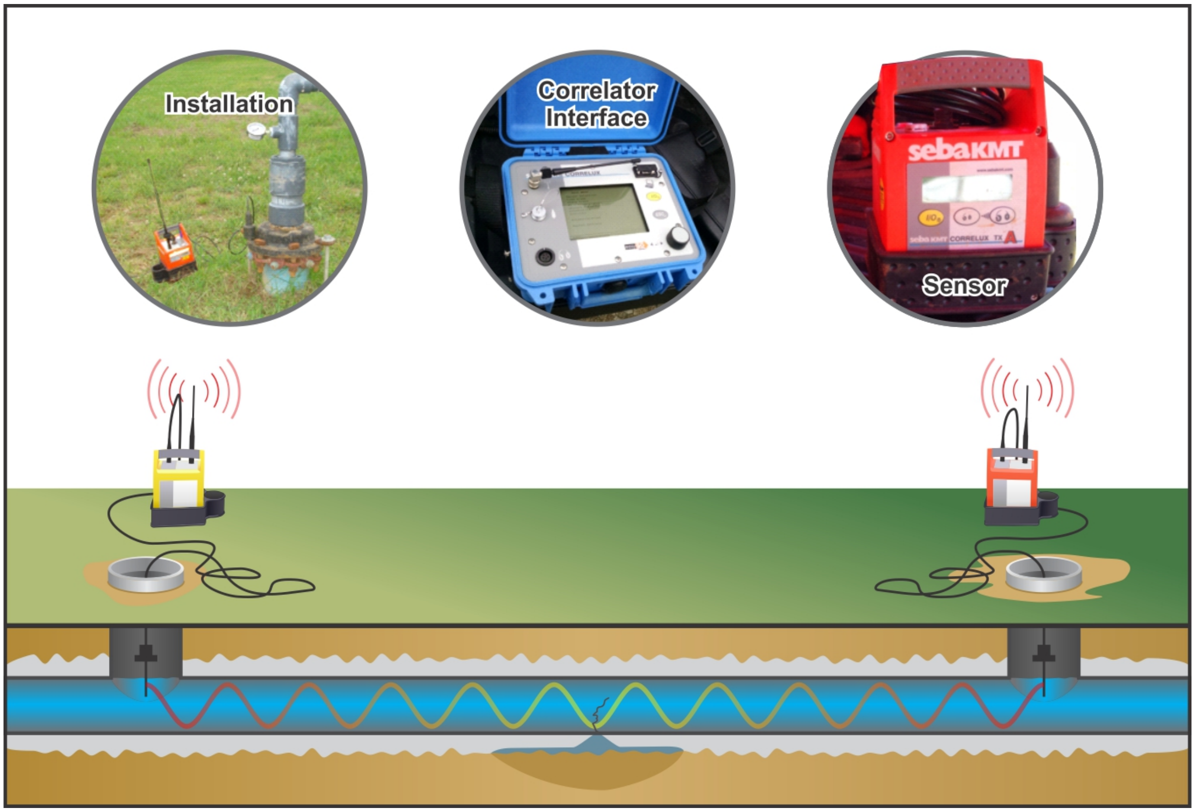

Figure 5.5. Correlux Installation and Components

5.4 OPERATIONAL TESTING

The operational testing for the TB was broken down into the following three phases:

- **Phase Test Bed (TB)-1 Collect Reference Data and Site Characterization**: This phase was conducted at project startup in 2013 to collect historical data from the facility in order to review the site-specific characteristics of the ERDC water distribution system. The layout of the water distribution system was reviewed and discussions were held at an on-site meeting in June 2013 to identify areas with a history of suspected leakage or water main breaks as discussed with the ERDC DPW. The TB location was also selected during this meeting. In addition, potable water, energy, and labor costs were collected.
- **Phase TB-2 Installation of the Pipeline TB, Hydraulic Testing, and Setup of Operational Flow Conditions:** Equipment procurement and TB installation occurred from March through July 2014. ERDC completed installation of the TB consisting of DI and PVC pipe in July 2014. The simulated leaks of varying sizes were established, along with the installation of a pressure gauge and water meter. The ERDC DPW conducted hydraulic testing to ensure that the pipe held pressure and that there were no unintended leaks within the system. The TB was monitored to ensure that it met the desired operational conditions.

- **Phase TB-3 Acoustic Sensor Installation, Calibration, and Simulated Leak Testing:** In this phase, the pipeline TB was used to simulate controlled leak conditions and to validate the performance of the three innovative leak detection technologies. The TB trials were initially delayed by sensor shakedown issues, which extended from July 22, 2014 through late October 2014. This extended shakedown period was needed to address several issues with the ZoneScan Alpha system primarily involving communications between the sensors, repeaters, and Alpha units. While shakedown was ongoing, preliminary TB trials were held in July and October 2014 with the ZoneScan Alpha and LeakFinderRT technologies. However, results from these trials were not satisfactory as they primarily involved multiple simulated leak scenarios. After these preliminary trials, a third technology, Correlux, was included in the demonstration program and the TB trials were adjusted to focus primarily on single leak scenarios. Testing for the full-scale demonstration with all three technologies proceeded between April and May 2015. During each demonstration run, the leaks were turned on or off using the corporation valves and the leak rates were determined based on the size of the orifice installed at the given location. Each technology was tested under the same leak scenarios. Data collection was conducted for the technology performance assessment. In addition, supplemental trials were conducted in July, September, and December of 2015 to test the technologies on an extended long run of PVC pipe and to repeat the lateral tests with various sizes of simulated leaks.

5.5 SAMPLING PROTOCOL

The sampling protocol resulted in the collection of sufficient data to validate leak detection technology performance under the TB scenarios. Upon the setup of each test run, the controlled leak information was documented including the selected orifice size(s), the known leak location(s), and the pressure and flowrate through the pipeline. The water temperature was measured twice each day at the start and end of the testing session. After this information was documented for each run of the TB, the leak detection information was collected from each technology in the form of acoustic leak signals that indicate the positive or negative presence of a leak and the leak location as correlated from both sensors on either side of the TB. The data collected during the simulated leak testing in the TB are summarized in Table 5.2.

Table 5.2. Sample Collection for the TB Leak Detection Trials

Data Description	Data Collection Frequency
Orifice Size(s) (in)	Once for each test run
Simulated Leak Location(s) (ft)	Once for each test run
Pipeline Pressure (psi)	Once for each test run
Pipeline Flow Rate (ft/s)	Once for each test run
Water Temperature (^{o}F)	Start/end of each testing day
Detected Leak Signal	Once per test run
Detected Leak Correlated Location(s) (ft)	Once per test run from each sensor location

The testing under real-world conditions using the ERDC water distribution system did not result in sufficient positive results that could be excavated for verifications. This portion of the field demonstration was subsequently discontinued.

5.5.1 Equipment Calibration and Data Quality

Equipment operation and TB operational parameters were documented with additional quality checks. This included ensuring proper operation of the flow meters and pressure gauges. The accuracy of the factory calibration for each water meter was verified in the field through flow rate measurements and water tank fill tests. For baseline testing in July 2014, the measured flow rate through the TB of 20.8 gpm from the water tank fill test was 13% lower than the average flow meter reading of 23.9 gpm. Later in July 2015, a second flow meter was procured to more accurately measure flow rates below 25 gpm. The results of the second flow meter calibration achieved up to 4.8% accuracy at 10 gpm.

5.5.2 Quality Assurance

Quality assurance of the test protocol was accomplished with review of flow meter and pressure gauge readings during each TB trial run to ensure proper operation and reasonable values.

5.6 SAMPLING RESULTS

The detailed sampling results from the leak detection trials are summarized in Section 6 in order to facilitate evaluation of the technology performance and comparison to performance objectives.

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6.0 PERFORMANCE ASSESSMENT

The performance criteria described in Section 3.0 were used to evaluate the innovative leak detection technologies considered in this study. The performance criteria included both quantitative and qualitative measures and were applied to the TB results as shown in Table 6.1. Both TB and field results were collected for the leak detection technologies as presented in these subsections. However, the field test performance criteria could not be assessed due to an insufficient number of leaks identified or excavated within the ERDC water distribution system. Therefore, the results are focused on the TB technology performance evaluation. The performance evaluation of the TB results provides a basis for selecting leak detection technologies for broader implementation.

6.1 DETECT KNOWN LEAKS (TRUE POSITIVE)

The most critical performance measure for a monitoring system is an acceptable rate of true positive results for detecting known leaks in the TB. Under TB conditions, the comparison of the result to the monitored condition is straightforward, since the leak being detected is a controlled condition of the test. The calculation for determining the performance criterion is the ratio of detected leaks indicated by the technology to the total leaks present in the pipe interval being evaluated. If less than 100% of the leaks present are detected, the undetected leaks indicate a false negative result. The threshold for the performance criterion acceptability is 90% of known leaks detected for the TB.

Results: All three accelerometer sensor-based technologies achieved 100% accuracy on notifying that the simulated leaks were present. All 14 leaks were identified by the ZoneScan Alpha, LeakFinderRT accelerometer, and the Correlux HL6000X. However, LeakFinderRT hydrophone-based technology only noted 86% of the simulated leaks and did not achieve the performance objective.

6.2 FALSE POSITIVE

False positive results for a leak detection technology are also an important consideration for determining acceptable performance. For a leak detection system to be implemented effectively, all indications of leaks must be addressed through field confirmation and repair of any detected leaks. Therefore, a false positive – an indication of a leak provided by the technology that does not reflect actual conditions – would result in evaluation of pipes that are not leaking. The expended effort would directly reduce the cost-effectiveness of the technology.

Results: Correlux was the only technology to achieve this objective with no false positives noted. The false positive rate was 25% (2/8) for ZoneScan Alpha, 33% (3/9) for LeakFinderRT with accelerometers, and 22% (2/9) for the LeakFinderRT with hydrophones. It should be noted that standard operating procedures for field deployment calls for a focused follow-up acoustic inspection at the correlated leak location, which could help to mitigate false positives in the field environment.

Table 6.1. Technology Performance Results for TB Leak Detection Scenarios

Performance Objective[a]	Success Criteria	ZoneScan Alpha	LeakFinderRT (Accelerometer)	LeakFinderRT (Hydrophone)	Correlux
Detect Known Leaks	90% of known leaks detected	100% (14/14) Achieved	100% (14/14) Achieved	86% (12/14) Not Achieved	100% (14/14) Achieved
False Positives	< 5% of leaks detected were false positives	25% (2/8) Not Achieved	33% (3/9) Not Achieved	22% (2/9) Not Achieved	0% (0/9) Achieved
Leak Location Overall	Locate 90% of leaks within ± 4 ft	86% (12/14) Not Achieved	100% (14/14) Achieved	50% (7/14) Not Achieved	93% (13/14) Achieved
Leak Location PVC Pipe	Locate 90% of leaks within ± 4 ft	100% (7/7) Achieved	100% (7/7) Achieved	86% (6/7) Not Achieved	86% (6/7) Not Achieved
Leak Location DI Pipe	Locate 90% of leaks within ± 4 ft	71% (5/7) Not Achieved	100% (7/7) Achieved	14% (1/7) Not Achieved	100% (7/7) Achieved
Minimum Detectable Leak Size[b]	Ability to detect leaks above 1 gpm	1.0 gpm Achieved	1.0 gpm Achieved	1.0 gpm Achieved	1.1 gpm Achieved
System Availability/ System Reliability	95% system uptime	96% Achieved	100% Achieved	100% Achieved	100% Achieved
Ease of Use	Ability of installation personnel to use/maintain	Skill Level: Intermediate Sensors: Moderately User-Friendly	Not Applicable	Not Applicable	Skill Level: Advanced Sensors: Very User-Friendly
		Desktop Software: Moderately User-Friendly PDA Software: Slightly User-Friendly	Not Applicable	Not Applicable	Device: Moderately-User Friendly

a) Insufficient data were available to assess water savings, energy savings, SIR, and operational efficiency gains.

b) Calculated using the operational pressure and Greely's formula; actual flow rate from the orifice may vary from 0.64 to 0.79 gpm based on flow verification testing.

6.3 LOCATION ACCURACY

Location accuracy is determined by comparing the actual location of a leak to the predicted location provided by the leak detection technology. The threshold of the performance criterion is a predicted location within ± 4 ft of the actual location. This value was selected based upon the practical consideration that limited accuracy of the location for a leak would require more excavation to expose a leak for repair. Typically, repairs are accomplished with trench boxes to shore up the excavation and 8 ft is a typical size utilized for this purpose. Outside of the ± 4 ft threshold, inaccurate location results would reduce the effectiveness of the leak detection system by requiring more excavation to locate and repair leaks. Because of potential variance of location results with differing pipe materials, this criterion was also reviewed by type of pipe material to determine effectiveness for each material (see Table 6.1).

Results: Two out of the four sensor configurations achieved this performance objective. The ZoneScan Alpha detected 86% (12/14) of simulated leaks with ± 4 ft of the known locations. The LeakFinderRT with the accelerometer detected 100% (14/14) of simulated leaks within ± 4 ft of the known locations. However, the hydrophone version of that technology had a lower performance at only 50% (7/14) simulated leaks detected within ± 4 ft of the known location. The Correlux system detected 93% (13/14) of simulated leaks within ± 4 ft of the known location.

6.4 LEAK SIZE THRESHOLD

All of the leak detection technologies in this study measure an acoustic signature produced by movement of water through a leak. The signal strength is related in part to the rate of leakage. Considering the signal-to-noise ratio and sensitivity of the sensors, the technologies are expected to have an effective lower limit of leak volume that can be detected under conditions where the systems would be deployed. In order to evaluate this aspect of performance, the controlled conditions of the TB were varied for each technology to determine whether the technologies could meet an effective leak size sensitivity threshold. Based on economic considerations on the cost of lost water and minimum costs of repair operations, it was determined that an effective leak volume threshold of 1.0 gpm would reflect a suitably reliable condition for detecting leaks that would significantly affect installation costs and resource consumption.

Results: The trials in the TB demonstrated that a leak signature was indicated for a minimum detectable leak size of 1 gpm. All leak detection technologies were able to detect leaks at approximately 1 gpm.

6.5 SYSTEM OPERATIONAL AVAILABILITY AND RELIABILITY

System availability and reliability are represented by the ratio of the time that a monitoring technology is effective

ely providing leak detection to the total time of the test period. As a technology's reliability increases and monitoring results are provided over more of the test period, the system availability and reliability approach 100%. The performance of the leak detection systems by these criteria are relevant for field test conditions, as system availability is relevant to a distribution system that is on line the vast majority of the time.

Results: All technologies met the criteria for 95% uptime. After an extensive shakedown period, uptime for the ZoneScan Alpha sensors was estimated at 96% over a 2-month period from November to December 2014. However, an extended shakedown period was needed from July 22, 2014 to October 2014 to address several issues involving sensor communications. These issues were primarily related to malfunctioning of repeaters and alpha units that required replacement or relocation to provide more consistent access to the sensor data. All issues related to the system were fully addressed by October 2014 and satisfactory operations were achieved from that point forward. The LeakFinderRT and Correlux technologies were provided as services and no significant downtime was observed during the field trials. However, on a few occasions, the trials for the LeakFinderRT and Correlux systems needed to be re-run because the equipment needed to reboot or the operator wanted to capture additional acoustic leak signature data.

6.6 EASE OF USE AND OPERATIONAL EFFICIENCY GAINS

Qualitative performance measures considered for the tests of leak detection technologies include ease of use and operational effectiveness. Both are based on experience of test personnel during field deployment of the techniques on an active distribution system.

Ease of Use: This qualitative performance measure is based on reported experience by field operators regarding the level of difficulty in operating the systems and gathering results. Ease of use is dependent on complexity of the setup and operation of equipment, quality of documentation on equipment operation, and susceptibility of equipment to outside sources of interference or other effects that complicate field operations. The ease of use was assessed by team members that had utilized the ZoneScan Alpha and Correlux equipment during the field demonstration project. The LeakFinderRT was performed as a service so was not assessed for this performance criterion.

For the ZoneScan Alpha system, it was estimated that one week was required to become familiar with the technology operations and capabilities. It was rated as requiring intermediate skills to operate. The leak detection components (i.e., sensors) and cross-correlation software (on the desktop) were rated as moderately user-friendly for deployment in the field for leak detection efforts. The system was recommended for in-house use by one team member and to be contracted as a service by another team member.

For the Correlux unit, it was estimated that one day was required to become familiar with the technology operations and capabilities. It was rated as requiring advanced skills to operate. The leak detection components (i.e., sensors) were rated as very user-friendly, while the cross-correlation device was rated as moderately user-friendly for deployment in the field for leak detection efforts. If a large installation was going to survey a large area, it was recommended to procure this technology as a service due to the time and manpower requirements.

Operational Effectiveness: This qualitative measure is based on a comparison of the level of effort to maintain and use the innovative leak detection systems in comparison to the conventional approach. Leak detection by other means could include evaluation of metering data and comparison of reported usage rates within the distribution system or field evaluation and observation of surface expression of leaks, such as wet ground in dry weather conditions or unexplained presence of water in utility vaults or other underground structures. Insufficient data were available to evaluate this performance objective as there were no pre-existing water meters at ERDC DPW and leak detection was only on a reactive basis in response to water main breaks (as is common practice for many U.S. water utilities).

7.0 COST ASSESSMENT

The cost models developed for this demonstration serve as a means to evaluate the expected life cycle costs for the use of innovative acoustic leak detection systems. The life-cycle cost estimates are calculated for operating in either a continuous monitoring mode or through periodic inspections. Water savings, energy savings, and SIR values for leak detection were estimated based upon typical breakage frequency per mile and assumptions about potential rates of water loss. Although the leak inspections conducted as part of this demonstration revealed potential losses of up to 37 million gallons per year, an insufficient number of leaks could be excavated or verified from the field tests to assess likely rates of water loss within the entire ERDC water distribution system. Therefore, industry data and other historical information provided the basis for the life cycle cost estimates as summarized below. The SIR estimates suggest that there can be a positive cost outcome for use of these innovative leak detection technologies depending on the level of water loss within the water distribution system.

7.1 COST MODELS

The life cycle costs were estimated over a 15-year period for all three technologies. Because the ZoneScan Alpha system is permanently installed on base, while the LeakFinderRT and Correlux systems are contracted services, the timeframe under consideration required normalization for comparison. The sensors and transmitters in the ZoneScan Alpha system are expected to last 15 years on site, so this was selected as the total life cycle timeframe. According to *AWWA Manual of Water Supply Practices M36: Water Audits and Loss Control Programs* (2009), leak detection surveys should be conducted every three years. Therefore, it was assumed that the LeakFinderRT or Correlux surveys would be performed at baseline and then every three years up to 15 total years (e.g., years 0, 3, 6, 9, 12, and 15). Note that the economic payback period for these technologies could be significantly shorter if a large number of leaks or high volume leaks are located. According to the National Institute of Standards and Technology (NIST) *Annual Supplement to NIST Handbook 135: Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis* (2015), the implied long-term average rate of inflation is only 0.1%, so inflation was not taken into account in the calculations below. A discount rate of 3% was used for the net present value (NPV) calculations as required for energy and water projects for Federal agencies (NIST, 2015).

The same water loss assumptions were used for each cost model. These are estimated values because the exact leakage rate within the ERDC water distribution system could not be established. As shown in Table 7.1, it is estimated that there would be 3.1 leaks at ERDC per year based on the size of its water distribution system, which would result in over 46 leaks in 15 years. Without leak detection efforts, the total water loss was assumed to be approximately 194 million gallons over 15 years based upon the typical breakage frequency of 0.25 breaks per mile per year (WaterRF, 2015) and a minimum detectable leak size of 1 gpm as identified from the demonstration results. Normalizing this to an annual basis would be an average water loss of approximately 13 million gallons per year. This is well below the high value of 37 million gallons of annual water loss estimated from the LeakFinderRT survey performed in 2014 as described in Section 6. With continuous leak monitoring efforts on a daily basis, it is assumed that the full amount of water and energy conservation would be realized from avoiding this water loss due to leakage. Therefore, the savings from 194 million gallons of conserved water is valued at approximately $560,119 over 15 years.

Using an NPV calculation, the current value of the water and energy savings would be approximately $415,133 with a continuous monitoring scenario for leak detection.

With periodic inspections conducted every three years, some water loss would not be avoided during the time intervals between inspections. For example, a three-year leak inspection interval would result in a cumulative 9.7 million gallons of water lost from three leaks running for 3 years, three leaks running for 2 years, and three leaks running for 1 year undetected until the next inspection interval (see Table 7.1). The amount of this lost water over the inspection intervals was subtracted out to arrive at a net water volume conserved of approximately 146 million gallons with periodic inspections. With inspections every 3 years, the value of the water and energy savings would be reduced by 25% to approximately $420,089 over 15 years. Using an NPV calculation, the current value of the water and energy savings would be $304,786 with periodic inspection for leak detection.

Table 7.1. Life Cycle Water Loss Estimated for ERDC Water Distribution System

Water Loss Estimate Assumptions	Data
ERDC Water Cost (per 1,000 Gallon)	$2.80
ERDC Electrical Cost (per kWh)	$0.08
ERDC Water Distribution Size (ft)	65,000
Leak Frequency (leaks per mile per year)	0.25
Total Number of Leaks Each Year	3.1
Total Number of Leaks in Life Cycle	46
Assumed Leak Size (gpm)	1.0
Life Cycle Period (years)	15
Leak Inspection Interval (years)	3
Water Loss Volumes and Cost Savings Estimates	**Results**
Estimated Life Cycle Water Conservation (gal)	194,113,636
Estimated Water Loss During Each Inspection Interval (gal)	9,705,682
Estimated Net Water Conservation with Periodic Inspection (gal)	145,585,227
Estimated Water Savings with Continuous Monitoring	$543,518
Estimated Water Savings with Periodic Inspection	$407,639
Estimated Total Energy Life Cycle Conservation (kWh)	211,477
Estimated Net Energy Savings with Periodic Inspection (kWh)	158,608
Estimated Energy Savings with Continuous Monitoring	$16,601
Estimated Energy Savings with Periodic Inspection	$12,451
Total Value of Savings with Continuous Monitoring	**$560,119**
Total Value of Savings with Periodic Inspection	**$420,089**
Discount Rate (NIST, 2015)	**3%**
NPV of Savings with Continuous Monitoring	**$415,133**
NPV of Savings with Periodic Inspection	**$304,786**

Sections 7.1.1 to 7.1.3 provide the SIR estimates based on these water and energy savings compared to the technology implementation costs. Since relatively conservative assumptions were made regarding the annual rate of water leakage, then a high SIR value would be a good indication of the cost-effectiveness of employing these technologies nationwide. Local repair costs could not be established during the demonstration as no leaks were excavated and repaired. Typical leak repair costs are approximately $900 to $5,000 each for small diameter water mains (PNNL, 2013b, Grigg, 2007).

The repair costs are not included in the SIR estimates as these costs are incurred when leaks are found, whether the leaks are detected through monitoring or eventually discovered through surface expression. While the leaks may increase when allowed to persist for longer periods before discovery and repair, the repair costs should be essentially the same. There may be additional cost savings in cases where leak detection leads to repair before water from leaks causes damage to other infrastructure or buildings. However, these damages would only occur in limited situations, and the impacts would be highly variable. Exclusion of these cost savings from the cost benefit analysis means the SIR values provided are a more conservative estimate. While leaks may start slowly with gradually increasing leak rates, or may result from more instantaneous breaching of pipes or fittings (such as cracking of a pipe during a freeze event), the cost models assume average frequencies of leaks and average water loss rates for determination of costs and benefits of leak detection and repair.

7.1.1 ZoneScan Alpha Life Cycle Cost Estimate

The life cycle cost estimate and SIR for the ZoneScan Alpha system are summarized in Table 7.2. The capital costs include the purchase of the loggers and other hardware components as described in Section 2. Installation, set-up assistance, and software training are included in the capital cost. The operations and maintenance (O&M) costs include primarily monthly data storage fees and battery replacement every five years. After the system is installed under guidance by the manufacturer, the local DPW personnel are responsible to monitor for leaks and to ensure that the system is running properly. The maximum water savings are realized with daily, continuous monitoring of the leak detection system. The SIR of 1.66 suggests a positive cost savings scenario for this technology.

Table 7.2. Cost Summary for ZoneScan Alpha

ZoneScan Alpha Leak Detection Cost Estimate	Data
ERDC Water Distribution System (ft)	65,000
ERDC Water Distribution Metallic Pipe (ft)	42,000
ERDC Water Distribution Other Pipe (ft)	23,000
Number of Loggers	150
Capital Cost of Equipment	$130,000
Annual O&M Cost	$2,700
Labor Cost	$20.06
Total Labor Per Day (hrs)	1
Monitoring Cost (per day)	$20
Total Duration of Monitoring (days per year)	365
Monitoring Coverage Per Event	100%
Life Cycle Period (years)	15
Total Number of Monitoring Events	5,475
Total Labor Cost for Annual Monitoring	$7,322
Total Life Cycle Cost	**$280,329**
NIST Discount Rate	**3%**
NPV Savings with Continuous Monitoring	**$415,133**
NPV Investment for Continuous Monitoring	**$249,641**
SIR	**1.66**

7.1.2 LeakFinderRT Life Cycle Cost Estimate

The life cycle cost estimate and SIR for the LeakFinderRT system are summarized in Table 7.3. In this case, the cost is a fee-for-service model for a one-time inspection versus purchasing the equipment for long-term use. The vendor costs include project planning, mobilization, field testing, analysis, and reporting. The total water and energy savings are reduced by about 25% under this scenario assuming an inspection interval of every 3 years over the 15-year life cycle timeframe. The SIR for this technology is less than one under the conservative assumptions made of a 1 gpm leak rate (e.g., the minimum detectable level). The SIR value could be positive if the typical leakage level in the system rose to 2.3 gpm on average with three breaks per year. This would be equivalent to a water loss at 446 million gallons over 15 years or 30 million gallons on average each year. This value is below the 37 million gallons of annual water loss identified in the LeakFinderRT survey in 2014 conducted under this demonstration for a select portion of the ERDC water distribution system. This suggests that a SIR value above one is possible for this technology depending on the level of water leakage within the water distribution system.

Table 7.3. Cost Summary for LeakFinderRT

LeakFinderRT Leak Detection Cost Estimate	Data
ERDC Water Distribution Size (ft)	65,000
Inspection Rate (ft/day)	5,000
Total Duration of Inspection (days)	13
Inspection Cost (Per Day)	$10,647
Inspection Coverage Per Event	100%
Inspection Interval (Years)	3
Life Cycle Period	15
Total Number of Inspection Events	6
Total Cost Per Inspection Event	$138,411
Total Life Cycle Cost	**$830,466**
NIST Discount Rate	**3%**
NPV Savings with Periodic Inspection	**$304,786**
NPV Investment for Periodic Inspection	**$672,994**
SIR	**0.45**

7.1.3 Correlux Life Cycle Cost Estimate

The life cycle cost estimates and SIR values for the Correlux system are summarized in Tables 7.4, 7.5, and 7.6. In this case, two scenarios were estimated including a fee-for-service model versus purchasing the equipment for in-house use by DPW personnel. For periodic inspections, the vendor costs include project planning, mobilization, and field testing. The total water and energy savings are reduced by about 25% under this scenario assuming an inspection interval of every 3 years over the 15-year life cycle timeframe. The SIR of 2.10 suggests a positive cost savings scenario for this technology using a fee-for-service model. The purchase of the equipment with a SIR of 5.43 is even more cost effective, but would place the burden of accurate leak detection and time on the DPW staff. Table 7.6 shows the SIR sensitivity for this scenario under varying hourly labor to water cost rates.

Table 7.4. Cost Summary for Correlux Contracted as Periodic Inspection Service

Correlux Leak Detection Cost Estimate	Data
ERDC Water Distribution Size (ft)	65,000
Inspection Rate (ft/day)	3,750
Total Duration of Inspection (days)	17
Inspection Cost Per Day	$1,725
Inspection Coverage Per Event	100%
Inspection Interval (years)	3
Life Cycle Period	15
Total Number of Inspection Events	6
Total Cost Per Inspection Event	$29,900
Total Life Cycle Cost	**$179,400**
Discount Rate	**3%**
NPV Savings with Periodic Inspection	**$304,786**
NPV Investment for Periodic Inspection	**$145,382**
SIR	**2.10**

Table 7.5. Cost Summary for Correlux Purchased for Periodic Inspections

Correlux Leak Detection Cost Estimate	Data
ERDC Water Distribution System (ft)	65,000
Inspection Rate (ft/day)	3,750
Total Duration of Inspection (days)	17
Capital Cost of Equipment	$22,295
Labor Cost	$20.06
Crew Size	2
Inspection Cost (Per Day)	$401
Inspection Coverage Per Event	100%
Inspection Interval (Years)	3
Life Cycle Period	15
Total Number of Inspection Events	6
Total Labor Cost Per Inspection Event	$6,954
Total Life Cycle Cost	**$64,020**
Discount Rate	**3%**
NPV Savings with Periodic Inspection	**$304,786**
NPV Investment for Equipment and Inspections	**$56,108**
SIR	**5.43**

Table 7.6. SIRs for Various Labor and Water Cost (for Correlux Purchased Scenario)

SebaKMT Correlux Purchase Labor Costs (per Hr)										
Water Cost (per 1000 gal)	$20.00	$25.00	$30.00	$35.00	$40.00	$45.00	$50.00	$55.00	$60.00	$65.00
	Savings-to-Investment Ratio (SIR)									
$0.50	1.10	0.96	0.85	0.76	0.69	0.63	0.58	0.54	0.50	0.47
$1.50	2.99	2.60	2.30	2.06	1.87	1.71	1.57	1.46	1.36	1.27
$2.50	4.88	4.24	3.75	3.36	3.04	2.78	2.56	2.37	2.21	2.07
$3.50	6.76	5.88	5.20	4.66	4.22	3.86	3.55	3.29	3.07	2.87
$4.50	8.65	7.52	6.65	5.96	5.40	4.93	4.54	4.21	3.92	3.67
$5.50	10.53	9.16	8.10	7.26	6.58	6.01	5.54	5.13	4.78	4.47
$6.50	12.42	10.80	9.55	8.56	7.75	7.09	6.53	6.05	5.64	5.28
$7.50	14.31	12.43	11.00	9.86	8.93	8.16	7.52	6.97	6.49	6.08
$8.50	16.19	14.07	12.45	11.16	10.11	9.24	8.51	7.89	7.35	6.88
$9.50	18.08	15.71	13.90	12.46	11.29	10.32	9.50	8.80	8.20	7.68

7.2 COST DRIVERS

In general, reported water costs are low in many regions of the U.S. These cost figures are based on operating expenditures, and generally do not include long-term maintenance costs for water infrastructure assets. Low unit costs for water have contributed to a largely reactive approach to addressing water main leaks and breaks among supply system operators. However, system operators are increasing prices to reflect the actual costs to maintain and upgrade their aging water distributions systems. The value of water in drought-prone areas and the cost of water are the primary drivers for the implementation of leak detection technologies as the benefits of leak detection are driven by the loss prevention achieved.

Water costs vary considerably nationwide depending on climate, water quality, available supply, and local demand considerations. Table 7.6 shows typical water costs from a survey of 50 U.S. cities for a customer using 15 m^3/month or 3,963 gal/month (Global Water Intelligence [GWI], 2014). On a unit basis, the average water cost ranges from $1.59/kilogallon (kgal) to $9.71/kgal and averages $5.01/kgal nationwide. The water cost at the ERDC facility of $2.80/kgal is moderate compared to these nationwide values and compared to other DoD installations located in more drought-prone regions. For example, unit water costs at Naval Facilities Engineering Command (NAVFAC) Southwest Naval Base San Diego are $14.82/kgal. The fact that a high SIR value is returned for a DoD installation with a moderate water rate and with a very conservative assumption of 13 million gallons of water lost per year suggests that the widespread application of these technologies would be beneficial.

Table 7.7. Regional Water Rates

Location	Unit Water Rate[a]
San Diego	$9.71/kgal
Miami	$1.59/kgal
Average of all 50 Cities	$5.01/kgal
ERDC	**$2.80/kgal**
Naval Base San Diego	**$14.82/kgal [b]**

(a) Calculated from GWI, 2014
(b) From FY 2016 Navy Working Capital Fund Stabilized Rates

Energy and labor costs also serve as cost drivers and vary considerably based on region. The electrical costs used in the economic analysis at ERDC is $0.08 per kWh and $0.14 per kWh (average commercial rate) for San Diego. Based on data from the Bureau of Labor Statistics (2015), the labor rate for plumbers and pipefitters nationwide ranges from $14.27 to $43.13/hr with the median hourly wage at $26.49/hr. Under the Davis-Bacon Act for federally-funded projects, contractors are expected to pay their laborers no less than the prevailing wage plus fringe benefits. For ERDC in Vicksburg, MS, the Davis-Bacon Act wage rate of $20.06/hr is approximately 24% below the national average for plumbers cited by the Bureau. However, the Davis-Bacon Act wage rate at $50.37/hr in San Diego was 17% higher than the 90th percentile labor rate of $43.13/hr for plumbers according to the Bureau. Because of this wide variation in water and labor rates nationwide, SIR assessment was limited to two regions with the different water and labor rates as discussed below.

7.3 COST COMPARISON

Table 7.7 compares the NPV and SIR for the three innovative acoustic sensor technologies for a moderate water cost scenario at ERDC in Vicksburg, MS to a high water cost scenario at Naval Base San Diego, CA. The comparison illustrates the impact or sensitivity of water and labor rates on the SIR values. The NPV and SIR results for these scenarios were derived using the existing water rate at ERDC of $2.80/kgal and the water rate at Naval Base San Diego of $14.82/kgal.

Table 7.8. NPV and SIR Estimates Using Moderate and High Regional Water Costs

Technology	NPV Technology Investment Cost Over 15 Years	Volume of Water Saved (Mgal)	NPV Savings with ERDC Water Rate	SIR with ERDC Water Rate	SIR = 1.0 Breakeven Labor Rate ($/hr)
ZoneScan Alpha	$250K	194[a]	$415K	1.66	$58.00
LeakFinderRT	$673K	146[b]	$305K	0.45	NA/Service
Correlux	$145K	146[b]	$305K	2.10	NA/Service

Table 7.8. NPV and SIR Estimates Using Moderate and High Regional Water Costs (Continued)

Technology	NPV Technology Investment Cost Over 15 Years	Volume of Water Saved (Mgal)	NPV Savings with San Diego Water Rate	SIR with San Diego Water Rate	SIR = 1.0 Breakeven Labor Rate ($/hr)
ZoneScan Alpha	$382K	194[a]	$2.15M	5.63	$457.00
LeakFinderRT	$673K	146[b]	$1.58M	2.35	NA/Service
Correlux	$145K	146[b]	$1.58M	10.88	NA/Service

a) Estimated based on continuous daily monitoring
b) Estimated based on period inspections every 3 years

Likewise, the electrical rates were varied based on region-specific values as discussed above, while all other variables were held constant. To be consistent with prior calculations, the Davis-Bacon prevailing wage rates (plus fringe) of $20.06/hr for Vicksburg, MS and $50.37/hr for San Diego, CA were used. These values are comparable to the 2015 Bureau of Labor Statistics data cited above.

Table 7.8 also includes an estimated breakeven point at which the SIR value would equal one for the ZoneScan Alpha continuous monitoring technology. Given the moderate water rate at ERDC, the labor cost could more than double and the technology could still achieve a SIR value of 1.0 based on the projection. The estimated breakeven labor rate of $58.00/hr for ERDC is well above the median labor rate of $26.49/hr for plumbers based on the Bureau of Labor Statistics (2015). For San Diego, the ZoneScan Alpha technology is even more cost-effective achieving a SIR value of 5.63 at the $50.37/hr prevailing wage rate for plumbers. Based on the projected breakeven labor rate analysis, the labor rate could increase over nine times and the technology would still achieve a SIR value of 1.0 at the given water rate of $14.82/kgal. Therefore, the sensitivity analysis has demonstrated that the continuous monitoring technology is likely to be cost-effective under a wide range of water and labor rates. The other two periodic inspection technologies (LeakFinderRT and Correlux) were services for a fixed daily inspection fee, so the unit labor rates are not applicable to hourly rate sensitivity analysis. However, the Correlux technology was found to be cost-effective under both moderate and high water rate scenarios with SIR values ranging from 2.10 to 10.88. The LeakFinderRT technology was found to be cost-effective under the high water cost scenario for San Diego.

8.0 IMPLEMENTATION ISSUES

This section provides information to aid in the future implementation of the technology including lessons learned as part of the demonstration and other key considerations related to technology performance.

8.1 PERTINENT REGULATIONS, EXECUTIVE ORDERS, CODES AND STANDARDS

EO 13693 requires the DoD to achieve a 36% reduction in water use by the year 2025 starting from baseline year 2007. A key element of achieving this goal will be reducing water losses from existing water distribution systems, many of which have components that have reached or exceeded their expected service life. A typical installation may have over 50 miles of potable water pipelines within its boundaries that vary in age, material, size and condition. Water loss through older pipes is often significant, and repair and replacement are urgently needed. At a frequency of 0.25 breaks per mile per year, 13 leaks per year would be typical at larger bases (WaterRF, 2015). Replacement of aging distribution system elements is a desirable outcome, but the expense can be great. Alternatively, finding and repairing the leaks will reduce water loss and avoid undermining other critical abovegrade infrastructure (e.g., roadways). Accurate and cost-effective technologies to pinpoint those leaks in underground piping, particularly leaks that have no visible surface expression, will substantially reduce water loss. This will also reduce costs, safeguard public health, and help to meet the EO water reduction requirement.

In addition to EO 13693, the Department of the Army revised Army Regulation AR-420-1, Army Facilities Management on 24 August 2012 to increase maintenance and inspection of building systems that impact water and energy consumption. Policy on the responsibility for attainment of installation water goals, including leak detection for installation water systems, has also been provided in a memorandum from the Assistant Secretary of the Army for Installations, Energy and Environment, dated 20 December 2012 (Hammack, 2012).

8.2 TECHNOLOGY IMPLEMENTATION

8.2.1 Intermittent Inspection

Leak detection systems that rely on an intermittent inspection approach hold the most promise for implementation at military installations at this time. This approach requires periodic surveys to be conducted at multiple locations to provide geographic coverage of an installation's distribution system. A widely accepted best management practice with this technology is to cover an entire base every 3 to 5 years (AWWA, 2009). Both the LeakFinderRT and Correlux leak detection systems process the leak signature data in the field without any requirement for IT security, or connection to government IT assets or the Internet. Leak detection using these systems can be procured as a service via a maintenance or job order contract. In addition, if an installation has the manpower, equipment can be procured for in-house use. (Note that the LeakFinderRT system would require IT approval for laptop computer use). The major downside to this intermittent inspection approach is that non-exposed leaks can go on for a significant period of time before detection. For example, water from a major underground leak may travel along the path of least resistance to a cracked sewer line with no surface expression. Still, periodic surveys would also result in water savings, but with less effectiveness than a continuous monitoring approach.

Since the Correlux technology met all of the performance thresholds for the TB evaluations, this technology could be considered for additional field testing and deployment in its current state. It is recommended that further evaluation under field conditions be undertaken at installations that would benefit the most from aggressively controlling water losses. This includes installations where water sources are constrained or supplied by providers at significant cost or where breaks are more likely to occur on a frequent basis because of the age and condition of installation infrastructure and site conditions such as corrosive soils.

8.2.2 Continuous Monitoring

Further development and investment would be required for widespread adoption of a continuous monitoring system at military installations. Continuous monitoring could be focused at older installations or in older or more problematic portions of the water distribution system (such as areas suffering from settling). Continuous monitoring systems have recently been used at numerous municipalities outside the military with reported success. However, software compatibility issues and the difficulties of securing IT approval would deter implementation at military installations under the current IT security environment. The primary operating concern to be addressed includes network security for information systems that are being deployed in conjunction with AMI systems. This concern prevented any field testing of the monitoring technologies that relied upon AMI infrastructure for data transmission by leak detection monitoring systems. This would be most problematic to address for the ZoneScan Alpha system, as this technology requires data to be transmitted to a corporate server now located in Europe for processing, and relaying of monitoring results back to the leak detection system users via the Internet.

The estimated cost of procuring and operating a US-based server for this specific technology was quoted at approximately $75,000. This is considered cost prohibitive for a single installation, but could be manageable if the cost for a centralized server was pooled across many DoD installations. In addition, based on limited research of similar leak detection systems, companies are now developing continuous monitoring systems that would not rely on Internet access and acquisition of out-of-country server technology for operation at an installation. This could potentially improve the chance of securing IT approval at DoD installations. Continuous monitoring systems hold significant long-term promise for reducing water loss as leaks can be detected near real-time allowing for repair in a shorter time frame. Competition in this emerging niche may drive down costs to a more feasible level in the near future.

8.3 GUIDANCE DOCUMENTS AND SUSTAINABILITY INITIATIVE

The *AWWA Manual M36: Water Audits and Loss Control Programs* provides specific guidance for conducting water audits (AWWA, 2009). Procedures for identifying water losses must account for procedural errors, unauthorized connections, known and undetected leaks. Contracts for audit services should follow guidance from the most recent audit manual. For in-house services, base repair crews should be thoroughly familiar with established procedures.

The Army ERDC’s Construction Engineer Research Laboratory (CERL) is currently developing a tri-service methodology known as the Sustainability Management System that will provide a computer modeling platform to track all military assets, including potable water systems to manage life cycle repair, degradation assessment, and maintenance. A complete geographic information system inventory of leak detection data should be integrated into the model input.

No Federal regulatory requirements must be met by leak detection systems, as water supply systems are regulated primarily for water quality. Some states have passed regulations on allowable leakage levels within water distribution systems. For example, New Hampshire, New Jersey, and Washington require water utilities to implement leak detection if their water losses exceed certain threshold values (AWE, 2012). State efforts related to water conservation are expected to accelerate over time.

8.4 LESSONS LEARNED

8.4.1 Accurate Drawings

Leak detection operators must have a good understanding of their equipment, correlator requirements and have quality drawings to work from. The layout drawings should show location of pipe segments (with lengths), valves, hydrants, directional transitions, pipe type transitions, size and location of all pipe laterals. The correlator output quality is highly dependent on entering accurate length measurements, pipeline material, and size. In many cases, pipelines are not laid out in straight lines and consequently must be addressed differently when entering data into the correlator, in cases where accurate drawings are not available. Operators unfamiliar with the pipe distribution system may have problems pinpointing a leak if provided with marginal quality drawings or there are laterals not identified on the drawings.

8.4.2 First TB Trials

The first trials conducted at the ERDC TB revealed that bracketing two types of pipelines (DI and PVC) to find artificial leaks was problematic. In over 50 percent of the trials, the accuracy of the correlated leaks was outside the established limits. The experienced Echologics crew believed that because the distance between the sensors was well within the limitation of the technology (i.e., less than 200 ft) that the technology would be able to accurately pinpoint the established leaks. This turned out not to be the case and the second set of trials which bracketed only one type of material generated more accurate results. This indicates that transitions from one type of pipe material to another may be problematic for leak detection location calculations using data from acoustic sensors. The TB trials also showed inaccurate leak location results when multiple leaks (e.g., two or more leaks) were located within the interval between sensors.

8.4.3 Information Network Security and Compatibility

As stated in Section 1.0, the planned evaluation of the continuous monitoring technology at an installation with an AMI system for water metering could not be performed. The primary barriers preventing the planned demonstration at JBPHH and other sites were:

- AMI systems for water were still in the process of being installed or not yet fully functional at some bases considered for the study including JBPHH.
- Compatibility issues existed between the DOD-managed AMI hardware and software and the continuous monitoring leak detection software systems. Although, customization was possible to adapt to different AMI brands, it was beyond the scope of the project.

- Compatible water AMI systems were identified at several privatized housing units located on DoD installations including JBPHH. However, approval could not be obtained from the private companies to participate in the field demonstration.

Although the continuous monitoring leak detection technology evaluated in this project was compatible with the AMI hardware and data transmission software at the privatized area of JBPHH and several other DoD sites, the study team was unable to get approval from the privatized utilities managers to integrate continuous monitoring leak detection with their AMI system based on prior IT contractual requirements. Future efforts at development or deployment of continuous leak detection monitoring systems at DoD locations with AMI systems should include resources for resolution of technology compatibility and security issues, as well as a review of AMI software and hardware variability across the DoD. One possible approach would be to solicit firms with demonstrated experience in integrating software and data transmission hardware from multiple vendors through federal "sources sought" notices published on the Commerce Business Daily and FedBizOpps web sites. In retrospect, it would have been prudent from a demonstration perspective to use ERDC as the host site, as their charter is uniquely positioned to serve as a site for validating technologies. Approval may have been more forthcoming for integration with an AMI system. Unfortunately, the AMI infrastructure was not yet in place at ERDC during the execution of the project. However, ERDC is currently implementing AMI in its pipe network and a future study could include integrating it with continuous leak monitoring technologies.

8.5 OTHER OBSERVATIONS

In the field demonstration at ERDC, a known leak was identified with evidence of significant water flow on the surface. The field test excavation revealed that the leak was under the slab of a building. Further research and development is needed to address location of leaks that may be underneath building slabs or other surface features. In an actual field application, the lateral and leak may be under a building.

8.6 PERFORMANCE OF THE TECHNOLOGIES

This study has evaluated three technologies for leak detection that can be deployed on existing water distribution systems. The ZoneScan Alpha system is deployed to monitor infrastructure over time, while both the LeakFinderRT and the Correlux technologies are used to conduct periodic surveys by deploying the systems in the field to gather data on specific reaches of the piping in a distribution system. The periodic approach requires the field surveys to be conducted at multiple locations in order to provide geographic coverage of an installation’s distribution system. Only the Correlux technology met all of the established performance measures for the TB evaluations. Insufficient leaks were observed during the field evaluation conducted at ERDC to assess the performance measures of any of these technologies under field conditions.

While the ZoneScan Alpha technology provides some operational advantages by providing monitoring over time, additional investigation would be required to determine whether suitable performance can be obtained from monitoring systems as currently offered, or whether further technological development is required to justify deployment at DoD installations.

Benefits of the systems will also require further evaluation under field conditions. More data are needed on the net costs of the systems, including contractor services or additional labor provided by installation staff. Similarly, more operational experience is needed to assess cost savings for installations that would be realized through decreased water losses and operational efficiencies in proactively locating and addressing leaks identified through a continuous monitoring technology. However, given the data on hand, conservative estimates indicate high SIR values for these acoustic leak detection technologies, which would make their more widespread application beneficial.

8.7 FUTURE USE OF THE TB FACILITY

The TB facility at ERDC-Vicksburg is located in a relatively isolated portion of the research station. It is probable that the area will be not be disturbed for 5 to 10 years, and perhaps longer. This facility will therefore remain available for further pipe testing in the immediate future. These experiments could include testing of new leak detection equipment. However, a natural progression would investigate in situ means of pipe repair. The pipe gallery could also be used to test water security issues, such as conditions that promote lead corrosion or addressing pipes contaminated in a chemical release. Currently, land surrounding the TB gallery is unoccupied and the TB could be expanded to accommodate new projects.

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