ESTCP
Cost and Performance Report

(CP-9904)

Advanced Passive Acoustic Leak Location and Detection Verification System for Underground Fuel Pipelines

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LIST OF ACRONYMS

A/D	Analog to Digital
AEC	Army Environmental Center
API	American Petroleum Institute
AST	Aboveground Storage Tank
CBC	Construction Battalion Center
CERL	Construction Engineering Research Laboratory (Army)
DEM/VAL	Demonstration/Validation
DESC	Defense Energy Supply Center
DoD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Program
FISC	Fleet and Industrial Supply Center
GUI	Graphical User Interface
LRAFB	Little Rock Air Force Base
LUST	Leaking Underground Storage Tank
NAS	Naval Air Station
NFESC	Naval Facilities Engineering Service Center
NWGLDE	National Work Group on Leak Detection Evaluations
PALS	Passive Acoustic Leak-Location System
PD	Probability of Detection
PFA	Probability of False Alarm
STPF	SERDP Test Pipeline Facility
UST	Underground Storage Tank

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DEM/VAL Site 1: U.S. Navy's Construction Battalion Center (CBC), Port Hueneme, California. We appreciate the opportunity to use the Construction Battalion Center (CBC) pipeline for the first DEM/VAL. We appreciate the support and coordination provided by Mr. George Watson of NFESC.

DEM/VAL Site 2: Little Rock Air Force Base (LRAFB), Little Rock, Arkansas. We appreciate the active and enthusiastic support and coordination provided by Mr. Michael Ramsey and Mr. Robert Seay, Civil Engineering, and Mr. Dick Robertson, Supervisor of Liquid Fuels Maintenance, and his staff (Mr. John Gray, Technician, SSgt Michael Banas, SSgt Timothy Giddens, and SSgt Maria Miller).

DEM/VAL Site 3: Navy Test Loop, SERDP Test Pipeline Facility (STPF), Edison, New Jersey. We appreciate the opportunity provided by the Urban Watershed Management Branch of the U. S. Environmental Protection Agency (EPA) to perform the DEM/VAL of the Pipeline Acoustic Leak-Location System at the SERDP Test Pipeline Facility (STPF). We appreciate the support and coordination provided by Dr. John Carlyle, Carlyle Consulting, during the planning and conduct of the DEM/VAL. Dr. Carlyle operated the pipeline, established the leaks and observed the tests during the DEM/VAL. We also appreciate the support of Mr. George Watson of NFESC, who coordinated the tests with the EPA, and Mr. James W. Starr and Mr. Richard F. Wise of Vista Research, who provided field support during the tests.

DEM/VAL Site 4: Campbell Army Airfield and the Sabre Army Heliport, Fort Campbell, Kentucky. We appreciate the enthusiastic support provided by Mr. Mark Linkous, Mechanical Engineer Technician, for coordinating and supporting these tests. We also appreciate the field support provided Dr. John Carlyle of Carlyle Consulting and Mr. Michael J. Talhami of Vista Engineering Technologies, L.L.C.

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

Accurate location of leaks in buried bulk and hydrant fuel pipelines is a challenging, time-consuming, and expensive problem. This problem has both operational readiness and environmental implications to the Department of Defense (DoD). Under the Environmental Security Technology Certification Program (ESTCP), the Pipeline Acoustic Leak-location System (PALS) was demonstrated and validated under a wide range of operational conditions. All of the objectives of the project were met, and the PALS is ready for commercial use.

This ESTCP project was a follow-on to research and development projects conducted on this technology by the Strategic Environmental Research and Development Program (SERDP) and the U.S. Environmental Protection Agency (EPA). PALS is a portable, computer-controlled, passive-acoustic system where the innovation is the application of robust signal processing algorithms that allows small leaks to be located accurately over separation distances that are operationally practical. PALS can be retrofitted to existing lines or designed into new lines.

The PALS consists of three cylindrical acoustic sensors, three small pre-amplifiers and, a field-worthy notebook computer having a data acquisition card. The sensors are attached with epoxy directly to the pipe wall or to a flange connection. Each sensor measures the acoustic signal generated by the turbulent flow through a hole in the pipe. A pair of sensors brackets the leak and determines the location of the leak relative to one of the two sensors, called the "Reference" sensor. A second pair of sensors that do not bracket the leak is used to measure the speed of propagation of the acoustic wave in the pipe. A leak-location measurement can take as little as 2 to 5 minutes to complete. The PALS is operated using a Graphical User Interface (GUI) software package. The PALS is easy to set up and can be operated by a field technician with a minimal amount of training.

The PALS is a real-time system utilizing a coherence function signal-processing algorithm to locate a leak. This approach overcomes the difficulties experienced by amplitude and correlation analyses. The PALS uses the coherence function to determine the existence of an acoustic signal and to determine the frequency band containing the signal. The existence and frequency band are determined using both the magnitude-squared and the phase displays. Once the frequency band containing the signal is selected, the computer automatically outputs the location of the leak relative to the Reference sensor. A threshold-based algorithm is also available for calibration purposes and for location of impulsive leak signals.

PALS is best used only after a leak has been detected. PALS first verifies the existence of the leak and then quickly and accurately locates it. The pipeline can then be uncovered, and the hole can be visually confirmed and repaired. Once the integrity of the pipeline can be demonstrated, it can be brought back into service, and any environmental damage due to the leak can be remediated.

The performance and operational utility of this technology were successfully demonstrated on bulk and hydrant pipeline systems found at Air Force, Army, Navy and EPA facilities. As summarized below, four sets of DEM/VALs were conducted between April and October 2000 on different types and configurations of underground bulk and hydrant pipelines over a wide range of hole sizes, line pressures, leak rates, backfill conditions and background noise conditions.

- ***A 10-in.-diameter, 457-ft, bulk fuel pipeline at the U. S. Navy's Construction Battalion Center (CBC), Port Hueneme, California.*** Leaks were induced through removable leak plugs (with holes drilled though the plugs with diameters of 0.01 and 0.04 in.) at 30 to 175 psi into different types of backfill conditions. The PALS located leaks at separation distances up to 125 ft with an error of 0.1 to 5 ft.

- ***Two 1,000-ft, 6-in.-diameter hydrant fueling pipes on the operational flight line at the Little Rock Air Force Base (LRAFB), Little Rock, Arkansas.*** This DEM/VAL was conducted during high noise conditions produced by day and night C-130 training operations. The results of simulated leak tests showed that the PALS could locate leaks at sensor separation distances up to 700 ft during normal C-130 flight line operations to within several ft (i.e., 1% of the sensor separation distance).

- ***The 12-in.-diameter Navy Test Loop of the SERDP Test Pipeline Facility (STPF) located U. S. Environmental Protection Agency (EPA) site in Edison, New Jersey.*** Leaks in the line were produced using removable leak plugs provided by the EPA with diameters of 0.01 and 0.04 in. Over 18 tests were conducted at a line pressure of 70 psi with 10 different sensor separation distances, ranging from 135 to 517 ft. For half of the tests, the reference sensor was mounted on a blind flange at the end of a vertical riser and the other sensors were mounted directly on the pipe wall. In these 18 tests, the mean location error was 3.1 ft (1.1% of the sensor separation distance) and the one standard deviation uncertainty was 2.0 ft (0.8% of the sensor separation distance).

- ***A 2,300-ft, 4-in.-diameter hydrant line at the Sabre Army Heliport and an 8-in., 550-ft segment of the hydrant fuel system at the Campbell Army Airfield, Fort Campbell, Kentucky.*** Simulated leak tests on the heliport line showed that, with distances of 600 ft between the sensors bracketing a simulated leak, the PALS could locate leaks with an accuracy of better than 1% of that distance. The results of the tests at the Sabre Army Heliport are particularly significant because the protective coating on the pipe did not have to be removed. It was found that the sensors could be mounted on the flanges connecting adjacent sections of piping rather than directly on the pipe wall itself. The tests conducted at the Campbell Army Airfield line illustrated the difficulties encountered with PALS when the acoustic reflections were unusually high.

The results of the DEM/VALs showed that, with the PALS sensors spaced at distances up to 200 ft, the system located leaks though holes of 0.01 in. to within 3 ft of where they actually were. For the longer distances between sensors, the PALS' accuracy was better than 1.5% of the sensor separation distance. The system was routinely operated on pipe segments of 500 ft or longer, allowing sensors to be placed on a line using available access points without the need for excavation. It is significant that the system was successfully deployed on the flight line of an Air Force base during routine operations.

PALS has significant cost, operational and performance advantages over the most common method of locating leaks (excavation of the buried pipe) as well as other leak-location technologies such as tracer methods. The cost advantages are realized because of the high performance of the technology, the real-time output of the system and the short duration of the measurements. There is a 15 to 1 cost advantage of using PALS to locate a leak instead of excavation and a 4 to 1 cost advantage of using PALS over using liquid-tracer methods. For large pipelines, the cost of PALS is as low as

$0.22 per linear foot compared to $12.50 per linear foot for excavation and $5.00 per linear foot for tracer methods. Also, PALS is the only viable leak-location methodology that can be used on 25% to 50% or more of the potentially leaking pipelines. Furthermore, it is estimated that the cost of regulatory compliance using volumetric systems for leak detection and PALS for leak location is a factor of three smaller than liquid-tracer tests. Finally, the PALS has the potential to save DoD many hundred of millions of dollars in terms of cost avoidance, readiness and life extension. The payback on capital equipment purchases is less than one year.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The Pipeline Acoustic Leak-location System (PALS) is an innovative technology that was developed for the reliable location of fuel leaks in underground, pressurized fuel pipelines (Figure 1). It is an outgrowth of the previous work performed by EPA [1-3], DOE [4-8], and SERDP [9-15].

2.1.1 Problem

Pipeline leaks represent a large environmental risk. The risk is larger for pipeline leaks than for tank leaks because (1) most of the leaks occur in the pipelines rather than in the tanks, (2) the pipelines are pressurized, while tanks are not, and thus can potentially release more fuel into the ground than tanks if a leak goes undetected for the same period of time, and (3) there are more pipelines than tanks. Unlike small leaks in tanks that may seal over time due to debris, the higher operating pressures associated with pipelines insure that once a leak occurs, it will continue to leak until it is detected and repaired.

Accurate location of leaks in buried fuel pipelines is a challenging, time-consuming, and expensive problem. This problem has both operational and environmental implications to DoD. Pipeline leaks can significantly affect operational readiness if the location of the leak cannot be readily found, repaired, and re-tested for integrity. Until the location of the leak is known, the environmental damage due to the leak cannot be remediated. PALS was developed because of the lack of technology, poor performance of available technology, and the expense and downtime associated with those technologies that are viable (e.g., tracer methods).

2.1.2 System Description

As shown in Figure 1, PALS consists of three cylindrical acoustic sensors (1.5 in. in diameter and 3 in. in height), three small pre-amplifiers (6 in. x 3 in. x 2 in.), and a field-worthy notebook computer having a data acquisition card. The pre-amps need to be located in close proximity to the sensors; typically, the pre-amps are within 10 ft of the sensors. The cables connecting the pre-amps to the data acquisition card in the computer can up to a thousand ft in length. Communication between the sensor-pre-amp subsystem and the computer could also be accomplished by wireless communication, but this would be substantially more expensive.

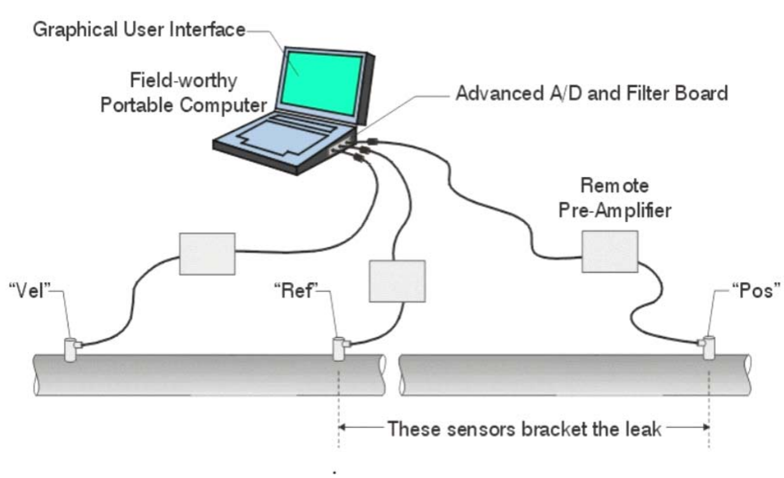

Figure 1. Schematic of the PALS.

The sensors are normally attached with epoxy directly to the pipe wall or to the end of a flange connecting two sections of pipe. The sensors can also be attached to a blind flange at the termination of a pipe section. The sensors can also be mounted on the pipe using petroleum jelly to obtain good communication between the pipe and the sensor. This attachment procedure was used when the sensor needed to be attached to the end of a staff to gain access to the pipe wall. Other mounting techniques (e.g., magnets, clamps) can be used if implemented without grounding the system. There are two requirements for mounting the sensors. The first is that the sensors (accelerometers) be attached to the wall in such a way that any acceleration in the pipe produced by the leak signal be communicated to the sensor. Second, it is important that the sensors not be grounded to the pipe because the epoxy and the petroleum jelly prevent grounding due to the fact that there is no metal to metal contact between the pipe and the sensors.

Each sensor measures the acoustic signal generated by the flow through a hole in the pipe. A pair of sensors called the Position (Pos) and Reference (Ref) sensors brackets the leak and determines the location of the leak relative to the Reference sensor. A second pair of sensors, that do not bracket the leak, is used to measure the speed of propagation of the acoustic signal in the pipe. The propagation speed is measured using the Velocity (Vel) and the Reference sensors. For the leak to be properly located, the distances between the sensors must be known-since the measurement made by the PALS determines the location relative to the Reference sensor for the sensor configuration (Vel-Ref-Pos). These distances and this sensor configuration must be entered into the PALS software before a measurement can be taken. A second measurement configuration can also be used in which both the Vel and Pos sensors are located to the left or right of the Ref sensor (Ref-Vel-Pos). The Ref-Pos sensors still bracket the leak, while the Ref-Vel sensors do not. A leak-location measurement can take as little as 2 to 5 minutes to complete.

PALS is operated using a Graphical User Interface (GUI) software package written specifically for this application (see Appendix A of the Final Report [18] for a brief description of some of the user input screens). The PALS is easy to set up and can be operated by a field technician with a minimal amount of training. Its operation utilizes a set of straightforward setup, monitoring and processing pull-down menus and screens. While the algorithms used to process the acoustic data may be complex mathematically, the graphical output of these analyses is fairly easy to use and interpret from simple, easy-to-recognize features in the output that occur when a leak is present. The software is designed to exploit the two types of leak signals that may be generated. The GUI allows the user to exploit one type of signal using a coherence-based analysis algorithm, and another type of signal using a time-of-arrival, threshold-based analysis algorithm.

The system uses automatic gain control and has a 16-bit data acquisition capability. The data acquisition card allows data to be collected at a maximum sample rate of 200,000 samples/second (200 kHz) and can process up to 200 ensembles per second comprising up to 16,384 samples per ensemble. The Nyquist sample rate is 100 kHz, which is sufficient to exploit the leak signal over the frequency band of interest. The sample rate and ensemble length control the maximum separation distance allowed for the Position and Reference sensor pairs and can be selected to maximize the number of ensembles averaged together in the shortest time. The software prints out the maximum separation distance possible for the choice of sample rate and ensemble size and warns the user if the selection of these parameters is not sufficient.

2.1.3 Measurement Approach

The PALS is mainly intended to verify the presence of, and to locate, a leak once it has been detected. The first step is to test the line volumetrically to determine whether or not the line is leaking. The second step is to attempt to isolate the line by volumetrically testing the line between isolation valves to better localize the leak. The third step is to use the PALS system on the section or sections of the line suspected of leaking. The fourth step is to excavate the line using the location estimates made with PALS to find the leak. The fifth step is to repair the leak and re-test the line for volumetric and structural integrity. Once this fifth step is completed, the line can usually be brought back into service.

2.1.4 Leak Signal

Two types of signals may be produced by a pipe leak, and PALS is designed to detect both types of signals. The first is an impulsive signal that is produced by the breaking of bubbles in the backfill surrounding the pipe [10]. Tests have shown that this signal is either very weak or non-existent when the backfill saturates due to the leak, groundwater, or when the backfill is not composed of dry granular material. If it is present, however, it is usually very strong and should be exploited. This signal was not observed in any of the DEM/VALs conducted during this project.

The second type of signal is a continuous, random signal generally produced by the turbulent flow through the hole in the pipe. This type of leak signal is always present when there is a leak in the line and the line is under pressure. This signal will be largest under dry, granular backfill conditions. This signal is exploited using coherence and correlation analyses.

The continuous acoustic signal produced by a leak can be masked by background noise. The time series that is recorded at each acoustic sensor-and that contains the leak signal-is “banded,” and appears random in nature. Signal processing techniques, which permit the detection of the signal in the presence of background noise, must therefore be applied. Simple systems that attempt to infer the location of the leak from the relative amplitude of the acoustic signal measured at two sensor locations do not work reliably. The most widely used approach to acoustic leak location is correlation analysis [e.g., 7]. In this approach, a correlation function is computed from the time series collected at the two sensors bracketing the leak. This approach is also not robust because the frequency band containing the leak signal and the strength of the signal in this frequency band is not known prior to the measurement [1-3]. The strength and frequency band of the signal will vary as a function of pipe diameter, wall thickness, wall material, fluid, pipe geometry, propagation mode, flow rate, line pressure, hole size and shape, and backfill type and condition. If the signal band is not known, the location estimate may be made in a frequency band highly contaminated by noise. It is also possible that this frequency band may not even contain the leak signal.

The dispersion relationship for acoustic propagation in a pipe predicts the presence of three propagation modes: (1) fluid, (2) wall, and (3) interface between the fluid and the wall called the peristaltic or flexural mode [1-3, 6, 9]. This relationship indicates that several propagation modes can be present in the same frequency band. In general, one of the propagation modes dominates, but the velocity estimate may be contaminated by the presence of two or more modes. To develop accurate location estimates, the velocity should be measured. It is important to understand that the dispersion relationship and, therefore, the propagation modes can change dramatically with pipe diameter, wall thickness, wall material, fluid and pipe geometry. As a consequence, robust leak location requires the use of a signal processing approach that does not require any *a priori* knowledge about the leak or the pipe.

2.1.5 Detection Algorithm

PALS uses a coherence function signal-processing algorithm to locate a leak [1-3, 6]. To address the possibility of impulsive leak signals and for calibration purposes, a time-domain algorithm that processes impulsive signals was also developed and included in the PALS. These algorithms are described in Appendix B of the Final Report [18], which also includes examples of PALS outputs.

2.1.5.1 Coherence Algorithm

The coherence approach overcomes the difficulties experienced by amplitude and correlation analyses. The PALS uses the coherence function to determine the existence of an acoustic signal and to determine the frequency band that contains the signal. The existence of the signal and the frequency band containing the signal are determined using both the magnitude-squared (γ^2) and the phase (φ) displays. Once the frequency band containing the signal is selected, the computer automatically outputs the location of the leak relative to the reference sensor from the phase data.

Unlike the correlation function, the coherence function determines the relationship between two time series as a function of frequency. This means that the coherence function can be used for leak location independently and without *a priori* knowledge about the properties of the pipeline or the leak. This is not possible using the correlation function. Once the coherence function has identified the leak signal frequency band, the correlation function can be used to verify that only one leak signal exists and that reflections from other sections of the pipeline do not interfere with the location estimate. Multiple reflections, multiple propagation modes, or multiple peaks simply show up as multiple peaks in the correlation function. Eqs. (B-1) and (B-2) in Appendix B of the Final Report [18] can be used to compute the position of the leak and the propagation speed of the leak signal in the pipe using the output of the coherence function [1-3, 6].

An example of the output of the coherence function (γ^2, φ) is shown in Figure 2 for a 1.9 gal/h-leak through a 0.01-in.-diameter hole in the line at a line pressure of 70 psi. The results are summarized in Table 1. The distance between the Pos-Ref and the Vel-Ref was 360.0 ft and 137.3 ft, respectively. The reference sensor was mounted on the blind flange at the top of the pipe. The presence of the leak signal is clearly seen in Figure 2 for frequencies above 10 kHz for both the Pos-Ref and the Vel-Ref coherence functions. Values of γ^2 are greater than 0.6 and are clearly greater than the values of γ^2 outside the leak signal frequency band (frequencies less than 10 kHz). While the phase φ is highly linear, the phase slope, dφdf, changes slightly with frequency in the vicinity of the three peaks in γ^2 found at frequencies of 13.5, 15.0 and 18.0 kHz. The analysis for leak location was performed between 12.6 and 14.0 kHz. As shown in Table 1, PALS located the leak to within 0.4 ft (or 0.1% of the 360.0-ft Pos-Ref separation distance). The PALS location was 233.1 ft from the Ref sensor, and the actual location of the leak was 233.5 ft. A propagation velocity of 1,409 m/s was measured and used in the analysis.

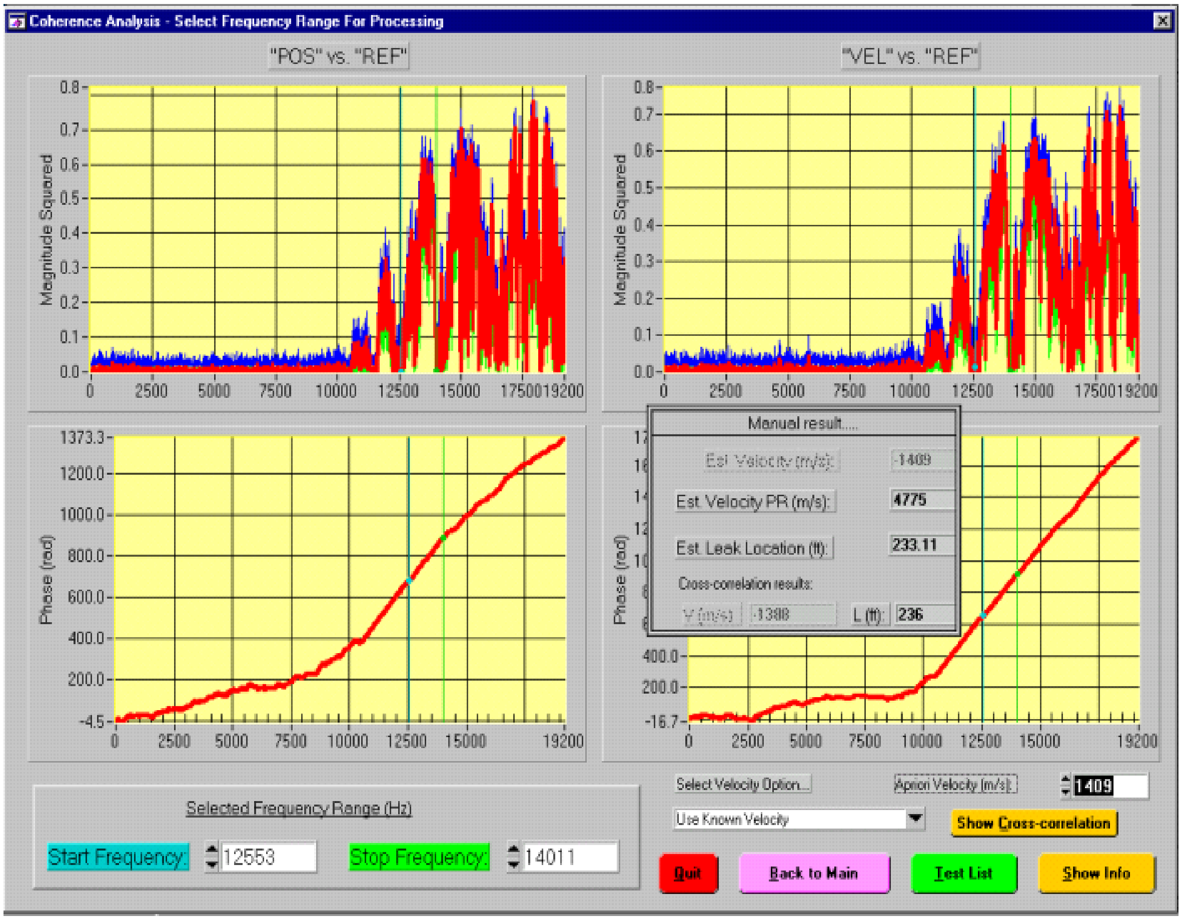

Figure 2. Output of the PALS.

Table 1. Leak Rate of 1.9 gal/h for a 0.01-in.-Diameter Hole at STPF.

Measurement	PALS Test Results 0.01-in. Hole 081500 1805
For Configuration (see Figure in Appendix C of the Final Report [18])	Figure C-6
Reference – Position Sensor Separation Distance – ft	360.0 ft
Reference – Velocity Sensor Separation Distance – ft	137.3 ft
Velocity – m/s	1,409 m/s
PALS: Reference – Leak-Location Distance – ft	233.1 ft
Actual: Reference – Leak-Location Distance – ft	233.5 ft
PALS: Error: Reference – Leak-Location Distance – ft	0.4 ft
PALS: Reference – Leak-Location Distance - % of Ref-Pos Distance	0.10%

2.1.5.2 <u>Impulsive Algorithm</u>

If the leak signal has impulsive characteristics, then it can be located by setting a threshold that identifies the leading edge of the impulsive signal in the time domain. The relative time of arrival of these leak signals is used to compute the velocity and location of the leak using Eqs. (B-3) and (B-4) given in Appendix B of the Final Report [18].

2.2 PROCESS DESCRIPTION

2.2.1 Mobilization

The PALS system is portable and easily transported to a measurement site. The PALS is stored in a special case that can be carried or rolled by one person. The computer and accessories, sensors, pre-amps, cable connection box and short sections of cable, and sensor attachment material (epoxy, scrapers, files, batteries) fit into this case. A second case with three 500-ft lengths of cable and additional cable/cable extensions are packaged in either a separate case or in reels.

2.2.2 Test Set-Up

The PALS system can be set up in less than an hour. This set-up time includes the system checkout and placement of the three acoustic sensors on the pipe. This assumes that there is access to the line without having to excavate a pothole. Based on the results of these ESTCP DEM/VALs, it has been determined that the sensors can also be placed on circular ends of the flanges connecting two pipe sections, which is helpful if the pipe is covered with insulation or protective material that should not be removed.

2.2.3 Precision and Accuracy

A detailed discussion of the precision and accuracy for the PALS is given in [1, 2] assuming that the noise is white random noise. Our field experience suggests that a 500-ensemble average is required for an accurate leak-location estimate.

2.2.4 Regulations

The UST regulations do not specify any requirements for leak location [3], only leak detection. However, the regulations do require that any environmental damage produced by the leak be remediated. In Subpart D of the UST regulations [16], all known or suspected releases must be reported in 24 h, and the appropriate corrective action must be taken as prescribed in Subpart F-Corrective Action for UST Systems Containing Petroleum. Reliable and accurate leak location is required to find these leaks and support the remediation efforts. Unlike tanks, which are generally replaced if a leak is found, pipelines are generally repaired and brought back into service. Thus, fast and accurate leak-location can minimize the clean-up costs and bring the line back into service quickly so there is minimal impact in terms of readiness and cost.

2.2.5 Training

A field technician with experience in operating computer-controlled equipment can learn to operate the system in less than a day. The physical set-up of the equipment and the methods for mounting the sensors on the pipe wall or flanges are straightforward. The system checkout and use of the software is also straightforward. The Graphical User Interface is nearly self explanatory. While the processing algorithms and displays are mathematically complex, there is no inherent need to understand the details of the algorithm. A field technician with the ability to recognize certain very well defined features or patterns in the data can be easily trained to operate the system. As a result of the DEM/VALs, the database of different leak signals and ambient background is sufficient for training purposes. The system could have been made more fully automated but this was not done because the operational experience gained during the DEM/VALs and future operation of the system is needed to make the automation robust.

2.2.6 Health and Safety

The PALS system is safe to use and poses no health risk to the user or the pipeline. The system requires 110 VAC power but can, and was, operated off of a generator during one of the DEM/VALs (Little Rock AFB). The main concern is not to over-pressurize the pipeline, but this is the same concern during normal pipeline transfer operations or when testing the line for leaks.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Passive acoustic systems have been used to locate leaks in underground district heating and cooling pipes [7]. In a set of field tests performed at the Argonne National Laboratory in the late 1980s, it was demonstrated that, by means of cross-correlation analysis, leaks of approximately 90 gal/h could be detected in a 4-in.-diameter, 85-ft-long pipe [7]. This capability was not good enough for application to pipe containing hazardous materials like petroleum products.

In 1991, Vista Research demonstrated the improvement in performance that can be realized for this technology by using a coherence signal-processing approach. This technology was successfully demonstrated on a 2-in.-diameter underground fuel pipeline at EPA's UST Test Apparatus in Edison, New Jersey [1-3]. A 100-fold improvement in performance (in terms of the size of the leak and the spacing between sensors) was realized vis-à-vis the traditional correlation analysis approach. Field tests on a 2-in.-diameter pipeline containing fuel, and pressurized to 30 psi, showed that, with a sensor spacing of 125 ft, leaks could be determined to within several ft of their actual locations. In 1995, Vista Research demonstrated a similar capability on a 100-ft, 6-in.-diameter pipe at EPA's Test Apparatus. Location estimates as small as 0.5 gal/h were made to within 6 in. [6]. The results of these early tests indicated that passive acoustics using coherence-based processing could be used to find leaks of environmental interest and was the basis for the previous SERDP project and the present ESTCP project.

As part of the SERDP project, a 12-in.-diameter, 1,015-ft underground pipeline was built (called the Navy Test Loop). This pipeline, one of several built as part of the SERDP Test Pipeline Facility (STPF) [6], was used to further develop the capability for locating leaks on bulk underground fuel lines. The main focus of this SERDP work was to evaluate an impulsive time-domain location approach. For this approach to work, bubbles created from entrained air (in the pipe or in the backfill) must be trapped in the immediate vicinity of the leak and must break. For leaks positioned at the top of the Navy Test Loop pipeline, leaks of 20 gal/h were located over distances of up to 200 ft. The presence of air occurred because of a large flow constriction in the pipe (produced by a flowmeter inserted into the pipe) downstream of the leak. In addition, all measurements were made on a section of pipe far removed from the ends or elbows. Some attenuation work was performed that indicated the loss in acoustic signal energy was 1 dB/m, which limited sensor spacing to between 150 and 200 ft. Experimental work performed on the location of the leak around the circumference of the pipe showed that the largest leak signals occurred with holes located at the top and bottom of the pipe and was weakest when the holes were located on the side of the pipe. Not enough work was accomplished to evaluate the use of coherence-based or correlation-based algorithms. The main conclusion was that these algorithms were not tested successfully but should be further investigated.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Beside visual evidence of a leak, leaks can be located using five general approaches: (1) passive-acoustics; (2) liquid tracer; (3) gas tracer; (4) cable system; and (5) excavation. Conventional acoustic systems are not generally used to locate fuel leaks because they do not have adequate performance due to a poor measurement approach and lack of adequate signal processing. Gas tracer methods, using helium or some other gas tracer, are not operationally attractive because all fuel must be removed before this method can be applied. There are two types of liquid-tracer methods, but the only liquid-tracer method that is viable releases a unique gas once the fuel is released into the ground. This latter method, offered commercially through Tracer Research Corporation, is currently the most frequently used method to locate leaks in pipelines; however, it is expensive and time-consuming to use, is subject to false alarms, and is not particularly suitable when the water table is high. Cable systems can be used if they were installed alongside the pipe before a leak occurs. These systems are expensive and have not received widespread use as either a leak-detection or leak-location system, because the system is easily damaged during installation and is subject to high rate of false alarms during use. Cable systems are mainly used only with double-wall piping. The most common method of leak location is excavation of the pipe. This is an expensive approach, but it is the approach most frequently used due to the failure of other technologies to accurately locate leaks.

While alternative technologies have been sought, until recently tracer methods have been the only viable solution. Passive acoustic methods offer the following advantages over tracer methods.

- Passive acoustic methods are less expensive to use that tracer methods.

- Passive acoustic methods can locate leaks with a much better accuracy than tracer methods, so the cost of excavation and the downtime during a repair can be reduced.

- Passive acoustic methods can locate a leak within minutes while a tracer system may take several days to several weeks. This reduces the cost of remediation and environmental damage.

- Passive acoustic methods can also be used for detection verification, and because it is a different technology than the technology used for detection (e.g., volumetric), it increases the overall reliability of the detection.

- The availability of acoustic methods for leak location allows less expensive methods than tracer methods of leak detection, like volumetric methods, to be used.

The passive acoustic technology offered in the PALS has the performance to find the location of pipeline leaks. The key system features are that the system:

- is easy to set up;

- has sufficient flexibility to address different pipeline and leak conditions;

- can be used to conduct a test in less than an hour;

- can be used regardless of the leak signal characteristics, and does not require an *a priori* knowledge of the leak signal characteristics or the propagation velocity;

- can be used under normal ambient noise conditions found at airfields, fuel farms, and with nearby vehicular traffic;

- can operate at sensor separation distances consistent with normal access points (over 500 ft); and

- has an accuracy of 1.5% of the sensor separation distance.

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3.0 DEMONSTRATION DESIGN

The design of the demonstration, and a description of the four demonstration sites are summarized below. Additional details can be found in the Demonstration Plan [17] and the Final Report [18].

3.1 PERFORMANCE OBJECTIVES

The objective of this ESTCP project was to demonstrate and validate (DEM/VAL) a passive acoustic leak-location system for verifying the presence of, and for locating, leaks in underground pressurized piping. The output of the project would be a portable, computer-notebook-controlled system that can easily be set up and operated in the field and is ready for commercialization. The DEM/VAL sites and the types and configuration of pipelines at these sites were selected to address the most commonly expected testing situations. Many important operational considerations, which were not addressed during the SERDP project, were specifically included as objectives in each of the DEM/VALs. Specific tests were performed at each of the four DEM/VAL sites to address these considerations. These tests were designed to:

- operate with sensor separation distance of 500 ft or more (SERDP tests were limited to separation distances of less than 200 ft);

- operate with sensors mounted on available access points near the ends of the pipe, on flanges and blinds, and on hydrant pits (SERDP work was performed on a simple pipe configuration);

- operate on real pipelines with complex configurations and a highly reflective environment (end reflections) (not evaluated during the SERDP project);

- operate in the presence of normal airfield and fuel farm background noise (not evaluated during the SERDP project); and

- use a signal processing algorithm that is insensitive to the type of leak signal present (the SERDP project focused on the impulsive signal).

The performance of the technology is not well established for the range of operational conditions for which the technology might be applied. Furthermore, there are no regulatory standards specifying the accuracy of a leak-location system. Since bulk pipelines are typically buried 3 to 6 ft below grade, excavation equipment, such as a back-hoe, is required to verify the presence of a leak. The performance objectives were established by the back-hoe excavation process and the expected performance of the technology. If a leak is located acoustically to within 10 to 20 ft of its actual location, a back-hoe could verify this in 1 to 2 hours.

The performance objective established for the DEM/VALs is ±3 ft for sensor separations of 200 ft or less and 3% of the sensor separation for separation distances longer than 200 ft. This objective applies for leak signals with a signal-to-noise ratio of 10 dB or more. For a sensor separation distance of 500 ft, the accuracy is +15 ft. This criterion covers the range of potential leaks that have occurred (from several tenths of a gallon per hour to many tens of gallons per hour). If a leak can be located to within this tolerance, it should be able to be found and repaired quickly.

3.2 SELECTION OF A TEST SITE/FACILITY

A site from each of the three of the military services (Air Force, Army, and Navy), and the SERDP Test Pipeline Facility (STPF) in Edison, New Jersey, were selected to demonstrate and validate the PALS on both bulk and hydrant fuel distribution lines. Before the DEM/VALs were conducted, the PALS hardware and software were checked out on a special test section of buried 2-in. diameter pipe installed at Vista Research's Sunnyvale facility. The DEM/VAL sites included:

- DEM/VAL Site 1: U.S. Navy's Construction Battalion Center (CBC), Port Hueneme, California,

- DEM/VAL Site 2: Little Rock Air Force Base (LRAFB), Little Rock, Arkansas,

- DEM/VAL Site 3: Navy Test Loop, SERDP PipelineTest Facility (STPF), Edison, New Jersey, and

- DEM/VAL Site 4: Campbell Army Airfield and the Sabre Army Heliport, Fort Campbell, Kentucky.

The sites were selected so that tests could be conducted on lines:

- supporting different military services, missions, facilities and types of pipelines;
- where a leak can be induced;
- that may actually have a leak;
- with different and realistic noise conditions; and
- with different pipeline configurations and appurtenances.

The Navy and SERDP sites were selected because the leak signal could be generated for different type of backfills and hole sizes. The Air Force and Army sites were selected because the PALS could be demonstrated on hydrant fuel distribution lines under operational background noise conditions. In particular, the Air Force site was selected because it was an operational training base with 24-hour aircraft operations and two of the hydrant lines, which had been removed from service, were believed to be leaking from previous tracer and pressure tests.

3.2.1 DEM/VAL Site 1: U.S. Navy CBC, Port Hueneme

The objectives of the Navy DEM/VAL conducted at CBC, Port Hueneme were to:

- verify and refine the hardware and software of the PALS on a bulk pipe;

- develop procedures for the best way to use the system; and

- determine the accuracy of locating leaks in a 10-in.-diameter, bulk, underground pipeline for different leak holes, backfills, lines pressures and sensor spacing.

3.2.2 DEM/VAL Site 2: Little Rock Air Force Base

The objectives of the DEM/VAL conducted at the Little Rock Air Force Base were to:

- locate an actual leak, if one existed, in an underground 6-in.-diameter hydrant pipe;
- determine if the system could be operated under actual operational airfield conditions at a busy training facility;
- determine if the system could be used on a hydrant line in which the sensors were mounted on a blind flange on the top of a vertical riser; and
- determine the maximum separation distance between sensors.

3.2.3 DEM/VAL Site 3: Navy Test Loop, SERDP Test Pipeline Facility

The objectives of this DEM/VAL conducted on Navy Test Loop at the SERDP Test Pipeline Facility were to determine the:

- accuracy of locating leaks in a 12-in.-diameter, underground bulk pipeline in a sand backfill;
- maximum separation distance between the two sensors bracketing the leak for a variety of holes sizes and leak rates; and
- accuracy of locating a leak using an acoustic sensor mounted on the end of the pipeline and on the top and side of a vertical riser.

3.2.4 DEM/VAL Site 4: Campbell Army Airfield and the Sabre Army Heliport

The objectives of the DEM/VAL conducted at Fort Campbell were to:

- locate an actual leak, if one existed, in underground hydrant pipe;
- determine if the system could be operated at an Army airfield and an Army heliport during normal operational flight-line conditions;
- determine if the system could be used on two different configurations of bulk fueling piping not encountered in the previous ESTCP DEM/VALs; and
- determine the accuracy and maximum separation distance between sensors.

3.3 SITE/FACILITY CHARACTERISTICS

DEM/VALs of the technology were conducted at the four selected sites. A brief description of each site is provided below. For more details, see the ESTCP Demonstration Plan [17].

3.3.1 DEM/VAL Site 1: U.S. Navy CBC, Port Hueneme

The first DEM/VAL was conducted on a bulk fuel pipeline at the U. S. Navy's Construction Battalion Center (CBC), Port Hueneme, California. The line is 10 in. in diameter and 457 ft in length. The line extends from a pump station, under a road and an asphalt-paved area, to a marine fueling pier. The line is over 50 years old and was taken out of service as part of a base program of decommissioning this fueling facility. The line is coated with a 0.75-in. layer of asphalt and is buried approximately 3 ft in a sand backfill. The steel under the asphalt is in excellent shape. The line was filled with water for the tests.

3.3.2 DEM/VAL Site 2: Little Rock Air Force Base

The second DEM/VAL was conducted on two (Line B and Line Z) of the thirty 1,000-ft, 6-in.-diameter hydrant fueling pipes located under the apron of the operational flight line at the Little Rock Air Force Base (LRAFB), Little Rock, Arkansas. The LRAFB is the home of the 314th Airlift Wing and is the only C-130 training base for the Department of Defense (DOD). Flight operations occur 24 h a day. In addition to C-130s, jets (e.g., F-14s and F18s) and other aircraft also use the airfield. These hydrant feeder lines are used to fuel the aircraft on a 2-mile by 0.25 mile 18-in.-thick concrete apron. Fuel is obtained from the main hydrant distribution pipe that transfers fuel approximately 2 miles from an aboveground storage tank facility to several pumping stations where fuel is temporarily stored in 50,000-gal USTs. The aircraft are fueled from the 50,000-gal USTs through the 30 hydrant fuel lines.

The two hydrant feeder lines tested had been taken out of service, because they were suspected of leaking. There are six hydrant pits along each line at intervals of 140 ft. Sensors could be placed on either line at any of these hydrant fueling pits. The lines were filled with water and pressurized to 100 psi for the leak-location tests. The tests were conducted during routine flight operations for 50 C-130 aircraft. These operations occurred continuously throughout the day and night.

3.3.3 DEM/VAL Site 3: Navy Test Loop, SERDP Test Pipeline Facility

The Navy Test Loop at the SERDP Test Pipeline Facility was used in the third DEM/VAL. The Navy Test Loop, located at the U. S. Environmental Protection Agency (EPA) site in Edison, New Jersey, is 12 in. in diameter and 1,015 ft in length. It was filled with water from a water hydrant for these tests. The pipe was buried between 3 and 5 ft in a sandy soil. All tests were conducted at a pressure of 70 psi or less. Ten different sensor separation distances, ranging from 135 to 1,015 ft, were used in the DEM/VALs. Three potholes were dug along the line to install sensors on the line. A fourth pothole had already been dug along the line and was the location of the leak holes. The line also contained over ten 2-in.-diameter access holes to the top of the pipe. Tests were conducted using sensors at the both the potholes and the standard access points.

3.3.4 DEM/VAL Site 4: Campbell Army Airfield and the Sabre Army Heliport

The fourth and final DEM/VAL was conducted on two different types of hydrant fueling systems at Fort Campbell, Kentucky. The first set of tests were conducted on a 550-ft segment of 8-in.-diameter bulk pipe that was part of the Campbell Army Airfield hydrant fueling system, while the second set of tests were conducted on a 2,300-ft loop of 4-in.-diameter aluminum piping at the

Sabre Army Heliport. There was fuel in both lines during the testing, and both were pressurized to 70 psi. Flight operations were very light at both sites during the acoustic measurement periods. The aluminum piping at the Sabre Army Heliport was covered with a protective coating, so the sensors were mounted on ends of the flanges.

3.4 PHYSICAL SET-UP AND OPERATION

Four DEM/VALs were planned and conducted to address the objectives presented in Section 3.2. In each DEM/VAL, the line was pressurized with the volumetric measurement shown in Figure 3. This volumetric system, which is a prototype of the Vista LT-100 leak detection system, is capable of keeping the line at constant pressure and measuring the total volume and leak rate to a leak point [28, 29]. The system was attached at one end of the line, and the tests were performed with pressures ranging from 0 to over 150 psi were used and leaks ranging from 0 to over 20 gal/h. A detailed description of, and a figure illustrating, the configuration of each of the pipelines used in the DEM/VALs are given in Appendix C of the Final Report [18].

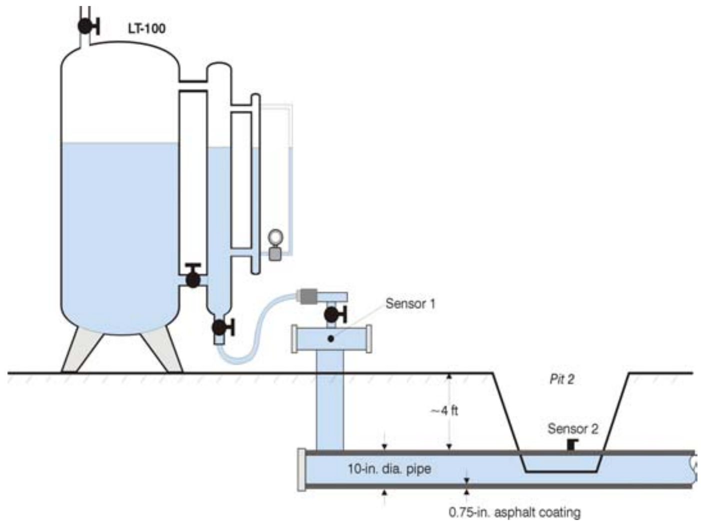

Figure 3. Schematic of the Constant-Pressure, Volumetric Leak Detection System.

3.5 SAMPLING/MONITORING PROCEDURES

The same measurement approach was generally followed during each DEM/VAL.

- Step 1: Determine the integrity of the line to be used in the DEM/VAL with the volumetric measurement system.
- Step 2: If the line is found to be tight, use the acoustic measurement geometries developed to address the DEM/VAL objectives at that site and attach acoustic sensors to the line with epoxy.
- Step 3: Conduct one or more sets of leak-location tests to address these specific objectives. These tests should be performed under the full range of ambient noise conditions present.
- Step 4: If a leak is determined to be present, add acoustic sensors to the line to locate the leak.
- Step 5: Once a location estimate is made, excavate to uncover leaking the pipe section.
- Step 6: Isolate and contain the leak.

- Step 7: If possible, before repairing the line, conduct additional tests with different sensor separations bracketing the leak to determine the maximum separation distance for an actual leak.

The acoustic measurement configurations on each of the DEM/VAL pipelines at each site are described in detail in the Final Report [18]. Different measurement configurations were implemented at each site, as necessary, to address the specific test objectives given in Section 3.2. Each acoustic data set lasted between 1 minute and 30 minutes. A header file created as part of the data collection process archived the important aspects of the test.

3.6 ANALYTICAL PROCEDURES

The acoustic data obtained during the DEM/VALs were analyzed using the leak-location algorithms described in Appendix B of the Final Report [18].

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

At least 25 to 50 or more acoustic tests were performed during each of the four DEM/VALs. These acoustic data files were archived for additional post-test analyses. Many of the test runs conducted during each DEM/VAL (defined in terms of sensor geometries, leak position, hole size, line pressure, flow rate, backfill and ambient noise conditions) were repeated one or more times to assess repeatability of the measurement and the impact of changing background noise. The test conditions are described in Appendix C of the Final Report [18]. The test results of some of the important and most illustrative test results are also presented and described below in Section 4.3.

4.2 PERFORMANCE CRITERIA

As stated in Section 3.1, the performance criterion in terms of location accuracy was based on the expected performance of the technology as determined in previous acoustic test results (e.g., SERDP and EPA) and the size of the excavation area required to safely uncover buried pipe 4 to 6 ft below grade. The performance of the technology at the start of the DEM/VALs was not well established. As a consequence, it was assumed that the technology should be able to find leaks in pipelines less than 200 ft to within 3 ft and for longer pipelines to within 3% of the separation distance for the two sensors bracketing a suspected leak. Given the capabilities of a backhoe operator to uncover a buried pipe over a period of 2 hours or less, location estimates made to within 10 to 20 ft of the actual leak location were considered successful.

4.3 DATA ASSESSMENT

A brief summary of the test results, main conclusions, and recommendations from each of the four test sites are presented below and are described more fully in the Final Report [18]. Examples of typical results from each DEM/VAL are included in the appendices to the Final Report [18]. The specific tests and test emphasis during each DEM/VAL depended in part on the measurement applications successfully completed during the previous DEM/VALs.

4.3.1 DEM/VAL Site 1: U.S. Navy CBC, Port Hueneme

Three types of acoustic tests using the PALS were conducted: (1) system checkout tests; (2) leak tests; and (3) simulated leak tests. These tests were conducted to address the DEM/VAL objectives listed in Section 3.2.1.

Simulated impulsive signal leak-location test. A 10-in. crescent wrench was used to hit the top of the pipe to create an impulsive calibration signal. Hitting the top of the pipe with a crescent wrench simulated the impulsive signal produced by bubbles breaking in the backfill. (The impulsive calibration signal was used to verify the functionality of the software because there was no evidence of the presence of any impulsive leak signals produced through a hole in the pipe, even when a leak was generated through a hole in the top of the pipe.) Each impulsive signal was qualified (using a no-impulse window signal processing technique) to insure that there was an extremely high probability that the threshold exceedance is from the same impulsive leak signal (or in this case, hitting event). The position and velocity were determined from the histogram with the most hits.

As summarized in Table 2, the PALS located the simulated leak at 29.7 ft using a measured velocity of 1,439 m/s. The actual position of the simulated leak was 28.7 ft. An error of 1 ft in the measured configuration was easily possible due to the curvature in the 90-degrees bends were not included in the actual measurement of the pipe distance.

Ambient background acoustic noise. A leak-location test was conducted without the presence of a leak in the pipe to examine the ambient background noise. The coherence (and correlation) function indicated that there were no coherent sources of noise to interfere with the leak-location measurements. Throughout the entire frequency band, the coherence was nearly zero. In practice, this background noise can always be found by reducing the pipeline pressure to zero-an inherent advantage of the acoustic method.

Leak test results. (Only the coherence algorithm was operational during these tests; the correlation function was added to the program after the completion of these tests.) Artificially induced leak tests were conducted using a 0.01-in.-diameter leak hole at pressures ranging from 30 to 175 psi and leaks ranging from 1 to 4 gal/h. The output from one of the tests is summarized in Table 2 for a 2-minute test conducted at 105 psi. The PALS measured the position of the 3.0-gal/h leak to be 17.05 ft using a measured velocity of 1,140 m/s. The actual position of the leak was 17.1 ft. The position and velocity were determined using the 12.9 to 17.3 kHz frequency band where the signal was strong and the phase was linear. The use of the measured velocity is important, because the propagation is complex and the velocity can change for different propagation modes.

Table 2. Results of Two PALS Tests for Induced Leaks through a 0.01-in.-Diameter Hole on the CBC Port Hueneme Bulk Pipeline.

Measurement	PALS Test Results (2-3-4): 042400 1044 0.01-in. hole at 100 psi	PALS Test Results (3-4-6): 080800 1800 0.01-in. hole at 100 psi
For Configurations (see Figures in Appendix C of the Final Report [18])	Figure C-4	Figure C-3
Reference - Position Sensor Separation Distance -ft	18.1 ft	123.7 ft
Reference - Velocity Sensor Separation Distance - ft	34.3 ft	34.3 ft
Velocity - m/s	1,140 m/s	1,433 m/s
PALS: Reference - Leak Location - ft	17.05 ft	30.0 ft
Actual: Reference - Leak Location - ft	17.10 ft	28.7 ft
PALS: Error: Reference - Leak Location - ft	0.05 ft	1.3 ft
PALS: Reference - Leak Location - % of Ref-Pos Distance	1.6 %	1.0 %

Another leak test summarized in Table 4 was conducted with a 123.7-ft and are shown in Figure D-2, and separation distance between the Ref and Pos sensors, which were placed in a different configuration. The leak was produced at pressure of 30 psi using a 0.01-in. into a pea gravel backfill. The leak rate was over 10 gal/h. The analysis was performed between 9.5 and 13.4 kHz. Both the coherence and correlation analyses estimated the leak to be 30 ft from the Reference, which is an error of 1.3 ft.

Simulated continuous signal leak test results. As part of this DEM/VAL, a number of ways of producing a simulated leak signal were investigated to develop a simple method of verifying the functionality of the PALS before its use and to produce a leak signal during the future DEM/VALs if the lines tested did not contain a leak. A large and a small leak signal were simulated by lightly rubbing a 0.75-in. cold chisel and a 3/32-in. jeweler's screwdriver on the pipe wall. The rubbing produces a random signal that is similar to the response of a leak. It was found that when the signal, produced by either the cold chisel or the jeweler's screw drive, could be accurately detected and located, a leak through a 0.01-in. hole could also be successfully detected and located. As a consequence, successful tests with these simulated leak signals were prognosticators of successful tests on a line with a small leak and could be used for system checkout during future DEM/VAL testing. Examples are given in the next three DEM/VALs.

Summary. The DEM/VALs conducted on the CBC line at Port Hueneme, California, over an extended period of time were successful in verifying the functionality of the hardware and software of the PALS. These tests also provided the first opportunity to demonstrate the capability of the system for locating a leak. The PALS accurately located leaks (1 to 3 ft) in two pipeline configurations with the spacing between acoustic sensors mounted directly on the pipe being 18.1 and 123.7 ft. The leaks were produced using 0.01- and 0.04-in. diameter holes with pressure between 30 and 175 psi. The leak signals produced in a pea gravel backfill were stronger than the leak signals produced in a sand backfill. It was noted that the signal strength decreased as the sand backfill became fully saturated.

This first DEM/VAL demonstrated that the system works and how it should be used. This first DEM/VAL also helped establish and refine the objectives of the next three DEM/VALs. For the system to be operationally useful, the performance of the system must be demonstrated:

- on a variety of pipelines with different configurations and realistic ambient noise conditions,
- when at least one of the sensors is located near or on the end of a pipe,
- when at least one of the sensors is located on a vertical riser from the pipe, and
- over longer distances typical of available access points (e.g. 500 to 700 ft between hydrant and valve pits).

4.3.2 DEM/VAL Site 2: Little Rock Air Force Base

The test matrix for this DEM/VAL was designed to address the DEM/VAL objectives listed in Section 3.2.2. The DEM/VAL at the Little Rock Air Force Base provided the first opportunity to use the PALS system on a hydrant line and under actual operational airfield conditions. It was not known how well the PALS system would perform under the loud noise conditions found on the flight line and with the acoustic sensors attached to vertical risers (and not directly to a straight run of pipe).

Two types of tests were conducted on each line: (1) volumetric leak-detection tests and (2) acoustic leak-location tests. The results of these tests are described below.

Volumetric leak-detection test results. Each line was checked for leaks using the volumetric measurement system shown in Figure 3. An actual leak-detection test was not performed with the system. However, a series of manual volumetric readings were made with the system to determine if a leak existed in the line that was large enough to be located with the PALS system. While the volumetric measurements did not indicate the presence of a leak on either line, it is still possible that one or both lines actually had one or more holes, and debris in the lines filled the hole(s) and prevented any outflow. The volumetric measurements indicated that if a leak were present it would be smaller than 0.05 gal/h.

Ambient background acoustic noise. Since neither Line B nor Z was leaking, background tests were conducted with the line under pressure. Background tests were performed under normal flight-line operations, when C-130s, F-14s and other aircraft were nearby or moving past the test configuration, during takeoff and landings of C-130s and other aircraft, and with our generator and the flight-line generators working in the immediate vicinity of the test configuration. The background noise, which did not interfere with the simulated leak measurements, was mainly confined to low frequencies (less than 3 kHz). The lower than expected impact of the background noise was probably due to the fact that the manway covers on each hydrant pit were closed during the measurements.

Simulated continuous signal leak-location test results. Since both lines were not leaking, a series of scratch tests were performed to simulate a small leak using a small jeweler's screwdriver that was lightly rubbed on each top of the hydrant blind flanges of Line B. The acoustic tests were conducted by mounting the acoustic sensors directly on the top of the vertical riser in the hydrant pit. The volumetric measurement system was used to set and maintain a constant pressure on the line during these tests. The distance between the Reference sensor and the Position sensor was 136.0 ft. Because of the high airplane and generator noise on the flight line, the noise produced by this scraping could not be heard by the person doing the scraping even though is was clearly identified in the PALS data.

Table 3 summarizes the results for a simulated leak located 2 in. away from the Position sensor on Line B. The measured acoustic location of 138.3 ft was within 2.3 ft (1.7%) of the actual distance between the Reference sensor and the simulated leak. The magnitude squared of the coherence function in the frequency band where the leak signal was present (500 to 1,600 Hz) was greater than 0.40, and the magnitude squared of the coherence function of the ambient noise outside this frequency band was generally less than 0.02, which indicates that the signal-to-noise (SNR) ratio of the signal was very strong. The position and velocity were determined from the linear phase relationship for the frequency band.

A number of other simulated leak tests were performed to determine what the maximum separation distance between sensors could be for line B. Since the Reference and Position sensors need to bracket the leak (or simulated leak) to estimate the position, the ability to operate the system was judged from the magnitude and phase of the coherence function and the velocity estimates made with the PALS. The simulated leak signal at Hydrant Pit No.1, with a separation distance between the leak (located 2-in. from the Position sensor) and the Position sensors of 693.6 ft, indicated that the signal was strong and the system could be operated at longer distances. Because the simulated leak was not bracketed by the Reference and Position sensors, only the velocity could be measured (as a negative number). As shown in Table 4, agreement between the measured velocity for the

Table 3. Simulated Leak Signal Test on Line B of the LRAFB Hydrant Piping.

Measurement	PALS Test Results Line B 080900 0728
For Configuration (see Figure in Appendix C of the Final Report [18])	Figure C-5
Reference - Position Sensor Separation Distance - ft	136.0 ft
Reference - Velocity Sensor Separation Distance - ft	136.2 ft
Velocity - m/s	m/s
PALS: Reference - Leak Location - ft	138.3 ft
Actual: Reference - Leak Location - ft	135.8 ft
PALS: Error: Reference - Leak Location - ft	2.1 ft
PALS: Reference - Leak Location - % of Ref-Pos Distance	1.5 %

Reference-Velocity sensors (1,327 m/s) and the Reference-Position sensors (1,331 m/s) was within 0.3%. The correlation estimate made using the Reference and Velocity sensors was 1,352 m/s. Similar results were found when the leak was simulated at Pits 2, 3, and 4.

Table 4. Simulated Leak Signal Velocity Test on Line B of the LRAFB Hydrant Piping.

Measurement	PALS Test Results Line B 080900 0813
For Configuration (see Figure in Appendix C of the Final Report [18])	Figure C-6
Reference - Position Sensor Separation Distance - ft	551.6 ft
Reference - Velocity Sensor Separation Distance - ft	136.0 ft
Velocity: Reference - Position - m/s	1,331 m/s
Velocity: Reference - Velocity - m/s	1,331 m/s
Velocity Error - ft	4 ft
Velocity Error: - % of Ref-Pos Distance	0.3%

Summary. The DEM/VAL was highly successful, and a number of very important results were derived from these tests. First, the PALS was able to consistently locate the simulated leak to within several ft of their actual location with sensors located at each hydrant pit. The performance was similar to tests previously conducted when the sensors were mounted directly on the pipe along a straight section of piping. Second, the PALS worked under the high and realistic noise conditions found at the airfield during normal flight operations. This is significant because it suggests that the acoustic system can be used at an airfield to locate leaks without shutting down the airfield. More tests are required to validate this observation. Third, the PALS worked with the sensors mounted directly onto the top of the vertical riser pipe in the hydrant pit. This is significant because it was the first time that sensors were mounted on vertical risers and at the end or termination points of the line. Fourth, the equipment was easy to set up and use. On the Line B, the equipment was set up and removed from the hydrant pits, and 11 leak-location tests were conducted in less than two hours. Fifth, the tests showed that the simulated leaks could easily be detected at distances over 700 ft, which was the maximum distance between the first and last hydrant pit. This result is very important because such distances are required to make this a useful tool that does not require significant excavation to use.

4.3.3 DEM/VAL Site 3: Navy Test Loop, SERDP Test Pipeline Facility

The test matrix was designed to address the DEM/VAL objectives listed in Section 3.2.3.

Volumetric leak detection test results. As in previous DEM/VALs, the volumetric system shown in Figure 3 was used to check the integrity of the line. The volumetric measurements indicated the presence of a small leak in the line due to a poorly sealed plug (previous location of a leak plug) and subsequently verified that it had been successfully repaired before the PALS tests were conducted. The volumetric system was connected to the line at the vertical riser on the inlet side of the line.

Leak test results. A large number of leak-location tests under controlled conditions were conducted on the pipeline using four sensor pipeline test configurations. All of the analyses were performed using the horizontal distances measured between the sensors and the leak. The results of the leak-location tests are summarized in Table 5. In addition, background tests and simulated leak tests were also conducted. The background tests were conducted on a nonleaking line to determine the presence of any local sources of noise. None were identified and the output of the coherence function was very similar to the one shown in Figure 2.

The results of a 10-gal/h leak test with a 0.04-in. leak plug are summarized in Table 5. This test result is representative of the best performance achieved during the DEM/VAL, whereby performance is judged in terms of the maximum separation distance between the Reference and Position sensors that can be obtained with a high degree of accuracy. The separation distance between the Reference and Position sensors was 516.5 ft. In addition to the long distance, one of the sensors (Reference) was mounted on the end of the pipe, and the other sensor (Position) was located around a 90-degree bend in the pipe. The position measured with the PALS was 236.4 ft, and the actual position was 233.5 ft. The leak position was determined using the measured velocity of 1,442 m/s. The error is 2.9 ft or 0.6% of the separation distance between the Reference sensor and the Position sensor. The output of the coherence function for both the Reference and Position sensors and the Reference and Velocity sensors showed high coherence (magnitude squared was greater than 0.5) and the linear phase was in the region of high coherence. The analysis was performed for the frequency band between 11.9 and 15.7 kHz. The output of the correlation analysis placed the leak at 237 ft. The position and velocity estimates were made using the time delay of the strong peak in each correlation function.

In general, identical results for both the coherence and correlation results are expected when the acoustic data are analyzed using the frequency band determined by the coherence function. If there is more than one leak, or if there are multiple reflections of the acoustic signal, then the correlation function should be used, because it separates the signals in time. It should be emphasized that the correlation function only gives accurate results once the signal band with the strongest signal and linear phase is determined by the coherence function.

Table 5 summarizes the results for a 2.5-gal/h leak through a 0.01-in. diameter hole at a line pressure of 70 psi into a saturated, sand backfill. The separation distance between the Reference and Position sensors is 159.5 ft. The position measured with the PALS was 231.8 ft, and the actual position was 233.5 ft. The leak position was estimated using the measured velocity of 1,394 m/s. The error is

1.7 ft or 0.7%. The analysis was performed for the frequency band between 12.9 and 13.9 kHz. The output of the correlation analysis placed the leak at 235 ft. Similar results were obtained over longer distances when the Position sensors were mounted on the line in the special access points (where the separation distance between the Reference and Position sensors ranged from 188.2 to 432.2 ft).

Also summarized in Table 5 are the results for a free jet of water through the 0.01-in.-diameter hole at 70 psi. The signal is weaker and more limited in frequency content than the acoustic signals produced into a backfill at a sensor spacing that is greater than 159.5 ft.

Table 5. Simulated and Leak Tests Conducted on the STPF Navy Test Loop.

Measurement	PALS Test Results 0.04-in. Hole 10.3 gph 081600 1256	PALS Test Results 0.01-in. Hole 2.5 gal/h 081500 1858	PALS Test Results Scratch 081500 1622	PALS Test Results Free Jet 0.01-in. Hole 1.9 gal/h 081500 1521
For Configurations (see Figures in Appendix C of the Final Report [18])	Figure C-11	Figure C-10	Figure C-10	Figure C-8
Reference - Position Sensor Separation Distance - ft	516.5 ft	360.0 ft	360.0 ft	159.5 ft
Reference - Velocity Sensor Separation Distance - ft	137.3 ft	137.3 ft	137.3 ft	63.2 ft
Velocity - m/s	1,442 m/s	1,394 m/s	1,389 m/s	1,847 m/s
PALS: Reference - Leak Location - ft	236.4 ft	231.8 ft	234.8 ft	34.5 ft
Actual: Reference - Leak Location - ft	233.5 ft	233.5 ft	233.5 ft	33.0 ft
PALS: Error: Reference - Leak Location - ft	2.9 ft	1.7 ft	1.3 ft	1.5 ft
PALS: Reference - Leak Location - % of Ref-Pos	0.6 %	0.7 %	0.4 %	0.9 %

At times, more than one run was made on the same test configuration at several different points in time to verify that similar results would be obtained. Similar performance was obtained for the different sensor/pipeline configurations and leak sizes.

The accuracy of the PALS system for 19 tests is summarized in Table 6 and is approximately 1% of the separation distance between the Reference and Position sensor bracketing the leak. The average error for these tests is about 3 ft over distances that ranged from 159.5 to 516.5 ft. In general, the accuracy of the test results ranged between 0.5% and 2.5% of the spacing between the Reference and Position sensors.

Table 6. Summary of the Accuracy of the Leak-Location Test Results Conducted at the STPF.

	PALS Location Error (Ft)	PALS Location Error (% of Sensor Separation)
Average	3.10	1.10
Median	2.65	0.80
Standard Deviation	2.02	0.77

Simulated continuous signal leak-location test results. Table 5 also summarizes the results of a simulated leak produced by scratching the pipe with a jeweler's screwdriver for the same sensor configuration and leak location as conducted for the 0.01-in.-diameter hole. The simulated leak was found to within 1.3 ft or 0.4% of the 360.0-ft sensor separation. The coherence function for the Reference and Position sensors is somewhat weaker than that obtained for the test for the 0.01-in.-diameter EPA leak plugs in the line at 1.9 gal/h and 2.5 gal/h and for the 0.04-in.-diameter EPA leak plug at 10.3 gal/h. This is important, because this was the only type of leak signal that could be generated in the LRAFB DEM/VAL.

Summary of the results. The DEM/VAL was highly successful, and a number of very important results were derived from these tests. First, we were informed that the PALS was the first commercial acoustic leak-location system to successfully locate leaks in the STPF pipeline. Second, leaks were located to within 1.0% or 3 ft at separation distances between the two sensors bracketing the leak up to 516.5 ft. Leaks were generated with a 0.01- and 0.04-in.-diameter holes into a sand backfill at a pressure of 70 psi. The leaks ranged from 2 to 3 gal/h for the 0.01-in. leak hole to 10 and 16 gal/h for the 0.04-in. leak hole. Third, the PALS worked with one of the sensors mounted on the end and side of the vertical riser at the end of the pipe. The leak signal was stronger when the sensor was mounted on the end plate as compared to the side of the pipe. Fourth, random, continuous leak signals could be produced by lightly rubbing a jeweler's screwdriver or a cold chisel on the pipe. These simulated signals were weaker than the actual leak signals produced with the EPA leak plugs. Fifth, the maximum distance obtained in these tests was 516.5 ft. The strong leak signals present in the data obtained at this distance suggested that the PALS could have been successfully operated over longer distances. Sixth, the PALS measures the velocity to use for measuring the position of the leak with regard to the Reference sensor. This is important because the propagation velocity changes as a function of frequency band and is not necessarily the theoretical propagation velocity for the liquid in the pipe. The propagation velocities ranged from 1,100 to 1,900 m/s. Seventh, a combination of the coherence and correlation analysis algorithms were used for all of the analyses. The approach requires no special a priori knowledge of the signal or its propagation mode. The coherence analysis is first used to determine the presence of the leak-signal frequency band to be used in the coherence and correlation analysis. When reflections were present, the correlation analysis produced the most accurate results. Otherwise, as expected, both types of analyses gave similar results. Eighth, the leak and simulated leak produced the strongest response in the frequency band between 10 and 20 kHz. This signal was present for all tests for which a leak was located. For some of the tests, a strong signal was produced between 500 and 1,500 Hz and between 2 and 4 kHz. Ninth, the data collection period for each test was between 1 and 2 minutes. While this was sufficient for a first estimate, longer integration times (e.g. 10 to 20 minutes) produced better results. Thus, once a leak is first located, it is recommended that a test longer than 1 or 2 minutes be performed.

4.3.4 DEM/VAL Site 4: Campbell Army Airfield and the Sabre Army Heliport

The test matrix for this DEM/VAL was designed to address the DEM/VAL objectives listed in Section 3.2.4. The DEM/VAL at Fort Campbell provided the opportunity to use the PALS system on two pipeline configurations not encountered in previous DEM/VALS. These additional pipeline configurations are important, because vertical risers and complex termination conditions, comprising elbows and tees, tend to degrade the performance of acoustic leak-location systems. In addition, the tests at the Sabre Army Heliport provided the first opportunity to tests the PALS on an aluminum hydrant pipe. Tests were not initially planned on the heliport hydrant line, but permission was obtained to use the line during a 4-h window on 26 October 2000. This was also the first DEM/VAL in which the PALS was used to test the line with fuel (not water) in the line. Except for the propagation velocity differences there did not appear to be any performance difference that could be attributed to the type of liquid in the pipe.

Volumetric leak-detection measurements. The 800-ft section of hydrant piping at Pumphouse 1 of the Campbell Army Airfield was checked for leaks using the volumetric measurement system shown in Figures 3. The volumetric system was connected to the line at Valve Pit 2. In this case, the volumetric measurements made over a period of 3 hours, at a constant pressure of 69 psi, showed no indication of any outflow. The volumetric measurement results indicated that even if a leak was present in the line, the leak would be too small (less than 0.01 gal/h) to be located with the PALS system. There was not enough time to test the hydrant line at the Sabre Army Heliport for leaks and only PALS measurements were made.

Sabre Army Heliport: Simulated continuous signal leak test results. It was very fortunate that the DEM/VAL included measurements on the heliport hydrant line because several very interesting results were obtained. One or more of the sensors was mounted on the ends of the flanges connecting two pipes together. Prior to this test, it was not known whether or not mounting the sensors on the ends of the flanges, instead of the pipe well itself, would degrade the response of the system. In the ambient response of the PALS with no simulated leak present, the response of the circulation pump was seen in the coherence function for frequencies less than 500 Hz. Table 7 summarizes the response of the PALS to a simulated leak 9 in. away from the Pos sensor and 175.5 ft from the Ref sensor. The position of the simulated leak measured with the PALS was 175.7 versus its actual position of 175.5 ft.

Table 7. Simulated Leak Signal Tests on the Sabre Army Heliport Hydrant Line.

Measurement	PALS Test Results Scratch 102600 1146	PALS Test Results Scratch 102600 1139
For Configurations (see Figures in Appendix C of the Final Report [18])	Figure C-14	Figure C-15
Reference - Position Sensor Separation Distance - ft	414.0 ft	414.0 ft
Reference - Velocity Sensor Separation Distance - ft	176.3 ft	176.3 ft
Velocity - m/s	m/s	m/s
PALS: Reference - Leak Location - ft	175.7 ft	66.9 ft
Actual: Reference - Leak Location - ft	175.5 ft	64.0 ft
PALS: Error: Reference - Leak Location - ft	0.2 ft	2.9 ft
PALS: Reference - Leak Location - % of Ref-Pos Distance	0.1 %	0.7 %

The response of the PALS over the full 590 ft was excellent as shown by the strength of the magnitude of the coherence function and the linearity of the phase for both sensor pairs. For the correlation function, the measured position of 180 ft was not as good as the coherence estimate because the peak of the correlation function was broad.

Table 7 also summarizes the response of the PALS to a simulated leak on the 2-in.-diameter riser. The position of the simulated leak measured with the PALS was 66.9 ft. The distance between the simulated leak and the Ref sensor was 94 ft. However, the distance between the Ref sensor and the location of the tee in which the leak signal enters the main pipeline being tested was 64 ft. This is an important result because it indicates that additional measurements are required to locate the position of any leak not on the main line being tested. The PALS measured position is within 2.9 ft (0.7% of the 414 ft between the Ref and Pos sensor).

Campbell Army Airfield: Simulated continuous signal leak-location test results. This piping geometry was more complex than the piping encountered in any of the other DEM/VALs and provided a good opportunity to evaluate the performance of the PALS under these piping conditions. The bulk piping in Valve Pits 1, 2, and 3 was complex because the pipe entering pits 1 and 3 have two 90-degree elbows and a valve termination, and the pipe entering pit 2 has a tee, a 90-degree elbow and a valve termination.

This piping geometry produced many acoustic reflections, which degraded the quality of the acoustic leak signal. This highly reflective environment can be observed in the output of the correlation function (Figure H-1). Table 8 summarizes the best response of the PALS obtained with the simulated leak signal generated with a cold chisel 1.8 ft from the Reference sensor.

Table 8. Simulated Leak Signal on the Campbell Army Airfield Hydrant Line.

Measurement	PALS Test Results Scratch (Val Pit 3-2-1) 102400 1729
For Configuration (see Figure in Appendix C of the Final Report [18])	Figure C-12
Reference - Position Sensor Separation Distance - ft	280.0 ft
Reference - Velocity Sensor Separation Distance - ft	280.0 ft
Velocity - m/s	1,358 m/s
PALS: Reference - Leak Location - ft	1.3 ft
Actual: Reference - Leak Location - ft	1.8 ft
PALS: Error: Reference - Leak Location - ft	0.5 ft
PALS: Reference - Leak Location - % of Ref-Pos Distance	0.2 %

The presence of a simulated leak signal in the magnitude-squared display was obvious, but the phase was not sufficiently stable to make reliable estimates, and none would have been reported for this test. While the location error was only 0.5 ft for the frequency band 1.6 to 1.8 Hz, small changes in the frequency band dramatically changed the result. Averaging over a longer period of time might improve the reliability of the result. For this pipeline configuration, moving the sensors away from the termination points on the pipe test would have improved the results. Additional measurements were planned for the second day, but these were not made because of restricted opportunities to conduct tests on the hydrant line at the Sabre Army Heliport.

Summary of the results. The DEM/VAL was also highly successful. First, the PALS was able to consistently locate the simulated leak to within 1% of the separation distance between the Ref and Pos sensors on the Sabre Army Heliport hydrant line. The tests also indicated that the acoustic system could locate leaks at distances of more than 600 ft. The strength of the simulated leak signals on the heliport line was so strong that similar performance would be expected on a line that was several hundred ft longer. The strength of the acoustic signals on the heliport line was much stronger than at the airfield line. The reason for this is not known but is probably due to reflections from the elbows and tee at the ends of the pipe in each valve pit. Second, the PALS worked under the operational noise conditions found at the airfield and the heliport during normal flight operations. The accuracy and separation distances achieved with the PALS in this DEM/VAL is consistent with the previous measurements made during the other DEM/VALs of the system.

As in previous DEM/VALs, a number of new and very significant results were derived. First, two of the three acoustic sensors used by the PALS on the heliport line were mounted on the ends of the flanges connecting two sections of the pipeline and not directly on the wall of the pipe. Although no direct comparisons were made with a sensor mounted on the pipe and a sensor mounted on the flange, the response of the flange-mounted sensors were excellent. This is significant because mounting the sensors on the flanges means that the coating on the pipe does not have to be removed to use the PALS. Second, if a leak occurs in a pipe section extending from the main pipe between the Ref and Pos sensors, its position will be output at the intersection of the two pipes. When this occurs, additional acoustic measurements are required on the pipe extension to find the location of the leak.

The acoustic leak-location tests conducted at the Campbell Army Airfield were not as successful as those conducted on the Sabre Army Heliport line. These tests highlighted the problems encountered when the sensors were attached near the ends of the pipe, when the ends of the pipe produce a highly reflective environment. While it was clear from a comparison of the magnitude of the coherence function for a background test and a simulated leak test that the leak signal was detected, the phase was not highly linear and there were generally too many peaks in the correlation function to determine a reliable location estimate. However, in one test, an exception is only one correlation peak was observed, and a reasonable estimate of the leak-location was obtained. More work needs to be done to better understand how to deal with end-reflections. The end-reflections would not have been a problem if the sensors could have been mounted 10 to 20 ft further away from the positions used in this DEM/VAL.

4.3.5 Summary of the DEM/VAL Results

In summary, the PALS was field-tested between April and October 2000 over a wide range of leak rates, backfill conditions, pipeline configurations and background noise conditions to demonstrate and validate the capability of the PALS for locating leaks on pipeline systems at operational facilities without impacting the conduct of operations. Each of the field tests provided different and realistic pipeline configurations representing operational conditions that could be encountered in the use of the PALS. None of the lines used in the DEM/VALs had real leaks (i.e., leaks due to a damaged pipeline), although several lines at one of the sites were taken out of service because of suspected leaks. All lines suspected of leaks were tested volumetrically prior to the start of the PALS measurements. Leak plugs, with holes 0.01 and 0.04 in. in diameter, were inserted into the pipes at two of the field sites, and leaks between 2 and 20 gal/h were generated for the tests. On lines that did not have leaks, leak signals were simulated by randomly rubbing a jeweler's screwdriver (or a small cold chisel) on the wall of the pipe.

An estimate of the performance of the PALS was made, based on demonstration and validation (DEM/VAL) field tests of the system on 4- to 10-in.-diameter bulk and hydrant fuel pipelines located at three military facilities, and on the 12-in.-diameter Navy Test Loop at the SERDP Test Pipeline at EPA's facility in Edison, New Jersey. The PALS achieved approximately the same degree of accuracy in all the field tests. For sensor separation distances less than 200 ft, its accuracy was within 3 ft. For longer sensor separation distances it was better than 1.5% of the distance.

In three of the field tests, the PALS was successfully and routinely operated at sensor separation distances of more than 500 ft. This is significant and makes the system operationally practical because it means that, for most bulk and hydrant lines, the sensors can be mounted on the pipe at available access points without the need for excavation. Prior to this ESTCP project, the largest separation distances obtained at the STPF during the SERDP program was 200 ft. It was also found that the sensors could be mounted on the ends or sides of a flange connection without sacrificing performance. This is important because it means that the pipe coating used for corrosion protection does not have to be removed in order to perform a leak-location test. It is also significant that the system was successfully deployed on the flight line of an Air Force base during routine operations.

There are still a number of questions to be answered before the technology is universally applicable. More tests are required to better estimate the maximum Reference-Position sensor spacing as a function of leak rate. More tests are also required to examine the performance when the sensors are attached to vertical risers that are composed of a number of sections of pipe of different diameters. Similarly, more tests are required on lines with more than one or two 90-degree bends. At the present time, it is not known how small a leak can be located, but the performance to date has been for leaks that are commonly encountered in the field.

4.4 TECHNOLOGY COMPARISON

There are passive acoustic leak-location systems that are commercially available. Some of these systems have been evaluated by the American Petroleum Institute (API). The results of these evaluations were poor, but they were not using the signal processing approach used by PALS. The systems were either not able to detect the leaks of interest or locate them accurately.

5.0 COST ASSESSMENT

This section summarizes the cost and cost savings achievable with the PALS for locating leaks in underground piping associated with hydrant fuel distribution systems, bulk storage tanks, and facilities. This section also compares the cost of the PALS to excavation, tracer and cable methods of leak location. The cost advantages of the PALS are realized because of the high performance of the PALS, its real-time output, and the low cost of using the system.

5.1 COST REPORTING

The normal activities involved in conducting a PALS test at an operational military facility are described below. An estimate of the amount of time associated with each of the DEM/VAL activities required to perform the PALS measurements is also provided. A two-person field crew was used in the testing. However, a single person is all that is required to implement the PALS.

Pre-DEM/VAL

(1) Pre-DEM/VAL review of the engineering drawings of the underground pipeline to identify access and sensor-measurement points.

DEM/VAL

(2) On-site operational meetings and briefings at the military facility to establish safety, access, badge requirements, escorting, operational procedures, site staff support, previous testing of the line, the test plan, the engineering drawings and the measurement work schedule (4 h).

(3) On-site inspection of the pipeline(s) to be tested and identification of the sensor measurement positions and the location for conducting a volumetric leak detection test (< 1 h).

(4) Volumetric leak detection test to determine whether or not the line has a leak (<4 h).

(5) Pre-test calibration of the functionality of the PALS system, installation of the acoustic sensors on the line, and measurement of the distances between sensors (< 1 h).

(6) PALS measurements to locate the position of the leak (1 to 2 h).

(7) On-site briefing of the test results (<1 h).

Post-DEM/VAL

(8) Post-test analysis and reporting.

Table 9 summarizes the approximate costs of the four DEM/VALs. The number of measurement days is shown in the table. A two-person technical staff made the PALS and volumetric pipeline measurements. The travel and the equipment shipping costs are included. The third person at the STPF ran the test facility. A third person at Fort Campbell supported the second set of pipeline tests. Based on these tests, it was concluded that a single person can set up and perform the PALS measurements.

Table 9. Summary of the Costs of the DEM/VALs.

DEM/VAL	Testing Days	Number of Technical Staff	Measurement Dates	Cost of the DEM/VAL
DEM/VAL 1: CBC Port Hueneme	5 days*	2	25-28 Apr 2000, 17 May 2000	$15,000
DEM/VAL 2: Little Rock Air Force Base	4 days	2	7-9 Aug 2000	$12,500
DEM/VAL 3: SERDP Test Pipeline Facility	4 days	3	14-16 Aug 2000	$17,500
DEM/VAL 4: Fort Campbell Army Airfield and Sabre Army Heliport	3 days	3	24-26 Oct 2000	$12,500
TOTAL				**$57,500**

* While the DEM/VAL illustrating the performance of the PALS lasted only 5 days, a total of 10 measurement days were made to verify the functionality of the system hardware and software.

5.2 COST ANALYSIS

An estimate of the costs and the cost savings associated with the use of PALS is presented below. In comparison to other methods, direct cost savings can be realized in terms of (1) less expensive and quicker leak location, and (2) less expensive regulatory compliance for leak detection. Furthermore, for many pipelines, PALS is the only method that can be reliably used for leak location. In the absence of regulations and without the availability of accurate and reliable leak location methods, there has been a reluctance to test bulk and hydrant pipelines for leaks, or if tests were conducted, they were not performed frequently enough for effective environmental protection. With the addition of PALS, better environmental protection can occur, particularly as regulations are put in place. In addition, because PALS tests can be completed significantly quicker than other methods, mission readiness is less impacted, and any loss of revenues due to pipeline shutdowns are minimized. While it is difficult to estimate the cost avoidance savings, the capability for accurate and reliable leak location means that leaking pipelines will be detected sooner and the cost of remediation and the number of lines that are replaced rather than repaired will be reduced.

There are four methods of locating a pipeline leak: (1) passive acoustics; (2) liquid-tracer methods; (3) cable systems; and (4) excavation. In general, a cable system is not a viable means of pipeline leak location, because this type of system cannot be retrofitted into existing lines, and the costs for new lines (purchase, installation, maintenance, and operational) are too high to be competitive. In addition, these systems tend to have significant false alarm problems and tend to break during installation. While gas-tracer methods can also be used to locate a leak, their costs are generally more expensive than liquid-tracer methods because the fuel in the line must be removed in order to conduct a test. While constituents of the fuel have been used as tracers, this approach results in too many false alarms, and the most viable liquid tracer approach is one in which a unique tracer is added to the fuel.

Except in special cases, on-line leak location is not cost effective due to the lack of monthly leak detection regulatory requirements for bulk and hydrant piping systems and the fact that the number of bulk and hydrant lines that leak are a small fraction of the total population. As a consequence, testing services are more cost effective than on-line monitoring systems. This may change if and when monthly leak detection rather than annual testing is required. Thus, the cost estimates and the cost comparisons presented below are based on the implementation of the technologies in terms of a testing service. As will be shown below, the cost of the equipment is quickly amortized over the number of lines tested, and the payback is less than a year.

At the present time, excavation is the baseline and has been and still is the primary method of locating leaks. The cost of excavation is between $15 and $60 per linear foot or more. In addition to these costs, there are significant costs associated with excavation of streets and other operational facilities that must be shutdown or must be repaired due to excavation damage.

The cost of regulatory compliance can be greatly reduced by the use of a volumetric leak detection system to meet regulatory standards if leak-location does not need to be an inherent part of the leak-detection system. The other methods used for compliance are pressure and liquid-tracer methods. Pressure-based systems do not have the accuracy or reliability for leak detection and are more expensive than volumetric methods. As a consequence, this type of system will not be discussed further. Liquid-tracer methods, on the other hand, can be used to both detect and locate leaks in existing lines when a unique tracer is added to the line. As the analysis presented below will show, while the liquid-tracer methodology has the capability to perform both the leak detection and leak-location tests, it is expensive and less reliable.

An estimate of the cost of leak location using PALS is summarized in Table 10. The assumptions are included at the top of the table, and the results are presented in the bottom half of the table. The cost estimates are presented in terms of finding a leak in a small bulk or hydrant pipeline (assumed to be 1,000 ft) or in a large bulk or hydrant pipeline (assumed to be either 5,000 or 10,000 ft). The costs are presented in terms of the cost per linear foot so that it can be compared with excavation and tracer methods. (No estimate of costs or cost savings are made for pipelines found at retail service stations, although the PALS would be particularly cost effective for these pipeline systems, especially the larger service stations and truck stops.)

Table 10 includes an estimate of the mobilization travel costs for a one-person field crew to complete the PALS measurements for leak-location tests on a short line (1 day) and on a long line (3 days). Some conservative assumptions are made about equipment purchase and utilization. It is assumed that the equipment will be depreciated over three years and only 25 tests will be performed each year. An estimate of the cost of equipment is summarized in the Final Report [18]. Approximately two-thirds of this cost is due to the purchase of a field-worthy notebook computer system.

The resulting costs for locating a leak in a short line is $2,300 or about $2.30 per linear foot and for a long line is $4,400 or $0.44 per linear foot. Because PALS is a real-time measurement system, the actual cost per linear foot to locate a leak in the longer lines is about 50% less on average, because the leak will generally be found before half the line is tested. This is also true for excavation, but not true for cable and tracer systems.

Table 10. Estimate of the Cost of Leak-Location Testing Service Measurements with PALS on Short and Long Pipelines.

	Small Pipeline Test Services	Large Pipeline Test Services
ASSUMPTIONS		
Airline Travel	$1,000	$1,000
Line Length - ft	1,000	10,000
Days of Testing	1	3
Number of Persons	1	1
Number of Tests/Year	25	25
Equipment Life - years	3	3
Equipment purchase price	$15,000	$15,000
ESTIMATED COSTS		
Mobilization Travel	$1,300	$1,600
Facility preparation	$100	$100
Equipment Use Fee	$200	$600
Labor to operate equipment	$600	$1,800
Utilities	$40	$120
Consumable and supplies	$10	$100
Equipment maintenance	$20	$20
Training of Operators	$32	$32
Total Cost per Test	**$2,302**	**$4,372**
Cost per Linear Foot	**$2.30**	**$0.44**
Portion of Line Tested	**100%**	**50%**
Cost per Job per Linear Foot	**$2.30**	**$0.22**

5.3 COST COMPARISON

A comparison of the relative cost of PALS, excavation, tracer, and cable methods for leak location is made below. To make the cost comparison, an estimate of the number of short and long bulk hydrant lines that might be leaking were made and is summarized in Table 11. These estimates were made for DoD bulk and hydrant military facilities, large and small commercial airports in North America, and petroleum marketing and transportation bulk storage facilities in the United States. Estimates of the number and the length of the lines for each type of facility were made and are aggregated in Table 11. (If the international airport and petroleum pipeline markets are considered, these estimates would more than double. The savings would also increase if pipelines were included that contained other types of hazardous substances.)

The number of leaking lines was estimated to be a small percentage of the total number of lines. Since many of these bulk and hydrant lines have not been routinely tested for leaks, the percentage of leaking lines used in this analysis may be too low. It was also assumed that a larger percentage of shorter lines leak than longer lines. This assumption was made because the longer lines were probably better designed and have less connections, appurtenances and flanges where the lines are most apt to leak. For this estimate it was assumed that 2.5% of the shorter lines may develop a leak over time and that 1.5% of the longer lines may leak. A simple sensitivity study shows that changes

Table 11. Estimate of the Number and Length of Leaking Bulk and Hydrant Pipelines in the United States.

Type of Line	Number of Facilities	Number of Lines	Average Length per Line (ft)[1]	Length of Piping (ft)	Length of Leaking Pipe (ft)
Total U.S. Military	**852**	**5,964**		**23,088,000**	**380,400**
- Large Lines		2,556	7,700[2]	19,680,000	295,200
- Small Lines		3,408	1,000	3,408,000	85,200
Total North American Airports	**810**	**2,100**		**5,340,000**	**97,500**
- Large Lines		360	10,000	3,600,000	54,000
- Small Lines		1,740	1,000	1,740,000	43,500
Total U.S. Petroleum	**2,200**	**20,700**		**38,300,000**	**737,500**
- Large Lines		4,400	5,000	22,000,000	330,000
- Small Lines		16,300	1,000	16,300,000	407,500
Total U.S. Market	**3,862**	**28,764**		**66,728,000**	**1,215,400**
- Large Lines		7,316	6,189	45,280,000	679,200
- Small Lines		21,448	1,000	21,448,000	536,200

[1] Assumed line length to the nearest 5,000 and 10,000 ft for large lines and 1,000 ft for small lines
[2] Large lines consist of 10,000-ft and 5,000-ft lines

in these percentages will not materially affect the conclusions drawn. For this analysis, it is assumed that 1,215,400 ft of pipe (out of 66,728,000 ft of pipe) may be leaking.

5.3.1 Leak Location

Table 12 compares the cost of leak location for these four methods. Even though it cannot be used for over 95% of the leak-location jobs and has been demonstrated to have poor performance, a cable method in included in the analysis in Table 12 simply to illustrate the high cost of this system. The cost of all of the technologies are estimated in terms of the cost per linear foot. The costs per linear foot of pipe tested for PALS were determined in Table 10. The costs for tracer, cable, and excavation methods used in this analysis are assumed to be \$5/ft, \$20/ft, and \$25/ft, respectively. A cost reduction is assumed for PALS and excavation, because the entire line, if it is long enough to require more than one day to find the leak, may not need to be tested to implement the method.

It is assumed that on average the leak will be found before the entire line is tested. This assumption was not made for tracer or cable methods, because these methods are implemented to test the entire line.

The cost savings are presented for each type of petroleum facility. The results indicate that all methods do a better job than excavation and that PALS is a factor of at least 4:1 more cost effective than tracer methods. Like excavation methods, cable methods are prohibitively expensive.

As stated above, no estimate of costs or cost savings are made for pipelines found at retail service stations. If these lines were included, significant cost savings can be realized because there are so many pipes that are easy to test with PALS. There are over 350,000 active petroleum service stations with an estimated 800,000 USTs. Assuming there are two lines per tank, there are over

Table 12. Comparison of the Cost and Cost Savings of PALS for Leak Location as Compared to Tracer, Cable, and Excavation Methods ($ per Linear Foot).

	Length of Leaking Pipe	PALS Cost	Excavation	Tracer Cost	Cable Cost
Cost of Large Lines per Linear Foot		$0.22	$12.50	$5.00	$20.00
Cost of Small Lines per Linear Foot		$2.30	$25.00	$5.00	$20.00
Total U.S. Military	**380,400**	**$260,661**	**$5,820,000**	**$1,902,000**	**$7,608,000**
- Large Lines	295,200	$64,531	$3,690,000	$1,476,000	$5,904,000
- Small Lines	85,200	$196,130	$2,130,000	$426,000	$1,704,000
Total North American Airports	**97,500**	**$111,941**	**$1,762,500**	**$487,500**	**$1,950,000**
- Large Lines	54,000	$11,804	$675,000	$270,000	$1,080,000
- Small Lines	43,500	$100,137	$1,087,500	$217,500	$870,000
Total U.S. Petroleum	**737,500**	**$1,010,203**	**$14,312,500**	**$3,687,500**	**$14,750,000**
- Large Lines	330,000	$72,138	$4,125,000	$1,650,000	$6,600,000
- Small Lines	407,500	$938,065	$10,187,500	$2,037,500	$8,150,000
Total U.S. Market	**1,215,400**	**$1,382,806**	**$21,895,000**	**$6,077,000**	**$24,308,000**
- Large Lines	679,200	$148,473	$8,490,000	$3,396,000	$13,584,000
- Small Lines	536,200	$1,234,332	$13,405,000	$2,681,000	$10,724,000
Cost Savings Relative to PALS		**1.0**	**15.8**	**4.4**	**17.6**

1,600,000 underground lines that have the potential for leaking. Since most of these lines are typically 100 to 200 ft in length, PALS can be implemented simply by positioning a sensor at either end of the line. If 2% of these lines develop leaks, 32,000 lines will have to be shutdown and repaired or replaced. Assuming that the use of PALS reduces the downtime by only one day, this will result in an increase of revenues, which might otherwise be lost, of $160,000,000, if the price of petroleum fuel was only $1.00 per gallon.

There are a number of types of pipeline installations and configurations in which leaks cannot be accurately or reliably located using tracer methods or extensive excavation. This may include runways, roads, large paved areas, airfield and airport apron areas. At Little Rock AFB, for example, the apron area containing 30 1,000-ft hydrant feeder lines to fuel aircraft is about 0.2 miles by 2 miles and is over 18 in. thick. In these areas, only PALS can accurately and cost effectively locate a leak, if one exists. Excavation is simply not an option unless it can be highly localized. An estimate of the cost savings achieved by PALS for these pipeline configurations is presented in Table 13. To make this estimate, it was assumed that the percentage of DoD, airport, and petroleum facilities so affected are 20%, 50% and 15%, respectively. The cost of testing these lines using PALS, excavation and tracer methods is given in Table 13. Without PALS, such leaks would not be located and would allow subsurface contamination to continue until visual evidence of a leak is manifest. The cost savings associated with the use of PALS as opposed to tracer or excavation methods is more than $3.5 M.

Table 13. Estimate of the Cost Savings Achieved with PALS Because Tracer and Excavation Methods Cannot Be Used.

	Length of Leaking Pipe	PALS Cost*	Excavation	Tracer Cost	Cost Savings Because PALS Can Be Used
Total U.S. Military	**380,400**	**$39,099**	**$873,000**	**$285,300**	**$833,901**
- Large Lines	295,200	$9,680	$553,500	$221,400	$543,820
- Small Lines	85,200	$29,420	$319,500	$63,900	$290,080
Total North American Airports	**97,500**	**$55,971**	**$881,250**	**$243,750**	**$825,279**
- Large Lines	54,000	$5,902	$337,500	$135,000	$331,598
- Small Lines	43,500	$50,069	$543,750	$108,750	$493,682
Total U.S. Petroleum	**737,500**	**$151,530**	**$2,146,875**	**$553,125**	**$1,995,345**
- Large Lines	330,000	$10,821	$618,750	$247,500	$607,929
- Small Lines	407,500	$140,710	$1,528,125	$305,625	$1,387,415
Total U.S. Market	**1,215,400**	**$246,600**	**$3,901,125**	**$1,082,175**	**$3,654,525**
- Large Lines	679,200	$26,403	$1,509,750	$603,900	$1,483,347
- Small Lines	536,200	$220,198	$2,391,375	$478,275	$2,171,177
Cost Savings Relative to PALS		**1.0**	**15.8**	**4.4**	

* Add 10-20% to PALS Cost for 10-foot excavation to confirm leak and repair pipe.

5.3.2 Regulatory Compliance

Table 14 presents an estimate of the cost savings for regulatory compliance because the existence of a leak-location method like PALS allows the use of less expensive volumetric methods to be used for leak detection. It was assumed that a volumetric test can be performed for $3,500 on short lines and $6,000 on long lines. The cost of tracer methods was assumed to be $5 per linear foot of pipeline tested. As can be seen from the estimates in Table 14 that there is almost a 3:1 cost savings in regulatory compliance, which amounts to over $200 M for the assumed number and type of pipelines to be tested.

5.3.3 Other Benefits

In addition to the aforementioned cost savings, there are important benefits to be realized in operational readiness by quick repair of a leaking pipeline and significant cost savings in clean-up cost avoidance.

Cost and performance aside, the true benefit of an acoustic leak-location method like PALS is that it minimizes downtime and optimizes readiness. For commercial facilities, there is a significant loss of revenue associated when fuel cannot be transferred and sold to a customer. For DoD and airport facilities, the impact on mission readiness due to a leaking line can be significantly reduced. For example, a leak in an 18-in.-diameter, 2,500-ft underground fuel pipeline underneath an asphalt area and the main four-lane highway through Pearl Harbor was located and the line was repaired and bought back into service in less than a week. In this instance, the leak needed to found and repaired so that the line could be used for marine fuel transfers. The penalty for not having a line capable of such transfers was $50,000 per day.

Table 14. Estimate of the Cost Savings Achieved with PALS for Regulatory Leak Detection Compliance Using Volumetric Methods and PALS Versus Tracer Methods.

	Number of Facilities	Number of Lines	Volumetric Leak Detection with PALS	Tracer Leak Detection	Volumetric-PALS Compliance Cost Savings
Total U.S. Military	**852**	**5,964**	**$27,524,661**	**$115,440,000**	**$87,915,339**
- Large Lines		2,556	$15,400,531	$98,400,000	$82,999,469
- Small Lines		3,408	$12,124,130	$17,040,000	$4,915,870
Total North American Airports	**810**	**2,100**	**$8,361,941**	**$26,700,000**	**$18,338,059**
- Large Lines		360	$2,171,804	$18,000,000	$15,828,196
- Small Lines		1,740	$6,190,137	$8,700,000	$2,509,863
Total U.S. Petroleum	**2,200**	**20,700**	**$84,460,203**	**$191,500,000**	**$107,039,797**
- Large Lines		4,400	$26,472,138	$110,000,000	$83,527,862
- Small Lines		16,300	$57,988,065	$81,500,000	$23,511,935
Total U.S. Market	**3,862**	**28,764**	**$120,346,806**	**$333,640,000**	**$213,293,194**
- Large Lines		7,316	$44,044,473	$226,400,000	$182,355,527
- Small Lines		21,448	$76,302,332	$107,240,000	$30,937,668
Cost Savings Relative to PALS			**1.0**	**2.8**	

There is also a cost savings associated with the better accuracy and potentially higher reliability of PALS than tracer methods because needless excavation due to inaccurate or false locations can be avoided. At this juncture, it is difficult to quantify this, but during the DEM/VALs two lines had been declared to be leaking by a tracer method when they were not, and locations had been given, which clearly were in error. In addition, there are only a limited number of tracers that can be used and previous contamination from the line being tested or other lines or tanks nearby could lead to false alarms.

The Army Environmental Center (AEC) estimates the average cleanup cost associated with tank and piping leaks to be $193,000 and even higher if the groundwater is contaminated. Future cost avoidance at 659 Navy LUST sites is estimated at $890 M. This number becomes approximately $2.5 B when all three services are included. Even a 10% saving due to efficient site assessment and more rapid leak detection would result in significant savings. Our preliminary analysis of the direct and indirect cost savings associated with having a robust leak location system suggests that several hundred million dollars, perhaps more, can be realized.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

There are numerous performance, operational, and cost benefits associated with implementation of the PALS leak location system. The most frequently used and most costly option for leak location is excavation to uncover and visually inspect for a leak. Trenching costs, which typically range from $15 per linear foot to $60 per linear foot or higher, is significantly more expensive than the use of PALS at approximately $2 per linear foot.

The use of PALS for leak location is over four times more cost effective than tracer methods for finding a leak. Greater saving can be realized when compared to cable systems. Because the entire line does not need to be tested (i.e., the sections most likely to leak can be tested first), the per-foot-cost of using PALS as compared to tracer and cable methods can be further reduced when the cost of the location project is assessed as a daily charge. For some pipelines, only PALS can be used (e.g., when the line is buried beneath roadways, runways, airfield/airport aprons, and other concrete/asphalt structures). In many such cases, the accuracy of tracer methods is not good enough to be used for location because the gas tracer is trapped beneath, and spreads horizontally underneath, the concrete and asphalt away from the position of the hole in the line. Finally, the availability of PALS for leak location can greatly reduce the cost of environmental compliance for leak detection, because simple, less expensive volumetric methods, which do not locate leaks, can be used for detection. This is particularly true on long lines. Cost savings of over 250% can be realized over tracer methods when addressing regulatory requirements for leak detection using volumetric systems for leak detection and PALS for leak location.

The total time required to perform PALS measurements on a line was estimated to take approximately two days. Most of the time associated with the DEM/VAL is not associated with the actual PALS measurements. The time required to set up the PALS equipment and to conduct a test is less than 4 h.

The time required to actually perform the leak-location measurements with PALS was typically completed in less than 30 min. Additional PALS measurements were made as part of the DEM/VAL to better understand the performance of the system. On each line, more than one 2-h measurement period was planned and implemented to collect additional acoustic data that would be beneficial for future implementation of the technology. These measurements were made within the planned schedule. More time would be required if the access points along the line were too large and a pot hole had to be excavated. This was not the case for any of the five lines used in the three DEM/VALs.

The volumetric test is an important part of the test procedure. The two hydrant lines tested at LRAFB were selected because they were believed to have a leak (based on previous leak-detection test results using another method) and were taken out of service. The volumetric tests indicated that the lines were tight. This was confirmed by the PALS. The STPF at Edison also showed the presence of a leak before the PALS measurements were begun. A plug used in previous testing was found be weeping slightly. The plug was tightened and the PALS measurements were made by introducing leaks of different sizes in the line using calibrated hole-plugs.

The time required to complete testing could be reduced by a factor of two or more using an operational system that is better packaged for field use.

6.2 PERFORMANCE OBSERVATIONS

All of the planned DEM/VAL measurements were made at the DEM/VAL sites within the planned schedule and budget. At each site, real-time output from the PALS correctly indicated the location of actual and simulated leaks. This was verified by extensive post-test analyses of all the data collected.

The performance objectives of this program were met. The PALS was successfully demonstrated in four DEM/VALs on six different pipelines with five different geometries and operational configurations, and four different background noise conditions. In each DEM/VAL, operational experience was obtained on actual pipelines and realistic noise conditions.

Four very important technical issues were not addressed sufficiently during the SERDP program to predict performance on operational lines. These issues, which are critical to use of the technology on operational lines, are: (1) maximum separation distance between sensors; (2) managing the acoustic reflections from line terminations, elbows and tees; (3) ambient acoustic background noise; and (4) the use of coherence and correlation analysis methods for leak-location.

The projected/expected limitation of 100 to 200 ft on sensor separation made during the SERDP tests proved not to be a limiting factor. Sensor separations of 500 ft or more were realized during the DEM/VALs, which meant that the PALS sensors could be placed on the line at available access points (e.g., valve pits, flanges, etc.).

The signal reflection issue is a significant technical issue but was overcome in these DEM/VAL tests by judicious placement of the sensors to minimize the effect of the reflections of the acoustic leak signal and by use of the correlation function to distinguish such reflections. Reflections, if not properly managed, can degrade the performance of the system. Additional work is required to manage and compensate for such reflections.

The PALS was used under a variety of operational noise conditions. The largest sources of noise were encountered at Little Rock AFB, where acoustic measurements were made in the presence of airplane (C-130s) landings and take-offs, service generators, and road traffic. This was possible because the line that was being tested and the sensor access points were below grade. The least amount of background noise was on pipeline at the Edison STPF pipeline.

A coherence-based approach was used to locate the leaks. This approach was successful due to no *a priori* information about the leak signal, such as the frequency band to exploit, was needed. This approach allowed the signal frequency band to be identified as part of the measurement. The correlation function was checked once this frequency band was identified to insure that reflections and multiple leak signals were not present. This approach was successfully used in all of the DEM/VALs.

6.3 SCALE-UP

The DEM/VALs were all conducted on full-scale, operational underground piping systems covering a wide variety of the types of piping for which the PALS might be used. The DEM/VALs were conducted on bulk piping typically found in bulk storage facilities, marine ports, and hydrant fuel distribution pipe (both the main and refueling lines). The diameters ranged from 4 to 12 in., the wall material was both steel and aluminum, and sensor access points were limited to normal access points (e.g., line termination and valve pits).

6.4 OTHER SIGNIFICANT OBSERVATIONS

All fuel transfer operations through the pipe must cease during a test. In general, such operations have already been terminated as soon as a leak is suspected. This temporary shutdown of the tank is minimized by the PALS in comparison to other leak-location methods because the duration of the test is shorter than the other methods.

6.5 LESSONS LEARNED

The benefits of using the combination of using a volumetric approach for leak detection and the PALS for leak location was nicely demonstrated during the Little Rock AFB DEM/VAL. The two hydrant feeder lines selected for the DEM/VAL measurements were both believed to have leaks based on previous tracer tests. Both lines were taken out of service and filled with water for the DEM/VALs. The volumetric tests indicated that both lines were sound. Leak signals were simulated during the DEM/VALs.

The sensors can be attached to the ends or sides of a flange for implementation of the technology. This is important because the protective coating on the line does not need to be removed to use the technology.

The presence of reflections due to complex pipe configurations due to blinds, tees, and elbows can degrade the performance of the acoustic technology. Compensation algorithms need to be developed. At the present time, these reflections are minimized by judicious positioning of the sensors on the pipe and by identification of problems areas with the correlation function. While this approach worked fine on four of the five lines tested, degradation was observed on the Campbell Army Airfield hydrant line.

The line must be pressurized in order to conduct a test. If the valves used to isolate the line weep, then this produces another signal that might interfere with a real leak signal. This issue can be minimized by reducing the test pressure and by using sensors that do not bracket the valve. This problem can be eliminated by using valve blinds. This is not a particularly serious problem for leak location, because the problem of weeping valves was already addressed as part of the leak detection testing. The problem of improperly sealed valves is an issue for leak detection because every line has to be tested, and the added expense and trouble associated with verifying that the valves have sealed can be expensive and time consuming. In contrast, only a small percentage of lines have leaks and the added expense of using valve blinds, if necessary, is small in comparison to quickly finding, repairing and bringing the line back into service.

6.6 END-USER ISSUES

The PALS is ready for commercialization. The drawings, specifications and software screens are described in the Final Report [18]. Vista Research, Inc., has commercialized the PALS and is now offering leak-location services. Product description and product specification sheets are available in the Final Report [18].

The technology was requested by the Fleet and Industrial Supply Center (FISC), Pearl Harbor, to locate a leak in a 2,500-ft, 18-in. underground fuel line. Under contract, Vista Research tested the line volumetrically to verify the presence of a leak and then used PALS to locate the leak. The leak was located in real-time to within 20 ft of its actual location. (Post-test analysis showed that the algorithms located the leak to within 4 ft.) The leak was repaired, and the line was re-tested volumetrically so that it could be brought back into service. The total time required to verify the leak, locate it, repair it, re-test the line and bring the line back into service was less than a week.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The Federal regulations 40 CFR Parts 280 Underground Storage Tanks - Technical Requirements, and the states' implementation of these regulations, require petroleum storage systems (including underground pipelines) be periodically tested for leaks according to Subpart D-Release Detection [16]. The UST regulation, issued in 1988 by the EPA, deferred the requirements for testing bulk or field-erected USTs and ASTs and their associated pipelines for leaks. In addition, the EPA deferred the testing of hydrant fuel distribution systems. The main reason for these deferrals was the lack of any technologies in 1988 that could reliably test these large pipelines. Even more importantly, even if a leak could have been detected, there were no reliable ways of locating it. Thus, only the small USTs and associated piping typically used at service stations were strongly regulated. These pipelines were typically 50 to 200 ft long, 2 in. in diameter and operated under pressures of only 30 psi.

In contrast, the deferred piping systems were typically 8 to 12 in. (large in diameter), thousands of ft to many miles in length, and operated under pressures of 50 to 175 psi. These large systems did not need to meet the rigorous leak-detection performance standards for monthly monitoring or annual tightness testing established for the small USTs. Even though these large pipes were deferred from periodic testing, they were not released from the corrective action required if a leak is identified.

During the past 3 to 5 years, systems for testing bulk and hydrant lines for leaks have been developed. As a consequence, various states have implemented regulations for testing these piping systems (e.g., California [19]), and all of the large commercial airports in the U. S. and Canada are now installing on-line leak detection systems. In addition, DoD has been very proactive in addressing these environmental issues. As more testing is done, the need for leak location increases, because more leaking pipes will be found.

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APPENDIX A

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