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Demonstration of Acoustic Sensing Techniques for Fuel-Distribution System Condition Monitoring

Final Report on Project F07-AR07

Michael K. McInerney and John M. Carlyle

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Demonstration of Acoustic Sensing Techniques for Fuel-Distribution System Condition Monitoring

Final Report on Project F07-AR07

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Location with Remote SCADA Interoperability for Fuel Distribution Systems”

Abstract

Leaks in fuel storage tanks and distribution piping systems have been identified as a mission-critical problem by the Department of Defense and the U.S. Army. Fuel system leaks are often hard to locate and virtually inaccessible for efficient repair because the piping is often installed under a concrete pad or tarmac. Leak repair could cost up to \$2,000, and the cost of cleanup and remediation for fuel spills can exceed \$50,000. In this project an acoustic remote sensing system was installed to monitor an Army heliport refueling system to determine whether it could detect and accurately locate fuel leaks using computer software technologies to distinguish acoustic leakage signatures from normal fuel system operational noise.

Demonstration and validation efforts were disadvantaged by the fact that no fuel leaks occurred in the monitored system for the duration of the project. However, the monitoring system did identify several unusual acoustic events within the fueling system and interpret them as indications of intermittent malfunctions of a check valve and a fuel pump.

The 30-year ROI is 6.42. Further work is required before the technology can be fully implemented: its ability to detect fluid leaks must be proven, and the system specifications must be certified through an EPA third party.

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Preface

This study was conducted for the Office of the Secretary of Defense (OSD) under Corrosion Prevention and Control Program Project Fo7-ARo7, Advanced Acoustic Leak Detection and Location with Remote SCADA Interoperability for Fuel Distribution Systems (OMA). The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM) and the stakeholder was the U.S. Army Installation Management Command (IMCOM). The technical monitors were Robert A. Herron (OUSD(A&S), Materiel Readiness, Corrosion Policy and Oversight), Ismael Melendez (IMPW-E), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time this report was prepared, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Michael K. McInerney, CEERD-CFM, was the ERDC CPC Program Coordinator. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Lance D. Hansen.

The authors acknowledge the contributions to this project by Sean W. Morefield and Gary Schanche, both of ERDC-CERL. Mr. Morefield provided planning and contracting assistance. Mr. Schanche assisted with project execution, primarily with technology installation at Fort Campbell, including obtaining approval for operation of the AFDMS radios on post. Acknowledgments are also offered to Fort Campbell personnel who provided support in executing this demonstration—Terry Ennis, Safety Manager for Sabre Heliport; and Larry Aikens, Fort Campbell Directorate of Public Works.

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters

1 Introduction

1.1 Problem statement

Fuel distribution systems are a critical component of military training and deployment systems. Fuel system readiness is important for training of maneuver forces and fulfilling mission-essential deployment requirements. Leaks in fuel storage tanks and piping systems have been identified as a mission-critical problem by the Army and other Department of Defense (DoD) services. Maintenance of DoD fuel systems due to corrosion problems is one of the top ten Facilities and Infrastructure costs by craft (Herzberg et al. 2014). Thousands of miles of direct-buried fuel distribution lines are exposed to corrosive conditions at most Army installations. The Army's replacement cost for double-wall fuel-distribution lines is approximately \$100 per foot. Repair of a single leak can cost \$2,000 or more due in large part to the extensive trenching required in order to conclusively identify the source. The cost of cleanup and remediation for even small fuel spills can exceed \$50,000, not including any possible fines that may be imposed. Because hydrant systems are often installed below a concrete pad or tarmac, it is often difficult or impossible to locate fuel leaks unless they are large enough to be detected indirectly.

Corrosion-driven failures can even compromise brand new and well-designed fuel hydrant systems. In one such case, a fuel hydrant system at Hickam Air Force Base, HI, experienced a pitting corrosion failure before the system was accepted by the Government.

New and highly improved technologies for monitoring fuel distribution systems, including leak detection and location, have been tested both in the laboratory and in the field. The current state of the art in leak detection technology includes gas chromatography and two-wire conductivity systems. Disadvantages of gas chromatography include false positives due to fuel spills not associated with leaks. The primary disadvantage of the two-wire system is that once the wires are wet, the system is unable to discriminate between water entry into the annulus (the space between the conduit and carrier pipes) and a fuel leak in the carrier pipe.

Acoustic technologies permit more cost-effective monitoring, including timely, accurate leak detection and location, than previously established

techniques (Tafari 1997). When a pressurized liquid leaks from a pipe, the flow creates acoustic waves that travel through the liquid inside the pipe. The acoustic waves created by a leak can be detected hundreds of feet away from the leak site using sensors designed for the purpose. Mechanical components of the distribution system, such as pumps and check valves, also generate acoustic signals during operation, and these also can be detected as they propagate through liquid in the pipeline.

For single-wall pipelines, the acoustic sensors are mounted on the outside of the pipe. For double-wall pipelines, the sensor mounts on one end of a waveguide that penetrates the outer conduit pipe with the other end acoustically coupled to the inner carrier pipe. A signal processing application is used to remove incidental noise caused by vehicular traffic and the environment while preserving acoustic data from the distribution system. The data are further processed to obtain system condition including leak detection (single sensor) and leak location (dual sensors). Leak location processing is generally done using cross-correlation.

Acoustic leak detection should not be considered as simply a means for minimizing environmental damage - it can actually help avoid environmental damage completely. Consider that on a double-wall pipeline that the leak detection is being done on BOTH pipes - the carrier and the conduit. If the carrier springs a leak, then acoustic leak detection can alert operators immediately. In this case, environmental damage can be avoided because the conduit will completely contain the spill, and the operators can schedule repairs before there is a possibility of the conduit failing. Alternatively, if the conduit is breached while the carrier is still solid, acoustic leak detection will alert the operators to that fact, too. This will prevent ground water from having an opportunity to corrode the carrier. It will also eliminate the possibility that environmental contamination will take place should a carrier leak happen to occur after the conduit is breached, as the operators will have been able to schedule repairs in a timely fashion.

Previous research performed by the U.S. Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) studied acoustic leak detection technologies on pipelines carrying potable water, high-temperature hot water, and other fluids (see for example: Morefield, Hock, and Carlyle 2006; Carlyle and Hock 2001; Carlyle, Van Blaricum, and Hock 2003). In the demonstration/validation project reported here, ERDC-CERL researchers implemented an Acoustic Fuel

Distribution Monitoring System on the 4,300 foot long underground steel and aluminum pipelines of the Sabre Heliport Hot Refueling System (SHHRS) at Fort Campbell, KY.

1.2 Objective

The objective of this project was to demonstrate the feasibility and effectiveness of a permanently installed acoustic fuel distribution monitoring system (AFDMS) for buried fuel lines at Fort Campbell, KY.

1.3 Approach

The system was designed using approximately 20 acoustic sensors located at critical points along the pipeline. The project included the following tasks:

- Design the acoustic monitoring system
- Install the monitoring system sensors, preamplifiers, and slave radio units
- Install and hook up the Central Computer and master radio unit
- Install the SCADA (Supervisory Control and Data Acquisition) network
- Collect sensor data
- Analyze the data
- Evaluate the performance of the system after 36 months of operation

1.4 Metrics

The metrics of success for the AFDMS were

- to detect operational deficiencies in distribution system components
- to detect and locate fuel leaks.

Apart from leak prevention, there are no DoD regulations prescribing operational parameters for fuel system components. However, general guidance on maintaining an operationally efficient system is available in Unified Facilities Criteria (UFC) 3 460 03 2017. Maintenance includes periodic performance checks, manual inspections, and diagnostics. An in situ monitoring system that can detect deficiencies could improve operational awareness of system condition without using additional manpower.

The U.S. Environmental Protection Agency (EPA) publishes leak detection regulations for underground storage tanks (UST) and piping. Two EPA criteria (EPA 2016) are applicable to this project. The system must be able to

1. detect a release of at least 3 gallons per hour (gph) at a line pressure of 10 pounds per square inch (psi) within 1 hour, with a probability of detection of at least 95 percent and a probability of false alarm of no more than 5 percent
detect a leak of at least 0.1 gph with a probability of detection of at least 95 percent and a probability of false alarm of no more than 5 percent when the line pressure is 1.5 times higher than its normal operating pressure (or, at lower pressure, a correspondingly lower leak).

2 Technical Investigation

2.1 Technology overview

Monitoring of fuel distribution systems has emphasized leak detection because of the safety hazards and high costs that result when a failure occurs. ERDC-CERL has collaborated with industry partners on several projects to develop and advance acoustic leak detection technology.

As discussed in Chapter 1, when liquid under pressure leaks out of a pipe it creates turbulence. The sound waves generated by the turbulence propagate through the liquid in both directions from the leak, producing slight vibrations of the pipe wall. A highly sensitive microphone (i.e., acoustic sensor) acoustically coupled to the pipe can detect these vibrations and convert them to electrical signals. Also, the system would include pressure sensors to provide the AFDMS data about fuel distribution system operation and pressure drops that may indicate the development of a leak.

Several previous ERDC-CERL leak-detection laboratory studies using 12 in. diameter steel pipes (Carlyle et al. 1996; Miller et al. 1998; Miller et al. 1999) demonstrated that acoustic sensing could reliably detect and locate leaks of

- 0.014 gph through a valve with no flow at 70 psi and a 20 foot spacing (± 1 in.)
- 0.75 gph from a drill hole with no flow at 70 psi and a 100 foot spacing (± 2 in.)
- 12 gph from a drill hole with no flow at 70 psi and a 700 foot spacing (± 18 in.).

Earlier versions of this technology were demonstrated in the field on buried heating and water lines (Carlyle et al. 1998; Carlyle 1999; Carlyle et al. 2001; Carlyle et al. 2003; Carlyle 2004; Carlyle 2006). The acoustic technology located leak rates of between 2 and 50 gph under ambient and operational flow noise conditions at pressures between 15 and 150 psi with an accuracy of between 0.5% and 1.5% of the sensor separation distance. The sensor separation was up to 3,000 ft. This technology meets the EPA metric to detect a release of at least 3 gph at a line pressure of 10 psi. However, because water and fuel properties differ, it is necessary to modify the processing algorithms for this fuel leak detection project.

Table 1 shows the progression of technological improvements leading to the current project.

Table 1. Technology comparison of previous leak detection projects and the current project.

	Dugway Proving Ground, FY04 (Carlyle 2004)	Fort Hood, FY05 (Carlyle 2006)	Fort Campbell (Planned Project)
Sensor Mount	Temporary	Permanent	Permanent
SCADA Connection	None	Central CPU only	Full connection
System Monitored	Fuel Tank Farm Interconnects	Water Distribution	Fuel Hydrant System
Carrier Pipe Type	Double wall	Single wall Ductile Iron	Double Wall
Medium	Fuel Oil	Potable Water	Diesel Fuel
Acoustic Sensor Type	Coincidence Detection Survey	Passive listening	Programmable listening with history and capability to locate leaks

The project final report for the Dugway Proving Ground is reproduced in Appendix C. The final report for the Fort Hood project is reproduced in Appendix D.

The accuracy of leak location with acoustic technology is very accurate. A breach of the double-wall containment found in the Dugway Proving Ground study (Figure 1) was located to within 1 ft of its actual position.

Figure 1. Water leak found with 2,200 ft of sensor separation (left) and containment breach found in double-wall pipeline with 450 ft sensor separation.

More typical location accuracy is 0.5% of the sensor separation distance, which is fully adequate for locating repairs since the margin of error represents less than the size of the typical backhoe excavation hole. Note that

this result was achieved from a walk-through survey, and not from a permanently installed system. In a walk-through survey the acoustic sensors are temporarily attached to the pipes. Data is collected, the sensors are removed, and the survey crew moves to the next location. Passive or active correlation equipment can be used, as well as auditory links to the pipe where a technician listens directly to the acoustic signals. A permanent installation is where the units remain attached to the pipeline for many months (or years) and the data is collected periodically through a wired or wireless collection unit.

The EPA requirement (i.e., metric) to detect a fuel leak of at least 0.1 gph was realized under the Strategic Environmental Research and Development (SERDP) through the development of a Pipeline Acoustic Leak-location System (PALS). The goal of the SERDP project was to develop and demonstrate acoustic techniques for accurately locating small (0.1 gallon per hour) leaks in underground petroleum pipelines during a short-term walk through survey. Under the Environmental Security Technology Certification Program (ESTCP), the PALS was demonstrated and validated under a wide range of operational conditions (ESTCP 2003).

The PALS demonstrated technology was leveraged in the development of the AFDMS. Fuel systems have different acoustic and hydrodynamic properties than water systems, so those properties had to be determined for fuels and programmed into the leak detection algorithm for this project. The relevant properties are carrier pipe and conduit stiffness, and fuel density. The signal-processing requirements were more demanding for the AFDMS because the nearby fuel pump creates more acoustic noise than in a water system, where the pumping station is often miles from the assessment area.

2.2 System design and layout

The technology consists of several subsystems, as shown in Figure 2.

Figure 2. Block diagram of leak detection system.

The functions performed by each subsystem are as follows:

- *Waveguide* (if needed) conducts the acoustic signals from the inner carrier pipe through the outer conduit pipe to the sensor. A waveguide guides sound waves with minimal loss of energy.
- *Sensor and preamp* convert the acoustic signals into electrical signals. Because it is mounted inside the fuel line access pit, it must meet or exceed NEMA 8 specifications (NEMA 2003).
- *Barrier and radios* transmit electrical signals to the SCADA system. The complete subsystem consists of the barrier,* digitizer, radios, antennas and power supplies. The electrical power output from the pre-amp is limited by the barrier in order to assure intrinsically safe (NEMA 2003) operation.

One of the important design considerations was that the AFDMS was going to be used in a hazardous area (i.e., flammable fuel, explosive gases).

* The barrier is a critical electrical and fire safety component discussed in section 2.3.1.

The ability of the AFDMS to function safely in hazardous areas is guaranteed by the use of components that exceed the NEMA 8, Class I, Division 1, Zone 1, Groups A, B, C, or D standard. This standard is also specified by Fort Campbell DPW for equipment operating in hazardous fuel areas. It covers indoor or outdoor use, with explosive gases, vapors or liquids, that exist all or some of the time under normal conditions, that are likely to exist under normal conditions, and which include acetylene, hydrogen, ethylene, and propane.

No acoustic and pressure sensors and preamps with NEMA 8 certification were available. To fully meet the requirements of NEMA, the project team instead procured sensors and preamps that had a European ATEX II 1 GD Eex ia IIC T4 certification, (ATEX 2014) * and mounted them inside IP66-rated cases. These specifications exceeded the Fort Campbell requirements of a NEMA 8 certification. The Intrinsically Safe designation goes further in that it permits Zone 0 usage, where explosive gases, vapors or liquids are present continuously under normal conditions.

2.2.1 Waveguide

The function of the waveguide (be leakproof and pressure-tight, so a sealant is used. Mounting tabs are included to firmly affix the plug to the pipe.

Figure 3, left) is to bring acoustic signals from the inner carrier pipe through the outer conduit pipe to the sensor in a double-wall piping system. The waveguide tip (smaller end of shaft) must be acoustically coupled to the carrier pipe, which is accomplished with an epoxy adhesive. The shaft of the waveguide must be acoustically isolated from the outer conduit, which is done with a Teflon plug (be leakproof and pressure-tight, so a sealant is used. Mounting tabs are included to firmly affix the plug to the pipe.

Figure 3, right). The conduit penetration must be leakproof and pressure-tight, so a sealant is used. Mounting tabs are included to firmly affix the plug to the pipe.

* Definitions of terms: ATEX (explosive atmosphere) II (explosive gases or dust) 1 (gas zone 0, dust zone 20) GD (gas and dust), Eex (European explosive) ia (intrinsic safety with 2 faults applied) IIC (groups A, B, C, D) T4 (surface temp < 135 °C), IP (ingress protection) 6 (totally protected against dust ingress) 600 (protected against high pressure water jets with limited ingress).

Figure 3. Diagram of waveguide components.

Because the SHHRS is a single-wall aluminum and steel pipeline the acoustic sensors did not require waveguides. Within the access pits the carrier pipes were exposed so that the sensors could be epoxied directly onto the carrier pipes. See Figure 9.

2.2.2 Acoustic sensors and preamp

The function of the sensors and the preamp is to convert acoustic signals into electrical signals. Because these components were designed to be placed inside the access pits, the devices were specified to meet or exceed NEMA 8 safety standards. The sensor and preamp chosen had ATEX certification (Ex II 1 GD Eex ia IIC T4), and therefore they exceeded the NEMA 8 requirement.

The sensor/preamp subsystem, shown in Figure 4, was acoustically coupled and attached to either the pipe or the top of the waveguide with epoxy.

Figure 4. Acoustic sensor (left) and preamp (right).

2.2.3 Barrier and radio

The function of the barrier and radio, shown in Figure 5, is to transmit the electrical signal to the SCADA system. This subsystem consists of the barrier, digitizer, radio, antenna, and power supply. The barrier limits the electrical power output from the sensor and preamp to $10\text{V} < V_o < 12\text{V}$, $I_o < 163\text{mA}$, $P_o < 0.49\text{W}$ in order to assure intrinsically safe (IS) operations as required by NEMA (2003). The radio has a 4–20 mA input and digitizes the analog input signal using a 20 bit analog-to-digital converter and transmits the digital data to a master radio using spread spectrum technology at 900 MHz (Freewave FGRIO-S with $\frac{1}{4}$ wave 3 ft whip antenna using the industry-standard Modbus communication protocol).

The power supply has a 12 V, 7 AH battery with 12 V, 5 W solar panel charging through a 5 A controller. The components are mounted in a NEMA 4 weatherproof enclosure (9.5 x 11.5 x 4.5 in.) on stands outside of the access pit.

Figure 5. Typical barrier, radio, and power supply shown in a weatherproof enclosure with attached solar panel.

The master radio receives data from the acoustic sensors and one pressure sensor, then feeds the data into the SCADA system via the RS-232 interface (Freewave FGR09CSU).

2.3 Field work

The SHHRS consists of a JP8 fuel storage tank, a pump house, a filter house, six fueling helipads (one inactive), a control house, four underground pipeline access points (pits), a tanker offloading area (for refilling the tank). The distribution lines comprise 4,300 feet of 2, 3, 4, and 8 in. diameter steel and aluminum underground piping in the form of a continuous loop, two crossovers to permit flow adjustments, and a check valve to prevent pressurization of the system by fuel in the tank. The general layout of the refueling facility is shown in an aerial photograph (Figure 6) with specific details intentionally obscured.

Figure 6. Aerial view of refueling system pipeline layout.

The distribution system piping requires ten acoustic sensors to obtain the necessary coverage. The system has four access pits. Of those, pits 1, 2, and 4 were each allocated two acoustic sensors, and pit 3 received one. The remaining three acoustic sensors were placed in two new pits; pit 3A was located 15 ft southeast from pit 3 and received one acoustic sensor, and pit 4A was located 300 feet southwest of pit 3 and received two acoustic sensors. Five slave radios (1, 2, 3, 5, and 6) were positioned for acoustic data and one other (radio 4) for pressure data.

A schematic layout of the AFDMS on the SHHRS is shown in Figure 7. The supply fuel piping is drawn in light orange and the return fuel piping is drawn in light purple. The helicopter refueling pads are drawn in green, and fire hydrant water piping is drawn in blue. Components of the AFDMS system are drawn in dark orange. Acoustic sensors were installed on both the supply and return lines. A photographic view of the SHHRS is shown in Figure 8.

Figure 7. Schematic diagram of AFDMS components on a map of the SHHRS.

Figure 8. Photograph of the SHHRS with an AFDMS radio station in foreground.

The photo was taken roughly from the top right corner of Figure 7, looking toward the lower left. In the foreground is the enclosure for slave radio 1, along with its solar panel and protective bollards. Immediately in back of slave radio 1 is refueling Helipad 1. To the immediate right of Helipad 1 is

Pit 1 (revealed by the red steel plate and concrete in the foreground, almost hidden in the grass). The white building on the tree line at the right is the SHHRS control house. The white building on the tree line in the center is the filter house. The fuel tank is on the tree line at the left of the picture; while just to its right is the white pump house. The large brownish structure is a temporary hangar. By referencing Figure 7 for exact positions and carefully examining Figure 8, the solar panels of radios 2, 3, 4, 5, and 6 can be discerned.

2.3.1 AFDMS system operation

Leak detection starts with receiving an acoustic signal from within the pipeline that may indicate a leak (Figure 9). The sensor signal is amplified by the preamplifier and transmitted out of the hazardous area (the pit) to the barrier. The acoustic signals are converted to a 4–20 mA electrical signal by the barrier, which has a frequency range of 3–30 kHz.

Figure 9. Acoustic sensors (black cans) mounted on fuel supply (right) and return (left) lines, with preamps (gray boxes) on pit walls.

The barrier is a key component of an intrinsically safe system; its function is to ensure that very low electrical energy is used within the hazardous area. After the barrier, the sensor signal is sent to the slave radio, where the signal is digitized and transmitted to the central computer. The radio digitizes the signal using a 20-bit A/D converter and transmits the data to the master radio using secure, frequency-hopping spread-spectrum tech-

niques at 902–928 MHz. The power supply for the sensor, preamp, barrier, and radio consists of a 12 V battery, a solar panel, a solar controller, and a voltage doubler.

An AFDMS barrier, slave radio, voltage doubler, and their power supply are shown in Figure 10.

Figure 10. Slave radio (lower right), solar controller (top), barriers (green boxes), voltage doubler and battery inside a NEMA 4 weatherproof enclosure.

The voltage doubler was necessary because the sensor, preamp, and barrier are designed to work at 28 volts DC. The solar panel and its controller were optimized to work with 12 VDC batteries. The voltage-doubler increased the 12VDC solar power supply output to 24 VDC, close enough to the 28 VDC necessary for the sensor, preamp, and barrier to operate properly.

The system saved battery power by turning the sensor, preamp and barrier off, and putting the radio into sleep mode when the fuel system was not operating.

The central computer and master radio were located inside the SHHRS control office, housed in a dustproof, lockable box with a transparent front to show the display screen (Figure 11).

Figure 11. Central computer, display, and master radio inside lockable box (left) and AFDMS on control house wall (right).

The locked box prevented tampering while enabling real-time leak detection results to be viewed by the operators. The master radio antenna was mounted outside the office and provided direct line of sight communications with all six of the slave radios, while being clear of helicopter traffic (Figure 12).

Figure 12. The master radio antenna and its mount.

Because fluid pressure is an important system parameter for leak detection, an intrinsically safe pressure sensor was installed in the supply pipe at the filter house, downstream from the filter (Figure 13). The cable from

the pressure sensor was routed underground from the filter house to a slave radio station, where the signal went through a barrier to ensure that very low electrical energy would exist within the filter house hazardous area. The slave radio transmitted the pressure signal to the central computer.

Figure 13. Intrinsically safe pressure sensor.

Because this is a pressurized system there cannot be a leak in the piping of the SHHRS unless there is a pressure differential across the wall of the pipe. Therefore, it is unnecessary to monitor the SHHRS for leaks unless the pump is running. The pump is wired such that whenever it is running a red warning lamp is lit in the control house. A current detector was installed onto the power wire of the pump warning lamp and the current detector was wired to the master computer. (This lamp can be seen in Figure 11; it is the red floodlight to the left of the AFDMS cabinet.) The warning lamp was used as the trigger to start the data collection and leak monitoring process.

2.3.2 AFDMS control software

The monitoring system control and graphical display program runs on the central computer. This program was written using an application program sold by AzeoTech, Inc., called DAQFactory (DF).^{*} DF combines supervisory control and data acquisition (SCADA), human/machine interface (HMI), factory automation, test and measurement, quality control, and remote monitoring and control software into one package.

The display screen, shown in Figure 14, shows the leak detection status of all the acoustic sensors—green for no leak, yellow for possible leak, red for

^{*} <https://www.azeotech.com>; <https://www.azeotech.com/j/products/what-is-daqfactory.html>.

definite leak. The screen also shows the operating condition of the pump (shown as “On” in this screen shot), the pressure inside the refueling system supply lines (69.5 psi in this screen shot), and the state of charge and temperature of all the slave radio batteries. Below nominal values for line pressure, as well as charge and temperature of the slave radios will be highlighted in red. The supply line is shown in brown and the return line is shown in gray.

The AFDMS software uses ten threads (sub-programs) running simultaneously but with different priorities. The graphical display shown in Figure 14 always runs but has the lowest priority. The two highest-priority threads consist of the main loop and the master radio thread. The main loop constantly reads the status of the pump warning light via the current sensor. If the pump starts, then the master radio thread is started.

Figure 14. AFDMS display showing normal operation of SHHRS on the central computer.

The master radio thread first turns on the data logging thread. Then, it starts the six slave radio threads, waking up all six of the slave radios and providing power to the sensors, preamps and barriers connected to each

slave radio. A continuous processing loop then begins during which data is continuously collected from each slave radio, logged into a database file on the main computer, and displayed on the screen.

When the pump stops, the pump warning light switches off. This changes the state of the current sensor and triggers the main loop to start a timer set for 25 minutes. Acoustic sensor data is still collected during this quiescent period. Because the pump has stopped, the fuel is in a quiescent state and the fluid pressure decreases as the fuel returns to the tank. This provides a quiet environment in which leaks can most effectively be detected.

When the timer expires the data-logging process stops and all six slave radios are powered down. This event automatically turns off the sensors, preamps, and barriers connected to each slave radio. Finally, the master radio thread is stopped. When the pump warning light goes on again, the data collection process repeats.

The software can also automatically send emails or text messages to designated personnel to notify them when a leak is detected. This capability does not depend upon being connected to a government network or to an industrial-grade SCADA system. During this project, however, because no leaks occurred, we could not fine-tune the leak detection algorithm without the possibility of returning false-positive alarms. Another capability of the software that could not be demonstrated was mirroring of the main AFDMS display (Figure 14) because the installation DOIM (Directorate of Information Management) did not approve of connecting the AFDMS to the local intranet. See section 2.5 for an explanation.

2.4 Commissioning

During testing of the AFDMS, four operational problems occurred:

- a configuration error in the uninterruptible power supply (UPS) software
- a manufacturing defect in the pressure sensor
- a broken resistor lead in a slave radio
- effects of battery aging.

The AFDMS uses a UPS to power the central computer, master radio, and electrical current detector. The purpose of the UPS is to assure that the al-

ternating current (AC) supply continues without interruption and to enable a 'graceful' power-down if the UPS battery is below 70% of its capacity. This shutdown mode enables AFDMS control software to save all files, power-down the sensors, preamps and barriers, put the slave radios to sleep, and then close. After that, the Windows operating system and the central computer would shut down, in that order. When AC power is restored to the control house, the UPS will first charge the battery up to 50% capacity and then deliver power to the computer. The computer and operating system will boot up, restart the control software, and resume normal AFDMS operation.

One of the UPS settings provided by customer service was inaccurate and resulted in a sequence of errors that prompted the power supply to turn off the computer 30 minutes after a shutdown/reboot sequence had occurred. Fortunately, this error occurred only once and was identified within a few days, before the SHHRS could be used.

Also during commissioning, it was discovered that pressure data was missing from several monitoring runs. The pressure sensor was removed from the filter house and sent to the manufacturer, where it was found that several internal wires had been crushed during manufacturing of the pressure sensor. Vibration of the sensor cable eventually caused these wires to short. The pressure sensor was repaired, and a longer cable was installed to permit looser routing of the cable to the sensor. After repair and replacement, the pressure sensor returned valid readings for the duration of the project.

The analysis of the first leak data files revealed that slave radio 4 always reported battery power to be 14.86 volts, which was 2.86 volts higher than nominal. Inspection revealed that a lead had broken on one of the resistors used in the voltage monitoring circuit. The cause for this failure was unknown. The resistor was replaced and the voltage reading returned to nominal.

After obtaining full 24-hour access to the AFDMS system the performance of the solar charging system was evaluated. It was discovered that after 26 months of operation the lead-acid batteries powering the six slave radios were failing to hold their charge (see Appendix A, Figure A13). New batteries were ordered and sent to the installation personnel for replacement. It

was determined that the batteries should be replaced every 24 months or sooner in order to avoid repeating the problem.

Standing water in the access pits caused an increase in the acoustic noise levels. When the AFDMS was installed in October 2009, the typical acoustic sensor trace was fairly quiet. At the time of system installation, water in all of the pits had been pumped out using a trash pump. Over time, some of the sensors showed a marked increase in noise when the pump was running. By this time, water had again seeped into the pits and covered the sensors, the supply pipe, and the return pipe. In pit 4 this resulted in the increase of detected noise when the pump was running. We believe pump noise was conducted through the water and was detected by the AFDMS sensors, thus raising the noise level on the sensor traces. When the pump stopped, this directly coupled sound also stopped, restoring the sensor traces to the levels they had immediately after the AFDMS was installed.

2.5 Performance monitoring/testing

It was noted in section 2.3.2 that the project team needed approval from the Fort Campbell DOIM to establish an internet connection between the AFDMS central computer and the installation local area network (LAN). The DOIM did not grant approval because we were using the connection to access the AFDMS from outside Fort Campbell in order to monitor the system remotely. An internet connection was finally established when it was noted that the local cable communications company had installed a cable drop across the street from the SHHRS control office. The DOIM had no issues with us getting internet from the commercial provider, as long as we did not connect to the base internet. Installation took about one week after an application was submitted to the cable company. At that point the project team could remotely monitor AFDMS operation and retrieve data files shortly after they are recorded. This connectivity also enabled the project team to reprogram the AFDMS software as needed. This solution eliminated the requirement for a member of the project team to travel to Fort Campbell periodically to collect the data, greatly simplifying the monitoring process.

3 Discussion

3.1 Results

System validation efforts were disadvantaged by the fact that, during the 30-month project, the AFDMS reported no SHHRS leaks and none were detected by installation personnel using conventional pipe-inspection methods.* Consequently, AFDMS leak-detection capability could not be evaluated.

The quiescent state of the AFDMS acoustic sensors immediately after system installation is shown in Figure 15. (At this time the SHHRS was defect free.) If any of the sensor traces rise higher than this initial condition, it could indicate a hydraulic or mechanical event affecting the system, including leakage.

* Past results using this technology on Army water pipeline systems has validated the ability to detect leaks at rates between 2 to 50 gph under ambient and operational flow noise conditions, at pressures between 15 and 150 psi (Carlyle 1999). Previous demonstrations have also validated that the acoustic technology used in the AFDMS can detect liquid leaks, including leaks whose fluid never rises to the surface.

Figure 15. AFDMS display on the central computer showing normal SHHRS operation.

However, environmental noises from various sources also can increase sensor traces to levels higher than normal, potentially creating false alarms. Such ambient noise sources can include pumps and check valves that control fuel flow through the system. Another example is noise made by automobile or truck traffic passing over or near the pipelines. Unsurprisingly, helicopters and other low-altitude air traffic also can induce noise into the pipeline.

To detect leaks in the midst of competing ambient sounds, the AFDMS relies on inherent differences between a leakage signal and the pipeline noise: (1) pipeline noise becomes much lower after the SHHRS pump is turned off following a refueling operation and (2) pipeline leaks continuously make noise after they form, and they only become silent if the internal pipeline pressure falls to zero. Thus, a leak will increase the sensor trace in a constant manner as long as the fuel system remains pressurized. A leak is not indicated by acoustic transients whether the fueling system is pressurized or not, so these transients can safely be ignored. Appendix A presents a variety of examples showing data plots that identify the probable sources of the recorded signals.

Although no leaks occurred during the performance period, the AFDMS did serve to identify other defects in the refueling system that were revealed by anomalous signals in the data. These results, including prospective diagnoses of the problems they indicated, were reported to SHHRS personnel.

- a. The data indicated that the check valve may be defective. In many runs of the SHHRS in 2010, the system was not able to hold pressure after the pump shut down. Because no system leaks had occurred during the project duration, the only other explanation for such pressure data would be a defective check valve. Appendix A provides more analysis.
- b. Based on data analysis, the pump at times appeared to make more noise than usual in the system. These noise events often occurred concurrently with pressure changes detected in the SHHRS. The project team was not able to develop a positive diagnosis of the problem creating this noise. One explanation might be that the check valve was not seating correctly, forming a poor seal that sometimes caused the pump to work harder without achieving the correct pressure. Another possible explanation is that, for reasons unknown, the pump sometimes started cavitating, which caused lower pressure due to loss of pumping efficiency. Regardless of the cause, the AFDMS system acoustically detected operational anomalies that needed to be checked by maintenance personnel. More details are presented in Appendix A.

3.2 Lessons learned

3.2.1 System communications technologies and networking

Design and setup of a remote-monitoring system must include early and ongoing coordination with all installation authorities responsible for reviewing and authorizing the use of communications technologies on post. One potential communications issue is the use of devices that may allow unauthorized access to an installation information system, such as slave radios that are insufficiently secure. In this project, Fort Campbell DOIM approval of the radio subsystem was fairly straightforward. The design specified the use of secure spread-spectrum, frequency-hopping radios. DOIM acceptance only required submittal and approval for frequency spectrum allocation using Form DD 1494, APPLICATION FOR EQUIP-

MENT FREQUENCY ALLOCATION, which depends on equipment compliance with Military Communications-Electronics Board (MCEB) operating restraints.

A more serious and almost intractable problem was receiving the DOIM approval for AFDMS internet connectivity for remote access outside the installation fenceline. For information security reasons, the DOIM would not approve establishing AFDMS internet connectivity from outside the installation. Without remote connectivity, the monitoring system worked only in a stand-alone mode. The project team had to retrieve the data by traveling to the installation or have installation personnel retrieve the data and send to us. Two problems with AFDMS operation were identified by analyzing the retrieved data, but both were addressed and caused very little data loss. But because of the delays in transmitting and analyzing the data, serious problems could have gone unaddressed for months. The data-retrieval problem was eventually solved by using an existing commercial cable network access point located across the street from the SHHRS control office. The DOIM had no issues with us getting internet through that provider, as long as we did not connect to the base internet. Remote web access was established by incorporating a cable modem, virtual private network (VPN) software, and data encryption. For others planning to implement this system at an Army installation, we recommend early coordination with all onsite information security stakeholders. Also, where possible and assuming monitoring system data are not restricted from transmittal via the web, it may be advantageous to establish connectivity through a commercial internet service provider. However, the monitoring system budget would have to include funds for this service.

An ancillary problem caused by the lack of on installation internet connectivity was that the system was not able to take full advantage of the AFDMS control software capabilities. The control software can be configured like a node on a SCADA system. Such a configuration could feasibly produce valuable benefits, such as integrating AFDMS output directly into reports generated by the SCADA system. This type of system extension would require full involvement and careful planning by all installation stakeholders.

3.2.2 Excavation approvals

Obtain prior approval to dig at all locations necessary to install the sensors and slave radios. Communication cables, fiber optic cables, and gas lines

sometimes run close to underground pipelines, so it is critical to verify that digging will not damage in-place infrastructure. This effort should include acquisition of the most accurate utility maps available. Because few maps are completely up to date information can sometimes be beneficially supplemented with multi-spectral images, which for this project were very helpful in finding the trench lines that marked the route of unmapped pipelines. Also, commercial RF pipe-location equipment can be valuable in utility location.

3.2.3 Sensor location

Specify acoustic sensor positions so the fuel pump is at the edge of each sensor's listening distance. Operating pumps can make the interpretation of leak data difficult, yet it is still important to obtain leak detection coverage in the vicinity of pumps. In the current project the location of a pit made it necessary to mount sensors 6S and 6R close to the pump house. (S designates a supply line sensor and R designates a return line sensor.) Sensor 6S is within 75 ft of the pump, as measured through the liquid of the pipeline, while sensor 6R is about 250 feet away. The effect of these two sensor placements can be seen in Figure A4. Note at about midpoint in the plot where dark blue trace (sensor 6S) shows an abrupt drop when the pump turns off. Compare that line with the dark blue trace in the bottom plot of sensor 6R, which remains unaffected by pump operation. These plots illustrate that placing sensors distant from the pump, but within listening distance, is the optimal layout.

3.2.4 Equipment mounts and housings

The heliport environment may pose unexpected hazards to system equipment and housings. In this project, bollards were used to protect the remote radio and solar panel from vehicles—primarily lawn mowers. Strong hinges, braces and strapping were used to hold the solar panels in position in the face of helicopter rotor wash. Raising the solar panel above the bollards resulted in better adjustment possibilities, and also helped protect the panel from possible damage by rocks thrown from lawn mowers.

4 Economic Analysis

4.1 Costs and assumptions

Total project costs were \$945,000. A rough breakdown of project expenses is presented in Table 2**Error! Reference source not found..**

Table 2. Breakdown of total project costs.

Description	Amount
Labor	\$82,257
Materials	\$0
Contracts	\$813,000
Travel	\$19,307
Reporting	\$25,436
Air Force and Navy Participation	\$5,000
Total	\$945,000

The field demonstration costs for this CPC project are shown in Table 3**Error! Reference source not found..**

Table 3. Project field demonstration costs.

Item	Description	Amount
1	Labor for project management	\$110,000
2	Labor for project execution	\$406,000
3	Travel for project management	\$9,000
4	Cost of 10 sensors and preamplifiers	\$75,000
5	Cost of data sampling systems (including 10 barriers, 10 digitizers, 6 radios, 6 antennas)	\$80,000
6	Cost of 6 power supplies (including solar panels, batteries, electronics, enclosures, and support structures)	\$95,000
7	Cost of computer system (including computer, peripherals, UPS, and enclosure)	\$5,000
8	Cost of receiver system (including receiver, power supply, and antenna)	\$12,000
9	Installation costs	\$21,000
0	Total	\$813,000

The acoustic fuel distribution monitoring system (AFDMS) has the capability to save the Army money, through the timely and accurate detection

of small fuel leaks in underground pipelines. Timely detection alone is a big cost saver because it directly impacts the cost of cleaning up the contaminated soil and aquifers, and the cost of fines imposed by legal jurisdictions for the contamination. Limiting the amount of fuel that leaks into the ground greatly reduces the extent of the contamination and the subsequent clean-up effort.

The cost of a leak is made up of six factors:

- the cost of finding the leak
- the cost of repairing the leak
- the cost of cleaning up the contaminated soil and aquifers
- the cost of fines imposed by legal jurisdictions for the contamination
- the cost of buying the lost fuel
- the cost of shipping the lost fuel.

The costs of replacing the lost fuel are not included in the return on investment (ROI) calculation since they are anticipated to be minor compared to the other costs.

The ROI calculation assumes nine miles of a double-wall direct buried fuel distribution system. Aggregate cost comparisons between the two systems, baseline costs (Alternative 1), new system costs (Alternative 2), and new system benefit cost savings (Alternative 2) are listed in Table 4. Descriptions of these costs are given in the following sections.

Table 4. Costs (in \$) used in ROI computation.

Year	Alternative 1					Alternative 2									
	Baseline Costs					New System Costs						New System Benefits/Savings			
	Replace distribution system	Maintain	Total	Benefits/ Savings	Repair leaks	Replace distribution system	Operate	Maintain	Service AFDMS	Total	Repair leaks	Repair leaks	Salvage	Total	
1		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
2		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
3		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
4		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
5		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
6		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
7		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
8		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
9		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
10		1,305,000	1,305,000		369,500		4,000	1,044,000	15,000	1,063,000	37,500	332,000		332,000	
11		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
12		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
13		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
14		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
15		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
16		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
17		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
18		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
19		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
20		1,305,000	1,305,000		369,500		4,000	1,044,000	15,000	1,063,000	37,500	332,000		332,000	
21		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
22		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
23		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
24		1,305,000	1,305,000		369,500		4,000	1,044,000		1,048,000	37,500	332,000		332,000	
25	30,000,000		30,000,000	50,000			4,000	1,044,000		1,048,000				0	
26		1,305,000	1,305,000				4,000	1,044,000		1,048,000				0	
27		1,305,000	1,305,000				4,000	1,044,000		1,048,000	37,500			0	
28		1,305,000	1,305,000				4,000	1,044,000		1,048,000	37,500			0	
29		1,305,000	1,305,000				4,000	1,044,000		1,048,000	37,500			0	
30		1,305,000	1,305,000		369,500	30,000,000	4,000		15,000	30,019,000			50,000	50,000	

4.1.1 Alternative 1 (Baseline scenario using conventional leak detection technology)

Double wall pipes are designed with the assumption that the carrier will develop a leak during the system design life. It is assumed that the system will develop leaks in the carrier piping, eventually leading to an environmental release. The cost to precisely locate, repair, and cleanup one leak using conventional methods without leak detection is given in Table 5. For this calculation, one leak per 9 miles of piping is assumed. In the baseline system, these leaks would be located through conventional means and only after a fuel release occurred.

Table 5. Calculation of total cost for conventional leak detection and cleanup.

Number of Excavations Per Mile of Distribution	Number of Miles of Distribution Pipe	Number of Excavations Required	Cost per Excavation	Cleanup Cost	Noncompliance Financial Costs	Piping Repair Cost Per Leak	Total Cost for System-Wide Conventional Leak Detection
3	9	27	\$3,500	\$55,000	\$210,000	\$10,000	\$369,500

The occurrence of leaks is assumed to increase as the pipeline ages. This is reflected in the decrease in years between incident in the Repair leaks column of Table 4.

Refueling systems are typically taken out of service earlier than other fluid delivery systems due to the potential breakdowns in system integrity and resulting fuel leaks. For Alternative 1 the entire distribution system will

need to be replaced in Year 25 at a cost of \$30,000K with a \$50K salvage value. The \$50K salvage is listed a Benefit/Savings.

The baseline scenario also includes \$1,305K/year for pipeline maintenance costs.

4.1.2 Alternative 2 (New system scenario using AFDMS)

The AFDMS has a reduced cost to repair corrosion related problems since leaks are detected very early, before a fuel release occurs. The cost to precisely locate, repair, and cleanup one leak using the AFDMS is given in Table 6. Note that the cost difference for leak repair between the conventional technology and AFDMS is approximately \$332K per leak. This is shown as a New System Benefit in Table 4.

Table 6. Calculation of total cost for AFDMS leak detection and cleanup.

Number of Excavations Per Mile of Distribution	Number of Miles of Distribution Pipe	Number of Excavations Required	Cost per Excavation	Cleanup Cost	Noncompliance Financial Costs	Piping Repair Cost Per Leak	Total Cost for System-Wide AFDMS Leak Detection
1	9	9	\$3,500	\$5,00	\$0	\$1,000	\$37,500

The occurrence of leaks is assumed to increase as the pipeline ages. This is reflected in the decrease in years between occurrences.

Since the fuel distribution system will be repaired at the earliest sign of degradation throughout the system lifetime, use of the AFDMS is expected to slightly increase the useful life of the fuel distribution system compared to the baseline system without leak detection. The estimated system life extension with the AFDMS is about 20%. For Alternative 2 the distribution system is replaced in Year 30 (a 20% increase in service life) with a \$50K salvage value. The \$50K salvage is listed a Benefit/Savings.

In addition to the \$1,044K/year of pipeline maintenance costs (we assume that maintenance costs are 20% less than those for the baseline system) there is a small AFDMS operational and maintenance cost of \$4K/year for power consumption and calibration. Also, every 10 years the sensors will require new batteries and possible replacement or upgrade.

4.2 Projected return on investment (ROI)

The ROI for this technology was computed using methods prescribed by Office of Management and Budget (OMB) Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*.

Comparing the costs and benefits of the two alternatives, the 30-year return on investment is projected to be about 6.42, as shown in Table 7.

Table 7. OMB return on investment calculation.
Return on Investment Calculation

Investment Required					945,000		
Return on Investment Ratio					6.42	Percent	642%
Net Present Value of Costs and Benefits/Savings					16,831,818	22,897,339	6,065,522
A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	1,305,000		1,048,000		979,461	1,219,653	240,192
2	1,305,000		1,048,000		915,323	1,139,787	224,464
3	1,305,000		1,048,000		855,482	1,065,272	209,789
4	1,305,000		1,048,000	332,000	799,519	1,248,867	449,348
5	1,305,000		1,048,000		747,224	930,465	183,241
6	1,305,000		1,048,000		698,282	869,522	171,239
7	1,305,000		1,048,000	332,000	652,590	1,019,360	366,770
8	1,305,000		1,048,000		609,936	759,510	149,574
9	1,305,000		1,048,000		570,007	709,790	139,782
10	1,305,000		1,063,000	332,000	540,323	832,087	291,764
11	1,305,000		1,048,000		497,905	620,006	122,101
12	1,305,000		1,048,000	332,000	465,312	726,828	261,516
13	1,305,000		1,048,000		434,920	541,575	106,655
14	1,305,000		1,048,000	332,000	406,414	634,829	228,414
15	1,305,000		1,048,000		379,795	472,932	93,137
16	1,305,000		1,048,000	332,000	354,958	554,452	199,494
17	1,305,000		1,048,000		331,797	413,163	81,366
18	1,305,000		1,048,000	332,000	310,103	484,388	174,285
19	1,305,000		1,048,000		289,772	360,833	71,061
20	1,305,000		1,063,000	332,000	274,679	423,001	148,322
21	1,305,000		1,048,000		253,092	315,158	62,066
22	1,305,000		1,048,000	332,000	236,534	369,471	132,937
23	1,305,000		1,048,000	332,000	221,023	345,243	124,220
24	1,305,000		1,048,000	332,000	206,561	322,653	116,092
25	30,000,000	50,000	1,048,000		202,252	5,526,000	5,323,748
26	1,305,000		1,048,000		180,466	224,721	44,255
27	1,305,000		1,048,000		168,623	209,975	41,351
28	1,305,000		1,048,000		157,619	196,272	38,653
29	1,305,000		1,048,000		147,349	183,483	36,134
30	1,305,000		30,019,000	50,000	3,944,497	178,047	-3,766,450

The original ROI ratio from the Project Management Plan (PMP) was estimated at 12.76. Many of the cost and benefit estimates used in the PMP were refined during the project, but those changes were minimal. The biggest difference between the original and revised ROI assumptions was the frequency of leak repairs. The original assumption (one per year) was revised to reflect a more realistic frequency.

5 Conclusions and Recommendations

5.1 Conclusions

The AFDMS as designed and constructed uses intrinsically safe components that exceed NEMA 8 safety certification requirements. NEMA 8 devices are rated for indoor or outdoor use in hazardous (classified) locations classified as Class I, Division 1, Groups A, B, C, and D as defined in NFPA 70.

During 30 months of operation at Fort Campbell, no leaks were detected by the AFDMS in the SHHRS underground pipelines. This result agrees with the ground truth: no leaks were discovered using conventional inspection methods. Although there were no leaks to be detected, AFDMS functionality is validated to perform as designed. System sensors detected pump and check valve noise on numerous occasions, and these signals may carry diagnostic information related to other types of SHHRS operational issues that should be investigated by qualified personnel. During the project, the check valve noise data, as correlated with pump noise data and system pressure data, made it clear that the valve was not holding pressure or completely sealing. Also, based on pump noise data, abnormal sounds may indicate that cavitation is occurring inside the pump, which will rapidly erode and damage the impeller.

Several important lessons were learned during the execution of the project:

1. It is critically important to closely coordinate with installation personnel responsible for information management and security in order to avoid delays and to achieve system communications requirements.
2. It is essential to obtain good mapping information and supplemental data sources for purposes of accurately tracing underground pipes and other critical infrastructure near the pipe network.
3. Carefully planning the location of acoustic sensors can significantly reduce the amount of extraneous pipeline noise that is captured as data.

5.2 Recommendations

5.2.1 Applicability

The acoustic leak detection technology is applicable to all fuel distribution systems, buried or above ground, double- or single-wall. System hardware and programming will vary between applications. For example, we demonstrated the technology on a small buried double-wall system, and although we developed an acoustic sensor attachment method for double-wall systems, we did not need to use that method because we attached the sensors in the access pits where the pipeline was single wall. Also, the signal-processing requirements were more demanding because the nearby fuel pump created more acoustic noise.

The ROI will be much higher for buried applications versus above ground because it is much easier to locate a leak using conventional methods above ground.

5.2.2 Implementation

The DoD Fuel Facility Engineering Panel discussed proposed changes to UFC 3-460-01, *Design: Petroleum Fuel Facilities* on 24 February 2011 after performing research on the technology. The panel's decision at that time was to recommend against revising the UFC at that time. The panel agreed that acoustic leak detection is a viable technology, and indicated its willingness to revisit the issue of DoD implementation once the technology's ability to detect fluid leaks has been more thoroughly demonstrated and validated, and the system specifications have been EPA third-party certified.

Once this technology has been more thoroughly demonstrated and validated it could be implemented as an option for military installations by revising UFC 3-460-01 paragraph 9-4.8.1 to read as follows:

“For aircraft direct fueling systems, provide an automatic leak detection system approved by Service Headquarters, to test all buried portions of the piping system. Automatic leak detection systems may measure changes in either the volume or pressure of the fuel in a fixed piping system, while accounting for variations in ambient temperature or changes in the acoustic properties of the pipe. The pressure type shall work by measuring the time rate of change of line pressure at two different pressures. The volume type

shall work by measuring the amount of fuel required to maintain a constant pressure in a line, also at two different pressures. Acoustic types actively or passively detect changes in the signature of acoustic waves propagating either in or on the pipe. The system shall have sufficient sensitivity to detect leaks of at least 0.004 percent of line volume with a Probability of Detection = 95 percent and a Probability of False Alarm = 5 percent. All leak detection systems shall be third-party certified.”

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Appendix A: Data Analysis

The acoustic signals detected by the nine acoustic sensors of the Acoustic Fuel Distribution Monitoring System (AFDMS) which monitor the underground pipelines of the Sabre Heliport Hot Refueling System (SHHRS) were digitized by the six slave radios and recorded on the hard disk of the central computer in building A6631.

When the AFDMS program was written using DAQFactory there were several choices available for the format of the data on the hard disk. We chose to use ASCII format, mainly because it would be readable by Excel and text editors, and so offered the greatest versatility. The other formats offered a more compact (binary) file for the same amount of data but required specialized programs to read and display the data.

The data in each ASCII data file is in the form of rows and columns. Except for the first row, which gives a terse description of the data in each column, the file is composed entirely of numbers. Each row after the first one gives data for the second of time following the row before.

The first column in the AFDMS data file is the time at which the data were taken. It is an integer representing the number of seconds past midnight of January 1, 1970. This is different from the standard time in Excel, which is a decimal number giving the days since January 1, 1900. The remaining columns are: Sensor 1 Xover (Volts), Sensor 2 Supply (Volts), Sensor 3 Supply (Volts), Pressure (Psi), Sensor 5 Supply (Volts), Sensor 6 Supply (Volts), Unused, Sensor 2 Return (Volts), Sensor 3 Return (Volts), Unused, Sensor 5 Return (Volts), Sensor 6 Return (Volts), Pump Current (Amps), Radio 1 Temp (degC), Radio 2 Temp (degC), Radio 3 Temp (degC), Radio 4 Temp (degC), Radio 5 Temp (degC), Radio 6 Temp (degC), Radio 1 Battery (Volts), Radio 2 Battery (Volts), Radio 3 Battery (Volts), Radio 4 Battery (Volts), Radio 5 Battery (Volts), Radio 6 Battery (Volts), Solar 6 Output (Volts), Solar 5 Output (Volts), Solar 4 Output (Volts), Solar 3 Output (Volts), Solar 2 Output (Volts), Solar 1 Output (Volts).

As explained in the AFDMS Control Software Description section, data recording is started when the SHHRS pump turns on. The data recording is stopped when a timer expires after the pump stops. There is no special character written into the data file to indicate a pause in the data; there

will only be a gap in time (of much greater than 1 second) between two rows to indicate that the SHHRS was started up again.

The data files are named using the central computer clock values for year, month, day, hour, minute and second when the files were first opened. Thus, a data file with the name *Sabr_110504_065624.txt* started recording data on 2011 May 4 at 06:56:24.

Multiple SHHRS runs can be contained inside one AFDMS data file, but the file is limited in size (to about 12 MB). When an AFDMS file reaches its capacity, a new data file will be opened automatically. If the SHHRS is running at the time a new data file is opened, the data for that run will be split between two data files.

We used DAQFactory rather than Excel to create a program to read and plot the data contained within the AFDMS data files. Figure A1 shows the output of this program on the first test run of the AFDMS after it was installed on the SHHRS.

Figure A1. AFDMS data obtained from the initial test run immediately after installation.

Not all of the data recorded in the AFDMS data file is being plotted – only the pressure inside the SHHRS supply line, the pump status (current), and the nine leak detection sensor values are shown (a legend below each graph identifies the quantity being plotted). We felt that the radio temperatures, the radio battery voltages from the voltage doublers, and the solar cell voltage outputs would be of limited interest to the user.

The pressure behavior of the AFDMS is very important, because pressure is the driving force behind leaks. Several things of interest appear in Figure A1. First, the pump takes about three seconds to increase the pressure inside the SHHRS supply line from 0 to about 70 psi. Second, after the pump shuts off the pressure inside the SHHRS stays around 65 psi. Third, all of the acoustic sensors detect the initial noise of the pump turning on; decaying to a quiescent value at the time maximum pressure is reached. Fourth, the sensors in the supply line closest to the pump detect more noise than sensors further from the pump, while the sensors in the return line detect the same amount of noise no matter where they are located relative to the pump.

The fact that the pressure inside the SHHRS stayed high after the pump turned off was very important to us. As explained in the AFDMS Control Software Description section, we desired to listen for leaks in the quietest possible environment, e.g., after the SHHRS pump had shut down. When the pump is running it creates noise, which can mask the sound of small leaks. When the pump quits, however, there should be no noise coming from the piping of the AFDMS. However, since leak sounds depend upon a pressure difference across the wall of the pipe, it follows that there can be no leak sounds to detect if the SHHRS did not hold pressure after the pump quit running. Unfortunately, in later runs of the SHHRS, this is the exact behavior that occurred.

The device that causes the pressure to stay within the SHHRS piping is a check valve. It can be seen in the piping schematic of Figure 14, on the gray return piping just to the right of the pump. In real life, it can be seen in Figure A2. It is the silver object in the foreground piping. The pump house is in the background of the picture (on the right), and the fuel storage tank with its concrete containment basin appears on the left.

Figure A2. SHHRS check valve (silver object).

The DAQFactory program we wrote to read and plot the data contained within the AFDMS data files automatically determines the number of SHHRS runs contained in the data file, as can be seen by the text at the top right of Figure A3. In this example the number of runs is 7. A provision was made for the user to select and plot each individual run, (or the entire data file), by using the list box and button at the top right of Figure A3. To plot another data file, the button at the top left of Figure A3 brings up a normal Windows file list, allowing selection of a different AFDMS data file or normal Windows navigation to other folders on the hard disk.

Figure A3. Showing multiple SHHRS runs in one AFDMS data file in June and July of 2011.

Data from the AFDMS system obtained on Oct 6, 2009 during the very first refueling run of the SHHRS is shown in Figure A4.

As can be seen from the top plot in Figure A4, the pump was on for about 1 hour. The pressure in the SHHRS piping (red trace in top plot) was about 65 psi, and after the pump shut down the pressure remained at this value, i.e., the check valve was holding pressure. Note that the pump was briefly turned on again after the 1 hour refueling period was over and then quickly turned off (green trace in top plot). The middle and lower plots show the output of the AFDMS acoustic sensors. Seven of the acoustic sensors detected low level noise that was unaffected by the pump status. Sensor 5S (cyan trace in middle plot) detected a constant, higher amount of noise unaffected by the pump status, while sensor 6S (dark blue trace in middle plot) detected pump noise when the pump was running. There are also some random noise spikes on several of the sensors – their cause is unknown, but they can be considered inconsequential since they were short-lived.

Figure A4. AFDMS data obtained from the first refueling run on Oct 6, 2009.

The effect of helicopter operations on the AFDMS is shown in Figure A5 and Figure A6. Figure A5 shows a normal SHHRS refueling run monitored by the AFDMS, followed by a single helicopter taking off after the pump was shut down. Sensor 1X (red trace in middle plot), sensor 2S (brown trace in middle plot) and sensor 2R (brown trace in bottom plot) show the helicopter starting and then taking off. Note in the top plot of Figure A5 that the pressure inside the SHHRS (red trace in top plot) stays high after the pump shuts off (green trace in top plot), i.e., the check valve was holding pressure.

Figure A6 shows the effect on the AFDMS of several helicopters taking off. The effect is much more dramatic than that caused by a single helicopter shown in Figure A5. The helicopters started up before the pump shut off (green trace in top plot), and their noise can be easily seen on sensors 1X (red trace in middle plot), 2S (brown trace in middle plot), 3S (green trace in middle plot), 5S (cyan trace in middle plot), 6S (dark blue trace in middle plot), 2R (brown trace in bottom plot), 3R (green trace in bottom plot), 5R (cyan trace in bottom plot) and 6R (dark blue trace in bottom plot).

Figure A5. AFDMS data obtained on Oct 6, 2009 showing a helicopter taking off.

Figure A6. AFDMS data obtained on Mar 24, 2010 showing several helicopters taking off.

In addition to helicopter noise, note the difference in the pressure behavior (red trace in top plot) between Figure A5 and Figure A6 after the pump shuts off (green trace in top plot). In Figure A5 the pressure inside the SHHRS stays high after the pump shuts off, but in Figure A6 the pressure dropped to 5 psi once the pump was shut off. We believe that this is due to the check valve (see Figure 14 and Figure A2) sticking open, and unfortunately it seemed to happen most of the times after SHHRS refueling runs were completed. This is unfortunate, because it deprived us of the chance to listen for leaks in the quietest possible environment.

Figure A7 shows a suspected pump problem (red trace in top plot) detected by the AFDMS, with the pump briefly turned on again after the refueling period was over and then quickly turned off (green trace in top plot). It can be seen that the pump went to very high pressure (70 psi, red trace in top plot) three times, but was unable to hold pressure at other times even though the pump was drawing current (green trace in top plot). The effect that the pump had on the AFDMS sensors was fairly dramatic on sensors 2S (brown trace in middle plot), 3S (green trace in middle plot),

and 6S (dark blue trace in middle plot), but much less so on the other six sensors.

Figure A7. AFDMS data showing suspected pump problem on Oct 21, 2009.

Figure A8 shows a different kind of suspected pump or check valve problem detected by the AFDMS. We are not sure what is happening, but it may be pump cavitation (Neill et al. 1997; Alfayez et al. 2005). Whatever the cause, a drop in the pump pressure (red trace in top plot) from 65 psi to 55 psi occurs for about 15 minutes, the pressure drops to 0 psi quickly and then recovers to 65 psi, before the pump is shut off (whereupon the pressure drops to 5 psi). During the time the pump pressure is at 55 psi dramatic changes occur on the traces of sensors 5S (cyan trace in middle plot) and 6S (dark blue trace in middle plot), 2R (brown trace in bottom plot) and 5R (cyan trace in bottom plot).

Figure A8. AFDMS data showing suspected pump or check valve problem on Mar 31, 2010.

Figure A9 shows a suspected check valve problem detected by the AFDMS. In contrast to Figure A8, the pump pressure (red trace in top plot) remains fairly constant at 55 psi (except for two brief spikes) while the pump is on (green trace in top plot). However, sensors 5S (cyan trace in middle plot), 6S (dark blue trace in middle plot), 5R (cyan trace in bottom plot) and 6R (dark blue trace in bottom plot) are dramatically affected by the problem until the pump is shut off. We suspect that the check valve has a seating problem. Unlike all other AFDMS plots shown so far, note that the SHHRS pressure rises constantly once the pump is turned off.

Figure A9. AFDMS data showing suspected check valve problem on Oct 20, 2009.

Figure A10 shows another example of a suspected check valve problem detected by the AFDMS. It is kind of a combination of what occurred in Figure A8 and Figure A9. Note that there are two runs in Figure A10. The first run is very analogous to the situation in Figure A8, where a 5 psi drop in pump pressure causes a dramatic change in sensors 2S (brown trace in middle plot), 5S (cyan trace in middle plot) and 6S (dark blue trace in middle plot), 2R (brown trace in bottom plot) and 5R (cyan trace in bottom plot). The second run is analogous to the situation in Figure A8, where once the pump turns on sensors 5S (cyan trace in middle plot) 6S (dark blue trace in middle plot), 5R (cyan trace in bottom plot) and 6R (dark blue trace in bottom plot) are dramatically affected by some sort of problem (check valve seating?) until the pump is shut off.

Figure A10. AFDMS data showing suspected check valve problem on Mar 24, 2010.

Figure A11 shows another kind of a suspected pump or check valve problem detected by the AFDMS. In this example the pump slowly builds up pressure in steps, with some spikes and a brief drop to 0 psi. It is somewhat analogous to the situation in the first run of Figure A10, but there are some differences. Sensors 2S (brown trace in middle plot), 5S (cyan trace in middle plot) and 6S (dark blue trace in middle plot), 2R (brown trace in bottom plot) and 5R (cyan trace in bottom plot) are all affected by these problems. Some problems are transient in nature, while others occur over several minutes.

Figure A11. AFDMS data showing suspected pump or check valve problem on Mar 29, 2010.

Figure A12 is similar to Figure A8, showing a suspected pump or check valve problem detected by the AFDMS. Here a drop in the pump pressure (red trace in top plot) from 65 psi to 50 psi occurs for about 5 minutes after which the pressure increases again to 65 psi before the pump is shut off (whereupon the pressure drops to 5 psi). During the time the pump pressure is at 60 psi dramatic changes occur on the traces of sensors 5S (cyan trace in middle plot) and 6S (dark blue trace in middle plot), 2R (brown trace in bottom plot) and 5R (cyan trace in bottom plot). Also note that in contrast to Figure A8 (recorded on Mar 31, 2010), Figure A12 (Mar 30, 2010) has no plots for sensors 2S (brown trace in middle plot) and 2R (brown trace in bottom plot).

Figure A12. AFDMS data showing suspected pump or check valve problem on Mar 30, 2010.

Figure A13 shows a different sort of problem than do the previous AFDMS plots. Here only four sensors seem to be detecting acoustic data. We believe that this was due to aging of the lead-acid batteries used by the slave radios. After the AFDMS was connected to the internet in Nov 2011 we were able to remotely view and control the system, and discovered that the batteries were not holding their charge through the night. Replacement batteries were ordered and installed in all of the slave radios, and the problem documented in Figure A13 didn't recur.

Figure A13. AFDMS data showing suspected battery problems on Aug 17, 2011.

Appendix B: AFDMS Data File Summary

The AFDMS installed on the underground pipelines of the Sabre Heliport Hot Refueling System (SHHRS) at Fort Campbell was operated for a total of 30 months. Because of troop deployments to Iraq and Afghanistan, the SHHRS was not continuously in use during the entire 30 months. Nevertheless, the AFDMS recorded 23 data files over that time period, containing 103 operational runs of the SHHRS. A summary of the main information in each run is summarized below. Runs (or files) highlighted in red text are those that are depicted in Figure 14 and Figure 15 in the main body of the report; and in Figure A3 — Figure A13 in Appendix A.

Sabr_091002_190047_Test1

Run 1, current square, pressure goes high and stays high, initial sensor peak then quiescent, 5S highest, 6S next, others similar but low

Sabr_091002_190629_Test2

Run 1, current square, pressure high and decays slowly, initial sensor peak then quiescent with few small peaks, 5S highest, 6S next, others similar but low

Sabr_091003_131728Test3

Run 1, current square, no pressure, initial sensor peak for all but 5S and 5R, others quiescent

Sabr_091006_082633

Run 1, current square w/ spike after run, pressure goes high and stays high, sensors mostly quiescent, 5S highest, 6S next, others similar but low

Run 2, current square, pressure high and stays high, initial sensor peak then quiescent with few small peaks, 5S highest, 6S next, others similar but low, helicopter take-off on 1X, 2S and 2R

Run 3, current square, pressure high w/ some spikes then stays high, initial sensor peak then quiescent with lots of peaks, 5S highest, 6S next, others similar but low

Run 4, current square, pressure only 55 w/ some spikes then goes low and gets higher, initial sensor peak then quiescent with few small peaks, 6R and 5R highest, 6S and 5S next, others similar but low. Check valve problem?

Run 5, 7 current spikes, pressure below 10, initial sensor peak then quiescent with few peaks, 5S highest, 6S next, others similar but low. Pump problem?

Run 6, current spike then square, pressure to 70 then cycles 20 times to 0 where it stays before pump shut off, initial sensor peak then quiescent with peaks on 6S, 2S and 3S, 6S highest, 5S next, others similar but low. Pump problem?

Run 7, current square, pressure high and stays high then drops abruptly, initial sensor peak then quiescent with few small peaks, 5S highest, 6S next, others similar but low

Run 8, current square, no pressure, initial sensor peak for all, noise on 3S, 3R, 1S, 6S and 5S high then 6S drops, others quiescent. Pump problem?

Run 9, current square, pressure 70 then 65 w/ one dropout then goes low and gets higher, initial sensor peak then quiescent with few small peaks, 6R highest, 6S and 5S next, 2R and 5R next, others low. Check valve problem?

Run 10, current always high (run continues), pressure high and stays high, initial sensor peak then quiescent with few small peaks, 6R highest, 6S and 5S next, 2R and 5R next, others low.

Sabr_091027_084059

Run 1, current square (run continued), pressure high and stays high then goes low and gets higher, no initial sensor peak but quiescent with few small peaks, 6R highest, 6S and 5S next, 2R and 5R next, others low.

Run 2, current square, pressure to 65 then cycles 4 times to 0 where it stays before pump shut off then gets higher, initial sensor peak then quiescent with few small peaks, 6R highest, 5S and 6S next, 2R and 5R next, others low. Check valve problem?

Run 3, current spike, pressure 5 constantly, initial sensor peak then quiescent with few small peaks, 5S highest, 6S next, others low. Shows 25 minute pump timer operation

Run 4, incomplete 30 second file, current always high, pressure increasing to 60, initial sensor peak then quiescent, 6R increases off scale, others low.

Sabr_100323_150855

Run 1, current square, pressure high and stays high then drops abruptly, initial sensor peak then quiescent with few small peaks, 6R highest, 6S, 5R and 5S next, others similar but low

Run 2, 2 current squares first w/ 2 spikes, pressure high then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R, 6S and 5S next, noise on 2S and 2R, others similar but low. Check valve problem?

Run 3, current square, pressure 70 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, others similar but low

Run 4, 2 current squares both w/ spikes, pressure high then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, noise on 2S and 2R, others similar but low. Check valve problem?

Run 5, current square (run incomplete), pressure increasing to 60, initial sensor peak then quiescent, 6R, then 5R increases off scale, 6S and 5S next, others low.

Sabr_100324_191956

Run 1, current square (run continued) w/ 3 more current squares, pressure high with spikes then drops abruptly, no initial sensor peak but quiescent with few small peaks, 6R highest, 5R next, 6S and 5S next, noise on 2S and 2R, others low. Check valve problem?

Run 2, current square, pressure 60 then drops abruptly, initial sensor peak then quiescent with few small peaks, 6R highest, 5R next, 6S and

5S next, others similar but low, helicopter take-off seen on 1X, 2S, 3S, 5S, 6S, 2R, 3R, 5R and 6R. Check valve problem?

Run 3, current square, pressure 60 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, others similar but low

Run 4, current square w/ 2 spikes, pressure 60 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R, 6S and 5S next, helicopter landing noise on 2S, 2R and 5S, others similar but low. Check valve problem?

Run 5, current spike, pressure varies up to 5, initial sensor peak then quiescent with few small peaks, 5S highest, 6S next, others low. Shows 25 minute pump timer operation

Run 6, current square, pressure 55 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 5S and 6S next, others similar but low

Run 7, current square, pressure 60 w/ spike then drops abruptly, initial sensor peak then quiescent with few small peaks, 6R highest, 6S and 5S next, others similar but low, helicopter take-off seen on 2S, 5S, 6S, 2R, 5R and 6R. Check valve problem?

Run 8, current square w/ 2 spikes, pressure 55 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S and 5S next, noise on 2S, and 2R, others similar but low. Check valve problem?

Run 9, 2 current squares w/ second incomplete, pressure 55 with small spikes and spikes to 0 then drops abruptly, initial sensor peak then quiescent, 6R highest, 5R next, 5S and 6S next, noise on 2S and 2R, others low. Pump problems?

Sabr_100329_200649

Run 1, current square (continued run) w/ 1 more current square, pressure 55 with spikes then drops abruptly, no initial sensor peak but quiescent with few small peaks, 6R highest, 5R next, 6S and 5S next, noise on 2S and 2R, others low. Check valve problem?

Run 2, current square, pressure 60 w/ 5 spikes then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S and 5S next, noise on 2S, 2R and 5R, others similar but low. Check valve problem?

Run 3, current spike, current square, current spike, pressure 65 w/ 3 spikes then drops abruptly, no initial sensor peak but quiescent with few small peaks, 6R highest, 6S and 5S next, noise on 5R, 6S, 5S and 1X, others similar but low. Check valve problem?

Run 4, current square, pressure 65 w/ 4 spikes then drops abruptly, initial sensor peak then quiescent with few small peaks, 6R highest, 5R next, 6S and 5S next, noise on 2S, and 2R, others similar but low. Check valve problem?

Run 5, 4 current squares, pressure 65 w/ lots of spikes then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, noise on 2S, 2R as well as 5R, 6S and 5S, others similar but low. Check valve problem?

Run 6, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S and 5S next, others similar but low

Run 7, current square (run incomplete), pressure increasing to 60 w/ spike then 65, initial sensor peak then quiescent, 6R highest, 5R next, 6S and 5S next, others low.

Sabr_100331_154528

Run 1, current square (continued run), pressure 65 with spike then drops abruptly, no initial sensor peak but quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, noise on 6R, 5R, 6S, 5S w/ drop on 2R, others low. Check valve problem?

Run 2, 2 current squares, pressure 65 w/ lots of spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, noise on 5R, 6S and 5S, others similar but low. Check valve problem?

Run 3, current square w/ spike, pressure 65 w/ lots of spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R next, 6S and 5S next, noise on 5R, 6S and 5S, others similar but low. Check valve problem?

Run 4, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S and 5S next, others similar but low

Run 5, current square, pressure 65 w/ spike and drop then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S and 5S next, noise on 5R, 6S, 5S and 2S, others similar but low. Check valve problem?

Run 6, current square, pressure 65 w/ lots of spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R next, 5S next, noise on 5R, 5S, 2S and 2R, others similar but low. Check valve problem?

Run 7, 2 current squares, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S highest, 5S and 5R next, noise on 5R, 6S, 5S, 5R, 2S and 2R, others similar but low. Check valve problem?

Run 8, current square, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S, 5R and 5S next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Pump or check valve problem?

Sabr_100406_190919

Run 1, current spike and square, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 5R highest, 6S, 5S and 2S next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Check valve problem?

Run 2, current square, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 5R highest, 6S and 5S next, noise on 5R, 6S, 5S, and 2R, others similar but low. Check valve problem?

Run 3, current square, pressure 60 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 5R highest, 6S, 2S and 5S next, noise on 5R, 6S, 5S, 2S, and 2R, others similar but low. Check valve problem?

Run 4, 4 current squares (2nd with spike), pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S highest, 5R, 5S, 2R and 2S next, noise on 5R, 6S, 5S, 2S, and 2R, others similar but low. Check valve problem?

Run 5, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S, 5R and 5S next, noise on 5R, others similar but low. Pump or check valve problem?

Run 6, current square, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S, 5R and 5S next, 2R and 2S next, noise on 5R, 6S, 2S and 2R, others similar but low. Pump or check valve problem?

Run 7, 2 current squares, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 5R, 6S, 5S, 2S and 2R next, helicopter landing noise on 5R, 2S, 2R, 6S and 5S, others similar but low. Check valve problem?

Run 8, current square, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R highest, 6S, 5R and 5S next, 2R next, noise on 5R, 6S, 5S and 2R, others similar but low. Pump or check valve problem?

Run 9, current square (run incomplete), pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R, 5S and 2R next, others similar but low. Check valve problem?

Sabr_100408_113956

Run 1, current square (continued run), pressure 65 w/ drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R, 5S and 2R next, others similar but low. Check valve problem?

Run 2, 2 current squares, pressure 65 w/ drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R, 5S, 2S and 2R next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Check valve problem?

Run 3, 6 current squares, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R, 5S, 2S and 2R next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Check valve problem?

Run 4, 3 current squares, pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R and 6S off-scale, 5R, 5S, 2S and 2R next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Check valve problem?

Run 5, current square (run incomplete), pressure 65 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R off-scale, 5R, 6S, 5S and 2R next, others similar but low. Check valve problem?

Sabr_100409_083747

Run 1, current square (continued run), pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R off-scale, 6S, 5R, 5S and 2R next, others similar but low. Check valve problem?

Run 2, current square, pressure 60 w/ spikes and drops then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6R off-scale, 5R, 6S, 5S, 2S and 2R next, noise on 5R, 6S, 5S, 2S and 2R, others similar but low. Check valve problem?

Sabr_101214_101354

Run 1, current square, no pressure, initial sensor peak then quiescent with lots of small peaks, 6R and 6S highest, 5S next, others similar but low. Pressure sensor problem?

Sabr_110426_135932

Run 1, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6S off-scale, 6R and 5S next, others similar but low. Check valve problem?

Run 2, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6S off-scale, 6R and 5S next, others similar but low. Check valve problem?

Sabr_110427_071206

Run 1, current square, pressure 65 w/ drop then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 1X, 3S, 5S, 3R and 5S off-scale, 6S, 6R, 2S and 2R next. Check valve problem?

Sabr_110504_065624

Run 1, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 1X, 5S, and 5R off-scale, 6S, 6R, 2S, 2R, 3S and 3R next. Check valve problem?

Run 2, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6S off-scale, 6R and 5S next, others similar but low. Check valve problem?

Run 3, current square, pressure 65 w/ spike then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6S and 6R very high, 5S next, others similar but low. Check valve problem?

Run 4, current square, pressure 65 w/ spikes then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 1X, 5S, 3S, 3R, and 5R off-scale, 6S and 6R very high, 2S and 2R low. Check valve problem?

Run 5, current square, pressure 65 then drops abruptly, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, 5S next, others similar but low. Check valve problem?

Run 6, current square (run incomplete), pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 5S and 5R off-scale, 6R, 3S, and 1X next, noise in 1X and 3S, 2R and 3R low.

Sabr_110601_091933

Run 1, current square (continued run), pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 5S and 5R off-scale, 6R next, noise in 3S, 1X, 2R and 3R low.

Run 2, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 5S and 5R off-scale, 6R next, noise in 3S, 3R and 1X, and 2R low.

Run 3, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S off-scale, 6R and 5S next, noise in 3S and 3R, 1X, 2S, 2R, 3R and 5R low.

Run 4, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S off-scale then drifts on, 6R next, noise in 3R and 5S, 1X, 2S, 3S, 2R, 3R and 5R low.

Run 5, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S off-scale then drifts on, 5S off-scale, 6R next, noise in 3R, 1X, 2S, 3S, and 2R low.

Run 6, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 5S and 3S, 1X, 2S, 3S, 2R, 3R and 5R low.

Run 7, current square (run incomplete), pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S off-scale then drifts on, 6R next, noise in 1X, 2S, 3S, 5S, 2R, 3R and 5R low.

Sabr_110706_081357

Run 1, current square (continued run), pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 3R, 1X, 2S, 3S, 5S, 2R, and 5R low.

Run 2, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, and 3R off-scale, noise in 1X, 2S and 2R low.

Run 3, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 5S and 5R, 1X, 2S, 3S, 2R, and 3R low.

Run 4, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, and 1X off-scale, noise in 3R, 2S, 2R and 3S low.

Run 5, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S and 5R off-scale, noise in 3R, 1X, 2S, 3S and 2R low.

Run 6, current square (run incomplete), pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S and 5R off-scale, noise in 3R, 1X, 2S, 3S and 2R low.

Sabr_110803_084722

Run 1, current square (continued run), pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 5S and 5R off-scale, 6R off-scale then drifts on, 1X, 2S, 3S, 2R and 3R low.

Run 2, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 6R and 1X off-scale, noise in 3S, 5S, 5R and 3R, 2S and 2R low.

Run 3, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, noise in 1X, 2S and 2R low.

Run 4, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S and 5R off-scale, noise in 1X and 3R, 2S, 3S and 2R low.

Run 5, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 1X, 3S and 3R, 2S, 2R and 5R low.

Run 6, current square, pressure 65 with spikes and drops, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 1X, 3S and 3R, 2S, 5S, 2R and 5R low.

Sabr_110921_071919

Run 1, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Run 2, 3 current squares, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, noise in 5S and 5R, 1X, 2S, 3S, 2R and 3R low.

Run 3, current square, pressure 65 drops then rises, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, 1X, 2S, 3S, 5S, 2R, 3R and 5R low.

Run 4, current square, pressure 65, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Run 5, current square, pressure 65 drops then rises to 35, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Run 6, current square, pressure 65 drops then rises to 35, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, 1X, 2S, 3S, 5S, 2R, 3R and 5R low.

Run 7, current square, pressure 65 drops then rises to 35, initial sensor peak then quiescent with lots of small peaks, 6S and 6R off-scale, 1X, 2S, 3S, 5S, 2R, 3R and 5R low.

Run 8, current square, pressure 65 drops then rises to 25, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Run 9, current square (run incomplete), pressure 40 drops to 0, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Sabr_111116_082821

Run 1, current square (continued run), pressure spikes from 0, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Sabr_111123_070625

Run 1, current square, pressure spikes from 0, initial sensor peak then quiescent with lots of small peaks, 6S, 6R, 5S, 5R, 3S, 3R and 1X off-scale, 2S and 2R low.

Sabr_111207_065733

Run 1, current square, pressure 65 drops then rises to 35, initial sensor peak then quiescent with lots of small peaks, 6R off-scale, 6S next, 1X, 2S, 3S, 5S, 2R, 3R and 5R low.

Appendix C: Final report for Contract DACA42-01-P0282, U.S. Army Construction Engineering Research Laboratory, Champaign, IL

Acoustic Leak Surveys of AST Pipelines and UST Systems at Dugway Proving Ground

by

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2 August 2004

Introduction

During the period of 17-21 May 2004 we were at the Ditto Chemical Laboratory of Dugway Proving Ground, Dugway, UT. We acoustically surveyed the underground pipelines associated with the four Above-ground Storage Tanks (ASTs) at the Chemical Laboratory, as well as the tanks and the pipelines associated with five of the Underground Storage Tanks (USTs) located in and near the Chemical Laboratory for possible leaks. We discovered one definite and one potential leak in two of the AST pipelines, as well as definite leaks in the piping of three of the USTs. The Dugway Proving Ground person that we interacted with during our work was Steve Salas, of the Directorate of Environmental Programs.

Acoustic Leak Location Procedure

Detecting leaks with acoustics is a fairly straightforward process. But, an acoustic engineer must accomplish all of the following five steps in order to locate a leak:

Position two sensors so that they bracket (surround) a possible the leak. If the sensors do not surround the leak, location *cannot* be done, no matter what signal processing method is used! (If the sensors do not surround the leak only leak detection can be accomplished.)

Acoustically couple the sensors to the pipe so that both sensors receive distinct leak signals. Leak location cannot be performed without signal arrivals at *both* sensors. This step implies that quick, reproducible methods exist to acoustically couple sensors to pipes in the field.

Measure the distance between the sensors, D , and determine the velocity of sound in the media contained in the pipe, V .

Use signal processing (e.g., coincidence detection and cross-correlation) to determine a time difference, Δt , for the arrival of a specific signal feature at both sensors.

Using the time difference Δt obtained in Step 4, calculate the location of the leak using the following equation:

$$\text{Location from first sensor detecting signal} = (D - (V \times \Delta t)) / 2$$

Note that in order to successfully locate leaks it is absolutely necessary to (1) insure that the sensors are on the correct pipe, and (2) know the length, material and diameter of the pipe being monitored. We depend upon the piping system owner to provide this data accurately (in the form of maps and tables) so that the location we calculate using it will be reliable (and DPG did indeed provide such information to us).

Instrumentation Description

The acoustic instrument that we used during the leak location investigation on the DPG AST associated underground piping was a Fluid Conservation System's AccuCorr, a commercial leak location instrument. The most attractive features of this instrument for the two DPG pipelines were that it was battery powered and that it used wireless connections between the magnetically coupled sensors and the instrument base, which greatly simplified field use. The AccuCorr operates in the frequency range of about 1 Hz to 5000 Hz, and uses cross-correlation techniques to obtain a Δt value to locate leaks. Cross-correlation compares the shape of a signal received by sensor 1 with that received by sensor 2 for all possible arrival times by shifting them in time and adding the two signals together, yielding a single

value for each possible arrival time. This processing provides a peak when the time shift of the signals equals the exact time that a signal feature of a certain shape received at sensor 1 arrives at sensor 2. Cross correlation is sensitive to dispersion (when the shape of the signal changes with propagation, the comparison gets less good), but it generally has a good track record in the field.

To determine if the use of the AccuCorr would be justified on the sorts of leaks we would encounter in Army projects, we tested it on pedigreed leaks in an experimental pipeline that had been built using SERDP funding at the Environmental Protection Agency site in Edison, NJ. Our experimentation proved that we could reliably locate a 12 gph leak with a sensor spacing of 633 feet, and a 0.75 gph leak with a sensor spacing of 50 feet. Flow noise, vehicular traffic and even people talking near the sensors were easily picked up using the AccuCorr, but this did not seem to affect its leak location capabilities.

For the testing of the UST systems we hired Precision Testing Technologies, Inc., of Sandy, UT, as they had the specialized equipment needed to perform the work. A synopsis of the most important information regarding their equipment, the Estabrook EZY 3 Locator Plus, can be found at this web site: http://www.nwglde.org/evals/estabrook_ezy_check_d.html. The manufacturer's information page for this equipment can be found at this web site: <http://www.ezychek.com/the-system.html>. The ability of this equipment to find leaks has been certified by a third party, Ken Wilcox Associates. Precision Testing Technologies' personnel have also been trained and certified.

In essence, Precision Testing Technologies tested the USTs by first installing caps and shutting off valves to isolate the UST from the atmosphere. The depth of any water at the bottom of the tank is determined by using a tape measure whose end has been coated with water revealing paste. Then sufficient vacuum is established in the ullage space of the tank to overcome the weight of the product contained in a one square inch column from the bottom of the tank to the top of the product. While the vacuum is present the operator listens for any sounds detected by a microphone placed in the ullage space. Bubbling sounds reveal air being drawn through leaks in the tank below the product level; whistling sounds indicate leaks in the tank (or associated piping) above the product level; and silence indicates a leak-free tank and piping system. At the end of the test the water level at the bottom of the tank is measured again (to ensure

that water has not been drawn silently into the tank during the time the vacuum was present), the caps are removed and the valves that were shut are reopened, thus returning the tank to service.

Results

We surveyed a total of eight underground double-walled pipelines associated with the ASTs and five USTs and their associated piping. We obtained a definite leak indication in the AST fuel oil pipelines, a potential leak indication in the AST diesel fuel pipeline, and we discovered that three of the USTs and their associated piping were not leak tight (at Buildings 4258, 4361 and 4165).

Before starting our survey we were told that during the heating season the oil water separation system was extracting about 500 gallons of petroleum product every 14 days from the ground water, which meant that we were looking for a cumulative leak size on the order of 1.5 gallons per hour (gph). This size leak meant that it would be difficult to locate, because for the 345 foot sensor spacing that we would be forced to use our minimum reliably detectable leak size would be on the order of 5.9 gph.

Figure C1. Circulating pump pit end of the double-walled fuel oil pipeline.

The leak survey was started on the AST pipelines by removing the top mounted plugs in the vent ports of the conduits of the double-walled lines (see Figure C1). This photograph shows the Circulating Pump Pit end of

the double-walled fuel oil pipeline running from the Circulating Pump Pit to Building 4156. The vent plug was located where the galvanized steel/black iron piping is shown in the upper left. Note that the vent port on the conduit is located at 11 o'clock instead of the manufacturer's specified 12 o'clock position. The acoustic sensor is located to the right of the double-wall conduit termination plate. It is the dark gray cylinder attached to the gray wire.

Five of the six pipelines showed no problems during this inspection – there was no smell of fuel or diesel oil inside the annulus space, and no evidence of fuel or diesel oil visible on the inside bottom surface of the conduit. However, the sixth line, carrying fuel oil underground from the circulating pump pit to Building 4156, smelled strongly of fuel oil in the annulus space and also showed fuel oil traces on the inside bottom surface of the conduit. This was discovered when we removed the bottom mounted drain port plug in the circulating pump pit and saw that the dimple in the plug contained fuel oil.

We installed our acoustic sensors at each end of the fuel oil pipeline (in Figure 1 our acoustic sensor appears as the dark gray cylinder attached to the gray wire) and listened in turn for sounds of leaks in first the supply and then the return line that run through the outer conduit of the pipeline (Figure C1 shows our acoustic sensor on the supply line; the return line is the other pipe running through the end cap). These tests were inconclusive – we obtained peaks from our instrument but the peaks did not repeat in a consistent enough fashion for us to feel comfortable that we had definitely discovered a leak. We did determine, however, that the indications always appeared at the end of the pipeline closest to Building 4156 – this is a section of the fuel oil pipeline that had not been exposed during a prior leak location project at DPG.

At this point we decided to perform a conduit pipe air test to check the conduit wall integrity of the fuel oil pipeline, following the instructions in Section 7.02.1 of the pipeline manufacturer's installation guide:

http://www.permapipe.com/Install_guides/ultra.pdf. Figure C1 shows how we attached the air compressor to the double-walled fuel oil pipeline (via the galvanized steel/black iron piping). After starting the air compressor we waited for the pressure gauge to reach 15 psi, however, we were unable to exceed 11 psi in the fuel oil pipeline. Shutting off the air compressor we noted that the pressure dropped at a rate of 1 psi every 4 minutes. We applied soapy

water to all exposed portions of the conduit, but were unable to find any air leaks. Thus we concluded that the conduit of the fuel oil pipeline was leaking underground.

Figure C2. Shows 345 feet of fuel oil conduit line from Building 4156 (left side) to the Circulating Pump Pit (right side) under about 6 psi of air pressure. The peak at 70 feet from Building 4156 was produced by an air leak in the 9" conduit of the double-walled fuel oil pipeline.

Figure C3. Shows 345 feet of fuel oil conduit line from Building 4156 (left side) to the Circulating Pump Pit (right side) under about 9 psi of air pressure. The peak at 69 feet from Building 4156 was produced by an air leak in the 9" conduit of the double-walled fuel oil pipeline.

To find the site of the underground conduit leak in the fuel oil pipeline, we once again attached our acoustic sensors to each end of the line. With the compressor running we were able to get peaks with our acoustic equipment that showed the position of the air leak. The results for two different runs are shown in Figure C2 and Figure C3. It can be seen that there is a repeatable, small peak in both runs, located some 70 feet along the pipeline from Building 4156.

Having surveyed the fuel oil pipeline, we repeated the acoustic testing on the supply and return lines of the diesel fuel pipeline. The return line produced no peaks indicative of leaks, but the supply line showed a repeatable, small peak at 200 feet from the diesel fuel circulating pump pit. This is the point on the diesel fuel pipeline where the de-watering well discharge line goes under the diesel fuel pipeline, though, so without physical evidence of diesel fuel leakage we are reluctant to call this indication a definite leak location.

We attempted to perform a conduit pipe air test on the diesel fuel pipeline (similar to what we had done with the fuel oil pipeline) in order to check the integrity of the conduit wall. However, the nipple of the vent port was distorted and we were not able to thread the end of our pressurization pipe into the vent port. After we left DPG, though, Steve Salas was successful in reworking the vent port, and he carried out the pressurization testing. He discovered that the diesel fuel pipeline also was not airtight – it, too, lost pressure at a rate of 1 psi every 4 minutes. The leak site was found at a poor weld on the end cap of the conduit in the circulating pump pit.

The leak survey continued with the arrival of Precision Testing Technologies, Inc., who started testing the USTs. A total of five USTs, along with their associated piping, were surveyed. Two of these UST tank/pipe systems proved to be leak free, while the remaining three UST tank/pipe systems had leaks somewhere above the product level.

The worst case was the UST located at Building 4258, where a large leak could be heard under vacuum. We believe that this leak is located in the return lines (because we were able to isolate the supply lines at the tank), but the leak could also be in the vent line. This tank also had something which appeared to be a fill port, but which did not connect to the inside of the tank. This bogus fill port (at the west end of the tank) consisted of PVC piping (instead of the steel required by code), and it contained fuel oil, but at the bottom was some gritty substance rather than metal – we do not know if this bogus fill port was in fact sealed or if it could possibly be sending fuel oil straight into the ground.

Another problem UST was located at Building 4361, where again a large leak could be heard under vacuum. We were unable to isolate this leak to either the supply, return or vent lines; we can only say that it was above

the product level in the tank. We also found that this tank was not 550 gallons in size (as indicated on documents and on the capacity meter inside the building); instead the tank was about 5,000 gallons in capacity.

The last problem UST was located at Building 4165, where a very small leak was heard under vacuum. Again, we were unable to isolate this leak to either the supply, return or vent lines; we can again only say that it was above the product level in the tank.

We did not encounter any access difficulties during the leak location survey. However, we did discover a documentation problem – there is only one set of lines that run from the AST fuel oil circulating pump pit, not two. The map we were given shows two sets of lines; one going from the circulating pump pit to Building 4156 and another going from the circulating pump pit to Building 4153 (see Figure C4).

Discussion

One of the big benefits of acoustic leak location is that the instruments have the ability to locate leaks in underground lines *while they are operating* on a non-interference basis. Naturally, as with all nondestructive testing techniques, there are some limitations as to what can be done but there are also some very definite advantages. The major advantages of acoustic leak location are:

- The speed with which the acoustic leak survey can be conducted. Using field procedures that we have developed, the time that it takes to shoot a single section of pipeline can be as short as 20 minutes. When the average sensor spacing is high and access conditions are right, long pipelines can be surveyed for leaks quite quickly – we surveyed an entire 157,612 foot (29.85 miles) long potable water line using a 1,791 foot average sensor spacing in just 4 working days. Note that a 20 minute shot time is an ideal, realized when access to the pipeline is easy. When pipeline access is difficult (such as the pipeline exiting the ground inside secure, locked rooms, or when a hole needs to be dug to access the pipeline) shot times can rise to an hour or more. Of course, proper pre-survey preparation can help eliminate such delays.
- The sensitivity of the acoustic technique for finding small leaks. During the SERDP development program we determined that we could reliably locate a 12 gph leak using an sensor spacing of 633 feet, and that we could reliably locate a 0.75 gph leak using an sensor spacing of 50 feet on an experimental pipeline at EPA Edison.

- The accuracy with which acoustically detected leaks are located on the ground. Generally, a leak is located to within 1% of the sensor spacing, but sometimes the acoustic leak position is precisely correct. We were able to find holes in the 26" conduit of a high temperature hot water system at the Army Research Laboratories to the precise foot with a sensor spacing of 450 feet (the conduit was pressurized with 15 psi air).

We performed the pioneering work for conducting leak surveys on the conduits of double-walled underground pipelines during a project that we did for the Army at the Army Research Laboratories (ARL). We had successfully carried out leak surveys on the carriers of double-walled energy pipelines dozens of times, but before the ARL project we had never attempted to find conduit leaks. The difficulty that we envisioned was that the sound of the leak would not be conducted to the sensor sufficiently well by the thin conduit material, and also that any insulation between the conduit and the carrier would greatly attenuate the sound of the leak – both of these considerations might mean that conduit leak signals could not be detected.

However, double-walled pipes are constructed using spacers that physically connect the pipes together, and we felt that these spacers might conduct the sound into the carrier. Also, since we would use 15 psi air to pressurize the annulus space between the conduit and the carrier to reveal the presence of any leaks in the conduit, we felt that any leak sounds might be more intense than usual (air leaks tend to be louder than liquid leaks due to viscosity and choke flow considerations). In the end, these beliefs proved correct – we successfully located holes in a conduit to the precise foot of where they were located in a 450 foot double-walled pipeline.

We connected an air compressor to the vent port of the conduit at one end, and carefully monitored the air pressure so that it would not exceed 15 psi. When we found that the air compressor could only maintain 11 psi in the fuel oil pipeline at Dugway, we monitored the line with our sensors attached at each end, both with and without the air compressor running. Figures 2a and 2b show the results obtained with the air compressor running; similar plots were obtained with the compressor off. Both show a definite leak in the conduit at a location 70 feet along the pipeline from the spot where the supply and return lines emerge from the ground to enter Building 4156.

We feel that the conduit leak in the fuel oil pipeline may be the source of the elusive petroleum contamination of the Ditto ditch (a water drainage

ditch that has petroleum contamination along its end near the Ditto Chemical Laboratory. The reasoning behind this conclusion is:

1. The inside of the conduit of the fuel oil pipeline has fuel oil residue on it.
2. The fuel oil ASTs are large enough that product loss from a leak size of 500 gallons every two weeks would not be seen in quantity gauges.
3. The conduit leak position is uphill and near to both the area where the dewatering well is operating as well as the beginning of the Ditto ditch.
4. There were leak indications on both internal supply and return lines in a section near the end of the pipeline closest to Building 4156, but the indications did not locate consistently and reliably enough for a definite leak position to be inferred.
5. The three USTs that could potentially leak fuel into the ground were not used during the summer of 2004, when 100-200 gallons per month of petroleum was being taken out of the oil/water separation system.

As was stated in the Results section, the diesel fuel pipeline showed a slight leak indication in the supply line inside the containment line 209 feet from the circulating pump pit. It was also discovered after we left that the conduit on this pipeline would not hold air pressure. However, we do not feel that the diesel fuel pipeline is an active source of the Ditto ditch contamination. The reasoning behind this conclusion is:

1. There was no visible sign or smell of diesel fuel on the inside of the conduit of this line.
2. The air leak in the conduit was found to be at the very end of the pipeline, where the conduit enters the circulating pump pit.
3. The leak indication in the supply line was at the precise point where the de-watering well discharge line crosses the diesel fuel line, so the leak indication might simply be noise induction into the diesel fuel line.

We had not been involved in the testing of UST systems before, so it was quite interesting to watch Precision Testing Technologies go about verifying the integrity of five of the USTs near the Dugway Ditto Chemical laboratory. Their technique has been described in the Instrumentation Description section of this report, but basically they rely upon sealing the UST from the atmosphere, pulling a vacuum, and listening in the ullage space above the product. Leaks in the UST (or in the pipes attached to it)

will reveal themselves either by producing noise having distinctive characteristics or by raising the level of water in the bottom of the UST. In this manner two of the USTs were determined to be leak free, while three of the USTs had leaks either in the tank above the product level or in the associated piping.

We believe that the 4,000 gallon UST located at Building 4258 might be a source of the contamination of the Ditto ditch. This conclusion is based upon the fact that this tank has a bogus fill port at its west end, which might permit the introduction of fuel oil directly into the ground. The bogus fill port consists of PVC piping (instead of the code required steel), and it contained fuel oil at the time we inspected the tank. There was some gritty substance rather than metal at the bottom of this bogus fill port, and it was not possible for us to determine if the bottom was sealed or if the gritty substance was actually the fill material around the buried UST.

Still another reason that the UST at Building 4258 might be a source of contamination of the Ditto ditch is that there was a large leak somewhere above the product level in the tank. Based upon the fact that there was dripping associated with the hiss of an air leak, we conclude that the leak is probably in the return lines of the tank (as the supply lines were shut off at the top of the tank, using a valve on the Red Jacket extractor pumps located there). If the return line is indeed leaking, then fuel oil could flow into the Ditto ditch because this tank is relatively close to the beginning of the ditch and slightly uphill from it. Note that it is not possible to state at this time exactly where along the return line the leak might be.

The case against the UST at Building 4258 being a major source of contamination of the Ditto ditch is that it has not been filled since last winter, nor has it provided oil to the furnaces this summer. This means that neither the return lines, the vent lines or the bogus fill port have had any opportunity to introduce fuel into the ground since spring. However, the amount of petroleum being taken from the oil/water separator was 100-200 gallons per month in August 2004 – which means the major leak into the Ditto ditch is not UST 4258.

Two other USTs were also found to have leaks somewhere above the product level in the tank. One tank was located at Building 4361, while the other was located at Building 4165. Of the two, the one at Building 4361 had the biggest leak. This tank could also be a source of contamination of

the Ditto ditch, because it is relatively close to the beginning of the ditch and slightly uphill from it. Again, though, this system has not been used this summer, so neither the return lines or the vent lines have had any opportunity to introduce fuel into the ground. Also, we discovered that the Building 4361 UST was 10 times larger than listed in the as-built drawings – it was about 5,000 gallons in size as opposed to the 550 gallons listed in the as-built drawings and on the capacity meter inside the building.

The UST located at Building 4165, while it did have a small leak somewhere above the product level in the tank, is not thought to be an active source of contamination of the Ditto ditch. The reason for this conclusion is that the heating system in Building 4165 is not currently in use, and the product level in the tank has remained at the same level for the last year. Even though this is a 10,000 gallon tank, a leak size of 500 gallons every two weeks would easily be seen in the product level.

Conclusions

A leak survey was successfully conducted on the underground pipelines associated with the four ASTs at the Ditto Chemical Laboratory, as well as the tanks and the pipelines associated with five of the USTs located near the Ditto Chemical Laboratory of Dugway Proving Ground. Specific conclusions are as follows:

1. Acoustic techniques are well suited for locating leaks in buried pipelines *while they are operating* on a non-interference basis. The inherent advantages of acoustic leak location (survey speed, sensitivity to small leaks, and accurate leak location) lead to a successful leak survey on the underground pipelines associated with the four ASTs at the Ditto Chemical Laboratory of Dugway Proving Ground, Dugway, UT.

The most probable source of contamination of the Ditto ditch is a definite leak in the conduit of the fuel oil pipeline 70 feet along the line from the spot where the supply and return lines emerge from the ground near Building 4156 (see Figures 2a and 2b). This leak is thought to be the source of the Ditto ditch contamination because (a) the inside of the conduit has fuel oil residue on it, (b) the leak is in the right position to contaminate the ditch and the dewatering well, (c) the ASTs that feed the line are large enough that the leak would not be seen in quantity gauges, and (d) there were leak indications on both the internal supply and return lines in a section near the end of the pipeline closest to Building 4156. We consider this

to be the most probable source of the 100-200 gallons per month of petroleum that was being taken from the oil/water separator in the summer of 2004.

Two other possible sources of contamination of the Ditto ditch were found in the UST located at Building 4258. First, a bogus fill port (located at the west end of this UST) appears that it might permit the introduction of fuel oil directly into the ground during fuel oil deliveries. Second, a leak was discovered above the product level in the tank, most probably located in the return lines to the UST. Note that this UST was not used in the summer of 2004, so it cannot currently be an active source of contamination of the Ditto ditch.

Another possible source of contamination of the Ditto ditch was found in the UST located at Building 4361, again somewhere above the product level in the tank. This UST was also discovered to be 5,000 gallons in size, as opposed to the 550 gallons listed in the as-built drawings and on the capacity meter inside the building. Note that this UST was not been used in the summer of 2004, so it also cannot currently be an active source of contamination of the Ditto ditch.

Another potential source of contamination of the Ditto ditch was found in the UST located at Building 4165, somewhere above the product level in the tank. This UST has not been used for over a year, is not currently in use, and the product level in the tank has remained at the same level for the last year – thus it also cannot currently be an active source of contamination of the Ditto ditch.

The AST diesel fuel line was found to have a leak in its conduit (at the end where the conduit enters the circulating pump pit) but we do not believe that this pipeline is contributing in any way to the Ditto ditch contamination.

Recommendations

Specific recommendations are as follows:

1. We recommend that DPG carry out repairs on the fuel oil pipeline running from the circulating pump pit to Building 4156. There is a definite leak in the conduit of this pipeline, located about 70 feet along the pipeline from the spot where the supply and return lines emerge from

the ground to enter Building 4156. We were unable to pinpoint the position of leaks in the internal supply and return lines of this pipeline, but since the inside of the conduit has fuel oil residue on it the presence of a leak is not in question.

We recommend that DPG investigate the bogus fill port on the west end of the UST located at Building 4258, and take steps to prevent any more fuel oil from being pumped into this port during deliveries.

We recommend that DPG investigate the piping systems associated with the USTs located at Buildings 4258, 4361, and 4165. Prioritize the repairs of the leaks that exist in the return, supply or vent pipes of these tanks, doing Building 4258 first, 4361 second, and 4165 third.

We recommend that DPG make repairs to the conduit on the AST diesel oil pipeline, so that it will be able to effectively contain any leaks that might occur in the future in the internal supply and return lines.

Disclaimer

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the US Army.

Figure C4. Map supplied by DPG, showing AST pipelines and 3 of the 5 USTs that were tested by Carlyle Consulting. Orange annotations show 2 of the leaking USTs we found, and the location where a leak was found in the buried AST fuel oil pipeline.

Appendix D: Final Report for Contract 5014-CARL-001, S&K Technologies, Inc., St. Ignatius, MT.

**Data from Permanent Acoustic Leak
Sensors on Potable Water Lines in
West Fort Hood**

by

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15 December 2006

Contract 5014-CARL-001

S&K Technologies, Inc.

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Introduction

During the period of 10 July 2005 through 6 December 2006 we made 5 trips to Fort Hood in Killeen, TX. The purpose of the trips was to retrieve leak data from the 25 permanent acoustic leak monitoring sensors that we had installed on 7 miles of potable water lines in the West Fort Hood section of the installation.

The project was funded by the Office of the Secretary of Defense (OSD) and the Assistant Chief of Staff for Installation Management (ACSIM), and managed by the Engineering Research and Development Center's Construction Engineering Research Laboratory (ERDC/CERL) personnel Vincent Hock and Sean Morefield. Carlyle Consulting was contracted through S&K Technologies, Inc., under contract number 5014-CARL-001.

During a prior visit we had installed acoustic leak sensors to monitor about 7 miles of potable water lines in remote un-traveled areas, where a water leak would not likely be discovered for a very long time. Two different mechanisms are used to retrieve the leak status from the 25 sensors; one using a special radio receiver that can be driven past the sensors periodically, and the other using a central computer equipped with cell phone modems that retrieve the data automatically. During each of the 5 data gathering visits we made at least 2 drive-by patrols, and correlated the data with the automatically retrieved data.

In 18 months of operation at Fort Hood the acoustic leak sensors have discovered 5 leaks, four of which showed surface water. One leak that showed water was located near a fire hydrant that had leaked in the past, that had been repaired, and which re-developed a leak after the permanent leak monitoring system was operational. Another leak showing water was also located at a fire hydrant, this one in the middle of a vacant field. Still another leak showing water was located at a watering point for wildlife, while the final leak showing water was located near a concrete pad in an area where underground tunnel vents were located.

The fifth leak showed absolutely no surface water whatsoever, and was located in a very secure area. This leak was initially found as a result of examining the permanent acoustic leak sensor's database, and was later verified by Carlyle Consulting using a cross-correlation leak location instrument during the final project inspection by OSD, ACSIM, ERDC/CERL and Fort Hood personnel.

The principal Fort Hood person that we interacted with during our five visits was Gary Goodman, Drinking Water Program Manager.

Instrument Descriptions

The permanent acoustic leak sensors that we installed at Fort Hood were made by Fluid Conservation Systems, and are known as PermaLogs. The PermaLogs use an unlicensed radio frequency band (463.9125 MHz), and were approved in writing by DOIM and DOL for use in West Fort Hood. A picture of ten PermaLog sensors and their drive-by data retrieval unit is shown in Figure D1. Each of the PermaLogs is about the size of a 12 oz. can of soda, and has a magnet on the bottom that allows it to both hold tightly to the pipeline and to acoustically couple any tiny leak sounds propagating through the pipe into the PermaLog.

Figure D1. Ten PermaLog acoustic sensors with a Patroller data retrieval unit.

Each PermaLog contains a clock, which instructs the unit to start listening for 5 minutes at 0200 every night. If leak noises are heard, the unit will again listen for 5 minutes at 0300, and if leak noises are still heard it will listen once more for 5 minutes at 0400. During any listening period, if no leak noise is heard a “no leak” entry is made. If leak noise is heard during all 3 listening periods, though, a “leak detected” entry is made. This logic allows the PermaLog to reject noises from transient flows, such as water

pumps cycling on and off, or flushing toilets. The acoustic data is stored inside the unit for twenty-four hours, when it is overwritten by the next night's data. Actual data collected from the 25 PermaLogs during the project is shown in Figure D2.

Figure D2. Leak monitoring results at Fort Hood. Yellow area indicates an 8" line; blue area indicates a 3" line; tan area indicates another 8" line, and green area indicates a 2" line. LS16 shows a leak, as does LS20. LS4 through LS8 are under the influence of a pump located between LS6 and LS7. LS17 through LS21 are under the influence of a pump near LS17.

Sensor	30-May-05	10-Jul-05	11-Jul-05	30-Aug-05	31-Aug-05	12-Dec-05	13-Dec-05	08-Jun-06	09-Jun-06	04-Dec-06	05-Dec-06
LS 1	14	10	13	0	12	4	6	3	3	4	3
LS 2	8	17	15	20	17	17	19	19	21		
LS 3	14	13	15	20	28	10	14	24	18	56	56
LS 4	36	16	16	23	17	x	x	28	22	26	25
LS 5	22	22	34	56	56	56	56	27	22	19	21
LS 6	33	33	50	50	47	37	41	42	37	30	32
LS 7	27	34	33	15	11	38	36	34	27	30	34
LS 8	24	25	19	19	56	22	21	57	57	46	46
LS 9	12	12	12	12	7	10	10	14	7	20	19
LS 10	15	8	9	10	11	14	11	47	56	56	56
LS 11	10	8	7	8	11	15	12	9	12	11	13
LS 12	16	11	6	9	9	10	11	15	13	13	12
LS 13	7	4	4	9	9	6	4	9	10	5	5
LS 14	10	14	14	13	12	6	4	10	9	5	4
LS 15	4	5	5	7	7	4	4	5	5	6	8
LS 16	24	28	29	35	33	28	28	28	28	25	28
LS 17	61	54	53	55	33	58	58	54	47	54	52
LS 18	44	44	41	41	24	41	37	42	32	35	32
LS 19	36	36	30	36	21	36	31	57	39	34	36
LS 20	32	31	31	30	30	37	36	37	34	45	45
LS 21	26	13	11	10	6	14	13	46	46	10	11
LS 22	4	5	5	3	4	3	4	5	4	5	4
LS 23	6	6	6	9	6	4	6	6	5	7	5
LS 24	5	6	7	10	10	12	12	13	12	11	12
LS 25	10	10	10	18	17	9	9	15	15	6	5

The listening range of a PermaLog depends upon the ambient environmental noise around the pipeline where it is installed. Because we were installing them in remote areas of West Fort Hood where there was no air or ground traffic at night, we were able to space them about 1,500 feet apart, although some adjustments were made in the vicinity of pumps.

Information is retrieved from the PermaLog sensors using a special radio receiver called a Patroller. This device is taken by vehicle into the vicinity of all of the PermaLogs, and their acoustic leak data is retrieved automatically. The retrieval takes place quickly; at West Fort Hood the drive takes only 45 minutes, and vehicle speed limits rather than any technological issue were primarily responsible for the time expended.

Three of the PermaLog sensors at West Fort Hood are equipped with special equipment known as PermaComs, which allow the PermaLog data to be uploaded into a central computer without human intervention via cell

phone modems. Many different retrieval schedules can be set up, but the one that worked well at Fort Hood has been a weekly upload at 0900 Sunday morning. It should be noted that a PermaCom interrogates its attached PermaLog daily, and stores up to 14 days of leak data in its memory. Thus if cell phone communications aren't established one weekend, the entire 2 weeks of leak data will be retrieved the next weekend. The PermaCom data and the PermaLog data sets are identical, of course, which can be seen in Figure D3.

Figure D3. Comparison of data retrieval results at Fort Hood. Except for the periods when hardware difficulties were being experienced, the agreement is exact between the two data retrieval methods.

Sensor	Source	30-May-05	10-Jul-05	11-Jul-05	30-Aug-05	31-Aug-05	12-Dec-05	13-Dec-05	08-Jun-06	09-Jun-06	04-Dec-06	05-Dec-06
LS 9	PermaLog	12	12	12	12	7	10	10	14	7	20	19
	PermaCom	12	*	4	*	7	10	10	14	7	*	*
LS 15	PermaLog	4	5	5	7	7	4	4	5	5	6	8
	PermaCom	4	*	*	*	7	4	4	5	5	6	8
LS 22	PermaLog	4	5	5	3	4	3	4	5	4	5	4
	PermaCom	4	*	*	*	4	3	4	5	4	5	4

* PermaCom Hardware Problem Experienced (no data)

Once the PermaLog sensors have detected the presence of leaks, we use another acoustic instrument to precisely locate the leak on the pipeline, a Fluid Conservation System's AccuCorr. The most attractive features of this instrument for the West Fort Hood pipelines were that it was battery powered and that it used wireless connections between the magnetically coupled sensors and the instrument base, which greatly simplified field use. A technical description of the process we used for locating leaks in the field is located at the end of this report. The AccuCorr operates in the frequency range of 1 Hz to 5000 Hz, and uses cross-correlation techniques to obtain a Δt value to locate leaks. Cross-correlation compares the shape of a signal received by sensor 1 with that received by sensor 2 for all possible arrival times by shifting them in time and adding the two signals together, yielding a single value for each possible arrival time. This processing provides a distinct peak when the time shift of the signals equals the exact time that a signal feature of a certain shape received at sensor 1 arrives at sensor 2. Cross correlation is sensitive to dispersion (when the shape of the signal changes with propagation, the comparison gets worse), but it has a good track record in the field. The ability of the AccuCorr to locate a hidden underground leak for which absolutely no surface water indication was present is shown in Figure D4.

Figure D4. AccuCorr verification of a hidden underground leak 5.8 feet from a buried shut-off valve. The leak was first detected in the PermaLog data set received from sensor 16. There was no surface water from this leak.

We occasionally used another acoustic instrument at Fort Hood, a Fluid Conservation System's Xmic. This instrument consists of a battery powered control console, a "ground microphone" sensor, and headphones. This type of sensor can detect sounds coming through the ground, and thus can be used to find the exact spot along the pipeline where the leak sounds are the loudest. The instrument lets the user amplify the leak sounds to a comfortable level, and also lets the user set filters to eliminate distracting background noises (such as vehicle traffic or pumps). At Fort Hood we used the Xmic's "ground microphone" capabilities as still another confirmation procedure for verifying the presence of a leak location detected by the PermaLog sensors.

Results

The first retrieval of data from the PermaLogs occurred on 17 May 2005, while the pipeline location and sensor housing installation work was still in progress, and only 13 PermaLogs were active. We were very pleasantly surprised to discover that the Patroller, from over 6,600 feet away on a public road, could interrogate PermaLog sensor 16, located inside a secure area that was extremely difficult to gain access to. We also found that the Patroller could interrogate from public roads the four other sensors located inside secure areas. We obtained the baseline data for all 25 of the newly installed sensors on 30 May 2005.

Three sensor locations were selected to have PermaCom units, so they could automatically upload leak data over cell phone modems to a central

data computer. A picture of a PermaCom unit and its installation inside a sensor housing is shown in Figure D5. We chose three locations that were geographically diverse and not inside secure areas as places to put the PermaComs (sensor locations 9, 15 and 22).

Figure D5. Blue PermaLog sensor and the black PermaCom unit (Top). PermaLog sensor on the pipeline at the bottom of the vertical riser (Left). PermaCom inside the leak sensor housing (Right).

Sean Morefield and I made our first data retrieval visit on 10 July 2005, and we obtained another set of PermaLog leak data the next day. It was during this visit that we formally informed Fort Hood that they had the capability to obtain leak data at any time of their choosing from all 25 acoustic leak sensors, using the Patroller data retrieval method.

On 30 and 31 August 2005 Sean Morefield and I again traveled to Fort Hood and retrieved leak data from the PermaLog sensors on both days.

Problems with the PermaCom/PermaHost hardware and software were resolved during this visit, and for the first time data was received from all 3 PermaCom equipped sensors by the PermaHost program running on the central data computer.

Another leak data retrieval visit was made to Fort Hood on 12-14 December 2005 to fulfill a contractual commitment for Carlyle Consulting to obtain Patroller data from all 25 PermaLog sensors. Everything was working correctly, and it was found once again that the 3 PermaCom equipped sensors were reporting values that were identical to the Patroller data for the relevant sensors (see Figure D3).

From 7-10 June 2006 another visit was made to Fort Hood, for the dual purposes of fulfilling another contractual commitment by Carlyle Consulting to obtain Patroller data from all 25 sensors, and to have the final project inspection by OSD, ACSIM, ERDC/CERL and Fort Hood personnel. Leak data was again successfully obtained via the Patroller, and the PermaLog/PermaHost system was also working fine.

During the 7-10 June 2006 visit we demonstrated data retrieval from all 25 of the PermaLog sensors using the Patroller, while OSD, ACSIM, ERDC/CERL and Fort Hood personnel viewed the process. We then obtained access to a highly secure area, where the data from PermaLog sensor 16 had indicted the presence of a leak. At this site there was absolutely no surface indication of a leak, but the use of the AccuCorr and the Xmic instruments proved to everyone there that a non-visible buried leak was present. The AccuCorr produced a very definite result about 6 feet from a deeply buried shut-off valve, as shown in Figure D4, and listening with the Xmic made the sound of the leaking water obvious.

A final leak data retrieval visit was made to Fort Hood on 4-6 December 2006. During this visit 4 PermaLog sensors were replaced. One (sensor 2) had stopped working, while three (sensors 3, 8 and 10) had frozen due to infiltration of fine silt into their mechanisms. All sensors were replaced under the manufacturer's warranty, and the entire permanent leak monitoring system was left in excellent working order for Fort Hood personnel to use at their discretion.

Discussion

Most of the important findings of this project have been documented extensively in a prior report, including: (1) the method's ability to find leaks, (2) the method's ability to save money, (3) lessons learned from the project, (4) longevity of the equipment, (5) calibration requirements, and (5) needed modifications to hardware and software. The reader is referred to this prior report for more details. The 5 leak gathering trips added to the knowledge gained during the sensor installation project, and that knowledge will be discussed in this section.

Leak Finding Ability

The ability of the permanently mounted PermaLog sensors to find leaks in the potable water pipelines of West Fort Hood has been demonstrated to be quite good – five leaks were discovered during the project using the data collected by the PermaLogs.

The basic premise of acoustic detection of leaks is simple – when water under pressure leaks out of a pipe it creates turbulence. The sound waves generated by the turbulence propagate in the water down the pipe in both directions from the leak, creating slight motions in the wall of the pipe as they travel. A sensitive special microphone, acoustically coupled to the pipe, can detect these motions and turn them into electrical signals.

The problem is that things other than leaks can generate also sound inside pipes. Normal use of the water inside the pipeline by customers, such as opening and closing faucets or flushing toilets, creates noise, as does the use of pumps to distribute the water through the system. Further, environmental noises, such as truck, car or train traffic passing over or near the pipelines, or even airplanes flying overhead, can also induce noise into the pipeline.

To detect leaks in the face of these masking noises, the PermaLogs use two simple facts: (1) normal use of the water system as well as vehicle traffic is much lower during the nighttime hours than during the day, and (2) leaks constantly make noise after they form.

As was explained in the Instrument Descriptions section of this report, each PermaLog contains a clock, which instructs the unit to start listening for 5 minutes at 0200 every night. If leak noises are heard, the unit will again listen for 5 minutes at 0300, and if leak noises are still heard it will

listen once more for 5 minutes at 0400. During any listening period, if no leak noise is heard a “no leak” entry is made. If leak noise is heard during all 3 listening periods, though, a “leak detected” entry is made. This logic allows the PermaLog to reject transient flow noises from the use of the water system, as well as environmental noises.

Figure D2 shows the data obtained from all 25 PermaLog sensors on various days during the project. The leak values from each PermaLog appear in their own row, with individual days shown in every column. The yellow block contains the results from sensors 1 through 10, which are on the main 8” line leading into West Fort Hood. The blue block contains the results from sensors 11 through 16, which are on a 3” line leading through an ACP area into a highly secure area. The tan block contains the results from sensors 17 through 21, which are on another 8” line leading to a water tower. The green block contains the results from sensors 22 through 25, which are on a 2” line leading through another ACP area into a remote building.

PermaLog sensors that indicate possible leaks in the West Fort Hood potable water system are shown in bold face type. At first glance it would appear that there are a number of leaks in the yellow, blue and tan pipelines. However, this is not the case. There are only 4 true leaks being indicated, by sensors 6, 16, 19, and 20 (one leak, between sensor 22 and 23, is so small that it isn’t being heard) The other nine bold faced leak sensors are being fooled into reporting leaks by the presence of two constantly running pumps in the system, and the failures of sensors 3, 8 and 10.

One pump is located on the yellow 8” line, between sensors 6 and 7. This pump runs 24/7, and the noise that it makes propagates up and down the 8” pipeline. The pump makes enough noise that sensors 5, 6, 7 and 8 can hear it. Sensors 5 and 8 are about 2600 feet distant from the pump, and therefore the pump noise is weaker than it is at sensors 6 and 7, which are only about 1100 feet distant from the pump. As can be seen from Figure 2, there is some variability in the pump noise, which we do not understand.

Another pump is located upstream of sensor 17, and it too runs 24/7. The noise that it makes is loudest at sensor 17 (which is only 700 feet distant), is less intense at sensor 18 (which is 1300 feet further down the line), and is even less intense at sensor 19 (which is another 1300 feet down the line). For some reason, there is not as much variability in the pump noise here.

Sensor 6 is unfortunately located in an area where pump noise is high, as described above. During the 4-6 December 2006 visit we discovered that a fire hydrant in a vacant field between sensor 6 and Old Copperas Cove Road had water near it. Apparently, this fire hydrant developed a leak sometime between 9 June and 4 December 2006. However, the leak is small enough that the noise it makes is being overwhelmed by the noise from the pump between sensors 6 and 7, and thus isn't being properly reflected in the data.

Sensor 19 is located near a wildlife watering station, whose feeder pipe had failed. This leak, too, is unfortunately located in an area where pump noise is high, as described previously. Again, the leak is small enough that the noise it makes is being overwhelmed by the noise from the pump located before sensor 17, and thus isn't being properly reflected in the data.

The leak near sensor 20 is a special case. It is 1100 feet away from sensor 19, and seems to be picking up a little bit of the pump noise coming from the direction of sensor 17. However, the values from sensor 20 suddenly increased in value between August and December 2005. We also noticed in December that the ground was wet around a fire hydrant located 30 feet from sensor 20. We had found this fire hydrant to be leaking in September 2004, and Public Works had fixed it in late 2004. Sometime in the August to December 2005 period the leak had clearly re-appeared, and the newly installed PermaLog sensor detected that fact.

Another special case is a leak at a concrete pad, which connects to a line at a point between sensors 22 and 23. This leak is quite small. Acoustically it is located closer to sensor 23 than to sensor 22, and it can be seen in Figure D2 that sensor 23 consistently sees a higher noise level than sensor 22. However, the leak is so small and so far away that it doesn't really rise to a signal level that can be reliably detectable as a leak. If it gets bigger, though, it most probably will be declared a leak by sensor 23.

Sensor 16, where another leak was found, is a clearer cut case than at sensor 20. Sensor 16 is isolated at the end of a dead end 2" pipeline, and although it appears to be near sensor 17 when looking at Figure D2, in actuality there is no sound path connecting the two sensors – sensor 16 is acoustically connected only to sensor 15. As can be seen in Figure D2, sensor 15 has always been extremely quiet. The fact that the leak data from sensor 16 has always been 6 to 7 times louder than the leak data received at sensor 15 implies that there is a leak in the 2" pipeline. It was also clear that the leak would be on the far side of sensor 16 from sensor 15, since the

leak data at sensor 15 was even lower than the leak data received by sensor 14.

In June 2006 we used an AccuCorr leak location instrument to investigate the situation at sensor 16. The AccuCorr enables us to locate the position of a leak between two sensors. We put one AccuCorr sensor (the red one) on the 2" pipeline where PermaLog sensor 16 normally resides. The other AccuCorr sensor (the blue one) was placed on a buried shut-off valve 291 feet distant from sensor 16, in the direction going away from sensor 15. When the AccuCorr finished its calculations we obtained the graph shown in Figure D4, which shows a very sharp peak 5.8 feet from the blue AccuCorr sensor. We then used our Xmic instrument with its ground microphone to listen at a spot over the pipeline 6 feet away from the buried shut-off valve. The sound of leaking water could clearly be heard in the Xmic's headphones.

There was absolutely no water present on the surface of the ground near the shut-off valve. However, when a flashlight was shown down the vertical riser to the shut-off valve it could be seen that some water was present at the valve. Because this shut-off valve was located in a secure area, and because there was absolutely no surface water present, it is safe to conclude that this leak would not have been discovered if the permanent leak detection PermaLog sensors had not been installed at West Fort Hood.

Equipment Issues

During the initial two month installation of the acoustic leak sensors at Fort Hood we experienced a few equipment failures. Four of the PermaLog sensor problems took the form of an inability to communicate to the Patroller unit. Three sensors would communicate if we got the Patroller up close to the sensor housing, but at the other sensor the data would simply not come in at all. This problem was traced to water getting into the sensor's radio through a faulty connector. During the December 2006 visit one sensor totally died; it had no communication and its status lights also did not work. This failure was also traced to water ingress, in this case shorting out the sensor's computer.

Over the life of the project five of the PermaLog units started showing very peculiar data. Their data value would shoot up to a fairly high level, where it would remain constant. It was discovered that the fine silt soil present in some areas of Fort Hood had infiltrated into the mechanism that channeled the tiny vibrations from the magnet of the PermaLog into its sensing

system. The silt interfered with the channeling mechanism, causing the constant readings.

The manufacturer of the sensors was extremely good to work with. First, they replaced under warranty every sensor that failed in the field, no matter what the cause. Next, they redesigned the sensing mechanism to permit the units to operate in the fine silt present at Fort Hood. Since all of the PermaLog units originally installed at Fort Hood did not have this modification, and since it has turned out to be such a severe problem for us, the manufacturer has agreed to keep on replacing under warranty all Fort Hood PermaLogs that fail in service.

Lessons Learned

During the course of this project we learned a number of lessons that would be of value to others embarking on the installation of a similar permanent leak sensor system. Some of these lessons were related to installation, where simple changes led to better hardware reliability and improved data gathering capability.

During the June 2006 visit we discovered that honeybees had entered a sensor housing through a hole in the cover. It was decided to replace the covers with solid ones, and accordingly 25 new covers were procured. However, the new covers had a problem – they had a metal handle on them to allow the cover to be removed. This metal handle interfered with the radio signal emitted by the sensors, cutting our operating range to a fraction of the 1,000 feet we obtained with an entirely plastic sensor housing. The lesson is clear – don't use metal around the PermaLogs!

Another problem was discovered when one of our PermaCom units suddenly went off the air in October 2006. During the December 2006 visit we discovered that someone had cut the antenna cable for the cell phone modem with a weed whacker, while clearing brush from the pipeline right of way. In future installations we will need to cover the antenna cable with a plastic pipe to protect it.

Finally, during our second of three patrols in the December 2006 visit, we suddenly found ourselves unable to receive data from any PermaLog sensor. This turned out to be due to the breaking of the external antenna cable on the Patroller unit, at a point where the cable entered the BNC connector. The cable had been repaired at this spot in August 2005, after the

factory connection failed. Clearly, the antenna cable is subject to strain at this point during patrols! Future installations will require a much more substantial strain relief on the cable.

Access to Sensors

Locations of the 25 acoustic sensors at West Fort Hood are shown on the maps in Figure D6 through Figure D9. The maps begin with an overall view of the entire sensor layout, Figure D6. Three views, each showing about a third of the system per view, are shown in Figure D7 through Figure D9.

Table D1 lists the coordinates of the sensors in two ways. The first, Easting and Northing, are used with the electronic Fort Hood GIS map coordinate system. The second, Longitude and Latitude, are used with handheld GPS devices in the field.

Seven of the acoustic leak sensors are now located in highly secure areas, and it is important to know how to gain access.

At the start of this project only sensor 16 was located in a highly secure area, known as the Emergency Services Training Facility. During the 4-6 December 2006 visit we discovered that sensors 17, 18, 19, 20, 21 and 22 were now located in a new highly secure area, called the Underground Training Facility. The UTF Operations Office in Building 92051 controls access to all of these sensors.

Four other sensors are located in ammunition storage areas. Sensor 13 is located in an area known as the DRB, while sensors 23, 24 and 25 are located in an area called the ASP. The ASP Operations Office in Building 92075 controls access to all of these sensors.

Conclusions

Twenty-five permanent leak detection sensors were successfully installed on about 7 miles of potable water pipelines in West Fort Hood. Specific conclusions are as follows:

1. The PermaLog acoustic sensors installed at West Fort Hood have proven that they can detect water leaks, including leaks whose water

never rises to the surface. Two separate leaks, one that was totally hidden from view and probably would never have been found without the use of the PermaLog system, were discovered. Three other leaks, which showed water on the surface, were also discovered.

A detailed procedure has been developed for collecting data from the sensors locations, which can be performed by Fort Hood personnel.

The sensors have proven to be reliable in the harsh environment in which they are installed, and the manufacturer is standing behind his product.

A number of lessons were learned about some installation and operation pitfalls that will be beneficial to others that undertake the installation of permanent sensors on pipelines at other Army installations.

Recommendation

We recommend that the Army give serious consideration to installing PermaLog permanent acoustic sensors at other installations where potable water pipelines run in poorly traveled areas. The PermaLog sensors have successfully proven their ability to detect water leaks at Fort Hood. In addition, according to civilian water utility experience, payback periods are on the order of 5 years for the necessary leak detection equipment.

Disclaimer

Any opinions, findings and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the US Army.

Acoustic Leak Location Procedure

Detecting leaks in pipelines with acoustics involves a fairly straightforward process. A special instrument with a highly sensitive microphone is placed on valves and other objects that connect directly to the pipeline being surveyed. A leak in the pipeline reveals itself by the sounds that the water, fuel or air inside the pipe makes as it escapes. A generalized location of the leak can be determined by moving the microphone from valve to valve along the pipeline until the loudest noise is received. After that, a specialized microphone can be used on the ground above the pipeline along its length to obtain a little better idea of the position of the leak.

In order to precisely locate a leak in a pipeline it is necessary to determine a time difference, using the following five steps:

1. Position two sensors so that they bracket (surround) a possible the leak. If the sensors do not surround the leak, location *cannot* be done, no matter what signal processing method is used! (Only leak *detection* can be accomplished if the sensors do not surround the leak.)

Acoustically couple the sensors to the pipe so that both sensors receive distinct leak signals. Leak location cannot be performed without signal arrivals at *both* sensors. This step implies that quick, reproducible methods exist to acoustically couple sensors to pipes in the field.

Measure the distance between the sensors, D , and determine the velocity of sound in the media contained in the pipe, V .

Use signal processing (e.g., coincidence detection and cross-correlation) to determine a time difference, Δt , for the arrival of a specific signal feature at both sensors.

Using the time difference Δt obtained in Step 4, calculate the location of the leak using the following equation:

$$\text{Location from first sensor detecting signal} = (D - (V \times \Delta t)) / 2$$

Note that to successfully locate leaks it is absolutely necessary to (1) insure that the sensors are on the correct pipe, (2) know the length, material and diameter of the pipe being monitored (in order to calculate the speed of sound in the media contained in the pipe), and (3) know the exact distance ***along the pipe*** between the sensors. We depend upon the piping system owner to provide this data accurately (in the form of maps and tables) so that the location we calculate will be as accurate as possible (and Fort Hood did indeed provide such information to us).

Figure D6. An overall view of the locations of all 25 acoustic sensors installed at West Fort Hood.

Figure D9. Locations of acoustic sensors 10 – 25 installed at West Fort Hood.

Table D1. Geographic locations of the 25 acoustic sensors at Fort Hood.

Sensor ID	Easting	Northing	Longitude	Latitude
LS 1	612737 m	3443093 m	97 49 03.7W	31 6 58.7N
LS 2	612494 m	3442776 m	97 49 13.0W	31 6 48.5N
LS 3	612254 m	3442456 m	97 49 22.2W	31 6 38.2N
LS 4	612014 m	3442137 m	97 49 31.3W	31 6 27.9N
LS 5	611774 m	3441818 m	97 49 40.5W	31 6 17.6N
LS 6	611532 m	3441500 m	97 49 49.8W	31 6 07.4N
LS 7	611093 m	3440914 m	97 50 06.6W	31 5 48.5N
LS 8	610890 m	3440518 m	97 50 14.4W	31 5 35.7N
LS 9	610749 m	3440089 m	97 50 19.9W	31 5 21.8N
LS 10	610609 m	3439660 m	97 50 25.4W	31 5 07.9N
LS 11	610037 m	3439640 m	97 50 46.9W	31 5 07.5N
LS 12	609765 m	3439779 m	97 50 57.2W	31 5 12.1N
LS 13	609352 m	3439715 m	97 51 12.8W	31 5 10.2N
LS 14	608940 m	3439646 m	97 51 28.3W	31 5 08.1N
LS 15	608530 m	3439576 m	97 51 43.8W	31 5 05.9N
LS 16	608136 m	3439453 m	97 51 58.8W	31 5 02.1N
LS 17	609590 m	3439425 m	97 51 03.9W	31 5 00.7N
LS 18	609279 m	3439191 m	97 51 15.7W	31 4 53.2N
LS 19	608959 m	3438975 m	97 51 27.9W	31 4 46.3N
LS 20	609044 m	3438792 m	97 51 24.8W	31 4 40.3N
LS 21	608643 m	3438778 m	97 51 39.9W	31 4 40.0N
LS 22	608785 m	3438584 m	97 51 34.6W	31 4 33.6N
LS 23	608915 m	3438330 m	97 51 29.8W	31 4 25.3N
LS 24	608602 m	3438102 m	97 51 41.7W	31 4 18.0N
LS 25	608192 m	3438157 m	97 51 57.1W	31 4 19.9N

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14. ABSTRACT <p>Leaks in fuel storage tanks and distribution piping systems have been identified as a mission-critical problem by the Department of Defense and the U.S. Army. Fuel system leaks are often hard to locate and virtually inaccessible for efficient repair because the piping is often installed under a concrete pad or tarmac. Leak repair could cost up to \$2,000, and the cost of cleanup and remediation for fuel spills can exceed \$50,000. In this project an acoustic remote sensing system was installed to monitor an Army heliport refueling system to determine whether it could detect and accurately locate fuel leaks using computer software technologies to distinguish acoustic leakage signatures from normal fuel system operational noise.</p> <p>Demonstration and validation efforts were disadvantaged by the fact that no fuel leaks occurred in the monitored system for the duration of the project. However, the monitoring system did identify several unusual acoustic events within the fueling system and interpret them as indications of intermittent malfunctions of a check valve and a fuel pump.</p> <p>The 30-year ROI is about 6.42. Further work is required before the technology can be fully implemented: its ability to detect fluid leaks must be proven, and the system specifications must be certified through an EPA third party.</p>					
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