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Project Summary

Acoustic Location of Leaks in Pressurized Underground Petroleum Pipelines

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Experiments were conducted at the Underground Storage Tank (UST) Test Apparatus Pipeline in which three acoustic sensors separated by a maximum distance of 38.1 m (125 ft) were used to monitor signals produced by 11.4-, 5.7-, and 3.8-L/h (3.0-, 1.5-, and 1.0-gal/h) leaks in the wall of a 5-cm- (2-in.-) diameter pressurized petroleum pipeline. The line pressures and hole diameters used in the experiments ranged from 69 to 138 kPa (10 to 20 psi) and 0.4 to 0.7 mm (0.01 to 0.03 in.), respectively. Application of a leak location algorithm based on the technique of coherence function analysis resulted in mean differences between predicted and actual leak locations of approximately 10 cm. The standard deviations of the location estimates were approximately 30 cm. This is a significant improvement (i.e., smaller leaks over longer distances) over the cross-correlation-based techniques currently being used.

Spectra computed from leak-on and leak-off time series indicate that the majority of acoustic energy received in the far field of the leak is concentrated in a frequency band from 1 to 4 kHz. The strength of the signal within this band was proportional to the leak flow rate and line pressure. Energy propagation from leak to sensor was observed via three types of wave motion: longitudinal waves in the product and longitudinal and transverse waves in the steel. The similarity between the measured wave speed and the nominal speed of sound in a gasoline suggests that longitudinal waves in the product dominate the spectrum of received acoustic energy. The effects of multiple-mode wave propagation and the reflection of acoustic signals within the pipeline were observed as non-random fluctuations in the measured phase difference between sensor pairs.

Additional experiments with smaller holes and higher pressures (138 to 345 kPa [20 to 50 psi]) are required to determine the smallest leaks that can be located over distances of several hundred feet. The current experiments indicate that improved phase-unwrapping algorithms or lower noise instrumentation, or both, are required to optimize system performance.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Underground pressurized pipelines are frequently used to transfer liquid products for many industrial applications. Some of these pipelines are associated with the underground storage tanks typically found at retail gasoline stations and others with tanks at industrial storage facilities; they can contain petroleum products or a variety of other chemicals. The many systems used to detect leaks in underground pressurized pipelines are designed for use on pipelines that are typically 5 cm (2 in.) in diameter and generally 15.2 to 61.0 m (50

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to 200 ft) in length. EPA regulations (40 CFR Part 280 Subpart D) require that the leak detection equipment used to test a pipeline on a monthly basis be capable of detecting leaks at least as small as 0.76 L/h (0.2 gal/h) with a probability of detection (P_D) of 95% and a probability of false alarm (P_{FA}) of 5%. If the equipment is used to test the line annually, it must be able to detect leaks as small as 0.38 L/h (0.1 gal/h); in the regulations, this type of test is designated as a line tightness test.

If a leak is found, remediation must follow, and the first step is to locate the leak. Presently, two methods are used, but neither is totally acceptable. The first method is to systematically uncover the line and perform a visual inspection for leaks. Although this method works, it is time consuming, disruptive to operations, and costly. In addition, the line is subject to damage during the excavation process. The second method is to use a helium- or halogen-tracer technique, but both of these have operational and accuracy problems. There is a need for a nondestructive method of leak location that is accurate, relatively simple to use, and applicable to a wide variety of pipelines and pipeline products.

One method of expediting the remediation process is to apply remote sensing techniques to the pipeline as a means of accurately locating the leak. Passive-acoustic measurements, combined with advanced signal-processing methods, may provide a means for locating small leaks in limited-access pipeline delivery systems. Although passive acoustics has been used for some time to determine the spatial location of leaks, this concept has not been applied to underground petroleum pipelines. With the use of cross-correlation techniques, leaks of approximately 113 L/h (30 gal/h) have been successfully located in water-filled pipelines that are pressurized to 827 kPa (120 psi) and are less than 30 m long.

Cross-correlation analysis works well when the signal is very strong or the background noise is not excessive. When the acoustic signal is weak in relation to the level of background noise or has a finite frequency bandwidth, more sophisticated signal processing techniques are available. Advanced signal processing is required if any of the following objectives are to be achieved: (1) the detection of leaks smaller than several gallons per hour, (2) a reduction in the number of false alarms and missed detections due to operational or ambient noise, and (3) an increase in the distance between sensors bracketing the leak. One such advanced technique is *coherence function analysis.*

The best way to locate the signal source is to apply coherence function analysis to signals measured by two or more transducers. Coherence function analysis, which estimates the correspondence between two measurements as a function of frequency, is analogous to the squared correlation coefficient but is a *far more powerful tool* in estimating and locating signals. The coherence magnitude measures the strength of the correspondence, and the coherence phase measures the relative time delay. In contrast, the correlation coefficient is a measure of correspondence that is the result of an integration over all frequencies. If the correspondence is frequency-dependent, or if the phase dependence of the correspondence is a nonlinear function of frequency, the correlation is degraded. By contrast, coherence is a direct measure of the complex frequency correspondence between two measurements, and, therefore, preserves the actual correspondence between the two measurements of the signal.

The last 5 to 10 years have seen significant advances in commercially available acoustic sensors, in powerful computers that are both small and inexpensive, and in digital signal processing. This means that an acoustic leak location system can be made available in a portable package, a possibility that makes it an attractive and viable option. Acoustic systems are attractive from an operational standpoint because the test is short (a few minutes) and the sensors can be mounted directly on the outside of the pipeline. Acoustic systems have direct application to the 15.2- to 61.0-m (50 to 200 ft) pipelines found at retail service stations because the sensors can be placed at each end of the line.

The objective of this work was to estimate, by means of passive acoustic sensors mounted on the outside wall of the pipeline, the accuracy of locating a leak in a pressurized petroleum pipeline as a function of leak rate and distance between acoustic sensors. There are no regulatory requirements for leak location. For rapid repair of the pipelines and rapid remediation of any contamination that might have occurred from the leak, however, it would be highly desirable if the leak could be located within 10% of the length of the pipeline in the case of a line longer than 30.5 m (100 ft), or within 3.0 m (10 ft) in the case of a line shorter than 30.5 m (100 ft). This limits the excavation to only a small fraction of the line. Theoretical estimates suggest that when coherence analysis is used, acoustic sensing techniques can detect a leak within 35 cm of its actual location.

Results

Experiments were conducted on a pipeline at the UST Test Apparatus in which 3 acoustic sensors separated by a maximum distance of 38.1 m (125 ft) were used to monitor signals produced by 3.8-, 5.7-, and 11.4-L/h (1.0-, 1.5-, and 3.0-gal/h) gasoline leaks. These flow rates were generated through drilled holes 0.4 to 0.7 mm in diameter. The three-transducer system enabled the propagation speed of acoustic waves to be measured for particular combinations of product, pipeline geometry, and analysis frequency band. Data recorded at the higher leak flow rates (5.7 and 11.4 L/h [1.5 and 3.0 gal/h]) correspond to full line pressure (103 to 138 kPa [15 to 20 psi]); data recorded at the lower flow rate (3.8 L/h [1.0 gal/h]) were obtained under partial line pressure (69 kPa [10 psi]) because of the limitation imposed by the minimum available hole diameter (0.4 mm). Application of a leak location algorithm based on the technique of coherence function analysis resulted in mean differences between predicted and actual leak locations of 8.7 cm (at 11.4 L/h [3.0 gal/h]), 3.6 cm (at 5.7 L/h [1.5 gal/h]), and -11.6 cm (at 3.8 L/h [1.0 gal/h]). Standard deviations of the location estimates were 26.1 cm (at 11.4 L/h [3.0 gal/h]), 26.3 cm (at 5.7 L/h [1.5 gal/h]), and 39.1 cm (at 3.8 L/h [1.0 gal/h]). The mean propagation speed was 915 m/s with a standard deviation of 146 m/s.

Data recorded in the presence of a 1.9-L/h (0.5-gal/h) leak were obtained as part of an investigation of signal strength as a function of line pressure for a fixed-diameter hole (0.4 mm). The 1.9-L/h (0.5-gal/h) leak produced a detectable signal; however, because of the reduced line pressure, the algorithm, as applied, yielded no location estimates.

Spectra computed from leak-on and leak-off time series indicate that the majority of acoustic energy received in the far field of the leak is concentrated in a frequency band from 1 to 4 kHz. The strength of the acoustic signal within this band was proportional to the leak flow rate and line pressure, as expected. Energy propagation from leak to sensor was via three forms of wave motion: longitudinal waves in the product and both transverse and longitudinal waves in the steel. Isolation of each of these propagation modes was achieved through the use of gasoline and CO_2 as the product fluids and through the generation of impulsive calibration signals. Though each of these propagation modes is believed to contribute to the overall received signal, longitudinal wave motion in the product was clearly the dominant propagation mode for liquid-filled pipelines. The effects of multiple-mode wave propagation and the reflection of acoustic signals within the pipeline were observed as non-random fluctuations in the measured phase difference between sensor pairs.

Accurate leak location requires the identification of frequency bands within which a high degree of similarity is maintained between acoustic signals propagated along different paths from leak to sensor. Coherence function analysis provides the best means of gauging this similarity and, thus, separating useful information concerning the leak location from ambient or system noise. While the signal-to-noise ratio (SNR) was observed to be generally high within the entire 1- to 4-kHz frequency band, continuous regions of high coherence appropriate for source location were typically 100 to 500 Hz in width. Several data sets recorded in the presence of the 11.4-L/h (3-gal/h) leak exhibited high coherence over a 2-kHz bandwidth. Location estimates obtained by means of the cross-correlation technique showed that without the detailed knowledge of signal similarity provided by the coherence function, cross-correlation analysis cannot locate small leaks with acceptable accuracy. The observed correspondence between measured and predicted phase shifts within the 1- to 4-kHz frequency band demonstrates the need to develop a more sophisticated location algorithm such that a greater fraction of the information contained in coherent leak signals may be processed.

Buried pipelines provide a generally quiet ambient environment in which to perform acoustic measurements. Since the SNR for a given leak largely determines the ability of a passive acoustic system to locate the leak, the system noise level should be determined by ambient acoustic noise rather than by electronic noise. The combination of sensors (CTI-30s*) and preamplifiers (Panametrics 5660-Cs) used in this work was incapable of resolving the low levels of ambient acoustic noise associated with the pipeline at the UST Test Apparatus. Improved system performance may be attained through the use of transducers with greater sensitivity in the low-frequency range (1 to 10 kHz) and low-noise preamplifiers.

Conclusions

Passive acoustic measurements, combined with advanced signal processing techniques based on coherence analysis, offer a promising method for the location of small leaks in pressurized petroleum pipelines found at retail gasoline service stations and industrial petroleum storage facilities. Although the results presented in this work represent a significant improvement over previous pipeline leak location efforts, additional research and development are required before system performance can be optimized. Location of leaks of several tenths of a gallon per hour over distances of several hundred feet should ultimately be possible.

Recommendations

The full capability of the location algorithm was not evaluated in these tests. The smallest hole used to generate a leak in the experiments was 0.4 mm. A line pressure of 138 kPa (20 psi) resulted in a leak rate of 3.8 L/h (1.0 gal/h). It is recommended that additional experiments be performed with smaller holes at higher line pressures (138 to 345 kPa [20 to 50 psi]) to determine the minimum leak rate that can be reliably located. The current work indicates that further improvement can be realized through the application of better phase-unwrapping algorithms and better instrumentation. A better understanding of the underlying physics of pipeline acoustics, including the propagation modes and source mechanisms of the acoustic leak signal, will help optimize the algorithms and the hardware. It is recommended that the following work be performed to extend the technology:

- develop a location algorithm capable of processing the coherence phase over an arbitrarily wide-frequency band,
- characterize the wave propagation modes excited by the acoustic leak signal and the degree to which each mode enhances or degrades the leak location estimate,
- reduce system noise through transducers specifically designed for low-frequency, high-sensitivity applications and through low-noise, audio-range preamplifiers, and
- automate the data acquisition system and signal processing algorithm, and evaluate system performance on a variety of actual pipelines.

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* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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The complete report, entitled "Acoustic Location of Leaks in Pressurized Underground Petroleum Pipelines," (Order No. PB92- 207 687/AS; Cost: $19.00, subject to change) will be available only from:
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