

An Engineering Evaluation of Acoustic Methods of Leak Detection in Aboveground Storage Tanks

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An Engineering Evaluation of Acoustic Methods of Leak Detection in Aboveground Storage Tanks

Health and Environmental Affairs Department

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ABSTRACT

The design of an aboveground storage tank (AST) leak detection system based upon passive-acoustic methods requires a detailed understanding of the acoustic leak signal and the ambient noise field against which the signal is measured. As part of Phase III of the American Petroleum Institute's (API's) project to develop and evaluate the performance of different technologies for detecting leaks in the floor of ASTs, a set of controlled experiments was conducted in a 40-ft-diameter tank during June 1992. Two sets of holes of various diameters, ranging from 0.5 to 3 mm, were drilled in the tank floor. These holes released product (water) into one of two backfill materials: native soil or sand. Two types of acoustic signals were generated and studied: (1) the continuous leak signal produced by turbulent flow through a hole in the floor of the tank, and (2) the impulsive leak signal produced by bubbles collapsing in the backfill beneath the tank floor.

The analytical and experimental results of this project suggest that a passive acoustic system can be used to detect small leaks in ASTs. The experiments have shown that the impulsive leak signals identified through laboratory and field simulations are persistent and measurable within an AST. The experiments yielded two very significant findings, which must be addressed in the data collection and signal processing schemes used to detect leaks with the passive-acoustic method: (1) the multipath signals (leak-to-wall-to-sensor or leak-to-surface-to-sensor), which are associated with the direct path signal (leak-to-sensor), are very strong and may be stronger than the direct path signal, and (2) the time delays of the multipath signals relative to the direct path signal for each sensor in the wall array may be very different. Both phenomena are due to acoustic propagation in the highly reflective confines of a right circular cylinder AST.

During the experiments, a data collection procedure and a signal processing algorithm were used to separate the impulsive events associated with the leak from the strong multipath reflected signals. All of the leaks that were generated in the floor of the 40-ft-diameter tank were successfully detected and located.

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EXECUTIVE SUMMARY

INTRODUCTION

The design of a leak detection system based upon passive-acoustic methods requires a detailed understanding of the acoustic leak signal and the ambient noise field against which the signal is measured so that robust data collection and signal processing algorithms can be developed. As part of Phase III of the American Petroleum Institute's (API's) project to enhance and evaluate the performance, in actual operational environments, of different technologies for detecting leaks in the floor of aboveground storage tanks (ASTs), a set of controlled experiments was conducted in a 40-ft-diameter tank at the Mobil Oil refinery in Beaumont, Texas, during June 1992.¹ The tank was filled with water and two sets of holes of different diameters, ranging from 0.5 to 3 mm, were drilled in its floor. The holes in the center of the tank floor released product into a native-soil backfill, and the holes along the periphery of the tank floor released product into a sand backfill. Two types of acoustic leak signals were generated and studied under realistic conditions: (1) the continuous leak signal produced by turbulent flow through a hole in the floor of the tank and (2) the impulsive leak signal produced by bubbles collapsing in the backfill beneath the tank floor.

BACKGROUND

The API has completed three phases of a leak detection project for ASTs. The purpose of Phase I was to assess different leak detection technologies to determine which had the greatest potential for field application. Phase II addressed in detail two of the methods studied in Phase I: passive-acoustic and volumetric methods. Phase III built on the insight gained in Phase II with regard to the acoustic leak signal and ambient noise field.

The objectives of Phase III, which addressed both volumetric and passive-acoustic leak detection technologies, were:

- to determine, in the case of acoustic methods, the nature of the acoustic leak signal resulting from realistic leaks in the floor of an operational AST;
- to determine, in the case of volumetric systems, if differential pressure (mass-measurement) systems have significant advantages over the conventional level and temperature measurement systems;

¹ Experiments were also conducted as part of Phase III to evaluate the performance of volumetric methods of leak detection for ASTs. The results of the volumetric study are provided in a separate API document entitled *An Engineering Evaluation of Volumetric Methods of Leak Detection Systems for Aboveground Storage Tanks* by James W. Starr and Joseph W. Maresca, Jr.

- to characterize the ambient noise encountered under a wide range of test conditions for both detection technologies;
- to evaluate data collection and signal processing techniques that would allow the detection of the leak signal against the ambient noise;
- to identify any operational issues for implementation of methods based on either technology;
- to demonstrate the capabilities and, if possible, make an estimate of the performance, of both technologies through field tests; and
- to identify, in the case of both volumetric and passive-acoustic technologies, those features of a leak detection test that are necessary for achieving high performance.

CONCLUSIONS

The analytical and experimental results of this project suggest that a passive-acoustic system can be used to detect small leaks in ASTs. The experiments have shown that the impulsive leak signals identified through laboratory and field simulations during Phases II and III appear to be persistent and are measurable within an AST.

The experiments yielded two very significant findings, which *must* be addressed in the data collection and signal processing schemes used to detect leaks with passive-acoustic methods: (1) the multipath signals (leak-to-wall-to-sensor or leak-to-surface-to sensor), which are associated with the direct-path signal (leak-to-sensor), are very strong and may often be stronger than the direct-path signal, and (2) the time delays of the multipath signals relative to the direct-path signal for each sensor in the wall array may be very different.

Both phenomena are due to acoustic propagation in the highly reflective confines of a right circular cylinder AST. The former phenomenon, which is produced by wall focusing, is particularly important, because the inherent assumption in the design of the existing acoustic detection algorithms is that the largest leak signal is produced by the direct-path signal. The impulsive leak signal is detectable, because, as part of the signal processing, the direct-path signal can be distinguished in time delay from the multipath signals associated with it. While the multipath complicates the signal processing for impulsive leak signals, it makes it impractical to exploit the persistent leak signal.

During the experiments, a data collection procedure and a signal processing algorithm were used to separate the impulsive events associated with the leak from the strong multipath reflected signals. All of the leaks that were generated in the floor of the 40-ft-diameter tank were successfully detected and located.

This document presents the results of these acoustic experiments in two separate technical papers, which are attached as appendices. The first discusses the characteristics of the acoustic leak signal and ambient noise field in an AST, and the second presents an engineering assessment of a methodology for detecting small leaks in the tank floor.

1 INTRODUCTION

This report summarizes Phase III of a research program conducted by the American Petroleum Institute (API) to evaluate the performance of different technologies that can be used to detect leaks in the floors of aboveground storage tanks (ASTs). During Phase I, an analytical assessment of the performance of four leak detection technologies was investigated (Vista Research, Inc., 1989; Maresca and Starr, 1990). The four technologies included: (1) passive-acoustic sensing systems, (2) volumetric systems, especially differential pressure (or “mass”) measurement systems, (3) enhanced inventory reconciliation methods, and (4) tracer methods. During Phase II, field tests were conducted on a 114-ft-diameter AST containing a heavy naphtha. The purpose of these tests was to make an engineering assessment of the performance of two of the above technologies, passive-acoustic sensing systems and volumetric detection systems. These tests were conducted at the Mobil Oil Corporation refinery in Beaumont, Texas, during May 1992. The results of the Phase II research program are described in two API final reports and three professional papers (Vista Research, Inc., 1991, 1992; Eckert and Maresca, 1991, 1992). During Phase III, additional field tests were conducted on a pair of ASTs in order to test the acoustic and volumetric leak detection strategies that emerged from the Phase II study and to further evaluate the current state of leak detection technology. These tests were also conducted at the Mobil refinery at about the same time of year as the Phase II tests. The acoustic tests were conducted in a 40-ft-diameter AST containing water, and the volumetric tests in a 117-ft-diameter tank containing a light fuel oil. In the case of the acoustic tests, holes were drilled in the floor of the tank to allow realistic simulation of leaks into two different types of backfills beneath the floor. This report describes the results of the Phase III acoustic tests; the results of the volumetric tests are described in a separate report, which consists of a brief overview of the work and two technical papers (Vista Research, Inc., 1993).

The specific objectives of the Phase III acoustic experiments were:

- to characterize the two general types of acoustic leak signals (i.e., continuous and impulsive) produced by leaks in the floor of an operational AST;
- to characterize the ambient noise that would interfere with each type of acoustic leak signal and that would be found in a typical AST under a wide range of refinery and environmental conditions;
- to demonstrate in a series of field tests data collection and signal processing techniques that would allow the detection of leaks in the floor of an AST; and

- to identify those features of a leak detection test that are crucial to achieving high performance.

The body of this report consists of a short technical summary of the work. Section 2 summarizes the relevant Phase II results that were further investigated in Phase III. Sections 3 and 4 summarize the important results, conclusions, and recommendations of this experimental project. Section 5 presents the general features of a passive-acoustic method that will achieve a high level of performance. A detailed description of the field tests and analyses are presented in two professional papers, which are attached as appendices to the report.

2 BACKGROUND

The choice of a particular strategy for the acquisition and processing of acoustic signals is strongly tied to the nature of the signal and the background noise field in which the signal is immersed. Studies of simulated leak signals have shown that the acoustic signal produced by a leak contains two distinctly different components (Vista Research, Inc., 1992; Eckert and Maresca, 1991, 1992). Turbulence associated with the leak flow field produces a *persistent* acoustic signal that is believed to be present in all AST leaks. The magnitude of the persistent leak signal is dependent upon the backfill conditions beneath the AST floor and on the flow rate through the hole in the floor. The second type of acoustic leak signal is *impulsive* in character and is caused by the interaction of air bubbles beneath the AST with the turbulent leak flow field. While the impulsive leak signal is much greater in magnitude than the persistent signal, the degree to which the impulsive signal is associated with AST leaks is unknown. Phase II laboratory tests showed that air must be entrained into the leak flow field in order for an impulsive signal to be produced; no impulsive signals were observed when the backfill was completely saturated with product or groundwater. The approach to AST acoustic leak detection adopted by the industry exploits only the impulsive component of the leak signal. This approach is based upon the success with which flaws and cracks in a variety of materials have been identified through the use of acoustic emissions (AE) techniques. Though a number of firms offer AST leak detection services based upon passive acoustics, very little technical information has been published concerning the performance of such systems or the nature of the acoustic signal produced by leaks in operational ASTs. Many proven techniques have been developed in order to locate sources of continuous signals, for example, sonar and radar beamforming systems. The primary focus of the API work is the development of data acquisition and signal processing techniques that will allow the impulsive and/or the persistent components of the acoustic leak signal to be successfully exploited for the purpose of leak detection.

The Phase III field tests were designed to evaluate and refine the results of the Phase II tests. The most important results of the Phase II experiments and analyses are summarized below.

- Many of the false alarm and missed detection problems experienced by commercial vendors are predictable and can be attributed to inadequate data collection and signal processing algorithms; they are produced by the use of a detection threshold that is too low compared to background noise, by improper time registration of signal events, and by incorrect assumptions that large noise events are signal events. The typical threshold settings used by the testing community are based upon the persistent contributions to the ambient noise field, which leads to an excessive number of threshold exceedances based solely on the noise and not the leak signal or the impulsive noise that might mask the leak

signal. Observations of the leak signal suggest it is 10 to 20 times larger than the persistent noise. To process the data, the acoustic signal from each individual collapsing bubble event must be correctly identified by each acoustic sensor. If acoustic signals from different bubble events are processed together, then erroneous location estimates are made. This mixing of the impulsive leak signals is difficult to avoid unless a continuous time history of data is collected. Because none of the vendors is recording continuous time histories, impulse mixing cannot be avoided with the AE data collection approach, and it becomes an important source of error. Simple calculations, assuming only the presence of leak signals (i.e., no noise), suggest that the probability of a false alarm is 50% if the rate of occurrence of events is 12 per second. The probability of false alarm increases dramatically if the rate of occurrence is higher or if the ambient noise is also included in the calculation. These problems can be minimized by collecting data continuously, using a higher threshold for detection, devising better sensor geometry, and employing more robust algorithms to identify and avoid noise. A detailed description and analysis of these problems are provided by Eckert and Maresca (Vista Research, Inc., 1992; Eckert and Maresca, 1991).

- The strongest acoustic signal produced by a hole in the floor of a tank propagates through the liquid. Sensors responded similarly to the impulsive leak signal regardless of whether they were submerged in the liquid inside the tank or located on the exterior wall of the tank. The noise field seemed to be lower, however, for the submerged sensors than for those mounted on the wall. The multipath reflections observed in the data are predictable using simple ray tracing techniques.
- Both the persistent and impulsive signals exhibited a positive signal-to-noise ratio. More information is required about the characteristics of the persistent signal, however, before a determination can be made on whether such a signal can be successfully exploited. More information is also required about the impulsive signal so that more robust data collection and signal processing algorithms can be developed.
- The only mechanism that produced strong impulsive signals in the laboratory tests was the collapsing of air bubbles in the flow field of a well-drained backfill beneath the tank. When the backfill became saturated and all the entrained air escaped, the impulsive signal ceased. This raised questions about whether such a signal would persist in an operational environment where the void space that develops in the backfill beneath the leak could fill with product (or with water resulting from precipitation that accumulates in the diked areas surrounding the AST). Except for the Phase II laboratory experiments, the controlled experiments that were used by the commercial testing community to develop their testing approach were conducted under extremely well-drained backfill conditions in which such a signal would always be present. More realistic information about the presence and persistence of the impulsive acoustic leak signal is needed in order to justify the exploitation of this signal.

- A signal-processing approach that uses a beamforming algorithm was developed as a means to exploit both the persistent and impulsive leak signals. Exploitation of the persistent signal is the primary reason for using this approach. The beamforming approach requires a high degree of similarity between the signal wave forms recorded by spatially separated sensors. Stated another way, the coherence between any two time series containing the signal should be high in the signal frequency band. If the coherence of the persistent leak signal is found to be high between the various sensors in the wall-mounted arrays, the performance achieved using this signal should be as good as, if not better than, the conventional leading-edge, threshold-detection approach being used by industry for impulsive signals. The performance of the beamforming approach increases as the number of sensors and the integration time increase.
- The optimal configuration for acoustic sensors in an AST should incorporate the following: (1) an array of sensors that are separated both vertically and horizontally so that surface noise and reflected signals can be distinguished from leak signals emanating from the bottom; (2) one or more subarrays of closely spaced sensors for time registration; and (3) one or more subarrays of widely spaced sensors for accuracy in locating the leak. Optimal geometries for radar and sonar sensors consist of one wide-aperture array that has three narrow-aperture subarrays and that provides for both horizontal and vertical separation of sensors. Theoretically this would be an ideal configuration for acoustic sensors in an AST. However, the beam pattern resulting from a point response must be calculated before any sensor geometry can be finalized.

3 SUMMARY OF RESULTS

Three types of field experiments were performed in Phase III. The first type was designed to characterize the acoustic signal produced by a hole in the tank, the second to characterize the ambient noise field that existed during the entire data collection period, and the third to assess the merits of the data collection and signal processing approach developed in Phase II. Two sets of tests (each including all three types of experiments) were conducted, one to exploit the persistent leak signal and one to exploit the impulsive leak signal.

All of the acoustic experiments in this phase of the API project were conducted in a 40-ft-diameter AST especially outfitted with controllable leaks for these tests. The tank was filled with water to a depth of 25 ft for all of the tests. Three sets of holes were used to investigate the nature of the acoustic leak signal. Five holes ranging in diameter from 0.5 to 3 mm and spaced at 5-ft intervals were drilled into the floor near the center of the tank; a similar set of holes was drilled near the tank walls. The backfill under the center holes was native soil, and that under the side holes was sand. A leak simulator having a similar configuration was also installed in the tank, but at a different location; in the simulator, the flow rate of the leak could be controlled and measured. A specially designed flowmeter was used to measure the flow rate in each floor hole. A hydrophone was used to verify that each hole not used to generate a leak during a test was closed and did not generate any additional acoustic leak signals. The smallest hole in the AST that produced a measurable flow rate was 2.0 mm in diameter. The three holes smaller than 2.0 mm were presumed to be clogged with debris. The lack of flow in these smaller holes was verified with the flowmeter and a hydrophone.

The AST had a false bottom that was filled with sand. A section of the false bottom was removed for these tests, and the sand under this section was replaced with the native-soil backfill. Large-amplitude, impulsive leak signals were observed whether the leak flowed through the false bottom into a sand backfill or through the "single bottom" into a native-soil backfill. However, both the frequency and strength of the impulsive leak signals were dependent upon the backfill material and backfill conditions. The leak from the 2.0-mm-diameter hole in the false bottom into the sand backfill produced impulses at a greater rate (typically 1 to 20 per minute) than did the corresponding leak from the single bottom into native soil (typically 1 every 5 minutes). The frequency of these signals was significantly lower than that of the impulsive signals measured in the laboratory (typically 10 to 50 per second) in well-drained, granular backfills. The broadband frequency content of the impulsive leak signal, combined with the low level of

ambient noise observed at frequencies above 10 kHz, allowed the impulsive signal to be easily detected by both internal and external sensors. The impulsive leak signal was generally 10 to 20 times larger than the standard deviation of the random ambient background noise.

The persistent leak signal associated with turbulent flow and the entrainment of small-diameter particulates into the leak flow field was detectable above the ambient noise. However, at frequencies below 10 kHz, the leak signal was largely masked by ambient noise. Persistent leak signals produced by the 2.0-mm-diameter leak through the false bottom into the sand were significantly larger in amplitude than those produced by the corresponding leak through the single bottom into native soil. If the time history of the no-leak condition were not available for comparison, however, one would have no way to determine, based on signal strength alone, if the acoustic data were produced by noise or a leak signal.

Measurements of the acoustic leak signal are made against a noise field that is highly variable both in strength and frequency distribution. The complex variety of noise sources encountered at a refinery ensures that acoustic data recorded within any frequency band and over any time scale are subject to some form of contamination by ambient noise. Sources of persistent acoustic noise observed during the field tests included industrial activities associated with the refinery and nearby factories, traffic, and leaking valves in aboveground steam-distribution pipelines. While these sources produce consistently high levels of ambient noise, the frequency content of persistent noise is largely confined below 10 kHz. Distinctive, impulsive sources of noise are also observed as part of the AST ambient noise environment. Mechanisms observed to cause impulsive noise included rain, condensation, and mechanical stresses imparted to the AST through connecting pipelines during product transfers. Most impulsive noise sources can be effectively avoided through careful choice of the measurement period and sensor location or minimized through robust data collection and signal processing.

The current method by which the presence of an AST leak is inferred is detection-through-location. This approach requires that the differential arrival time of acoustic signals at the elements of a sensor array be measured. Accurate source location (and hence acceptable performance as a leak detection system) demands that the recorded signals maintain a high degree of similarity with respect to one another. The similarity between time series of both impulsive and persistent leak signals recorded by spatially separated sensors was degraded by multipath signal propagation within the reflective confines of the AST. The observed lack of coherence between measurements of the persistent leak signal was such that the differential arrival time of the signal could not be measured. The low coherence, which was observed at

sensor separations of only 4 in., is due to multipath reflections resulting from the circular geometry of the tank. As a consequence, the persistent leak signal cannot be exploited for the purpose of leak detection and instead must be viewed as a source of noise.

Investigations of multipath propagation within the AST were conducted through measurements of the impulsive leak signal and through ray-tracing simulations. The ray-tracing simulations, which modeled single and double reflections of impulsive signals from the AST shell and air-/water interface, accounted for much of the observed multipath contamination of impulsive leak signals. Experimental evidence that the amplitude of multipath signals could actually exceed that of the direct-path (source-to-sensor) signal was supported by the results of the ray-tracing studies. That the direct path acoustic return may not be the strongest signal has significant ramifications in the design of a robust leak detection system since all the detection algorithms assume that the direct-path impulsive signal is stronger than the multipath reflections. A simulation was conducted which showed that a wide-aperture array of externally mounted sensors will be subject to multipath contamination regardless of the location of the leak.

Leak detection experiments that concentrated on the impulsive component of the leak signal were conducted using a pair of 2.0-mm-diameter leaks and the leak simulator. Because the impulsive signals appear infrequently, data acquisition was initiated by the exceedance of a pre-set threshold signal level at one element of a sensor array. The collected data consisted of continuous time series of the leak signal that contained the impulsive event. Although multipath propagation reduces the similarity between time series of impulsive leak signals, successful detection of leaks based upon these signals was accomplished through the application of a data quality test to each set of time series and the processing of these time series by a modified beamforming algorithm. The data quality test employed a secondary threshold (lower than the primary threshold used to initiate data acquisition) in order to determine whether the recorded event corresponded to direct-path propagation from source-to-sensor or was caused by multipath reflection signals. By varying the level of the secondary threshold it was possible to get either an image of the actual leak location or virtual images of the leak lying outside the AST boundary. The double-threshold approach led to accurate location estimates of 2.0-mm-diameter leaks through both the false bottom and the single bottom, as well as accurate location estimates of the leak simulator. The modified beamforming algorithm was used to develop contour maps of the signal-to-noise ratio, and these were used as the basis for determining whether a leak was present or not. The accuracy of the location estimates was within the predictions of theoretical model calculations based on the integration time and the number and location of the sensors.

4 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of the Phase III acoustic experiments is that accurate and reliable leak detection is possible; moreover, the important features of a test with high performance have been identified. It may be possible to detect leaks from holes even smaller than those used in the experiments. (It will be recalled that the three smallest holes [0.5, 1.0, and 1.5 mm in diameter] were clogged with particulates and could not be used.) The mechanism producing the impulsive leak signal (i.e., collapsing bubbles) should be independent of hole size, therefore making leaks from holes smaller than those investigated in this set of experiments detectable.

These experiments demonstrated that a detectable acoustic leak signal exists. In order to achieve reliable performance, though, significant modifications must be made to the current data collection and signal processing routines. Of the two existing types of leak signal, persistent and impulsive, only the latter can be exploited when strong multipath reflections are present in the acoustic data. These multipath signals are predictable and their presence has been verified with a simple ray-tracing model. Analysis of the experimental data shows that the multipath signals may be stronger than the direct-path signal. This finding is particularly significant because such strong multipath signals would confuse the simple threshold signal processing algorithms used for detection of the impulsive leak signal. There are a number of data collection and signal processing approaches that can be used to distinguish the direct-path from the multipath signal. One simple algorithm was developed and successfully used to detect leaks in both backfills from holes at three locations in the tank.

The success achieved with the passive-acoustic leak detection method is critically important, because until now the accepted procedure for determining whether or not an AST is leaking has been to take the tank *out of service*, drain it, and inspect the tank floor. This process is not only expensive and time-consuming but also poses environmental risks connected with the transfer and temporary storage of product. Acoustic tests have a number of important features that make them an operationally viable tool, principally in terms of minimizing interruptions to AST operations. First, the tank does not need to be taken out of service during equipment setup. Second, the test is short---it takes only a few hours to collect the data. Third, the level of product in the tank is not a factor; unlike volumetric tests, which require that the product level be lowered to within 3 to 5 ft of the bottom, no exacting level changes are needed, and a test can be conducted at the extant level. (For best performance, however, the product level should be as high as possible.)

Three general recommendations are made as part of API's Phase III effort. The first is to demonstrate that the data collection and analysis approach developed in the Phase III field tests works by using this approach to perform leak detection tests on a variety of operational ASTs whose integrity has been or will be checked by tank inspection procedures. The Phase III data are limited in that they represent only one type and size of tank, one product, and one season of the year. Although some work was done during Phase II on a 114-ft-diameter AST filled with a petroleum product, most of the acoustic experiments were conducted in the specially configured tank filled with water. Less than a month's worth of experimental data was collected, and these data are limited to ASTs in the same geographic location and under the same climatic conditions. While these experiments were carefully controlled, the data collection and analysis methods developed as part of Phase III have not yet been evaluated over a wide enough set of conditions to be definitive.

The second recommendation is to develop and validate a *standard test procedure* for evaluating the performance of acoustic leak detection methods in terms of probability of detection (P_D) and probability of false alarm (P_{FA}). The development and implementation of a standard test procedure is particularly important because it is an extremely effective means of technology transfer; it almost ensures that industry will integrate the important findings of this research into its leak detection systems, because by doing so industry can achieve the highest performance possible when evaluating these systems. Such procedures also ensure that all leak detection systems have a minimum level of performance and that the performance of one system can be compared to that of any other system. The advantages of standardized evaluation procedures, in terms of both technology transfer and performance estimation, have been successfully demonstrated and implemented as part of the underground storage tank (UST) program.

The third recommendation is to encourage the continuation of applied R & D by other organizations, especially the federal government, as a way to improve the performance of acoustic and volumetric technologies and to extend their application over a wider population of tanks. Three areas of further technology development are recommended for acoustic methods: (1) determine the presence and persistence of impulsive leak signals for a wide range of backfills and product fuels, (2) characterize the noise environment over a wider range of testing conditions, and (3) develop and evaluate more robust detection algorithms. While the goals of each of these three recommendations seem somewhat unrelated, addressing any one of them will offer significant input to the other two.

While not a specific recommendation, the importance of technology transfer cannot be overemphasized, because it must be recognized that it is expensive and time-consuming for industry to implement some of the features that have been identified as being important for achieving high performance with a passive-acoustic system. This is typically accomplished by the publication and presentation of technical results. Even more important, perhaps, is direct communication with the intended users (in this case, the commercial vendors and the owners of ASTs) for review of and comment on the test plan before each set of field tests and the test results afterward. While publication and direct interaction with the user community has been actively and vigorously pursued by API, these efforts may not be sufficient to effect the necessary changes. In our opinion, the most effective method of ensuring technology transfer involves the implementation of the second recommendation, the development of a standard test procedure.

5 IMPORTANT FEATURES OF A PASSIVE-ACOUSTIC METHOD WITH HIGH PERFORMANCE

To detect leaks in the floor of an AST, a passive-acoustic system should be designed to detect the impulsive leak signal. Off-the-shelf frequency-selective sensors that are available commercially appear to be more than adequate for this purpose.¹ For high performance, however, it is necessary to formulate data collection and signal processing algorithms that will detect this type of signal. The general features that such data collection and algorithms must possess are derived from the results of the Phase II and III field tests and analyses. The first of these features is a very high threshold; a high threshold is the best way to detect the impulsive acoustic signal produced by a leak and to minimize false alarms due to noise fluctuations. Second, digital time series of the raw acoustic wave form from each sensor must be collected and made available for analysis. Without digital data, the analysis required for robust leak detection cannot be performed. Although it would be desirable to collect continuous time histories, this would not be practical since the quantity of data collected during a normal test is prohibitively large. In effect, continuous time histories are not essential provided that each time series is sufficiently long to correctly identify the leading edge of the direct-path signal in the presence of multiple events, multipath reflections, and noise. The third important feature is an algorithm for distinguishing multipath and noise signals from direct-path signals. It is possible to devise such an algorithm because of the fact that in a high-quality threshold exceedance, the main multipath reflections relative to the direct path signal and the amplitude of the noise can be predicted. A number of approaches can be used to develop this algorithm. The fourth important feature is that the algorithm be designed in such a way that the impulsive returns from discrete bubble events are isolated and that the direct-path signals are properly time-registered. This is particularly difficult if more than one event occurs during the time it would take for an acoustic signal to propagate across the tank. The fifth feature is the spacing of sensors in such a way as to strike a balance between two opposing effects. Close spacing makes the pattern of the direct-path and multipath reflections from a single bubble event much easier to identify and thus enhances the proper identification of the direct-path signal. Unfortunately, however, as the aperture of the array decreases, so does the accuracy of the leak *location* estimates. The optimal sensor configuration (confirmed by theoretical analyses published in the literature) is thus one that addresses both issues, accurate location estimates and proper registration of impulses in the time series (Van

¹ The sensors used in all field tests described here have a resonant response at approximately 30 kHz. It is likely that frequency-selective sensors that are resonant at other frequencies will also be effective, although we did not verify this. Simple laboratory tests can be used to demonstrate the response of a sensor to an impulsive signal.