

# **An Engineering Assessment of Acoustic Methods of Leak Detection in Aboveground Storage Tanks**

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# **An Engineering Assessment of Acoustic Methods of Leak Detection in Aboveground Storage Tanks**

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API PUBLICATION NUMBER 307  
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## Executive Summary

### Introduction

Though a number of firms offer aboveground storage tank (AST) leak detection services based on passive acoustics, very little information has been published concerning the performance of such systems or the nature of the acoustic leak signal. This document provides the results of an engineering assessment of passive-acoustic sensing methods for detecting small leaks in large ASTs.<sup>1</sup> The assessment consisted of laboratory experiments, analyses of unpublished data collected by industry in a 10-foot-diameter AST containing water, and field experiments at the Mobil Oil Refinery in Beaumont, Texas on a 114-foot-diameter AST containing a heavy naphtha petroleum product.

### Background

The American Petroleum Institute (API) has completed two phases of a leak detection project for aboveground storage tanks (ASTs). The purpose of Phase I was to assess different leak detection technologies to determine which had the greatest potential for field application. Because acoustic and volumetric methods were found to have significant operational and performance advantages, they were the ones chosen for testing under Phase II of the project.

The purpose of Phase II was to perform an engineering assessment of acoustic and volumetric methods for detecting small leaks in large ASTs. The principal objectives of Phase II were:

- to determine, in the case of acoustic methods, the nature of the leak signal and the ambient noise in an AST;
- to determine, in the case of volumetric methods, the sources and magnitude of ambient noise associated with measurements in an AST;
- to perform field experiments on a large, full-scale AST; and
- to recommend ways to improve existing AST leak detection methods.

### 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 a detectable leak signal does exist, but that the current approach to data acquisition and signal processing needs to be improved for the technology to achieve its full potential. As part of the field tests under Phase II, an algorithm based on radar beam-forming techniques was developed; this algorithm improved the detection of leaks. An example of the application of the algorithm to both impulsive and continuous leak signals is presented in this report. Both the beam-forming algorithm and the data collection strategy must be evaluated by means of further experiments designed to estimate the performance of a passive-acoustic system in the presence of real leaks in the floor of an AST. Section 3 of the body of this report consists of a short but detailed summary of the technical results of this engineering assessment. A description of the experiments and analyses are presented in two professional papers, which are attached as appendices to the report.

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<sup>1</sup> The results of the volumetric study are provided in a separate API document entitled *An Engineering Assessment of Volumetric Methods of Leak Detection in Aboveground Storage Tanks*, by James W. Starr and Joseph W. Maresca, Jr.

## 1 Introduction

This report summarizes Phase II of a research program conducted by the American Petroleum Institute (API) to evaluate the performance of technologies that can be used to detect leaks in the floors of aboveground storage tanks. During Phase I, an analytical assessment of the performance four leak detection technologies was investigated [1, 2]. The four technologies included: (1) passive-acoustic sensing systems, (2) volumetric systems, especially differential pressure (or "mass") measurement systems, (3) advanced inventory reconciliation methods, and (4) tracers methods. During Phase II, field tests were conducted on an aboveground storage tank to make an engineering assessment of the performance of two of these technologies, passive-acoustic sensing systems and volumetric detection systems. This report describes the engineering assessment of the acoustic systems that were examined; the engineering assessment of volumetric systems is described in a separate report [3].

The specific objectives of the Phase II research in the area of acoustics were to:

- assess the current state of AST leak detection technology
- determine the nature of the leak signal and the ambient acoustic noise in an AST
- perform field experiments on a full-scale AST
- recommend ways to improve existing AST detection systems

The field tests were conducted at the Mobil Oil Refinery in Beaumont, Texas, on a 50,000-bbl, 114-ft-diameter AST containing a heavy naphtha petroleum product. The experiments focused on identifying and quantifying the acoustic leak signal and its source mechanisms, and on formulating the strategies necessary to detect the leak signal.

## 2 Background

The choice of a particular strategy for the collection 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. The approach to AST acoustic leak detection adopted by the industry 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, and the ease with which such systems may be designed and operated. 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 leak signal. While tank owners and operators covet the operational features of the technology, there is a need to provide convincing evidence that the technology is effective. A first step toward providing this evidence is to review the few available test results provided by the leak detection industry and to perform a system analysis of the data collection and processing approach being used. The assessment of passive acoustic leak detection technology presented in this work is based both on the industry-derived data and on laboratory and field experiments.

The current method by which the presence of an AST leak is inferred is detection-through-location. In order to locate a region of the AST floor that emits acoustic energy in excess of a measured, average level, an array of transducers is used to construct a sound-level map. Currently available acoustic leak detection systems require that the leak emit impulsive signals whose amplitude greatly exceeds the background noise level. The process of converting these impulsive signals into a sound-level map can be described as follows. For each element of the sensor array, an impulse arrival time is recorded when a preset threshold signal level is exceeded. Sets of impulse arrival times then serve as input to a location algorithm that predicts the most likely origin of the signal. A large number of such location predictions are plotted on a diagram of the AST floor to produce the sound-level map. Regions of the map in which significant clustering of source locations is observed are interpreted as likely leak locations. Published results of field tests on full-scale ASTs, and unpublished results made available for review, offer little convincing evidence that this approach to passive-acoustic leak detection performs adequately when applied to the AST leak detection problem. An analysis of the problems associated with the current generation of leak detection systems was performed in which two fundamental questions were addressed. First, are large-amplitude, impulsive signals (i.e., background noise) expected to dominate the acoustic signal in the case of real AST leaks? Secondly, if leak-generated impulsive signals exist, are they being acquired and processed correctly?

### 3 Summary of Results

The nature of both the acoustic leak signal and its corresponding source mechanisms was investigated in a series of laboratory experiments. A leak simulator was constructed in order to control the flow rate, backfill material, and pressure head above the leak. Time series of acoustic signals were recorded by a pair of transducers placed in close proximity to the leak. The results of these experiments showed that the acoustic leak signal is comprised of both impulsive and continuous components. Turbulent flow, cavitation, and particulates in the backfill colliding with each other and with the tank floor were identified as the most likely source mechanisms for the production of continuous leak signals. The interaction between the leak flow field and air bubbles trapped within the backfill material was the only source mechanism found to produce the large-amplitude, impulsive signals upon which the current leak detection technology is based. In addition, once the backfill material became fully saturated, the production of impulses ceased. These results brought into question the persistence of impulsive leak signals in an operational AST, but also identified detectable, persistent signals that have not yet been exploited by the industry.

The published results of field tests show a high degree of scatter in the data used to form sound-level maps. On the assumption that the backfill conditions present during these tests were appropriate for the production of impulsive leak signals, an analysis was made of the data collection and signal processing methods currently employed by the testing industry. The results of this study indicate that the manner in which data are acquired, i.e., collecting a set of impulse arrival times whenever a threshold exceedance occurs on any element of the sensor array, tends to produce inaccurate location estimates in proportion to the rate at which impulses are emitted from the leak. When only impulse arrival times are collected, as opposed to continuous time series, the possibility exists that a given set of arrival times are not correlated with the emission of a single impulsive signal, but instead are correlated with two or more distinct events. The processing of these mixed-arrival time sets by the location algorithm was suggested as a probable source of error. For a full-scale tank, it was shown that the inaccurate collection of impulsive signals would occur 50% of the time for a rate of impulse emission of only  $12 \text{ s}^{-1}$ . This analysis assumed that the noise was zero and that only detectable signals were present; the percentage of improperly collected signals would increase significantly if noise were included or the rate of impulse emission were increased.

The detectability of acoustic leak signals and alternative methods for the processing of these signals were investigated through the analysis of data obtained during field tests on 10- and 114-ft-diameter ASTs. One of the vendors provided continuous time series of impulsive leak signals recorded in a 10-ft-diameter AST by internal hydrophones and external resonant sensors. The primary results of this analysis were that: (1) impulsive signals dominated the acoustic leak signal produced in a 10-ft-diameter test tank, and (2) the impulses were detected equally well by external and internal sensors. The presence of impulsive leak signals in the test-tank data is consistent with the laboratory results cited above. The backfill material was well drained, thus allowing for the entrainment of air bubbles into the leak flow field.

An extensive series of tests were conducted on a 114-ft-diameter AST located at the Mobil Oil Refinery in Beaumont, Texas. The primary goals of the Beaumont experiment were to: (1) investigate the detectability of impulsive-vs.-continuous acoustic leak signals, (2) measure the ambient noise field against which the leak signals must be detected, and (3) obtain continuous time series on a variety of sensor arrays so that improved detection algorithms could be tested. In order to gain a degree of control over the presence or absence of the leak signal, and over the source mechanisms that give rise to the leak signal, a pair of leak simulators were constructed for use in the AST. Both impulsive and continuous components of the simulated acoustic leak signal were found to be detectable in an AST of this dimension. The character of the impulsive leak signal produced by leakage into partially saturated backfills was such that currently used data collection and signal processing techniques would be unlikely to detect the leak in a reliable, convincing manner. The ambient noise field was found to be strongest at frequencies below 10 kHz, thus masking a substantial portion of the continuous leak signal received by external sensors. Because the typical AST leak signal will most likely be influenced by a variety of source mechanisms, the possibility that both impulsive and continuous signals can be processed by the *same* detection algorithm was investigated. A leak detection algorithm based upon beam-forming techniques was applied to the impulsive and continuous leak signals collected during the Beaumont test. Good agreement between the predicted and actual leak location was obtained for both types of signals.

The analytical and experimental results of this project are very encouraging, suggesting as they do that a passive-acoustic system would be capable of detecting small leaks in ASTs. These experiments have shown that a detectable leak signal does exist, but that the current approach to data acquisition and signal processing needs to be improved for the technology to achieve its full potential. The beam-forming algorithm developed to detect a broad range of acoustic leak signals may provide a means of detection that is largely independent of the particular source

mechanisms associated with a given AST leak. The beam-forming detection algorithm and data acquisition system should be refined by means of experimental data obtained from a sensor array that contains a large number of optimally spaced elements. In addition, the uncertainty concerning the character of the signals produced by real AST leaks must be addressed through further experiments.

## 4 Report Organization

The work performed as part of the Phase II program is summarized in two technical papers prepared for publication in the engineering and scientific literature. A copy of each paper is presented, respectively, in Appendices A and B of this report. Both papers describe the results of the experiments with the passive-acoustic sensing system. One has already been published [4], and the other [5] will be submitted for publication shortly.

The paper attached as Appendix A [4] provides a description of the current generation of AE-based leak detection systems and presents the results of an analysis of the data collection and signal processing procedures being used by these systems. This paper also presents an analysis of data that were collected on a 10-ft-diameter AST by a vendor and that were subsequently provided to the API. These data were analyzed for the purpose of investigating the nature of impulsive leak-signal propagation and the detection of impulsive signals by internal vs. external sensors. Finally, the paper presents the results of an extensive set of laboratory experiments in which the nature of the leak signal and its source mechanisms was investigated.

The paper attached as Appendix B [5] describes the field experiments conducted on a 114-ft-diameter AST and a test of a detection algorithm based on the principles of classical beam forming. Source mechanisms identified in [4] were produced through the use of a leak simulator placed inside the AST. The detectability of acoustic leak signals over typical AST dimensions was investigated. This was done by recording continuous time series with arrays of sensors mounted on the external wall of the tank and with a pair of hydrophones deployed internally. Suggestions for improved performance of passive-acoustic leak detection systems are based on the results of these field experiments, and on the development of data collection and signal processing techniques appropriate for the detection of a broad class of relatively weak acoustic leak signals against a strong ambient noise field.

## References

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3. J. W. Starr and J. W. Maresca, Jr. "An Engineering Assessment of Volumetric Methods of Leak Detection in Aboveground Storage Tanks." Final Report for the American Petroleum Institute, Vista Research, Inc., Mountain View, California (25 October 1991).
4. E. G. Eckert and J. W. Maresca, Jr. "Detection of Leaks in the Floor of Aboveground Storage Tanks by Means of a Passive Acoustic Sensing System." *Proceedings of the 84th Annual Meeting and Exposition of the Air and Waste Management Association*, Vancouver, B.C. (16-21 June 1991).
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## Appendix A

### Detection of Leaks in the Floor of Aboveground Storage Tanks by Means of a Passive Acoustic Sensing System

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This paper was published by the Air and Waste Management Association in its *Proceedings of the 24th Annual Meeting and Exhibition* held in Vancouver, British Columbia, on 16-20 June 1991. The paper contained in this appendix is essentially the same as the one published by the Air and Waste Management Association, except that a correction was made to Figure 6, which had inadvertently been reversed in the original.

The description of data collection and processing found in the section of the paper entitled "Description of Commercially Available Acoustic Leak Detection Systems" (and the analysis based on this description in the section entitled "Impulse-Mixing Analysis") is based on the system used by one of the firms that offers acoustic testing services. It should be noted that several firms, upon reviewing the data collection and processing method described in the paper, pointed out that their methods differed slightly from the one described and were actually more complex and robust. While this may be true, it is the opinion of the authors that the conclusions of the impulse-mixing analysis would not change materially even if this analysis were done repeatedly in such a way as to model more precisely the methodology used by *each* of the firms providing services or systems for detection.

## Detection of Leaks in the Floor of Aboveground Storage Tanks by Means of a Passive Acoustic Sensing System

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### Abstract

The acoustic signal produced by a leak in the floor of an aboveground storage tank (AST) was investigated through laboratory and field experiments. Detectable leak signals observed under laboratory conditions were found to be caused by three primary source mechanisms: (1) turbulent flow through the leak aperture, (2) particulate collisions with the tank floor, and (3) air bubble/flowfield interactions. While turbulent flow noise was present in all recorded leak signals, mechanisms (2) and (3) were strongly dependent on backfill conditions. Leak signals recorded in a 10-ft-diameter AST were analyzed in order to verify the existence of the impulsive leak signal, to investigate the propagation mode of leak signals, and to determine the detection/location capability of a narrow-aperture, three-dimensional acoustic array suspended in the fluid. Successful location of a 2-mm hole in the floor of the 10-ft-diameter tank was accomplished by applying a least squares estimation algorithm to the data obtained from the submerged acoustic array. A statistical analysis of the data collection procedures currently being used shows that frequent false alarms and missed detections result from improper time registration of impulsive leak signals. Several recommendations for minimizing this problem are made.

### Introduction

Detection of small leaks in the floor of a large aboveground storage tank (AST) is an extremely difficult task. The American Petroleum Institute (API) has undertaken a program to evaluate the performance of different technologies for detecting small leaks. During Phase 1 of the program, the API described and made a preliminary analysis of the operational and performance features of four technologies<sup>1,2</sup>. During Phase 2, it will conduct a set of experiments in a 77,300-barrel (3.3-Mgal), 117-ft-diameter AST in Beaumont, Texas. These experiments will investigate the important sources of noise and signal-plus-noise of two leak detection approaches, one using an array of passive acoustic sensors and another using mass/volumetric measurement systems. This paper provides a description of commercially available acoustic detection systems and a preliminary assessment of the technology for detection of leaks in large tanks.

Passive acoustic detection systems play an important role in successfully identifying structural defects in a wide variety of materials. The use of acoustic systems to detect leaks in the floor of an AST evolved from and is based on the technology used to detect flaws and cracks

in the walls of a pressurized vessel by means of acoustic emissions. A distinction should be made between an acoustic emission associated with the concentration of stresses in a material and the hydrodynamic acoustic signal produced by a small leak in an AST floor. While many important AST structural problems can be identified through acoustic emissions, the techniques used to acquire and process acoustic emissions data may not be applicable to detecting the acoustic signal produced by a leak.

A review of the industry shows that firms providing acoustic leak detection services for ASTs have been involved principally in using acoustic emissions techniques. The main differences in the acoustic systems used by each firm are the type of sensors and the type of arrays. In general, all of the firms use the same approach to data collection and analysis. This technology is desirable from an operational standpoint because tests can be conducted with only minimal disruption to transfer operations. The sensors are mounted on the outside wall of the tank and a test can be conducted in a short time (approximately 1 h).

The performance of this technology for detecting leaks in the floor of ASTs is at present unknown. A review of the literature shows that very little technical information is available to evaluate the capability of acoustic technology. Most of the technical information has not been published because it is considered proprietary. Of the papers that have been published, most concentrate primarily on the results of leak detection tests but do not adequately describe the fundamentals of the technology. One paper describes some laboratory and small-tank experiments with water<sup>3</sup>, suggesting that a detectable signal exists, but does not describe the character of the signal or how to detect it. Another paper describes the results of some field tests of an acoustic leak detection system<sup>4</sup>. These tests were designed to demonstrate the technology and do not investigate the background noise or the characteristics of the signal, which are required to estimate the performance of a system. Unfortunately, these field tests, which are supposedly a good example of the technology, are not overwhelmingly convincing even as a demonstration. This same statement is true of other unpublished demonstrations conducted by other testing services. As a result of this paucity of technical information and the lack of overwhelmingly convincing leak detection demonstrations, tank owners and operators, while they covet the operational features of the technology, are unable to determine whether this technology is effective.

The performance of a leak detection system depends on how easy or difficult it is to unambiguously identify the signal in the presence of the noise. The noise is any acoustic return produced by either the instrumentation, or any man-made or ambient source that has characteristics similar to the signal. If the signal can be isolated from the noise, then performance will be high; if not, performance will be poor. The objective of the data collection

and signal processing is to minimize the noise. In order to do this, the first step is to determine the basic characteristics of the signal. This paper addresses the signal. It does not address the magnitude and frequency content of the potential sources of ambient noise that might be encountered during a leak detection test. Until the ambient noise field is addressed, however, no estimates of performance are possible. The magnitude of the ambient noise field and its frequency content will be identified during Phase 2 of the API program, through field tests in an operational 117-ft-diameter tank containing light petroleum products.

A number of important questions are addressed in this paper.

- What are the current approaches to acoustic leak detection and how effective are they?
- Does a leak signal exist? If it does, what is it, how is it affected by backfill, how does it propagate, and how detectable is it?
- What approaches to data collection, array configuration, and signal processing can be used to enhance performance?

The analysis and experiments reported herein were completed in support of the design of field tests on a 117-ft-diameter tank and are part of a preliminary evaluation of the technology by the API. This paper consists of the analysis of the data from (1) three experiments conducted and provided by DNV Industrial Services, Inc., (2) laboratory experiments conducted by Vista Research, Inc., using sensors and amplifiers provided by Hartford Steam Boiler Inspection Technologies, and (3) published data from MQS Inspection, Inc.<sup>4</sup>. The results of the analyses presented in this paper suggests that the technology has high potential for detection of leaks in the floor of an AST, but performance is hampered by the way in which data is currently being collected and processed.

## Description of Commercially Available Acoustic Leak Detection Systems

Acoustic leak detection systems currently available in the United States are designed to detect impulsive signals in the time domain that are much larger than the background noise level. The acoustic signal is sampled by a multi-channel transient recorder at a very high rate (e.g., 1 MHz), and an array of frequency-selective sensors is used to acquire data for a time-of-arrival analysis. (Examples of time series that contain impulsive leak signals are shown in Figures 4 and 14.) It is assumed by leak detection firms that these large impulsive signals exist and that multiple signals can be uniquely distinguished in time from one another. The procedure by which a set of impulse arrival times is acquired from the acoustic array is as follows: a threshold signal level is set and whenever it is exceeded at one sensor, the time of arrival of the next threshold exceedance at each sensor in the array is recorded. This is done during a preset window, after which time no further data are admitted. A second window allows for multipath

and reverberation signals to diminish. After the second window has passed, the transient recorder again begins sampling the acoustic signals until another threshold exceedance occurs at one of the sensors. The transient recorders used here can process up to 2000 threshold exceedances per minute. Though the data acquisition systems currently employed by testing firms are able to record time series of the acoustic leak signals as well as impulse arrival times, this capability has not been exploited for the purpose of leak detection. The threshold is set low to ensure that the leak signal is not missed. Discussions with the testing services indicate that the thresholds are set near the peak values of the background noise between the large impulsive signals the systems are designed to detect. As a consequence, many threshold exceedances occur during a test, and it is likely that many of these exceedances are simply the result of large noise fluctuations. (It should be pointed out that the testing services have many restrictions on when a test can be conducted. To minimize the ambient noise fluctuations, for example, tests are not conducted if it is raining or if the wind velocity is too high.) Given a set of impulse arrival times, the location of the impulse source is estimated through the application of a triangulation algorithm. This analysis assumes that each sensor receives a signal from the same impulsive event; false locations will occur if this assumption is violated. These false locations will increase the probabilities of false alarms and missed detections.

Figure 1 illustrates three types of acoustic arrays currently used by the testing services. The first array, shown in Figure 1(a), consists of 12 sensors spaced uniformly around the circumference of the tank. The sensors are located near the bottom of the tank, but above any sludge that might accumulate. In a 100-ft-diameter tank, the 30° spacing results in a 26-ft separation between sensors. The second array, shown in Figure 1(b), is similar to the first, but with the addition of a vertical element. In this array, 6 sensors spaced at 60° intervals are used. The vertical sensor is used to distinguish signals arriving from the top of the tank. For the purposes of discussion in this paper, these types of arrays will be called wide-aperture arrays. In Figure 1(c), a narrow-aperture array is shown. This array consists of 6 sensors positioned along the circumference of a circle that is less than 1 m in diameter. The array is attached directly to the external wall of a tank. To avoid shadowing of the signal, this array is sometimes located at two or more different positions around the circumference of the tank. This circular array has both vertical and horizontal elements. Since the sensors in all three arrays are attached directly to the wall for the measurements, good contact between the sensor and the wall is important.

The data obtained from each threshold exceedance is analyzed in real time and the estimated source locations are then plotted graphically; the number of threshold exceedances (i.e., hits) depends on the number of the sensors in the array and the nature of the analysis. If the source location is outside the circumference of the tank it is identified as a false hit and removed from the analysis. The vertical sensors are used to discriminate against impulses that do not

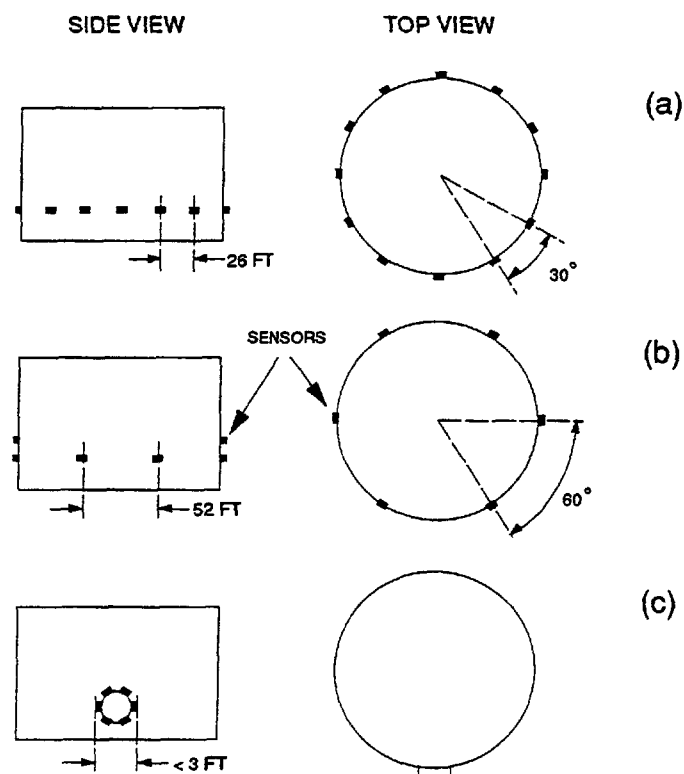


**Figure 1.** Three sensor array geometries being used by commercial testing services: (a) wide-aperture horizontal array, (b) wide-aperture horizontal array with vertical elements, and (c) narrow-aperture array with horizontal and vertical elements.

arrive from the bottom of the tank. In addition to the measurement of the time of arrival, other parameters of the signal envelope are sometimes measured; at this juncture, this information is stored but is not used as part of the detection or analysis. The duration of a leak detection test is typically 1 h. All of the source locations estimated from the threshold exceedances during a test are used to determine whether the tank is leaking or not. While the algorithms used for detection differ slightly, a leak is declared if a large number of hits are closely clustered in one or more locations. Visual interpretation of the graphical display by the operator has been the most frequent method of analysis. Recently, some of the testing services have begun using a statistical approach to display the number of hits in predetermined areas within the tank.

Figure 2 presents the results of a leak detection test published in Miller<sup>4</sup>. The data from the entire 60-min test is shown in Figure 2(a) and the data from three different 10-min portions of the test are shown in Figures 2(b) - (d). The clustering of data in Figure 2(c) suggests the presence of a leak. This clustering is not observed in the other four 10-min periods (of which only one is shown). It is argued in Miller<sup>4</sup> that the reason why the signal occurs primarily in only a few of the 10-min periods is that the impulsive signals produced by the leak do not occur uniformly in time; however, no evidence is presented to support this argument. The large

number of false source locations observed in Figure 2 is also representative of the test data collected by other testing services using a wide-aperture array. The analysis presented in Section 5 offers a probable explanation for the large scatter in the estimated source locations.

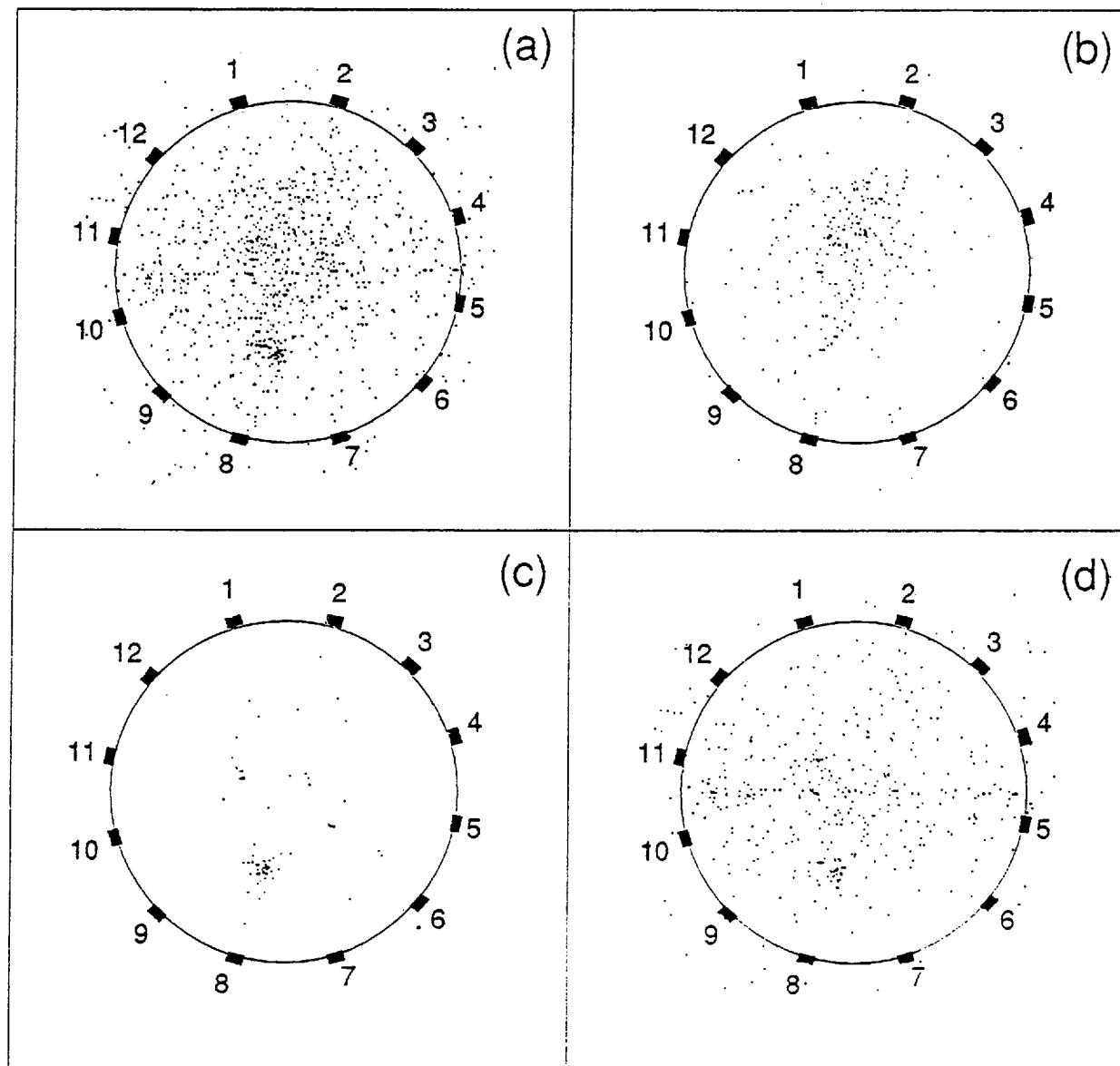


**Figure 2.** Results of a 1-h leak detection test. Each display shows the location of each threshold exceedance. A clustering of hits indicates the possible location of a leak. Display (a) shows all hits obtained during the 1-h test, and (b) through (d) show the hits during three separate 10-min periods.

## Experiments in a 10-Ft-Diameter AST

DNV Industrial Services provided data from a variety of experiments conducted in 1989 in a 10-ft-diameter, open-top AST that was specially assembled in an asphalt parking area for these tests. The tank, approximately 10 ft in height, was filled with water to a level of approximately 9 ft. It was located on a thick layer of river-sand backfill that was contained by a square wood

frame. All of the data analyzed were from experiments in which the tank had a 2-mm-diameter hole in its floor. The water released during the experiments freely drained through the backfill and onto the parking lot. Between experiments, the hole could be plugged from the top of the tank. However, no data were provided on this tank when it was in a nonleaking state, precluding a control analysis. The results of two experiments are presented below. The first experiment compares the time series of the acoustic return simultaneously received from an acoustic sensor mounted on the external steel wall of the tank and one suspended in the water near the top of the tank. The second experiment illustrates the detection capability achieved by a three-dimensional array suspended in the water.

All of the data provided by DNV consisted of time series obtained with a multi-channel transient recorder. Once the threshold established at the beginning of the test was exceeded at any sensor, a 1- to 10-ms time series was recorded and stored for later analysis; the initial threshold exceedance was included in the recorded time series.

### Internal Sensor vs. External Sensor Response to a Leak

Time series of pressure fluctuations measured by an internally suspended hydrophone (BK-8105) and an externally mounted resonant sensor were analyzed in an attempt to identify the acoustic leak signal due to the presence of a 2-mm-diameter hole and to estimate the leak's location within the tank. Tank geometry and sensor positions are shown in Figure 3; the

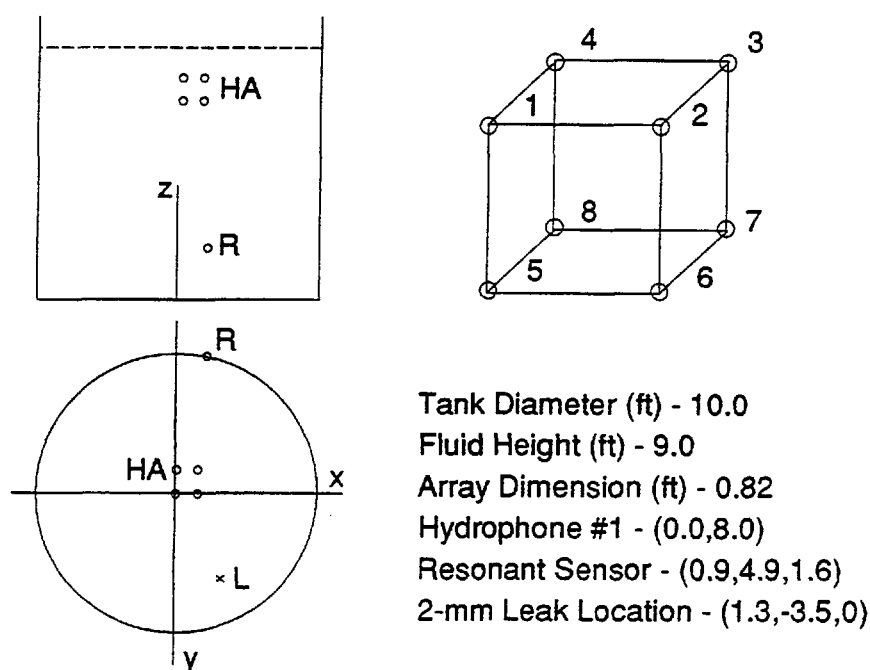


Figure 3. Geometry of the acoustic sensors in the 10-ft-diameter tank.

hydrophone for this experiment was located in approximately the same place as element number 1 of the hydrophone array (HA), while the resonant sensor was located on the outside tank wall at position R. Figure 4 shows time series recorded by both the internal and external sensors. A time-of-arrival analysis with respect to the primary pulse (P) indicates that the observed signal most likely originated near the site of the 2-mm hole. The appearance of this impulse in both the internal and external traces shows that the strongest signals are propagated through the fluid rather than through the tank shell. The relatively small impulse which appears near the  $t = 2.0$  ms time in the external trace is believed to be the leak signal propagated to the sensor via the tank shell. The delay time between this impulse and the primary impulse is consistent with the difference in sound velocity between steel and water (approximately 5,000 m/s as compared to 1,500 m/s). The internal hydrophone receives a secondary impulse (S) delayed by approximately 0.25 ms relative to the primary signal. An analysis of multipath propagation for this particular leak site shows that the time delay of the secondary impulse is consistent with reflections of the acoustic signal from the tank's side wall and/or the fluid surface. The two sources of multipath are shown in Figure 5; the difference in the arrival times for each of these two reflected paths is approximately 0.02 ms, which is not discernible in the time series shown in Figure 4.

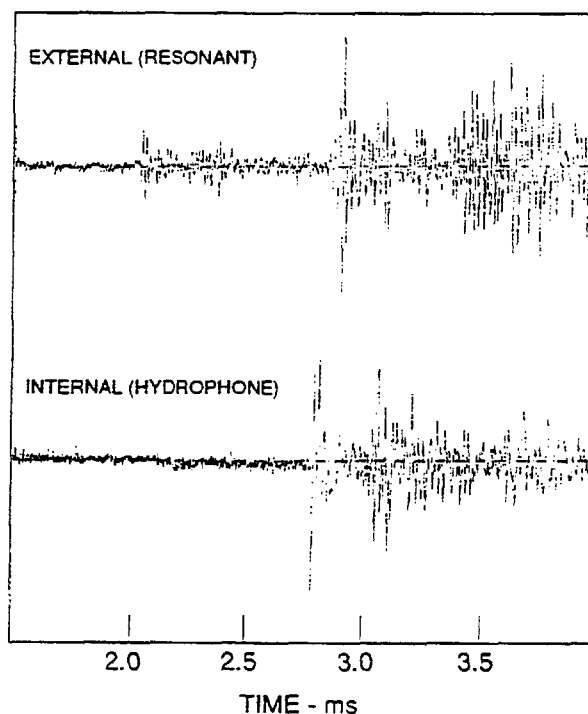


**Figure 4.** Response of the acoustic sensor mounted on the external shell of the steel tank and the acoustic sensor suspended near the top of the tank. Both sensors are approximately 10 ft from the leak.

Several conclusions may be drawn from the data:

- The impulse arrival time is consistent with a signal emitted from the site of the leak.

- The strongest signals are propagated through the fluid, and a weaker signal is observed to propagate through the tank shell.
- Under relatively quiet conditions in a small tank, externally mounted sensors should be as effective as internal sensors in receiving impulsive leak signals.

### Three-Dimensional Internal Array

The hydrophone array used by DNV consisted of eight broadband acoustic sensors located at the corners of a cube with elements spaced at approximately 25 cm. The array was positioned along the center axis of the tank at a height of approximately 8 ft from the tank floor. A 2-mm-diameter hole located at coordinates (1.3 ft, -3.5 ft, 0.0 ft) was open throughout the measurement period (see Figure 3). Figure 6 shows a typical data record obtained during a 1-ms interval within which a large-amplitude event was recorded on seven of the array elements. In

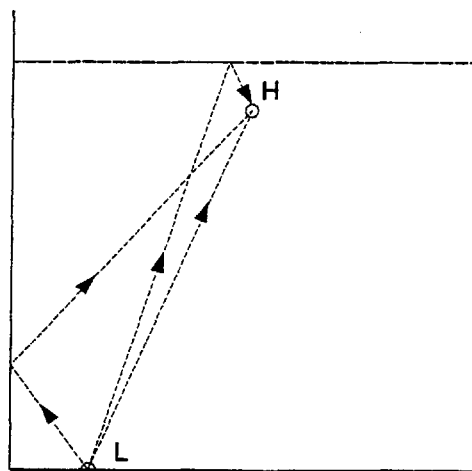


**Figure 5.** Multipath signals received by the internal array. Both paths have approximately the same time of arrival.

order to estimate the source location corresponding to the primary impulse, the relative arrival time of the impulse was estimated for each of the time series shown. Combining the measured arrival times with the array geometry and speed of sound, a least squares method of estimation was used to determine the most likely origin for the acoustic impulse. All of the data records analyzed in which the primary impulse is easily identified suggest a leak located near coordinates (1.4 ft, -2.8 ft, -1.3 ft) with a standard deviation of 0.2 ft (Figure 7). The difference between the predicted source location and the actual leak site cannot be accounted for by a simple adjustment in sound speed. It is believed that the small array size coupled with an inexact knowledge of array dimensions and orientation is consistent with the error in the predicted source location.

A secondary impulse, occurring approximately 0.3 ms after the primary impulse, is clearly visible in six of the array element time series. The secondary signals occur as a result of reflections of acoustic impulses from the tank wall or air/water interface. An analysis of the

expected arrival times of impulses reflecting off of the tank's side-wall or off of the air/water interface above the array shows that the particular secondary signals observed in DNV's data are most likely due to reflections off the tank's side-wall. Though not attempted thus far, it should be possible to use the relative arrival times between secondary impulses to compute a second, independent estimate of source location within each data record.

### Interpretation of the Results

These tests clearly illustrate the existence of a signal produced by a leak and show that this signal propagates both through the steel walls of the tank and through the water. The signal that propagates through the water is much stronger than that which propagates through the wall. The experiments also show the primary propagation path (i.e., the direct path from the leak to the sensor), the discrete multipaths (i.e., the leak-wall-sensor path and the leak-surface-sensor path), and the reverberation. Registering these signals and correctly identifying the same signal in each sensor is important to the detection scheme. Due to gain peaking near the sensor cutoff frequency, the DNV time series provide no information as to the spectral content of the leak signal at high-frequencies; furthermore, at approximately 1 ms, they are too short for any low-frequency analysis. Nevertheless, there is no doubt that the data collection scheme and signal analysis employed are adequate for locating single leaks within a small storage tank. However, no background noise data were collected during these experiments, so the strength of the signal relative to the background level is unknown. Neither did these experiments give any insight into the source mechanism(s) which give rise to the acoustic leak signal.