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

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ABSTRACT

There are two approaches to detecting leaks in an aboveground storage tank (AST) by means of the volumetric method. The first is the conventional approach in which measurements of the level and temperature of the product are made with a precision level sensor and a vertical array of temperature sensors. The second is a mass measurement approach which employs a differential pressure sensor to measure the level changes. In a tank with vertical walls, a differential pressure sensor inherently compensates for the level changes produced by thermal expansion and contraction of the product between the pressure port and the product surface.

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 controlled experiment was conducted in a 117-ft-diameter tank during late May and early June 1992. The purpose of this experiment was to evaluate the performance of both approaches to volumetric testing. The tank contained a light fuel oil, and data were collected over a continuous 28-day period.

The analytical and experimental results of this project suggest that a volumetric system can be used to detect small leaks in ASTs. Analysis of the level temperature approach indicates that the largest source of volume fluctuations was thermal expansion of the product. It was found that effective compensation for this expansion could be achieved, and leak rates as small as 1.9 gal/h could be reliably detected in a single 24-h test. Furthermore, extending the test period to 48 h would significantly improve leak detection performance, resulting in a detectable rate of about 1.0 gal/h.

While in theory differential pressure systems should achieve a higher level of performance than the level temperature systems, this was not the case. The setup of the differential pressure measurement system is extremely sensitive to air temperature changes, and to a lesser extent, the location of the bottom pressure reading.

Regardless of the approach used, volumetric leak detection tests achieve their highest performance when the level of the product in the tank is low (approximately 3 ft), and the test duration is at least 24 h (48 h if possible), the test is begun and ended at night, and accurate temperature compensation is applied. When the test duration is significantly less than 24 h, it is not possible to accurately compensate for the effects of diurnal temperature changes.

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INTRODUCTION

There are two approaches to detecting leaks from an aboveground storage tank (AST) by means of the volumetric method. The first is the conventional approach in which measurements of the level and temperature of the product are made with a precision level sensor and a vertical array of closely spaced, precision temperature sensors. The second is a mass-measurement approach, which employs a differential-pressure sensor to measure the level changes. In a tank with vertical walls, a differential-pressure sensor inherently compensates for the level changes produced by the thermal expansion and contraction of the product betweeen the pressure port, which is located near the bottom of the tank, and the product surface. Because of the possibility of large horizontal gradients in the rate of change of temperature of the product in an AST (gradients which cannot be accurately measured with a single vertical array) the mass-measurement approach should, in theory, have a performance advantage over the conventional approach.

As part of Phase III of the American Petroleum Institute's (API's) project to develop and evaluate the performance, in actual operational environments, of different technologies for detecting leaks in the floor of ASTs[1], a controlled experiment was conducted in a 117-ft-diameter tank at Mobil's refinery in Beaumont, Texas, during late May and early June 1992. The purpose of this experiment was to evaluate the performance of both approaches to volumetric testing. The tank contained a light fuel oil, and data were collected over a continuous 28-day period. Two vertical arrays of thermistors were placed at two locations inside the tank to determine the magnitude of the horizontal gradients in the rate of change of product temperature. Temperature measurements of the tank's exterior shell were also made.

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 in order 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. The results of the volumetric experiments indicated that, in order for a test to achieve sufficient compensation for the temperature-induced changes in the product and in the wall needed for high performance, the product should be at lower levels and test duration should be approximately 24, 48 or 72 hours.

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1 Phase III also included an engineering evaluation of passive-acoustic methods of leak detection for ASTs. The results of the acoustic study are provided in a separate API document entitled *An Engineering Evaluation of Acoustic Methods of Leak Detection for Aboveground Storage Tanks*, by Eric G. Eckert and Joseph W. Maresca, Jr.

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;
- 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 volumetric system can be used to detect small leaks in ASTs. Analysis of the float-based system indicated that the largest source of volume fluctuations was thermal expansion of the product. During this project it was found that effective compensation for this expansion, as well as compensation for the thermal expansion of the tank walls, could be achieved. Analysis of the test results suggested that leak rates as small as 1.9 gal/h could be detected in a single 24-h test at a probability of detection (P_D) of 95% and a probability of false alarm (P_{FA}) of 5%. Furthermore, test results suggest that extension of the test period to 48 h would significantly improve leak detection performance, resulting in a detectable rate of about 1.0 gal/h. This high level of performance was achieved in tests begun and ended at night because the horizontal gradients in the rate of change of product temperature were negligible during the night. Both estimates could have been improved with more extensive measurement of the vertical temperature profile of the product, particularly in the upper layers of the product where the greatest rates of temperature change persistently occurred. Some degradation of the performance estimates probably occurred as a result of non-uniform inflow of product from neighboring tanks through leaking isolation valves. This inflow condition was present during the entire 28-day data collection period.

While in theory differential pressure systems should achieve a higher level of performance than temperature and level systems, this was not the case in the field tests conducted as part of this project. We found that the setup of the differential pressure measurement system is extremely sensitive to air temperature changes and, to a lesser extent, the location of the bottom pressure reading. In principle, these setup problems can be eliminated by careful design; in practice, however, as shown by these tests, they are sometimes difficult to avoid. Regardless of the approach used, volumetric leak detection tests achieve their highest performance when the level of product in the tank is low (approximately 3 ft), the test duration is at least 24 h (48 if possible), the test is begun and ended at night, and accurate temperature compensation is made for the thermal expansion and contraction of the instrumentation, the tank shell and the product. When the test duration is significantly less than 24 h, it is not possible to accurately compensate for the effects of diurnal temperature changes.

This document presents the results of these volumetric experiments in two technical papers, which are attached as appendices. The first provides a description of the capabilities of a level-and-temperature leak detection system for use in ASTs. This paper quantifies the sources of ambient noise, describes those features of a leak detection system that are crucial for high performance, and estimates the performance of the volumetric method of testing. The second describes the capabilities of a differential-pressure leak detection system for use in ASTs. This paper focuses on the temperature compensation requirements necessary to achieve high performance with this type of measurement system.

1 INTRODUCTION

This report is one of two that summarize 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 for the purpose of making an engineering assessment of the performance of two of these technologies, passive-acoustic sensing systems and volumetric detection systems. 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 acoustic and volumetric leak detection strategies that emerged from the Phase II study, and to further evaluate the current state of leak detection technology. To evaluate the performance of the volumetric method, volumetric tests were conducted in a 117-ft-diameter tank containing a light fuel oil. A nearly continuous time series of level and temperature data was collected over a 28-day period. The acoustic tests were conducted in a 40-ft-diameter AST, which contained water and was especially configured to assess the nature of the acoustic signal produced by a hole in the floor of the tank. This report describes the results of the Phase III volumetric tests; the results of the acoustic tests are described in a separate report (Vista Research, Inc., 1993), which consists of brief overview of the work and two detailed technical papers (Vista Research, Inc., 1993).

There are two approaches to detecting leaks from an AST by means of the volumetric method. The first is the conventional approach in which measurements of the level and temperature of the product are made with a precision level sensor and a vertical array of closely spaced, precision temperature sensors. The temperature array is used to estimate the level changes produced by the thermal expansion and contraction of the product so that they can be removed from the measured level changes. The second is a mass-measurement approach, which employs a differential-pressure sensor to measure the level changes. In a tank with vertical walls, a differential-pressure sensor inherently compensates for the level changes produced by the thermal expansion and contraction of the product. Although there are other sources of noise that affect both approaches, thermal expansion and contraction of the product is the largest. Thus, in ASTs, a mass-measurement system would appear to have a significant performance advantage over the conventional level-and-temperature measurement approach.

The specific objectives of Phase III research in the area of volumetric measurement systems were

- to determine if differential pressure (mass-measurement) systems have significant advantages over the conventional level and temperature measurement systems;
- to characterize the ambient noise that is encountered under a wide range of test conditions and that affects the performance of both types of volumetric leak detection system;
- to identify any operational issues related to the implementation of either type of volumetric system;
- to demonstrate the capabilities and, if possible, make an estimate of the performance of volumetric measurement systems through field tests; and
- to identify those features of a volumetric leak detection test that are required for 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 program. Section 5 presents those features of a volumetric test that will ensure a high level of performance (both for the mass-measurement and the level-and-temperature approaches). 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

A methodology for testing ASTs for small leaks with a volumetric test method was developed in the Phase II field tests. Volumetric measurements were made in a 114-ft-diameter AST containing a heavy naphtha. Two three-day data sets were collected, one in which the tank was filled to a level of 17 ft and the other to a level of 10 ft. Estimates of the magnitude of the important sources of ambient noise were made at each level. The results of the field tests indicated that compensation for thermally induced volume changes is essential for the detection of small leaks. Changes in the temperature of the product, in response to diurnal cycles, were found to be the largest source of volume fluctuation. These were difficult to measure with sufficient accuracy for effective compensation when only a *single* vertical array of thermistors was used. The reason for the insufficiency of the single array was that the rate of change of temperature differed at various locations along the horizontal axis of the tank. The volume changes induced by the thermal expansion and contraction of the wall were found to be much smaller, but because they were still large in comparison to a small leak, compensation was required if robust detection performance was to be achieved. The peak-to-peak variation of the thermally induced product volume changes over a 24-h diurnal period was sometimes over 1,000 gal. The results also indicated that test durations of at least one or more diurnal cycles (i.e., at least 24 h) are required in order that there be (1) a high level of compensation for diurnally induced thermal changes and (2) sufficient time that the volume changes induced by small leaks in a large tank can be sensed. The Phase II results also indicated that, for a high degree of performance, volumetric tests must be performed when product level is lower than 10 ft. Volume changes due to evaporation and condensation, also controlled by large diurnal changes in air temperature, were identified in the Phase II tests but could not be quantified. Because it cannot be easily compensated for, evaporation/condensation as a source of noise will ultimately be the limiting factor in performance.

The Phase II experimental work suggested that a mass-measurement (or differential-pressure) system would perform better than a level-and-temperature measurement system because it is not affected by large thermally induced changes in the volume of product. A level-and-temperature system is subject to errors in thermal compensation because of horizontal gradients in the rate of change of temperature that are difficult to account for. This error is expected to be much greater than (1) any error due to the low-level measurement precision of most differential-pressure (DP) sensors; (2) any error due to the thermal sensitivity of such a DP sensor; or (3) any error due to the inability of a DP measurement system to compensate for the thermally induced volume changes that occur below the lowest pressure port. Whether or not sufficient performance could be achieved with a mass-measurement system still depends on the magnitude of the other errors and sources of noise that affect both types of volumetric measurement systems equally, for example, thermal expansion and contraction of the tank walls, evaporation and condensation, etc. The test methodology developed in Phase II was based on two simple points: use a long test duration that approximately covers integral multiples of a diurnal cycle (24, 48, or 72 h), and conduct a test when the level of product is low (approximately 3 ft).

3 SUMMARY OF RESULTS

The Phase III field tests were designed to evaluate the performance of volumetric methods designed for testing ASTs with diameters of approximately 100 ft. The experiment design focused on mass-measurement systems, because the Phase II results suggested that such systems had performance advantages over the conventional level-and-temperature measurement systems in terms of compensation for thermally induced diurnal changes in the volume of product. The data collected by the level-and-temperature system was intended mainly for use as diagnostic information for the mass-measurement system. As it turned out, however, the level-and-temperature measurements also proved adequate for use in a leak detection test; furthermore, they provided the basis for most of the conclusions drawn in this phase of the work.

An estimate of the performance of both types of volumetric method was made from the 28-day data set collected during experiments on a 117-ft-diameter AST. The experiments took place in late May and early June at the same refinery used in Phase II. The tests were conducted at about the same time of year, and the tank was of similar size and type as that used in Phase II. The main differences were in the type of product and the level of product. The light fuel oil used in the Phase III tests was less volatile than the heavy naphtha used in the Phase II tests, and product levels were lower during Phase II.

Two vertical arrays of thermistors were placed at two locations inside the tank to determine the magnitude of the horizontal gradients. Additional temperature measurements were made on the tank exterior to estimate thermally induced changes in the tank walls. Precision level measurements were made with an electromagnetic sensor provided by Vista Research and with two differential-pressure sensors. Vista Research also provided the various thermistor arrays.

All data were collected at a nominal product level of 37.5 in. This low level helped to minimize the volume fluctuations associated with expansion and contraction of both the product and the tank wall. During the entire test period, volume fluctuations exhibited strong diurnal influence, with peak-to-peak volume changes of as much as 150 gal occurring over a 24-h period; the thermally induced volume changes of the product accounted for approximately 90% of the total thermally induced volume changes. While the rate of change of volume could be as high as 30 gal/h over a 4-h period, it was generally less than 10 gal/h over a 24-h period. Since even the best methods of temperature compensation can remove only 90 to 99% of the unwanted noise fluctuations, long tests are essential for accurate compensation. Other sources of volume change during these experiments, such as evaporation and condensation of the product, which are also thermally driven, appeared to be extremely small.

Throughout the entire test period, the mean inventory in the tank was found to increase linearly at about 2.8 gal/h. It is suspected that this increase, which was measured with the level-and-temperature system, is due to inflow from neighboring tanks through leaking isolation valves. Because the inflow appeared to be relatively uniform over the 28-day period, it was possible to make estimates of performance under these conditions. No independent measurement of the flow rate was made, however, and so it cannot be determined whether day-to-day non-uniformities in this inflow degraded the performance estimates. Some degradation probably occurred.

The temperature-and-level measurements were made by a float-based system. Analysis of these measurements indicated that the largest single source of volume fluctuations was thermal expansion of the product. When compensation was made for this expansion, as well as that caused by thermal growth of the tank walls, it was possible, in a single 24-h test, to detect leaks as small as 1.9 gal/h with a probability of detection (P_D) of 95% and a probability of false alarm (P_{FA}) of 5%. When the test period was extended to 48 h, with no alteration of the thermal compensation scheme, leak detection performance improved significantly, resulting in a detectable leak of about 1.0 gal/h. The high performance achieved by the temperature-and-level measurement approach was due to the fact that all tests were begun and ended at night, when horizontal gradients in the rate of change of product temperature (and shell temperature as well) were negligible. The estimates of leak rate were made from only one of the two vertical arrays; both arrays gave approximately the same results in tests beginning and ending at night. Better performance would have been achieved if there had been more temperature sensors on the array; more sensors would have provided a more extensive measurement of the vertical temperature profile of the product, particularly near the surface where most of the temperature changes occurred. The high performance achieved with the temperature-and-level measurement system was unexpected; this measurement approach is viable for leak detection in ASTs provided that tests are begun and ended at night and that product level is very low.

In examining the mass-measurement approach, two different implementations of the differential-pressure system were used. In each case the sensor was extremely sensitive to changes in ambient air temperature; this was the result of having to use vertical tubes to connect the sensor to the tank. The volume changes measured by the DP cell were three to five times greater than the uncompensated volume changes measured by the level sensor, a fact that could be attributed to the thermal sensitivity of the tube geometry. A number of temperature compensation schemes for the DP cell were therefore devised. These schemes used temperature data obtained from thermistors attached directly to the tubes. While some of the schemes worked for short data segments, they were not universally applicable. In principle, this thermal sensitivity could be minimized by using only horizontal tube connections between the differential pressure sensor and the tank. We do not know whether or not this is sufficient to avoid the thermal sensitivity observed during these tests. Some limited data were collected with a differential pressure sensor configured with only horizontal tube connections, but residual thermal fluctuations still occurred. We believe, however, that when the differential pressure system is properly implemented, it should be possible to obtain performance similar to or perhaps better than that of the level-and-temperature measurement system.

A differential-pressure system does not compensate for any thermally induced product changes below the lowest pressure port, a source of error that is not present in level measurement systems. The peak-to-peak volume changes over a diurnal period that were produced by thermal expansion and contraction of the product in this bottom layer were as large as 30 gal during these tests. This means that hourly rates as high as 1 gal/h could occur during test periods significantly shorter than one diurnal fluctuation period. Fortunately, these changes were small when measured over a complete diurnal period (i.e., 24 h)---less than 10% of the peak-to-peak gross product volume changes (i.e., approximately 0.04 gal/h). The same shell-mounted temperature sensors were used to compensate for changes in volume induced by the thermal expansion and contraction of the tank walls.

4 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of Phase III volumetric tests is that accurate and reliable detection of small leaks in ASTs is possible. Leaks as small as, or perhaps even smaller than, 1 gal/h should be detectable with a P_D of 95% or greater and a P_{FA} of 5% or less. In addition, the important features of a volumetric leak detection test with high performance have been identified and validated.

The anticipated performance advantage of the mass-measurement approach over the level-and-temperature approach was not realized. It was found that horizontal gradients in the rate of change of temperature of the product were negligible during the night; it was therefore possible to achieve accurate temperature compensation with a single vertical array of temperature sensors as long as a test was conducted entirely during night-time hours. This discovery, which makes the level-and-temperature approach feasible, is a surprising and important finding, and one which should be verified under a wider range of conditions, both for the tank and the product. The reason for the high performance of the level-and-temperature approach was the fact that product level was low. If the horizontal gradients are large, a differential-pressure system should in theory achieve a higher level of performance than a level-and-temperature system. If, however, the horizontal gradients are small (as they were in these tests) the two should perform more or less equally. This turned out not to be the case. The DP system's performance was not as good as that of the level-and-temperature system. We found that because of the way the DP system is set up it is extremely sensitive to ambient changes in air temperature and (to a lesser extent in these tests) is influenced by the position of the bottom tube of the DP sensor along the vertical axis of the tank. In principle, these setup problems can be eliminated by careful design, but in practice, as was our experience during these tests, they are sometimes difficult to avoid. Further work is required before these implementation issues can be understood.

Regardless of the approach used, volumetric leak detection tests achieve their highest performance when the level of product in the tank is low (approximately 3 ft), the test duration is at least 24 h (48 h, if possible), a test is begun and ended at night, and the thermal expansion and contraction of the instrumentation, tank shell, and product are accurately compensated for. When a test is significantly shorter than 24 h, it is not possible to achieve a high level of performance because it is not possible to compensate adequately for thermally induced changes in the volume of product that are the result of the diurnal temperature cycle. To allow thermal inhomogeneities to dissipate, as well as for any deformation of the tank shell to subside, it is necessary to include as part of the *pre-test* protocol a waiting period of at least 24 h, during which time no product is added to or removed from the tank.

In general, the performance of both the mass-measurement and level-and-temperature approaches will decrease (1) as the diameter of the tank increases, (2) as the level of product in the tank increases and (3) when the tank contains more volatile products than the one used in these experiments, such that evaporation or condensation becomes an important noise source. Tests at higher product levels, although not optimal for performance, may be possible in smaller ASTs. Additional modeling and experimental data will be necessary to determine when or if this is possible.

The success achieved with the volumetric 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. Volumetric methods represent a way to test a large AST for leaks before it is taken out of service. Since testing may take several days, and since product may have to be removed from the tank, a volumetric test is most efficiently used when another type of test has already suggested the possibility of a leak or when product level is low enough that no liquid has to be removed and temporarily stored elsewhere.

Three 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 data obtained in the Phases II and III tests are limited in that they represent only one type and size of tank, two products, and one season of the year. Less than a month's worth of experimental data were collected with the test procedures outlined here, and these data are limited to ASTs in the same geographic location and under the same climatic conditions. While the data collection and analysis methods developed as part of Phase III are based on sound experimental evidence, these methods have not yet been evaluated over a wide enough set of conditions to be definitive. In addition, there are some implementation issues yet to be resolved, namely, the issue of horizontal gradients with regard to the level-and-temperature approach and that of the set-up geometry of the DP sensor with regard to the mass-measurement approach.

The second recommendation is to develop and validate a *standard test procedure* for evaluating the performance of leak detection methods in terms of probability of detection (P_D) and probability of false alarm (P_{FA}). 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 EPA's underground storage tank (UST) program. The development and implementation of a standard test procedure for ASTs 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 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 these technologies and to extend their application over a wider population of tanks. Three areas of further technology development are recommended for volumetric methods: (1) characterize the noise environment over a wider range of tank and tank testing conditions, (2) evaluate the performance of volumetric leak detection systems (both mass-measurement and level-and-temperature-measurement systems) over a wider range of tank types and testing conditions, and (3) develop better methods of temperature compensation for each approach. It is especially important to determine the magnitude of the horizontal temperature gradients and the evaporation and condensation in tanks as a function of the type of product stored. It is also important to examine the thermal sensitivity of different setup configurations for the DP system and to develop compensation methods that minimize the noise contribution from the instrumentation. 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 volumetric 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 and comment of the test plan before and the test results after each set of field tests. While publication and direct interaction with the user community has been actively and vigorously pursued by

API, it may not be sufficient to effect the necessary technology transfer. In our opinion, the most effective method of insuring technology transfer involves the implementation of the second recommendation, the development of a standard test procedure.

5 IMPORTANT FEATURES OF A VOLUMETRIC METHOD WITH HIGH PERFORMANCE

The features of a volumetric test that are crucial to high performance have been identified. The design of a volumetric test must carefully address the diurnal temperature fluctuations observed in the volume data that are controlled by the ambient air temperature. Let us first examine the general features (those that are important to both the mass-measurement and the level-and-temperature approach). These "general" features apply to tests conducted on ASTs having diameters of approximately 100 ft. Important features particular to one approach or the other are described later. Note that either approach can be implemented with commercially available, off-the-shelf measurement systems.

- ***Waiting Period.*** Before starting a test, it is necessary to observe a waiting period of at least 24 h, during which time no product is added to or removed from the tank. This allows thermal inhomogeneities in the product to dissipate and any deformation of the tank shell to subside. (The waiting period is an established part of the protocol for testing USTs; because of the continuous nature of the data in the experiments described here, the importance of the waiting period was not verified independently as part of the current work.)

- ***Low Product Level.*** Product level should be low enough to optimize the signal-to-noise ratio. Good performance was achieved when the product level was at approximately 3 ft. This minimized the overall thermally induced volume changes and resulted in horizontal gradients at night that were small enough to be negligible.

- ***Long Test Duration.*** The duration of the data collection period during a leak detection test should be at least 24 h and preferably 48 h. Test durations that are whole multiples of a diurnal cycle should be used unless it is demonstrated a slightly longer or shorter duration will yield better temperature compensation. This would be the case if, for example, differences in temperature (whether of the ambient air, the shell, or the product) were less over a period of 22 or 26 h than over the full 24 h.

- ***Test at Night.*** For best performance, a test should begin and end at night, when there are no large changes in ambient air temperature and no sunlight heating the tank perimeter unevenly. Testing at night is equally important to both measurement approaches, since both are affected by expansion of the tank shell and by evaporation and condensation. There are also *different* reasons for testing at night that are particular to each approach. The fact that horizontal gradients in the rate of change of product temperature are sufficiently small at night means that a level-and-temperature system is a viable tool in leak detection; and the fact that the rate of change of the ambient air temperature is constant at night permits more accurate compensation of the thermally sensitive differential pressure sensor used in a mass-measurement system.

- *Digital Data Collection/Sampling Rate.* All data should be collected digitally at a sampling interval between 1 and 10 min. This permits the development and application of a variety of the more complex noise cancellation and data analysis algorithms.

- *External Temperature Sensors.* To permit compensation for thermally induced changes in the tank shell, a horizontal array of 6 external temperature sensors is recommended. These should be mounted on the outer steel wall and around the perimeter of the AST; they should be shaded from direct sunlight. When the data processing algorithm uses only the data from the beginning and end of a test initiated at night, fewer temperature sensors may suffice.

- *Known Coefficient of Thermal Expansion and Known Height-to-Volume Conversion Factor.* The coefficients required for temperature compensation and for conversion of level changes to volume changes should be known beforehand or should be measured as part of the test. A different set of constants will be required for each measurement approach. Errors in these constants will produce a bias in the test results that might be large enough to suggest the presence of a leak.

- *Sufficient Instrumentation Precision.* The "combined" precision of the level-and-temperature instrumentation used to measure the rate of change of the thermally compensated volume, regardless of approach, must be sufficient to sense a leak approximately one-third the size of the smallest leak to be detected reliably. A low-precision level sensor, for example, can be improved by increasing the test time. A method for estimating the minimum duration of a test conducted with a level sensor having a given precision is discussed by Starr and Maresca (Vista Research, Inc., 1989; Maresca and Starr, 1990). A method for estimating the minimum duration of a test conducted with a temperature sensor having a given precision is presented in the same works.

- *Compensation for Thermally Induced Volume Changes.* All thermally induced volume fluctuations need to be compensated for, or they must be minimized by means of a long test. Because the leak signal does not have a diurnal period, any diurnal fluctuations remaining in the compensated volume data are indicative of an error.

Additional features that are important for high performance and that are particular to level-and-temperature measurement systems are listed below.

- A single array of closely spaced temperature sensors with a precision of 0.001°C is required in order that thermally induced changes in the product can be compensated for. It should be possible to position this array at any location in the tank if a test is begun and ended at night. The temperature sensors should be located at closely spaced intervals (e.g., 8- to 12-in., or closer); since most of the temperature changes occur in the upper portion of the product, and strong gradients are present in the lower portion, it is recommended that sensors be spaced more densely in the upper and lower layers of product (e.g., 4 in., or closer).

- The coefficient of thermal expansion of the product and steel shell, the volume of product in the tank, and the height-to-volume conversion factor must be known before a test is conducted. The coefficient of thermal expansion should be experimentally determined as part of the test procedure.

Additional features that are important for high performance and that are particular to mass-measurement systems are listed below.

- The thermal sensitivity of the instrumentation must be minimized as part of the setup. It is essential that all tubes used to connect the DP sensor to the tank be horizontal and that all trapped air be completely removed from the tubes and the sensor. Additional temperature sensors attached to the body of the DP sensor and to the connecting tubes might be required to compensate for changes in ambient air temperature. Since we were unable to develop a compensation algorithm during the course of this analysis that could be universally applied to all of the differential pressure data, we cannot state with certainty that additional thermal problems will not occur when the pressure connections are made with horizontal tubes. The data obtained from a system configured with horizontal tubes suggest that thermal fluctuations still persist, even after thermal compensation.

- The coefficient of thermal expansion of the steel shell, the specific gravity of the product, and the height-to-volume conversion factor are required. If an accurate experimental estimate of the height-to-volume conversion factor is made during a test, then the specific gravity does not have to be known.

There are several ways to determine whether a signal is a false alarm or a real leak signal. The first step is to simply repeat the volumetric test. Previous analysis has shown that two or more tests will reduce the possibility of a false alarm. Since these tests are not totally independent, the performance improvement achieved by repeat testing may be only a factor of two or three. If, after a test has been repeated one or two more times, a leak is still suspected, another approach can be used. In this approach, a test based on a completely different technology, such as acoustics, is then conducted. This approach can be very effective because the mechanism generating the leak signal, and the noise interfering with it, are very different in an acoustic test than they are in a volumetric test. It is unlikely that the same false alarm mechanism will affect both methods similarly. Another effective approach is to drop a hydrophone over the purported leak and listen for the strong return of the continuous signal. The presence of a signal can be determined by comparing this acoustic return to the return obtained at one or more different locations in the tank where the leak signal is not present. This approach works because the strength of the signal produced by turbulent flow decays quickly as the distance from the leak increases. While this approach may be operationally inconvenient, it is a very effective way of verifying the presence or absence of a leak.

6 REPORT ORGANIZATION

The work performed as part of the Phase III 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 conducted at the Mobil refinery in Beaumont, Texas. The paper attached as Appendix A provides a description of the capabilities of a level and temperature leak detection system for use in ASTs. This paper quantifies the sources of ambient noise, describes the important features of a leak detection method required for high performance, and makes an estimate of performance for this method of testing for different test durations between 4 h and 48 h. The second paper, attached as Appendix B, describes the capabilities of a differential-pressure leak detection system, commonly referred to as a mass-measurement leak detection system, for use in ASTs. This paper focuses on the requirements for temperature compensation that are crucial to achieving high performance with this type of measurement system.

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APPENDIX A

LEAK TESTING ABOVEGROUND STORAGE TANKS WITH LEVEL AND TEMPERATURE MEASUREMENT METHODS: FIELD TEST RESULTS

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LEAK TESTING ABOVEGROUND STORAGE TANKS WITH LEVEL-AND-TEMPERATURE MEASUREMENT METHODS: FIELD TEST RESULTS

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ABSTRACT

In order to characterize more fully the environment under which a successful volumetric leak detection test might be conducted on an aboveground storage tank, experimental measurements were made on a 50,000-bbl tank containing light gas oil. Instrumentation deployed inside the tank and on its exterior walls provided information on (1) changes in product level and (2) changes in the temperature of both the product and the tank wall. Tests were conducted over a period of 28 days, and product was kept at the same level throughout this time. The measurements, which confirmed earlier observations, indicate that the volume of product in the tank changes significantly in response to ambient temperature changes. Moreover, since these temperature changes are large enough to influence the outcome of a test, a temperature-compensation scheme must be employed if small leaks are to be detected with accuracy.

In the experiments described here, diurnal volume changes of as much as several hundred gallons over a 24-h period were not uncommon. Basic thermal compensation calculations applied to the data collected in these experiments can remove a large part of the diurnal fluctuations. Any compensation scheme employed, however, must account for the effects of temperature on both the product and the tank shell. The residual compensated time series indicated that there was a fairly long-term inflow of product into the tank, at a rate of about 2.8 gal/h.

Different leak detection algorithms that had been developed from alternative compensation schemes were applied to volume time series. Analyses of the time series suggested that, for the range of environmental conditions experienced during these experiments, leak rates as small as 1.9 gal/h should be detectable given a 24-h test. Increasing the test duration to 48 h was found to improve detection; the longer test lowered the detectable leak rate to approximately 1.0 gal/h.

INTRODUCTION

Aboveground storage tanks (ASTs) are commonly used in the petroleum and chemical industries to store a wide variety of liquid products. These can range in size from 500 bbl (21,000 gal) in capacity, such as those found in producing fields, to 100,000 bbl (4,200,000 gal), such as those found in larger processing facilities. Because of the large number of tanks currently in service, the potential for adverse environmental impact caused by undetected leakage is significant. The U.S. Environmental Protection Agency has thoroughly addressed this type of problem in the case of underground storage tanks (USTs) containing hazardous substances, and allows the owners or operators of USTs to utilize a wide range of acceptable options, including precision volumetric tightness testing and inventory reconciliation, to detect leakage from these tanks.

Although the underground storage tank regulations are well established, a similar set of comprehensive requirements for aboveground tanks has yet to be developed. It may be reasonable to expect that when such regulations are developed they will be patterned after the existing requirements for testing USTs. To assess the feasibility of extending UST leak detection approaches to ASTs, however, one must have a basic understanding of the physical processes occurring in the larger, aboveground tanks. Toward this end, experiments were conducted on a 117-ft-diameter AST containing light gas oil. These experiments, which were based on the results of previous work (Vista Research, Inc., 1991), were part of a larger data collection effort focused on utilizing mass measurement techniques to assess changes in the volume of product in a tank. The purpose of the experiments described in this paper was to quantify the long-term volumetric characteristics that could directly influence the accuracy of a precision volumetric test and to provide diagnostic data for the mass measurement tests. The collected data were subsequently used to develop estimates of the leak detection capabilities of different approaches to testing.

EXPERIMENTS

The purpose of the experiments, conducted over a 28-day period at the Mobil Oil Corporation refinery in Beaumont, TX, was to characterize the temperature and volume changes that might be encountered during the conduct of a volumetric leak detection test. The tank used in the experiments contained light gas oil and had a diameter of 117 ft, a 42-ft-high cylindrical sidewall, and a fixed, conical roof having an 8° pitch. It was isolated from the remainder of the tank farm by means of valves on the associated piping linking it to other tanks. (Tightly closing these valves was the chosen method of isolation, since it was not expedient to install pipe blinds.) The initial product level during all tests was 3 ft 1 5/8 in. Because of a slight inflow condition, the product level at the end of the experiments was 3 ft 1 15/16 in. A summary of the tank configuration is given in Table 1.

Table 1. Configuration of the Tank Used in the Experiments

Diameter	117 ft
Height	42 ft
Roof type	fixed
Construction type	riveted
Foundation	native (no ring wall)
Product	light gas oil
Product expansion coefficient	0.00044/°F
Nominal product level	37-1/2 in.
Water bottom	approximately 6 in.
Sludge depth	approximately 4 in. at tank center

Multiple sensors were deployed both inside and outside the tank as a means of monitoring the tank environment during the experiments. Temperature changes in the product were measured by two vertical arrays of thermistors. One array was located near the center of the tank, while the second was mounted in the normal gaging port, located on the west side of the tank. On each of these arrays, thermistors having a calibrated precision of less than 0.001 °C were mounted as shown in Figures 1 and 2.

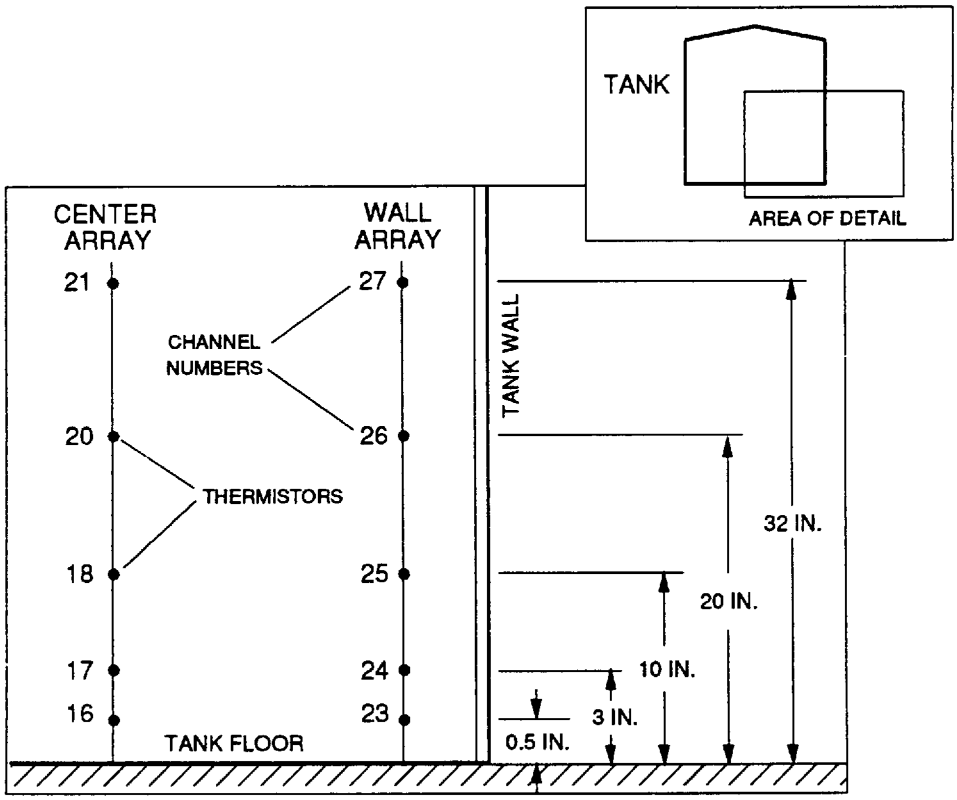

Figure 1. Elevation view of primary thermal sensors deployed in tank.

In order that the magnitude of the volume changes associated with thermal expansion and contraction of the structure itself could be assessed, the temperature of the tank shell was also monitored. Sensors were mounted circumferentially at 60° intervals on the tank's exterior, 18 in. above the tank floor. These sensors were calibrated to the same level of precision as that of the internal temperature sensors.

Changes in product level during the test were monitored by a single float-based sensor having a high degree of precision along with a corresponding limited dynamic range. This level sensor, positioned inside the tank near the center temperature array, was supported by a tripod arrangement that rested on the bottom of the tank, providing lateral stability. Placing the level sensor in the center of the tank did not completely eliminate the influence of expansion and

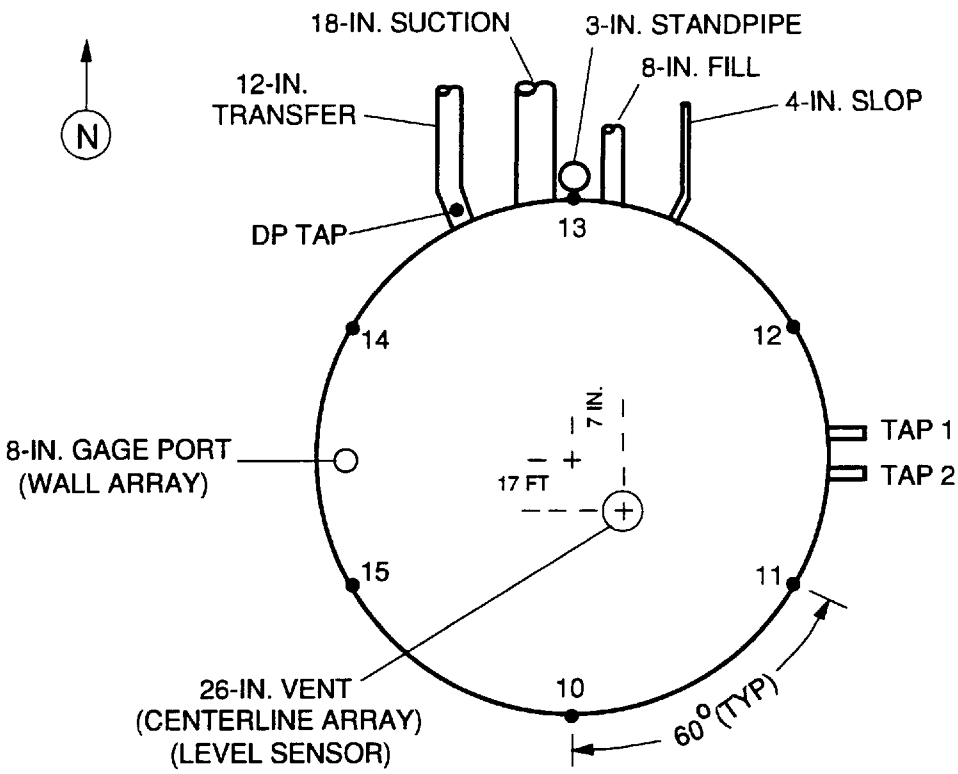

Figure 2. Plan view and orientation of primary thermal sensors in tank, with connecting piping shown for reference.

contraction of the tank shell (because the product level still fluctuated in response to this phenomenon), but this influence was less than it would have been had the sensor been placed on the tank wall. The precision of the level sensor was estimated to be approximately 0.0005 in. This low numerical value represents a high precision, which ensured that the height changes associated with *small* leaks could be readily detected and that the output of the level sensor could be used as a reference for mass measurement sensors (differential-pressure sensors) also deployed on the tank's exterior.

All of the temperature sensors, in addition to the outside air temperature and the local barometric pressure, were recorded at a rate of 1 sample/min. Product level measurements were recorded at 1 Hz and averaged down to 1 sample/min in real time during data collection. Data were collected by an HP 3497A under the control of a 386 portable computer via an IEEE-488 data bus. All data were recorded digitally on the 386 computer for post-test examination and analysis.

TEST CONDITIONS

As noted previously, the experiments were conducted on a fixed-roof storage tank having a capacity of approximately 51,400 bbl (2,160,000 gal). The true condition of the tank bottom was not known prior to the experiments. Based upon observations, however, the tank was thought to be non-leaking. Also as noted previously, piping connections to the tank were not blinded; isolation from the refinery environment was provided by valves.

Multiple hydrometer measurements of a sample of the light gas oil, taken before data collection was initiated, yielded an API gravity of 48.15 at 60°F/60°F, with a corresponding coefficient of thermal expansion of 0.00044 /°F. Data collection began after all the sensors had been deployed and continued virtually uninterrupted for the entire 28-day period. As a result, a wide variety of weather conditions was experienced, ranging from hot, sunny days to cool windy periods during strong thunderstorms.

Ambient conditions, which dominated the volumetric behavior of the tank, could be broken down into two distinct periods, as illustrated both by the local, outside air temperature, shown in Figure 3, and by the temperature in the vapor space of the tank, shown in Figure 4. During the first period, up to 28 May (day 13), temperatures gradually increased, and no appreciable precipitation occurred. Then, for about a week (from day 14 to day 20), a sharp decrease in ambient temperature excursions was experienced, along with a considerable amount of precipitation. There were occasional periods of rainfall throughout the remainder of the test period, and diurnal temperature cycles began to return to more seasonable levels. As a result of the amount of rainfall, and the tank's location, the tank bottom was directly exposed to standing water for the majority of the second period, which began on 1 June (day 17). At its maximum depth, on the south side of the tank, the water level was nearly 1 ft deep.

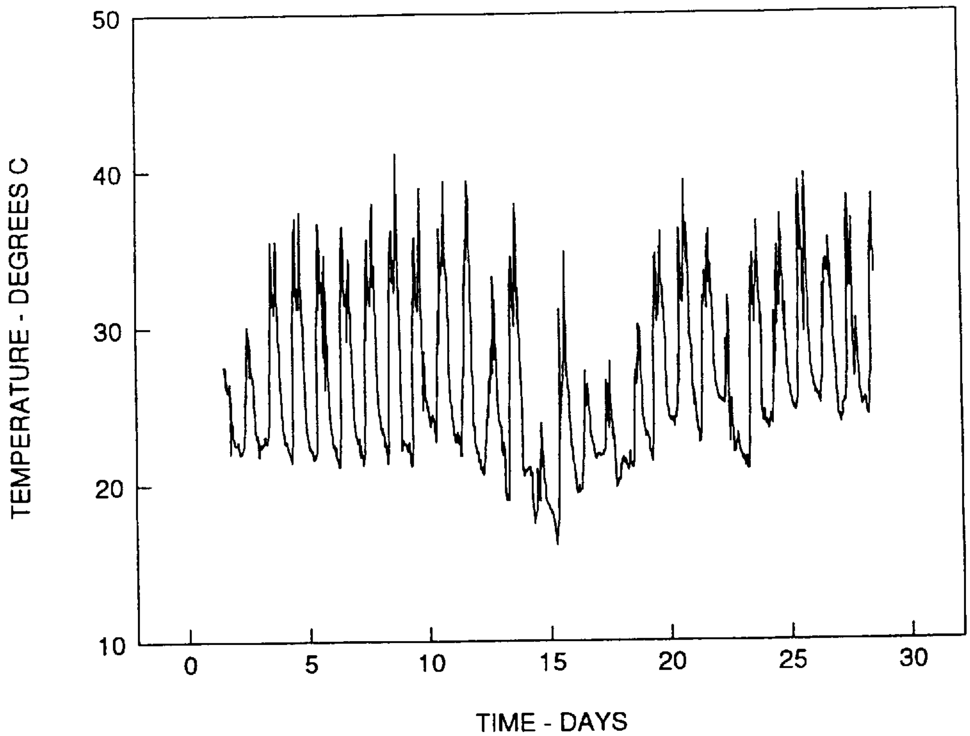

Figure 3. Daily air temperature cycles during the full 28-day test period.

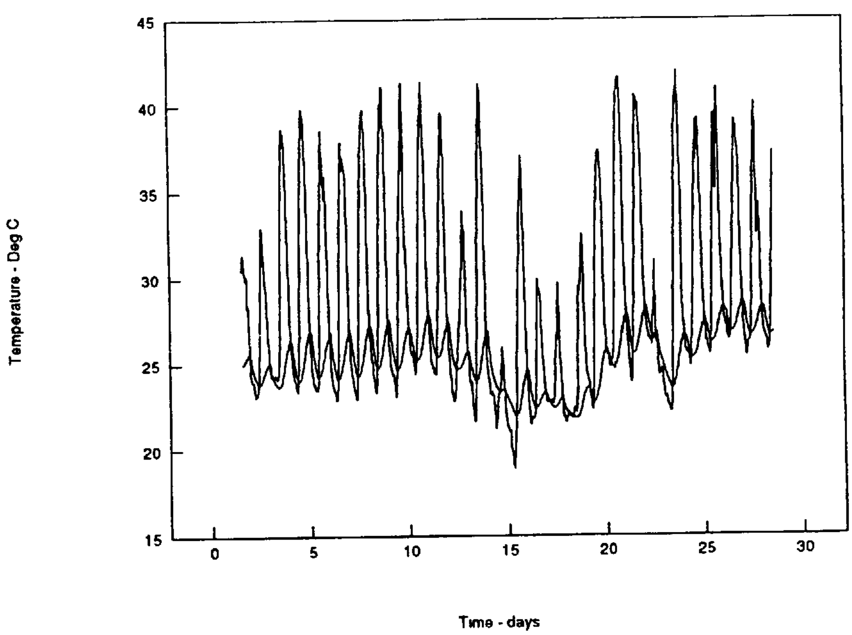

Figure 4. Temperatures in the freeboard (vapor space) of the tank during the full 28-day test period. The curve at about 22°C represents the temperature measured 4 in. below the product surface at the center thermistor array (Channel 21).

Careful inspection of the plots in Figures 3 and 4 shows that temperature in the vapor space of the tank undergoes significantly larger diurnal fluctuations than does the ambient air temperature. Over a typical 24-h period, temperature in the vapor space was found to exceed that of the outside air during the daytime, while at night it was frequently lower. It is possible, therefore, that the thermal processes which predominate in the freeboard (vapor space) of the tank differ from what might be expected given the thermal conditions outside the tank.

RESULTS

The results of the experiments described above were analyzed in terms of their implications for volumetric testing on aboveground storage tanks. Since temperature influences the accuracy of volume measurements, three types of measurements are discussed: volume measurements (of the product), temperature measurements of the product, and temperature measurements of the tank shell.

VOLUME MEASUREMENTS

Gross changes in the volume of product in the tank, characterized by a diurnal fluctuation of about 200 gal, were monitored for the entire 28-day experiment period. These fluctuations strongly coincide with diurnal ambient temperature fluctuations, suggesting that the periodic portion of the volume changes is due to thermal expansion of the product. In addition to these fluctuations, the tank inventory was found to increase fairly linearly throughout the entire period. A composite gross volume history is shown in Figure 5. As can be seen in this plot, significant deviations from the overall linear volume increase were experienced during the middle part of the experiment period; these deviations correspond to the period of cool weather and subdued ambient thermal fluctuations.

The generally increasing trend of the inventory was not inconsistent with the possibility of inflow into the tank through the isolation valves, which, although closed, may have been leaking. Periodic inspections indicated that high product levels (i.e., greater than 20 ft) were being maintained in other tanks connected to the common suction and transfer piping; such levels, because of the pressure they placed on the valves, would have been sufficient to cause seepage and would account for volume increases of the magnitude observed in the test tank. A linear regression through all data collected during the experiments indicated that the gross inflow rate during this time was approximately 2.8 gal/h. Blinding of all pipeline connections would thus appear to be essential prior to conducting a volumetric test on a tank whose integrity is unknown.

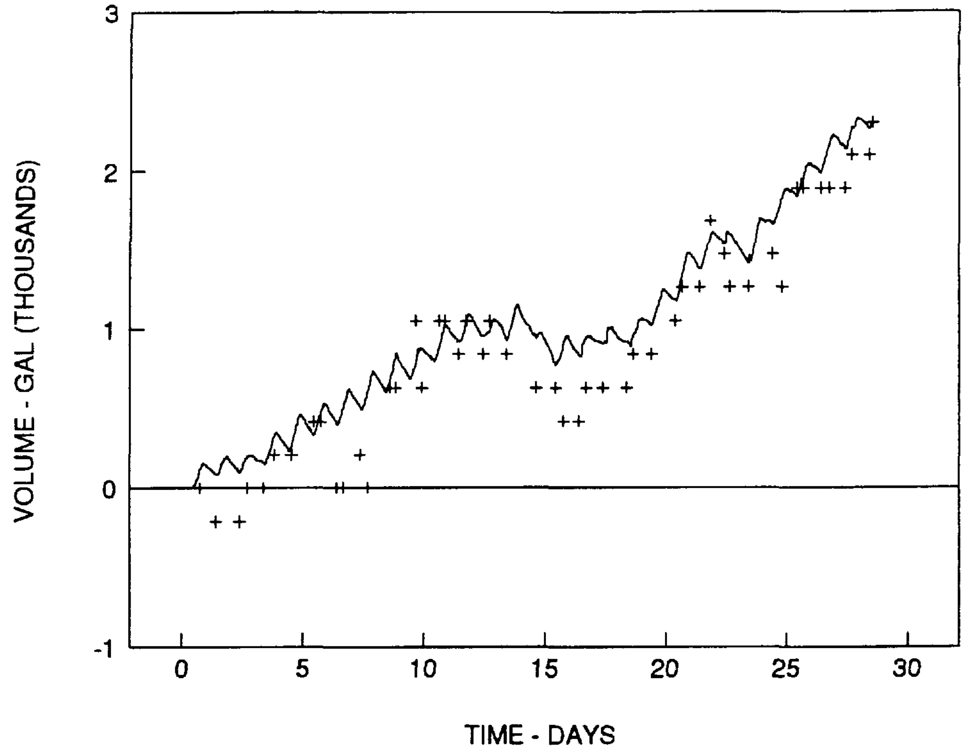

Figure 5. Gross volume time history measured by the float-based level sensor. Symbols denote manual level readings taken from a level gauge permanently installed on the tank wall.

THERMAL MEASUREMENTS OF THE PRODUCT

The purpose of making thermal measurements of the product was to assess the magnitude of thermal expansion and contraction and to gain a better understanding of how the product responds to a wide variety of ambient temperature fluctuations. Figures 6 and 7 illustrate the typical response of the two thermistor arrays over a period of 96 h. Two things were noted: there were strong thermal gradients in the region near the tank floor (this region also exhibited a weak response to diurnal temperature fluctuations); and the rate of change of temperature was highest in the top layers, which is the reason thermal compensation is needed. Figures 6 and 7 show that increased distance from the tank floor is equated with gradually increasing temperatures, the highest of which are found closest to the free surface of the product. The diurnal contribution to temperature fluctuations also increases the closer one gets to the free surface. In the plots shown in Figures 6 and 7, the majority of the thermal fluctuations induced by changes in ambient air temperature occur in the top 11 in. of product.

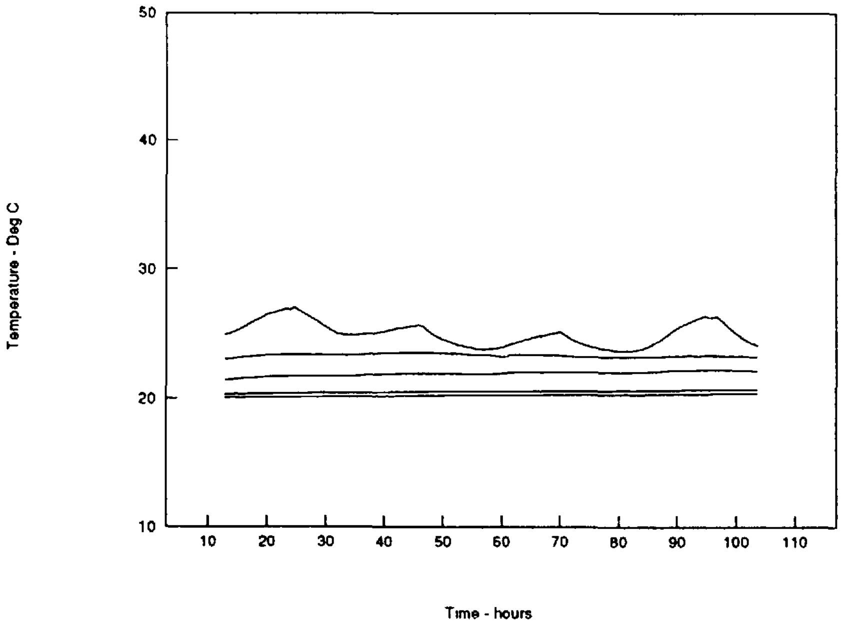

Figure 6. Four-day temporal history (selected from the 28-day data set) of immersed thermistors on the center array. Diurnal fluctuations are most pronounced in the readings by the uppermost thermistor.

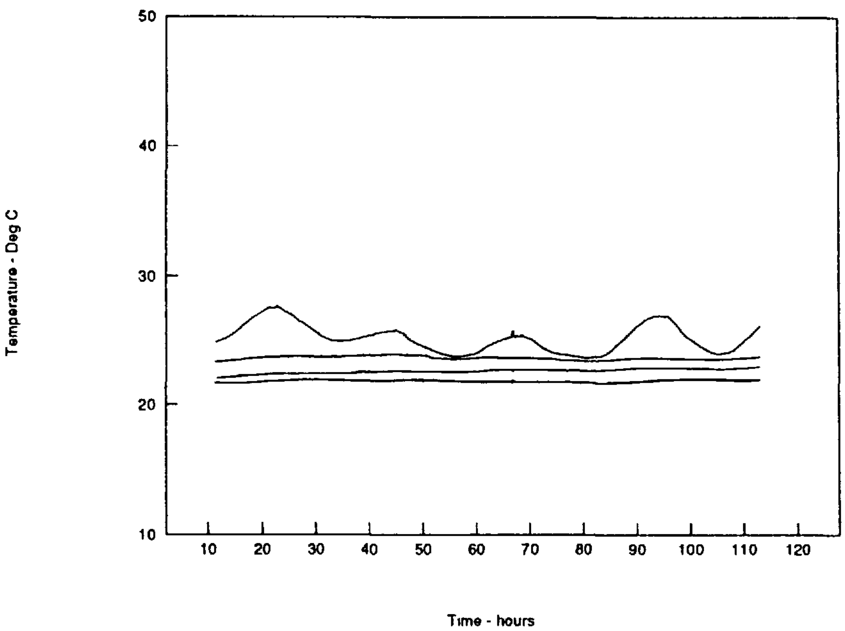

Figure 7. Four-day temporal history (selected from the 28-day data set) of immersed thermistors on the wall array. Due to their proximity to the tank wall, all four wall-array thermistors show more pronounced diurnal fluctuations than do the center-array thermistors (Figure 6).

Small differences were noted between measurements made by the center array and those made by the wall array. The most pronounced of these concerns the vertical extent of the diurnally induced temperature fluctuations. The wall array seems able to discern these fluctuations at much lower product levels, with peak-to-peak changes approaching several tenths of a degree C. This response is not unexpected, because of the array's proximity to the tank wall and because of the strong temperature fluctuations in the ambient air outside the tank.

Maximizing the performance of a volumetric leak detection test requires that some form of compensation be employed to properly account for the thermally induced volume changes arising from corresponding temperature changes. In the experiments described here, this was achieved by converting the measured temperatures at each array to volume changes using the relationship

$$\Delta TV = \sum_{i=1}^{n} C_{ew} V_{wi} \Delta T_{wi} + \sum_{i=1}^{n} C_{ep} V_{\pi} \Delta T_{\pi}$$

where

ΔTV	=	thermal volume change (gal)
C_{ew}	=	coefficient of thermal expansion of water (/°F)
V_{wi}	=	water bottom volume (gal)
ΔT_{wi}	=	water bottom temperature change (/°F)
C_{ep}	=	coefficient of thermal expansion of the product (/°F)
V_{pi}	=	product volume (gal)
ΔT_{pi}	=	product temperature change (°F)

From this relationship, the change in volume associated with each thermistor in the array (i.e., the "weighted" change) was estimated, and the unequal spacing between thermistors was thus accounted for. Utilizing this approach ensures that the strong thermally induced volume changes associated with the upper layers of product are properly accounted for.

The results of the calculations are shown in Figure 8, which summarizes the thermal volume changes associated with each array over the entire 28-day data collection period. It can be seen that thermally induced volume fluctuations are generally on the order of several hundred gallons, increasing or decreasing in response to the diurnal temperature cycle. Because product temperature was different at the center of the tank than it was near the walls, there are differences in the thermal volumes calculated from measurements made by the two arrays; the center array produced values slightly lower than those of the wall array. This suggests that, for the purposes of leak detection, it may be difficult to develop a

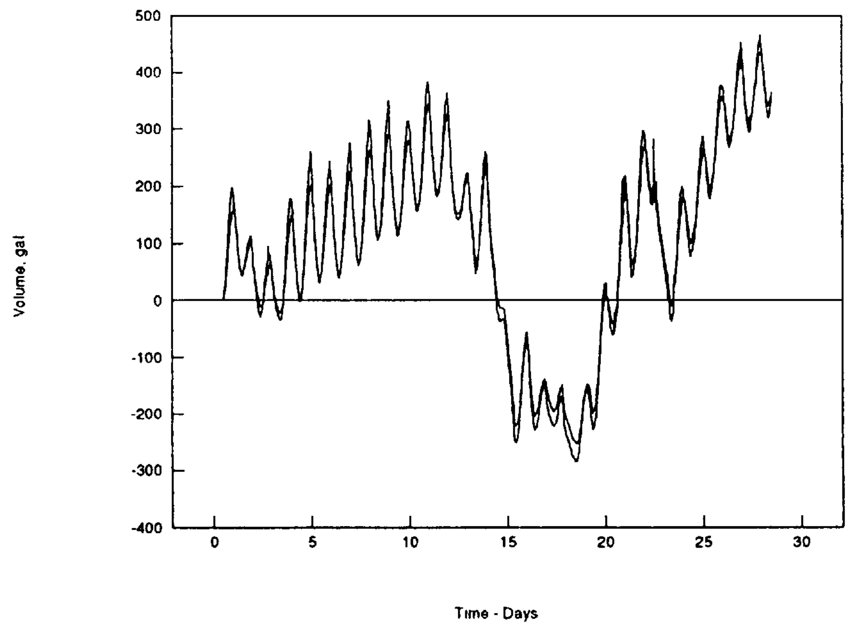

Figure 8. "Weighted" thermally induced changes in the volume of product during the 28-day data collection period. Due to greater temperature fluctuations in the vicinity of the tank wall, the volumes changes recorded by the wall array (the curve with sharper peaks and troughs) are more pronounced than those recorded by the center array (the curve with less exaggerated peaks and troughs).

representative estimate of thermally induced volume changes from a single array, even if this array has a sufficient number of sensors to resolve the vertical temperature gradient. Another difference between the two arrays can be observed in Figure 8. Although the thermal volume changes calculated from the center and wall arrays are qualitatively equivalent, their respective maximum values occur at different times. When temperatures are increasing, thermally induced volume changes calculated from the wall array peak 2 to 3 h earlier than those calculated from the center array. When temperatures are decreasing, the offset between the two is minimal.

The behavior evidenced in Figure 8 may be attributable to the proximity of the wall array to the ambient air. Changes in ambient air temperature initially influence that portion of the product closest to the tank walls; it takes longer for the influence of these changes to reach the center of the tank, and this results in a temporal lag between the two sensor arrays. This response pattern is then modified by the influence of temperature fluctuations in the vapor space, which tend to be greater than those of the ambient air.

The characteristic behavior of the two temperature arrays suggests that, depending on the manner in which it is implemented, thermal compensation may prove to be a limiting factor in obtaining high levels of leak detection performance. Consider, for example, Figure 9, which shows the differences in thermally induced volume change as calculated from the two arrays. The diurnal fluctuation occurs because of the 2- to 3-h lag between the arrays. Despite the generally similar shape of the two estimates in Figure 8, they differ sufficiently to introduce a degree of uncertainty as to whether a true average of the thermally induced volume changes can be adequately represented by a single sensor array.

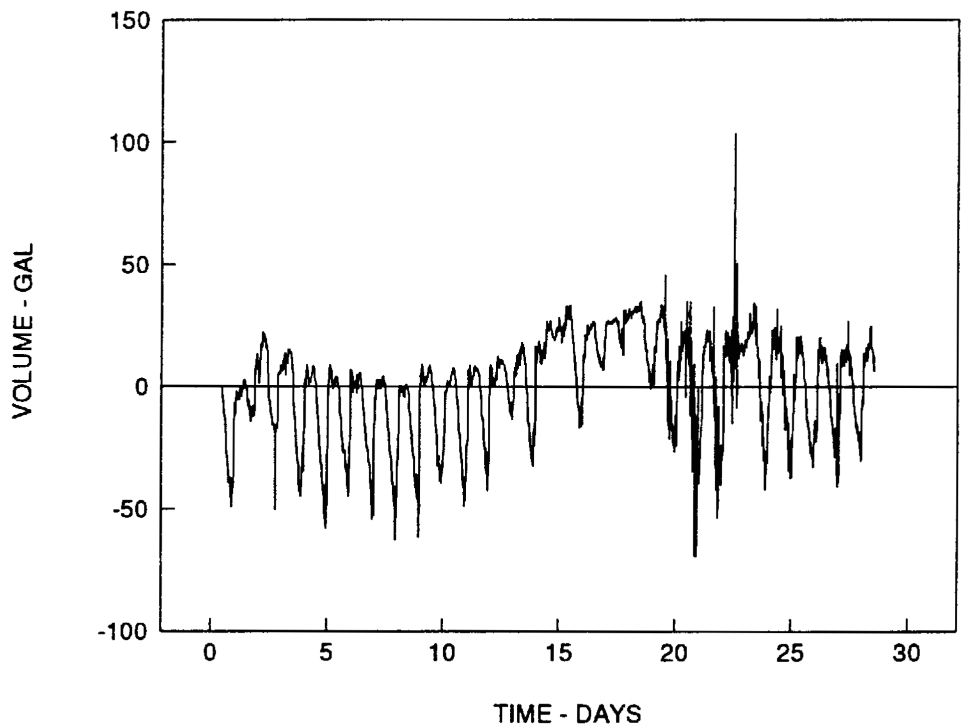

Figure 9. Difference in weighted thermal volume estimates derived from the two thermistor arrays.

THERMAL MEASUREMENTS OF THE TANK SHELL

Thermal changes affect not only the volume of the product but also the capacity of the tank itself, whose walls expand and contract circumferentially in response to temperature changes; this expansion and contraction in turn influences the *level* of product (which can be mistaken for a change in volume). Expansion and contraction of the tank shell can thus be responsible for significant errors in volumetric testing. The experiments addressed the phenomenon of expansion and contraction by treating the tank shell as a frustum of an inverted cone whose bottom is firmly attached to the tank floor. (The top of the inverted cone represents the circular plane described by the surface of the product; the point of this cone can be found somewhere beneath the tank floor; and the plane that bisects the inverted cone somewhere between its top and its point is the tank floor.) Changes in shell temperature then result in changes to the enclosed volume according to the relationship:

$$\Delta T_{SH} = \{(C_o + C_o\alpha\Delta T)^2 - C_o^2\}\frac{1}{\pi}\frac{h}{2}\frac{1}{4}7.4801$$

where

ΔT_{SH} = thermally induced change in the volume of the tank shell (gal)
C_o = original shell circumference (ft)
α = coefficient of thermal expansion of the shell (/°F)
ΔT = change in shell temperature (°F)
h = nominal product level (ft)

It is important to recognize that for a given set of thermal conditions this volume fluctuation is opposite that experienced by the contained product. That is, increases in shell temperature are found to increase the tank shell volume, resulting in a *decrease* in product level in the tank. This level decrease can be easily confused with volume decreases caused by tank leakage. The way to compensate for the effect of expansion is to estimate the thermally induced changes in shell volume (i.e., changes in the capacity of the tank) and add these to the measured, raw changes in the volume of product.

Temperature, however, is not the only causative factor in the expansion and contraction of the tank shell. The magnitude of this phenomenon is also a direct function of the product level and the physical size of the tank. As a result, increasing the product level tends to produce larger thermally induced changes in shell volume. As the product level increases, the phenomenon of expansion and contraction may be better modeled by a cylindrical representation rather than a frustum cone. Adopting this type of representation will increase the shell volume by a factor of 2 for a fixed product level.

Estimates of thermally induced changes in shell volume throughout the experiment period are shown in Figure 10. This figure shows that thermally induced changes in shell volume, like those in product volume, coincide with diurnal temperature fluctuations. In Figure 10, however, the amount of fluctuation caused by expansion and contraction of the shell is only about 25 gal, as compared with fluctuations of approximately 200 gal in the product (p. 7). Careful inspection of the temporal history of these volume fluctuations indicates that the majority occur during the morning and late evening hours (i.e., sunrise and sunset). During daylight hours, fluctuations of 5 to 10 gallons are not uncommon, in response to fluctuating insolation levels, periods of precipitation, and air temperature changes. During evening hours, fluctuation levels tend to subside significantly, since, in the absence of strong thermal input from sunlight, the entire structure approaches thermal equilibrium.

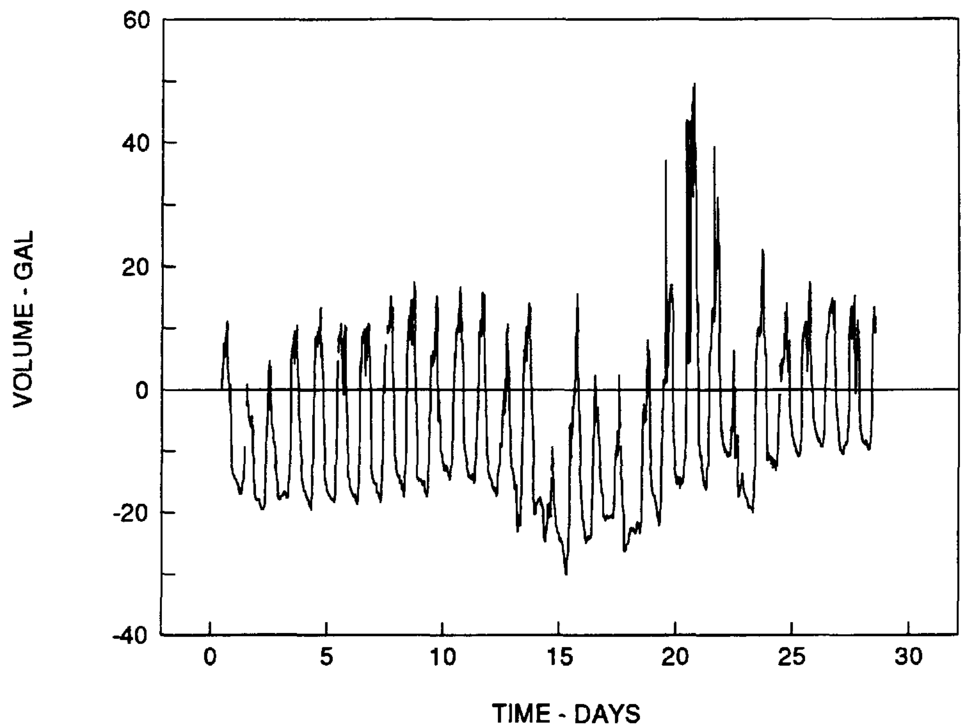

Figure 10. Summary of thermally induced fluctuations in the capacity of the tank shell. The calculations assume that the shell can be represented by a frustum of a cone.

Since these changes occur rather abruptly, their implication in introducing errors into a volumetric test must be carefully considered. In general, any test having a duration approximately equal to the time required to complete the temporal shell volume transients can be expected to experience an error roughly equal to the transient. For example, a shell volume transient having a magnitude of 30 gal, and occurring over a 5-h period, could introduce an error of up to 6 gal/h into a volumetric test having a duration of 5 h, if the two happened to coincide. This type of error is endemic to both float-based and mass-measurement-based testing approaches, and must be compensated for if high levels of detection performance are to be achieved.

Two basic compensation approaches can be readily applied. First, the magnitude of the phenomenon can be estimated from a basic set of sensors mounted on the tank wall. The volumes changes estimated from the sensors can then be added to the measured gross volume changes. A less rigorous alternative is to increase the test duration so that several daily cycles of thermal volume change in the shell can be included in the test data. Since, under reasonably consistent thermal conditions, the shell volume returns to roughly the same level during each overnight period, multiple cycles should be removed by averaging the resulting data.

THERMALLY COMPENSATED VOLUMES

The leak detection capabilities of a volumetric test were estimated by developing a thermally compensated volume time series upon which various data analysis algorithms could be imposed. The compensated volume was generated from the following relationship:

$$T_{CV} = V - TV + TV_{SH} - TV_{SENS}$$

where

T_{CV}	=	thermally compensated volume change (gal)
V	=	raw volume change measured by float-based sensor (gal)
TV	=	thermally induced changes in volume of product (gal)
TV_{SH}	=	thermally induced changes in volume of tank shell (i.e., tank capacity) (gal)
TV_{SENS}	=	thermally induced changes measured by level sensor (gal)

Measurements made by the center array of thermistors were used in the above equation, resulting in a thermally compensated volume time series for the entire 28-day period. The plot of this time series is shown in Figure 11. The most striking feature of this plot is that, after compensation, a small residual diurnal fluctuation exists in the volume time series. Extensive analyses were performed to try to identify the mechanism responsible for this behavior. Particular attention was given to thermal phenomena that could have affected the float-based level measurement system. Examinations were made of thermal effects on the level sensor's tripod supporting structure, as well as any changes in float's buoyancy that might have occurred as a result of thermal fluctuations near the product surface. In all cases, the volume changes associated with these phenomena were found to be insufficient in magnitude to account for the residual fluctuations.

Careful inspection of the raw volume time series suggests that the periodicity in the compensated volume time series is largely due to a difference between the response of the level sensor and the shape of the estimated product thermal volume time series. A possible explanation for this difference is the presence of horizontal thermal gradients in the tank. These gradients may be such the two arrays do not adequately represent the average temperature condition of the product. The difference between the estimates made from the two existing arrays, shown in Figure 12, may be significant when compared to the residual fluctuations in the compensated volume time series.

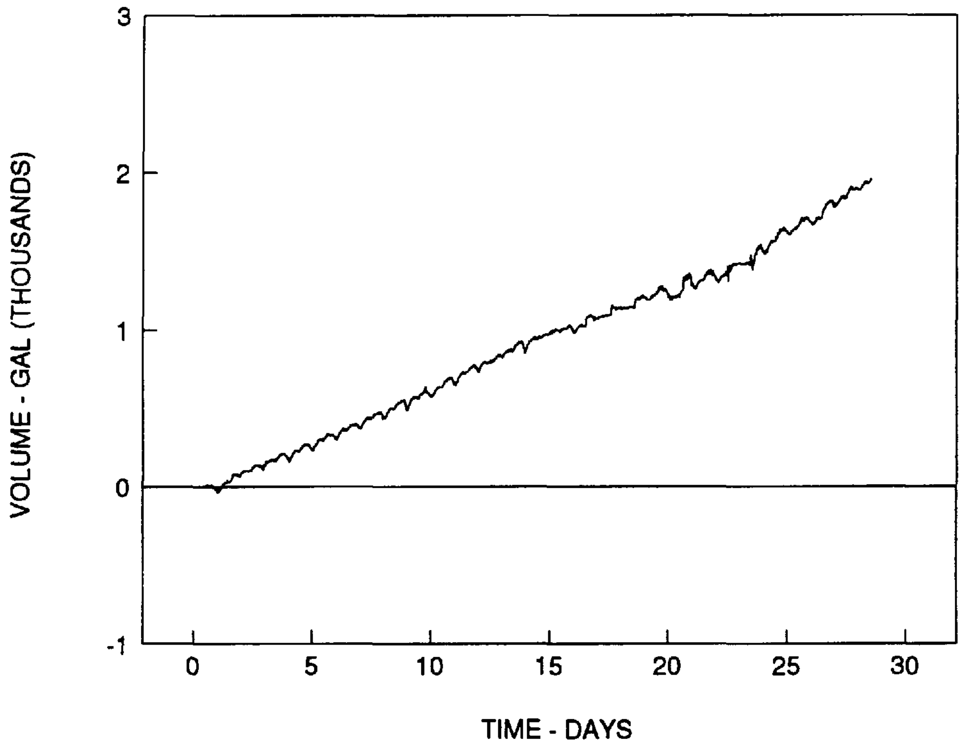

Figure 11. Thermally compensated volume time series for the full 28-day data collection period. The time series is based on measurements made by the volumetrically weighted thermistors in the center array.

A fraction of the difference may be explained by the thermal fluctuations occurring in the upper layers of the product. The majority of the temperature changes occurred near the free surface of the product (p. 8), where temperatures are a function of numerous complex phenomena that are occurring simultaneously, including thermal conduction from the vapor space and the tank wall, buoyant stratification of the product, and vertical convection of product near the wall.

The interaction of these phenomena, along with the physical changes in tank geometry and mass transfer phenomena (evaporation and condensation), combine to produce the output of the level sensor. As a result, the sensor's necessarily limited spatial coverage of the tank may not be sufficiently detailed to reflect the true average changes, resulting in a less than perfect match between thermal changes and volume changes.

The largest compensated volume fluctuations occurred between sunrise and midday; prior to sunrise, temperature and level are still decreasing, but during the morning hours they typically increase. These changes in temperature can be seen in Figure 13, which shows the fully compensated volume time series for the first week of data collection. During the morning hours, significant differences in the two estimates of compensated volume are consistently observed, particularly at midday, when thermal input from the sun is at its maximum. The differences tend to subside dramatically during the late night and early morning hours, suggesting that the two thermistor arrays were experiencing the same thermal environment.

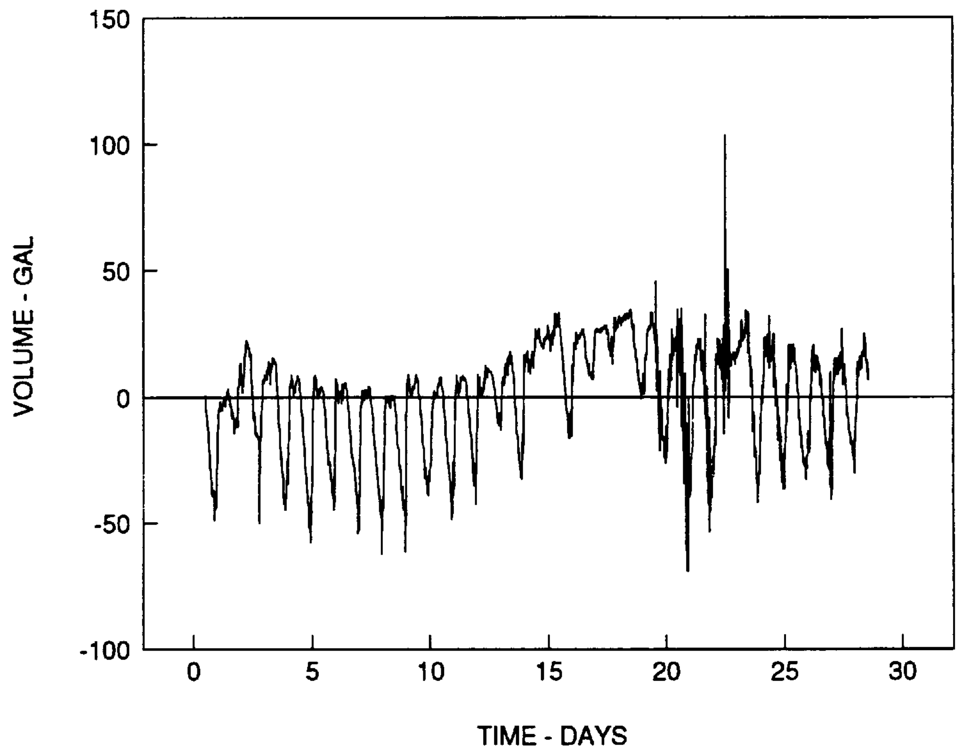

Figure 12. Difference in thermally induced changes in the volume of product as estimated from data collected by the center array and the wall array.

Although not observed directly, condensation and evaporation may also play a role in moderating the output of the level sensor. A careful examination of the compensated volume time series reveals that the peak negative fluctuations occur coincidentally with a decrease in the temperature of the vapor space, at which point the vapor space is colder than the upper layer of product. Under these conditions, it is not unreasonable to expect that condensation of water vapor and small amounts of product may occur.

LEAK DETECTION PERFORMANCE

A variety of protocols, or algorithms, can be used when a volumetric test is conducted. In the experiments, test duration was the principal variable in these algorithms. Several different algorithms were applied to the fully compensated volume time series, and the leak detection performance of each algorithm was estimated. Straight lines were fitted to the time series, and the slopes of the lines were computed. A specific performance estimate for a given test protocol (i.e., test duration and starting time) was derived from the standard deviation of the slopes.

To assess the impact of different compensation schemes on the performance of an algorithm, three time series were used: the fully compensated time series derived from the wall array; the fully compensated time series derived from the center array; and the compensated time series derived from the *weighted* center array. In the third case, the effects of thermal expansion

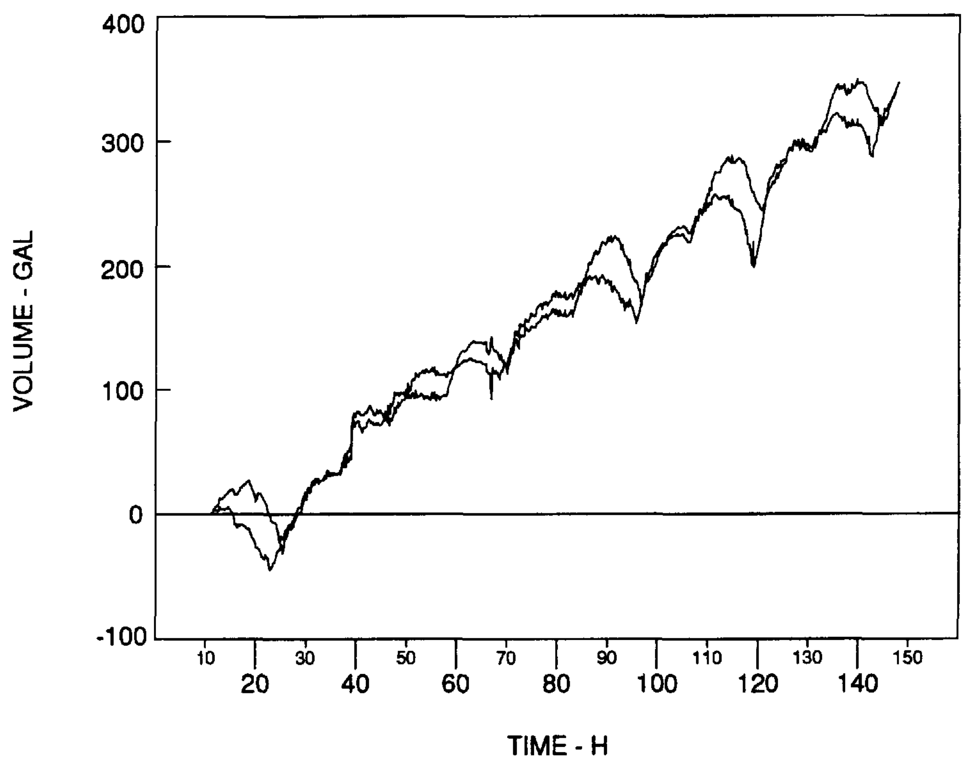

Figure 13. Comparison of the thermally compensated volumes derived from the two thermistor arrays during the first seven days of testing. At hour 40, 25 gal of product were added.

of the tank shell were not included, the purpose being to find out how much degradation in performance (if any) could be expected if shell expansion were ignored. In all three cases, a test duration of 24 h was assumed. Two additional performance estimates were done; these were based on the fully compensated time series derived from the center array, but the test duration, instead of being 24 h, was 4 h in one case and 48 h in the other.

In all five cases, the performance of a leak detection test was controlled by the residual diurnal fluctuations in the compensated volume time series, along with any bias that might have been present in the regression results. This bias, which may have been due to characteristics inherent in either the instrumentation or the algorithm, can easily be confused with a leak. In these experiments, the bias was found to be positive: the mean tank level increased during the entire 28-day data collection period. Since the increase could have been due to one of several factors, or a combination of these (for example, leaking isolation valves, water condensing during the night, instrumentation noise, etc.), it was not possible to determine how much of the bias was attributable to the instrumentation alone. In the discussion below, leak detection performance is based on a bias of 0.0 gal/h. This was achieved by fitting a straight line to the compensated volume time series for the entire 28-day experiment period. The resulting slope was then removed from the volume rates calculated by the three different algorithms.

Although the tank was believed to be non-leaking, its true condition was unknown at the time of the experiments. Because of this, it was necessary to corroborate the leak detection performance of each algorithm. During selected periods in the data collection, therefore, leaks of known size were induced. The ability of an algorithm to identify a leak was verified through comparisons of the measured and induced leak rates, the latter being true and known values that served as a reference for the former, which were estimates.

The results of the volume rate calculations, along with the algorithms that were examined, are summarized in Table 2. Basically, all the algorithms use a temperature-compensated volume time series, and different periods of that time series are examined. The variable in the algorithms was test duration: 4, 24, and 48 h. The start time selected for each test, regardless of its duration, reflected an attempt to provide an initially uniform thermal condition in the tank, so that the effects of incomplete temperature compensation stemming from horizontal thermal gradients would be minimized.

Several basic observations can be made about the summaries in Table 2. Not unexpectedly, it is clear that increasing the duration of a test tends to reduce the standard deviation of the test results. A reduction in the standard deviation means that it should be possible to detect smaller leaks with the same probability of detection (P_D) and the same probability of false alarm (P_{FA}) as currently detectable leaks. Given the fully compensated volumes based on the center array, and assuming a normal distribution of volume rates, it was found that increasing the test duration from 4 to 24 h reduced the detectable leak rate from -10.50 gal/h to -1.81 gal/h while still maintaining a P_D/P_{FA} of 0.95/0.05. Similar improvements in detection performance were observed when these compensated volume time series were viewed in terms of the cumulative frequency distribution (CFD). In the CFD plots in Figures 14 and 15, the 0.95 percentile suggests that with test durations of 4 and 24 h it is possible to detect leaks of 9 and 1.9 gal/h, respectively. These estimates of leak rate could be refined further if more test data were available, since the capability of a given test is controlled by the tails of the distributions. The data also suggest that additional improvements in performance could be obtained with a 48-h

Table 2. Summary of Volume Rate Calculations Based on Thermally Compensated Data from the Center Array (To determine the volume rate for each test segment, a least-squares line was fitted to the data. All test segments start at 0200; test duration was as noted.)

Day	Compensated Volume Rate (gal/h)				
	4-h Test	24-h Test	4-h Test (No Shell Compensation)	24-h (No Shell Compensation)	48-h Test
Induced Leak = 0.0 gal/h					
516	0.593	2.119	1.022	2.092	2.488
517	3.832	1.931	3.831	1.701	
518	10.775	2.706	11.246	2.373	2.751
519	9.538	2.487	9.728	2.222	
520	8.338	2.569	8.604	2.162	2.950
521	9.651	3.064	10.172	2.558	
522	12.007	2.928	12.569	2.707	2.798
523	10.163	2.446	10.492	2.130	
524	9.708	4.107	10.038	3.736	3.454
525	11.695	3.424	11.804	3.180	
526	6.805	2.896	7.184	2.520	3.074
527	5.885	2.436	7.980	2.211	
Mean	8.249	2.759	8.722	2.466	2.919
Std. Dev.	3.261	0.563	3.225	0.521	0.300
Bias	5.445	-0.045	5.918	-0.330	0.115
Induced Leak = 2 gal/h					
530	9.758	1.219	9.734	1.046	*
531	1.791	0.642	1.732	0.930	*
605	7.781	2.702	7.974	3.092	*
Mean	6.444	1.521	6.480	1.689	*
Std. Dev.	3.387	0.868	3.434	0.993	*
Bias	3.640	-1.283	3.676	-1.115	

* Insufficient data to calculate volume rate

test. However, because of the limited number of tests of this length that could be constructed from the available data set, the tails of the distribution are not well defined. From the standard deviation of the fully compensated 48-h tests that were available, it was estimated that a leak of 0.97 gal/h could be detected with a P_D/P_{FA} of 0.95/0.05.

The improvement in performance associated with increased test duration is easily explained by the residual diurnal fluctuations in the compensated time series. Since these fluctuations are periodic, extending the test duration to cover at least one full cycle (i.e., 24 h) tends to dramatically reduce the uncertainty in the slope of the line. When the test duration is less than one diurnal cycle, there is a strong possibility that straight lines will be fitted to portions of the volume time series *that do not reflect the mean trend.* This is the primary cause for the wide distribution of results, as well as the strong positive bias, in the 4-h tests. Conversely, when the test duration covers two diurnal cycles, the uncertainty in the mean trend of the compensated volume time series is reduced. This pattern was observed in all of the compensated volume time series that were examined. The differences that arise in performance, then, are due to differences in the manner or degree of temperature compensation.

It is important to consider that the above performance estimates, derived from the data summarized in Table 2, are based on an assumed constant inflow into the tank of 2.804 gal/h. To the extent that this condition is not valid, errors in the performance estimates may result. In particular, the level increase observed during the data collection period may be attributable to either product inflow or water condensation during overnight periods. Deployed instrumentation was unable, however, to segregate or independently quantify these phenomena. As a result, the individual contributions of these two phenomena to the residual compensated volume fluctuation in the tank were not identified.

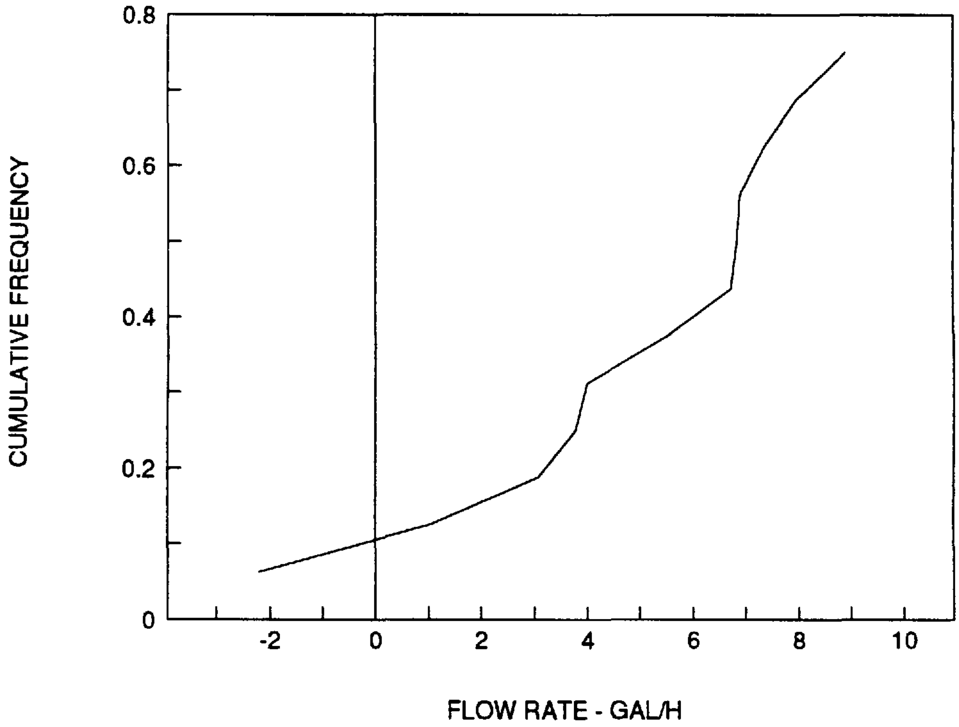

Figure 14. Cumulative frequency distribution (CFD) for 4-h tests on a non-leaking tank. The bias of 2.804 gal/h has been removed from the data. Results from tests in which leaks were induced have been included (i.e., the known leak rate has been added to the CFD) in order to more fully characterize the tails of the distribution. All tests were begun at 0200.

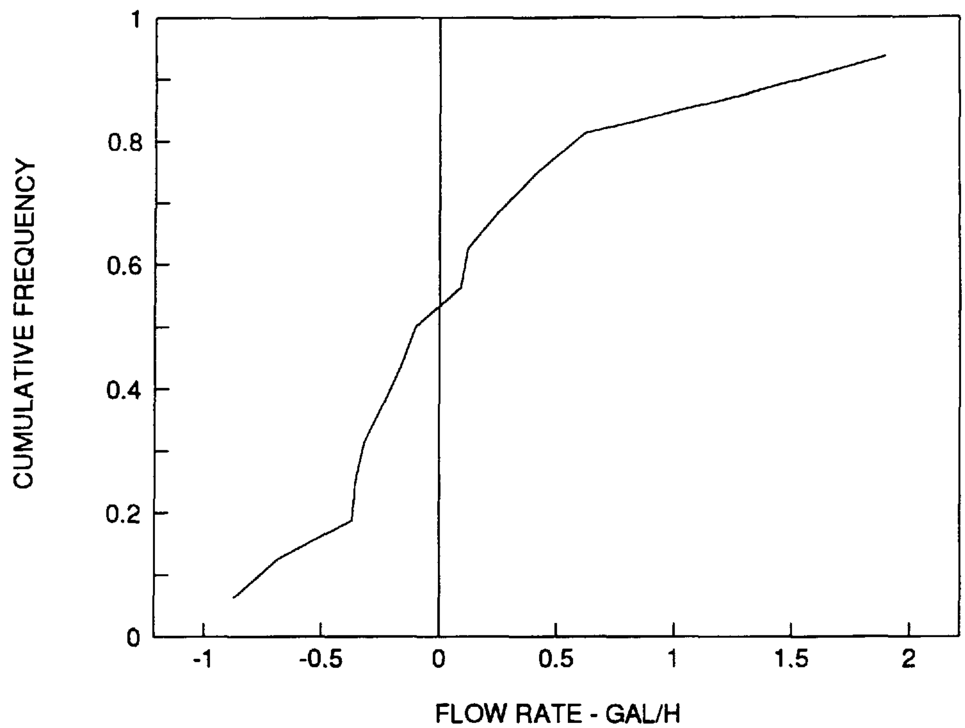

Figure 15. Cumulative frequency distribution (CFD) for 24-h tests on a non-leaking tank. The bias of 2.804 gal/h has been removed from the data. Results from tests in which leaks were induced have been included (i.e., the known leak rate has been added to the CFD) in order to more fully characterize the tails of the distribution. All tests were begun at 0200.

Increasing the test duration to at least 24 h, with starting and ending times scheduled for early morning, also appears to minimize the effects of thermal expansion of the tank shell on the detectable leak rate. As can be seen in Table 2, there is only a minimal difference between the fully compensated volume time series derived from the center array and the same time series in cases when shell expansion was ignored. In a 24-h test, then, virtually identical leak detection performance could be expected regardless of whether an extra effort was made to monitor the temperature of the tank shell. It should be noted that although the temperature of the tank shell did not have a significant impact in these experiments, this finding may not be universally true.

The actual leak detection performance of a given algorithm, while strongly influenced by the distribution of test results (i.e., the standard deviation) also depends on the presence of any bias in the data. In the experiments described here, the presence of a bias may be indicative either of a systematic error in the application of an algorithm or of basic deficiencies in the algorithm itself. Because a bias is easily confused with a leak, it is important that it be both identifiable and accounted for in the measurements. In the current set of data, the bias was found to range from as little as -0.045 gal/h in the fully compensated 24-h tests to as much as 5.918 gal/h in 4-h tests that did not include compensation for expansion of the tank shell. The fully compensated 48-h tests had a bias of approximately 0.12 gal/h.

Including the bias in performance estimates for the various test durations requires that the threshold (the value which, if exceeded, is the basis for declaring a leak) be shifted by an amount equal to the bias. Failure to do so will result in an error in the estimated probability of detection and probability of false alarm. Thus, for the fully compensated 24-h test, a normal distribution of results would yield a threshold of -0.906 gal/h. Including the bias of -0.045 gal/h results in a new threshold of -0.951 gal/h, for a P_D/P_{FA} of 0.95/0.05. Utilizing the threshold of -0.906, but including the system bias, results in a P_D/P_{FA} of approximately 0.959/0.064. Thus, if the threshold were unadjusted, the presence of the bias could result, in this particular instance, in an increase in the P_D at the expense of the P_{FA}. It should be noted that these alterations in performance are a direct function of the size of the bias; if an improper threshold value is employed, larger bias values can be expected to result in more pronounced alterations to the P_D/P_{FA}.

CONCLUSIONS

Extensive data collected on a 117-ft-diameter aboveground tank containing light gas oil suggest that the ability of volumetric leak detection tests to identify small leaks will be challenged by an extremely dynamic thermal environment which is strongly driven by ambient diurnal temperature changes.

Test results obtained at a single nominal product level over a 28-day period exhibited a pronounced positive bias of about 2.8 gal/h, indicating a gain of product by the tank. Based on the known product levels of other tanks connected to a common piping manifold, it is strongly suspected that inflow was occurring through at least one isolation valve.

Because of the physical processes occurring in the tank, and the large transient volume changes associated with these processes, compensation techniques must be employed in order for the volume changes associated with small leaks to be detected. Currently available data indicate that a test duration of 48 h should be sufficient to average through any uncompensated fluctuations in the temperature-compensated volume rate, and should permit the detection of leaks as small as 1.0 gal/h with a P_D of 95%. This performance estimate assumes that no bias exists in the measurements; in practical applications, the magnitude of any residual bias must be included in the estimate of the detectable rate.

It is important to note that these performance estimates are based on a limited set of measurements obtained over a relatively narrow range of annual ambient conditions, and on a single type of product. More representative performance estimates can be developed by collecting data from a wider range of ambient conditions and fluid compositions. This extended data collection effort could then be utilized to confirm the basic conclusions developed from the experiments described in this paper, to validate test protocols, and to identify areas in which currently recommended procedures may encounter performance difficulties.

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APPENDIX B

LEAK TESTING ABOVEGROUND STORAGE TANKS WITH MASS-MEASUREMENT METHODS: FIELD TEST RESULTS

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LEAK TESTING ABOVEGROUND STORAGE TANKS WITH MASS-MEASUREMENT METHODS: FIELD TEST RESULTS

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ABSTRACT

In order to more fully assess the capabilities of mass-measurement (differential pressure) systems to detect leaks in an aboveground storage tank (AST), a series of experimental measurements were made on a single 50,000 bbl tank containing light gas oil at a refinery in Beaumont, Texas. When used in an AST, a mass-measurement system should inherently compensate for the thermally induced volume changes of the liquid product in the tank. Since this is the largest source of error in a volumetric test, a mass-measurement system should have performance advantages over the more conventional volumetric methods that are comprised of a level sensor and a vertical array of temperature sensors. The basic premise of the mass-measurement technique is that, in a right circular cylinder, the multiplicative product of the density and level of fluid remains constant. To determine if a mass-measurement system would yield enhanced performance, test data were collected at a single product level over a period of 28 days spanning late May and early June 1992. In addition to several differential-pressure (DP) sensor systems, other instruments were deployed both in the tank and on the tank exterior to measure changes in product level and changes in the temperature of both the product and the tank wall.

As was observed in tests conducted on a similar size tank at this refinery the previous year, all of the non-leak-related volume changes measured independently by the level and temperature sensors exhibited strong diurnal trends. This included thermally induced changes in the tank wall and changes in the temperature of the differential-pressure sensor itself; neither of these changes is inherently compensated for by the DP system. Attempts to compensate the current data for the effects of these temperature changes were not entirely successful because of the sensitivity of the instrumentation to temperature changes. The expected performance advantages of the mass-measurement system over the more conventional volumetric measurement systems were not realized in these tests. Although they showed that mass-measurement techniques have potential for facilitating the testing of large ASTs, these tests demonstrated that such techniques must be implemented with extreme caution in order to ensure that thermal effects associated with the instrumentation and its deployment configuration do not adversely affect test results.

INTRODUCTION

Aboveground storage tanks (ASTs) are commonly used in the petroleum and chemical industries to store a wide variety of liquid products. These can range in size from 500 bbl (21,000 gal) in capacity, such as those found in producing fields, to 100,000 bbl (4,200,000 gal), such as those found in larger processing facilities. The 500-bbl ASTs are typically 12 ft in diameter, and the 100,000-bbl ASTs are typically 134 ft in diameter. Because of the large number of tanks currently in service, the potential for adverse environmental impact caused by undetected leakage is significant. The U.S. Environmental Protection Agency has thoroughly addressed this type of problem in the case of underground storage tanks (USTs) containing hazardous substances, and allows the owners or operators of USTs to utilize a wide range of acceptable options, including precision volumetric tightness testing and inventory reconciliation, to detect leakage from these tanks.

Although the underground storage tank regulations are well established, a similar set of comprehensive requirements for aboveground tanks has yet to be developed. It may be reasonable to expect that when such regulations are developed they will be patterned after the existing requirements for testing USTs. To assess the feasibility of extending UST leak detection approaches to ASTs, however, one must have a basic understanding of the physical processes occurring in the larger, aboveground tanks. In previous tests, it was determined that large changes in the temperature of the product, which are controlled by the large diurnal swings in air temperature, need to be compensated for if small leak rates are to be reliably identified. It was also determined that, in addition to these large gradients (which make thermal compensation difficult), there existed horizontal gradients that may cause large errors when one attempts to compensate using a single vertical array of temperature sensors. Because a mass-measurement (i.e., differential-pressure or "DP" measurement) system is not adversely affected by thermal expansion or contraction of the product nor by horizontal or vertical gradients in the temperature field, this type of volumetric system has the potential to achieve a high level of performance. Toward this end, experiments were conducted on a 117-ft-diameter AST containing light gas oil to assess the capability of a mass-measurement system.

From a practical standpoint, a mass-measurement approach is attractive because it is non-invasive, i.e., it does not require that instrumentation be deployed inside the tank. The basic premise underlying this approach is the expectation that, for a right circular cylinder, the multiplicative product of fluid density and height remains constant, regardless of the temperature changes experienced by the fluid. This approach should then, in theory, alleviate the practical difficulties encountered in measuring the true average temperature change of the product during the course of a volumetric test.

Additional instrumentation was also deployed in and around the tank in order to provide a diagnostic capability to the data collection effort. In particular, thermistors were placed at numerous locations on the differential-pressure sensors, standpipe, and interconnecting tubing. The data from these sensors were extremely useful in helping to identify and quantify the effects of ambient influences on the differential-pressure measurements.

DESCRIPTION OF THE EXPERIMENTS

The purpose of the experiments, conducted over a 28-day period at the Mobil Oil Corporation refinery in Beaumont, Texas, was to characterize the temperature and volume changes that might be encountered during a volumetric leak detection test. The tank used in the experiments contained light gas oil and had a diameter of 117 ft, a 42-ft-high cylindrical sidewall, and a fixed, conical roof having an 8° pitch. The total capacity of the tank was approximately 51,400 bbl (2,160,000 gal). It was isolated from the remainder of the tank farm by means of valves on the associated piping linking it to other tanks. (Tightly closing these valves was the chosen method of isolation, since it was not expedient to install pipe blinds.) The initial product level during all tests was 3 ft 1 5/8 in. Because of a slight inflow condition, the product level at the end of the experiments was 3 ft 1 15/16 in. A summary of the tank configuration is given in Table 1.

Multiple hydrometer measurements of a sample of the light gas oil were taken before data collection was initiated. These measurements yielded an API gravity of 48.15 at 60°F/60°F, with a corresponding coefficient of thermal expansion of 0.00044 /°F.

Table 1. Configuration of the Tank Used in the Experiments

Diameter	117 ft
Height	42 ft
Roof type	fixed
Construction type	riveted
Foundation	native (no ring wall)
Product	light gas oil
Product expansion coefficient	0.00044/°F
Nominal product level	37-1/2 in.
Water bottom	approximately 6 in.
Sludge depth	approximately 4 in. at tank center

Redundant differential pressure cells were connected to the tank at the location shown in Figure 1. Previous experimental work suggested that, rather than utilizing an extremely sensitive pressure cell, commercially available cells commonly used in the process industry would be adequate for making the mass measurements (Vista Research, Inc., 1991).

Multiple sensors were deployed both inside and outside the tank as a means of monitoring the tank environment during the experiments. Temperature changes in the product were measured by two vertical arrays of thermistors. One array was located near the center of the tank, while the second was mounted in the normal gaging port, located on the west side of the tank. On each of these arrays, thermistors having a calibrated precision of better than 0.001 °C were mounted as shown in Figures 1 and 2. In order that the magnitude of the volume changes associated with thermal expansion and contraction of the structure itself could be assessed, the temperature of the tank shell was also monitored. As shown in Figure 1, thermistors were mounted circumferentially at 60° intervals on the tank's exterior, 18 in. above the tank floor. These sensors were calibrated to the same level of precision as that of the internal temperature sensors.

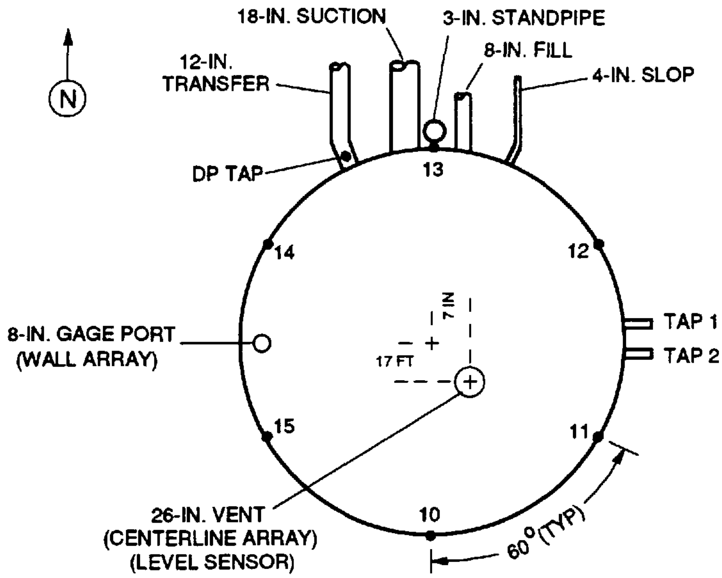

Figure 1. Plan view and orientation of primary thermal sensors in tank, with connecting piping shown for reference.

Changes in product level were monitored by a pair of commercially available differential pressure transmitters which were mounted on the tank exterior, as shown in Figure 3. Rather than installing a dedicated horizontal tap for the high-pressure ports of these sensors, the ports were connected to an existing vertical tap located in the nozzle of the 12-in. transfer pipe. The low-pressure ports were manifolded into a 3-in. diameter standpipe located nearby. The bottom of this standpipe rested on the exterior extension of the tank floor, which protruded past the tank wall, while the top was vented back to the freeboard (or vapor space) of the tank. Both DP transmitters and the standpipe were rigidly mounted directly to the tank structure, in order to minimize the effects of relative motion on the output of the DP sensor. Additional temperature sensors were mounted on the transmitters (the bodies of the DP sensors) and on selected portions of the interconnecting piping in order to provide a level of diagnostic capability for subsequent post-test analysis.

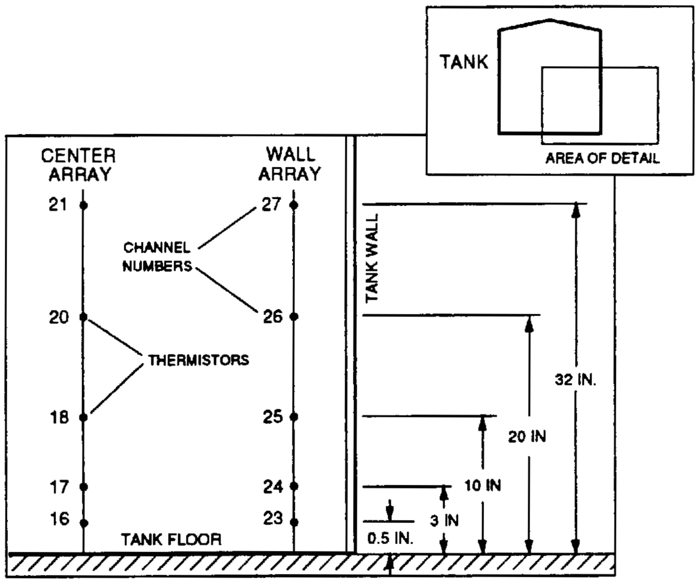

Figure 2. Elevation view of primary thermal sensors deployed in tank.

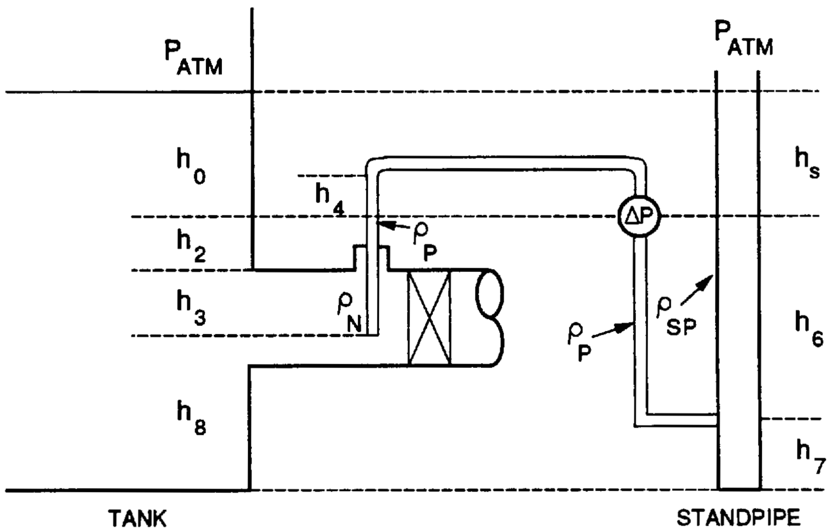

Figure 3. Schematic diagram of differential pressure cell installation on tank exterior.

Changes in product level during the test were also monitored by a single float-based sensor having a high degree of precision. This level sensor, positioned inside the tank near the center temperature array, was supported by a tripod arrangement that rested on the bottom of the tank, providing lateral stability. The tripod arrangement also ensured that the sensor did not move up and down in response to thermal expansion and contraction of the tank shell, as it would have if it had been suspended from the top of the tank. The precision of the level sensor was estimated to be approximately 0.0005 in. This low numerical value represents a high precision, which ensured that the height changes associated with *small* leaks could be readily detected and that the output of the level sensor could be used as a reference for mass-measurement sensors (differential-pressure sensors) also deployed on the tank's exterior.

The output of all of the temperature sensors, in addition to the outside air temperature and the local barometric pressure, was recorded at a rate of 1 sample/min. Measurements of product level were recorded at 1 Hz and averaged down to 1 sample/min in real time during data collection. Data were collected by an HP 3497A under the control of a 386 portable computer via an IEEE-488 data bus. All data were recorded digitally on the 386 computer for post-test examination and analysis.

TEST CONDITIONS

Data collection began after all the sensors had been deployed, and it continued virtually uninterrupted for the entire 28-day period. As a result, a wide variety of weather conditions was experienced, ranging from hot, sunny days to cool windy periods during strong thunderstorms. Ambient conditions, which dominated the volumetric behavior of the tank, could be broken down into two distinct periods, as illustrated both by the local, outside air temperature, shown in Figure 4, and by the temperature in the vapor space of the tank, shown in Figure 5. During the first period, up to 28 May (day 13), temperatures gradually increased, and no appreciable

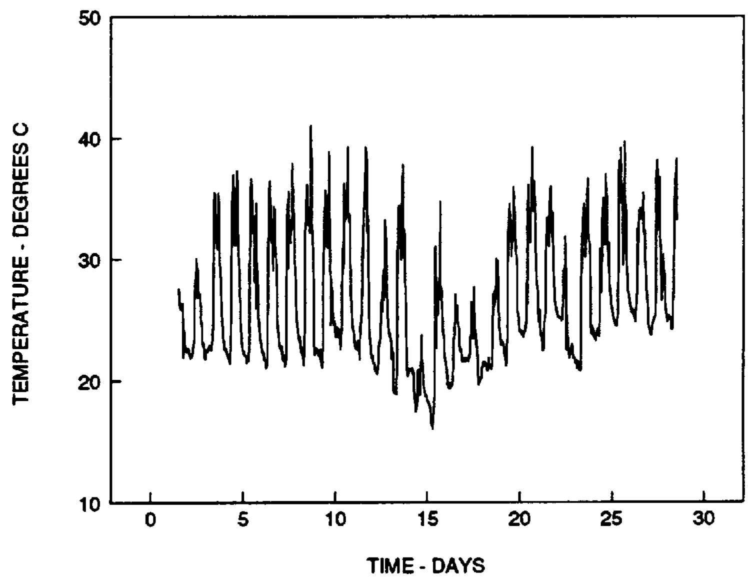

Figure 4. Daily air temperature cycles during the full 28-day test period.

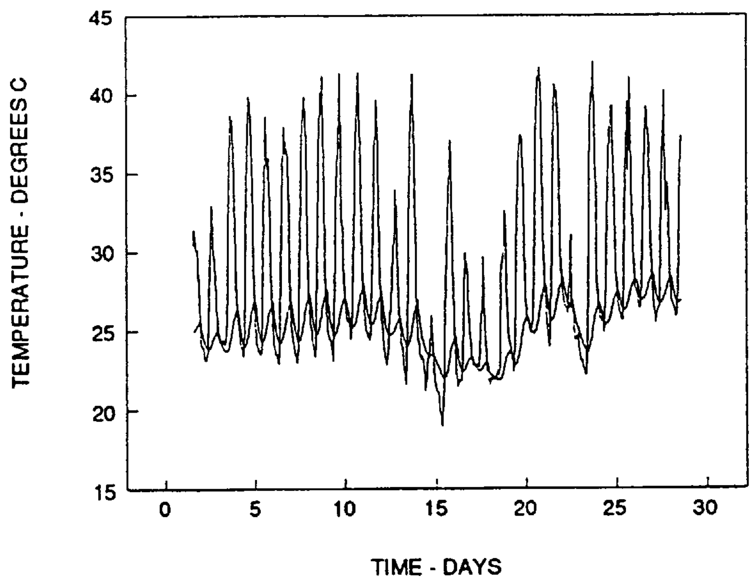

Figure 5. Temperatures in the freeboard (vapor space) of the tank during the full 28-day test period. The curve at about 22°C represents the temperature measured 4 in. below the product surface at the center thermistor array (Channel 21).

precipitation occurred. Then, for about a week (from day 14 to day 20), a sharp decrease in ambient temperature excursions was experienced, along with a considerable amount of precipitation. There were occasional periods of rainfall throughout the remainder of the test period, and diurnal temperature cycles began to return to more seasonable levels. As a result of the amount of rainfall, and the tank's location, the tank bottom was directly exposed to standing water for the majority of the second period, which began on 1 June (day 17). At its maximum depth, on the south side of the tank, the water level was nearly 1 ft deep.

Careful inspection of the plots in Figures 4 and 5 shows that temperature in the vapor space of the tank undergoes significantly larger diurnal fluctuations than does the ambient air temperature. Over a typical 24-h period, temperature in the vapor space was found to exceed that of the outside air during the daytime, while at night it was frequently lower. It is possible, therefore, that the thermal processes which predominate in the freeboard of the tank differ from what might be expected given the thermal conditions outside the tank.

RESULTS

The results of the experimental measurements are discussed in the following sections, and are analyzed for their implications for utilizing mass-measurement systems for the conduct of leak detection tests.

VOLUME MEASUREMENTS

Gross changes in the volume of product in the tank, characterized by a diurnal fluctuation of about 200 gal, were monitored for the entire 28-day experiment period. These fluctuations strongly coincide with diurnal ambient temperature fluctuations, suggesting that the periodic portion of the volume changes is due to thermal expansion of the product. In addition to these fluctuations, the tank inventory was found to increase fairly linearly throughout the entire period. A composite gross volume history is shown in Figure 6. As can be seen in this plot, significant deviations from the overall linear volume increase were experienced during the middle part of the experiment period; these deviations correspond to the period of cool weather, subdued ambient thermal fluctuations, and periods of significant rainfall.

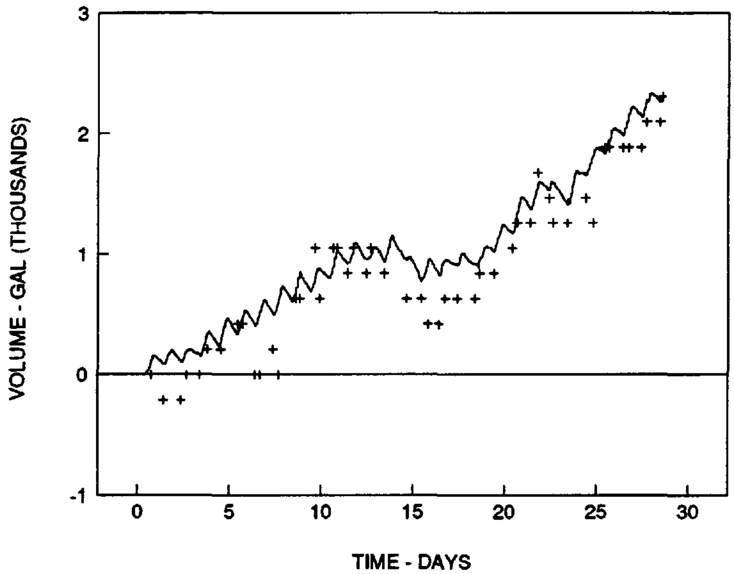

Figure 6. Gross volume time history measured by the float-based level sensor. Symbols denote manual level readings taken from a level gauge permanently installed on the tank wall.

The generally increasing trend of the inventory was not inconsistent with the possibility of inflow into the tank through the isolation valves, which, although closed, may have been leaking. Periodic inspections indicated that high product levels (i.e., greater than 20 ft) were being maintained in other tanks connected to the common suction and transfer piping; such levels, because of the pressure they placed on the valves, would have been sufficient to cause seepage and would account for volume increases of the magnitude observed in the test tank. A linear regression through all data collected during the experiments indicated that the gross inflow rate during this time was approximately 2.8 gal/h. Blinding of all pipeline connections would thus appear to be essential prior to conducting a volumetric test on a tank whose integrity is unknown.

For comparison, the output from a typical DP transmitter is shown in Figure 7. The most pronounced feature in this figure is the strong correlation of sensor output with diurnal temperature fluctuations.

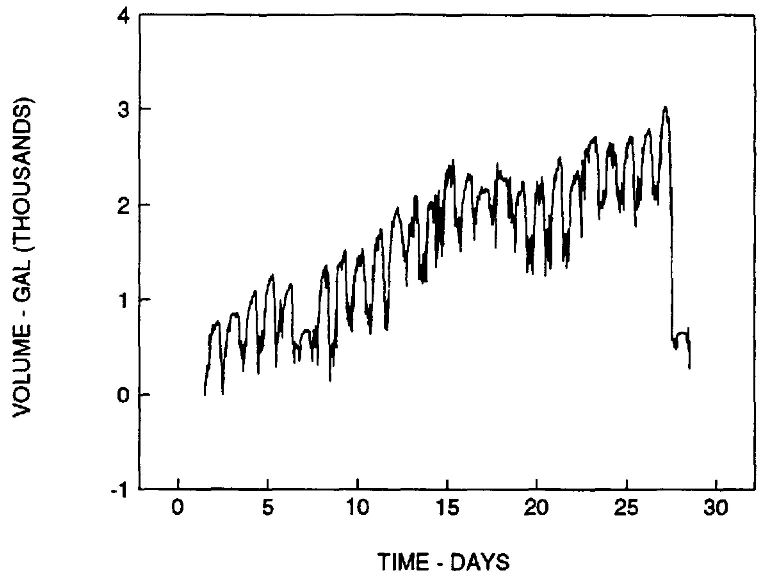

Figure 7. Raw volume measurements obtained from a typical DP transmitter attached to the tank exterior, during the same period shown in Figure 6.

The data in Figure 7 exhibit trends which are qualitatively similar to those obtained by the float-based system, suggesting that the concept of using differential-pressure measurements to monitor product levels is viable. The most striking feature of this figure, however, is that the magnitude of the gross volume fluctuations indicated by the transmitter is three to four times those obtained from the float-based sensor. These strong periodic changes are highly correlated with ambient diurnal temperature changes, and suggest that some form of thermal compensation will be required in order to reduce their impact on the conduct of a leak detection test. These changes can be segregated into those which affect conditions in the tank environment and those which are particular to the mass-measurement instrumentation.

As part of the diagnostic efforts during these tests, the hydraulic circuitry connecting the pressure sensor to the tank and standpipe was short-circuited twice during the course of the data collection period, the first time on day 4 and the second time on day 28. These measurements were used to ensure that there was no gross sensor drift occurring, and to aid in the understanding of the effects of thermal changes on the sensor output.

THERMAL LIFT IN THE PRODUCT

While the DP cell is theoretically self-compensating for thermal expansion of the product, practical aspects of installing the instrumentation will generally introduce some unavoidable measurement errors. One error that is particular to the mass-measurement approach is that of "thermal lift." This phenomenon can best be understood by carefully examining the manner in which both pressure ports of the differential transmitter communicate with the tank and the standpipe. Under ideal conditions, these ports (or taps) would be located at the bottom of their respective vessels, so that the entire depth of product would be monitored during a test. Practical considerations, however, generally result in having to locate these taps a nominal distance above the floor, so that for a portion of the contained fluid (the portion beneath the tap) there is no thermal compensation. Thermal expansion of this lower layer of fluid, should it occur, then lifts the fluid above it, causing an increase in transmitter output in response to the fluid expansion. In these experiments, the uncompensated fluid layer in the tank (denoted as h_8 in Figure 3) was approximately 11.4 in. deep, and that in the standpipe 7.25 in. deep. Estimates of the volume fluctuations in the tank arising from this phenomenon are shown in Figure 8, as made by each thermistor array mounted in the tank.

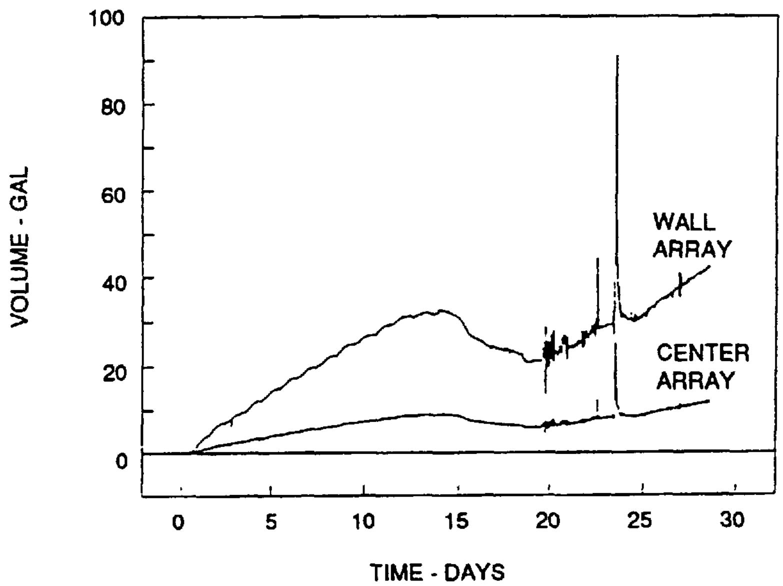

Figure 8. Tank thermal lift for each thermistor array, over the entire measurement period. The uncompensated fluid layer is approximately 11.4 in thick, and is comprised of a 6.5 in water heel beneath a 4.9 in product layer. The strong spikes occurring at day 24 are due to diagnostic activities which were performed on the instrumentation.

It is interesting to note that the fluctuations in the thermal lift coincide qualitatively with the fluctuations observed in other sensors in the tank. This is not unexpected, since ambient temperature changes are responsible for a large fraction of the tank behavior. The magnitude of the thermal lift is, however, moderated by both the presence of water in the bottom of the tank, and by the proximity of the tank floor to the unmeasured fluid layer.

Thermal expansion of the water in the tank, while contributing to the thermal lift, is not as pronounced as it would be for the same layer of product. The smaller coefficient of thermal expansion for water is primarily responsible for this. In addition, the presence of the tank floor tends to heavily dampen the temperature fluctuations which are experienced in the unmeasured fluid layers. Since these layers are located in the area of a strong thermal gradient caused by the tank floor, diurnal temperature fluctuations in these layers are greatly reduced. To some degree, this is expected, since previous experimental work suggested that testing at low product levels in the tank would be beneficial in moderating product thermal expansion [1]. The current data suggest that, in order to minimize this source of error in a mass measurement test, the high pressure tap in the tank should be placed as low as possible on the tank wall, thus minimizing the height of the unmeasured fluid layer. Placing the tap so that the unmeasured layer is comprised only of water (if this is possible) will further reduce the error due to the thermal lift.

THERMAL MEASUREMENTS OF THE TANK SHELL

Thermal changes affect not only the volume of the product but also the capacity of the tank itself, whose walls expand and contract circumferentially in response to temperature changes; this expansion and contraction in turn influences the *level* of product (which can be mistaken for a change in volume). Expansion and contraction of the tank shell can thus be responsible for significant errors in volumetric testing. The experiments addressed the phenomenon of expansion and contraction by treating the tank shell as a frustum of an inverted cone whose bottom is firmly attached to the tank floor. (The top of the inverted cone represents the circular plane described by the surface of the product; the point of this cone can be found somewhere beneath the tank floor; and the plane that bisects the inverted cone somewhere between its top and its point is the tank floor.) Changes in shell temperature then result in changes to the enclosed volume according to the relationship:

$$\Delta V_{SH} = \{(C_o + C_o \alpha \Delta T)^2 - C_o^2\} \frac{1}{\pi} \frac{h}{2} \frac{1}{4} 7.4801 \tag{1}$$

where

ΔV_{SH} = thermally induced change in the volume of the tank shell (gal)

C_o = original shell circumference (ft)

α = coefficient of thermal expansion of the shell (/°F)

ΔT = change in shell temperature (°F)

h = nominal product level (ft)

It is important to recognize that for a given set of thermal conditions this volume fluctuation is opposite that experienced by the contained product. That is, increases in shell temperature are found to increase the tank shell volume, resulting in a *decrease* in product level in the tank. This level decrease can be easily confused with volume decreases caused by tank leakage. The way to compensate for the effect of expansion is to estimate the thermally induced changes in shell volume (i.e., changes in the capacity of the tank) and add these to the measured, raw changes in the volume of product.

Temperature, however, is not the only causative factor in the expansion and contraction of the tank shell. The magnitude of this phenomenon is also a direct function of the product level and the physical size of the tank. As a result, increasing the product level tends to produce larger thermally induced changes in shell volume. As the product level increases, the phenomenon of expansion and contraction may be better modeled by a cylindrical representation rather than a frustum cone. Adopting this type of representation will increase the shell volume by a factor of 2 for a fixed product level.

Estimates of thermally induced changes in shell volume throughout the experiment period are shown in Figure 9. This figure shows that thermally induced changes in shell volume, like those in product volume, coincide with diurnal temperature fluctuations. In Figure 9, however, the amount of fluctuation caused by expansion and contraction of the shell is only about 25 gal, as compared with fluctuations of approximately 200 gal in the product (see Figure A-1 of appendix). Careful inspection of the temporal history of these volume fluctuations indicates that the majority occur during the morning and late evening hours (i.e., sunrise and sunset). During daylight hours, fluctuations of 5 to 10 gal are not uncommon, in response to fluctuating insolation levels, periods of precipitation, and air temperature changes. During evening hours, fluctuation levels tend to subside significantly, since, in the absence of strong thermal input from sunlight, the entire structure approaches thermal equilibrium.

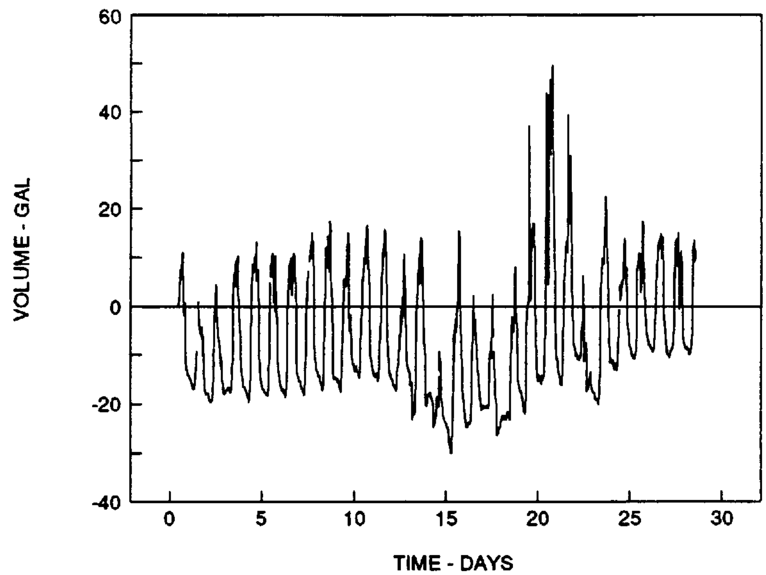

Figure 9. Summary of thermally induced fluctuations in the capacity of the tank shell. The calculations assume that the shell can be represented by a frustum of a cone.

Since these changes occur rather abruptly, their implication in introducing errors into a volumetric test must be carefully considered. In general, any test having a duration approximately equal to the time required to complete the temporal shell volume transients can be expected to experience an error roughly equal to the transient. For example, a shell volume transient having a magnitude of 30 gal, and occurring over a 5-h period, could introduce an error of up to 6 gal/h into a volumetric test having a duration of 5 h, if the two happened to coincide. This type of error is endemic to both float-based and mass-measurement-based testing approaches, and must be compensated for if high levels of detection performance are to be achieved.

Two basic compensation approaches can be readily applied. First, the magnitude of the phenomenon can be estimated from a basic set of sensors mounted on the tank wall. The volumes changes estimated from the sensors can then be added to the measured gross volume changes. A less rigorous alternative is to increase the test duration so that several daily cycles of thermal volume change in the shell can be included in the test data. Since, under reasonably consistent thermal conditions, the shell volume returns to roughly the same level during each overnight period, it should be possible to remove the diurnal changes by averaging the resulting data. This approach, however, is on occasion subject to the possibility of large errors, since the averaging process will not remove the effects of any long-term thermal trends that may be present.

EFFECTS OF THERMAL FLUCTUATIONS ON THE MEASUREMENT SYSTEM

While DP systems are not affected by thermally induced fluctuations in the volume of product in a tank, they can be adversely influenced by thermal changes that act directly upon the components of the measurement system and the piping that interconnects these components. Referring to Figure 3, one can see that the pressure sensor, standpipe, and interconnecting piping are mounted on the tank exterior; these components therefore experience generally greater temperature changes than those occurring in the product contained in the tank. As a result, careful accounting must be made for the influence these thermal changes have on the sensor output.

Given the configuration shown in Figure 3, the output of the DP system can be described by the following equation:

$$\begin{aligned}\Delta P_f - \Delta P_i = \; & \rho_{Tf}h_{of} - \rho_{Ti}h_{oi} + (h_2 + h_3)(\rho_{Tf} - \rho_{Ti}) - h_3(\rho_{Nf} - \rho_{Ni}) - h_2(\rho_{Pf} - \rho_{Pi}) \\ & -(\rho_{spf}h_{5f} - \rho_{spi}h_{5i}) - h_6(\rho_{spf} - \rho_{spi}) - h_6(\rho_{pf} - \rho_{pi}) \qquad (2)\end{aligned}$$

In this relation, the left hand term represents the output from the differential pressure sensor. The first term on the right hand side of the equation represents the change of mass occurring in the tank, while all other right hand terms are attributable to corrections required as a result of the physical arrangement of instrumentation piping. Examination of this relationship yields some insights into sources of potential measurement error, and provides a mechanism from which an optimum differential-pressure measurement system can be developed. The equation implies that the DP sensor's output, while directly influenced by changes in product mass in the tank, is also influenced by the density changes that occur in the vertical legs of the piping connecting the sensor to both the tank and the standpipe. These influences can be minimized by configuring the sensor and standpipe so that only horizontal piping connections are employed. Further reductions in unwanted sensor output can be obtained by minimizing the length of these horizontal runs.

Because the current experimental configuration employed some vertical instrumentation runs, additional temperature sensors were placed on selected piping runs in order to permit the sensor output to be compensated for thermal effects. The output from these sensors, along with measured physical dimensions of the interconnecting piping, was incorporated into Eq. (2) to estimate the thermal influence on the output of the DP sensor.

The results of the calculations in Eq. (2) are shown in Figure 10, along with the gross volume changes measured by the DP sensor. According to these data, a considerable fraction of the observable volume fluctuations can be attributed to thermal changes that affect the interconnecting piping. Even after these thermal effects have been accounted for, however, the residual volume fluctuations are sufficiently large that they preclude the conduct of a reliable leak test. These residual fluctuations are suggestive of additional thermal effects on the output of the DP sensor.

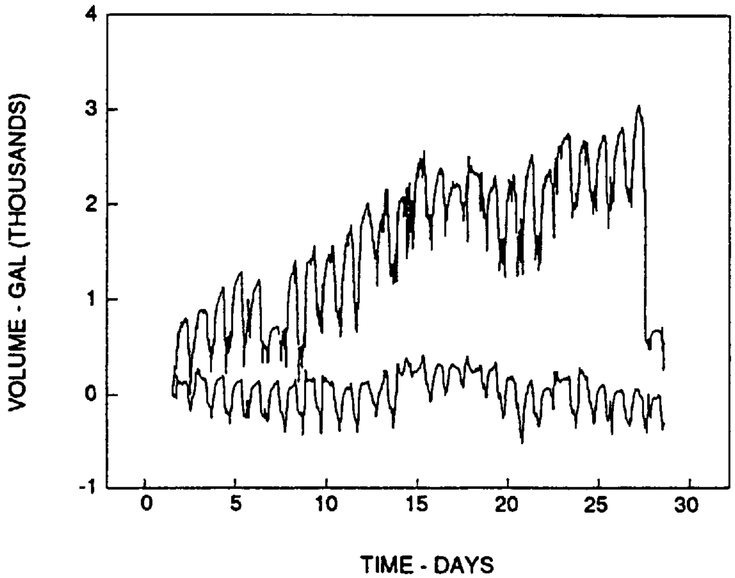

Figure 10. Thermally induced level fluctuations attributable to instrumentation piping (lower plot). The gross level measurements (upper plot) are also shown for comparison. Both plots depict the volume of oil, in thousands of gallons, in a 117-ft-diameter tank.

The most obvious of these effects is that of thermal sensitivity of the differential pressure sensor. The manufacturer's performance specifications provide some insights into how much thermal influence can be expected. In the current experiments, fluctuations of approximately 8 gal/°C could be expected. Additional experiments were conducted to try to confirm these predicted thermally induced volume fluctuations.

The results of these tests, for a sensor span of 1.7 in. H_2O, are shown in Figure 11. The data in Figure 11 characterize the particular sensor used to obtain thermal measurements of the product contained in the tank; these data suggest that a factor of -6.9 gal/°C should be used in the analysis of the current experimental data.

Application of the pressure sensor thermal factor to the data shown in Figure 11 is helpful in compensating for a portion of the residual level fluctuations. However, even after incorporating this correction, and then fully compensating for all other quantified sources of level fluctuation (shell growth, thermal lift, and thermal effects on instrumentation piping), a significant diurnal level fluctuation is still present in the data. This residual fluctuation, shown in

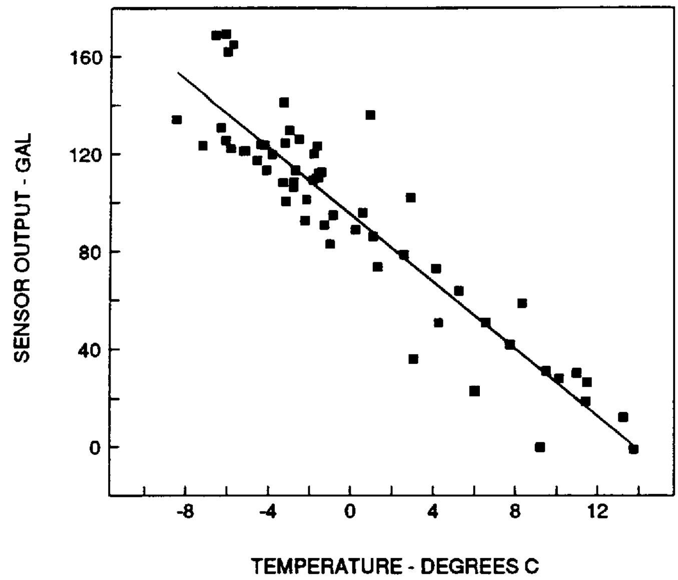

Figure 11. Change in differential pressure sensor output due to changes in sensor temperature. The plot depicts the volume of oil, in thousands of gallons, in a 117-ft-diameter tank. A constant liquid differential of 1.25 in. H_2O was applied to the sensor.

Figure 12, is sufficiently large to preclude the conduct of a viable leak detection test over a short time period. The data clearly suggest that there are additional diurnal influences that must be identified and compensated for in order to be able to detect small leak rates.

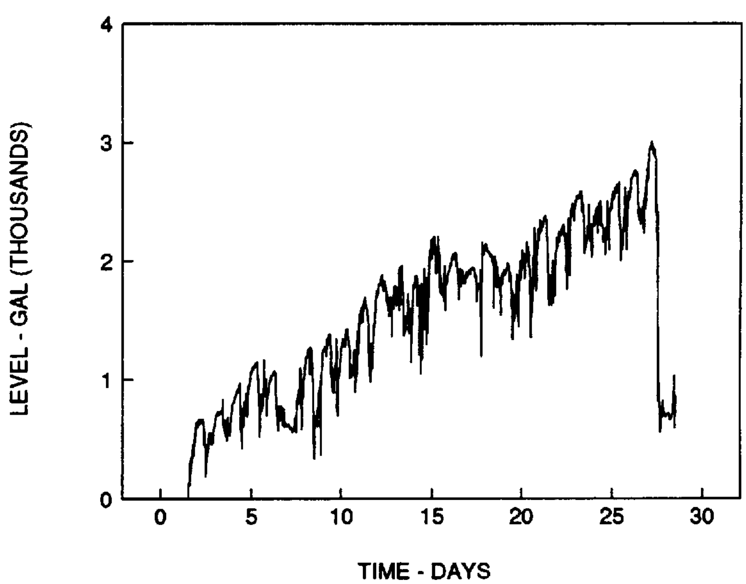

Figure 12. Residual level fluctuation after for thermal effects on both the tank and the measurement instrumentation have been fully compensated for. The plot depicts the level of oil, expressed in terms of volume (in thousands of gallons), in a 117-ft-diameter tank.

The source of these residual diurnal level fluctuations is not clearly understood. While these changes appear to be attributable to thermal influences, a clear physical mechanism which would account for them has not been identified. The strong changes which occur during the morning and evening hours (periods in which the rate of change of temperature is strongest) may be responsible for some of the observed fluctuations, particularly if the measurement system response lags behind the ambient temperature changes. Another possible source of error may be attributed to the effect of vertical piping runs on the measurement system output. In spite of the extensive number of thermal sensors placed on the DP instrumentation, unaccounted-for thermal influences may still occur, particularly at the point where the high pressure tap enters the tank via a short length of vertical tubing. These potential error sources should be minimized by eliminating as much vertical piping as possible: the ideal installation would be totally devoid of any vertical piping runs.

THERMALLY COMPENSATED MEASUREMENTS OF PRODUCT LEVEL

An alternative to coherently canceling the diurnal level fluctuations seen in Figure 7 is to utilize a multiple linear regression approach, using a selected set of temperature measurements as the independent variable. This empirical technique implicitly assumes that the indicated level fluctuations are thermally induced, but it does not rely directly on a mathematical model of physical processes occurring in the instrumentation or the tank in order to permit compensation to be accomplished. The temperature measurements used in the analysis are carefully selected so that they will cover those aspects of the tank system that are expected to influence the level measurement.

Figure 13 shows the typical output of the DP sensor compared to the thermally induced contributions, which were derived from a linear regression of temperature measurements of the sensor, the ambient air, and the vertical tubes. The plot shows good agreement between the two curves where low-frequency fluctuations are concerned. There is a distinct difference, however, in the high-frequency fluctuations. (These are unimportant in the detection of leaks provided that tests are long.) It is possible that this difference is due to cloud passage or other phenomena not predicted by the temperature sensors mounted on the various components of the DP system.

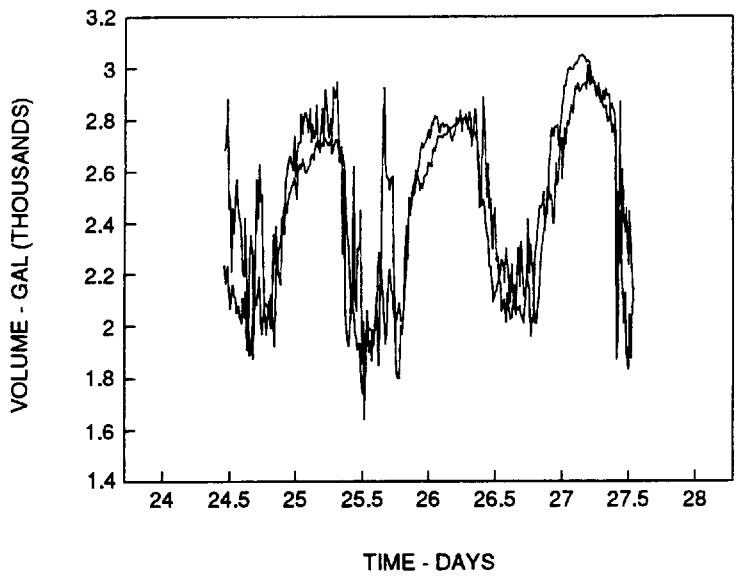

Figure 13. Comparison of the output of the DP sensor with predicted values.

Using this approach over the entire data collection period, six different temperature measurements were utilized as a means to improve the thermal compensation of the differential pressure sensor. Prior to this attempt at compensation, the zero-differential data segments on day 6 was removed, and all time series were detrended before the calculations were done. Appropriate thermal coefficients were then determined, and these were applied to the raw level measurements. The results are shown in Figure 14.

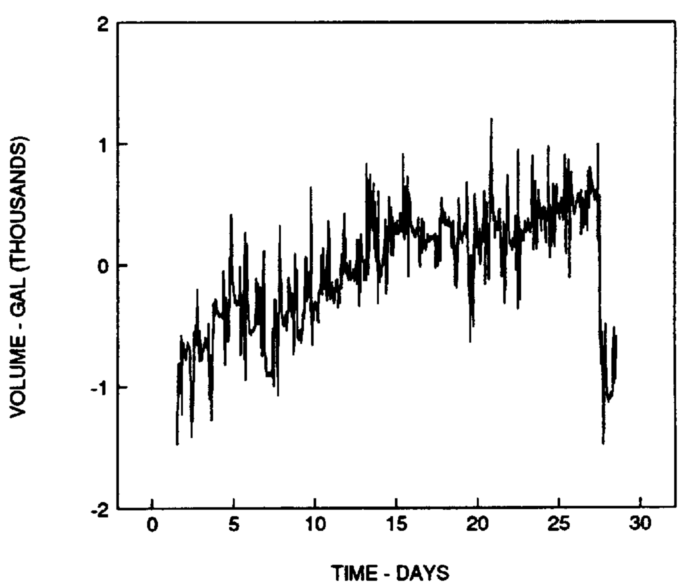

Figure 14. Thermally compensated DP sensor output, expressed as gallons in a 117-ft-diameter tank. Compensation scheme used a multiple linear regression of temperature versus indicated level.

The results shown in Figure 14, although improved over those in Figure 12, still exhibit large level fluctuations during periods of strong thermal transients. Careful inspection of the data suggests that these spikes are attributable to a phase difference between the response of the pressure sensor and the more rapid response of the temperature sensors used in the compensation scheme. For periods in which the temperature is changing rapidly, phase lags of as little as 1 h can produce large differences between the two types of sensors.

The empirically compensated volumes shown in Figure 14 were subsequently examined to determine whether the degree of compensation was sufficient that small leaks from the tank could be identified. This was accomplished by fitting least-squares lines to 24-h data segments, beginning a test at 0200 hours. Typical results are given in Table 2, which shows a three-day period beginning on 8 June.

The results shown in Table 2, although not conclusive, provide a preliminary indication of the type of leak detection capability that can be expected from this measurement approach.

Table 2. Comparison of Actual and Measured Leak Rates Estimated from DP Measurements, for Selected Test Periods, after Empirical Thermal Compensation of Raw Level Data (The actual inflow rate of 2.8 gal/h has been removed from the results.)

Run	Measured (Gal/h)	Actual (Gal/h)
608	0.05	0
609	-2.70	-2.0
610	0.58	0

LEAK DETECTION PERFORMANCE

To determine the actual leak detection performance that might be expected from this approach requires that additional data be acquired under a wider range of ambient conditions, typical of those under which a test might conceivably be conducted. In addition, these data should be collected from a system which more closely represents the preferred hardware arrangement.

Of particular concern in determining the detection capabilities of this approach is the potential sensitivity of the sensor (and its associated, interconnecting piping) to inappropriate installation and to subsequent thermal effects. Assuming that an ideal hardware configuration is established (in which only horizontal piping is used, and the lengths of piping are as short as possible) DP systems should be capable of attaining levels of performance comparable to those of a float-based system. Before the performance capabilities of the mass-measurement approach can be quantified, however, it will be necessary to collect additional data with the optimum hardware configuration in place.

CONCLUSIONS

Mass measurement approaches to leak detection, although capable of compensating for fluctuations in the product temperature field, are not entirely immune to the effects of ambient temperature fluctuations. In particular, the effects of tank shell thermal growth must be compensated for if small leaks are to be detected. Practical aspects of installing measurement instrumentation on the tank may also introduce additional errors which are thermally driven.

Data collected on a 117-ft-diameter tank containing light gas oil suggest that the ability of a mass-measurement technique to identify small leaks will be challenged by an extremely dynamic thermal environment that is strongly driven by ambient diurnal temperature changes. The concept of using the inherent characteristics of a mass-measurement approach to compensate for a portion of the thermal changes occurring in the tank is sound; however, it has been found that this approach is sensitive to specific details in its implementation. In particular, vertical instrumentation piping should be avoided if thermal sensitivity of the DP system is to be minimized.

REFERENCE

Vista Research, Inc., 1991. An Engineering Assessment of Volumetric Methods of Leak Detection in Aboveground Storage Tanks. API Publication No. 306. American Petroleum Institute. Washington, D.C.

APPENDIX

Thermally Compensated Product Levels

This appendix provides an estimate of the magnitude of thermally induced volume changes in the product during a 28-day period. These estimates were made by converting the measured temperatures at each array to volume changes using the relationship

$$\Delta TV = \sum_{i=1}^{n} C_{ew} V_{wi} \Delta T_{wi} + \sum_{i=1}^{n} C_{ep} V_{\pi} \Delta T_{\pi}$$

where

ΔTV = thermal volume change (gal)

C_{ew} = coefficient of thermal expansion of water (/°F)

V_{wi} = water bottom volume (gal)

ΔT_{wi} = water bottom temperature change (/°F)

C_{ep} = coefficient of thermal expansion of the product (/°F)

V_{pi} = product volume (gal)

ΔT_{pi} = product temperature change (°F)

The results of the calculations are shown in Figure A-1, which summarizes the thermal volume changes associated with each array over the entire 28-day data collection period. It can be seen that thermally induced volume fluctuations are generally on the order of several hundred gallons, increasing or decreasing in response to the diurnal temperature cycle. Because product temperature was different at the center of the tank than it was near the walls, there are differences in the thermal volumes calculated from measurements made by the two arrays; the center array produced values slightly lower than those of the wall array. It is also noted that when temperatures are increasing, thermally induced volume changes calculated from the wall array peak 2 to 3 h earlier than those calculated from the center array; the offset between the two are minimal when temperatures are decreasing. Conventional volumetric tests compensate for these volume changes by subtracting an estimate of the thermally induced volume change made with any one vertical array. Errors result from inadequate vertical and horizontal spatial coverage. Figure A-2 presents the difference in the thermal volume estimates made from both arrays. Such errors are not present in a mass-measurement system.

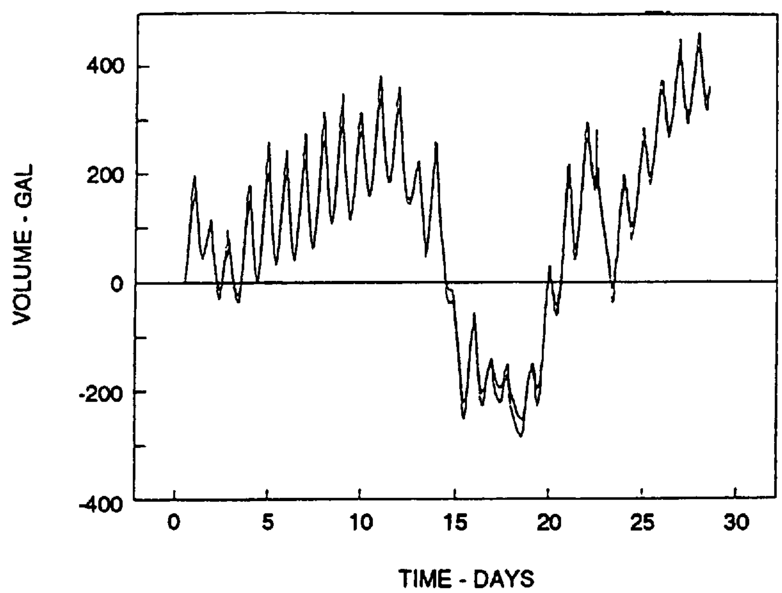

Figure A-1. "Weighted" thermally induced changes in the volume of product during the 28-day data collection period. Due to greater temperature fluctuations in the vicinity of the tank wall, the volumes changes recorded by the wall array (the curve with sharper peaks) are more pronounced than those recorded by the center array (the curve with less exaggerated peaks).

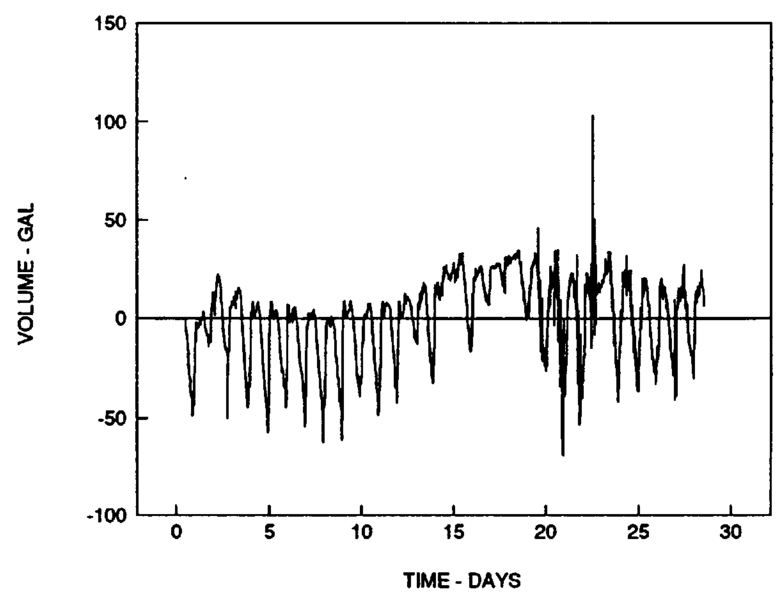

Figure A-2. Difference in weighted thermal volume estimates derived from the two thermistor arrays.

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