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

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Acknowledgments

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For providing invaluable assistance during the Beaumont field tests, we wish to thank Richard Wise of Vista Research, Inc. Finally, we acknowledge the help of Monique Seibel and Pamela Webster of Vista Research in editing and typesetting this document.

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Executive Summary

Introduction

Though volumetric methods of leak detection have been used successfully to reliably detect small leaks in underground storage tanks, their performance in large aboveground storage tanks (ASTs) is unknown. This document provides the results of an engineering assessment of volumetric methods for detecting small leaks in large ASTs.[1] To assess the environment under which a volumetric leak detection test might be conducted on an AST, a series of experiments were done on a 114-foot-diameter AST containing a heavy naphtha petroleum product and located at the Mobil Oil Refinery in Beaumont, Texas. Data concerning normally occurring volume changes that are not associated with a leak were provided by (1) precision level measurement systems and (2) horizontal and vertical arrays of thermistors placed in two locations: inside the tank, immersed in the product, and outside the tank along its external wall.

Background

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

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

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

Conclusion

The analytical and experimental results of this project suggest that differential-pressure-measurement methods (i.e., mass measurement methods), which are a type of volumetric method, can be used to detect small leaks in ASTs. Such methods can achieve a high level of performance because they are not affected by thermally induced volume changes in a tank with vertical walls. However, other sources of ambient noise, such as thermal expansion of the tank wall and evaporation and condensation of the product in the tank, do affect performance and must be compensated for separately.

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1 The results of the acoustic study are provided in a separate API document entitled *An Engineering Assessment of Acoustic Methods of Leak Detection in Aboveground Storage Tanks*. by Eric G. Eckert and Joseph W. Maresca, Jr.

Summary of Results

The analytical and experimental results of this project suggest that the performance of a volumetric test in detecting small leaks is limited by the magnitude of the uncompensated volume error and by the duration of the test. Because of the diurnal character of the volume fluctuations, tests that are less than 24 hours long may yield erroneous results. The data suggest that a test may have to be 48 to 72 hours long to reduce the effects of uncompensated volume fluctuations.

The field test data, collected at two different product levels over two three-day periods, indicate that volume changes of several hundred gallons per hour occur in response to ambient temperature changes. During both test periods, volume changes of as much as 1000 gallons were observed over a 24-hour period. Because of these large changes, it is necessary to compensate for the effects of temperature fluctuations occurring in both the product and the tank shell, and for the effects of evaporative product losses, if volume measurements are to be useful in detecting leaks. Analysis of the test data indicates that a small number of temperature sensors mounted on the external circumference of the tank can readily compensate for thermally induced changes in the volume of the tank shell.

The largest sources of uncompensated volume changes were horizontal product temperature gradients and evaporative losses. The data suggest that the size of these volume changes was approximately 10 gallons per hour, with as much as 80% of this value being due to non-uniformity of the product temperature field. The effect of these changes (the "thermal error") can be minimized by using a differential-pressure-measurement system to monitor changes in the level of product in the tank. With this approach, a volumetric test should be able to detect leak rates as low as 1 gallon per hour, if evaporative losses can be minimized and if tests longer than 24 hours can be tolerated.

1 Introduction

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

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

- assess the current state of AST leak detection technology
- characterize the sources of ambient noise associated with volumetric measurements in an AST
- perform field experiments on a full-scale AST
- recommend ways to improve existing AST detection systems

The field tests were conducted at the Mobil Oil Refinery in Beaumont, Texas, on a 50,000-bbl, 114-ft-diameter AST containing a heavy naphtha petroleum product. The experiments focused on the ambient noise field and how it affects accurate detection of the volume changes due to a leak.

2 Background

Volumetric systems are the most commonly used method of detecting leaks in *underground* storage tanks (USTs) [4-6]. These systems typically measure the change in the level of product in the tank; they compensate for the thermal expansion or contraction of the product by measuring changes in the temperature of that product. Their method of compensating for other sources of background noise is to wait for the volume changes to become negligibly small. Volumetric leak detection systems that compensate directly for the thermally induced volume changes in the product would seem to be directly applicable to the detection of leaks in ASTs. Differential-pressure-measurement systems (mass-measurement systems) are an example of this type of volumetric system. Because the cross-sectional area of the product surface is a constant regardless of the level of product, mass measurement systems compensate directly for thermally induced changes in the volume of product; they are, however, subject to other sources of uncompensated noise.

As with USTs, the nature of the leak signal in an AST is well known. Unlike USTs, however, the signal in an AST is not affected by the level of the groundwater, and, because the leak is in the floor of the tank, the pressure head above that leak is known. The primary focus of the field tests was to quantify the magnitude of the volume changes associated with important sources of system and ambient noise.

3 Summary of Results

In order to assess the environment under which a volumetric leak detection test on an AST might be conducted, a series of experiments were done on a single 50,000-bbl tank containing heavy naphtha. Instrumentation deployed in the tank provided information concerning level changes in the product as well as temperature changes in both the product and tank wall. The test data, collected at two different product levels over two separate three-day periods, indicate that volume changes of several hundred gallons per hour occur in response to ambient temperature changes. During both test periods, volume changes of as much as 1000 gal were not uncommon over a 24-h period. Because of these large changes, compensation schemes are required if one is to be able to account for the effects of temperature fluctuations occurring in both the product and the tank shell, and for the effects of evaporative product losses.

When a single array of product temperature sensors was used, compensation of the measured volume changes for these thermal effects resulted in a net loss of product from the tank during both test periods. A large fraction of this loss can be explained by the existence of horizontal temperature gradients in the product and by evaporative loss. Differences in the estimate of the product thermal volume obtained from two vertical thermistor arrays were found to range from less than 100 gal to as much as 400 gal for different test periods. In addition to these product volume changes, the thermal expansion of the tank shell was found to approach several hundred gallons over a 24-h period, and could be accurately estimated by as few as six temperature sensors placed around the tank circumference.

The product surface was found to experience periodic fluctuations having magnitudes approaching 100 gal. These volume changes, coupled with the thermally induced volume changes, are large compared to the range of volume rates of interest. This active product surface thus permits the use of less precise sensors for the primary volume measurement. The accurate estimate of the rate of change of volume can then be obtained by sufficiently averaging through a volume time series to reduce the uncertainty in the rate to acceptable levels. As a result, a range of mass measurements, i.e., those made by pressure sensors, should be suitable for use in a leak test.

The ability of a volumetric test to detect small leaks is limited by the test duration and the magnitude of the uncompensated volume error. The current data indicate that a test duration between 48 and 72 h is required in order for the effects of uncompensated diurnal volume fluctuations to be reduced. Shorter test durations (less than 24 h) would yield erroneous results because of the diurnal character of the volume fluctuations.

The largest sources of uncompensated volume were found to be evaporative losses and the non-uniform thermal expansion of the product. The data suggest that the magnitude of these effects was roughly 10 gal/h, with as much as 80% of this value being due to inadequate spatial coverage of the product temperature field. Since a mass measurement system is not affected by horizontal temperature gradients, and intrinsically compensates for thermally induced product volume changes, a volumetric test should be able to detect leak rates as small as 1 gal/h if the effects of evaporation can be minimized and if tests longer than 24 h can be tolerated.

4 Report Organization

The work performed as part of the Phase II program is summarized in a technical paper prepared for publication in the engineering and scientific literature [7]. This paper, a copy of which is presented in Appendix A of this report, describes the results of the experiments conducted with a volumetric leak detection system during April and May 1991. Two three-day field tests were conducted on a 114-ft-diameter AST, and two levels of product (10 and 17 ft) were used during these tests. The paper describes the volume changes associated with each source of noise at each level of product.

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Appendix A

Experimental Investigation of Volumetric Changes in Aboveground Storage Tanks

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Experimental Investigation of Volumetric Changes in Aboveground Storage Tanks

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10 September 1991

Abstract

In order to more fully characterize the environment under which a volumetric leak detection test might be conducted on an aboveground storage tank, a series of experiments were conducted on a single 50,000-bbl tank containing heavy naphtha. Instrumentation deployed in the tank provided information concerning product level changes as well as tank wall and product temperature changes. The test data, collected at two different product levels over a pair of three-day periods, indicate that volume changes of several hundred gallons per hour occur in response to ambient temperature changes. During both test periods, volume changes of as much as 1000 gal were not uncommon over a 24-h period. Because of these large changes, compensation schemes are required to account for the effects of temperature fluctuations occurring in both the product and the tank shell, and for the effects of evaporative product losses.

When a single array of product temperature sensors was used, compensation of the measured volume changes for these thermal effects resulted in a net loss of product from the tank during both test periods. A large fraction of this loss can be explained by the existence of horizontal temperature gradients in the product and by evaporative loss. Differences in the estimate of the product thermal volume obtained from two vertical thermistor arrays were found to range from less than 100 gal to as much as 400 gal for different test periods. In addition to these product volume changes, the thermal expansion of the tank shell was found to approach several hundred gallons over a 24-h period, and could be accurately estimated by as few as six temperature sensors placed around the tank circumference.

The product surface was found to experience periodic fluctuations having magnitudes approaching 100 gal. These volume changes, coupled with the thermally induced volume changes, are large compared to the range of volume rates of interest. This active product surface thus permits the use of less precise sensors for the primary volume measurement. The accurate estimate of the rate of change of volume can then be obtained by sufficiently averaging through a volume time series to reduce the uncertainty in the rate to acceptable levels. As a result, a range of mass measurements, i.e., those made by pressure sensors, should be suitable for use in a leak test.

The ability of a volumetric test to detect small leaks is limited by the test duration and the magnitude of the uncompensated volume error. The current data indicate that a test duration between 48 and 72 h is required in order for the effects of uncompensated diurnal volume fluctuations to be reduced. Shorter test durations (less than 12 h) would yield erroneous results because of the diurnal character of the volume fluctuations.

The largest sources of uncompensated volume were found to be evaporative losses and the non-uniform thermal expansion of the product. The data suggest that the magnitude of these effects was roughly 10 gal/h, with as much as 80% of this value being due to inadequate spatial coverage of the product temperature field. Since a mass measurement system is not affected by horizontal temperature gradients, and intrinsically compensates for thermally induced product volume changes, leak rates as small as 1 gal/h should be detectable with a volumetric test, if the effects of evaporation can be minimized.

Introduction

Aboveground storage tanks are commonly used in the petroleum and chemical industries to store a wide variety of liquid products. These tanks can range in size from small 500-bbl capacities in producing fields to over 100,000-bbl capacities in larger processing facilities. Because of the large number of tanks currently in service, the potential for adverse environmental impact caused by undetected leakage can be significant. The U.S. Environmental Protection Agency (EPA) has thoroughly addressed this type of problem for underground storage tanks containing petroleum products and other hazardous substances. The EPA allows the owner or operator of an underground storage tank a wide range of acceptable options to detect leakage, including precision volumetric tightness testing and inventory reconciliation [1].

While the underground storage tank regulations are well established, a similar set of comprehensive requirements for aboveground tanks has yet to be developed. In order to assess the feasibility of extending leak detection approaches from underground to aboveground storage tanks, however, a basic understanding of the physical processes occurring in the tank is essential. In Phase I of this program, the American Petroleum Institute (API) performed a systems analysis of the important errors that occur in volumetrical testing of aboveground tanks [2,3]. The experiments and results described in this paper were conducted on a 114-ft-diameter aboveground tank, and were focused on identifying and quantifying the basic volumetric characteristics which could directly influence the accuracy of a precision volumetric test.

Sources of Volume Change

In its basic form, a volumetric test will provide an accurate estimate of the leak rate after the effects of product thermal expansion, tank shell thermal expansion, evaporation/condensation, and structural deformation have subsided to sufficiently small levels. In an aboveground environment, these effects are almost never small enough to neglect, thus requiring some form of compensation to be employed in order to determine the true volume change in the tank.

Temperature Changes

Two primary thermal volume changes can be expected in an aboveground tank. The first of these is the most obvious, i.e., the expansion and contraction of the stored product as its temperature changes in response to ambient temperature changes. Because all sides of the tank except for the floor are exposed to ambient temperatures, the effects of diurnal cycles on the product temperature can be significant. Uneven heating of the tank, caused by fluctuating air temperatures, precipitation, and periodic cloud passage can produce measurable volume changes.

A simple model of product thermal expansion can be employed to provide a means for compensating for these effects. This can be accomplished by dividing the tank into a series of *i* horizontal slabs, starting at the bottom of the tank. A series of temperature sensors, each placed at the middle of one of the slabs, is then used to measure the temperature change. The net thermal volume change associated with the individual product temperature changes is then given by

$$TV = \sum_{i=1}^{n} C_e V_i \Delta T_i \tag{1}$$

where C_e is the coefficient of thermal expansion of the product, V_i is the volume of each slab of fluid, and ΔT_i is the temperature change of the fluid in that slab.

Eq. (1) provides a reasonable estimate of the thermal volume changes, provided that certain basic assumptions are valid. In particular, the model requires that the temperature measured in the slab be representative of the temperature throughout the entire slab. The presence of inhomogeneities and strong temperature gradients can introduce significant errors into the volume predicted by this equation. For testing in aboveground tanks, vertical gradients can be accommodated by increasing the number of temperature sensors deployed in the fluid. Radial temperature gradients (such as those which might be created by an uneven diurnal heating of the tank exterior) could also be addressed by this approach. Practical considerations, however, tend to limit the utility of doing this.

To a large extent, the product volume fluctuations associated with these temperature changes can be compensated for by a judicious selection of a volume measurement sensor. Since virtually all of the aboveground tanks in service can be represented by a right circular cylinder, product level (or volume) changes associated with product temperature changes can be canceled by measuring the pressure at the bottom of the tank. For a tight tank condition in which no mass is lost from the liquid-vapor system, the product of average liquid density and liquid height above the pressure sensor will remain constant. Changes in liquid density will result in corresponding changes in the liquid height, such that the product of the two is unchanged. The use of this approach should minimize the effects of thermal stratification and radial temperature gradients.

In addition to the product thermal volume changes, real volume changes occur in response to thermal expansion of the tank itself. Changes in shell temperature generate changes in the shell circumference, and as a result, changes in the cross-sectional area of the tank. Multiplying this area change by the gross product level provides an estimate of the change in the capacity of the tank. Compensation for this phenomenon requires that the average shell temperature be monitored. With this information available, the capacity change associated with shell expansion can be estimated from

$$\Delta V = \frac{H}{4\Pi}\left\{\left(C + \sum_{i=1}^{n} C_i C_e \Delta T_i\right)^2 - C^2\right\} \tag{2}$$

where C_i is that portion of the shell circumference represented by the temperature change ΔT_i, H is the nominal product height, and C is the shell circumference at the start of the measurement period. Because of the large size of many existing aboveground tanks, even small temperature changes can result in significant volume changes when compared to the losses that would be caused by small product leaks. In addition, because these are essentially changes in the tank capacity, independent compensation for these effects must be made regardless of the manner in which the gross volume changes are measured. Use of a pressure sensor or other mass measurement technique to monitor product level changes will not eliminate the need to employ this additional compensation, since the volume changes caused by shell expansion are unrelated to product density changes.

It is also important to recognize that the volume changes associated with shell thermal expansion generally tend to moderate or counteract the product level changes associated with product thermal expansion. Since the shell and product tend to track together thermally, temperature increases tend to produce both product volume increases and shell volume increases. However, since the shell expansion effectively increases the tank capacity, the apparent product level change is reduced by the amount of the shell expansion. Complete temperature compensation thus requires that the shell volume changes be properly accounted for.

Structural Deformation

Structural deformation as defined here consists of a change in tank capacity resulting from a change in product level. In theory, the resulting change in hydrostatic pressure applied to the tank floor could the induce a small, time-dependent displacement in the floor. Extensive experimental data obtained from underground storage tanks have indicated that this behavior can be complex, and can be strongly influenced by the type of soil or backfill surrounding the tank. As a result of this influence, the rate of volume change was found to have a basic exponential behavior, with the resulting volume changes decreasing with increasing time after the initial product level change. In addition, the specific behavior can be quite variable, depending upon the local subsurface conditions around the tank. For the current set of experiments, an effort was made to ascertain whether this phenomenon exists when levels are changed and, if so, what the magnitudes of these volume changes are for the particular test tank.

Evaporation/Condensation

Evaporation and condensation are liquid surface phenomena which are different from the previously identified volume changes. Whereas the previous volume changes related to apparent changes in the fluid quantity, or real volume changes of the fluid containment, these two processes represent the physical removal or addition of product to the system through vents in the tank. Since these losses or gains can be confused with the losses attributable to a leak, efforts must be made to either control them or account for them. This process is dependent upon numerous external factors, including vapor pressure, vapor temperature, liquid temperature, free surface area, and barometric pressure. In general, some evaporation can be expected during the normal breathing cycle of the tank, with higher product vapor pressures inducing higher loss rates.

Experiments

A series of experiments were conducted over a two-week period in order to obtain basic data regarding the types of temperature and volume changes which could be encountered during the conduct of a volumetric leak detection test. These tests were conducted at the Mobil Oil Corporation refinery in Beaumont, Texas, on a tank containing heavy naphtha. The tank had a fixed, conical roof having an 8° pitch, a 30-ft sidewall, and a diameter of 114.6 ft. Initial tests were conducted at a product level of 17 ft, 2 in., after which the product level was lowered to 10 ft, 0 in. for the second portion of the experiments.

In order to monitor the tank environment during the experiments, multiple sensors were deployed both inside and outside the tank. Temperature changes in the product were monitored by two vertical arrays of thermistors. One array was located at the center of the tank, while the second array was mounted in the normal gauging port, located on the north side of the tank. For each of these arrays, thermistors having a calibrated precision of less than 0.001 °C were mounted at 24-in. intervals starting 4 in. above the tank floor. Sensors suspended in the vapor space were set at 4-ft intervals, as shown in Figures 1 and 2. In addition to these vertical sensors, 20-ft-long horizontal arms were attached to each of the vertical arrays at a point 24 in. above the tank floor. Sensors were mounted at 4-ft intervals on each of these arms. Original test plans called for the deployment of these arms on a common tank radius in an attempt to determine whether any strong radial temperature gradients could be measured in the product. Internal roof supports precluded the proper positioning of these arms in the tank, thus severely restricting the capability for radial measurements.

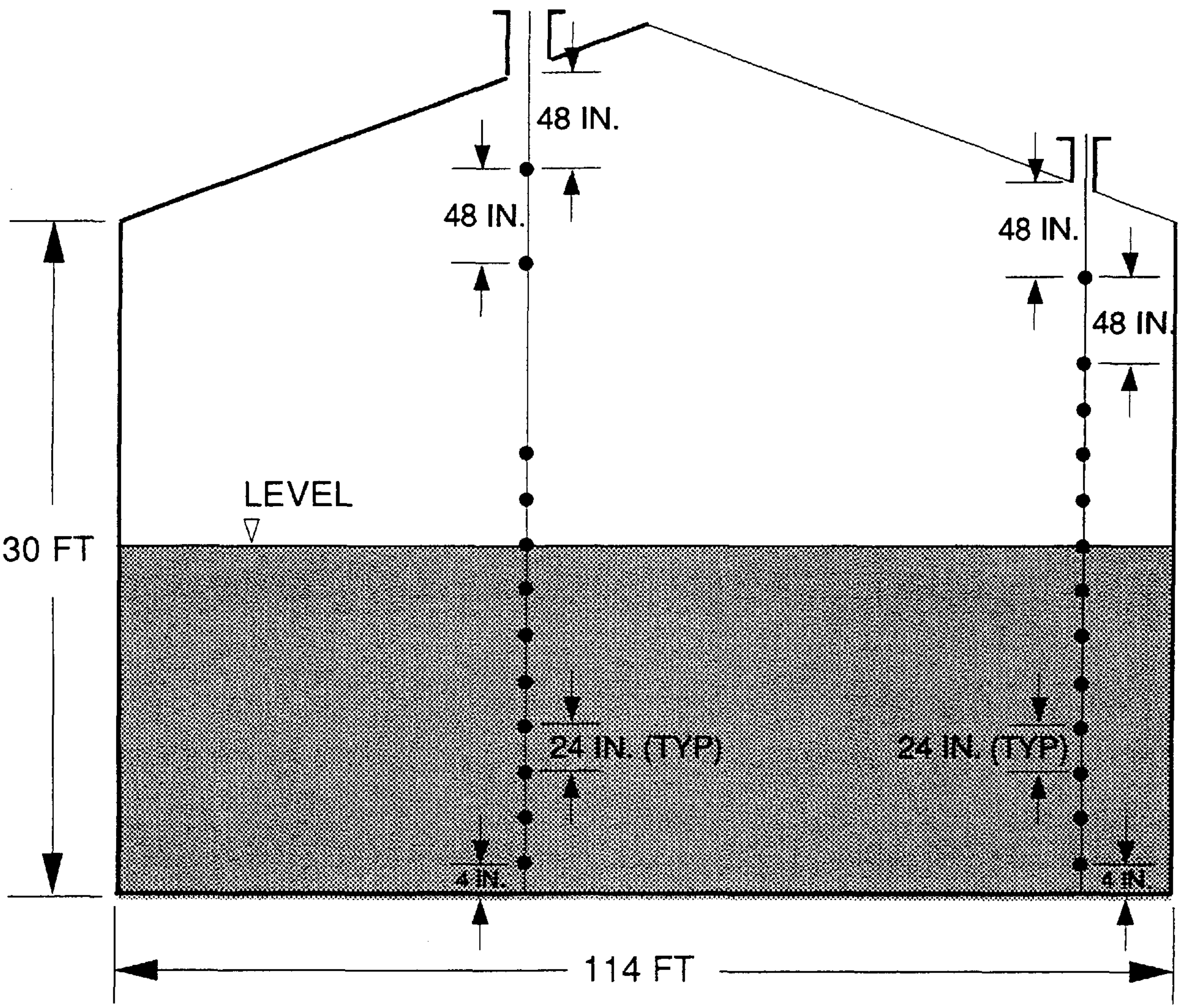

Figure 1. Elevations of primary sensors deployed in tank.

The temperature of the tank shell was also monitored during the course of the experiments, in order to assess the magnitude of the volume changes associated with thermal expansion and contraction of the structure. For these measurements, sensors were mounted circumferentially at 60° intervals on the shell exterior, utilizing a 4-ft foot vertical spacing starting 24 in. above the tank floor. These sensors were calibrated to the same level of precision as the internal temperature sensors.

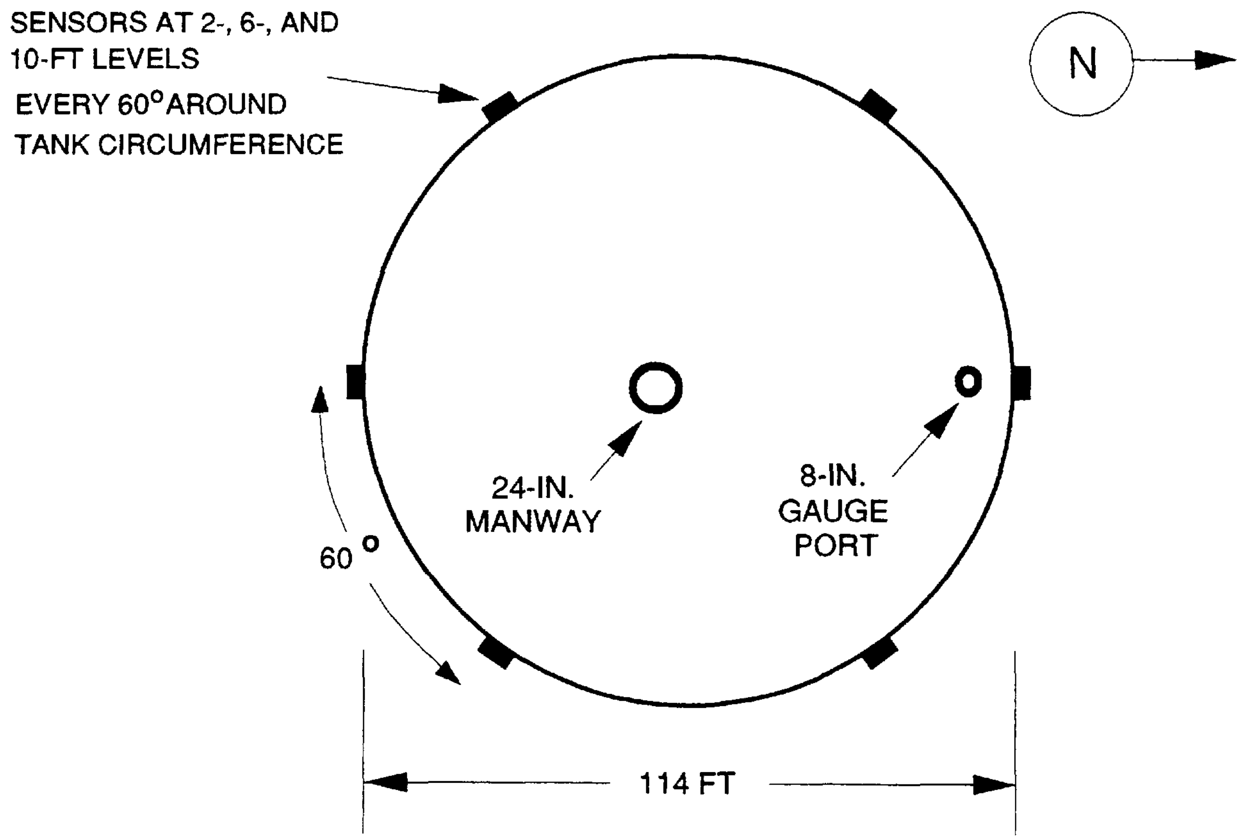

Figure 2. Plan view and orientation of primary sensors on exterior wall of tank.

Product level changes were monitored during the tests by a series of redundant sensors having a high degree of precision and a limited dynamic range. Internally, float-operated electromechanical sensors were mounted alongside each of the vertical temperature arrays. The support for these sensors rested on the bottom of the tank, and was fixed to the tank roof via a special mount designed to isolate the sensor from vertical tank motion. The precision of the sensors at the center of the tank and near the tank wall was 0.0005 in and 0.0002 in, respectively. The high-precision ensured that height changes associated with small leakage rates could be readily detected.

In addition to the internal float-based level measurements, a differential-pressure-based system was installed on the tank exterior. This system was intended to provide an indication of the measurement capability of an integrated system which incorporates inherent product thermal compensation as part of the measurement. When properly functioning, this type of system eliminates the need to directly measure product temperature, instead taking advantage of the fact that the product of density times product height remains constant when the fluid container is a right circular cylinder.

All of the temperature sensors, in addition to the outside air temperature and the local barometric pressure, were sampled and recorded at 1/min. Product level measurements were recorded at 1 Hz and block-averaged down to 1 sample/min during post-test data processing. Except where noted in the following sections, the results are based on the 1-min data rate.

Test Conditions

As noted previously, the current experiments were conducted on a fixed-roof storage tank having a capacity of approximately 51,400 bbl (2,160,000 gal). Based upon recent observations, the tank was believed to be non-leaking. This was not confirmed through visual internal inspection, however. Wherever possible, experiment personnel blanked off the piping connections to the tank rather than relying on valves to provide a leak-free seal. The only exception to this was on the primary suction line, which was sealed by double valving at the transfer pump manifold. Although they were believed to be non-leaking, the actual status of the valves was unknown.

For all tests, the tank contained heavy naphtha as the stored fluid. Multiple hydrometer measurements of a product sample taken during the tests yielded an API gravity of 48.15 at 60F/60F, with a corresponding coefficient of thermal expansion of 0.000530/°F. Subsequent laboratory analysis of another sample indicated a Reid vapor pressure of 1.68 psig. Data collection was initiated after sensor deployment had been completed, and continued uninterrupted for the two week period comprising the tests. As a result, a wide variety of weather conditions was experienced, ranging from hot, sunny days to cool windy periods during strong thunderstorms.

Results

The results of the experimental efforts are discussed in the following sections, and are analyzed for their implications for volumetric testing on aboveground storage tanks.

Volume Measurements

In order to be able to perform a volumetric test on a tank, it is essential to be able to relate product level changes to equivalent volume changes. Initial expectations were that, because of the large free surface area of the product (over 10,300 ft^2 for these tests) an ability to measure small product height changes would be required if small volume changes were to be identified. Typical detailed volume measurements, obtained at 1 sample/sec, tended to belie this preconception. Examples of this are shown in Figures 3 and 4, in which data were collected during two overnight quiescent periods.

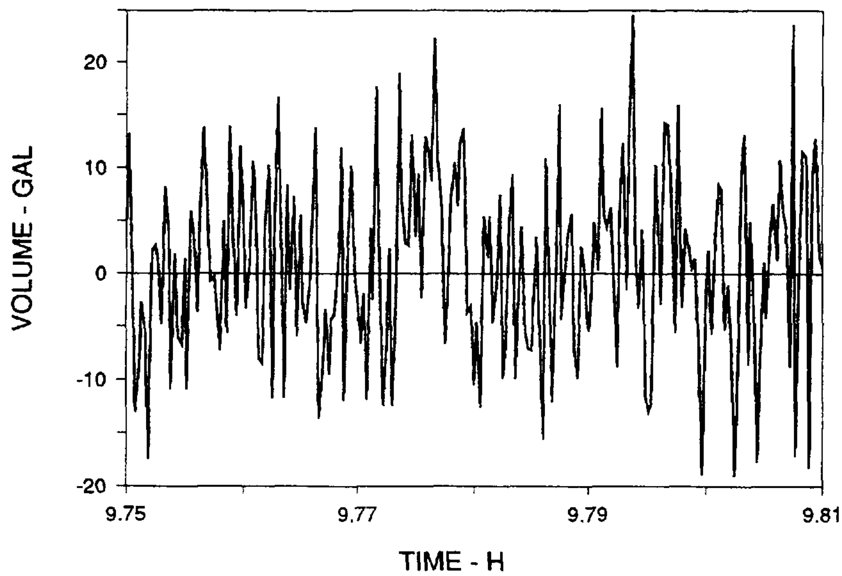

Figure 3. Surface fluctuations, expressed as volume, measured on the morning of 9 May.

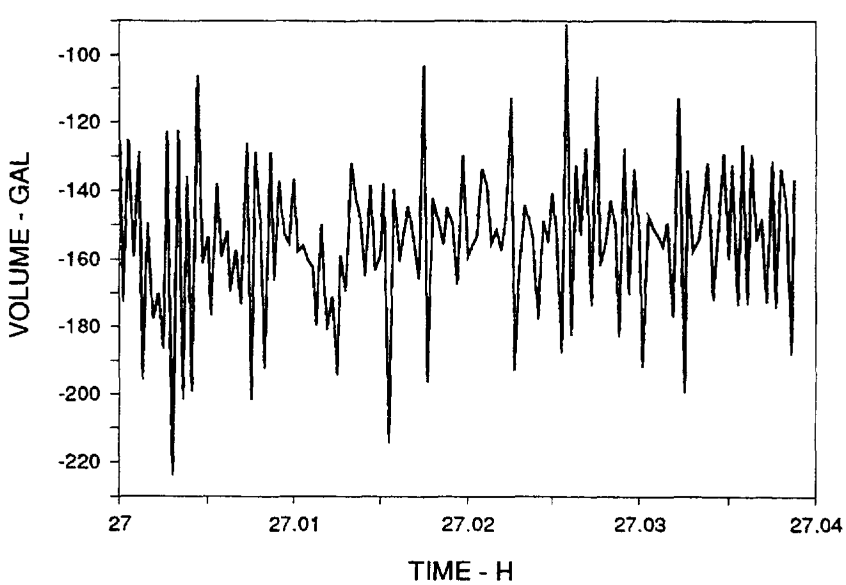

Figure 4. Surface fluctuations, expressed as volume, measured on the morning of 13 May.

As can be seen in these figures, second-to-second volume changes between 40 to 100 gal were measured, due to the presence of surface waves in the product. This corresponds to height changes of 0.006 to 0.015 in. for a tank of this diameter. The data in these figures were obtained by the internal height sensor located nearest to the tank wall. Because of the magnitude of these fluctuations, ambient activity can be expected to play a major role in establishing the preferred data collection approach, one which will minimize the degradation of test results.

Rather than an extremely precise level sensor for the collection of basic volume measurements, these data suggest that a less precise (and more readily available) level sensor can be employed, in conjunction with a more sophisticated data reduction procedure. Since the uncertainty in the slope of the temperature-compensated volume rate is dependent upon both the sensor precision and the length of the test, equivalent leak detection performance can be obtained by testing over a longer period of time while block-averaging high-frequency-level data to a lower frequency prior to attempting to establish the slope of the compensated volume curve. In effect, this reproduces the capabilities of a high-precision level sensor through suitable signal processing.

The periodic nature of the product surface fluctuations in the tank can be better appreciated by spectrally analyzing a typical 1-Hz volume time series. The results of this analysis is shown in Figure 5, corresponding to the raw data shown in Figure 3. The spectral peaks indicate the presence of predominant wave frequencies in this particular data segment, and suggest that, if aliasing is to be avoided, caution should be exercised in selecting a data sampling frequency. The strong peaks at frequencies of 9 and 20 cycles/min are equivalent to wave periods of 67 and 35, respectively. The spectrum also suggests that there is significant power in the 3 to 15 and 20 to 40 cycles/min frequency bands.

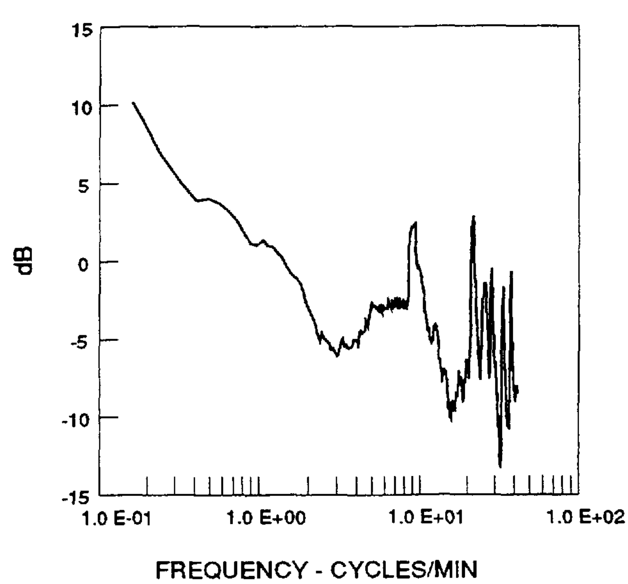

Figure 5. Spectral density of volume data presented in Figure 3.

While the detailed surface fluctuations provide an indication of the dynamic nature of the internal tank environment, the primary characteristic of interest for volumetric leak testing is the mean rate of change of product volume over a given period of time. Volume measurements over the duration of the two test periods, given in Figures 6 and 7, offer further evidence of the constantly changing tank environment. The most striking feature of the data from both test segments is the large diurnal volume fluctuation, with daily fluctuations of as much as 1600 gal occurring during the overnight period of 5/6 to 5/7. In addition to this cyclic volume fluctuation, a steady decrease in tank volume was also observed during the test periods. Because of the magnitude of these volume changes in comparison to the leak rates of interest, subsequent post-test analyses were focused on trying to identify and explain the processes responsible for them. Finally, the reason for the strong fluctuations in volume that were observed in Figure 6 observed during the last 8 h is unknown. The fluctuations occurred during a heavy rainfall and immediately before the level sensor failed.

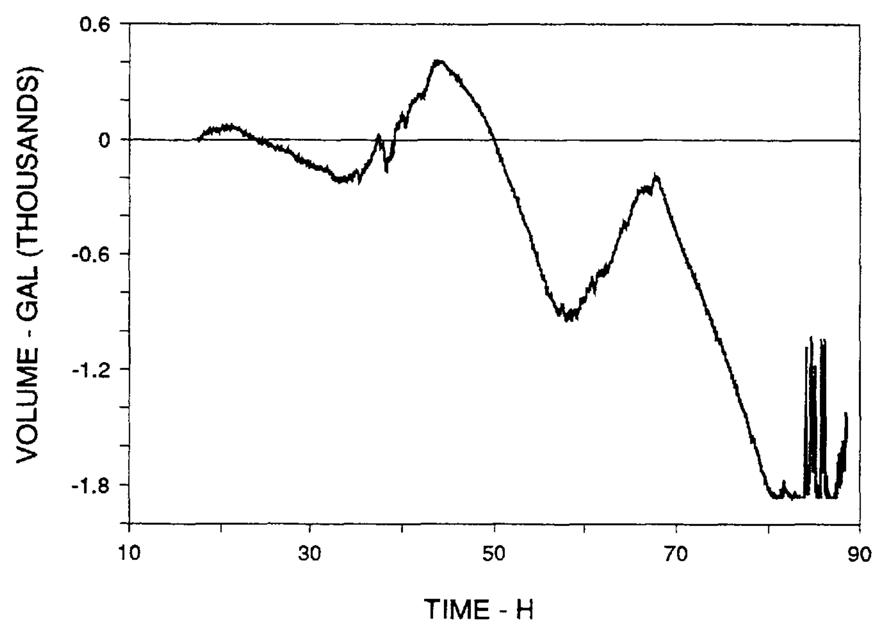

Figure 6. Gross volume fluctuations measured over a three-day period starting on 4 May. The nominal product level was 17 ft, 2 in.

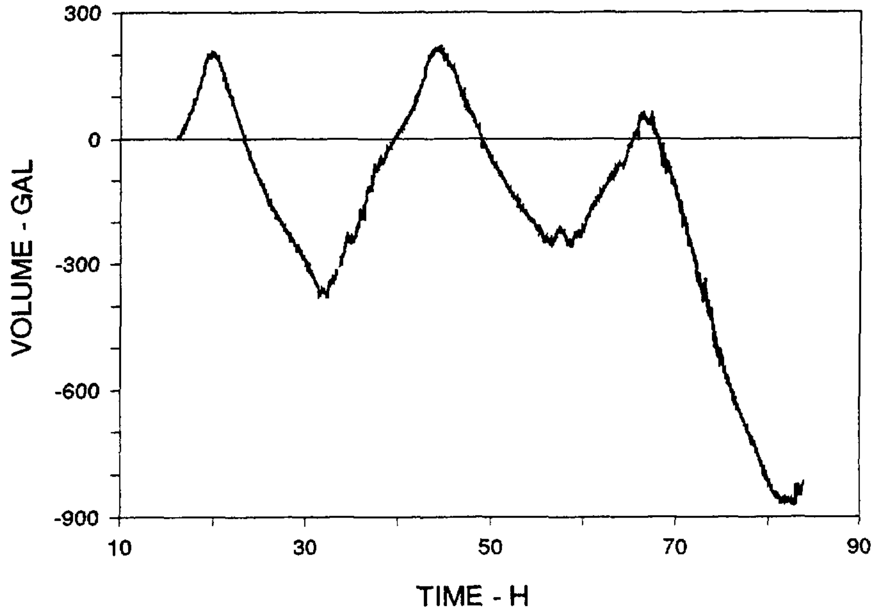

Figure 7. Gross volume fluctuations measured over a three-day period starting on 12 May. The nominal product level was 10 ft.

Product Thermal Measurements

The product temperature changes, along with virtually all other measured temperatures, were strongly impacted by the diurnal swings in air temperature. Air temperatures, measured at the top of the tank and shown in Figures 8 and 9 for the corresponding test periods, exhibited day/night fluctuations of as much as 20°C. While the product did not exhibit temperature changes of this magnitude, measured changes were sufficient to account for significant volume changes.

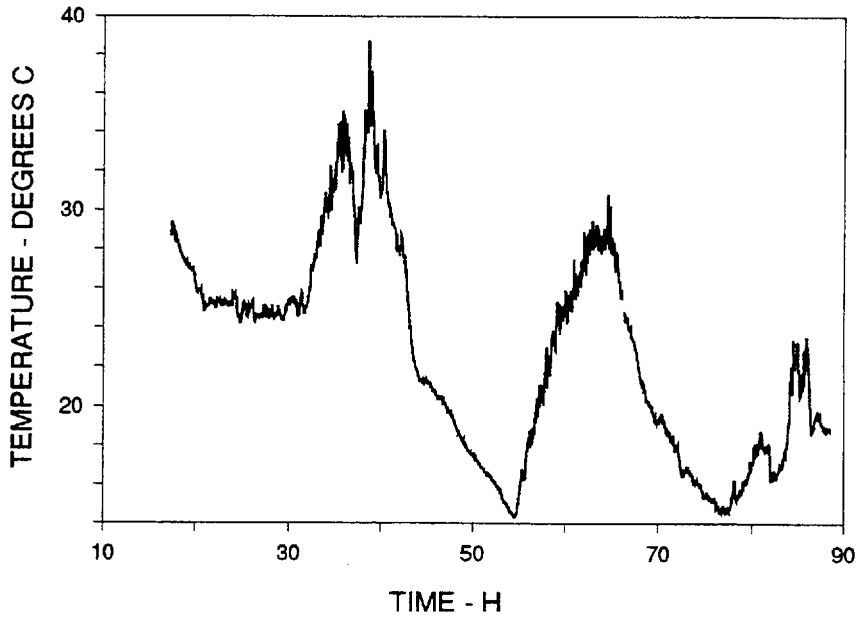

Figure 8. Air temperature changes during initial three-day test period.

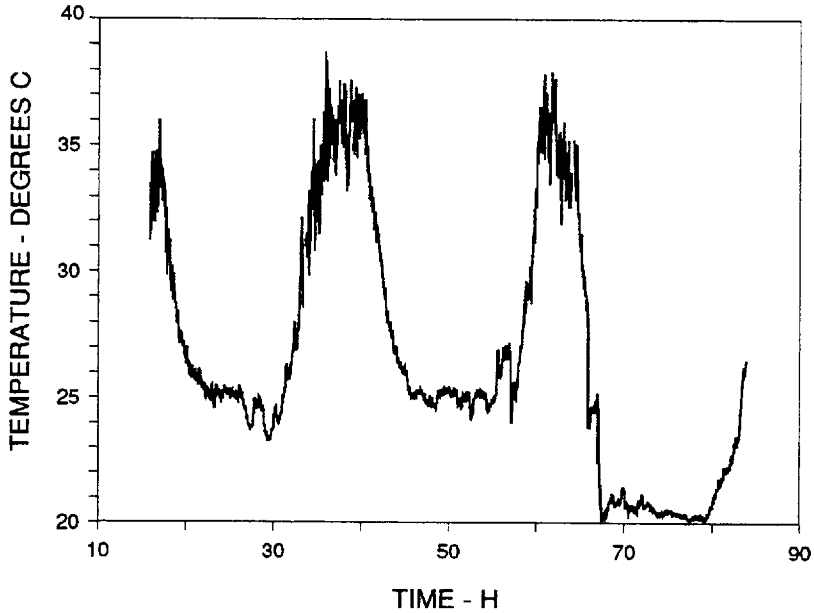

Figure 9. Air temperature changes during second three day test period.

The most obvious source of product volume changes is that arising from changes in the average temperature of the product. However, because the tank is exposed to strong ambient temperature changes, the possibility exists that horizontal temperature gradients will be present, a condition that could result in large errors in the thermal volume estimate. In order to investigate these effects, the temperatures measured by both vertical arrays were converted to volume and then differenced. The results of this procedure, which are shown in Figures 10 and 11, for the three-day test segments, suggest that there can be significant differences between the thermal volume calculated by the two arrays. This is most pronounced during the first three-day test period, where differences of as much as 300 gal were observed over a 4-h period. Data collected at the lower product level indicated a smaller degree of difference.

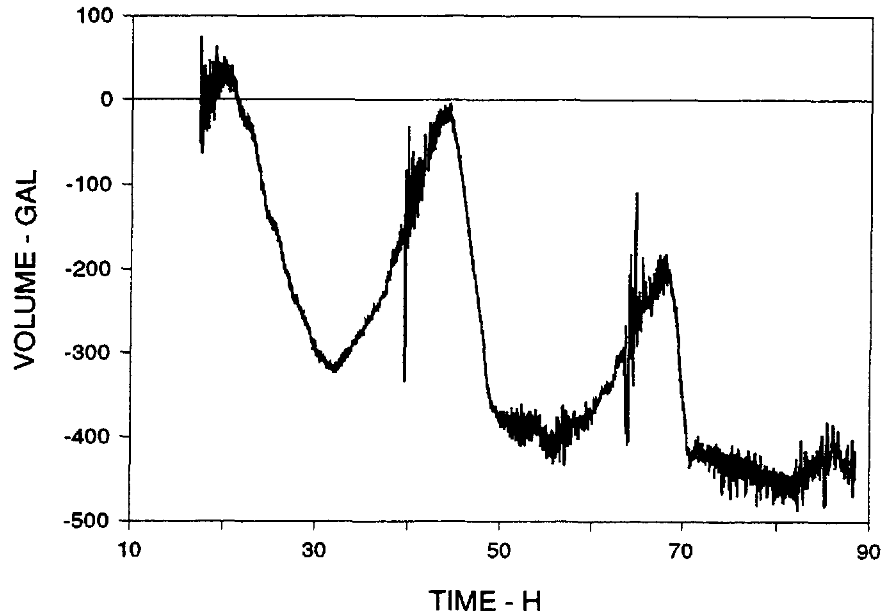

Figure 10. Difference in the product thermal volume estimate between the center array and the wall array for the first test segment.

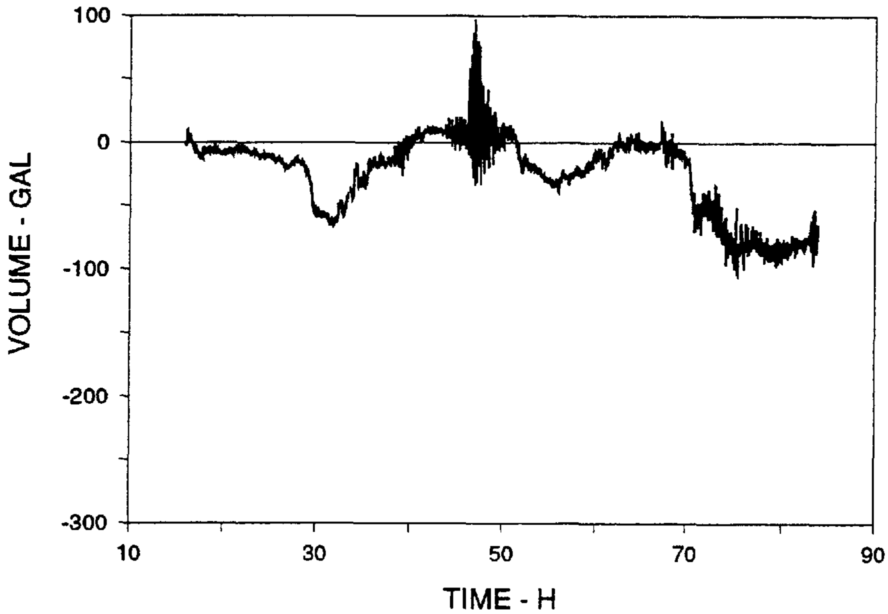

Figure 11. Difference in the product thermal volume estimate between the center array and the wall array for the second test segment.

These two figures suggest that, as larger quantities of product are stored in the tank, the difficulties of obtaining an accurate assessment of the product thermal volume changes from a single vertical array of sensors will increase. This is qualitatively consistent with the results of earlier parametric analyses which concluded that volumetric testing should be conducted at a level as low as is practical in order to reduce the impact of errors in the thermal volume estimate [2,3].

The behavior exhibited in the two figures above is consistent with what might be intuitively expected in the tank, and suggests that fairly strong transient thermal gradients are established in response to the diurnal heating cycle. More definitive conclusions could be made if an additional array had been placed at the southern side of the tank, near the tank wall. Since this side of the tank receives the strongest insolation, the presence of temperature differences between this location and the other two array locations would provide further confirmation of the degree of non-uniformity in the temperature field. Positioning an array at this location was anticipated during the experimental planning, but was precluded by the absence of an access port on the tank roof.

It should be noted that, because of the quantity of product stored in the tank, the temperature fluctuations required to generate significant volume changes are fairly small. For example, at a product level of 17 ft, 2 in., volume changes of approximately 1000 gal can be generated by a temperature change of only 0.79 °F. As a result, detailed knowledge of the temperature field is required if independent thermal compensation is to be successfully employed.

The effects of occasional horizontal temperature inhomogeneities in the tank having been observed, an examination of the vertical gradient was also undertaken. A portion of the data required to construct the vertical temperature profile was obtained from one of the incompletely deployed horizontal array arms. This arm, rather than being positioned horizontally, was situated such that its end rested on the tank bottom, thus forming an incline up to the pivot point on the vertical array. The evenly spaced sensors on this arm were then used to obtain "interpolated" temperature values from the tank floor up to an elevation of 24 inches. The results derived from this sensor configuration can be seen in Figure 12, which shows the 24-h period immediately following the lowering of the product level to 10 ft.

As can be seen in this figure, a considerable thermal gradient exists in the lower 2 ft of the tank, with temperature changes of about 2.5°C occurring over the bottom 24 in. Above this point, the temperature changes much more slowly, with changes of less than 1°C being observed

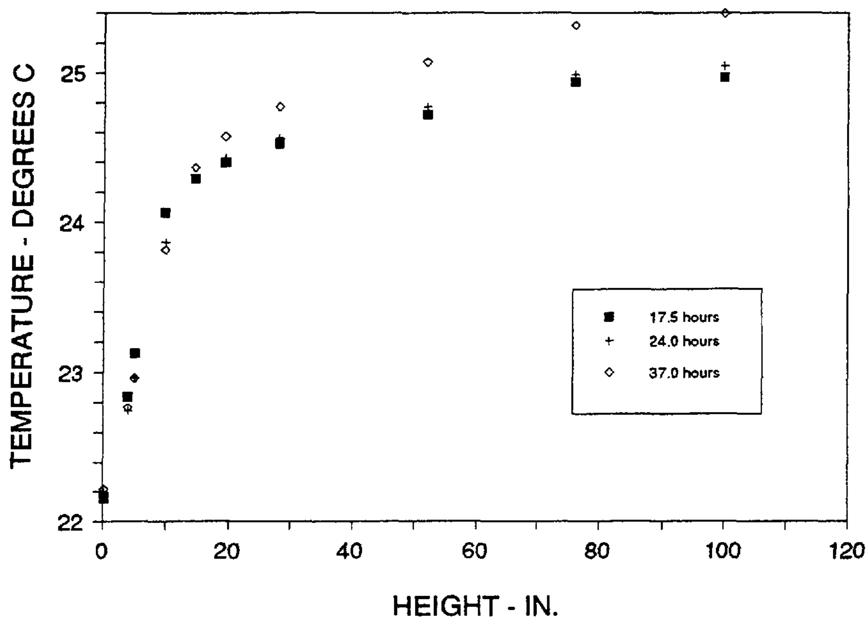

Figure 12. Product temperature profile for the 24-h period immediately after the product level has been changed from 17 ft to 10 ft.

over the remainder of the product height. The strong gradient at the bottom of the tank is not surprising, since the large thermal mass afforded by the tank foundation provides a cool, moist, semi-infinite heat sink to which energy can be readily transferred from the product.

In order to provide a common basis for comparison, subsequent analyses utilize the thermistor array at the tank center to estimate the thermal volume changes, as outlined earlier. Estimates of these volume fluctuations can be seen in Figures 13 and 14, which show, respectively, the high and low product levels. As is evident in these figures, the thermal volume changes can be quite large, and are closely coupled to the ambient air temperature. Corresponding gross volume changes are shown for comparison. The differences between these two pairs of plots provide an indication of additional volume changes which are not explained by the product thermal volume.

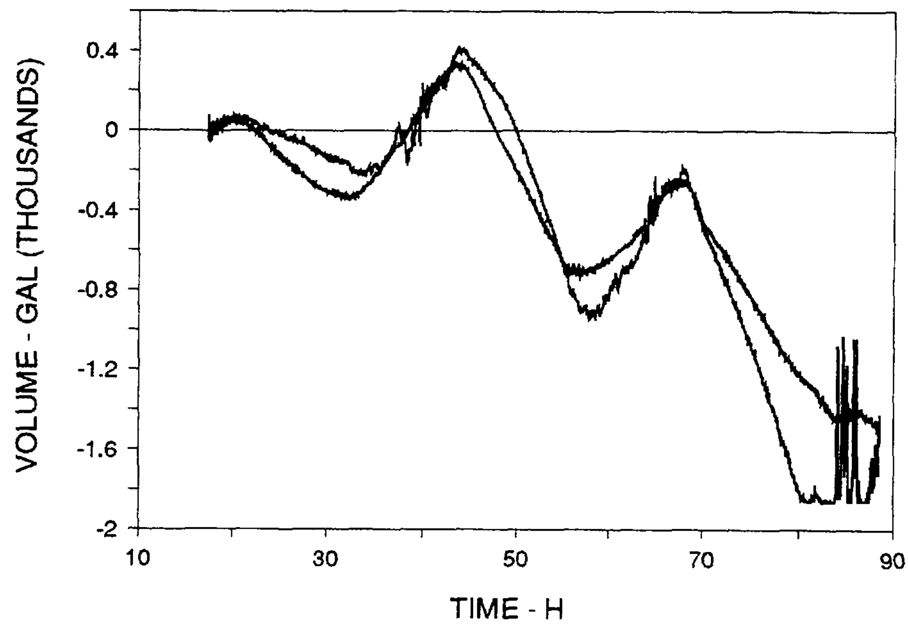

Figure 13. Product thermal volume changes during the first three day test period.

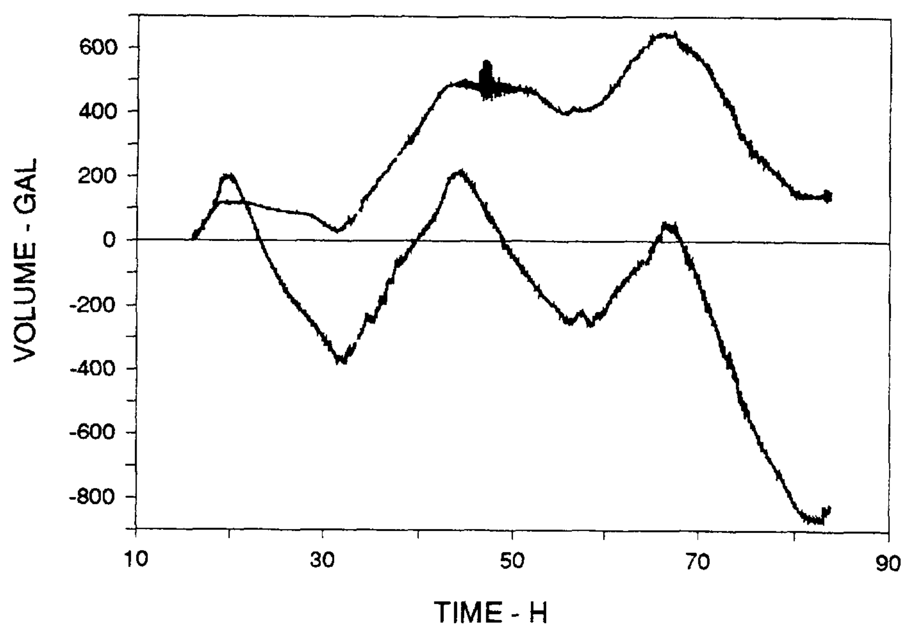

Figure 14. Product thermal volume changes during the second three-day test period.

These differences are plotted in Figures 15 and 16, and are representative of a test method which employs a mass measurement scheme (i.e., a hydrostatic pressure measurement) to monitor product level. The data suggest, after the product thermal volume has been subtracted, that a significant volume change occurs during both test periods. To some extent, these volume changes can be attributed to the thermal inhomogeneities in the tank, as noted previously. The residual volume change still exhibits a diurnal fluctuation, but with a reduced level. Thus, if a mass measurement technique were employed to test this particular tank, the thermal volume error could be minimized, but unless additional compensation were employed, significant errors would still be inherent in the test result regardless of which of the two product levels was used.

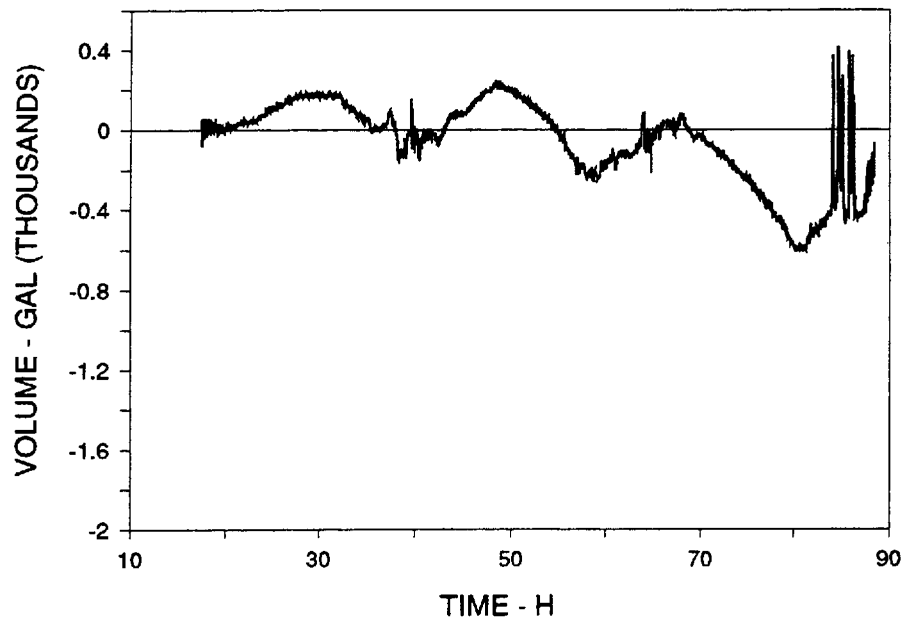

Figure 15. Residual volume changes, after product thermal volume has been removed from gross volume changes, during the first three-day test period.

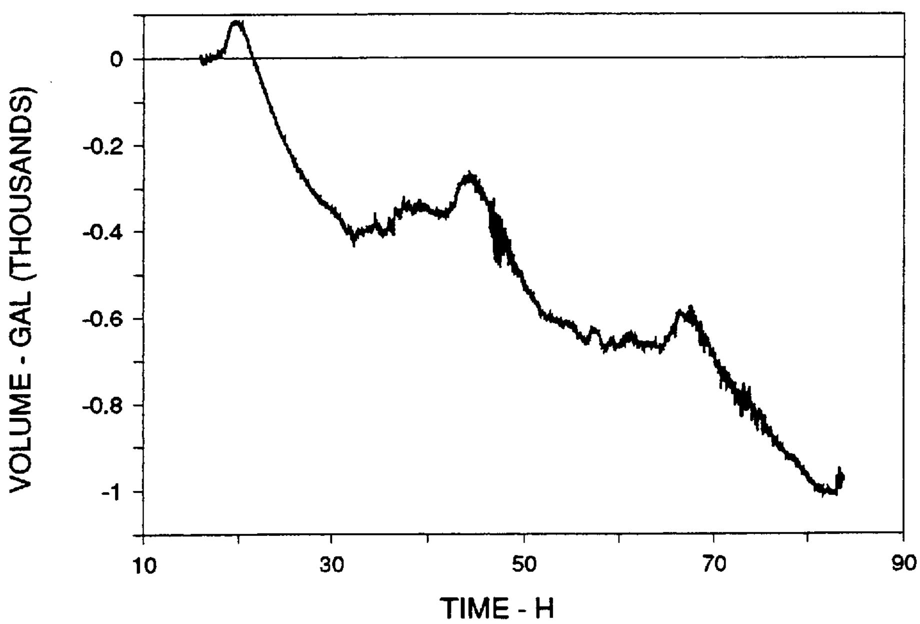

Figure 16. Residual volume changes, after product thermal volume has been removed from gross volume changes, during the second three-day test period.

Shell Thermal Measurements

Shell thermal expansion can account for a portion of the volume differences noted above. The increase in effective tank capacity caused by thermal expansion of the tank wall during the two test periods was estimated by utilizing all temperature sensors mounted on the tank wall. The increase in circumference was converted to volume assuming a right circular cylindrical shape for the tank and then integrating the temperature changes occurring at three different wall heights. The resulting volume time series for the two test periods are shown in Figures 17 and 18 respectively. Not surprisingly, the tank volume changes are closely correlated with ambient air temperature changes, with daily volume swings of as much as 300 gal being estimated during a single overnight period. It should be noted that the data shown in Figures 17 and 18 are based on a total of 18 temperature sensors mounted at three levels around the tank circumference. Additional analysis of the data from these sensors indicated, however, that a representative shell thermal volume could be developed as little as a single array of six circumferential sensors.

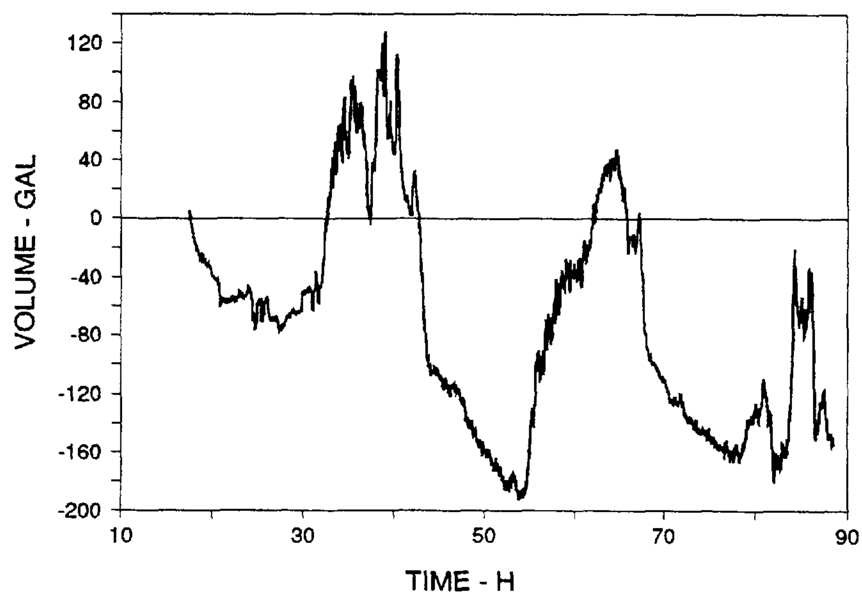

Figure 17. Tank capacity changes associated with thermal expansion of the tank wall during the first three-day test period. Tank capacity increases as the shell wall expands.

These volume changes, if improperly accounted for, can cause significant errors in volumetric test results, particularly if a short test duration is employed. Since since conventional thermal compensation techniques account only for expansion of the product during the test (either by direct temperature measurement or through a mass measurement technique) an additional step must be taken to reduce the impact of the shell volume changes. This step requires that the volume changes be estimated and then added to the temperature-compensated product volume changes, in order to arrive at a fully compensated volume time series. The net

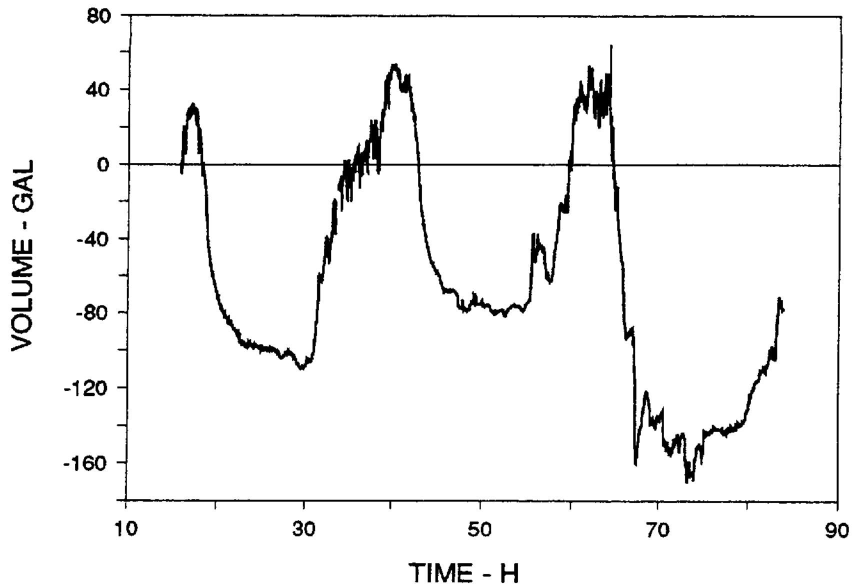

Figure 18. Tank capacity changes associated with thermal expansion of the tank wall during the second three-day test period. Tank capacity increases as the shell wall expands.

result of performing these operations is shown, for the two product levels, in Figures 19 and 20. Assuming that these are the only sources of volume fluctuation, and that the tank integrity (including connecting valves) is assured, the fully compensated volume time series in both cases should produce a flat, horizontal line. Deviations from this behavior are indicative of incomplete compensation, and indicate that additional analysis and interpretation are required.

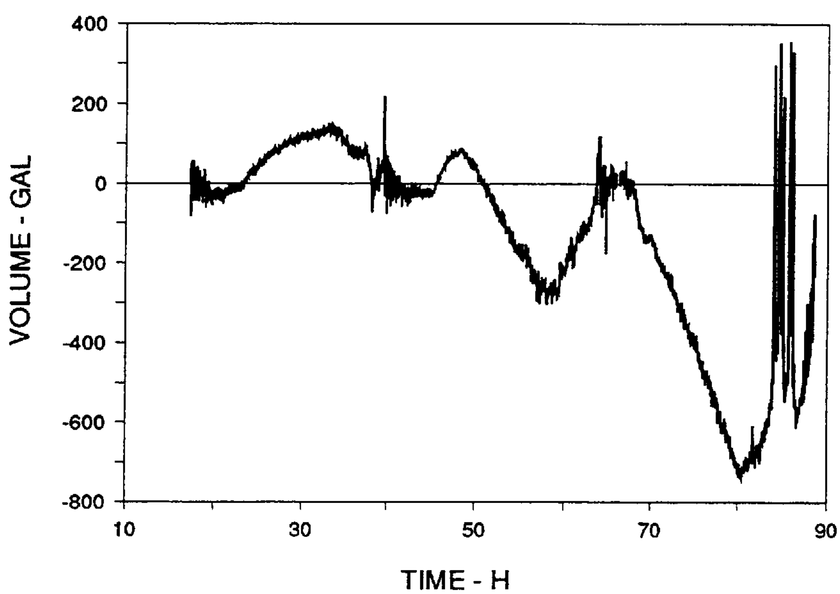

Figure 19. Temperature-compensated volume time series for the first test period. The effects of product thermal expansion and tank shell expansion have been removed from the gross product volume.

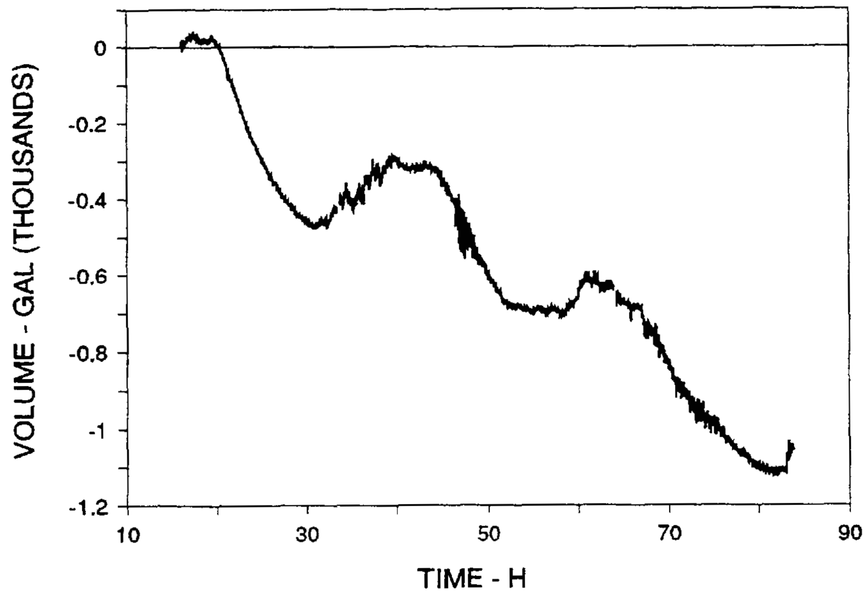

Figure 20. Temperature-compensated volume time series for the second test period. The effects of product thermal expansion and tank shell expansion have been removed from the gross product volume.

Structural Deformation

Another source of volume change that is of possible concern in a volumetric test is that due to structural deformation. Conceptually, this would occur in response to a change in hydrostatic pressure on the tank bottom (as occurs during product transfers), resulting in tank bottom deflection. Due to the interaction of the tank with the supporting foundation material, the response has been observed to exhibit an exponential behavior, with larger changes occurring immediately after the product level change, gradually tapering off as the shell attains a new equilibrium position. Experience with underground storage tanks has shown that this process can result in tank volume changes of several gallons over a period of 15 h after the level change. The comparatively large size of aboveground tanks suggests that, in this environment, volume changes could be larger than leak rates of interest. Since this behavior could be interpreted as a product gain or loss if a test were conducted immediately after a product transfer, the magnitude and temporal behavior of the phenomenon must be identified if a viable compensation approach is to be developed.

The presence of structural deformation was experimentally investigated by rapidly dropping the product level from approximately 17 ft to 10 ft, and then analyzing the temperature-compensated volume rate for an exponential characteristic over the next 24 h. The magnitude of the level change was dictated by operational constraints at the test site. The resultant compensated volume time series was then inspected for indications of an exponential response. The results are shown in Figure 21. Because of the large residual volume after thermal compensation, it is difficult to detect any curvature which could be described exponentially. This suggests that, for the specific set of conditions under which the test was conducted, volume changes attributable to structural deformation are substantially smaller than those caused by other phenomena. Currently available data are insufficient to determine whether the phenomenon did not occur in the experiment described here, or whether the tank bottom was so elastic that the response was completed at the end of the product transfer cycle.

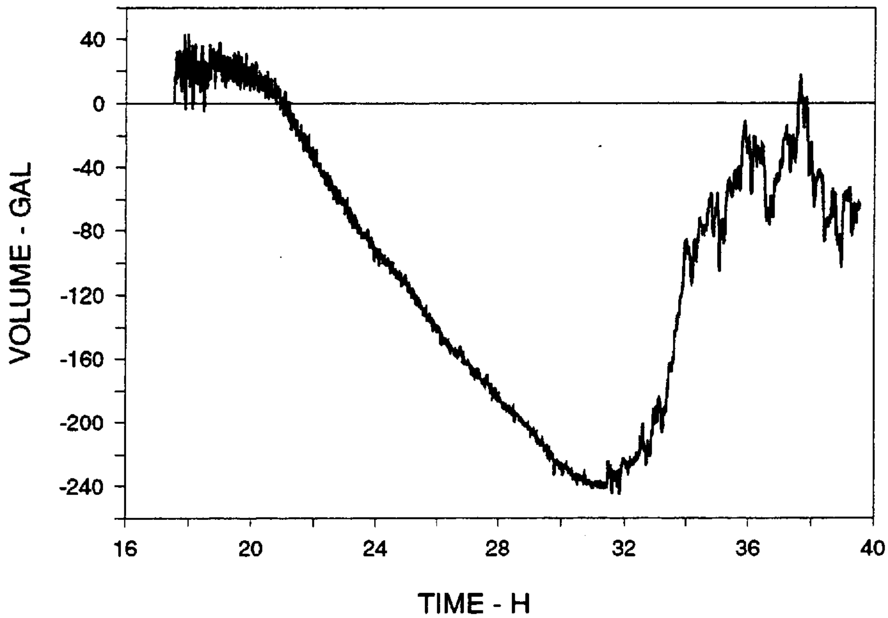

Figure 21. Temperature compensated volume time series immediately after a rapid change in product level from 17 ft to 10 ft. An exponential volume change typical of a deformation response does not appear to be present.

Evaporation/Condensation

In viewing the temperature-compensated volume time series at both product levels (Figures 19 and 20), it is apparent that additional physical processes are active in creating the volume losses that are occurring over both three-day test periods. Possible sources of volume loss include tank leakage, valve leakage, and evaporation of product from the free surface in the tank.

Since there was no internal provision to minimize surface exposure to ambient changes in the tank, evaporative losses were considered a potential explanation for at least a portion of the daily net volume decrease. The maximum loss which could be attributed to this process would occur if the vapor space were completely saturated with product during a diurnal breathing cycle. Under this worst-case scenario, the product loss could be estimated from a knowledge of the amount of vapor/air mixture expelled during the breathing process.

The amount of gas exchanged with the environment during breathing cycles can be estimated by treating the mixture as a perfect gas, and then incorporating the effects of temperature and barometric changes. For both of the three-day test segments, the cyclic change in the vapor-space volume was found to be the dominated by temperature change. This can be seen in Figures 22 and 23, in which the average vapor temperature is plotted, along with the temperature of the product near the liquid surface. It is interesting to note that, for the specific test periods, the vapor space temperature greatly exceeds the ambient air temperature during the daytime hours, with maximum values approaching 50°C. In addition, vapor temperatures were found to drop below the liquid temperature during nocturnal periods.

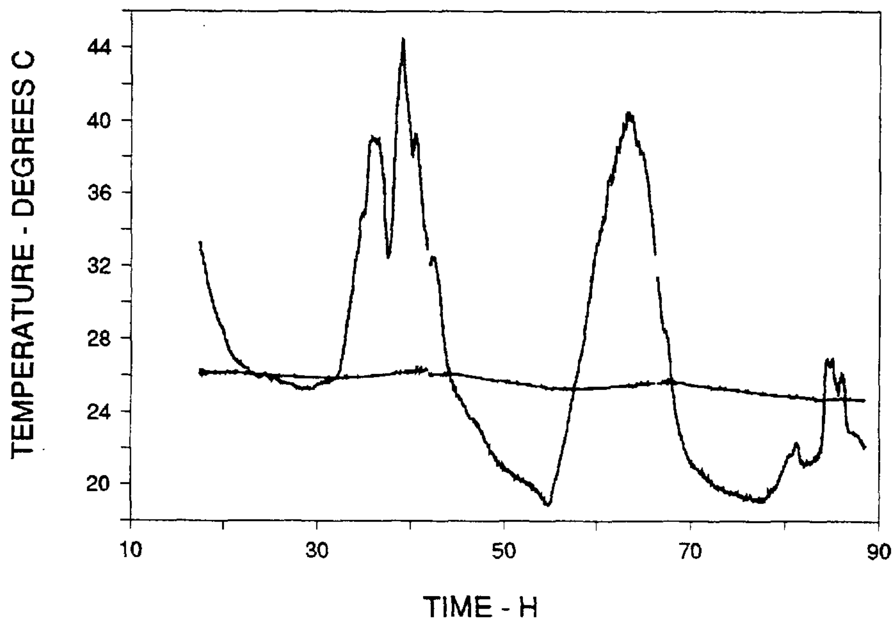

Figure 22. Average freeboard vapor temperature during the first test period. The product temperature near the liquid surface is shown for comparison.

Conversion of these thermal changes, after accounting for barometric fluctuations, results in the volume time series shown in Figures 24 and 25. The most striking feature of these plots is the magnitude of the volume changes which occur during a 24-h period. Since these magnitudes are dependent upon the initial volume, is not unexpected that the exchanges which occur at the 10-ft product level are larger than those observed at the 17-ft level. Based upon these calculations, air/vapor expulsions of as much as 100,000 gal were observed during daylight hours, followed by a corresponding induction of dry ambient air during nighttime periods.

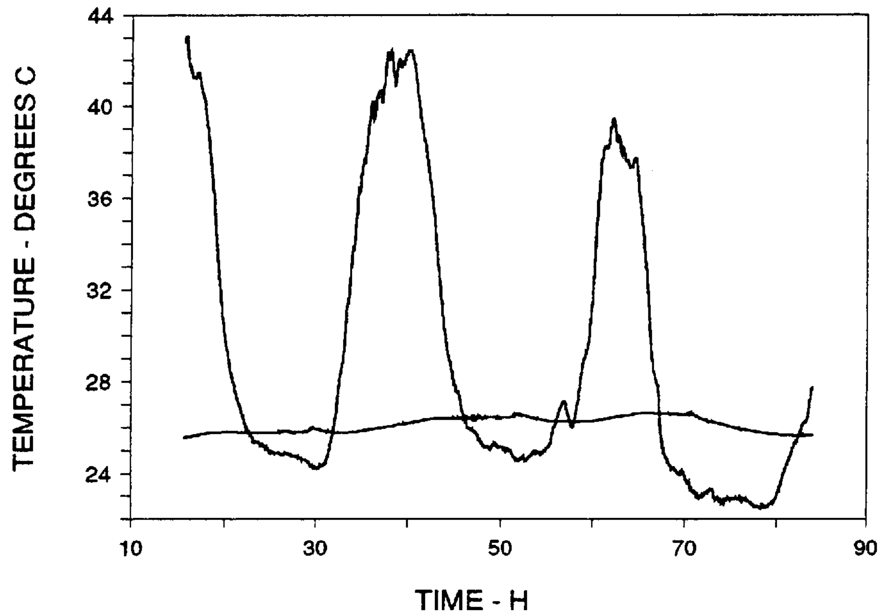

Figure 23. Average freeboard vapor temperature during the second test period. The product temperature near the liquid surface is shown for comparison.

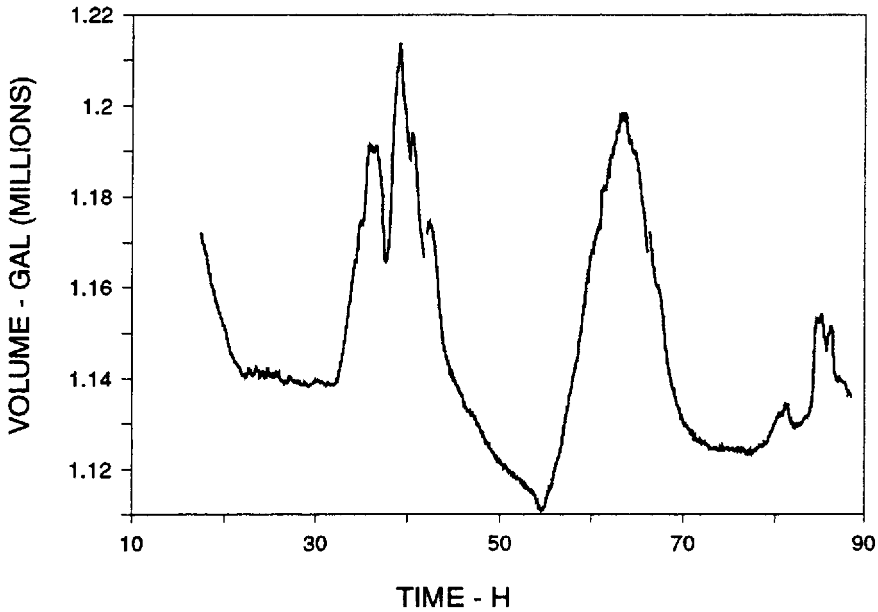

Figure 24. Vapor-space volume change during the first test period. The effects of barometric changes are included in the volume calculation.

This cyclic exchange of air and air/vapor mixtures during daily temperature swings was expected to explain a portion of the temperature-compensated volume deficit observed in Figures 19 and 20. The mechanism for this product loss was expected to occur in two parts. First, a saturated air/vapor mixture would be expelled through the tank vent during the daylight heating of the tank. This would then be followed by a nighttime period in which cool, dry air

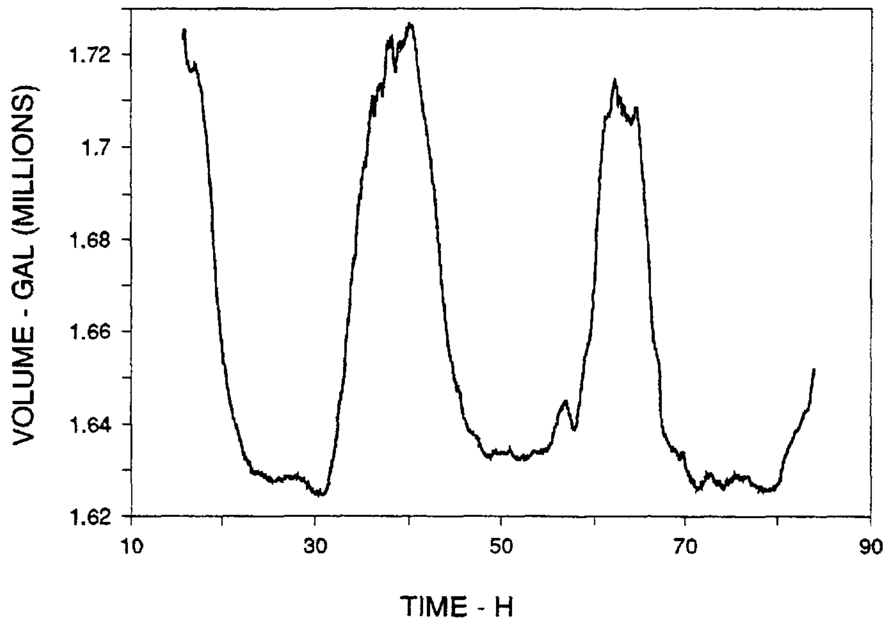

Figure 25. Vapor-space volume change during the second test period. The effects of barometric changes are included in the volume calculation.

was drawn into the vapor space. The temperature difference between the cool vapor space and the warmer product, along with the reduced vapor concentration, provided the stimulus for liquid evaporation into the freeboard.

A first approximation of the amount of product vapor which could be lost (assuming saturated conditions in the vapor space) was made for the largest observed vapor space expansion. In this process, the temperature-induced expansion (i.e., tank breathing) forces a mixture of air and product out of the tank vents after the vapor became saturated. However, based upon the true vapor pressure of the product (approximately 1 psia) and the estimated molecular weight (80 lb/lbmole), the maximum amount of product which could be lost through this process was estimated to be only 20 gal for each daily cycle. Thus, while this type of product loss can accumulate over time to a significant quantity, it is insufficient to explain the magnitude of the apparent losses that were observed during the three-day test periods.

The product loss estimates given above assume that the freeboard vapor space in the tank is isolated from the environment during the saturation process. Product losses then occur during the expulsion of saturated vapor as the temperature increases. In actuality, the presence of a constant breeze during the course of the tests may tend to aggravate the amount of vapor lost. Under these conditions, vapor-laden air can be siphoned from the tank during overnight periods as a result of wind passing over the tank vents. As a result, the partial pressure of the vapor is reduced, thus allowing additional product to evaporate. The product losses caused by this phenomenon are difficult to estimate, and may be controlled by the maximum evaporation rate that can be sustained at the product surface.

Volumetric Leak Detection

Preliminary inspection of the compensated volume time series suggests that either a leak is present in the tank (either a weeping valve or a leak in the tank floor) or additional volume change that are due to other sources and that have yet to be compensated for are occurring in the tank. Based upon the volume mechanisms which have already been considered, the only viable possibilities remaining are that there are some strong horizontal thermal gradients that exist in the tank which are not being accounted for.

The notion that a leak exists in the tank or associated piping provides a convenient explanation for the deficit in the temperature-compensated volume rates in Figures 19 and 20. Unfortunately, the test data obtained from two different product levels do not confirm that this is the source of the unexplained product loss. Assuming that the leak rate is proportional to the applied pressure at the leak location, the compensated volume rate at the 17-ft product level should be greater than that at the 10-ft level. Fitting a least-squares line to the three-day volume series in Figures 19 and 20 yields average rates of -8.8 gal/h and -14.9 gal/h, respectively, with corresponding slope uncertainties of 0.11 gal/h and 0.08 gal/h. This behavior is counter-intuitive, (i.e., higher product levels producing smaller leak rates) and suggests that another mechanism is involved.

The presence of a diurnal fluctuation in the overall negative trend of the compensated volume time series tends to support the suspicion that additional processes are involved. The fact that this fluctuation had a period aligned with the basic diurnal cycle suggests that it is associated with some form of thermal activity in the tank. One possible explanation for the bias in the compensated volume rate is that unmeasured thermal gradients exist in the southern half of the tank, such that the mean rate of temperature change in the tank is not adequately represented by the changes measured by either of the deployed arrays. Utilizing a mass measurement technique to obtain the basic product level changes would eliminate the errors associated with thermal gradients in the tank, and could provide a more focused assessment as to the nature of the compensation error.

Conclusions

Measurements in a 50,000 bbl-tank containing heavy naphtha indicate that the conduct of a volumetric leak detection test will be challenged by an extremely dynamic tank environment which is strongly driven by ambient temperature changes. Large fluctuations in product level associated with the presence of surface waves in the tank obviate the need for a level sensor which is capable of seeing minute height changes. Because of the magnitude of these waves, which occasionally produce peak-to-peak changes of 100 gal, more commonly available sensors having a coarser precision may be employed for the primary product level measurement, and the data may be subsequently processed to enhance the identification of small volume changes.

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 to enable the volume changes associated with small leak rates to be detected. Currently available data indicate that, with a sampling rate of 1/min, a test duration between 48 to 72 h should be sufficient to average through any uncompensated diurnal fluctuations in the temperature-compensated volume rate, and should permit leak rates as small as 1 gal/h to be detected with a probability of detection of 95%. This performance 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.

Test results obtained at two different product levels over 72-h periods exhibited a pronounced negative bias, indicating a loss of product from the tank. Extensive analysis of the available data was inconclusive in determining the source of this bias. Possible sources could include undetected thermal gradients in the stored product, or minor leakage from the tank or its associated piping and valves. Additional testing, specifically focused on clarifying these areas, is required before more definitive statements can be made concerning the viability of volumetric testing on this class of tank.

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