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Volumetric Leak Detection in Large Underground Storage Tanks

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VOLUMETRIC LEAK DETECTION IN LARGE UNDERGROUND STORAGE TANKS

VOLUME I

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FOREWORD

Today's rapidly developing and changing technologies and industrial products frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U. S. Environmental Protection Agency is charged by Congress with protecting the nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This document presents the results of experiments conducted on 190,000-L (50,000-gal) underground storage tanks (USTs) to determine how to test large tanks for leaks with volumetric leak detection systems. The work reported in this document has applications to the UST release detection technical standards in CFR 280 Subpart D.

E. Timothy Oppelt, Director
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ABSTRACT

The performance standards established by the EPA underground storage tank (UST) regulation (40 CFR Parts 280 and 281) for volumetric leak detection systems, which include tank tightness testing systems and automatic tank gauging systems (ATGS), were based upon experimental research in tanks having capacities of 30,000 L (8,000 gal) and 38,000 L (10,000 gal). However, the regulation requires the testing of tanks as large as 190,000 L (50,000 gal). The performance of volumetric systems in detecting leaks from large tanks is not well known, and there exist very little data from which an assessment can be made. As a consequence, there is not enough information to help owners and operators select systems that will be in compliance with the regulations when it comes to testing large tanks, i.e., those between 57,000 and 190,000 L (15,000 and 50,000 gal).

This report addresses three important questions about testing the larger underground storage tanks for leaks. First, can the EPA regulatory standards be met when volumetric methods are used to test tanks up to 190,000 L (50,000 gal) in capacity? Second, what is the precision required of the temperature and level sensors and what is the minimum duration of the data collection period in order for a volumetric system to accurately test larger tanks, particularly those that are partially filled? Third, what are the important features of a volumetric system that meets or exceeds the regulatory performance standards?

These questions were addressed in a set of experiments conducted on two partially filled 190,000-L (50,000-gal) underground storage tanks at Griffiss Air Force Base in upstate New York during late August 1990. The experiments suggested that the time required for the temperature inhomogeneities within the product and for the structural deformation of the tank system to become negligible after any large addition or removal of product and after topping is approximately the same as observed in 30,000-L (8,000-gal tanks); in tests on the 190,000-L (50,000-gal) tanks, however, the temperature inhomogeneities were greater than in tests on 30,000-L (8,000-gal) tanks. Thus, a system's performance in large tanks depends primarily on the accuracy of the temperature compensation, which is inversely proportional to the volume of the product in the tank. Volumetric tank tightness tests use a preset threshold value that, if exceeded, is the basis for declaring a leak; they employ a waiting period after any addition or removal of product so that both temperature inhomogeneities and structural deformation will have a chance to subside. The thermistors used in the Griffiss experiments were calibrated to better than 0.001°C and spaced at 30-cm (12-in.) intervals. The data from these experiments

suggest that, at the thresholds typical of those used in volumetric tank tightness tests, small leaks (up to 0.38 L/h (0.1 gal/h)) would be difficult to detect even if the waiting period were sufficient for temperature inhomogeneities and structural deformation to subside. Vertical gradients in the rate of change of temperature near the bottom and top of the tank and horizontal gradients between the centerline of the tank and the wall of the tank were still so large after the waiting period that the thermistor array used in the Griffiss experiments did not provide sufficient thermal compensation. The data also suggest, however, that if thresholds typical of monthly ATGS tests were used, reliable detection of leaks as small as 0.76 L/h (0.2 gal/h) would be possible.

As a result of the experiments on 190,000-L (50,000-gal) tanks, the important features of a volumetric leak detection system that would have the performance necessary to meet EPA's regulatory standards for volumetric tank tightness tests have been identified. These features include the instrumentation, test protocol, and analysis. The experiments suggest that volumetric systems now capable of testing 30,000- to 38,000-L (8,000- to 10,000-gal) tanks can be used to meet the regulatory standard for testing 190,000-L (50,000-gal) tanks if (1) the duration of the test is increased from 1 or 2 h to 4 h or more to ensure that the vertical gradients are accurately measured and to reduce the ambient and instrumentation noise, (2) the number of temperature sensors is increased from 5 to 10 or more so that the accuracy of estimating the average thermally induced volume change in the layer of product surrounding each sensor increases, (3) the waiting period after any addition or removal of product is increased from 6 h to 24 h or longer so that the horizontal and vertical temperature gradients dissipate, (4) the average rate of change of temperature in any one layer or in the tank as a whole is small enough to allow accurate temperature compensation, and (5) an accurate experimental estimate of the constants necessary for converting level and temperature changes to volume is made. The experiments further suggest that a multiple-test strategy is required to meet the tank tightness regulatory standard.

The duration of a test depends on the precision of the instrumentation and the amount of ambient noise present in the measured volume changes. The magnitude and frequency of the ambient noise observed in the Griffiss experiments suggest that a test should be at least 4 h long. Given a certain precision of the level and temperature instrumentation, the minimum duration can be calculated. Calculations based on the Griffiss experiments suggest that, when the level sensors have a precision of 0.0005 cm (0.00025 in.) and the temperature sensors have a precision of 0.001°C (0.002°F), the test must be at least 2 h long. When the instrumentation is less precise, the test must be commensurately longer.

The number of temperature sensors should be sufficient to cover the vertical extent of the tank, with denser coverage near the bottom and top of the product, where the rate of change of temperature and the gradients in the rate of change of temperature are greatest. In the Griffiss experiments it was observed that, during the first 9 h after product addition or removal, the 10 thermistors equally spaced at 30-cm (12-in.) intervals did not provide a sufficiently accurate estimate of the rate of change of temperature near the bottom of the tank, where the largest changes in temperature occurred, or near the surface of the product. (Even in the mid-region of the tank, 30-cm (12-in.) spacing was not sufficient in cases when temperature reversals occurred; this, however, can be monitored). Thus, it is recommended that the thermistors at the top and bottom of the tank be spaced at intervals of 15 cm (6 in.) or less. Reducing the space between sensors reduces the volume of product in the "layer" around each sensor, thus minimizing any potential measurement errors.

In the Griffiss experiments, a waiting period of 4 to 6 h after the addition or removal of product was deemed sufficient for the dissipation of horizontal gradients in the rate of change of temperature that were observed along the long axis of the tank. Those observed between the centerline of the tank and the wall, however, were large enough during the first 18 h to prevent the reliable detection of leaks up to 0.38 L/h (0.1 gal/h). It is therefore recommended that, with large tanks, a waiting period of 24 h be used. A longer waiting period may be required if the rate of change of temperature is very great. To determine whether the waiting period is sufficient, it is recommended that a measurement of the temperature changes in the area between the centerline and the wall be made; if this is not possible, repeated tests should be made until there is no observable change over time in the measured compensated volume.

Ten potential sources of error in temperature compensation are discussed, any one of which may be large enough to produce a testing mistake. Since all errors in temperature compensation are proportional to the average rate of change of temperature during a test, the most direct approach for improving the accuracy of temperature compensation is to wait until this rate has decreased substantially before beginning a test. This requires real-time measurements of temperature.

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SECTION 1
INTRODUCTION

The United States Environmental Protection Agency (EPA) regulation for underground storage tanks (USTs), published in the *Federal Register* (40 CFR Parts 280 and 281) on 23 September 1988, specifies the technical standards and a variety of release detection options for minimizing the environmental impact of tank leakage [1]. With several exceptions, the tanks covered by the regulation range in size from small (a few hundred gallons in capacity) to very large, with no clearly defined upper limit. (The regulation covers only *shop-assembled* tanks; requirements for large *field-erected* tanks have not yet been established). The number of large tanks (defined here as those between 57,000 and 190,000 L (15,000 and 50,000 gal) in capacity) represents a small but important portion of the total tank population. This number is increasing because of the preference of tank owners/operators for a smaller number of larger tanks to meet storage needs. Many large-volume storage facilities have tanks that are nominally 190,000 L (50,000 gal) in capacity. Unfortunately, there is not enough information to help owners and operators of large tanks select a testing system that will be in compliance with the regulations. Furthermore, it is not known whether volumetric leak detection systems can achieve the same level of performance in large tanks as they do in smaller ones.

1.1 Objectives

The program of experiments conducted at Griffiss Air Force Base was devised to expand the understanding of large underground storage tank behavior as it impacts the performance of volumetric leak detection testing. This report addresses three important questions about testing the larger underground storage tanks for leaks. First, can the EPA regulatory standards be met when volumetric methods are used to test tanks up to 190,000 L (50,000 gal) in capacity? Second, what is the precision required of the temperature and level sensors and what is the minimum duration of the data collection period in order for a volumetric system to accurately test larger tanks, particularly those that are partially filled? Third, what are the important features of a volumetric system that meets or exceeds the regulatory performance standards?

1.2 Background

Leak detection systems used as volumetric tank tightness tests on tanks currently covered by the EPA regulation (i.e., those up to 190,000 L (50,000 gal) in capacity) must be able to detect leaks as small as 0.38 L/h (0.10 gal/h) with a probability of detection (P_D) of at least 0.95 and a probability of false alarm (P_{FA}) of 0.05. Leak detection systems used as monthly tests, such as automatic tank gauging systems, must be able to detect leaks as small as 0.76 L/h (0.2 gal/h) with a P_D of 0.95 and a P_{FA} of 0.05. Most state regulations, which require that a tank tightness test be done annually, are more stringent than the federal regulation. These standards are based on the results of an extensive experimental program conducted by the American Petroleum Institute (API) on 38,000-L (10,000-gal) tanks at retail stations [2] and by the EPA on 30,000-L (8,000-gal) tanks at EPA's Underground Storage Tank Test Apparatus in Edison, New Jersey [3-8].

The EPA described the important features of a generic volumetric tank tightness system that would yield the required level of performance in tests conducted in overfilled and partially filled tanks [3,7,8]. The important features are the ones that compensate for or minimize errors in the measurement of volume changes not due to a leak; these errors, which are due to *ambient noise*, occur in both leaking and nonleaking tanks. Experiments on a 30,000-L (8,000-gal) tank showed that an array of five or more equally spaced temperature sensors, each weighted by the volume of product in the layer surrounding it, was sufficient to compensate for thermally induced volume changes. This temperature-sensing array is suitable providing that adequate waiting periods were observed after any addition of product, whether this addition represented a delivery to the tank or whether it constituted topping of the tank (as is required when testing an overfilled tank). The addition of product to the tank produced inhomogeneities in the temperature field that were large enough to prevent an accurate estimate of the mean rate of change of temperature. As a means of minimizing the effect of these thermal inhomogeneities, waiting periods of at least 3 h after topping and 4 to 6 h after a delivery were recommended. Any addition of product also changes the level of the liquid in the tank and, therefore, the pressure that is exerted on the tank walls. This change in pressure causes the tank to deform; observing a waiting period before the test allows deformation to subside, thus eliminating any errors that it might have produced. The waiting period may have to be as long as 12 to 18 h, depending on the properties of the tank and of the backfill and native soil surrounding it. In tests conducted on *overfilled tanks*, there is a third source of potential error: the temperature- and/or pressure-induced expansion or contraction of any vapor trapped in the tank. If the amount of trapped vapor is significant, or if the range of temperature and/or pressure changes within the trapped vapor is great, the error can have a detrimental impact on the test. Unfortunately, it is extremely difficult to identify the presence of small volumes of trapped vapor, and there is no satisfactory way to compensate for volume changes due to this phenomenon. A fourth source of potential error is unique to tests conducted in *partially filled tanks*: this is the error produced by evaporation or condensation at the liquid/vapor interface and the vapor/tank-wall interface. It is believed that the effects of evaporation and condensation are usually small, but available data show that under some air-temperature and atmospheric-pressure conditions they can be large enough to produce false alarms and missed detections. At the present time there is no systematic way to determine when these conditions will adversely affect the test; however, any adverse effects can be minimized through the use of a multiple-test strategy. The other sources of error, which are produced by surface and internal waves, can affect the test results in both overfilled and underfilled tanks. These can be minimized by proper sampling of the level and temperature data.

For best performance, the instrumentation noise, or *system noise*, should be less than the ambient noise. In small tanks, whether partially filled or overfilled, this can be achieved. However, as the volume or the surface area of the product in the tank increases, this becomes proportionately more difficult.

Because the EPA regulations (and the recommended "important features" of a volumetric tank tightness test that are described above) are based on experiments conducted on 30,000-L (8,000-gal) tanks, it is unclear whether a volumetric test that meets the EPA standard when used to test smaller tanks can achieve the same level of performance when used to test larger tanks. At the present time, there are no experimental data that can be used to make such an assessment, particularly for tanks as large as 190,000 L (50,000 gal). Additional information about the magnitude of the noise in large tanks would be required before such an assessment could be made. Based upon previous experimental and analytical work, we expected that four things would be necessary in order for a volumetric leak detection system to maintain the required level of performance when used to test large tanks: (1) more temperature sensors, (2) longer waiting periods after topping or after a delivery of product to the tank, (3) a longer test duration, and (4) an increase in the precision requirements of the temperature and level measurement systems

SECTION 2
CONCLUSIONS

EPA regulations require that all volumetric leak detection systems meet the same performance standards regardless of the size of the tank on which such systems are used. The EPA standards for volumetric tank tightness tests and for automatic tank gauging systems were developed from research on 30,000- and 38,000-L (8,000- and 10,000-gal) tanks. Performance evaluations of most of the volumetric systems in use today are based on their application to tanks 30,000 to 38,000 L (8,000 to 10,000 gal) in capacity, the size of tank for which they were designed. The EPA regulation, however, covers tanks as large as 190,000 L (50,000 gal). Since the performance of volumetric leak detection systems in large tanks is not known, and the design features necessary for such systems to meet performance standards when used in large tanks have not been investigated, it is evident that further research was necessary. Before the study reported here, there was no published information available on the errors associated with testing tanks up to 190,000 L (50,000 gal) in size.

In the present study, limited-scope field experiments were conducted during late August 1990 on two partially filled 190,000-L (50,000-gal) underground storage tanks located at Griffiss Air Force Base in upstate New York. The purpose of the experiments was to determine whether volumetric systems intended for use on 30,000- to 38,000-L (8,000- to 10,000-gal) tanks could successfully be used on larger tanks. The Griffiss tanks were 254.3 m (77.5 ft) long and 320 cm (10.5 ft) in diameter. A level sensor with a precision of 0.0005 cm (0.00025 in.) and an array of 10 submerged thermistors spaced at 30-cm (12-in.) intervals, each thermistor having a precision of 0.001°C (0.002°F), were used to collect the data. All experiments were conducted in partially filled tanks. Changes in product level were effected by shunting product from one tank to another by means of a pump. During the tests, fluctuations in the temperature of the product produced volume changes of several liters per hour or more.

The following observations were made:

- Temperature fluctuations observed throughout the tank after approximately 38,000 L (10,000 gal) of product had been added or removed were too great, unless at least 4 h had elapsed, to permit an accurate leak detection test. (The addition of 38,000 L (10,000 gal) simulated a delivery of product to the tank.)

- Temperature fluctuations observed after the addition of approximately 19 L (5 gal) of product 25°C warmer or 8°C cooler than the in situ product were too great, unless 2 to 3 h had elapsed, to permit an accurate leak detection test. (The addition of 19 L (5 gal) simulated the topping of an overfilled tank.)
- The difference in the average rate of change of temperature between any two locations along the long axis of the tank, as measured by any two thermistors at the same height but distanced horizontally, was less than 0.001°C/h beginning 4 h or more after product additions or removals. Furthermore, the mean temperature along the centerline of the tank was the same at each height, i.e., the horizontal gradient was negligible at the centerline.
- A horizontal gradient in the mean temperature was observed in the mid-region of the tank in the area between the centerline and the wall of the tank. The rate of change of temperature, as measured by three thermistors spaced at horizontal intervals of 30 cm (12 in.), was lower in the area of the centerline and higher in the area near the tank wall, an observation that is consistent with the physical process of heat transfer between the backfill surrounding the tank and the product inside it. The difference between the rate of change of temperature measured at the centerline of the tank and at locations off the centerline was large enough to suggest that a single vertical array is not sufficient for temperature compensation unless at least 18 h has elapsed. Additional horizontally oriented thermistors must be incorporated into the arrays to compensate for these temperature changes, or the test must not be started until the rate of change of temperature has subsided.
- The area near the bottom of the tank exhibited the largest vertical gradient and the greatest rate of change of temperature. In this region, a spacing of 30 cm (12 in.) between thermistors was not adequate for correct temperature compensation unless at least 10 h had elapsed since the last addition or removal of product.
- The temperature fluctuations that followed changes in product level in these experiments were so large that changes due to deformation were masked. As a consequence, none of the classical exponential level changes associated with tank deformation was observed in these experiments.

- Analysis of the level data revealed the presence of surface waves (seiches) having periods of 2 to 10 s and peak-to-peak amplitudes of 1 to 2 L. These waves were consistent with the fundamental and first harmonic of waves propagating along the long and short axes of the tank.
- Analysis of the temperature data revealed the presence of internal waves having periods of 3 to 30 min. These subsurface waves were large enough to produce periodic surface waves.
- Experimental estimates of the height-to-volume conversion factor were within 5% of the theoretical estimates made with a tank chart.
- When 10 h had elapsed after a product addition or removal, and thermistors spaced at 30-cm (12-in.) intervals were used for thermal compensation, the residual volume changes in each of three tests on nonleaking tanks were 0.36, 0.67 and -0.22 L/h (0.095, 0.177, and -0.58 gal/h) respectively. When 2 h had elapsed after topping and 20 h after a product addition or removal, residual volume changes in each of two tests were 0.036 and -0.043 L/h (0.0095 and -0.011 gal/h) respectively. These residual volume changes can be attributed to inadequate temperature compensation. (There was insufficient coverage near the surface of the product, at the bottom of the tank and in the area between the centerline and the tank wall, all locations where large temperature gradients were present.) The effects of evaporation and condensation within the tank could not be quantified, but their contribution to the residual volume changes appears to be smaller than the errors in temperature compensation.

The data collected during these experiments, combined with theoretical analysis, were sufficient for the researchers to address each of the technical objectives of this study. A summary of the key conclusions of this research project are provided below.

2.1 Volumetric Leak Detection Systems and EPA Performance Standards

Volumetric leak detection systems can meet EPA's performance standards for testing tanks up to 190,000 L (50,000 gal) in capacity. The experiments on 190,000-L (50,000-gal) tanks suggest that volumetric leak detection systems can meet the EPA standards for both volumetric tank testing and automatic tank gauging. That is, they can detect leaks of 0.38 L/h (0.10 gal/h) with a P_D of 0.95 and a P_{FA} of 0.05, which is the performance required of tank tightness tests. (By definition they can also meet the requirement for automatic tank gauging systems, which is the ability to detect a leak of 0.76 L/h (0.20 gal/h) with a P_D of 0.95 and a P_{FA} of 0.05.) However, achieving this goal is very difficult and probably requires a multiple-test strategy.

A 0.76-L/h (0.2-gal/h) leak was detectable with the thermistor array used in these experiments, but a smaller leak of 0.38 L/h (0.1 gal/h) could not be reliably detected. However, leaks as small 0.38 L/h (0.1 gal/h) were detectable if the waiting period after any addition or removal of product from the tank was at least 18 h. After some analysis, this was explained by the fact that there was an insufficient number of thermistors at the bottom of the tank, near the surface of the product, and between the centerline and the walls of the tank, areas where either the rate of change of temperature or the gradient in the rate of change of temperature was greater than in other parts of the tank. The upper portion of the layer closest to the surface was influenced by large changes in the temperature of the vapor, so that the implicit assumption that the rate of change of temperature varied linearly through the layer was violated. The thermistor closest to the surface was not physically centered in the layer, and the product surrounding it was not equally distributed above and below it. When the thermistor was too far away from the surface (e.g., 25 cm (10 in.)), the contribution from the surface was not properly included in the average. Any error in measuring the average rate of change of temperature was magnified by the volume of product in the layer. The error in measuring the average rate of change in temperature was even greater in the layer of product at the bottom of the tank. (In measurements made at the bottom, however, the magnitude of the error decreased with time; in measurements made near the surface it did not.) Although the temperature sensor is indeed centered in this bottom layer, the curvature of the tank is such that the volume of the product above the sensor is significantly greater than that below it. The average rate of change of temperature and the gradient in the rate of change of temperature were significantly greater here than in any other layer. While errors of similar magnitude in measuring the average rate of change of temperature are present in small tanks, the volume of each layer in a small tank is significantly less than in a large tank, particularly near the bottom. The largest source of error in measuring the average rate of change of temperature was due to horizontal gradients in the rate of change of temperature between the centerline of the tank and the wall of the tank. Better temperature compensation would have been achieved if additional temperature sensors had been located near the bottom of the tank and near the product surface, ensuring a better estimate of the rate of change of temperature in the layer surrounding each thermistor, or if a longer waiting period had been used, thus minimizing the rate of change of temperature in these layers and throughout the tank as a whole.

2.2 Features of a System That Meets EPA Standards

The important features of a generic volumetric leak detection system that can meet the EPA performance standards have been identified. The experiments on 190,000-L (50,000-gal) tanks allowed us to identify the key feature that a volumetric leak detection system used on larger tanks must possess in order to meet the EPA standard. It must have better temperature compensation than what is deemed sufficient for a 30,000- to 38,000-L (8,000- to 10,000-gal) tank, and it must have longer waiting periods and a longer test duration. All the other features required for accurate detection of leaks in small tanks are applicable equally to the detection of leaks in large tanks.

Five things are necessary for successful temperature compensation in tanks as large as 190,000-L (50,000-gal). First, a test must not be started until the horizontal gradients in the rate of change of temperature between the centerline and the tank walls have dissipated. Second, the number of temperature sensors must be sufficient that the volume of product in the layer around each sensor is not too great; the smaller the volume in each layer, the less likely it is that a temperature measurement error, when summed with measurements from the other layers, will adversely affect the test. Third, the duration of the test must be long enough that (1) the fluctuations in volume observed 6 h or more after any product additions or removals can be averaged and (2) the precision of the temperature and level is sufficient to detect a leak with a specified performance. Fourth, a test should not begin unless the average rate of change of temperature in the tank as a whole or in any one layer is small enough to allow accurate temperature compensation. Fifth, an accurate experimental estimate of the constants necessary for converting level and temperature changes to volume is required: these constants include the coefficient of thermal expansion, the volume of product in the tank or in each layer, and the height-to-volume conversion factor.

How long must the waiting period be? In testing tanks up to 190,000 L (50,000 gal) in capacity, the length of the required waiting period is controlled by the gradient in the rate of change of temperature between the centerline and the wall of the tank. This waiting period must be sufficiently long that the temperature fluctuations and tank deformation associated with a product addition or removal will have time to subside. A waiting period of 24 h or longer may be required.

The data suggest that the minimum duration of a test should be at least 4 h, long enough that an average of the ambient volume fluctuations can be made. Whether 4 h is sufficient depends on the resolution and precision of the temperature and level instrumentation.

The spacing between thermistors in a 190,000-L (50,000-gal) tank may need to be as small as 15 cm (6 in.) to detect leaks as small as 0.38 L/h (0.1 gal/h), particularly near the bottom and top of the tank where more dense coverage will result in a more accurate estimate of the rate of change of temperature. Since errors in temperature compensation increase as the average rate of change of temperature increases, the most direct way to avoid errors is to wait until the average rate of change of temperature has diminished before starting a test.

2.3 Test Duration

The precision of the instrumentation used to measure temperature and level changes establishes the minimum duration of a test. In order for a volumetric leak detection system to meet the EPA standards, the length of a test must be appropriate for the precision of the system's instrumentation for temperature and level measurement. Given a certain level of precision, the optimum duration of a test can be calculated. As part of the experiments, calculations were made to estimate the minimum duration of a test conducted on a 182,000-L (48,000-gal) tank as a function of the precision of the temperature and level sensors. It was assumed in the calculations that the resolution of the sensors was 2 to 3 times smaller than the most extreme level change that occurred over the duration of the test. The calculations indicated that the test duration must be at least 2 h in the case of a level sensor having a precision of 0.0005 cm (0.00025 in.) and a temperature sensor having a precision of 0.001°C (0.002°F). When the instrumentation is less precise, the test duration must be commensurately longer. For example, if the level sensor had a precision of 0.0025 cm (0.001 in.), the test would have to be at least 4 h long.

SECTION 3

RECOMMENDATIONS

The recommendations developed from this research project are based on a limited set of data. The recommendations for controlling the key sources of noise might be further refined if additional experiments were conducted. We believe, however, that additional data would not have any substantial impact on the general nature of the recommendations made here, and that further refinements to these recommendations would not materially change the effort or cost involved in developing or modifying a method of testing large tanks. Although the experiments were limited to tests conducted on partially filled tanks, many of the conclusions are applicable to the use of volumetric systems in overfilled tanks as well. The recommendations that emerged from this research project fall under three headings.

3.1 Temperature Compensation

The single most important cause of errors in testing large tanks with volumetric leak detection systems appears to be inaccurate temperature compensation. Two things are necessary for successful temperature compensation. First, the number of temperature sensors must be sufficient that the volume of product in the layer around each sensor is not too great. The smaller the volume in each layer, the less likely it is that a measurement error will adversely affect the test. This is because any erroneous measurement is averaged with presumably correct measurements from the other layers. Second, a test must not be started if the average rate of change of temperature of the product in the tank as a whole, or even in a single layer, is great enough to prevent the system from detecting a leak of given size.

The following procedure is recommended for compensating for the thermal expansion or contraction of the product.

- Place the lowest temperature sensor approximately 8 cm (3 in.) from the bottom of the tank and the uppermost sensor approximately 8 cm (3 in.) below the surface.
- Space the temperature sensors at intervals of 15 to 30 cm (6 to 12 in.) or less along the vertical axis of the tank; space the sensors at intervals of 15 cm (6 in.) or less in the bottom 46 cm (18 in.) of the tank and in the 15 to 30 cm (6 to 12 in.) of product located immediately beneath the surface. (A 30-cm (12-in.) spacing can be used if the rate of change of temperature between adjacent layers of product throughout the entire tank is nearly identical.)
- Partition the tank into layers, each of which is centered about a temperature sensor. Then calculate the volume of product in each layer.

- Wait at least 24 h for horizontal gradients in the rate of change of temperature to dissipate. (These horizontal gradients occur between the centerline and the wall of the tank.) Alternatively, measure these horizontal gradients directly, and do not attempt to compensate for temperature until they have dissipated. If the compensated volume rate exceeds the threshold, continue to test until the measured volume rate ceases to decrease and remains constant.
- Using real-time measurements, wait for the rate of change of temperature to diminish sufficiently that the maximum potential error in measuring the average rate of temperature for each test is small. The acceptable rate of temperature change depends on the number of thermistors, the precision of each thermistor, and the degree of compensation that can be achieved with the array of thermistors. A very conservative approach is to incorporate the following analysis tests.
  - Do not begin a test if the rate of change of temperature is great enough in any one layer to produce a volume change that will exceed the detection threshold. (When using a threshold of 0.19 L/h (0.05 gal/h) in a tank containing JP-4 fuel, this would limit the rate of change in temperature to less than 0.008°C in the largest layers of a 190,000-L (50,000-gal) tank divided into ten layers.)
  - Do not begin a test if the average rate of change of temperature throughout the tank is great enough to produce volume changes that exceed the threshold based on an average level of compensation to be achieved. (When using a threshold of 0.05 gal/h in a tank containing JP-4 fuel, this would limit the rate of change in temperature to less than 0.019°C throughout a 190,000-L (50,000-gal) tank if on average the method is able to compensate for 95% of the temperature changes.)
- Use the most precise temperature and level measurement systems available and calibrate them frequently and properly. It is recommended that temperature sensors have a precision of 0.001°C and the level sensors have a precision of 0.00025 cm (0.0001 in.).
- Check that all sensors function properly during a test. If a sensor malfunctions, the test should be repeated.
- Make sure the test is at least 4 h long so that ambient fluctuations will be properly averaged and will not affect the test. Longer tests may be required depending on the resolution and precision of the level and temperature sensors.
- Measure the coefficient of thermal expansion *experimentally*.
- Determine the height-to-volume conversion factor used to convert level measurements to volume measurements *experimentally*.
- Use a multiple-test strategy.

Whether this temperature compensation procedure is sufficiently adequate for a volumetric leak detection system to meet the EPA's regulatory standard for a tank tightness test (or a monthly monitoring test) will not be known until an actual performance evaluation [9,10] is conducted on a system that incorporates some or all of these procedures.

3.2 Evaluating a Volumetric Leak Detection System

Volumetric leak detection systems that will be used on large tanks should be experimentally evaluated according the EPA's standard test procedure for evaluating volumetric tank tightness tests [9]. This includes the performance of the system in terms of probability of detection and probability of false alarm. The primary features that should be examined are the method of temperature compensation, the waiting periods, and the duration of the test. The results of the present study suggest that, when a volumetric leak detection system is used to test larger tanks, longer waiting periods, a longer test duration and better temperature compensation are required if leaks are to be detected with reliability. Unfortunately, none of the existing facilities specializing in evaluations is equipped with 190,000-L (50,000-gal) tanks. Therefore, systems must be evaluated at large-volume storage facilities that are operational, and the EPA's standard test procedure should be modified to accommodate this type of evaluation.

SECTION 4
MEASUREMENT METHODOLOGY

The technical objectives of the project were addressed by means of a limited set of experiments and some theoretical calculations. The purpose of the experiments, which were conducted on two 190,000-L (50,000-gal) tanks containing a petroleum product, was to determine whether volumetric leak detection systems that meet the EPA performance standards when used on 30,000-L (8,000-gal) tanks are valid when used on tanks up to 190,000 L (50,000 gal) in capacity. These systems were examined in terms of the features they must possess in order to meet the EPA standards. The experiments sought to determine whether these features would allow volumetric leak detection systems to accurately test large tanks as well as small ones, and, if not, to determine what modifications would be necessary in order for them to do so.

Two such important features are the method of temperature compensation and the length of the waiting periods that allow structural deformation of the tank and temperature fluctuations in the product to subside. The experiments were designed to estimate the volume changes produced by structural deformation and temperature fluctuations (i.e., to estimate the amount of noise that could normally be expected in a large tank). Several thermistor arrays deployed in the tank measured thermally induced volume changes in the product and provided the data used (1) to estimate the magnitude of the horizontal and vertical changes in product temperature and (2) to compensate for the level changes resulting from the thermal expansion and contraction of the product.

The effects of temperature and deformation have been characterized in previous work conducted in tanks of a nominal 30,000-L (8,000-gal) capacity at the EPA's Test Apparatus in Edison, New Jersey [3-8]. The current work was thus focused on extending the experiments to tanks significantly larger than those installed at the Test Apparatus. The previous studies were used as a baseline against which to compare the results of the experiments. While the program described here is more limited in scope than the original study, it draws extensively from the instrumentation and experiment designs developed during the course of the previous work.

To find out whether volumetric leak detection systems would be applicable to large tanks, it was necessary to estimate the following as they relate to large tanks: (1) the vertical and horizontal characteristics of the product temperature field, (2) the structural deformation characteristics of the tank system, (3) the time required for the temperature inhomogeneities due to topping and delivery to subside, and (4) the precision required of the temperature and level instrumentation.

4.1 Temperature Field

Accurate temperature compensation requires that there be a sufficient number of thermistors along the vertical axis of the tank and that the horizontal differences in temperature be small. Two arrays of thermistors were used to make an estimate of the vertical and horizontal differences in temperature before, during, and after the addition of product in each of two circumstances, a delivery and topping.

4.2 Structural Deformation

Structural deformation of the tank occurs in response to any change in the hydrostatic pressure on the tank. Previous studies of this phenomenon suggest that the response of a tank to a change in pressure (or level) is exponential in form. The details of the shape of the exponential response are largely influenced by the tank material, type of backfill, water-table level, and local native-soil conditions. Experiments conducted on the EPA's 30,000-L (8,000-gal) tanks in Edison indicate that, for the backfill/soil conditions prevalent there, a relaxation time constant of 3 h is not uncommon.

The time constant of a tank can be determined in either of two ways. In the first, used when the tank is overfilled and product level is within the fill tube, a bar of known volume is inserted into the tank (after any deformation effects due to previous product additions have subsided), and the time history of the resulting volume changes required to maintain a constant level is monitored. Then an exponential curve is fit to the cumulative volume changes required to maintain a constant product level. This curve describes the time constant. The second way, employed when the tank is partially filled, is to induce one rapid change in the level of product (and continue as indicated above). The volume changes due to deformation may be difficult to isolate during the first several hours after a change in level, because the accompanying large temperature fluctuations cannot be compensated for.

4.3 Waiting Periods after Topping and Delivery

There are two effects of topping and delivery that will affect the performance of a volumetric leak detection system: (1) temperature inhomogeneities and (2) structural deformation. Both effects diminish with time and so can be minimized if there is a mandatory waiting period between filling/topping and testing. In these experiments, the sets of temperature and level data from which the effects of topping and delivery were determined were obtained immediately before and after product was added to the tank.

4.4 Instrumentation Requirements

In large tanks, the instrumentation noise can be a significant fraction of the total noise. One way to overcome high instrumentation noise is to increase either the sampling rate or the duration of the test. The precision required of the instrumentation can be determined from an analysis that includes the resolution, the system noise, the duration of the test, and the number of independent samples acquired during a test.

SECTION 5
INSTRUMENTATION

The experiments were conducted in two operational 190,000-L (50,000-gal) underground steel storage tanks containing JP-4 fuel and located at Griffiss Air Force Base in upstate New York. Each tank was taken out of service for several days to support these experiments. Five days of experimental data were collected between 27 and 31 August 1990. The experiments conducted on 28 August had to be repeated because an electrical storm that day caused a power outage that resulted in loss of data.

5.1 Configuration of the Tanks and Equipment Used in the Experiments

The two tanks used in these experiments are part of a large, hillside storage facility consisting of five clusters of four tanks. Each of the tanks is cut into the hill, buried under 76 to 91 cm (2.5 to 3 ft) of backfill, and covered by grass. The native soil is sandy, and, because of the hillside location, groundwater does not reach the area where the tanks are situated. Fuel is delivered to the tanks by pipeline. A pump house services each cluster of tanks, as shown in Figure 1, a plan view of one of the four-tank clusters. The labels Tank 1 and Tank 2 in this figure refer to the order of the experiments. Figure 2 is a cross section of one of the tanks, each of which is 320.0 cm (10.5 ft) in diameter and 23.62 m (77.5 ft) long and has a nominal capacity of 190,000 L (50,000 gal). Level measurements made in several of the openings of one tank suggest that the tank is nearly horizontal, with a difference of only about 1 in. in height between the two ends. The two tanks were considered identical for the purposes of the experiments.

The pump house, which overlaps the tanks by approximately 5.3 m (17.5 ft), is a single-story, flat-roofed building approximately 305 cm (10 ft) in height. By means of a pump, product can be transferred from one tank to another at a rate of up to 1,500 L/min (400 gal/min). The pump is located in the pump house, 76 cm (2.5 ft) from the end of the tank. Each tank has an overfill protection device that prevents its being filled above a height of 305 cm (10 ft), or beyond approximately 98% of its capacity.

In addition to the pump, there are six other openings into the tanks. There are three 76-cm (30-in.) diameter manways, a 10-cm (4-in.) diameter fill hole, and a 10-cm (4-in.) diameter, 3.7-m (12-ft) high vent located outside the pump house; a 25-cm (10-in.) diameter level control port is located inside the pump house. The manways provide entry into the tank. They are connected to the top of the tanks by a flange located 15 cm (6 in.) above the tank top. This connection is not liquid-tight and, as a consequence, the tanks could not be overfilled in these

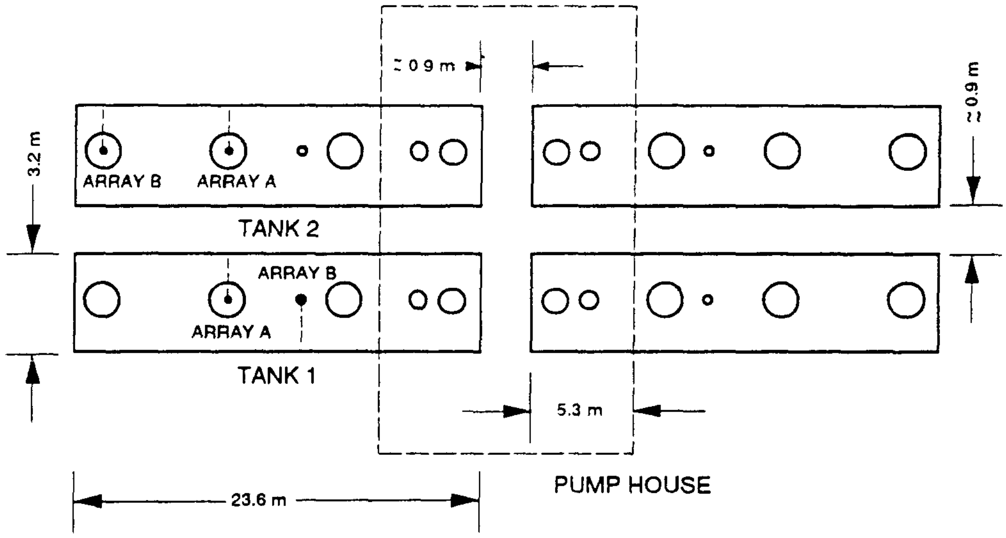

Figure 1. Plan view of the underground storage tank cluster at Griffiss Air Force Base.

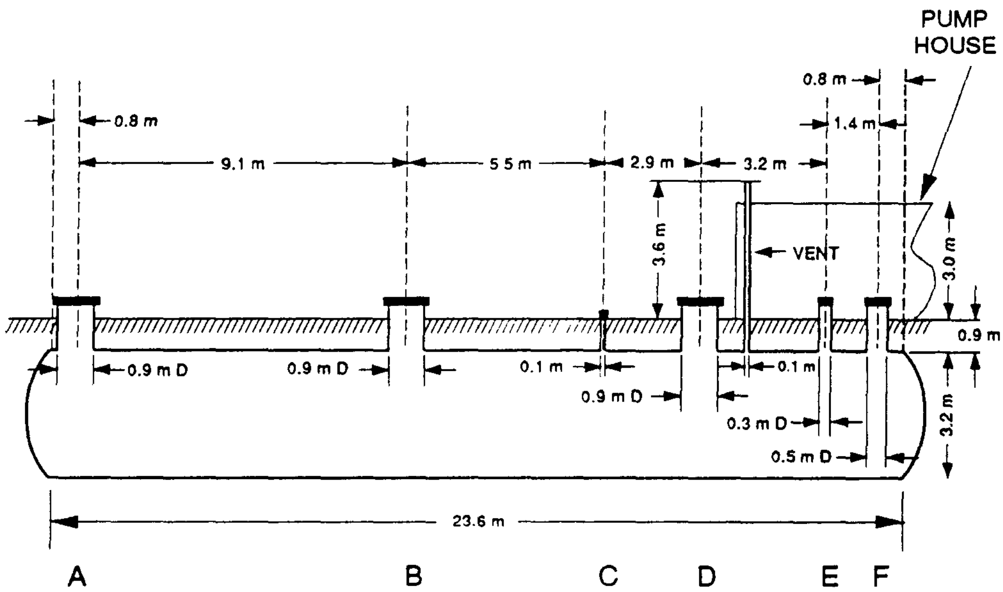

Figure 2. Cross-section of the 190,000-L (50,000-gal) tanks used in the experiments. The experiments were conducted in Tanks 1 and 2, and the thermistor arrays were located in Manways B and C in Tank 1 and in Manways A and B in Tank 2. The level sensor was located in Manway B in both tanks.

experiments. The first manway (A) is located 76 cm (2.5 ft) from the end of the tank and the other two manways (B and D) are located 9.1 and 17.5 m (30.0 and 57.5 ft) away. A ladder is permanently installed in each manway.

Experiments were conducted in Tank 1 between 1030 on 27 August and 0800 on 30 August and in Tank 2 between 1015 on 30 August and 1450 on 31 August 1990. In Tank 1, Thermistor Arrays A and B were inserted in Manway B and the vent hole at C, respectively, and in Tank 2 in Manways B and A, respectively. The distance between arrays was 5.5 m (18 ft) in Tank 1 and 9.1 m (30 ft) in Tank 2. The horizontal arms of the arrays, which extend from the center of the tank to the wall of the tank, were located on opposite sides of the tank in Tank 1 and on the same side of the tank in Tank 2. The array locations and the configuration of the horizontal arm on the arrays are shown in Figure 1. In both tanks, the level and pressure sensor measurements during the tests were made at Manway B. All of the level changes in the tanks were done by adding or removing product from the tank by means of a pump which was located 8.5 m (28 ft) away from the nearest thermistor array in Tank 1 and 46 ft away from the nearest thermistor array in Tank 2. A 2,470-ml cylindrical bar used to determine the height-to-volume conversion factor experimentally was inserted into and removed from the liquid in the tank at Manway A in Tank 1 and at Manway C in Tank 2; these openings were selected because there was no temperature or level measurement equipment located there. All stick measurements were made in these same openings. The small-volume product additions, whose purpose was to simulate the effects of topping, were done in each tank at the opening where Array B was located. With the exception of a limited number of experiments conducted to measure surface fluctuations at 1 sample/s (1 Hz), all data were collected at a sample rate of 1 sample/min (0.017 Hz).

The experiments adhered to the well-defined operational and security requirements of Griffiss Air Force Base. The tanks could not be filled above 10 ft, the level at which the overfill protection devices were set. The main constraint in designing the experiments, however, was that the technical staff were allowed to be present at the tank site only between 0700 and 1630 each day. Hence, the product transfers, the product additions to simulate topping, and the height-to-volume measurements, all of which were necessary to set up the conditions for the tests, had to be made during this period. It was also understood that normal operation of the tanks would take precedence over the experiments and that product might possibly be dispensed from the tanks being used in the experiments. As it turned out, the staff at Griffiss were able to use the other tanks to fulfill their operational needs, and no interruption of the experiments was experienced.

5.2 Temperature and Level Measurement Systems

The following data were required for these experiments: the change in the temperature of the product and vapor in the tank and the height and change in level of the product. The product temperature data were analyzed to estimate the thermally induced volume changes in the tank. The level data were converted to volume data by means of the experimental estimates of the height-to-volume conversion factor. The level data were used to estimate the volume of product in the tank during a test. Air temperature was also measured; air temperature data are not central to the experiments or the analysis, however, and were used only to characterize weather conditions during the experiments.

Two types of product level measurements were required. The first was a measurement of the height of the product from the bottom of the tank; a pressure sensor with a precision of 0.5 cm (0.2 in.) or better was used for this. The second was a measurement of the level changes in the tank; an electromagnetic sensor developed by Vista Research prior to these experiments was used for this second measurement. The electromagnetic sensor consists of a linear variable differential transducer (LVDT) and a float. The LVDT is a commercially available sensor that has a dynamic range of ±0.5 cm (±0.2 in.) over 10 volts. The sensor is read to the nearest 0.0001 volts, which results in a resolution of 0.0005 cm (0.0002 in.). The pressure sensor was located at the bottom of Thermistor Array A. In addition, each time the level was changed, it was measured to the nearest 0.3 cm (0.125 in.) with a calibrated stick.

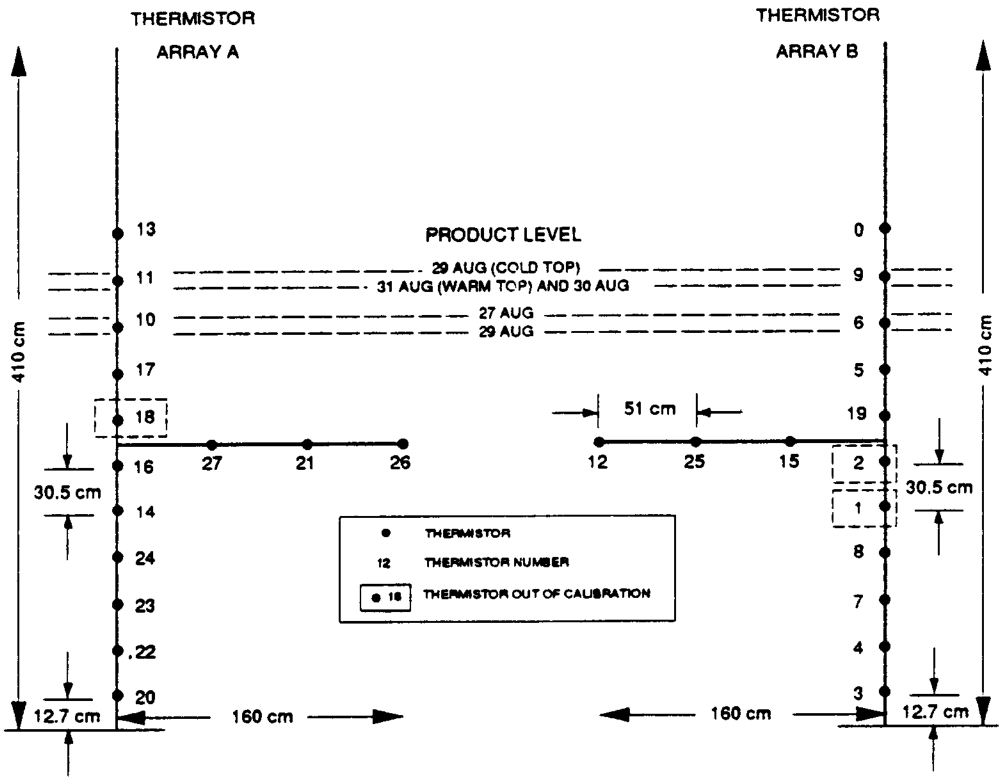

Figure 3. Configuration of Thermistor Arrays A and B.

To measure product temperature, two arrays of thermistors were used. Figure 3 shows Arrays A and B and the channel number of the thermistors on each array. The thermistors, attached to a stainless steel tube, were spaced at intervals of 30 cm (12 in.) along the vertical axis of the tank. The thermistor closest to the bottom of the array was located approximately 13 cm (5 in.) from the bottom of the tank. The vertical portion of the array contained a total of 11 thermistors and was used primarily to estimate the average thermally induced volume change of the product in the tank. Each array, placed in the tank through the fill hole or a manway, was equipped with a 1.5-m (5-ft) -long pivoting "arm" that could be lowered to a horizontal position after the array had been positioned. The pivoting arm provided for the measurement of horizontal thermal gradients between the tank's centerline and its walls. The arm contained three thermistors located at intervals of approximately 51 cm (20 in.); the thermistor located farthest from the centerline was within 7.6 cm (3 in.) of the tank wall. Each thermistor was accurate to within 0.64 cm (0.25 in.). Table 1 shows the nominal height of each thermistor from the bottom of the tank (except for the top and bottom ones) and shows the volume of product in the 30-cm (12-in.)-high layer centered about each thermistor.

Table 1. Summary of the Volume of Product Surrounding Each Thermistor on Arrays A and B

Thermistor Channel (Array A)	Thermistor Channel (Array B)	Thermistor Height (cm (in.))	Volume of Product (L (gal))
13	0	318 (125)	3884 (1096)
11	9	113 (45)	3661 (952)
10	6	101 (36)	4470 (1163)
17	5	89 (35)	5532 (1438)
18	19	77 (27)	5925 (1540)
16	2	65 (26)	6075 (1580)
14	1	53 (21)	6000 (1560)
24	8	41 (16)	5692 (1480)
23	7	29 (12)	5109 (1328)
22	4	17 (67)	4129 (1074)
20	3	5 (2)	2139 (556)

5.3 Data Quality Objective and Calibration

The data quality objective for the instrumentation used in the experiments is based upon the EPA performance standard for tank tightness tests [1] and is more fully described in Section 8 of this report and in the Quality Assurance Project Plan (QAPP) developed for these experiments [11]. All of the temperature and level measurement systems that were considered for use in the experiments have the capability to detect a leak of 0.38 ml/h (0.1 gal/h) with a P_D of 0.95 and a P_{FA} of 0.05 in a given measurement period. The range, resolution, precision, and accuracy of the temperature and level sensors that were actually used are summarized in Table 2. The minimum duration of the measurement period required for each sensor to meet the data quality objective is presented in the last column of this table. The values presented in Table 2 are based on the following definitions: (1) accuracy is defined as the difference between the measured and actual values; (2) precision is defined as one standard deviation of uncertainty in each measurement; (3) the resolution of a sensor is determined from the A/D converter in each instrument and is less than or equal to the required precision.

Table 2. Specifications of the Measurement Instrumentation

Sensor	Range	Resolution	Accuracy	Precision	Duration
Temperature					
Product	5 to 25°C	0.0008°C	0.05°C	0.001°C	1 to 2 h
Air	5 to 25°C	0.0008°C	0.5°C	0.1°C	< 1 min
Product Level					
Absolute Pressure	0 to 370 cm (0 to 144 in.)	0.0012 cm (0.00047 in.)	5.0 cm (1.95 in.)	5.0 cm (1.95 in.)	< 1 min
Electromagnetic	1 cm (0.39 in.)	0.00025 cm (0.000097 in.)	n/a	0.00064 cm (0.00025 in.)	2 h

The sensors were calibrated according to the procedures described in the QAPP [11]. All sensors used in the analysis (temperature, level, and pressure sensors) were within specification. The temperature sensors, or thermistors, were calibrated both before and after the experiments in a well-mixed water bath to attain a precision of 0.001°C or better over a range of 0 to 30 °C. The accuracy of the majority of the thermistors was generally better than 0.02°C. The second calibration, the one that took place after the experiments, was required because the location of the sensors in the data acquisition box had been changed in the field. Thermistor 18 on Array A and Thermistors 1 and 2 on Array B fell outside the required precision for temperatures above 20°C and below 10°C. Since all thermistors brought into the field were within the 0.001°C precision and 0.05°C specifications, these thermistors presumably functioned properly during the test, and it is probable that the error (the fact of the three thermistors falling outside the range) was in the calibration curve developed after the experiments were completed; a third calibration would probably have corrected this deficiency, but the loss of these thermistors did not impact the conclusions drawn from the study. These thermistors were removed from the analysis when the temperature of the product in the tank was above 20°C and below 10°C. The level sensor was checked with a precision caliper to verify that its response was within the LVDT specification; it was then calibrated in the 30,000-L (8,000-gal) tanks at the UST Test Apparatus by means of height-to-volume measurements with several different bar sizes. To calibrate the pressure sensor, the level of product in a 10-cm (4-in.) -diameter tube was raised from 0 to 3.0 m (0 to 10 ft) in 15-cm (6-in.) increments. The pressure sensor was checked in the field by means of stick measurements.

SECTION 6
EXPERIMENTS

A description of the test conditions, weather conditions, and the temperature and volume data is provided below.

6.1 Test Conditions

The conditions required to examine each source of noise were produced by adding or removing product from the tank. The time line presented in Figure 4 summarizes the nominal product level and the product additions and removals during the measurements. Also shown are the time of the height-to-volume calibrations and the time at which 19 L (5 gal) of product was added to the tank to simulate the effects of topping. Table 3 presents an overview of all the measurements of level and volume made over the five-day period.

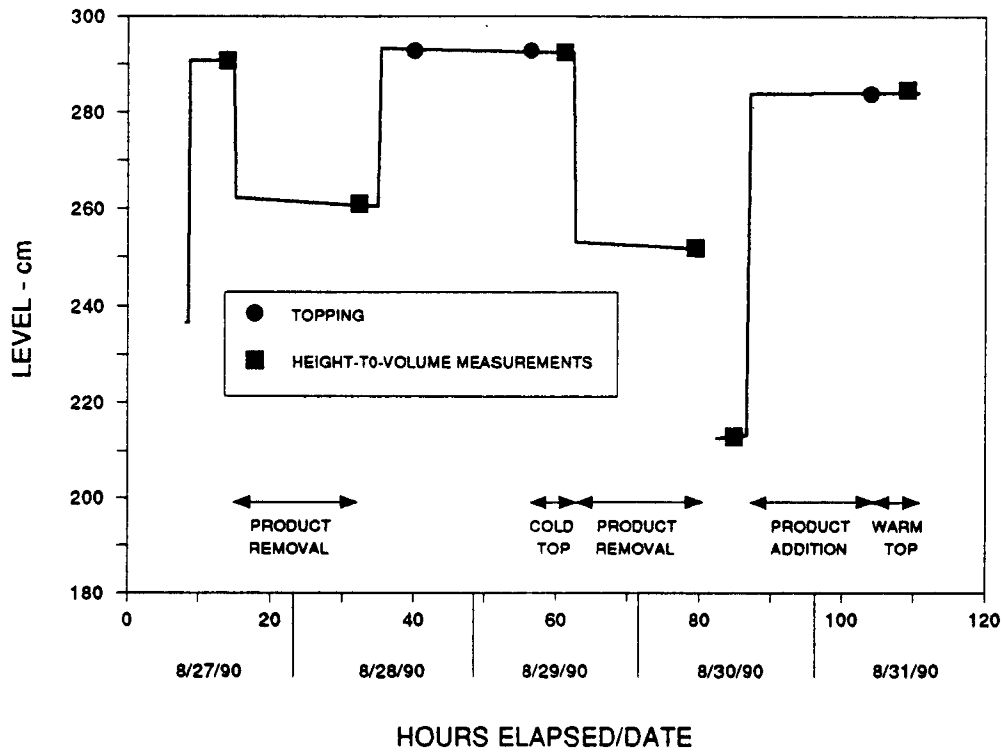

Figure 4. Summary of the product level measurements between 27 and 31 August 1990 and of the analyses performed on the data.

Table 3. Summary of the Product Level and Product Volume Measurements

Tank	Date	Time	Level (cm (in.))	Volume (L (gal))
1	8-27-90	0800	236.5 (93.125)	150,747 (39,775)
1	8-27-90	0845	290.83 (114.5)	181,583 (47,911)
1	8-27-90	1510	262.25 (103.25)	166, 836 (44,020)
1	8-28-90	1126	293.37 (115.5)	182,629 (48,187)
1	8-29-90	1400	292 42 (115.125)	182,269 (48,092)
1	8-29-90	1455	253.04 (99.625)	161,333 (42,568)
2	8-30-90	1008	212.73 (83.75)	134,280 (35,430)
2	8-30-90	1430	213.36 (84.0)	134,735 (35,550)
2	8-30-90	1513	283.84 (111.75)	178,383 (47,067)
2	8-31-90	1519	284.16 (111.875)	178,539 (47,108)

Four experiments were conducted on Tank 1 to estimate the time constant of the structural deformation and the magnitude of the residual volume changes after temperature compensation. The best method of conducting this type of experiment is to overfill the tank into a small-diameter fill hole or standpipe and instantaneously change the level approximately 61 cm (24 in.) by inserting or removing a bar of known volume. This procedure has the advantage that the temperature field in the tank is not disturbed, so that accurate estimates of the deformation-induced volume changes are possible even immediately after the product level has been changed. The Griffiss tanks, however, could not be overfilled, and a different method had to be used. The rapid change in level was induced by pumping product in or out with the transfer pumps. In general, it took 15 to 30 min to change the level by approximately 29 to 70 cm (11.25 to 27.75 in.). The same data used to estimate the time constant of the structural deformation were used to examine the vertical and horizontal temperature inhomogeneities that are produced by adding or removing product and to determine what degree of compensation can be achieved for the thermal expansion and contraction of the product.

Product was added to Tank 1 at 0800 on 27 August and 1100 on 28 August, and was removed at 1458 on 27 August and 1402 on 29 August. Approximately 19 L (5 gal) of product that was *5°C warmer* than the in situ product was added to Tank 1 at opening C (containing Array B) at 1543 on 28 August, approximately 7 h after 33 cm (13 in.) of product had been added. Approximately 19 L (5 gal) of product that was *8°C cooler* than the in situ product was added to Tank 2 at opening A (containing Array B) at 0818 on 29 August, approximately 21 h after the 33-cm (13-in.) product addition on 28 August. The product was poured into the tank without the use of a drop tube. The small volumes of product were added to examine the temperature effects that might be produced by topping the tank; the deformation effects produced by topping were examined independently.

Not all of the data shown in Figure 4 and Table 3 were used in the analysis. The temperature data collected between 0759 on 28 August and 0744 on 29 August and the level data collected between 1403 on 28 August and 0747 on 29 August were lost due to the power outage that occurred during the evening of 28 August. None of the data collected between 1100 on 28 August and 0747 on 29 August were analyzed. Thus, the data collected during the "warm topping" experiment and the "25-in. product addition" experiment were lost. The warm topping experiment was repeated in Tank 2 on 31 August. Another set of data that was not analyzed was that collected between 0845 and 1458 on August 27, the first day of tests, because the product addition that was completed at 0845 was done before the temperature and level instruments had been placed in the tank. Collection of temperature and level data was initiated at 1025.

Only one product addition and one topping experiment were done in Tank 2. At 1430 on 30 August, the level of the product in Tank 2 was raised approximately 70 cm (27.75 in.), and at 0820 on 31 August, about 18 h after 70 cm (27.75 in.) of product had been added to the tank, approximately 19 L (5 gal) of product that was 5°C warmer than the product in the tank was added.

The five data sets analyzed and discussed in this report are noted at the bottom of Figure 4 and in Table 4. The three tests begun between 1440 and 1505 on 27, 29, and 30 August will be referred to as *overnight tests* in this report; the other two tests will be referred to as either the *topping tests* or more specifically, as the *warm topping* or *cold topping* tests.

Table 4. Depth of the Thermistor Located Closest to the Product Surface

Tank	Start Date	Start Time	Nominal Product Level (cm (in.))	Thermistors Closest to Surface Array A/Array B	Nominal Thermistor Height (cm (in.))	Nominal Product Above Thermistor (cm (in.))
1	8-27-90	1510	262.25 (103.25)	10/6	256.5 (101)	5.7 (2.25)
1*	8-29-90	0819	292.4 (115.125)	11/9	287.0 (113)	5.4 (2.125)
1	8-29-90	1441	253.0 (99.6)	17/5	226.0 (89)	26.9 (10.6)
1	8-30-90	1505	283.8 (111.75)	10/6	256.5 (101)	27.3 (10.75)
2**	8-31-90	0820	283.8 (111.75)	10/6	256.5 (101)	27.3 (10.75)

*Test begun 2 h after topping with colder product

**Test begun after topping with warmer product

The temperature of both the vapor and the liquid in a tank is controlled by the addition or removal of product and the heating and cooling of the ground around the tank. In general, the fluctuation in air temperature during a given 24-h period will not have a strong influence on the temperature inside the tank. However, direct communication with the external, ambient environment, through the 76-cm (30-in.) -diameter manways, may influence temperatures inside the tank. These manways are large enough that the diurnal temperature changes do affect the temperature of the vapor in the tank. In addition, the pump house is large enough to block sunlight and produce shadows, changing the ambient heating and cooling of the ground around the tanks and the air in the manways. Since the tanks are so long, the temperature changes can differ from one manway to another.

6.2 Weather Conditions

In addition to the level and thermistor data, the air temperature, atmospheric pressure, dew point, and wind speed data collected at 30- to 60-min intervals by the Air Force are plotted in Figures 5 through 8 as a aid to interpreting the results. The vapor pressure in the tank, which controls the evaporation and condensation and the heating and cooling of the surface layer of the product, is influenced by these qualities. The air temperature shows a strong diurnal variation, which was observed in the thermistors in the vapor space on the arrays located in the 76-cm (30-in.) -diameter manways, but not in the 10-cm (4-in.) -diameter opening. The atmospheric pressure decreased continuously from 27 August until 2400 on 28 August and then increased continuously from 1200 on 29 August through the end of the experiments on 31 August. The wind speed was generally less than 5 m/s during the tests.

6.3 How Data Were Divided for Analysis

As shown in Figure 4 and Table 4, the data from five tests were divided for analysis. There were three overnight tests that followed the addition or removal of 15,000 to 43,500 L (4,000 to 11,500 gal) of product from the tank. The intent here was to simulate the effects of a delivery or product transfer prior to a leak detection test. There were two more tests that followed the addition of 19 L (5 gal) of warm and cold product, respectively. The purpose of these two tests was to simulate the effects of topping.

6.3.1 Coefficient of Thermal Expansion

Samples of product were taken from the tank on 27 August 1990, and an estimate of the coefficient of thermal expansion was made from measurements of the API gravity and from the API tables. The coefficient of thermal expansion obtained, 0.000104/°C, was used in all calculations found in this report.

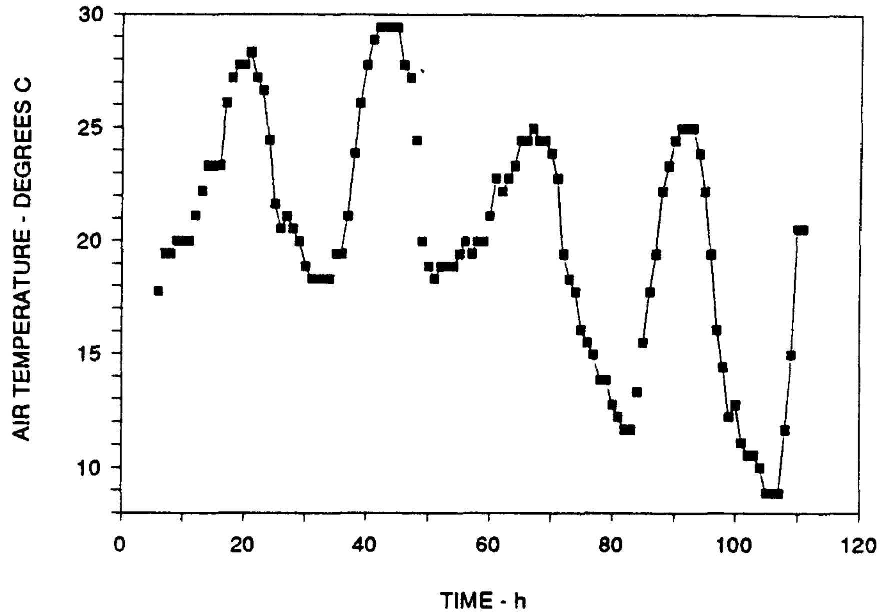

Figure 5. Time series of the air temperature measured at the Griffiss Air Force Base Weather Station. (0 h represents 0000 on 27 August and 120 h represents 2400 on 31 August.)

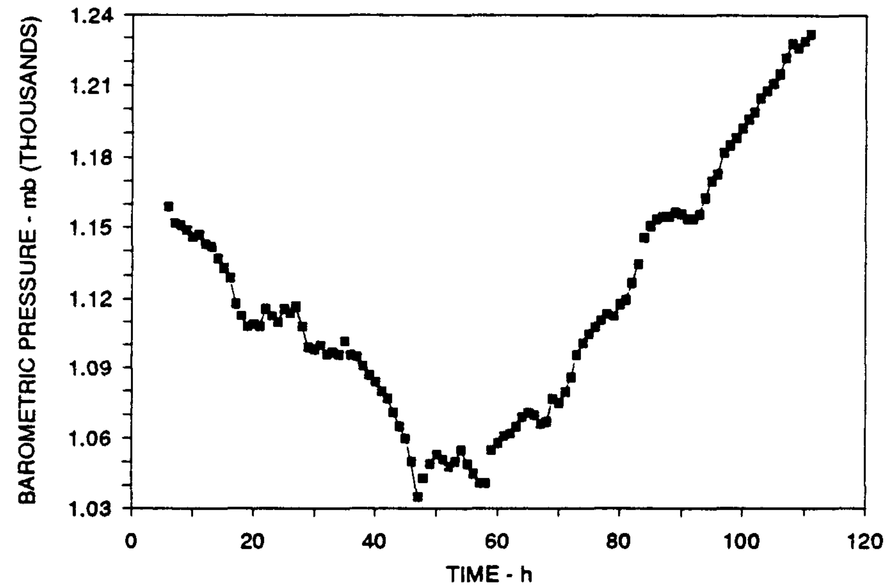

Figure 6. Time series of the barometric pressure measured at the Griffiss Air Force Base Weather Station. (0 h represents 0000 on 27 August and 120 h represents 2400 on 31 August.)

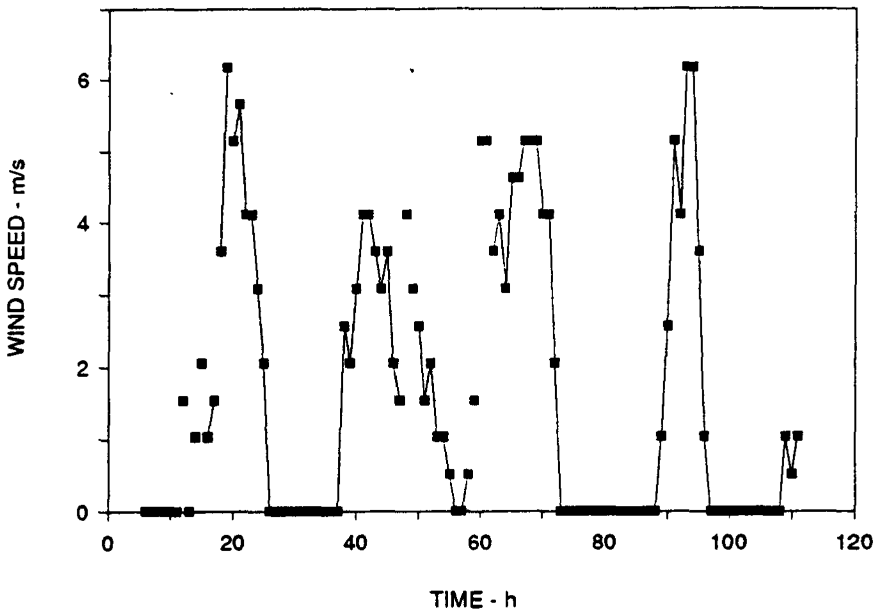

Figure 7. Time series of the wind speed measured at the Griffiss Air Force Base Weather Station. (0 h represents 0000 on 27 August and 120 h represents 2400 on 31 August.)

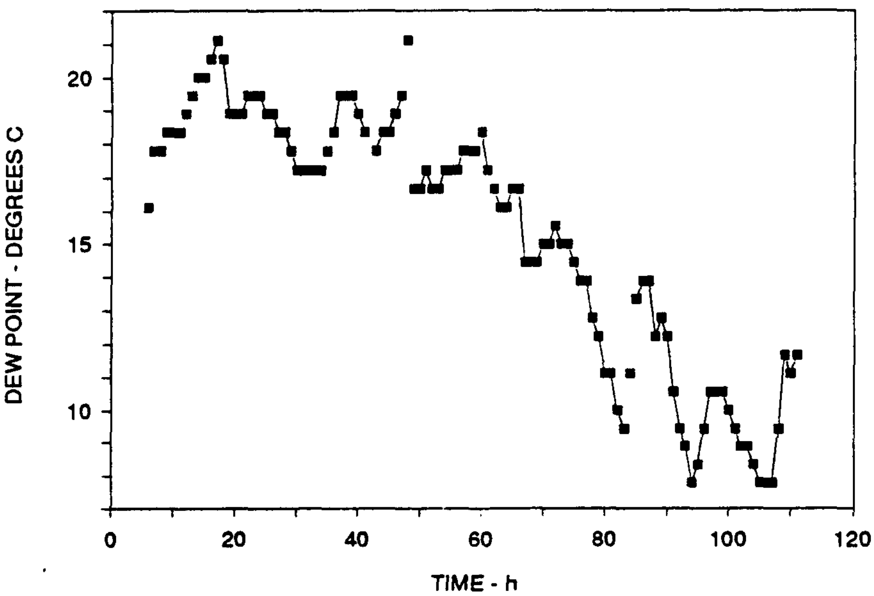

Figure 8. Time series of the dew point temperature measured at the Griffiss Air Force Base Weather Station. (0 h represents 0000 on 27 August and 120 h represents 2400 on 31 August.)

6.3.2 Height-to-Volume Measurements

As shown in Figure 4, an experimental estimate of the height-to-volume conversion factor was made at each level of product (near the end of each run) and compared to the theoretical estimate made from the tank chart. Except for the data collected at 291 cm (114.5 in.) on 27 August, all of the calibration measurements were done with a 2,470-ml bar. The bar was carefully inserted into and removed from the tank at 90-s intervals; to ensure that the bar was completely immersed in or removed from the liquid, and to minimize the large initial waves produced at the time the bar was inserted or removed, only the data from the last 60 s of each 90-s interval were used in the analysis. Ten or more repetitions were done at each level of product. The mean level change was calculated from the absolute value of the difference between the two levels (i.e., the level when the bar was in the liquid and the level when it was out). An example of the mean level changes induced by the bar is shown in Figure 9. The mean, standard deviation, and number of repetitions at each level are presented in Table 5. Except for the height-to-volume conversion factor measured on 31 August, the difference between the experimental and theoretical estimates was within 5%.

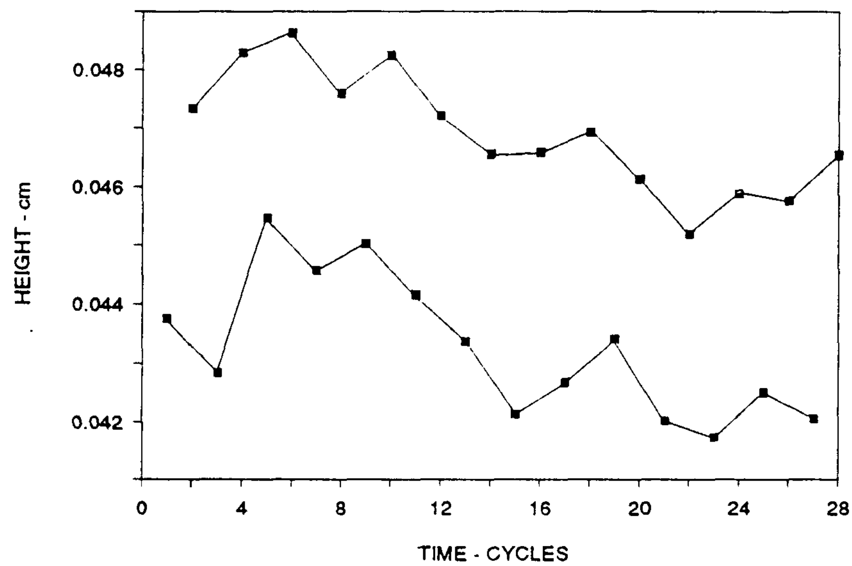

Figure 9. Average level change computed from the height-to-volume calibration data collected at 0730 on 30 August 1990.

Table 5. Summary of the Height-to-Volume Calibration Results

Tank	Date	Start Time (h)	Nominal Level (cm (in.))	Measured HVC (L/cm (gal/in.))	Standard Deviation (L/cm (gal/in.))	Tank Chart HVC (L/cm gal/in.))	Difference (%)
1	8-27-90	1406	290.8 (114.5)	-		435 (291.53)	-
1	8-28-90	0835	262.3 (103.25)	577 (386.69)		579 (388.04)	0.9
1	8-29-90	0913	293.4 (115.5)	401 (268.74)		417 (279.47)	4.0
1	8-30-90	0736	251.8 (99.125)	643 (430.93)		621 (416.19)	3.4
2	8-30-90	1312	213.4 (84.0)	702 (470.47)		712 (477.17)	1.4
2	8-31-90	1315	283.8 (111.75)	423 (283.49)		475 (318.34)	12.3

6.3.3 Level Data

Figure 10 shows the level data, after conversion to volume, that were obtained from the two topping tests on 29 and 31 August and from the three overnight tests on 27, 29, and 30 August, initiated after a large amount of product had been added or removed. All three of the overnight volume times series exhibit large fluctuations associated with the product addition or removal for a period of 3 to 4 h. The data collected on 27 and 30 August show a minimum of 1 to 2 h of fluctuations before midnight (24 h). The data collected on 29 August show a distinct change in slope at a point approximately 23.5 h after the start of the experiment. The volume changes decreased continuously between 18 and 23.5 h and increased continuously between 23.5 and 30 h after the start. This change in slope appears correlated with the change in slope of the product temperature data on the arm of the thermistor arrays and occurs about the time that the temperature of the vapor in the upper portion of the tank drops below the temperature of the vapor near the product surface and the product in the upper portion of the tank.

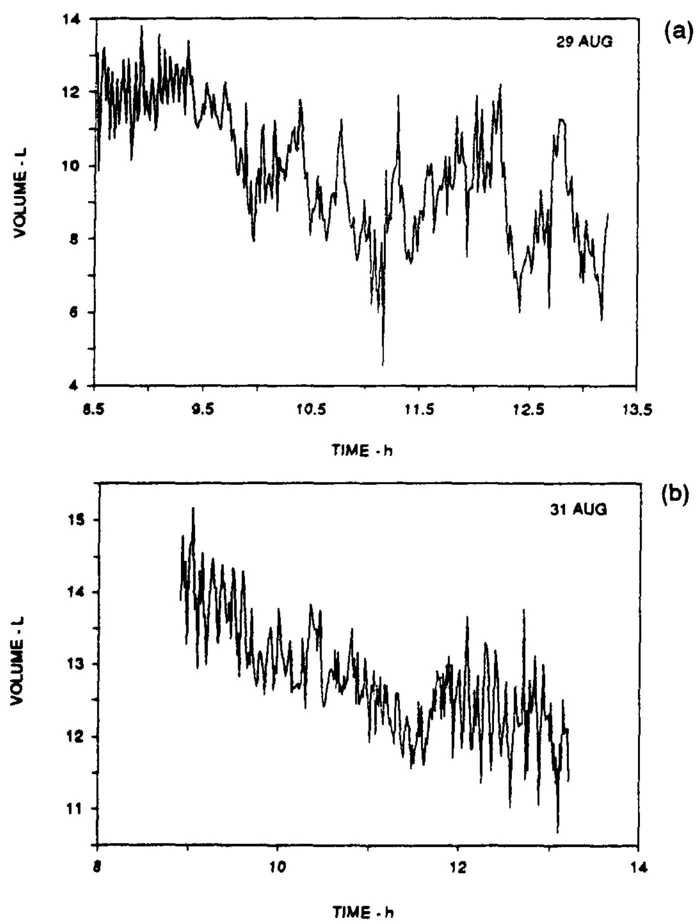

Figure 10. Time series of the volume changes measured with the level sensor beginning immediately after the addition of a small volume of (a) cold product to Tank 1 on 29 August and (b) warm product to Tank 2 on 31 August: time series of the volume changes measured with the level sensor beginning immediately after the initial level change done at (c) 1510 on 27 August, (d) 1441 on 29 August, and (e) 1505 on 30 August.

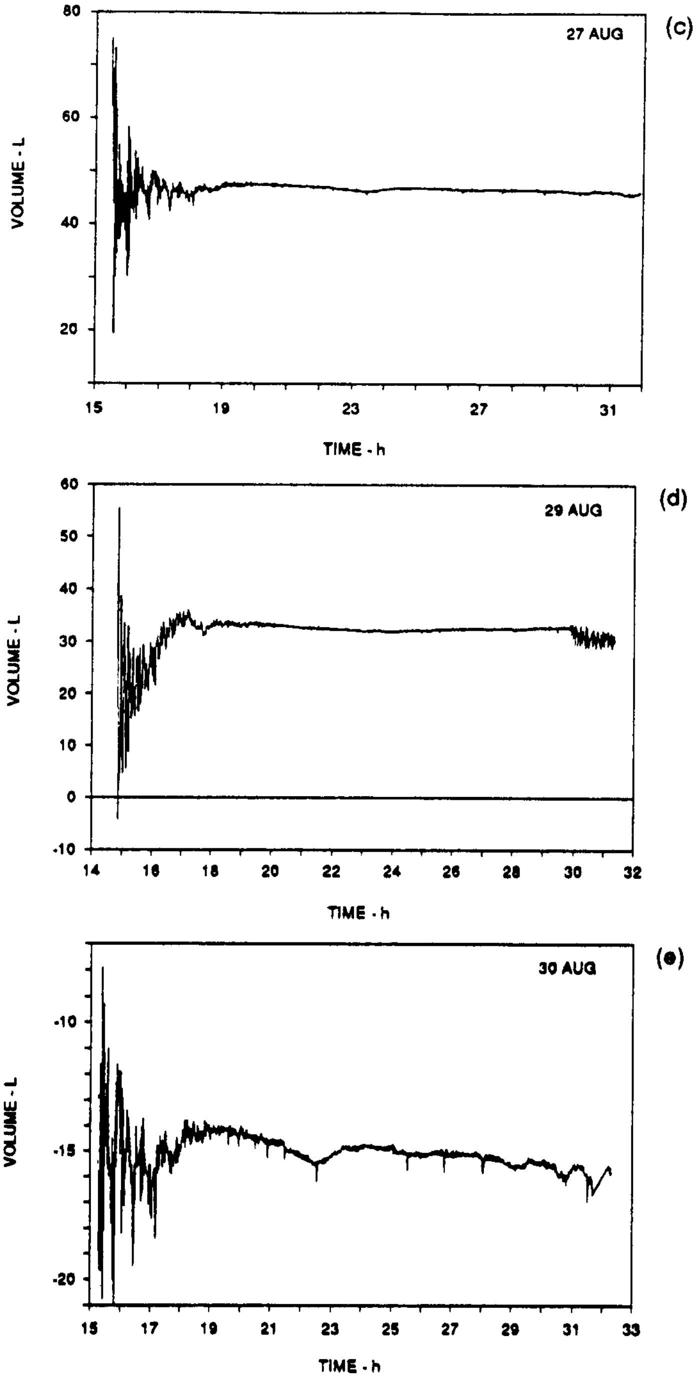

Figure 10 (concluded). Time series of the volume changes measured with the level sensor beginning immediately after the addition of a small volume of (a) cold product to Tank 1 on 29 August and (b) warm product to Tank 2 on 31 August; time series of the volume changes measured with the level sensor beginning immediately after the initial level change done at (c) 1510 on 27 August, (d) 1441 on 29 August, and (e) 1505 on 30 August.

6.3.4 Surface Waves

An experiment was conducted to determine the periods of the long waves that might be present in the tank. A 5,045-ml (1.3-gal) cylindrical bar 8.9 cm (3.5 in.) in diameter and 81.3 cm

(32.0 in.) long was inserted and removed with a rapid, gliding motion at the product surface. A 2048-s (34.1-min) time series of level data, which is shown in Figure 11 (a), was collected at a 1-Hz sample rate (1 sample/s) beginning approximately 2 min before the bar was inserted. The peak-to-peak fluctuation level was approximately 0.75 L (0.2 gal) before the bar was inserted. After the bar was removed, the peak-to-peak fluctuation level increased to approximately 4.0 L (1 gal), the equivalent of a height change of 0.0095 cm (0.004 in.) and then decreased exponentially over the next 30 min to about 0.5 L (0.13 gal), the equivalent of a height change of 0.0012 cm (0.000468 in.).

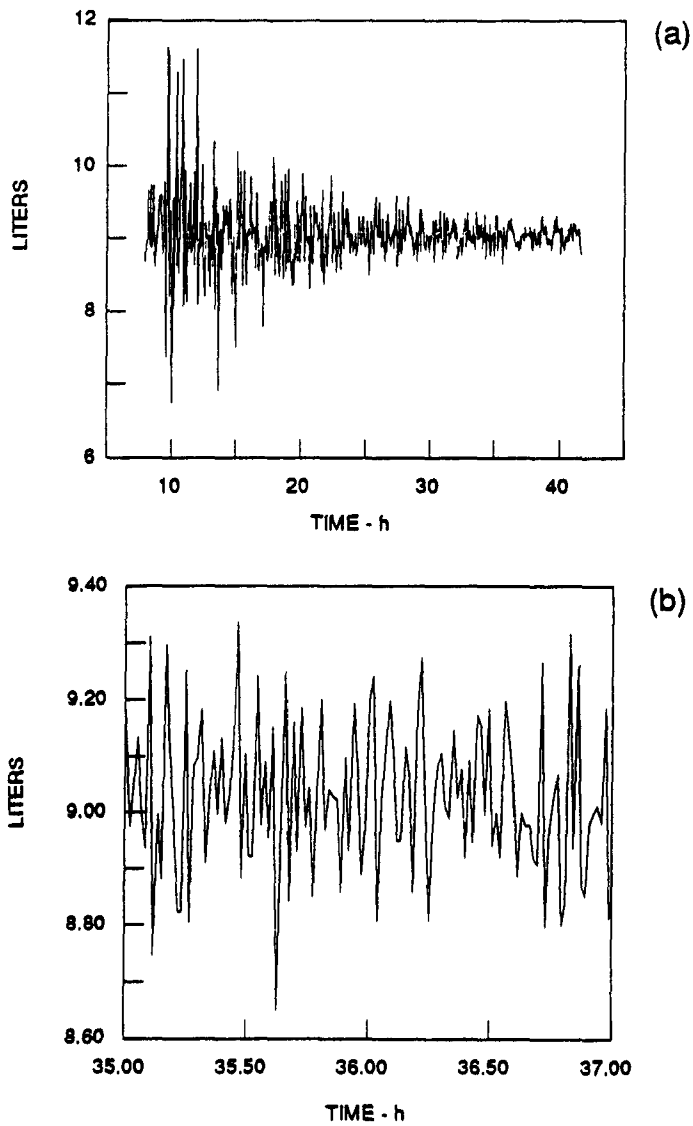

Figure 11. Surface-level fluctuations produced by an impulse (a) over a 34-min period after the impulse and (b) over a 2-min period between 35 and 37 min after the impulse.

Periodic fluctuations of 1 to 3 min can be seen in the data shown in Figure 11 (a). Figure 11 (b), which is a 2-min segment of the data recorded between 35 and 37 min after the impulse, shows periodic fluctuations of approximately 4 and 8 s. The frequency content is too complicated, however, to allow interpretation of the type of waves that are present and their periods in the time domain. This is done in Section 7.1, where frequency analysis of the time series is discussed. Waves with periods less than 10 s are produced by disturbances of the surface, while the waves with periods of several minutes to tens of minutes are generally a manifestation of internal waves (subsurface waves generated in regions of strong vertical temperature gradients). In general, internal waves do not usually affect the surface unless the temperature gradient is very large, as it was during these experiments. Because of the strong vertical gradients evident near the bottom and top of the tank, it is possible that internal waves were present at each location.

As shown in Figure 10, the level data collected during the overnight test beginning on 30 August show a range of wave fluctuation, even though no manmade disturbances of the tank environment occurred. The peak-to-peak fluctuation level of selected waves from a period in which the amplitude of the surface fluctuations was small (21 to 23 h after the start of the experiment) and a period when the amplitude of the surface fluctuations was large (27 to 28 h after the start) are 0.25 L and 2.0 L, respectively. The large-amplitude waves are comparable to those produced by a manmade disturbance and are generally associated with the wind blowing over the vent tube.

6.3.5 Temperature Data

Time series of the temperature data obtained with Arrays A and B can be found in Appendices A through E, which correspond to each of the five tests shown in Figure 4 and Table 4. The data for each test are grouped as follows: (1) air temperature, (2) vapor temperature, (3) product temperature for thermistors on the vertical portion of the array, and (4) product temperature for thermistors on the horizontal portion of the array. Figures 12 through 15 show the time series of the data from 29 August.

A number of observations can be made directly from the raw temperature data collected on 29 August; these observations are also valid for the data collected on 27 and 30 August.

- The rate of change of temperature is greatest near the bottom of the tank. The rate of change of temperature measured by the bottom thermistor (No. 20) is significantly greater than that measured by the thermistor located immediately above it. This suggests that additional thermistors would be required to accurately estimate the mean rate of change of temperature in this region of the tank.

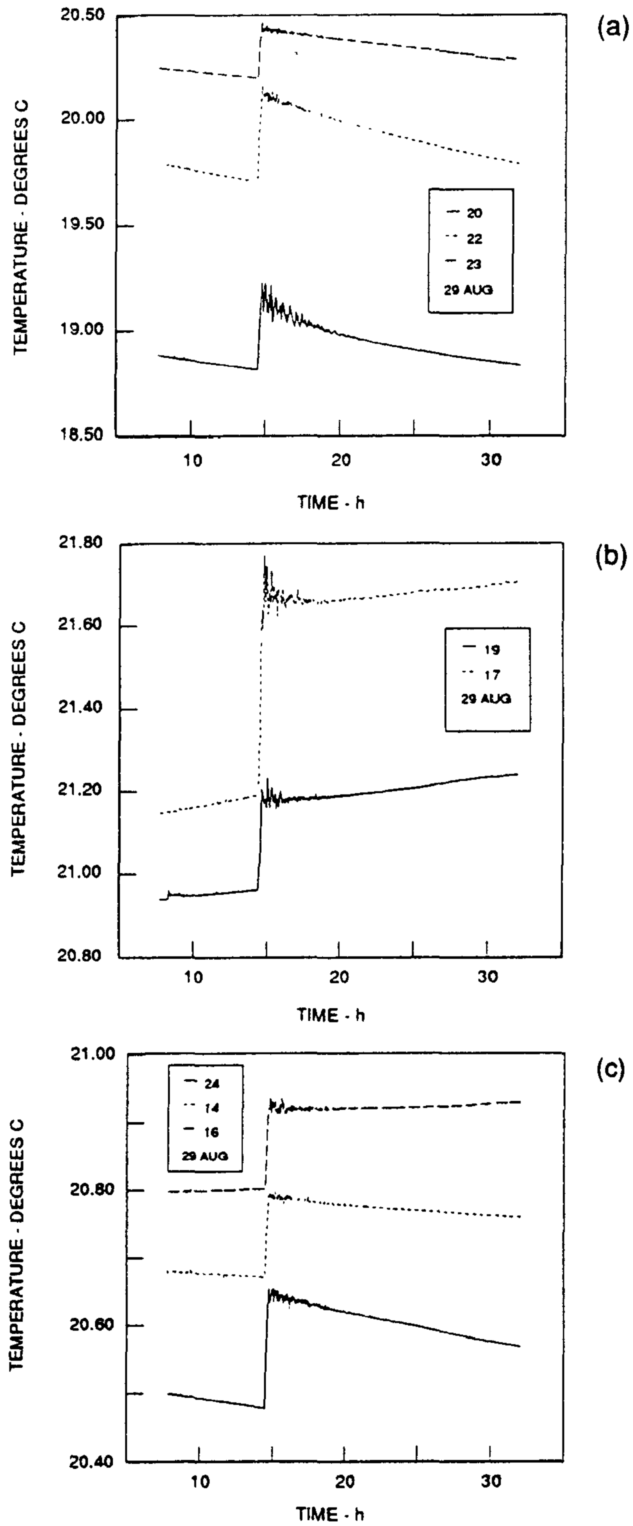

Figure 12. Time series of the product temperature changes on the vertical portion of Array A (with Thermistor 19 from Array B substituted for 18 on Array A) from the data collected after the product removal at 1441 on 29 August: (a) shows times series for Thermistors 20, 22 and 23, (b) for Thermistors 17 and 19, and (c) for Thermistors 14, 16 and 24.

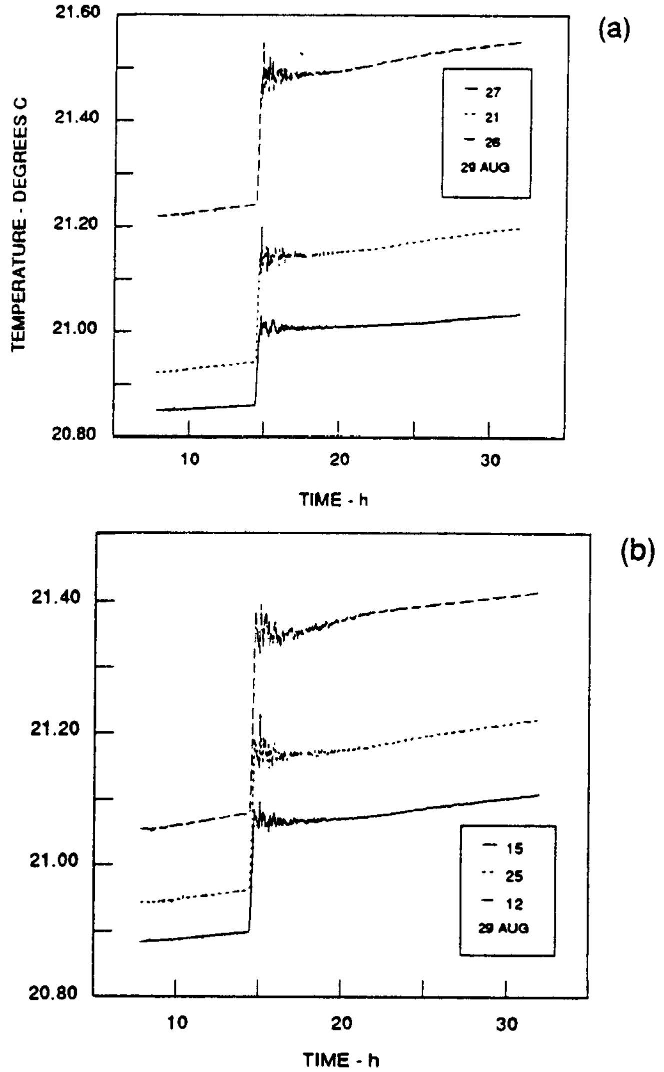

Figure 13. Time series of the product temperature changes on the horizontal arm extending from the center of the tank (a) on Array A and (b) on Array B. The arm, located at a height of approximately 180 cm (71 in.) from the bottom of the tank, is located at the midpoint between Thermistors 16 and 18 on Array A and Thermistors 2 and 19 on Array B.

- The rate of change of temperature decreases in the lower portion of the tank and increases in the upper portion of the tank. This occurs between Thermistors 14 and 16, about 135 and 165 cm (53 and 65 in.) from the bottom of the tank, in all of the overnight data collected on 27, 29, and 30 August.
- The temperature and the rate of change of temperature measured on the vertical portion of Arrays A and B are nearly the same, suggesting that there are no horizontal gradients in temperature along the long axis of the tank and that the temperature measurement required for temperature compensation can be made at any convenient location in the tank. This was true even when Array B was located within 0.8 m of the end of the tank.

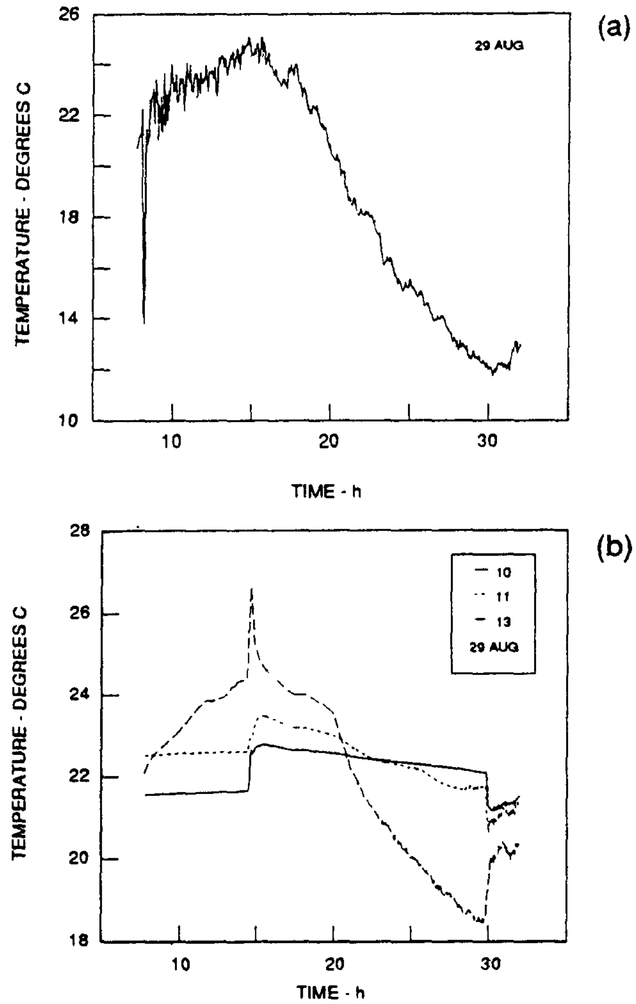

Figure 14. Time series of Array A thermistors measuring (a) air temperature and (b) vapor temperature obtained from data collected after product removal at 1441 on 29 August.

- The temperature and the rate of change of temperature measured on the horizontal arms extending from the midpoints of Arrays B (Thermistors 15, 25, 12) and A (Thermistors 27, 21, and 26) show that there is a horizontal gradient in the region between the tank wall and the centerline, and that it may be large enough to significantly affect the accuracy of temperature compensation if only the vertical portion of the array is used. The error could not be quantified given that there was only one horizontal arm on each array. Several arms at different heights would have been necessary.
- The rate of change of temperature in the vapor space of the tank, as measured by Arrays A and B in the 76-cm (30-in.) -diameter manways, reflected the rate of change of the ambient air temperature; this was as expected. On all three nights, 27, 29, and 30 August, the temperature of the vapor near the top of the tank (as measured by Thermistor 13 on Array A and Thermistor 0 on Array B) dropped below the temperature of the vapor closer to the product surface (as measured by Thermistor 11 on Array A and Thermistor 9 on Array B) and the upper layers of the product in the tank (as measured by Thermistors 17 or 10 on Array A and Thermistors 5 or 6 on Array B). Array B, located in the 10-cm (4-in.) -diameter opening at location C, which is 5.5 m (18 ft) away from Manway B containing Array A, did not show this same

behavior during tests initiated on 27 and 29 August. This suggests that the communication between the air and the tank is localized to the manway. This makes it difficult to interpret the influence of the vapor space on evaporation and condensation.

6.3.6 Temperature Profiles

To illustrate the gradient, profiles of the temperature field during the three overnight tests were generated from the data from Array A. (A 4-h wait after any addition or removal of product during the tests allowed the strong temperature fluctuations associated with such level changes to subside.) These profiles are shown in Figure 15. All three profiles are similar and are consistent with summer ground conditions. There is a very strong gradient in the bottom 50 cm (20 in.) of the tank and another near the top of the tank. The strength of the gradient near the bottom of the tank suggests that additional thermistors are necessary if the rate of change of temperature is to be accurately measured. During the summer the thermistors must be more densely spaced than they would have to be during the winter, when the profile would be more uniform from the top to the bottom of the tank.

The strong gradients support the propagation of internal waves. The volume and thermally induced volume data collected after 19 L (5 gal) of warm product was added to the tank at 0820 on 31 August show a strong 6-min periodicity in the data, an observation consistent with the presence of internal waves.

6.3.7 Thermal Volume Time Series

The data source for all estimates of the thermally induced volume changes in the tank was Array A. These time series were developed from Eq. (1) and are shown in Figure 16 for the three overnight tests on 27, 29, and 30 August and in Figure 17 for the two topping tests on 29 and 31 August. Data collection in all five cases started immediately after the level change had been completed. Since, as evidenced in the calibration, the ability of Thermistor 18 on Array A to measure temperatures above 20°C was suspect, Thermistor 19 on Array B was used in its place. Because of the horizontal gradients in the rate of change of temperature along the long axis of the tank, it was assumed that the temperature measured by Thermistor 19 would be in good agreement with that measured by Thermistor 18 after the strong initial temperature fluctuations had subsided.

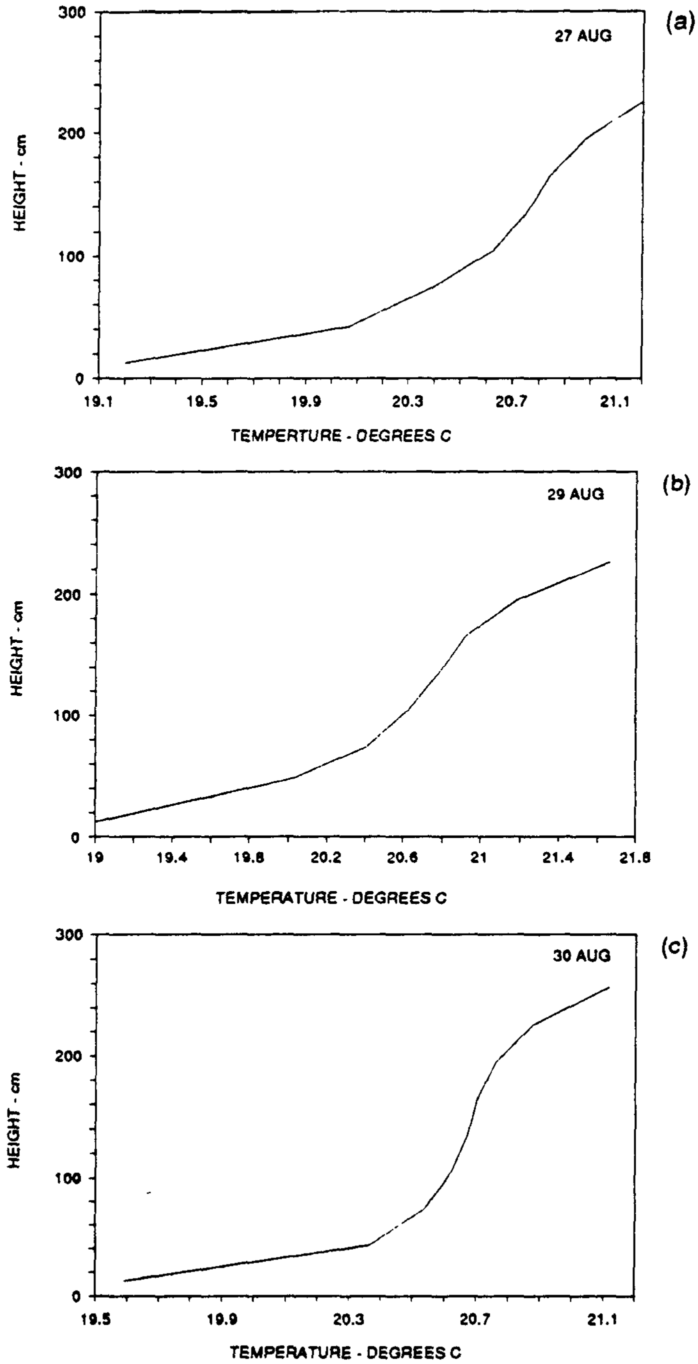

Figure 15. Vertical temperature profile computed 4 h after the initial level change at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August.

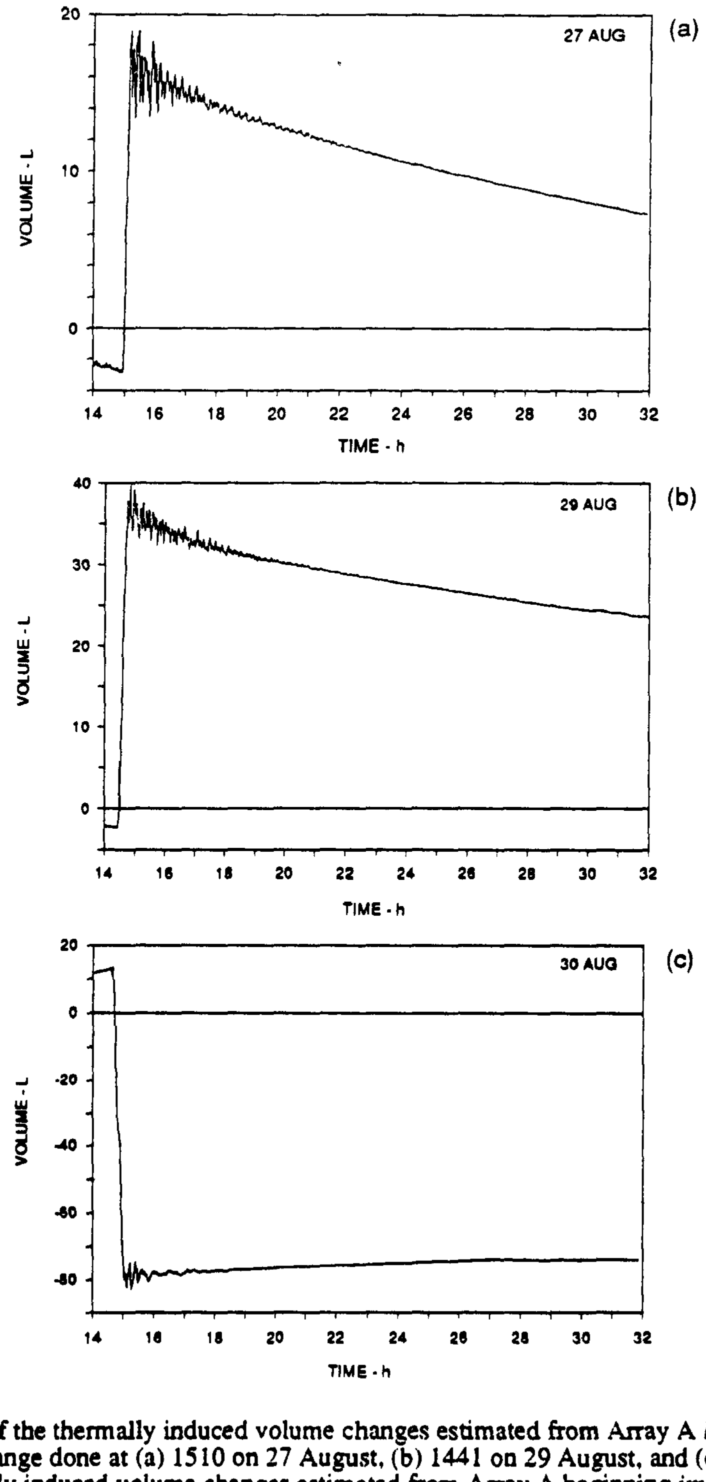

Figure 16. Time series of the thermally induced volume changes estimated from Array A *beginning 0.5 to 2 h before* the initial level change done at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August; time series of the thermally induced volume changes estimated from Array A beginning *immediately after* the initial level change done at (d) 1510 on 27 August, (e) 1441 on 29 August, and (f) 1505 on 30 August.

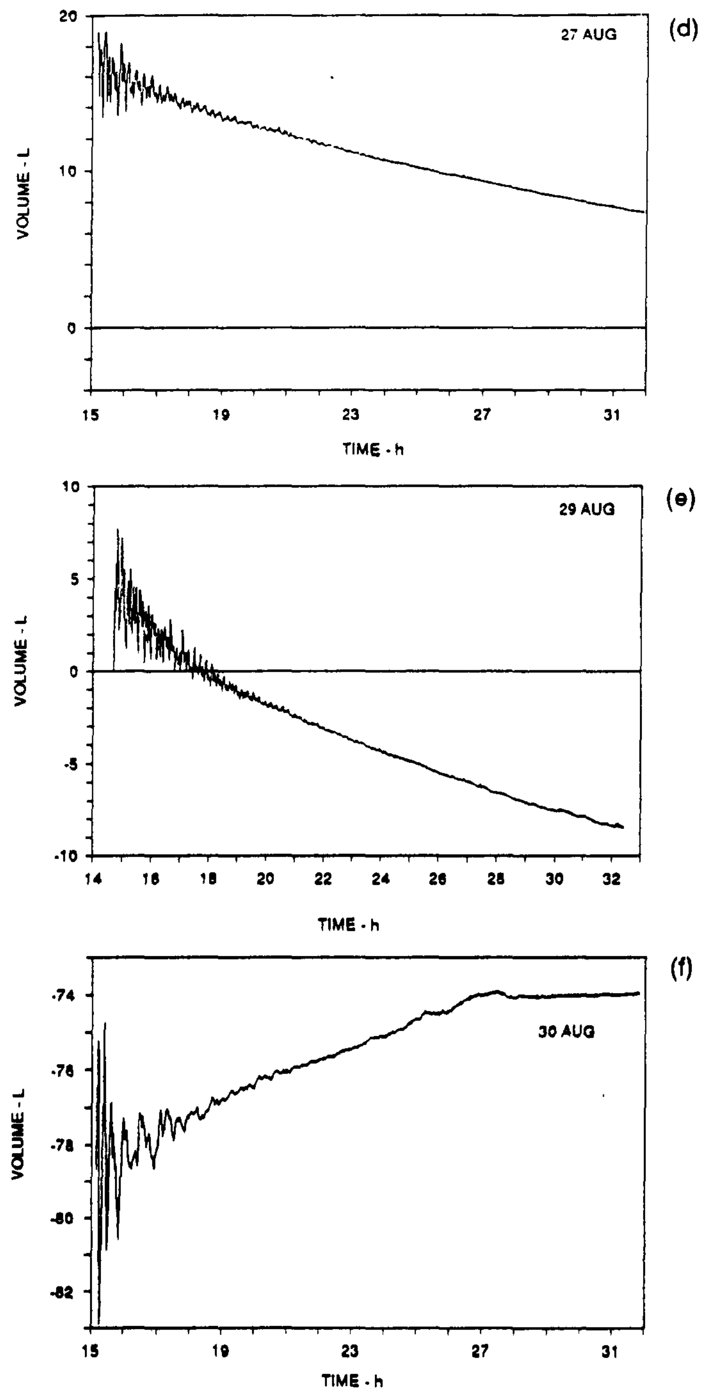

Figure 16 (concluded). Time series of the thermally induced volume changes estimated from Array A *beginning 0.5 to 2 h before* the initial level change done at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August: time series of the thermally induced volume changes estimated from Array A beginning *immediately after* the initial level change done at (d) 1510 on 27 August, (e) 1441 on 29 August, and (f) 1505 on 30 August.

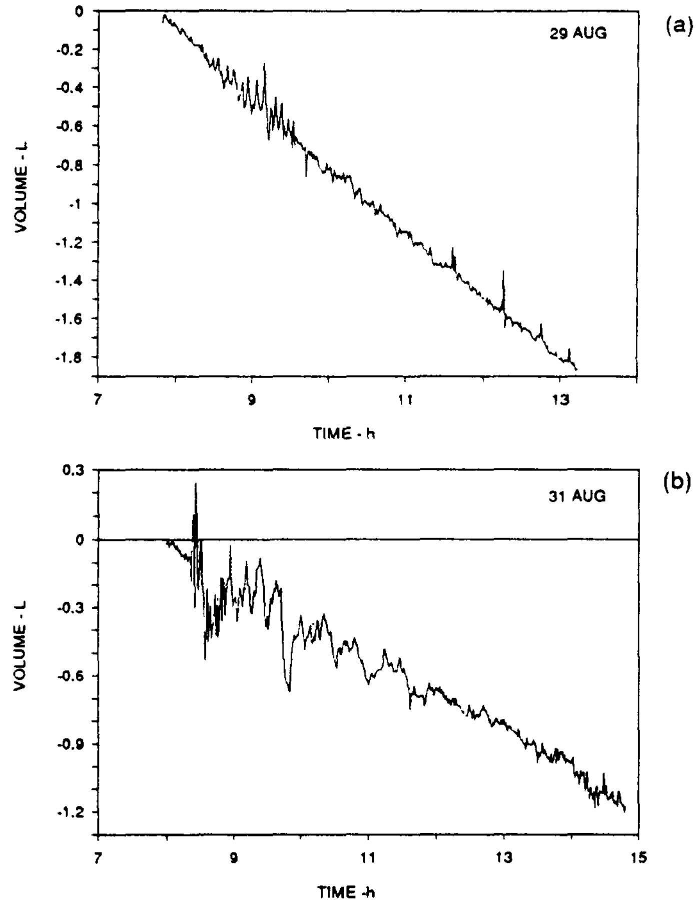

Figure 17. Time series of the thermally induced volume changes estimated from Array A beginning immediately after the addition of a small volume of (a) cold product to Tank 1 on 29 August and (b) warm product to Tank 2 on 31 August.

The temperature-volume time series developed after the product removals on 27 and 29 August show fluctuations of about 7.5 and 12 L (1 and 3 gal) during the 16-h test. The large volume fluctuations observed during the first 5 h of the time series are associated with vertical and horizontal mixing after product had been removed. The presence of large-amplitude, periodic internal waves is easily seen during the first 6 h in the 27 August time series; the period of these waves is approximately 7 min. The rate of change of volume is relatively large and is decreasing slowly over time.

The time series of the thermally induced volume changes estimated for the test begun after the product addition on 30 August shows an increase of about 4.5 L (1.2 gal) over the first 12 h before it levels outs abruptly at 2700. The increased level of temperature fluctuations is also observed during the first 6 h after the product addition. The abrupt shift in the thermally induced volume changes seems to be correlated with the abrupt shift in the temperature of the vapor during the same period.

6.3.8 Temperature-Compensated Volume Time Series

The temperature-compensated volume time series were compiled from the data from Array A. Figure 18 shows the time series for the topping tests initiated on 29 and 31 August, in which warm or cold product was added. Figure 19 shows the time series for the three overnight tests initiated on 27, 29 and 30 August, each of which followed a large product addition or removal. Several observations can be made about the temperature-compensated-volume time series shown in Figure 19.

- The effects of the strong temperature fluctuations that are associated with the addition or removal of product from the tank are present during the first 3 to 4 h of each time series.
- The distinct changes of volume observed in the volume time series were not removed by temperature compensation with the vertical portion of Array A.
- The fluctuations in volume have periods of 2 to 4 h.
- The data collected from Tank 1 on 27 and 29 August show that the rate of change of volume is still increasing long after the temperature effects due to product addition or removal have subsided; the data collected from Tank 2 on 30 August show that it is decreasing.

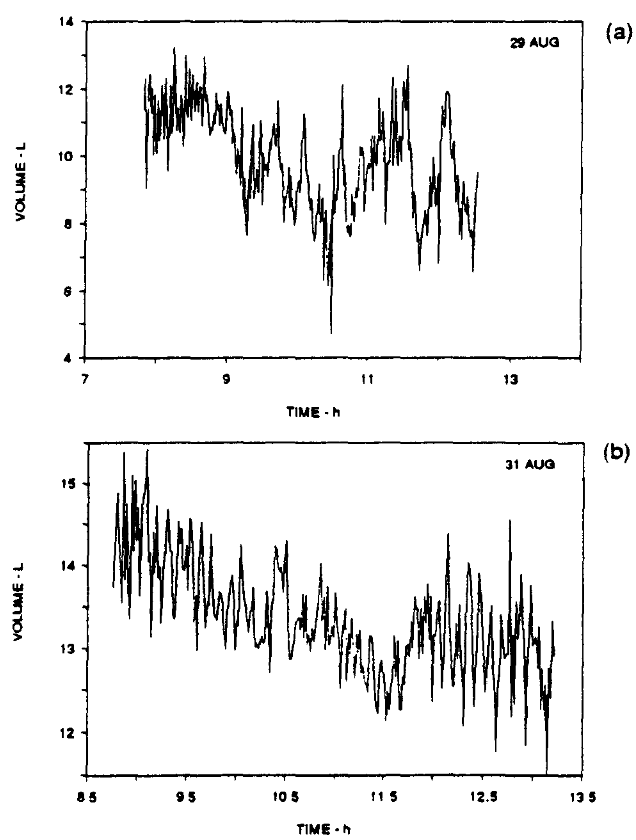

Figure 18. Temperature-compensated volume time series computed after the addition of a small volume of (a) cold product to Tank 1 on 29 August and (b) warm product to Tank 2 on 31 August.

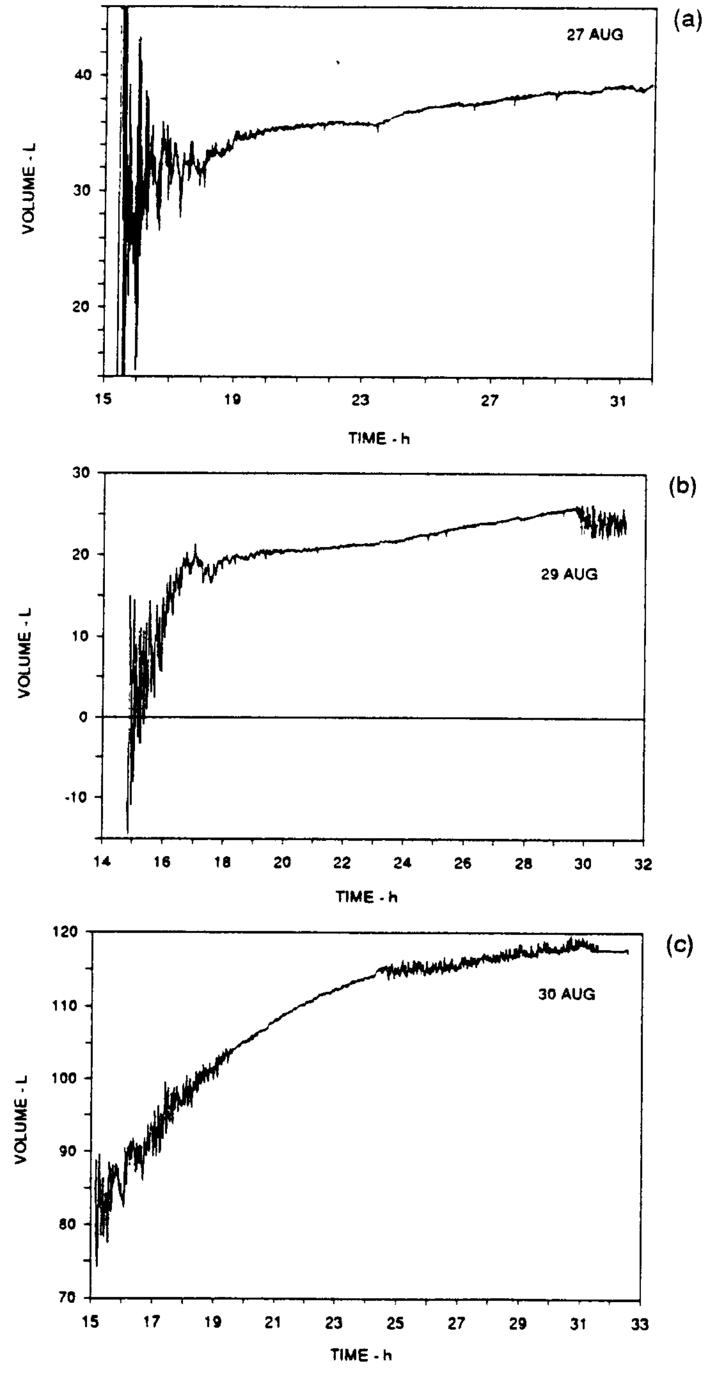

Figure 19. Time series of the temperature-compensated volume changes estimated with Array A beginning immediately after the initial level change at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August.

SECTION 7
SOURCES OF AMBIENT NOISE

An analysis of the data gathered in the experiments is presented below.

7.1 Surface Waves

Any disturbance of the product surface will generate a seich in an underground tank. A seich is a long wave whose fundamental period and higher harmonics are controlled by the boundaries of the basin. Waves will propagate both along the long axis of the tank and across its short axis. In a closed tank, wind blowing across the vent tube will create pressure fluctuations in the tank, which will generate waves. Any manmade disturbance, such as those that occur when equipment is inserted into or removed from the tank, will also create waves. Long waves can also be present in the product at places where the temperature (i.e., density) is high. At times, these internal waves can have enough energy to effect surface waves.

The fundamental frequency of the waves (and their higher harmonics) is predictable [13]. The period, T, of long waves in a rectangular basin in which the width is very much smaller than the length can be estimated by

$$T = (2\,L) / (g\,h)^{0.5}\,, \tag{1}$$

where n = 1, 2, 3, ..., L is the length of the tank (23.6 m (77.5 ft)), h is the height of the product in the tank (284 cm (111.75 in.)), and g is the acceleration due to gravity. In the Griffiss experiments, the fundamental frequency (n = 1) estimated with Eq. (1) is 8.95 s. It is also possible to predict the frequency of the surface waves produced by internal waves, but this is beyond the scope of this project.

The spectra indicate the presence of highly periodic waves in the 0.1- to 0.5-Hz region (2 to 10 s), typical of surface waves, and in the 0.001- to 0.1-Hz region (10 to 1000 s), typical of internal waves. The spectra in Figure 20 were smoothed in the frequency domain with a 10-point running average and were used to estimate the period of the waves with frequencies between 0.001 and 0.1 Hz. The period of the waves in the 0.1- to 0.5-Hz region was estimated with the spectrum after smoothing with a 25-point running average. Table 6 summarizes the periods of the main waves present in the tank. The spectra *suggest* that the fundamental (n = 1) and the first harmonic (n = 2) of waves propagating along both the long and short axes of the tank are present. The uncertainty in estimating the spectral peaks is several tenths of a second. In all cases the first harmonic (n = 2) is the larger wave. The fundamental and first harmonics for each pair of waves is also noted in Table 6. The experimental estimate of n for the first harmonic, which is estimated by dividing periods of the fundamental and the first harmonic, is also shown. The predominant period of the surface waves, which is between 8.1 and 8.4 s, is in reasonable agreement with the 9.0-s prediction for the fundamental period of waves moving back and forth along the long axis of the tank. Higher harmonics of the fundamental can be obtained by dividing the fundamental by 2, 3, 4, etc.

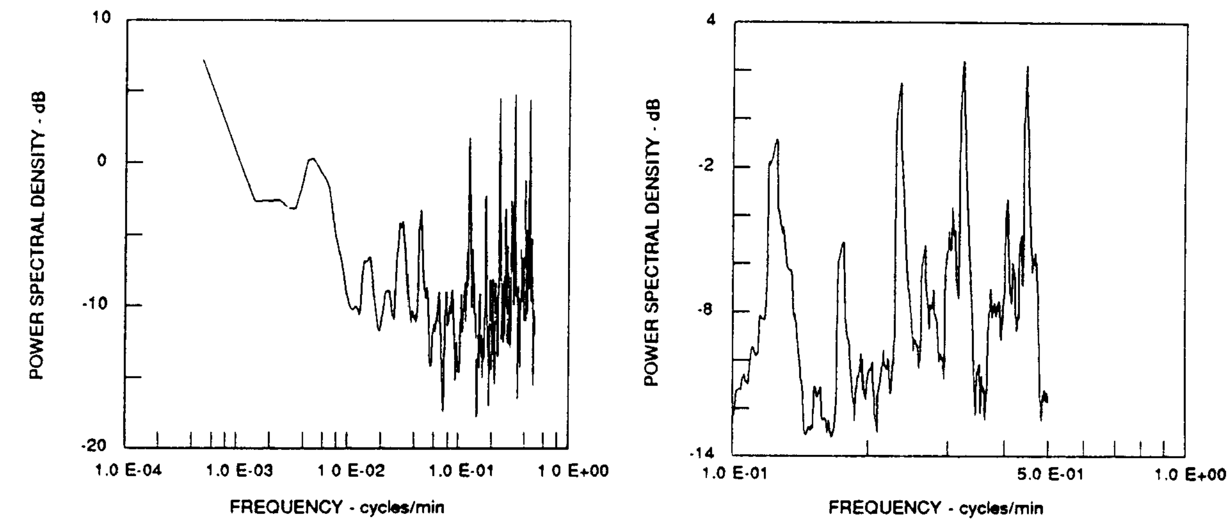

Figure 20. Power spectrum of the time series shown in Figure 11.

Table 6. Summary of the Periods of the Largest Waves Present in the 190,000-L Tank Filled to 283.8 cm (111.75 in.)

Wave Period (s)	Wave Frequency (Hz)	Wave Identification	Theory n	Meas. n	Generation Mechanism
188.4	0.0053		1	-	Internal Wave
63.1	0.0158	A - Long Axis	1	-	Internal Wave
42.9	0.0233	B - Short Axis	1	-	Internal Wave
31.9	0.0310	A - Long Axis	2	1.98	Internal Wave
22.1	0.0453	B - Short Axis	2	1.94	Internal Wave
8.25	0.121	C - Long Axis	1	-	Surface Movement
5.71	0.175	D - Short Axis	1	-	Surface Movement
4.27	0.234	C - Long Axis	2	1.93	Surface Movement
3.11	0.321	D - Short Axis	2	1.84	Surface Movement
2.25	0.443	?	-	-	Surface Movement

Because the amplitude of the waves can be large, equivalent to several liters of product, it is important during a leak detection test to sample the data at a high enough frequency to avoid aliasing, and to average the data over a long enough time to make an accurate estimate of the trend. To minimize the effects of aliasing, the data should be sampled at 1 s or better and averaged to 1 min. This will avoid aliasing the surface undulations produced by internal waves.

7.2 Temperature Inhomogeneities after Product Additions or Removals

Any addition and removal of product will alter the temperature field in an underground tank. The horizontal and vertical mixing of the product creates large temperature fluctuations that last for many hours. The horizontal gradients that develop make it difficult to accurately compensate for the thermally induced volume changes, because one array is not sufficient to measure the average temperature in the tank. The strong vertical mixing of product also prevents accurate estimates of the mean temperature changes in the tank, because the fluctuations are too large to permit an accurate estimate of the rate of change of temperature. These large temperature fluctuations can be observed in the raw temperature time series, the thermally induced volume time series, and the temperature-compensated time series. The temperature-compensated time series is also affected by the evaporation and condensation that occurs during the period of strong gradients because of the nonsaturated condition that is created as vapor is pushed out of the tank or air is drawn into the tank. Evaporation and condensation can be significant until a saturated condition is re-established in the tank; although no measurements of the evaporation and condensation were made in these experiments, it is known that a saturated condition will generally not be reached until fluctuations in product temperature have subsided.

7.2.1 Temperature Inhomogeneities after a Product Delivery or Product Transfer

The temperature fluctuations that occur immediately after product has been added to or removed from the tank can be clearly seen in the thermally induced volume changes shown in Figure 16; these are from the overnight tests conducted on 27, 29 and 30 August. The temperature fluctuations can also be observed in the raw temperature time series presented in Appendices A through C. The temperature fluctuations are particularly large for the first 3 to 4 h. During this period, any attempt to compensate for the thermally induced volume changes would result in large errors. This can be verified by inspection of the temperature-compensated volume time series presented for these three tests in Figure 18.

The level and duration of the temperature fluctuations observed in these tests are nearly identical to those observed in tests conducted on the 30,000-L (8,000-gal) tanks at the Test Apparatus and presented in [3, 4]. The data suggest that it takes at least 4 h for the temperature fluctuations to subside.

7.2.2 Temperature Inhomogeneities after Topping

Topping is a common practice with all volumetric leak detection systems that require that the tank be overfilled for a test. The temperature effects due to topping were investigated by adding 19 L (5 gal) of product that was approximately 25°C warmer or 8°C cooler than the product in a partially filled tank. The warm topping experiment was conducted at the end of the overnight test that began on 29 August; at the time of the topping nearly 21 h had elapsed since the beginning of the test. The cold topping experiment was conducted at the end of the overnight test that began on 30 August; in this case nearly 17 h had elapsed since the beginning of the test. Figure 21 shows raster displays of the temperatures measured on Array A. In these displays, the mean from the time series of each thermistor was removed and an offset of 0.02°C greater than that of the thermistor below it was added. In Figure 21 (a) and (b) the temperature fluctuations take approximately 2 h to subside after the addition of the cool product, and in Figure 21 (c) and (d) they take slightly longer than 3 h to subside. The temperature fluctuations can also be observed in the thermally induced volume time series shown in Figure 17 and the raw temperature time series presented in Appendices D and E. It is important to note that when the cold and warm topping tests were done, the tanks had not been disturbed for a long period of time. During this time, the mean rate of the thermally induced volume change had decayed to less than 0.38 L/h (0.1 gal/h), and it is safe to assume that the volume changes due to residual deformation had become negligible. As a consequence, it was expected that the temperature-compensated volume rate would approach zero.

Figures 17 and 19 present time series of the thermally induced volume changes and the temperature-compensated volume changes for both topping experiments. When a waiting period of 2 h was used, the temperature-compensated volume rate for the 29 August cold topping test was 0.04 L (0.01 gal/h), and for the 31 August warm topping test, -0.04 L/h (-0.01 gal/h). When there was no waiting period, the temperature-compensated volume rates were -0.53 L/h (-0.14 gal/h) and -0.41 L/h (-0.11 gal/h), respectively. Part of the error in estimating the temperature-compensated volume rate during the first 2 h may be due to large volume changes that are effected by evaporation and condensation, which occur when the saturated vapor in the tank is disturbed (when the tank is opened to the ambient environment so that product can be added).

Since the data used in this analysis came from a partially filled tank, the volume of product added to the tank was not large enough to produce a level change that would induce significant deformation. In an overfilled tank, however, the addition of even a small volume of product can produce a large level change, and the effects of deformation must therefore be accounted for during a leak detection test. As in tests on the 30,000-L (8,000-gal) tanks at the Test Apparatus, temperature fluctuations of equal magnitude were observed in both arrays, which were separated by a distance of 6.1 m (20 ft).

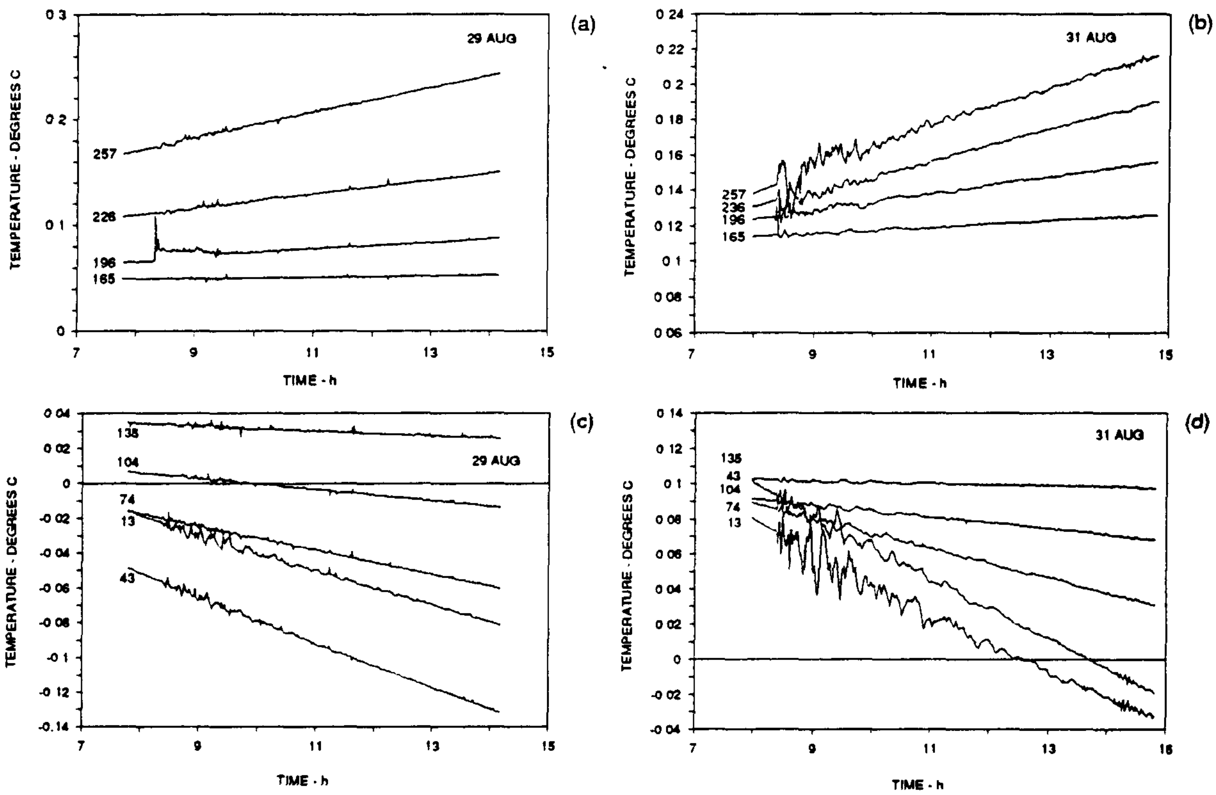

Figure 21. Raster display of the temperature-compensated volume time series under each of two conditions on different days: (a) cold product added to Tank 1 on 29 August and temperatures measured by upper four thermistors; (b) cold product added to Tank 1 on 31 August and temperatures measured by upper four thermistors; (c) warm product added to Tank 2 on 29 August and temperatures measured by lower five thermistors; and (d) warm product added to Tank 2 on 31 August and temperatures measured by lower five thermistors.

7.3 Horizontal Gradients

Accurate temperature compensation requires an accurate estimate of the average rate of change of temperature of the product in the tank. A single array of temperature sensors can be used provided that the horizontal gradients in the rate of change of product temperature throughout the tank are negligible.

7.3.1 Horizontal Gradient along the Long Axis of the Tank

To examine the horizontal gradients, the temperatures measured by each thermistor on Array A were differenced with those measured by the thermistors on Array B that were located at the same height. The horizontal separation between Arrays A and B was either 5.5 or 8.2 m (18 or 27 ft), depending on the test. Individual time series of the temperature differences during the overnight tests conducted on 27, 29, and 30 August are presented in Appendices A through C. The largest differences in temperature were generally less than ±0.001°C/h and showed no obvious bias in the vertical. Some differences showed an increase and some showed a decrease, suggesting that the errors are randomly distributed in the vertical. Because Thermistors 18, 1, and 2 were out of calibration, no estimate of the thermally induced volume changes could be calculated. However, the sum of all temperature differences along the vertical axis would probably be less than 0.001°C/h, which corresponds to an error of less than 0.19 L/h (0.05 gal/h) in a 190,000-L (50,000-gal) tank filled with product.

Thermistor 19 on Array B was used in place of Thermistor 18 on Array A for all estimates of the thermally induced volume. This substitution results in an error of less than 0.023 L/h (0.006 gal/h), as can be seen if the differences between Thermistors 17 and 5 (the two located directly above Thermistors 18 and 19) are measured.

7.3.2 Horizontal Gradient along the Short Axis of the Tank

The horizontal gradient in temperature and the horizontal gradient in the rate of change of temperature between the centerline of the tank and the wall of the tank were examined by comparing the temperature time series on the horizontal arm of each thermistor array. In all three overnight tests there is a difference of several thousandths of a degree per hour between Thermistor 27 on Array A and Thermistors 21 and 26 on Array A's horizontal arm (the two thermistors closest to the wall) and between Thermistor 15 on Array B and Thermistors 25 and 12 on Array B's horizontal arm (again the two thermistors closest to the wall). Large differences might be expected between the thermistors near the wall and those near the centerline. Because of the large volume of product, however, it is significant that there is a difference in the rate of change of temperature measured by the thermistors located in the middle of each arm (Thermistors 21 on Array A and 25 on Array B) and those closer to the center of the tank (Thermistors 27 on A and 15 on B). Figure 13 illustrates the amount of this difference during the overnight test initiated on 29 August; similar time series displays for the other two overnight tests (27 and 30 August) are presented in Appendices A and C. The thermistor closest to the wall shows that the mean temperature of the product and presumably that of the ground outside the tank is warmer than that of the product near the center of the tank. This explains why the temperature of the product is increasing in this region of the tank. Modeling calculations suggest that the differences in the rate of change of temperature will decrease over time, even though a difference in the mean temperature persists. This can be observed in the thermistor data taken during the topping experiments on 29 and 31 August. Except during the first 2 h after topping, the differences in the rate of change of temperature between thermistors on the arm are small.

The extent of the differences between the centerline and the first thermistor on the arm (Thermistor 27 on Array A and Thermistor 15 on Array B) cannot be accurately estimated because there is no thermistor located at the center of the tank at the same height as the arm. It was assumed that the rate of change of temperature at the centerline could be estimated by averaging the temperatures measured by the two thermistors bracketing the arm. Unfortunately, the arm was located in the region of the tank where the vertical gradient is large and the accuracy of the average is not known. The thermistor on the vertical portion of the array that is directly above the arm showed an increase in temperature over time and the thermistor below the arm showed a decrease.

7.4 Thermistor Spacing

The thermally induced volume changes estimated from thermistors spaced on 61-cm (24-in.) centers were calculated and compared to the estimates made from thermistors spaced on 30-cm (12-in.) centers. Array A was used in the calculations. The first calculation began with the thermistor closest to the bottom of the tank (Thermistor 20). The total number of thermistors in each estimate depended on the level of the product in the tank. Estimates made from the overnight test initiated on 29 August were based on 4 and 8 thermistors while those made from the tests initiated on 29 and 30 August were based on 5 and 9 thermistors. Figure 22 shows the thermally induced volume changes for the estimates made from the thermistors having a 61-cm (24-in.) spacing. A comparison of Figures 16 and 22 shows that there are large differences in the volume changes regardless of the spacing of the thermistors. The thermally induced volume time series made with 5 thermistors, from the test initiated on 27 August, suggests that the volume changes level off after 5 h; however, the time series made with 9 thermistors continues to show large volume changes. Slightly better agreement might occur if the bottom thermistor of the array having 61-cm (24-in.) spacing between thermistors were located 30 cm (12 in.) from the bottom of the tank rather than 13 cm (5 in.). The analysis suggests that 5 thermistors do not provide adequate thermal compensation in a 190,000-L (50,000-gal) tank.

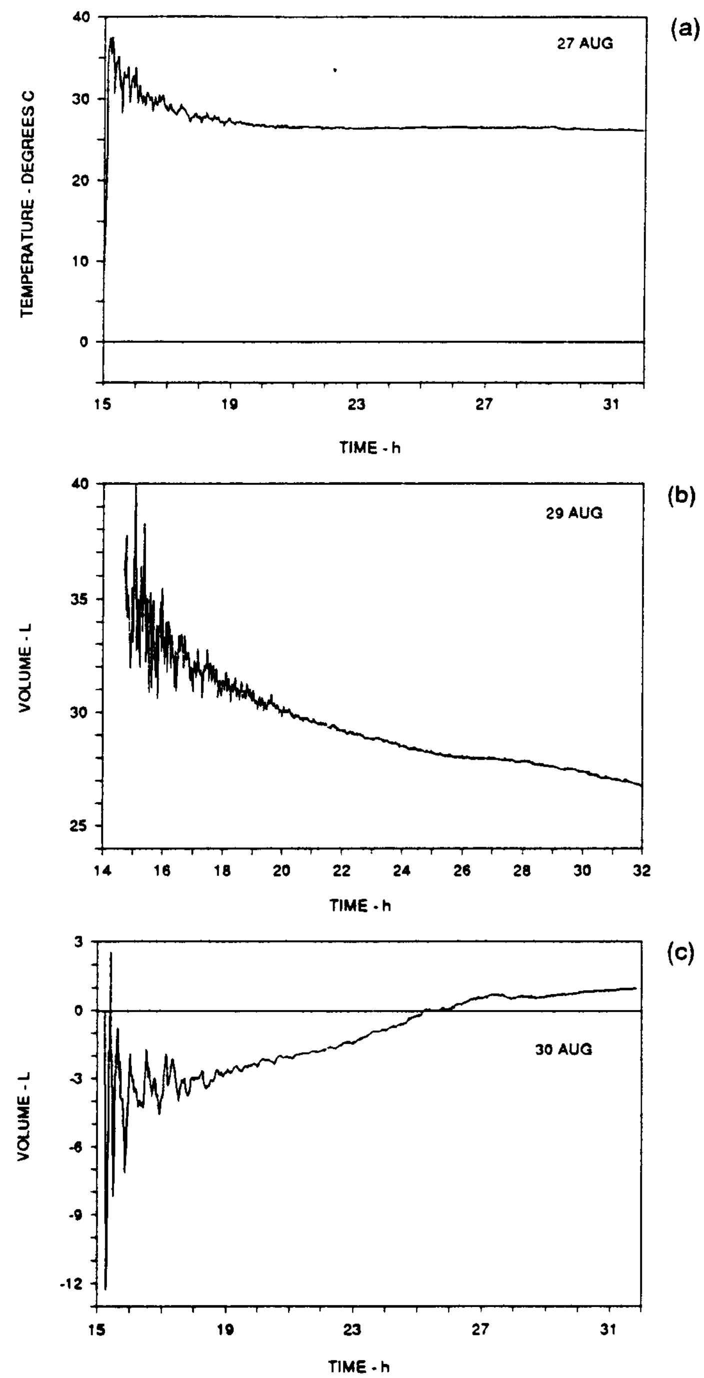

Figure 22. Time series of the thermally induced volume changes estimated by thermistors spaced at 24-in. intervals on Array A beginning immediately after the initial level change at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August.

7.5 Structural Deformation

If deformation is an important source of error in detecting leaks from a particular tank, the temperature-compensated volume times series will exhibit an exponential change in volume immediately after the level of the product in the tank has been changed [2, 3, 6, 13]. This behavior was not observed in the temperature-compensated volume time series of the three tests initiated on 27, 29, and 30 August, in which level changes of 29, 33, and 70 cm (11.25, 12.94, and 27.75 in.) were produced. These time series are shown in Figure 18. The strong temperature inhomogeneities produced immediately after product has been added or removed make it impossible to fit an exponential curve to the data to quantitatively estimate the time constant of the deformation (the time constant is the time required for 63% of the total volume change to occur). Also, as discussed in more detail in Section 7.8, the temperature-compensated volume estimates made for the first 10 h after the product addition or removal are controlled by the exponential error in compensating for the large thermally induced volume change in the layer closest to the bottom of the tank. Clearly, the dominating noise source centers around the thermally induced volume changes. A qualitative inspection of the data suggests that the time constant cannot be more than several hours, which is about the same as that observed in the 30,000-L (8,000-gal) tanks at EPA's UST Test Apparatus. These data suggest that after a waiting period of 6 to 10 h, structural deformation will no longer affect estimates of the temperature-compensated volume rate. It is important to note that the deformation observed in the large tanks at Griffiss Air Force Base does not differ significantly from that observed in tanks of smaller capacity. This is not unexpected; while a 190,000-L (50,000-gal) tank might be larger by a factor of 8 than a 30,000-L (8,000-gal) tank, important aspects of the tank's geometry, particularly its diameter, which controls end and wall deflection, are within 25% regardless of the size of the tank. The native soil surrounding the tanks in the Griffiss experiments is similar to the soil found around the tanks at the UST Test Apparatus. With only one set of tanks, it is not possible to generalize too much about the deformation. However, there is no indication that deformation is significantly greater in large tanks than it is in smaller tanks.

7.6 Evaporation and Condensation

The volume changes due to evaporation and condensation at the vapor/product and the wall/product interfaces are extremely difficult to quantify. At the present time, there is no simple measurement or combination of measurements that can be used reliably to identify or quantify the volume changes due to evaporation and condensation in an underground storage tank. This process is extremely complicated because it is not just the evaporation and condensation from the product surface that must be predicted, but the losses and gains from the tank walls. In general, contributions from the walls can be much larger than those from the surface. If the vapor is saturated, evaporation would be expected to increase as the temperature of the vapor relative to the temperature of the product increased or the pressure within the vapor space increased. If the vapor is not saturated, simple temperature and pressure measurements may not be sufficient to even indicate that volume changes due to evaporation and condensation are present.

The presence of evaporation or condensation can only be identified if the error in compensating for the thermal expansion and contraction of the product is small. Its presence is best identified when there is a distinct shift---one that cannot be explained by thermal fluctuations---in the measured temperature-compensated volume changes, or when there is a strong correlation between temperature and pressure measurements in the vapor space of the tank. The magnitude of these volume changes is best determined (1) after the volume time series has been accurately temperature-compensated, (2) after the effects of deformation and the temperature fluctuations associated with product addition or removal have subsided, and (3) after the vapors lost or gained when product is added or removed have reached a saturated condition. It is assumed that there are no other mechanisms, except for evaporation and condensation, that can generate large volume changes.

All of the data were extensively analyzed to determine if there were any simple and consistent correlations between atmospheric pressure, air temperature, vapor temperature, wind speed, and evaporation or condensation that were large enough to impact the accuracy of a leak detection test. The vapor temperatures measured in the 76-cm (30-in.) -diameter manways suggested that condensation was a dominant process and was responsible for the increase in volume still evident even 24 h after the start of each of the tests. Inspection of the vapor temperatures measured during each of the overnight tests, especially the 30 August test, shows a large decrease in the temperature within the vapor space, with the temperature of the vapor becoming colder than that of the product near the surface after 24 h. The data also indicate that the temperature in the vapor space becomes colder near the top of the tank than near the product surface, creating an unstable condition. The time at which the vapor temperatures became unstable or dropped below the product temperature is correlated with the time at which the volume changes dramatically increased. Similar temperatures were observed at both arrays during the 30 August test, when the arrays were located in 76-cm (30-in.) -diameter manways, but not during the 27 and 29 August tests, when one of the arrays was located in a 10-cm (4-in.) -diameter fill hole. Figure 23 illustrates these differences with data from the same thermistors on 29 and 31 August. The lowest thermistor in the vapor space was located within 5 cm (2 in.) of the surface, and the highest thermistor immersed in the liquid was located 25 cm (10 in.) below the product surface. The data collected on 29 August, from the thermistor array positioned in the smaller opening, suggest that the temperatures measured in the manways are localized in those manways. The array located in the manway detected an unstable temperature condition and a drop in the temperature of the vapor below that of the product, an indication that condensation was occurring. This did not happen when the array was placed in the smaller opening. While condensation was probably occurring at each of the three manways, it is not clear that condensation was also occurring at other locations in the tank. As a consequence, the vapor temperatures measured at the smaller opening were probably more representative of the vapor temperature within the tank as a whole. This is also suggested by the lack of correlation between the vapor temperature fluctuations and the volume fluctuations.

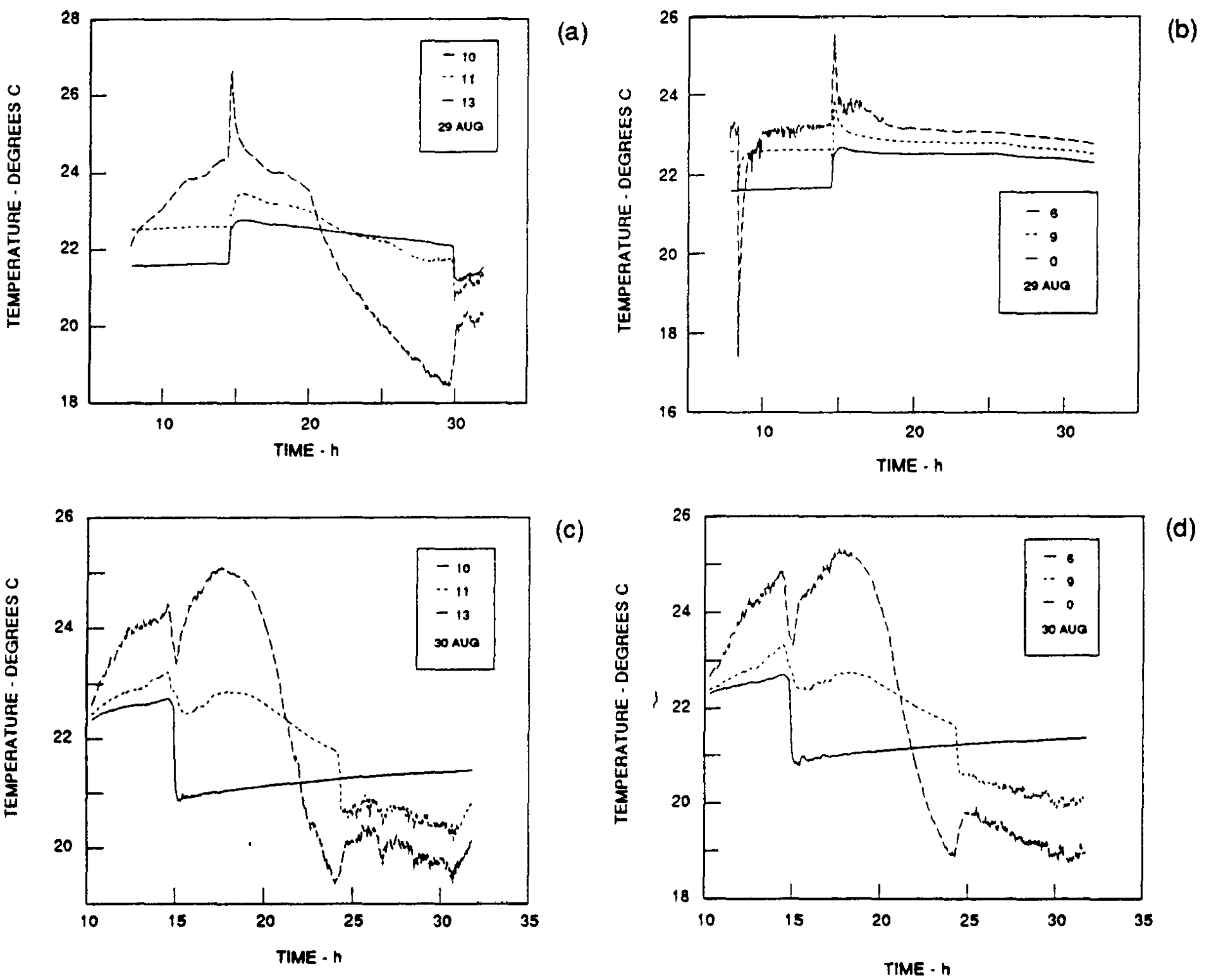

Figure 23. Time series derived from thermistors located in the vapor space and in the uppermost layers of product: (a) Thermistors 10, 11 and 13 on Array A on 29 August, (b) Thermistors 6, 9 and 0 on Array B on August 29, (c) Thermistors 10, 11 and 13 on Array A on 30 August, and (d) Thermistors 6, 9 and 0 on Array B on 30 August. On 29 August Array A was inserted in a 76-cm (30-in.) manway and Array B in a 10-cm (4-in.) fill hole; on 30 August Arrays A and B were inserted in two 76-cm (30-in.) -diameter manways.

7.7 Internal Waves

A frequency-domain analysis of the temperature data collected by the thermistors near the top and bottom of the tank suggests the presence of large-amplitude internal waves with periods ranging from 3 to approximately 30 min. Power spectra of the average of three thermistors during the warm topping test done on 31 August showed clearly defined spectral peaks at 3, 7, 18, and 25 min, or longer. Waves shorter than 2 min could not be observed because they were sampled at 1-min intervals; that they were present, however, is suggested by the level data. Slightly different wave periods were observed in the region near the top of the tank than in the region near the bottom of the tank. However, the 3-min waves were present in both, and the long-period waves were also present. These waves can introduce large errors if the data are not sampled fast enough to avoid aliasing and if the duration of a test is not long enough to average to two periods. The data suggest that a sample interval of 1 min and a test duration of several hours will suffice.

7.8 Residual Volume Changes after Temperature Compensation (Overnight Tests)

Accurate temperature compensation requires an accurate estimate of the average rate of change of temperature of the product in the tank. A single array temperature sensors can be used provided that the horizontal gradients in the rate of change of product temperature throughout the tank are negligible and that the vertical spacing of thermistors is dense enough to permit an accurate estimate of the average rate of change in each layer. Each layer must be thin enough that the change in temperature is linear within the layer and any errors in measuring the rate of change of temperature within the layer are small in comparison to the rate of change of volume. The largest errors occur when the layers are too thick or in those layers where the rate of change of temperature is largest or changes sense, usually the layers nearest the bottom and top of the tank. The larger the tank, the more significant these errors become, unless the volume of the product in each layer can be minimized through the use of additional thermistors. Errors that can affect the accuracy of temperature compensation are discussed in Section 9.

It is normally assumed that a leak detection test will result in an accurate estimate of the leak rate (1) after the volume changes due to deformation, product temperature fluctuations, and evaporation and condensation produced by product addition or removal have subsided, and (2) after the temperature contribution to the measured volume changes has been compensated for. For a partially filled tank, this assumption is valid provided that the effects of evaporation and condensation at the vapor/product interface and at the wall/product interface are small during a test. For an overfilled tank, the assumption is valid if the volume of trapped vapor is negligible. Accurate temperature compensation requires that the horizontal gradients in the rate of change of temperature be small enough that a single array of thermistors at any location along the centerline of the tank can be used for compensation. For an accurate estimate of the rate of change of temperature, the volume of product around each thermistor must be reduced, and to do this, an adequate number of thermistors is required.

In all three overnight tests, indications are that both tanks are tight, which means that the measured volume rate should be 0.0 L/h (0.0 gal/h). As observed in Figure 18, during the first 4 to 6 h after a product addition or removal, the temperature fluctuations are too large to permit an accurate estimate of leak rate or to allow us to determine if the effects of deformation are important. All three overnight tests began in late afternoon, between 1500 and 1600. If the three tests are examined in terms of a time line beginning at 0 h (the start of a test), it can be seen that the rate of change of the temperature-compensated volume exhibits a distinct shift at 19 h (approximately 4 h after the product addition or removal that occurred at 15 h) and again at 24 h and continuing on to 30 h. Figure 24 shows the same temperature-compensated volume data used to generate Figure 18, but enlarges an area of detail (the time between 18 h and 31 h). The data in Figure 24 were analyzed to determine why two distinct compensated volume rates were observed. The validity of the above-mentioned assumptions was investigated. The best estimate of leak rate would be provided by the data gathered during the second period, when the waiting period was longest; these estimates are presented in Table 7.

The temperature-compensated volume changes from the three overnight tests are discussed separately.

Table 7. Summary of the Leak Detection Results for Overnight Tests

Tank	Start Date	Start Time (h)	Nominal Level (cm (in.))	TCVR (L/h (gal/h))
1	8-27-90	24 - 29	262.3 (103.25)	0.36 (0.094)
1	8-29-90	24 -29	252.1 (99.25)	0.66 (0.172)
2	8-30-90	25.5 - 29.5	283.8 (111.75)	-0.22 (-0.057)

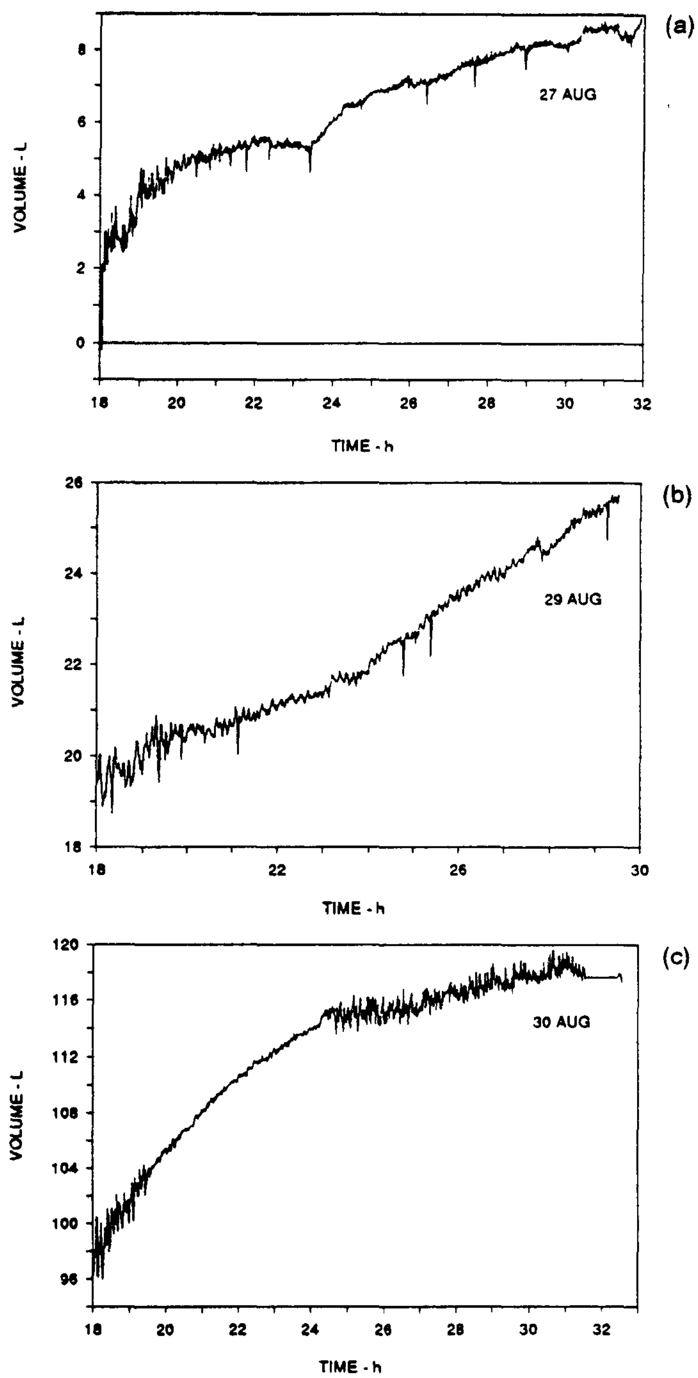

Figure 24. Time series of the temperature-compensated volume changes estimated from Array A beginning approximately 3 h after the initial level change done at (a) 1510 on 27 August, (b) 1441 on 29 August, and (c) 1505 on 30 August.

7.8.1 Overnight Test Starting on 27 August 1990

The period between 18 and 23 h on the time line suggests that the volume rate is approaching zero, as typically happens when deformation due to a rapid drop in product level is subsiding. However, at about 23.5 h, the temperature-compensated volume rate begins to increase and changes linearly at a rate of 0.31 L/h (0.08 gal/h) over a 6.5-h period between 24.5 and 31.0 h on the time line. This increase cannot be explained by deformation. It suggests that another mechanism is controlling the volume rate during both periods. As seen in Figure 16 (a), the thermally induced volume time series estimated from the vertical portion of Array A has a nearly linear change of approximately -0.4 L/h (-0.1 gal/h) between 18 and 31 h, much too large to account for the nearly 0-L/h (0-gal/h) volume changes observed in the volume time series shown in Figure 10 (a). In addition, the thermally induced volume time series does not exhibit the small-amplitude fluctuations observed in the volume time series. Inadequate temperature compensation or condensation of product could explain the observed 0.36 L/h (0.09 gal/h) temperature-compensated volume rate.

Since the tank was not leaking, the measured leak rate should have been 0 L/h. The 0.36-L/h (0.09-gal/h) error in measurement could have been reduced if the thermal volume changes had not decreased at such a fast rate. The shaded portions in Figure 25 indicate those regions of the tank where accurate temperature compensation is critical. In these regions, large horizontal or vertical gradients in the rate of change of temperature or an insufficient number of temperature sensors can produce errors large enough to affect the accuracy of temperature compensation. An error in estimating the temperature changes in one or more of these regions is the most likely cause of the 0.36-L/h error in the measurement of the leak rate.

In the overnight test initiated on 27 August, the largest errors in temperature compensation were likely to occur in the region near the bottom of the tank and near the walls of the tank. The error in the layer closest to the top of the tank was minimized because Thermistor 10 was located close to the surface (within 5 cm (2 in.) of it); thus, the rate of change of temperature in the upper 10 cm (4 in.) of the tank, which is due to heat transfer at the vapor/liquid interface, was accounted for. (In interpreting the overnight tests done on 29 and 30 August, it is important to note that the rate of change of temperature measured by Thermistor 10 is much greater than that measured by the thermistor located immediately below it.) As suggested by the time series of temperature for Thermistor 20 in Appendix A, the bottom region of the tank can be a significant source of error because the rate of change of temperature here is very large, as is the gradient in the rate of change. One thermistor is not enough to estimate these gradients, given their size. Inaccurate temperature measurement in the bottom layer explains almost all the error in the

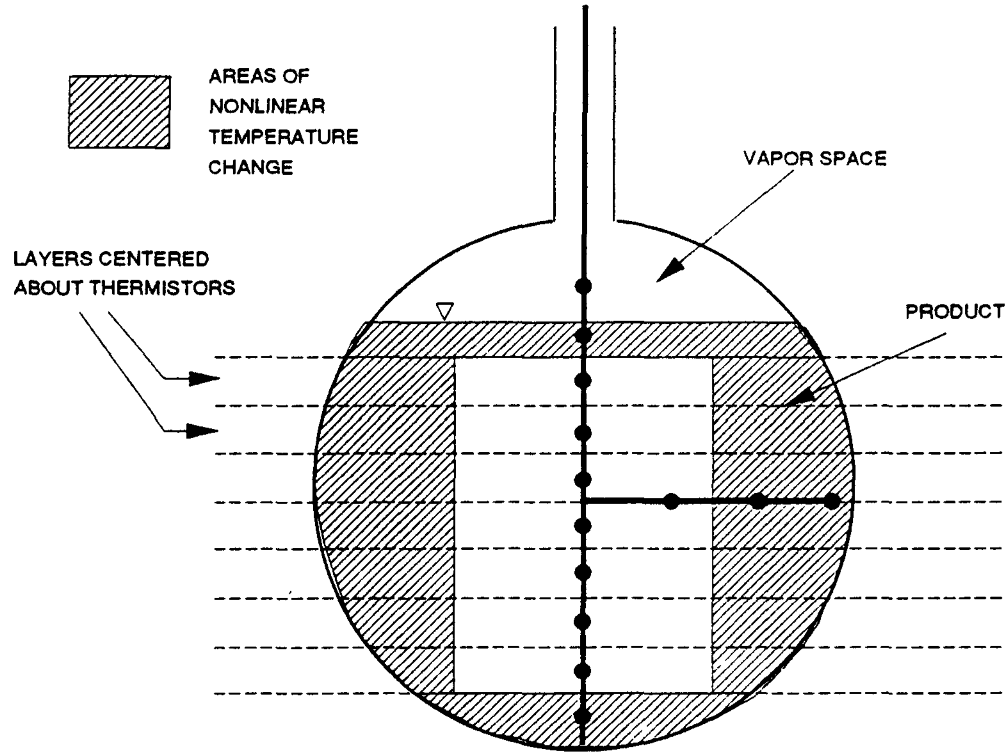

Figure 25. Accurate temperature compensation requires that the average rate of change of temperature be measured in four regions of the tank.

compensated volume rate during the first period, between 19 and 23.5 h on the time line. The discrepancy in the rate of change of temperature measured by Thermistors 20 and 22, the two closest to the bottom, suggests that the gradient in the bottom layer was large. Between 25 and 27 h on the time line, however, the discrepancy was negligible, and it can be assumed that by this time the thermally induced volume changes in the bottom layer were being accurately estimated. The error in the temperature-compensated volume rate during the second period might be explained by the horizontal gradient in the rate of change of temperature observed between the center of the tank and the wall, where an increase in the rate of change of temperature occurred between 24 and 31 h.

The time series displays of the temperature measured by the horizontal arms of Arrays A and B, shown in Appendix A, suggest that there are differences in the rate of change of temperature between the centerline of the tank and the tank walls. Beginning at about 23.0 h, the rate of change of temperature increased as the distance from the centerline to the wall increased; prior to this time, the rate of change of temperature was fairly uniform. The rate of change of temperature measured by Thermistor 21 was 0.0039°C/h, 0.0019°C/h greater than that measured by Thermistor 27. This would account for 0.201 L/h (0.052 gal/h) of the error in the temperature-compensated volume rate if this temperature change included 76,000 L (20,000 gal) of product. The rate of change measured by Thermistor 26 (the one closest to the wall) is about twice that measured by Thermistor 21 (the next thermistor in). The estimated contribution would be larger if it included the larger rate of change of temperature measured near the wall. This alone can explain the majority of the error. With only one horizontal arm, no quantitative estimate could be made. Additional arms at different levels along the vertical extent of the temperature array would have been required. Fortunately, a waiting period can resolve the problem; as noted in the discussion of the cold topping experiment, these horizontal gradients, as well as the vertical gradients near the bottom of the tank, had disappeared 21 h after the addition of product.

It is also possible that condensation, particularly from the wall, could have contributed to the residual volume changes, but there is no simple way to quantify the contribution or even to confirm this notion. Observations of temperature from Array A, located in the 76-cm (30-in.) manway at opening B, suggest that condensation occurred at 23.5 h on the time line, when the temperature measured by Thermistor 13 (in the vapor space) dropped below that measured by Thermistor 11 (located 12 in. below it), and also at 25.5 h when it dropped below that measured by the thermistor in the upper 5 cm (2 in.) of the product. However, this was not observed at Array B, located in the 10-cm (4-in.) -diameter opening at C. Here, the temperature measured by the immersed thermistors closest to the surface and the one 30 cm (12 in.) above the surface increased. This suggests that the temperature changes observed at the manway are not representative of the overall vapor temperature throughout the tank. The rate of change of temperature measured by the uppermost product thermistor was identical at both Array A and Array B, suggesting that the temperature change was governed mainly by the temperature differential between the product and the vapor. It is reasonable to conclude, therefore, that measurements of vapor temperature made in the 76-cm (30-in.) -diameter manways are representative of local conditions only and cannot be used as an indicator of vapor temperature in the tank as a whole.

7.8.2 Overnight Test Starting on 29 August 1990

The overnight test initiated on 29 August was similar to the one initiated on 27 August except that the product level was located 5 cm (2 in.) above Thermistor 10. Thus, the thermistor closest to the surface, Thermistor 17, was located 25 cm (10 in.) below the surface. Based on the observed rate of change in the 27 August data, it is likely that the temperature contributions near the surface, which are large, are not included in the estimates of the thermally induced volume changes used for compensation. In the 29 August test, the thermal contraction estimated in

Figure 16 (b) was greater than it should have been if the error had been due entirely to temperature compensation. In Figure 10 (b), measurements by the level sensor show that the volume decreased at a rate of -0.35 L/h (-0.091 gal/h) between 18 and 23.5 h on the time line and, after an abrupt change, increased at a rate of about 0.16 L/h (0.042 gal/h). The compensated volume rate also shows this distinct shift. The compensated volume rate for the period between 18 and 23.5 h is 0.38 L/h (0.099 gal/h); it increases abruptly to 0.70 L/h (0.18 gal/h) after 23.5 h. While the first period could reflect volume changes due to deformation that has not yet subsided, the increase in the compensated volume rate during the second period cannot be explained by the same mechanism. As with the 27 August overnight test, the increased rate again suggests that another mechanism is controlling the volume rate during both periods.

As with the overnight test done on 27 August, almost the entire error in the compensated volume rate during the first period, between 18 and 23.5 h, can be explained by an inaccurate estimate of the rate of change of temperature in the bottom layer. The data collected by the thermistors on the horizontal arm suggest that a portion of the error might also be explained by the increase in temperature as one moves from the centerline of the tank to the wall. By 25 or 26 h on the time line, however, the difference between the bottom two thermistors was negligible, and it can be assumed that the thermally induced volume changes near the bottom of the tank were being accurately estimated after 27 h.

The error in the temperature-compensated volume rate during the second period, between 23.5 and 29 h, might be explained by the horizontal gradient in the rate of change of temperature observed between the centerline and the wall of the tank, where the rate of change of temperature at Thermistors 26 and 21 during the second period was nearly twice the rate of change at Thermistor 27. The temperature change measured at Thermistors 26 and 21 was 0.004°C/h, while at Thermistor 27 it was 0.0022°C/h. Similar changes were observed in the arm on Array B. As in the 27 August test, this might account for 0.20 L/h (0.05 gal/h) of the 0.70-L/h (0.18-gal/h) error. Another portion of the error can probably be accounted for by the rate of increase in temperature near the surface of the product, which is not accurately represented by Thermistor 17, located 25 cm (10 in.) below the surface. Assuming the same rate of change of temperature in the upper 11.5 cm (4.5 in.) of the product (7258 L (1915 gal)) that was observed in the 27 August overnight test, this rate of change of 0.02°C/h would account for 0.15 L/h (0.039 gal/h) of the error. An analysis shows that the error in estimating the volume in the region between Thermistors 14 and 16, where the rate of change of temperature changes sense, is negligible.

The thermistors in the vapor space exhibited the same behavior as in the 27 August test. It is possible that there was condensation, particularly on the walls in the vicinity of the manways, but its total contribution cannot be estimated.

7.8.3 Overnight Test Starting on 30 August 1990

The overnight test that began on 30 August differed from the other two in that product was added to the tank and the thermally induced volume changes increased over time. Although this test was conducted in Tank 2 (whereas the 27 and 29 August tests had been conducted in Tank 1), there is no reason to believe that there were any substantial differences due to the change in tanks. As with the 27 and 29 August tests, the compensated volume rate showed a distinct change at about 24 h on the time line. The compensated volume change during the first period showed a large exponential increase until 24 h on the time line. At 24 h, the compensated rate and the fluctuation level changed abruptly. The compensated volume rate between 24 and 31 h was 0.57 L/h (0.15 gal/h). As in the 29 August test, the thermistor closest to the surface, in this case Thermistor 10, was located 25 cm (10 in.) below the surface.

As can be seen in Figure 24, the data show that fluctuations in the temperature-compensated volume rate increased at about 24 h on the time line. The reason for this remains unclear. The most likely explanation, that it was a response to weather changes, fails to provide a satisfactory answer. Usually, increased wave activity is associated with high winds. In this case, however, the wind was highest when the fluctuations were lowest, and vice versa. The thermistor monitoring the vapor space indicated a rapid decrease in temperature in the area above the product surface until 24 h on the time line, and then a leveling off until 31 h. As would be expected, the submerged thermistors showed cooler temperatures near the surface than farther down. (Thermistor 13, in the vapor space, gave a lower reading than the thermistors in the upper layers of product, but Thermistor 11, the submerged thermistor nearest the product surface (5 cm (2 in.) below it), gave a reading closer to that of Thermistor 13.) If the temperature measured by this one thermistor was not localized but was representative of conditions in the vapor space throughout the tank, it would indicate a high degree of condensation, which could be the cause of the increased fluctuation level. Although measurements of temperature made in the vapor space in the manways usually represent a highly localized phenomenon, the condensation explanation remains a possibility because the temperature in the vapor space was cooler than it was 25 cm (10 in.) below the surface. A final possibility is that the machinery in the pump house was turned on at about 24 h on the time line and that vibrations from this equipment induced a mechanical disturbance in the tank.

The exponential increase in the compensated volume rate during the first period, between 18 and 24.5 h, can be attributed to an error in estimating the mean rate of temperature in the bottom two layers. Thermistor 20 shows that the rate of change was exponential and was very high. By 27 h, the rate of change of temperature measured by the bottom two thermistors was approximately the same, suggesting that this source of error had diminished.

The compensated volume suggests that the product in the tank was expanding at a greater rate than estimated by the vertical array of thermistors. This could also be explained by the existence of horizontal gradients and the lack of a thermistor in the region immediately below the surface (during the 30 August test, product level was such that the uppermost submerged thermistor was 10 in. below the surface). As can be seen in the time series of the thermistors on the horizontal arm located on Array A in Appendix C, a horizontal gradient in the rate of change of temperature is present. However, there is no gradient in the rate of change of temperature measured by the thermistors on the arm attached to Array B. This is because Array B is located within 0.9 m (3 ft) of the end of the tank, so that all of the thermistors on the horizontal arm are being affected equally by the heat transfer from the end wall of the tank, as well as from the side walls. The temperature change measured by Thermistors 26 and 21 on Array A is 0.0073°C/h, over twice that measured by Thermistor 27 (0.0033°C/h). Assuming that this increase in temperature affects 75,800 L (20,000 gal) of product, this could account for 0.315 L (0.082 gal) of the 0.57-L/h (0.15-gal/h) change. As with the 29 August test, the uppermost submerged thermistor (Thermistor 10) is located 25 cm (10 in.) below the surface. It is difficult to determine the extent of the possible error in estimating the true rate of temperature change in this upper layer. However, it is likely that in the upper 11 cm (4.5 in.) of product, temperature would be increasing at a higher rate than in the area measured by Thermistor 10, a fact that would reduce the observed error in the compensated volume.

7.9 Residual Volume Changes after Temperature Compensation in Topping Tests

In both the cold and warm topping tests, the tank was filled to over 93% of capacity. As shown in Table 8, the temperature-compensated volume rates calculated after a 2-h waiting period were less than 0.05 L/h (0.013 gal/h). The duration of these tests was approximately 2.5 to 3 h, which may be a little shorter than would be desired for estimating the leak rate. The tests were done 21 and 17 h after product had been added to the tank. Inspection of the temperature time series shows that the horizontal and vertical gradients had dissipated, because the rate of change of temperature between adjacent thermistors near the top and bottom of the vertical array and along the horizontal array had diminished. Thus, the estimate of the thermally induced volume changes should be accurate. The compensated volume rate during the first 2 h after topping showed a decrease. While there was an increase in temperature fluctuations due to topping, it does not appear to change the overall linear trend in the thermal volume over the duration of the test. The error in the compensated volume is probably due to evaporation resulting from the manway being opened and the interior of the tank being exposed to the atmosphere. When the tank is opened, both unsaturated air entering the tank and saturated vapor leaving the tank will produce evaporation until such time as the vapor is saturated. In both morning tests, the air was at a much lower temperature than the vapor in the tank. Thus, the vapor, which was warmer than the air, escaped immediately from the tank and was replaced by the cooler air.

Table 8. Summary of the Topping Tests

Tank	Start Date	Start Time (h)	Nominal Level (cm (in.))	TCVR (ml/h (gal/h))
1*	8-29-90	10.3 - 13.2	253.0 (99.625)	36 (0.009)
2**	8-31-90	11.5 - 13.0	283.8 (111.75)	-43 (-0.011)

*Test begun 2 h after topping with product colder than product in tank

**Test begun after topping with product warmer than product in tank

7.10 Summary

The experiments yielded some important results that impact the performance of volumetric leak detection systems; these are summarized below.

- The temperature inhomogeneities produced by adding 19 L (5 gal) of product either 8°C cooler or 25°C warmer than the product in a nearly full tank persisted for 2 to 4 h. The temperature fluctuations were observed throughout the tank. It is not recommended that a leak detection test be initiated during this period.
- In a nearly full tank the temperature inhomogeneities produced by adding or removing 15,000 to 45,500 L (4,000 to 11,000 gal) of product were extremely violent and persisted for approximately 4 to 6 h. During this period, the temperature fluctuations were large enough to mask the deformation effects. The temperature fluctuations were observed throughout the tank. It is not recommended that a leak detection test be initiated during this period.
- After the temperature fluctuations due to product addition or removal had subsided, the differences in temperature along the long axis of the tank were generally less than

0.001°C/h. However, when only a single vertical array was used, the difference in temperature between the centerline of the tank and the walls of the tank remained large enough to affect the accuracy of compensation for at least 18 h.

- It was difficult to determine the duration of the deformation effects due to the errors in temperature compensation, but deformation effects did not appear to be large. Qualitative inspection of the data suggests that the time constant of the deformation could not have been larger than 1 to 2 h.
- The waiting periods required for the temperature inhomogeneities and deformation due to product addition or removal to subside in tests on 190,000-L (50,000-gal) tanks are the same in large tanks as in small tanks.
- The impact of evaporation and condensation on these test results is also difficult to assess, but their contribution to the error in the compensated volume rate appeared to be smaller than the error due to thermal expansion and contraction.
- The accuracy of temperature compensation increased as the number of temperature sensors increased. A minimum of 10 thermistors is recommended if the EPA requirements are to be met. Because of the large volume of product in the tank, one poorly calibrated or damaged thermistor or a small error in the coefficient of thermal expansion will significantly degrade the ability to compensate for the thermal expansion and contraction of the product.
- Both the fundamental and the first harmonic of surface and internal waves propagating along the long and short axes of the tank were observed. Peak-to-peak amplitudes of 0.5 to over 2 L (0.13 to over 0.52 gal) were observed.
- Internal waves with periods between 2 and 25 min were observed in the product. Internal waves were large enough after a manmade disturbance to affect the surface.
- Surface waves with periods of 2 to 10 s were observed propagating along the long and short axes of the tank. The spectra suggest that the first harmonic contained the most energy. Internal waves produced surface waves with periods of 20 to 190 s.
- Low-frequency fluctuations in the compensated-volume-rate data had periods of 0.5 to 2 h, which suggests that the minimum duration of a leak detection test be 4 h.

SECTION 8

TEST DURATION AND INSTRUMENTATION PRECISION

To meet the EPA performance standard for a tank tightness test, the instrumentation used to measure temperature and level in large tanks should not inhibit the detection of a leak of 380 ml/h (0.1 gal/h) and must allow for a P_D of 0.95 and a P_{FA} of 0.05. This requires that the instrumentation noise be sufficiently small that a one-standard-deviation uncertainty in the measurement of the rate of change of volume is less than 115 ml/h (0.03 gal/h). This 115-ml/h estimate assumes that the instrumentation noise is normally distributed with a zero mean and that the signal adds linearly with the noise. For instrumentation noise, the assumption of normality is generally justified. This estimate also assumes that the resolution of the sampled data is smaller than the standard deviation of the noise. Thus, the instrumentation or system noise estimated in terms of volume can be characterized by its standard deviation; the precision of the instrument is defined by the standard deviation of the instrument noise. If the resolution is greater than the inherent precision of the instrument, it is more difficult to characterize the performance of the instrument. To satisfy this data quality objective, the height and temperature sensors must have resolution and precision adequate to sense changes of 115 ml/h (0.03 gal/h).

The sensors, thus, must be able to measure changes to within a one-standard-deviation uncertainty of 115 ml/h (0.03 gal/h). To estimate the resolution and precision of these sensors, it is necessary to specify the *duration* of the test. For tanks less than 38,000 L (10,000 gal) in capacity (for which the EPA performance standard was developed), the duration of a test is usually 1 to 2 h. This is the minimum amount of time required to make a reasonable estimate of the rate of change of volume in the tank from level and temperature measurements. Larger tanks, which are usually only partially filled during testing, may require tests longer than 1 to 2 h, because the sensors required to measure level and temperature changes approach the technological limits of non-laboratory and affordable equipment. At present, most systems that are used to conduct a test on a partially filled tank are automatic tank gauging systems (ATGSs). The duration of tests conducted with ATGSs is typically 4 to 8 h. The precision of the level sensors is typically between 0.00025 and 0.0025 cm (0.00010 and 0.001 in.). In the Griffiss experiments, the duration of the measurements was based on the resolution and precision of the sensors being used [14].

8.1 Measurement of Small Level Changes

Tests conducted in half-filled tanks require the highest degree of precision because the height-to-volume ratio is lowest when the surface area of the product is greatest, as it is at the half-way point in the tank. A volume-change uncertainty of 115 ml/h (0.03 gal/h) in a half-filled

182,000 L (48,000 gal), 3.5-m (11.5-ft) underground tank will result in an uncertainty of 0.000174 cm/h (0.000069 in./h) in the corresponding product-level changes. The sensor precision required to measure a level change of 0.000174 cm/h can be estimated from

$$S_m^2 = n\, S^2 / (n\, \Sigma t^2 - (\Sigma t)^2) \quad (2)$$

where S_m = standard deviation of the slope of the least-squares line in centimeters per hour, S = standard deviation or precision of the sensor in centimeters, n = number of independent points (i.e., degrees of freedom), and t = time in hours.

Eq. (2) describes the one-standard-deviation error in the slope of a least-squares line fit to a number of independent points taken over a period of time in terms of the standard deviation of the ordinate (i.e., sensor precision). Eq. (2) can be used to estimate the minimum duration of the measurement required to obtain the desired S_m, given a sensor with a precision of S. Estimates made with Eq. (2) are valid providing that (1) the standard deviation of the sensor is greater than the resolution, and (2) each sample is independent. The standard deviation represents an estimate of the system noise or precision of the sensor. Eq. (2) can be used to estimate the minimum duration of a measurement made with a sensor whose precision is known, or it can be used to estimate the precision of a sensor given that the duration of the measurement period is specified. In general, the number of independent samples, and therefore the number of degrees of freedom, will be significantly less than the number of points acquired by the sensor, because ambient level and temperature data are highly correlated for periods less than 5 to 15 min.

Table 9 presents the level sensor precision required to obtain a specified S_m with measurement periods of 1, 2, 4, and 8 h. The way to use Table 9 is to match the precision, or standard deviation, S, of the sensor, found in the last column of the table, to the corresponding test duration shown in the first column; all corresponding elements in this table yield an S_m of 0.000174 cm/h (0.000069 in./h).

Table 9. Precision, S, of the Sensor Estimated at S_m = 0.000174 cm/h (0.00006786 in./h) for Different Measurement Periods (A level change of 0.000174 cm/h corresponds to a volume change of 115 ml/h (0.03 gal/h) in a half-filled, 182,000-L (48,000-gal) tank.)

Duration of Measurement (h)	Number of Independent Points (n)	Standard Deviation of Rate of Change of Sensor (S_m) (cm/h (in./h))	Standard Deviation of Sensor (S) (cm (in.))
1	13	0.000174 (0.00006786)	0.000196 (0.00007644)
2	25	0.000174 (0.00006786)	0.000523 (0.00019897)
4	49	0.000174 (0.00006786)	0.001435 (0.00055965)
8	97	0.000174 (0.00006786)	0.004000 (0.00156000)

For these calculations, it was assumed that the data were sampled once every 5 min. Thus, it was assumed that there are only 12 degrees of freedom (i.e., 12 independent points) each hour. If a level sensor with a precision of 0.0025 cm (0.001 in.) is used, the one-standard-deviation uncertainty in the measured level changes, S_m, is 0.00226 cm/h (0.00089 in./h) for a 1-h test with 12 degrees of freedom; this is equivalent to a volume change of 1,494 ml/h (0.395 gal/h) in a half-filled 182,000-L (48,000-gal) tank. Previous measurements of level and temperature in an underground storage tank suggested that the number of degrees of freedom might be as low as 3 or 4 each hour. As the number of degrees of freedom decreases, the duration of the measurement must increase or more stringent requirements must be placed on the precision of the sensor.

If the resolution of the level sensor is greater than the inherent precision of the measurement system, and the level changes are less than the resolution of the sensor, then the smallest level change that can be measured with a two-point estimate is a resolution cell divided by the measurement period. If the level changes are larger than a resolution cell, however, level changes can be estimated to better than a resolution cell by fitting a least-squares line to the data. The accuracy of estimating the rate of change depends on the number of resolution cells exceeded and the duration of the measurement. A better estimate can be made if we measure the time at which the level is located at intervals of one-half a resolution cell and fit a least-squares line to the data. The number of degrees of freedom is equal to the number of resolution cells minus 1. A more detailed discussion of how to estimate the performance of a system limited by resolution is given in [11].

8.2 Measurement of Small Temperature Changes

We can estimate, for both half-filled and completely filled tanks, the precision requirement of the product temperature measurement system assuming an uncertainty of 115 ml/h (0.03 gal/h) in the leak rate, a value of 0.00125/°C for the coefficient of thermal expansion, and a 182,000-L (48,000-gal), 3.5-m (11.5-ft) tank. A 115-ml/h volume change corresponds to a standard deviation of 0.0010 and a 0.00055°C/h rate of change of temperature in a half-filled tank and a full tank, respectively. Eq. (2) was used to estimate the thermistor precision required to obtain the specified standard deviation of the rate of change of temperature, S_m, in both a half-filled tank and a completely filled tank as a function of measurement period. This calculation also assumes that the number of independent degrees of freedom was 12 per hour. The results are presented in Tables 10 and 11. The minimum measurement period required to obtain a precision of 0.001°C is less than 1 h for the half-filled tank and approximately 1.5 h for the completely filled tank. If the test duration were 2 h or longer, the precision of the thermistors would not have to be as great (the precision could be higher than 0.001°C).

Table 10. Precision, S, of the Sensor Estimated at S_m = 0.0005°C/h for Different Measurement Periods in a Half-filled 182,000-L (48,000-gal) Underground Storage Tank

Duration of Measurement (h)	Number of Independent Points (n)	Standard Deviation of Rate of Change of Sensor (S_m) (°C/h)	Standard Deviation of Sensor (S) (°C)
1	13	0.0010	0.0011
2	25	0.0010	0.0030
4	49	0.0010	0.0084
8	97	0.0010	0.0233

Table 11. Precision, S, of the Sensor Estimated at S_m = 0.0005°C/h for Different Measurement Periods in a Full 182,000-L (48,000-gal) Underground Storage Tank

Duration of Measurement (h)	Number of Independent Points (n)	Standard Deviation of Rate of Change of Sensor (S_m) (°C/h)	Standard Deviation of Sensor (S) (°C)
1	13	0.0005	0.0006
2	25	0.0005	0.0015
4	49	0.0005	0.0042
8	97	0.0005	0.0116

SECTION 9
TEMPERATURE COMPENSATION

The recommended practice for compensating for the thermal expansion and contraction of product in a tank during a leak detection test is to estimate the average thermally induced volume change with an array of sensors that measure the change in temperature at many levels in the tank. The thermally induced volume change, Δv, is usually estimated from the following equation:

$$\Delta v = C_e \, \Sigma \, [(\Delta v_i/V) \, (\Delta v_i \, \Delta T_i)] \tag{3}$$

The product in the tank is divided into i layers, and the thermally induced volume changes, Δv_i, produced by the temperature change, ΔT_i, in each layer, are summed. The temperature sensors are uniformly spaced from the top to the bottom of the tank, and each layer is centered on a temperature sensor; thus, each layer has the same vertical dimension. Normally, only one value for the coefficient of thermal expansion, C_e, is used in the calculation. The tank chart is used to estimate the volume of product in each layer, v_i, and in the tank as a whole, V_1. The coefficient of thermal expansion is estimated from a table by means of API gravity measurements made with product samples taken from the tank. This method of compensation makes the following assumptions:

- **Assumption 1.** The number of temperature sensors (i.e., the number of layers) is sufficient to estimate the average rate of change of temperature throughout the vertical extent of the tank. Therefore, it is assumed that the rate of change of temperature measured at the center of each layer accurately reflects the rate of change of temperature throughout the layer, even at depths where the rate of change of temperature changes sense, where the gradients are largest (near the bottom or top of the tank), or where the sensor may not be centered in the layer (near the top of the tank).
- **Assumption 2.** The rate of change of temperature measured at each height in the tank is the same across the entire horizontal axis of the tank, i.e., only one vertical array is needed for compensation.
- **Assumption 3.** The coefficient of thermal expansion is the same in each layer, i.e., the coefficient of thermal expansion does not vary with depth.
- **Assumption 4.** The method used to estimate the coefficient of thermal expansion is sufficiently accurate that the required levels of compensation can be achieved.

- **Assumption 5.** The tank chart used to estimate the volume of product in each layer and the total volume in the tank is sufficiently accurate that the required levels of compensation can be achieved.
- **Assumption 6.** The temperature sensors have sufficient precision to measure the temperature changes occurring in each layer.

Eq. (3) indicates that any errors in the value of C_e or ΔT_i will vary with tank size. Errors in temperature compensation that were negligible in small tanks may be significant in larger tanks (those between 57,000 and 190,000 L (15,000 and 50,000 gal) in capacity). The key to accurate temperature compensation is to divide the tank into enough layers that the uncertainty in the thermally induced rate of change of volume estimated in each layer is small. This is particularly important in large tanks. For example, if five temperature sensors (the recommended number in a 30,000-L (8,000-gal) tank) are spaced at equal intervals in a 3.2-m (10.5-ft) diameter, 190,000-L (50,000-gal) tank, the layer of product surrounding each sensor is 64 cm (25 in.) deep and contains six times more product than the equivalent layer in the smaller tank. Since there is only one thermistor in each layer, the precision of this thermistor is very important. The greatest errors occur in the layers where the gradient in the rate of change of temperature is largest or changes sense, or where the temperature change is also great. The error in the estimate of the average rate of change of temperature in the layer is thus a function of the layer's thickness. Even a 30-cm (12-in.) vertical spacing between thermistors may be too much if the rate of change of temperature is very high.

The experiments suggest that the rate of change of temperature and the horizontal and vertical gradients in the rate of change of temperature occurring in the 190,000-L (50,000-gal) tank are about the same as they are in a 30,000-L (8,000-gal) tank. However, even though the rates are comparable, the volume of product in each layer is so much greater in a large tank that errors in temperature compensation can translate to errors in volume measurement that are 5 to 10 times greater than what they would be in a small tank. In a small tank, the effect of these errors on the test is negligible, whereas in a large tank it is significant.

The tables used to estimate the coefficient of thermal expansion were generated from measurements (made with a hydrometer) of the specific gravity of a large number of products. The coefficient is based not on a specific product but on many types of products having similar properties (e.g., different kinds of gasoline fuels). The tables have an uncertainty of 3.6%; therefore, the method used to estimate the coefficient of thermal expansion is accurate to 3.6%. The uncertainty is best illustrated in Figure 26, a plot of the raw data (i.e., the coefficient of thermal expansion at 15.56°C and the density of the product) used to generate the tables [15].

The tables are based on the least-squares line fit to these data. The one standard deviation about the ordinate is 0.000034/°C, which is 2.7% of the mean coefficient, and the one standard deviation about the abscissa is 10.2 kg/m^3, which is 2.4% of the mean density. The coefficient of thermal expansion at 15.56°C changes with density, which is estimated from specific gravity measurements. Any error in the tables stems from (1) incorrect measurements of specific gravity, (2) fluctuations of the data about each specific gravity, or (3) miscalculation of the coefficient of thermal expansion at temperatures other than 15.56°C. The fluctuation about each specific gravity is a function of the many different products used in the analysis. If the specific gravity is accurately measured, then the error is mainly a function of the scatter about the line. To reduce this error, a new set of curves would have to be generated for specific fuels, or the coefficient would have to be determined directly from measurements of specific gravity more accurate than those made with a hydrometer. Assuming that there is a 3.6% error in the coefficient, the error associated with a 0.01°C/h change in the temperature of JP-4 fuel as measured by a thermistor in a 30-cm (12-in.) layer located at the center of a 190,000-L (50,000-gal) tank would be 0.009 L/h (0.0023 gal/h). This translates into a 0.072-L (0.019-gal/h) error if the tank is completely filled. In the tank chart used to estimate volume, there can be an uncertainty of as much as 5%. In practice, the error in the coefficient and/or the volume of the product used for compensation cannot be reduced without significant effort or cost.

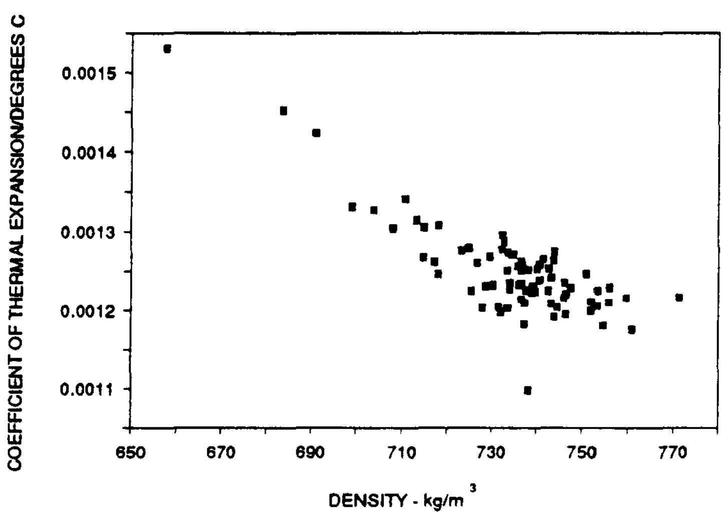

Figure 26. Scatter plot of the data used to estimate the coefficient of thermal expansion at 15.56°C. (Source: [15])

In larger tanks, the increased volume of product in each layer places greater importance on the instrumentation used to measure temperature. Even one malfunctioning sensor in the vertical array, or one that is out of calibration, would be sufficient to produce errors of 0.19 L/h (0.05 gal/h), which is the threshold normally used to declare a leak in a tank tightness test. Even if the rate of change of temperature is measured to within 0.001°C/h, a malfunctioning sensor would result in an error of 0.023 L/h (0.006 gal/h) in a 30-cm (12-in.) layer of product located near the center of a 190,000-L (50,000-gal) tank containing JP-4 fuel. If the error is random, the total error for 10 thermistors would be 0.003°C/h, which would result in an error of 0.061 L/h (0.016 gal/h).

Whether the error in estimating the thermally induced volume change involves one layer, several layers, or the entire tank, compensation becomes a problem only if this error is large. Errors in temperature compensation can be minimized by increasing the number of thermistors and by waiting long enough before starting a test that the potential error is less than a given value, e.g., the threshold used to declare a leak. Since the rate of change of temperature and the gradients in temperature decrease over time, the error will also decrease over time. Enhanced software, real-time temperature measurements, and additional sensors are required. More accurate temperature compensation is achieved if the rate of change of temperature during a test is low and if there are enough temperature sensors that the volume of product in each layer is small. The number of temperature sensors now used for temperature compensation in 30,000-L (8,000-gal) tanks will not suffice in tests on 190,000-L (50,000-gal) tanks.

Inaccurate temperature compensation can be due to any combination of the following errors.

(1) **Error Due to Too High a Rate of Change of Temperature.** If the rate of change of temperature is too high, accurate temperature compensation cannot be achieved. When the rate of change is acceptably low, compensation can remove 90 to 95% of all the thermally induced volume changes in any given layer or in the tank as a whole. Under optimal circumstances, it can remove up to 99%.

(2) **Error in the Coefficient of Thermal Expansion.** Since any error in C_e is magnified as the volume of product in the tank increases, the only way to minimize this error is to conduct a test only when the rate of change of temperature is less than a given value. It is possible to estimate the potential error thanks to three factors: the uncertainty in C_e is known, the volume of the product in the tank is known (it is derived from the tank chart, assuming that this chart is accurate), and the volumetrically weighted average of temperature is measured during a test. The one-standard-deviation uncertainty in C_e is 3.6%.

(3) **Error in the Volume of Product in the Tank.** An error in estimating the volume of product in the tank that stems from an inaccurate tank chart has the same effect as an error in C_e, because it magnifies any errors in estimating the rate of change of temperature. The error in a tank chart can be as much as 5% of the total volume of product in the tank.

(4) Error Due to Horizontal Temperature Gradients along the Long Axis of the Tank. Any horizontal differences in the rate of change of temperature will limit the accuracy of temperature compensation. Because only one array is used for compensation, it is not possible to estimate this error during a test. Available data suggest that horizontal differences in temperature along the centerline of a tank are less than 0.001°C/h.

(5) Error Due to Horizontal Temperature Gradients between the Center of the Tank and the Tank Wall. In the Griffiss experiments, horizontal differences in temperature near the tank wall were greater by a factor of 2 than those measured near the centerline of the tank. A waiting period that is long enough for the horizontal gradients to become negligible is the only way to minimize this error; at least 24 h is the recommended length of time. A shorter waiting period may be used if real-time measurements are made with one or more horizontal temperature arrays, so that the point at which horizontal gradients have sufficiently dissipated can be identified.

(6) Error Due to Significant Vertical Gradients. It is assumed that the rate of change of temperature varies linearly with depth. If the rate of change of temperature fluctuates rapidly in the vertical, and particularly if the sense changes, one or more layers can be subject to large errors. The potential error can be estimated by comparing the measured rate of change of volume within a layer to the interpolated rate of change of volume in the layers bracketing it. The error can be corrected by increasing the number of layers (i.e., thermistors) or by adjusting the position of either the array or the thermistors on the array.

(7) Error Due to Temperature Sensor Characteristics. The accuracy of temperature compensation is also limited by the precision of the temperature sensors. If the rate of change of temperature in each layer surrounding a temperature sensor is uncorrelated with the layers bracketing it, then the total error due to adding the contributions from each layer is equal to the average precision of the temperature sensors on the array; if, on the other hand, there *is* a correlation, the total error is greater than the average precision. Providing that the temperature changes that occur in each layer are greater than the resolution of the sensor, the total error can be reduced by increasing the duration of the test. Frequent and accurate calibration of the sensors is essential. The required precision of the sensors can be estimated from the procedure described in Section 8.

(8) Error Due to Sensor Malfunction. If one sensor malfunctions during a test in a small tank, the rate of change of temperature in that layer is sometimes estimated by linear interpolation from the sensors in the bracketing layers. This is done when the number of sensors exceeds the minimum number needed to achieve a given performance. Tests in a 190,000-L (50,000-gal) tank should be redone if a sensor malfunctions.

(9) Error Due to Level Sensor Characteristics. The accuracy of the temperature-compensated volume also depends on the precision of the level sensor. The uncertainty in measuring the level of product over the duration of a test can be estimated with the approach described in Section 8. Since the height-to-volume conversion factor will change as a function of the amount of product in the tank, the effective uncertainty of the level sensor will change accordingly. The uncertainty of the level sensor is estimated from the height-to-volume conversion factor at the product level at which a test is to be conducted.

(10) Error in the Height-to-Volume Conversion Factor. An experimental estimate of the height-to-volume conversion factor is required for each leak detection test. The uncertainty in this estimate can be determined from the standard deviation of the level changes used to estimate the height-to-volume conversion factor. The total error is obtained by multiplying the standard deviation of the height-to-volume measurements by the rate of change of level measured during a test.

The magnitude of these errors can range from several thousandths to tenths of a gallon per hour. A 0.001°C/h error would result in a 0.197 L/h (0.052 gal/h) error in a 190,000-L (50,000-gal) tank containing JP-4 fuel.

The size of the error stemming from thermal compensation can be reduced if tests are conducted only when the rate of change of temperature is low. Since the rate of change of temperature generally decreases with time after a delivery, it is possible to wait until it has dropped below some given value before beginning a test. Many volumetric leak detection systems use this approach in testing small tanks. The other approach is to reduce the total volume of product in each layer by increasing the number of temperature sensors.

Temperature compensation is not the only error that can influence a leak detection test. Volume changes due to such factors as residual deformation and evaporation/condensation may also occur. However, the data collected during the Griffiss experiments suggest that the 24-h waiting period that allows the horizontal gradients to dissipate is also sufficient to allow the effects of deformation effects subside.

SECTION 10

IMPORTANT FEATURES OF A VOLUMETRIC LEAK DETECTION SYSTEM FOR TESTING LARGE TANKS

The important features of a volumetric leak detection system that is capable of meeting the EPA performance standards for testing large tanks (up to 190,000-L (50,000-gal) in capacity) are described below. They are nearly identical to the recommended features of systems designed to test smaller tanks (up to 30,000-L (8,000-gal)), except that (1) the minimum number of thermistors required for temperature compensation has been increased from 5 for a 30,000-L (8,000-gal) tank to 10 or more for a 190,000-L (50,000-gal) tank, (2) the minimum duration of a test has been increased from 1 to 2 h to 4 h or more, (3) the minimum waiting period required for the horizontal and vertical gradients to dissipate has been increased from 6 to at least 24 h, (4) the average rate of change of temperature in any one layer or in the tank as a whole is small enough to allow accurate temperature compensation, and (5) accurate experimental estimates of the constants necessary for converting level and temperature changes to volume are made. The 24-h waiting period also allows adequate time for structural deformation of the tank to subside (it may take 6 h in a 30,000-L (8,000-gal) tank) and for the violent temperature fluctuations that occur immediately after any addition or removal of product from the tank to flatten out (these last approximately 4 to 6 h). The data suggest that, if a test is initiated within 10 h of a product addition or removal, more than 10 thermistors are required for adequate temperature compensation, and the thermistors must be more densely spaced near the surface of the product and the bottom of the tank; however, if there is a waiting period of at least 24 h, 10 thermistors are sufficient. While the instrumentation requirements are no different for larger tanks than for smaller tanks, they are more difficult to achieve. A longer test duration can be used to offset a lesser sensor precision providing that the level and temperature changes exceed at least one resolution cell.

Horizontal gradients in the rate of change of temperature between the tank's centerline and its walls appear to be the controlling source of error in temperature compensation. A waiting period of at least 24 h is recommended so that this gradient has time to subside. Unless the temperature is sampled with a horizontal array of thermistors similar to the one used in these experiments, however, it will not be possible to assess whether even a 24-h wait is long enough. This is true even if the horizontal gradients are small. The only alternative to direct measurement of the horizontal gradient is to conduct additional tests. These are recommended as a means of determining whether the volume rate is decreasing over time in cases when the threshold is exceeded during the first test. A measured volume rate that is decreasing indicates that the waiting period is inadequate. Testing should not be concluded until the measured volume rate has approached a constant value. A properly designed multiple-test strategy will, in general, reduce the number of false alarms and missed detections for all sources of noise.

The important features of a volumetric leak detection system suitable for testing 190,000-L (50,000-gal) tanks are:

(1) The level and temperature instrumentation has a precision that permits measurements of volume changes 3.3 times smaller than the leak to be detected (i.e., the instrumentation must be capable of measuring leaks as small as 0.11 L/h (0.03 gal/h)).

- The precision of level sensor depends on how large the surface area of the product is. (If the tank is overfilled, the surface area is very small; if the tank is underfilled, the surface area is very large.)
- The precision of temperature sensor depends on the volume and type of product in the tank during a test.

(2) The test is conducted at a nearly constant pressure.

(3) The height-to-volume conversion factor, the coefficient of thermal expansion, and any other numerical constants are measured *experimentally*.

(4) Temperature sensors are spaced at intervals of 15 to 30 cm (6 to 12 in.), with denser spacing if vertical gradients are large; or, an equivalent method of temperature compensation is used.

(5) There is a waiting period after delivery which is sufficient to allow

- temperature inhomogeneities to become negligible (4 to 6 h)
- deformation to subside (0 to 24 h)
- horizontal gradients in temperature to dissipate (24 h or longer)

(6) There is a waiting period after topping which is sufficient to allow

- vertical temperature inhomogeneities to become negligible (generally 2 to 4 h)
- deformation to subside (0 to 24 h)

(7) The test duration is 4 h or longer.

(8) The sample rate is sufficient to achieve instrument precision and avoid aliasing (data are sampled at 1 Hz and averaged to 1 min).

(9) An upper limit is placed on the rate of change of temperature that can occur during a test.

(10) A multiple-test strategy is used to minimize the number of false alarms and missed detections.

SECTION 11

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