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Evaluation of volumetric leak detection systems for large underground tanks

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Abstract

The performance standard for tank tightness testing established by the U.S. Environmental Protection Agency (EPA) regulation requires that the systems used to test underground storage tanks be able to detect leaks as small as 0.38 L/h (0.1 gal/h) with a probability of detection of 0.95 and a probability of false alarm of 0.05. This standard was developed to address tanks nominally 30,000 to 38,000 L (8,000 to 10,000 gal) in capacity or less, but also applies to tanks as large as 190,000 L (50,000 gal). The accuracy of detecting leaks in tanks as large as 190,000 L (50,000 gal) is not well known, and very little data from which to make an assessment are available. To meet EPA's regulatory standards for tank tightness testing of petroleum fuel tanks, volumetric leak detection systems must be able to accurately compensate for thermally induced volume changes in the stored fuel. A field study was done to investigate the magnitude of these volume changes. Three 24-h experiments were conducted in two partially filled, 190,000-L (50,000-gal) tanks in upstate New York during late August 1990; product was either added to or removed from the tank to initiate each experiment. The study showed that the procedures used to compensate for the thermally induced volume changes that occur during a tightness test performed on small tanks are not adequate for tanks as large as 190,000 L (50,000 gal). The volume of product in such tanks is large enough to cause significant errors in the estimates of the thermally induced volume changes required for compensation; these errors stem from the presence of horizontal and vertical gradients in the rate of change of temperature. In smaller tanks, the average rate of change of volume due to horizontal gradients is negligible, and a single vertical array of five temperature sensors is sufficient to compensate for the effects of thermal expansion of the product in a 1- to 2-h test. In larger tanks, however, a single array of temperature sensors does not suffice unless certain conditions are met. First, the number of sensors must be increased to at least 10 to ensure that the vertical gradients are accurately measured. Second, an adequate time (at least 24 h) must be allowed for the horizontal gradients to dissipate. Third, the duration of a test must be increased to at least 4 h so that the instrumentation and ambient volume fluctuations can be averaged. Fourth, the average rate of change of temperature in any one layer or in the tank as a whole must be small enough to allow accurate temperature compensation. Finally, an accurate experimental estimate of the constants necessary for converting level and temperature changes to volume must be made. Based on these experiments, a procedure has been developed for temperature compensation in tanks with capacities of 190,000 L (50,000 gal).

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Introduction

The United States Environmental Protection Agency (EPA) regulation for underground storage tanks (USTs), published on 23 September 1988, specifies the technical standards and a variety of release detection options for minimizing the environmental impact of tank leakage [1]. The regulation states that any volumetric leak detection system used as a tank tightness test 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 or better. Volumetric 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. With several exceptions, the regulation applies to *shop-assembled* tanks, which range in size from small (a few hundred gallons in capacity) to very large, with no clearly defined upper limit.

The regulatory standards were based on the results of an extensive program of experiments conducted by the American Petroleum Institute (API) on 38,000-L (10,000-gal) tanks at retail stations to evaluate the performance of automatic tank gauging systems [2] and by the EPA on 30,000-L (8,000-gal) tanks at the EPA's UST Test Apparatus in Edison, New Jersey, to evaluate volumetric tank tightness tests [3–8]. Tanks found at many retail service stations are typically 30,000- to 38,000-L (8,000- to 10,000-gal) in capacity. Unfortunately, there is not enough information to determine whether volumetric leak detection systems can meet the regulatory standards when tests are conducted on tanks as large as 190,000-L (50,000-gal). The number of large tanks (defined 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.

Accurate tests are not possible unless the volume changes due to the thermal expansion or contraction of the product can be compensated for. Experiments conducted on the tanks at the UST Test Apparatus showed that a 1- to 2-h test with 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 providing that adequate waiting periods were observed after any addition of product to the tank. These waiting periods allow the large temperature fluctuations associated with any product addition (or removal) to subside, so that a single array of temperature sensors suffices to make 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 (as required when testing an overfilled tank) and 4 to 6 h or longer after a delivery were recommended; many leak detection systems use a 6- to 12-h waiting period after a delivery to allow the deformation-induced volume changes to become negligible. Since a 190,000-L (50,000-gal) tank contains more than five times the volume of a 30,000- to 38,000-L (8,000- to 10,000-gal) tank, the error in temperature compensation will be at least five times greater than in a smaller tank.

A set of experiments was conducted on two partially filled, 190,000-L (50,000-gal) underground storage tanks to determine if the method used to compensate for the thermal expansion and contraction of the product in 30,000- to 38,000-L (8,000- to 10,000-gal) tanks could be applied to these larger tanks. The results of these experiments are summarized here; additional details can be found in [9].

Temperature compensation

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 addition or removal of product preparatory to a test have subsided, and (2) after the thermal expansion or contraction of the product in the tank has been compensated for. For a partially filled tank, this assumption is valid provided that during a test the effects of evaporation and condensation at the vapor/product interface and at the wall/product/vapor interface are minimal. For an overfilled tank, the assumption is valid if the volume of trapped vapor is negligible.

Accurate temperature compensation requires a correct estimate of the average rate of change of temperature of the product in the tank. A single array of temperature sensors suffices provided that two conditions are met. The horizontal gradients in the rate of change of product temperature throughout the tank must be negligible, and the vertical spacing between sensors must be dense enough to permit an accurate estimate of the average rate of change in the layer of product surrounding each sensor. Assuming that the temperature field is horizontally uniform, each layer will then be thin enough that the change in temperature is linear within that layer, and a temperature sensor positioned in the middle of the layer will accurately measure the average rate of change of temperature throughout that layer. If the rate of change of temperature is not horizontally uniform at each level in the tank, even a very dense spacing of sensors will not provide accurate compensation.

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

$$\Delta v = \Sigma \Delta v_i = C_e \Sigma (V_i \Delta T_i) \qquad (1)$$

The product in the tank is divided into n layers, and the thermally induced volume changes, Δv_i, produced by the temperature change, ΔT_i, in each layer, i, are summed, as indicated by the summation Σ, from $i=1$ to $i=n$. 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. A tank chart is used to estimate the volume of product in each layer, V_i, where the total volume of the product in the tank $V=\Sigma V_i$. The coefficient of thermal expansion is estimated from a table by means of API gravity measurements made with product samples taken from the tank.

Equation (1) indicates that, in estimating the thermally induced volume changes in the product inside a tank, the error due to any miscalculation of the value of C_e or ΔT_i will increase proportionally with the volume of product in each layer and the number of layers in the tank. Errors in temperature compensation that are negligible in 30,000- to 38,000-L (8,000- to 10,000-gal) tanks may be significant in tanks as large as 190,000 L (50,000 gal). 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, and to wait until any horizontal differences in temperature within the layer are negligible. This is particularly important in large tanks, in which the volume of product can be substantial. As shown in Table 1, the volume of product in a 31-cm (12-in.) layer can exceed 22,700 L (6,000 gal), an amount nearly as large as the entire capacity of the typical tank on which volumetric leak detection systems are normally used.

TABLE 1

Summary of the volume of product surrounding each thermistor on Arrays A and B

Thermistor channel		Thermistor height (cm (in.))	Volume of product (L (gal))
Array A	Array B		
13	0	125 (318)	14,703 (3,884)
11	9	113 (287)	13,859 (3,661)
10	6	101 (257)	16,922 (4,470)
17	5	89 (226)	20,942 (5,532)
18	19	77 (196)	22,430 (5,925)
16	2	65 (165)	22,998 (6,075)
14	1	53 (135)	22,714 (6,000)
24	8	41 (104)	21,548 (5,692)
23	7	29 (74)	19,341 (5,109)
22	4	17 (43)	15,631 (4,129)
20	3	5 (13)	8,097 (2,139)

The API tables [10] used to estimate the coefficient of thermal expansion were generated from measurements 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 a one-standard-deviation uncertainty of 3.6%; therefore, the method used to estimate the coefficient of thermal expansion is accurate to 3.6%. 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 31-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. By comparison, when tests are done in 30,000- to 38,000-L (8,000- to 10,000-gal) tanks, the rate of change of temperature can be measured and compensated for with an accuracy that is five to six times better.

In addition, the tank chart used to estimate volume can have an uncertainty of as much as 5%, primarily because the actual length or diameter of the tank may differ somewhat from the nominal dimensions used to generate the chart. This 5% uncertainty corresponds to an error of 0.098 L/h (0.026 gal/h) if the residual temperature changes are 0.01 °C/h. In practice, there are inherent errors in measuring the coefficient of thermal expansion and the volume of product used for compensation, and these errors cannot be reduced without significant effort or cost. The best way to minimize such errors is to avoid testing until the average rate of change of temperature has decreased acceptably.

The shaded portions in Fig. 1 indicate schematically those regions of the tank subject to the largest errors in estimating thermally induced volume changes by means of a single temperature array. In these regions, large horizontal or vertical gradients in the rate of change of temperature, or an insufficient number of temperature sensors for measuring these gradients, can produce errors large enough to affect the accuracy of temperature compensation.

The product's rate of change of temperature is controlled by the heat transfer (1) between the product inside the tank and the backfill surrounding it and (2) at the vapor/liquid interface within the tank, commonly called the product surface. This means that the rate of change of temperature is different at the centerline of the tank than it is in the vicinity of the walls. The rate of change of temperature near the wall of a 190,000-L (50,000-gal) tank is approximately the same as that of a 38,000-L (10,000-gal) tank. However, in a 190,000-L (50,000-gal) tank the volume of product in the region near the wall is five times greater than it is in a 38,000-L (10,000-gal) tank. Thus, small differences in temperature between the centerline and the walls, even though they may be insignificant in terms of their impact on thermal compensation in smaller tanks, cannot be ignored in the case of larger tanks.

The layers near the bottom of the tank are particularly susceptible to large errors because the rate of change of temperature is often greatest in this

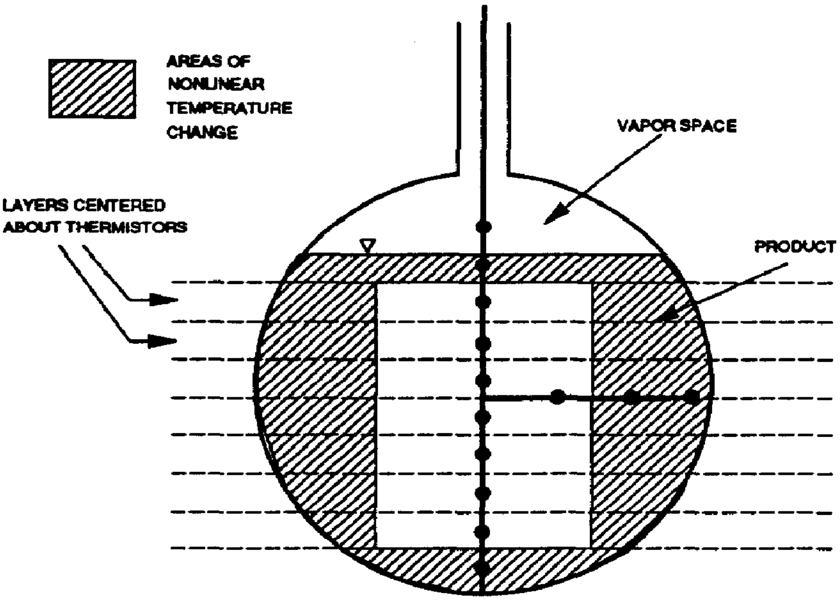

Fig. 1. Accurate temperature compensation requires that the average rate of change of temperature be measured in four regions of the tank.

region. The presence of groundwater at or above the bottom of the tank can complicate the product temperature field, because water has very different thermal diffusivity properties than the backfill and/or soil around the tank. Because of the curvature of the tank, the layers near the bottom are irregularly shaped, and it is difficult to estimate thermally induced volume changes with only one thermistor in the layer. In addition, the mixing that occurs when product is added to the tank in preparation for a test can significantly increase the rate of change of temperature in the bottom region. Large errors also occur in the layers near the surface of the product, especially because the temperature sensor in the uppermost layer is usually not centered in that layer. The greater the volume in the layer (whether at the top or bottom of the tank), the more significant the error will be. In general, the rate of change of temperature decreases over time as a state of thermal equilibrium develops between the product in the tank and the backfill and soil surrounding it. Thus, the accuracy of temperature compensation will improve as the number of temperature sensors increases (i.e., as the number of layers increase and the volume in each layer decreases) and as the waiting period between product addition and the start of the test increases. Increasing the waiting period is the only practical way to reduce the errors due to horizontal gradients. Any errors due to vertical gradients can be reduced by increasing the number of temperature sensors. Increasing the duration of the test and the precision of each temperature sensor reduces the error due to both types of gradients.

Experiments

The experiments were conducted in two nonleaking 190,000-L (50,000-gal) underground steel storage tanks containing JP-4 fuel. The tanks were located at Griffiss Air Force Base in upstate New York and were normally operational. 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 the data collected were lost due to a power outage caused by an electrical storm.

Configuration of the tanks and instrumentation

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. For the purposes of these experiments, the two tanks were designated as Tank 1 and Tank 2. Figure 2 is a cross-section of the tanks; each tank 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

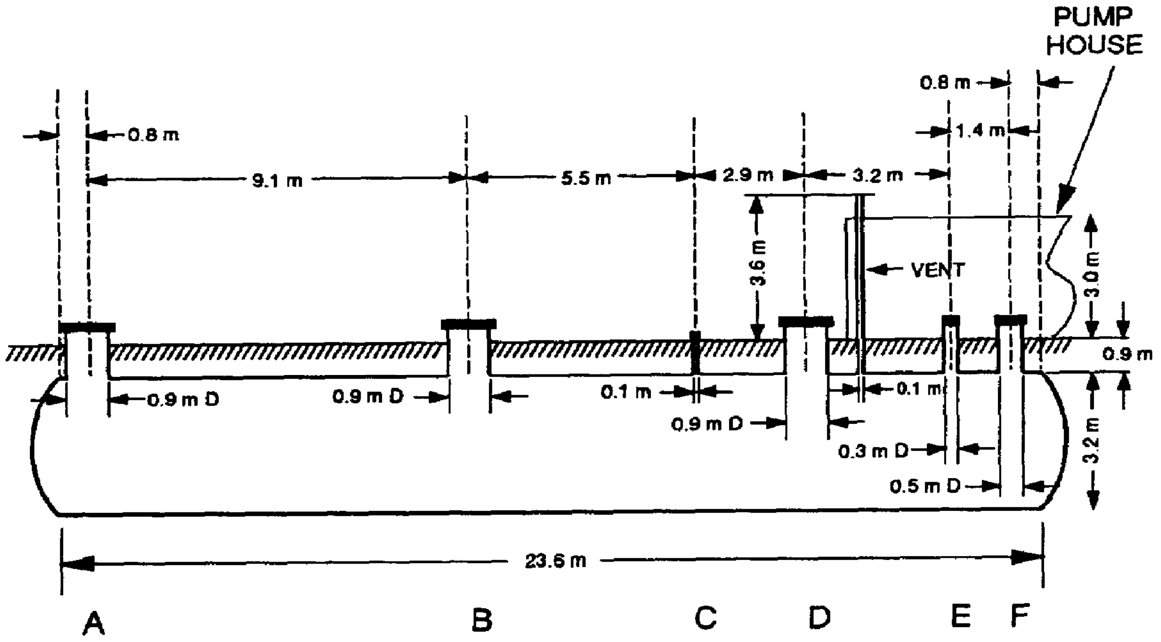

Fig. 2. Cross-section of the 190,000-L (50,000-gal) tanks used in the experiments. The thermistor arrays were located in Manway B and Vent C in Tank 1 and in Manways A and B in Tank 2. The level sensor was located in Manway B in both tanks.

(50,000 gal). Level measurements made in several of the openings of each tank suggest that the tanks are nearly horizontal, with a difference of only about 2.5 cm (1 in.) in height between the two ends.

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 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 tanks. They are connected to the top of the tanks by flanges located 15 cm (6 in.) above the tanks. This connection is not liquid-tight and, as a consequence, the tanks could not be overfilled in these 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 in Tank 1 were conducted between 10:30 h on 27 August 1990 and 08:00 h on 30 August and those in Tank 2 between 10:15 h on 30 August and 14:50 h on 31 August. Thermistor arrays were inserted into Tank 1 at Manway B (Array A) and the vent hole at C (Array B) and into Tank 2 at Manways A (Array B) and B (Array A). The arrays were separated by 5.5 m (18 ft) in Tank 1 and by 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, were located on opposite sides of the tank in Tank 1 and on the same side of the tank in Tank 2. During the tests, the level and pressure sensor measurements in both tanks were made at Manway B. All of the level changes in the tanks were done by adding or removing product by means of the pump located 8.5 m (28 ft) away from the nearest thermistor array in Tank 1 and 14.0 m (46 ft) away from the nearest thermistor array in Tank 2; at these distances, it is not likely that the pump would have any affect on the temperature measurements. In both tanks, the inlet and outlet of the pump were located near the bottom. A 2,470-ml cylindrical bar used to experimentally determine the height-to-volume conversion factor was inserted into and removed from the liquid in the tank at Manway A in Tank 1 and Manway C in Tank 2; these openings were selected because they contained no temperature or level measurement equipment. 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 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 rate of 1 sample/min (0.017 Hz).

The analysis of the data assumes that the tanks are not leaking and that all valves isolating the piping from the tanks seal sufficiently so that no leakage of product back into the tank occurs during the test. Once every three years the tanks are emptied and visually inspected for leaks; the last inspection was done within 12 months of these tests and no leaks were found. Although a formal volumetric leak detection test was not done, the five days of data suggest that the tanks are tight, or at the very least, the tanks or piping are not leaking at any significant rate. The temperature-compensated volume rates that were estimated from 2.5 to 3 h of data beginning 21 and 17 h after the start of the overnight tests on 29 August and 30 August, respectively, were both less than 0.05 L/h (0.013 L/h) [9]. Furthermore, many of the observations and conclusions derived from these experiments are independent of whether or not the tank or piping is leaking. As part of the analysis, the possible effect of the pump house and the large manways on the tank temperature field (vapor and product) was recognized and investigated; these effects are described in this paper and in more detail in [9].

Temperature and level measurement systems

The following data were required for the experiments: (1) the change in the temperature of the product and (2) 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-change data were converted to volume-change data using the experimental estimates of the height-to-volume conversion factor. The height data were used to estimate the volume of product in the tank during a test.

The data quality objective for the instrumentation was based upon the EPA performance standard for tank tightness tests [1] and is more fully described in [11]. All of the temperature and level measurement systems that were used in the experiments had sufficient precision 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 2-h measurement period [12]. The sensors were calibrated according to the procedures described in [11], and all sensors used in the analysis were within specification.

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 precision of this sensor was 0.00025 cm (0.0001 in.). The pressure and electromagnetic sensors were located at the bottom and top of Thermistor Array A, respectively. Each time the level was changed, it was also measured to the nearest 0.25 cm (0.125 in.) with a calibrated stick.

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

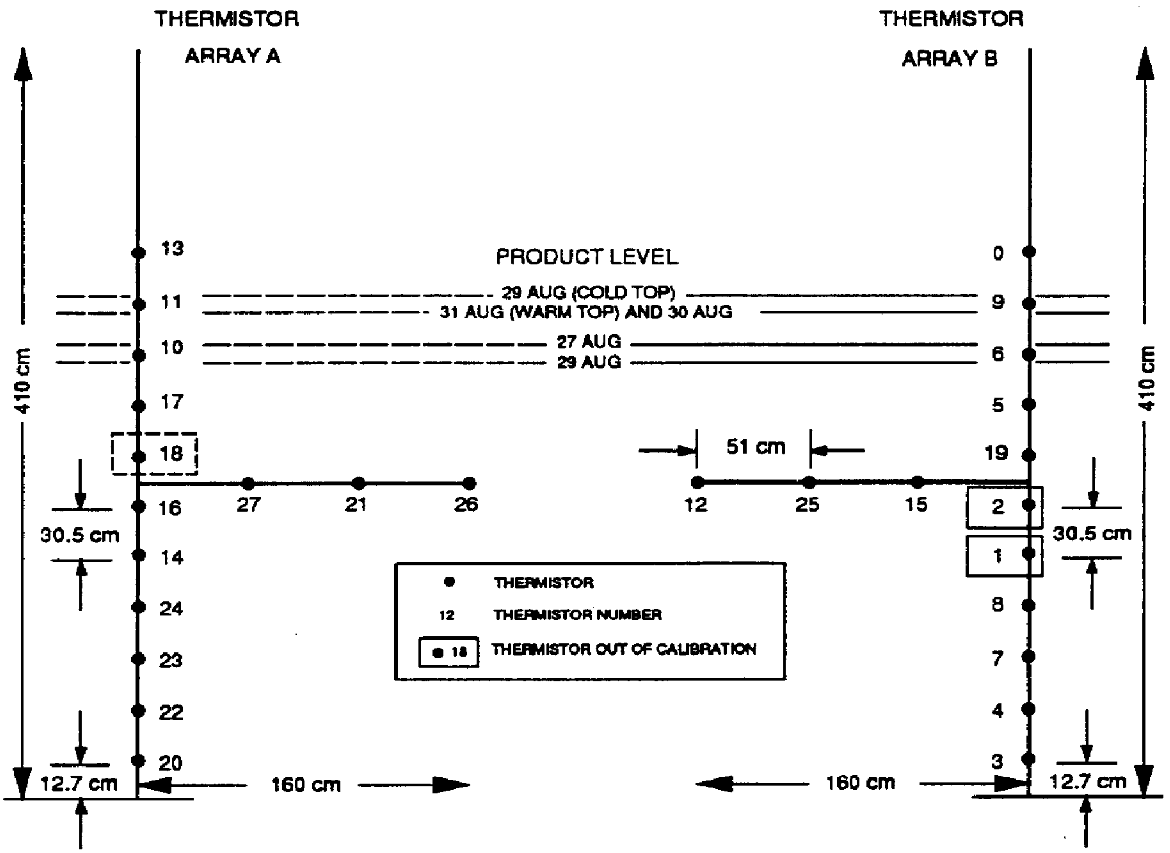

Fig. 3. Configuration of thermistor arrays A and B.

intervals of 31 cm (12 in.) along the vertical axis of the tank. The lowest thermistor was located approximately 13 cm (5 in.) from the bottom of the tank. The vertical portion of the array, containing a total of 11 thermistors, was used primarily to estimate the average thermally induced volume change of the product in the tank. To minimize any contamination of the product temperature measurements from changes in the temperature of the steel tube, each thermistor was inserted in a Teflon collar before being attached to the tube. 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 put in place. 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 and shows the volume of product in the 31-cm (12-in.)-high layer centered about each thermistor. The thermistors had been calibrated 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 thermistors was better than 0.02 °C.

Test conditions

Two "topping" tests and three "overnight" tests were conducted. The topping tests simulated the topping off of a tank prior to a test, whereas the overnight tests simulated the effects of a delivery or removal of product preparatory to a leak detection test. To simulate the effects of topping, 19 L (5 gal) of product that was either colder or hotter than the extant product was added to the tank. Figure 4 summarizes the nominal product level and the product additions and removals during the measurements. Also shown are the times of the overnight and topping tests and the height-to-volume calibrations. Table 2 gives more detailed information about the overnight tests.

During the first two overnight tests, initiated on 27 and 29 August in Tank 1, the levels were dropped by 29 and 39 cm, respectively, by removing 14,712 and 20,911 L (3,886 and 5,524 gal) of product from the tank, respectively. During the third test, the level in the tank was raised 70 cm by adding 44,054 L (11,637 gal)

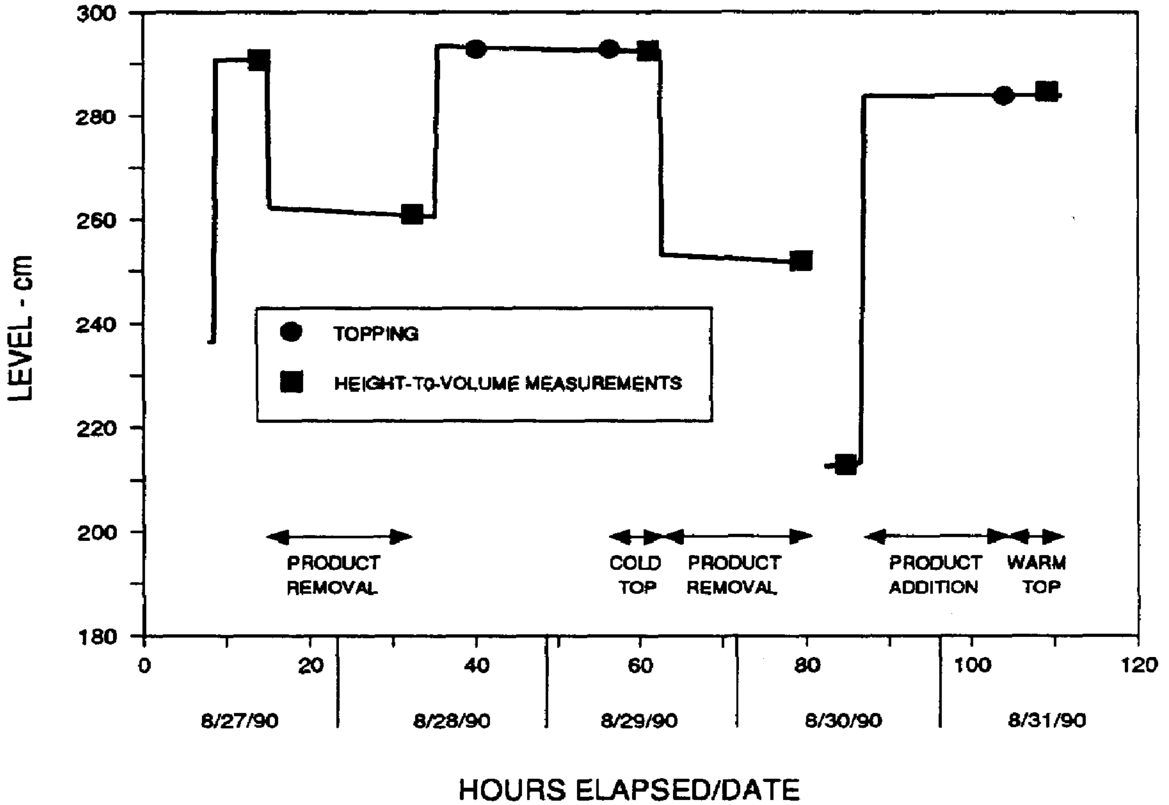

Fig. 4. Summary of the product level measurements between 27 and 31 August 1990 and of the analyses performed on the data.

TABLE 2

Height of thermistors closest to product surface

Tank	Start date	Start time	Nominal product level (cm (in.))	Thermistors closest to surface (Array A/B)	Nominal thermistor height from bottom (cm (in.))	Nominal product above thermistor (cm (in.))	Volume of product in upper layer[a] (L (gal))
1	Aug. 27	15:10	262.25 (103.25)	10/6	256.5 (101)	5.7 (2.25)	12,956 (3,422)
1	Aug. 29	14:41	253.0 (99.6)	17/5	226.0 (89)	26.9 (10.6)	28,346 (7,488)
1	Aug. 30	15:05	283.8 (111.75)	10/6	256.5 (101)	27.3 (10.75)	24,473 (6,465)

[a] Volume of product in the surface layer.

of product. All three overnight tests began late in the afternoon, between 14:30 h and 15:30 h, and ended between 07:00 h and 08:00 h the next morning. The nominal height of the product in the 3.2-m (10.5 ft)-diameter tanks and the number and location of the uppermost submerged thermistors are summarized in Table 2 and Fig. 3. The magnitude of the temperature effects induced by the removal or addition of product to the tank is discussed in the next section. The two topping tests, done on 29 August (with 19 L (5 gal) of product 8 °C colder than the product in the tank) and 31 August (with 19 L (5 gal) of product 5 °C warmer than the product in the tank) are described in [9].

Test results

Figure 5 shows, for each overnight test, profiles of the temperature field generated with the thermistor data from Array A. These profiles were generated 4 h after any addition or removal of product so that the strong temperature fluctuations associated with such volume additions or removals would have time to subside. 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 these gradients suggests that, especially during the summer, the thermistors must be more densely spaced than they were in these tests if the rate of change of temperature is to be accurately measured. During the winter, when the profile tends to be more uniform from the top to the bottom of the tank, less dense spacing would suffice.

The temperature-compensated volume time series for each overnight test was computed from the level and temperature data. First, the volume changes due to thermal expansion or contraction of the product were estimated from the temperature data, and the total volume changes were estimated from the level data. The two types of volume changes were then differenced to obtain the

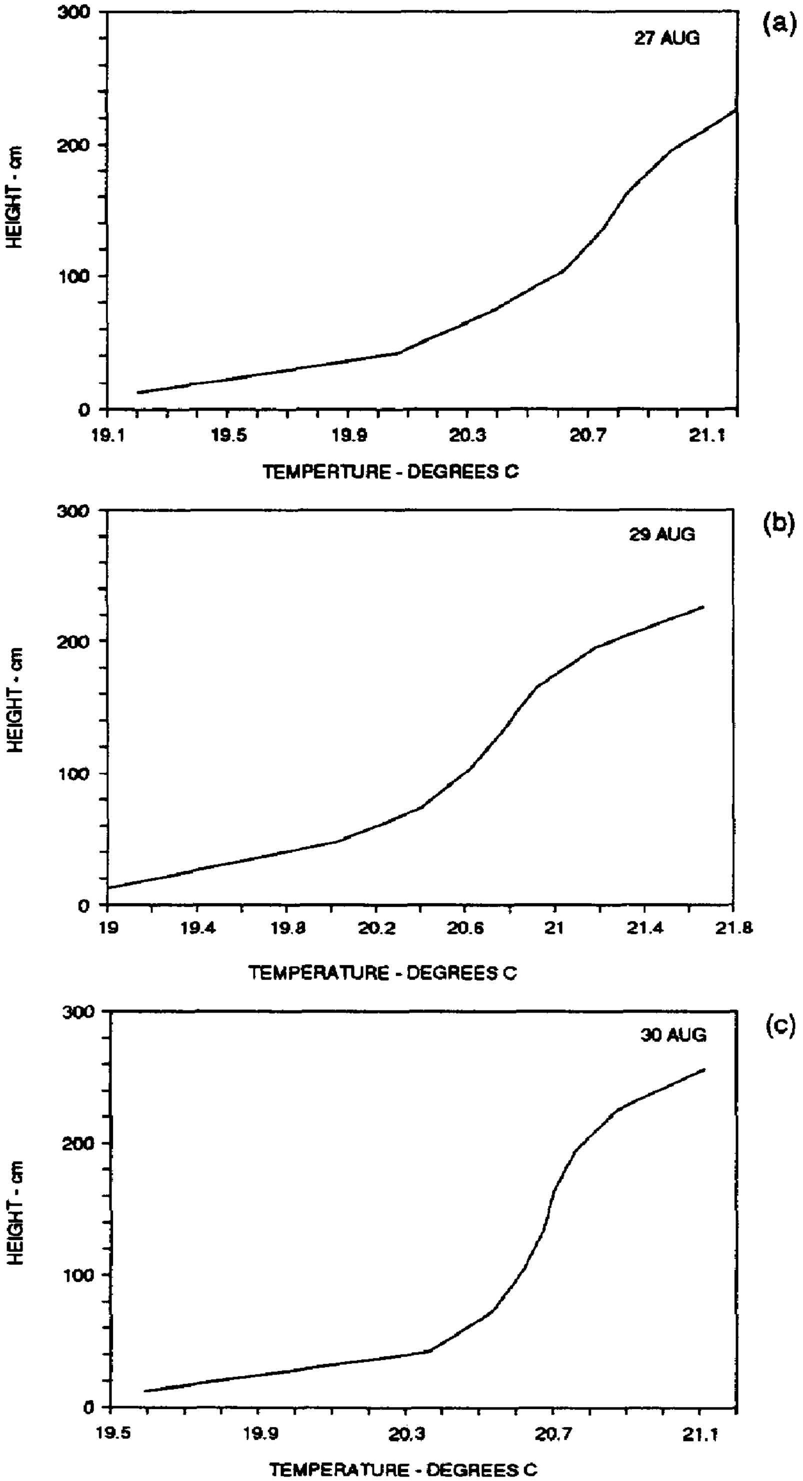

Fig. 5. Vertical temperature profile computed 4 h after the initial level change at (a) 15:10 on 27 August, (b) 14:41 on 29 August, and (c) 15:05 on 30 August.

temperature-compensated volume time series. The level data were converted to volume by means of an experimental estimate of the height-to-volume conversion factor. The thermally induced volume change, obtained from the temperature data from Array A, was computed from eq. (1). 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 volume calculations.

Figure 6 shows the time series of the thermally induced volume changes and the temperature-compensated volume changes. Only the volume changes that occurred immediately after the completion of the product transfer are shown. Figure 7 shows a portion of the temperature-compensated volume time series from Fig. 6 in greater detail. When product is removed from the bottom of the tank, as it was during the first two tests, the warmer product in the upper layers of the tank replaces the cooler product in the lower layers. The temperature of the product recorded at each layer showed a "step" increase that was associated with the removal. As shown in Fig. 6, once the product removal was completed, the temperature of the product began immediately to decrease in an attempt to come into equilibrium with the colder backfill and soil outside the tank. In the third overnight test, in which cold product was taken from the bottom of one tank and added to the other tank, a step increase in temperature was observed in the upper layers of the tank and a step decrease was observed in the lower layers. The step decrease in the upper layers occurred as the temperature of the colder product in the lower layers was raised; once the addition of product was completed, the temperature in these upper layers began to increase in an attempt to reach equilibrium with the temperature of the backfill and of the ground at that elevation. The step increase in the temperature at the bottom of the tank meant that the added product was warmer than the product and backfill/soil at the bottom of the tank. As shown in Fig. 6, a net increase in the temperature field was observed over time. The nature of these step changes in temperature is illustrated in Fig. 8 (for the bottom three thermistors in the 30 August overnight test) and Fig. 9 (for the thermistors on the horizontal arm located in the middle of the tank during the 29 August overnight test).

There is an initial "step" change in volume due to the addition or removal of product whose temperature differs from that of extant product, the backfill, and the soil beyond the backfill. This step change is not shown in Fig. 6. The thermally induced step change in the volume of product increased by 13.5 and 39.5 L (3.6 and 10.4 gal) in the first two tests, initiated on 27 and 29 August, respectively, and decreased by 93 L (24.6 gal) in the test initiated on 30 August. Calculation of the temperature difference between the added/removed product and the extant product is not straightforward, because the former was not of uniform temperature; in addition, the temperature of the product added to the tank on 30 August was not monitored. An estimate of the mean temperature of

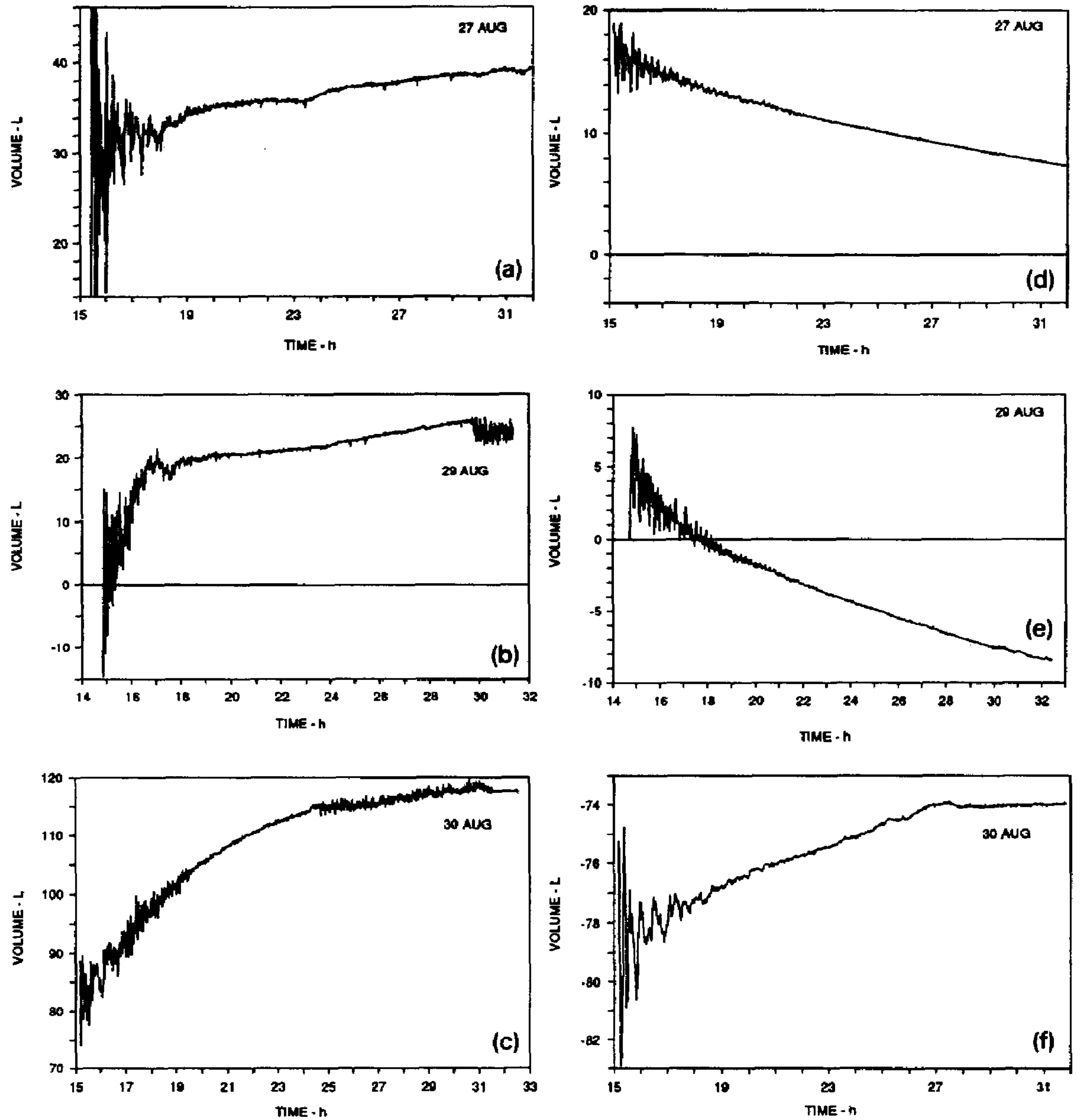

Fig. 6. Time series of the temperature-compensated volume changes (a–c) and the thermally induced volume changes measured by Array A (d–f) beginning *immediately after* the initial level change done at (a) 15:10 on 27 August, (b) 14:41 on 29 August, (c) 15:05 on 30 August, (d) 15:10 on 27 August, (e) 14:41 on 29 August, and (f) 15:05 on 30 August.

the added/removed product is necessary to effect the measured volume change. This estimate was made from

$$\Delta v = C_e(\langle T_2\rangle - \langle T_1\rangle)\, V_1 + C_e(\langle T_2\rangle - \langle T_a\rangle)\, V_a \tag{2}$$

and

$$\langle T_j\rangle = \Sigma(\Delta v_i / V_j)(T_j) \tag{3}$$

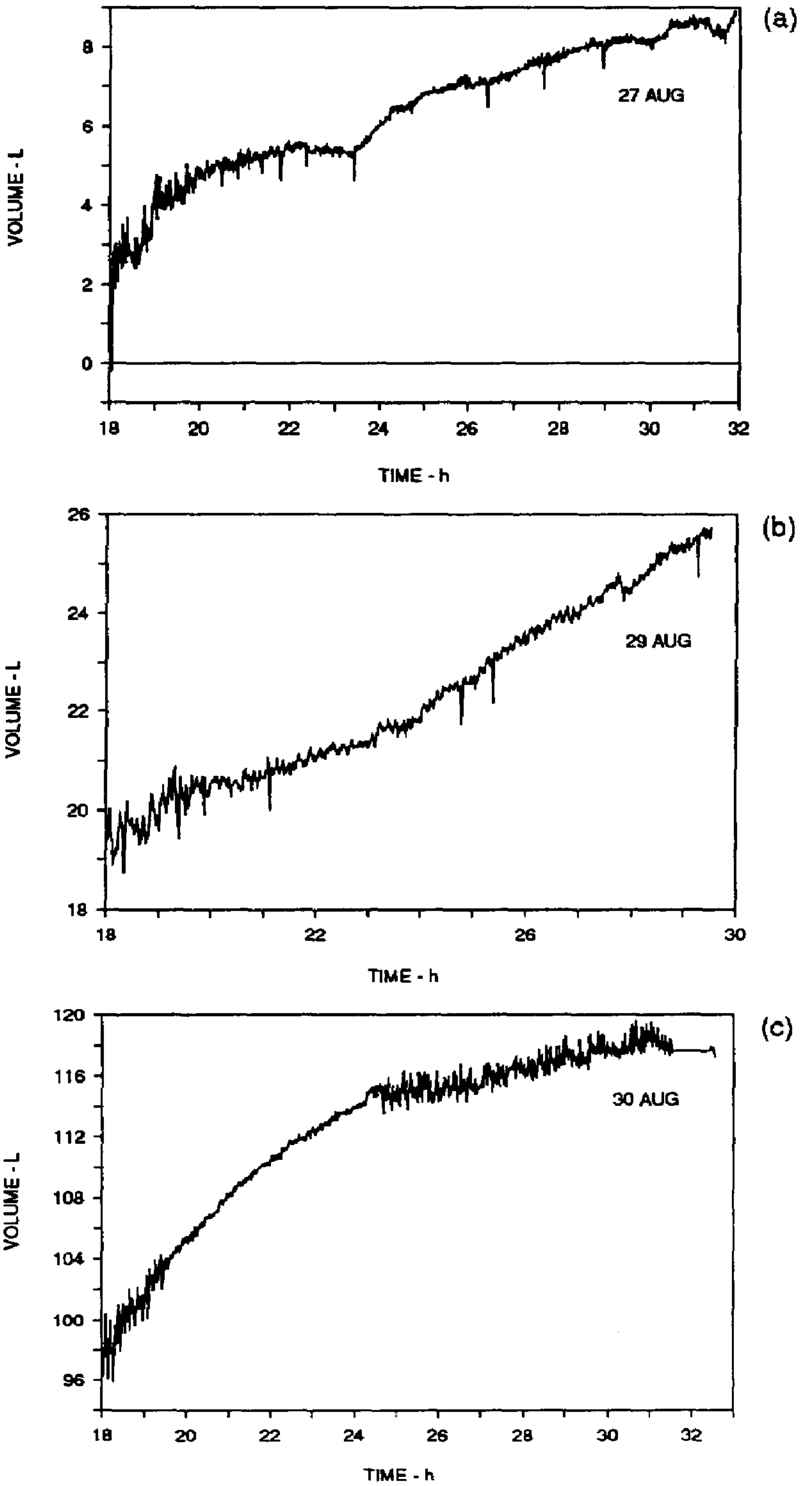

Fig. 7. Time series of the temperature-compensated volume changes estimated from Array A beginning approximately 3 h after the initial level change done at (a) 15:10 on 27 August, (b) 14:41 on 29 August, and (c) 15:05 on 30 August.

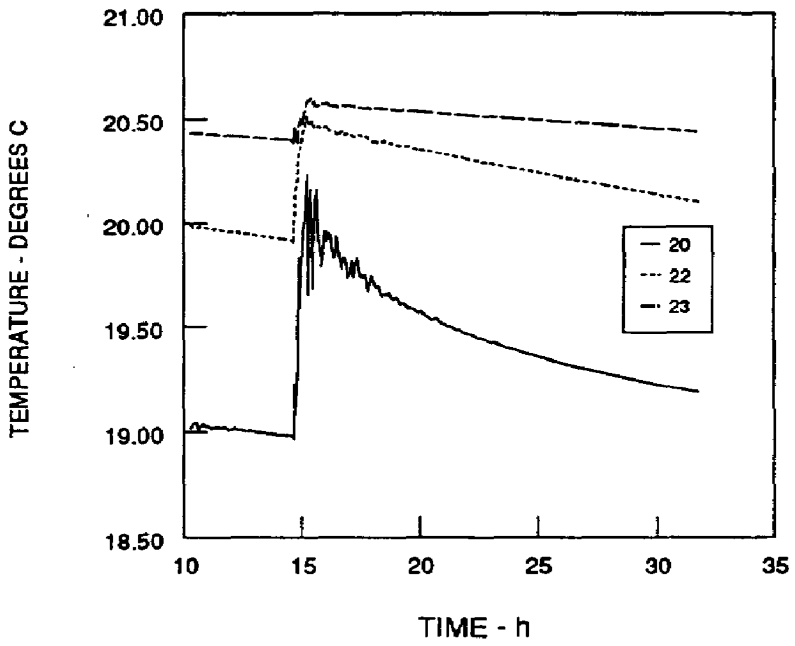

Fig. 8. Time series of the product temperature changes for the bottom three thermistors on Array A collected after the addition of product at 15:05 on 30 August.

where $\langle T_{j=2} \rangle$ is the volumetrically weighted mean temperature of the product in the tank immediately *after* the addition or removal of product; $\langle T_{j=1} \rangle$ is the volumetrically weighted mean temperature of the product in the tank immediately *before* the addition or removal of product; $\langle T_a \rangle$ is the mean temperature of the product added or removed, and necessary to effect the measured "step" volume change; Δv is the volume of product in the tank; V_1 is the volume of product in the tank immediately *before* addition/removal; V_2 is the volume of product in the tank immediately *after* addition/removal; and V_a is the volume added or removed. For each of the three overnight tests, an estimate of $\langle T_a \rangle$ was made by solving eq. (2) for $\langle T_a \rangle$, given the measured Δv and estimates of $\langle T_1 \rangle$ and $\langle T_2 \rangle$ made graphically from the time series generated for each thermistor (cf. Vol. II of [9]). The results are shown in Table 3. The mean difference in temperature between the extant product and the added/removed product was 1.6, 0.6, and −3.9 °C, respectively, in each of the three overnight tests.

Estimates of the thermally induced volume changes were made with five thermistors spaced at 61-cm (24-in.) intervals as well as with ten thermistors. Direct comparison of the temperature-compensated time series made with five and ten thermistors showed significant differences. The analysis suggests that five thermistors do not provide adequate coverage for accurate temperature compensation.

Several observations can be made about the temperature-compensated volume time series shown in Fig. 6.

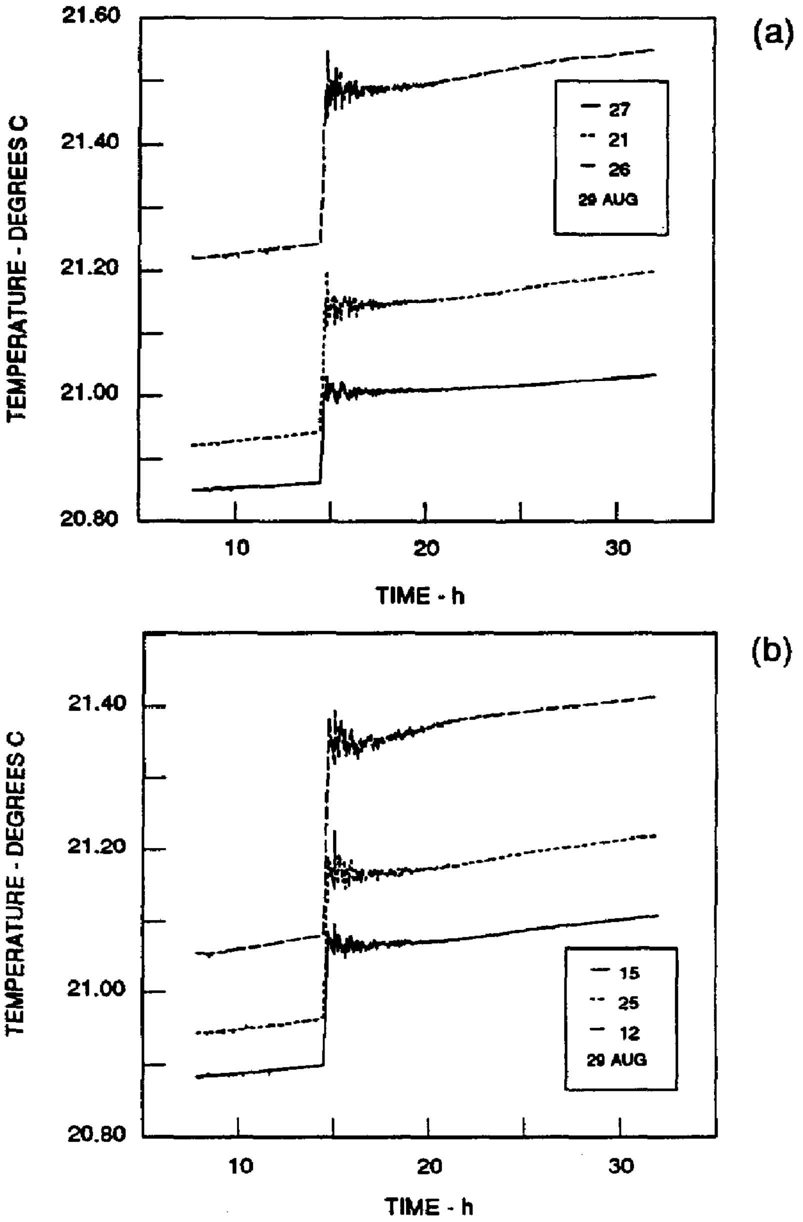

Fig. 9. Time series of the product temperature changes on the horizontal arm extending from the center of the tank (a) on Array A and (b) on Array B. The arm, located at a height of approximately 180 cm (71 in.) from the bottom of the tank, is located at the midpoint between Thermistors 16 and 18 on Array B and Thermistors 2 and 10 on Array A.

- Large volume fluctuations, which are tens of liters in magnitude, are present during the first 4 h or more of *each* overnight test.
- During the first 5 to 10 h after the addition or removal of product, an exponential increase in the temperature-compensated volume time series is observed. This behavior is especially definitive in the 30 August data.

TABLE 3

Estimate of the difference in temperature between the product added to or removed from the tank in each overnight test

Parameter	Dimension	August 27	August 29	August 30
Δv	L	13.5	39.5	93.0
V_1	L	47,911	48,092	134,735
V_a	L	14,712	20,911	44,054
$\langle T_1 \rangle$	°C	20.57	20.48	21.08
$\langle T_2 \rangle$	°C	20.76	20.73	20.63
$\langle T_a \rangle$	°C	22.20	21.09	17.23
$\langle T_a \rangle - \langle T_1 \rangle$	°C	1.63	0.61	−3.85

- A distinct change in the temperature-compensated volume time series is observed at approximately 24 h in all three overnight tests; this change in volume rate is especially evident in the 29 August test.
- Estimates of the temperature-compensated volume rate made 10 h after product has been added to or removed from the tank (Table 4) suggest that product is flowing into the tank. This is indicated by the size of the residual volume changes, which still persist after the exponential changes have subsided. Assuming that the inflow is not caused by an inadequately sealed valve, it would seem that the thermally induced volume changes have not been adequately compensated for, that the deformation of the tank has not subsided, and/or that condensation is occurring. Even if the tank did have a hole or fissure, no inflow of groundwater could occur because the water table is located below the level of the tank.
- The fluctuations in the temperature-compensated volume time series have periods of 2 to 4 h. These fluctuations are best observed in Fig. 7. Short leak detection tests, 1 to 2h in duration, would be adversely affected by these fluctuations, because they do not accurately represent the long-term trend.

After an extensive analysis, which is more fully described in [9], it was concluded that each of the five observations noted above can be explained by changes in the temperature of the product stored in the tank that have not been adequately measured. A discussion of each observation is provided below.

Large temperature fluctuations after product addition or removal

The large volume fluctuations observed in the calculated temperature-compensated volume time series are produced by the addition or removal of product. Any additions or removals will alter the temperature field. The horizontal and vertical mixing of the product creates large temperature fluctuations that last for many hours. During this period, an accurate leak detection test can not be conducted. It is significant that while the level of the temperature fluctuations observed in these tests is greater than those observed in

TABLE 4

Summary of results of overnight tests

Tank	Start date	Start time (h)	Nominal level (cm (in.))	TCVR[a] (L/h (gal/h))
1	Aug. 27	24–29	262.3 (103.25)	0.36 (0.094)
1	Aug. 29	24–29	252.1 (99.25)	0.66 (0.172)
2	Aug. 30	25.5–29.5	283.8 (111.75)	0.22 (0.057)

[a] TCVR is the abbreviation for temperature-compensated volume rate.

tests conducted on the 30,000-L (8,000-gal) tanks at the Test Apparatus [5, 8, 12], the duration is almost identical. The data suggest that it takes at least 4 h for the temperature fluctuations to subside.

Thermally induced exponential volume changes

The initial inspection of the temperature-compensated volume time series suggested that the exponential changes in volume were due to deformation induced by an abrupt change in the level of the product. While this could explain the volume changes during the first 4 to 6 h of the 27 and 29 August tests, the sense of the change is incorrect in the 30 August test. If deformation had been a dominant noise source in the 30 August test, the temperature-compensated volume time series would have decreased over time.

A more comprehensive analysis of the temperature data immediately after product addition to or removal from the tank showed that the exponential increase in the temperature-compensated volume time series seen in all three tests can be explained by inadequate estimation of the thermally induced volume changes in the bottom layer. Figure 8 displays the temperature time series for the bottom three thermistors on Array A recorded during the 30 August test. The rate of change of temperature measured by the bottom thermistor (No. 20) is exponential and significantly greater than that measured by the thermistor located immediately above it. As illustrated by the profiles in Fig. 5 and the shape of the bottom layer (see Fig. 1), this is a region where the temperature gradient is very strong and the volume of product surrounding the thermistor is large and asymmetrical. Simply locating the thermistor a few centimeters higher could result in a significantly lower rate of change of temperature, which would explain the exponential increase in volume. Additional thermistors, spaced at intervals of 15 cm (6 in.) or less, would be required for an accurate estimate of the mean rate of change of temperature-volume in this region of the tank. About 27 h after the product transfer, the rate of change measured by the bottom two thermistors is approximately the same, suggesting that this source of error has decreased sufficiently that an accurate leak detection test can be conducted.

The temperature fluctuations recorded by the bottom thermistor (No. 20) and observed during the first two hours after the product addition are large enough to explain most of the thermally induced volume changes in Fig. 6(f). These volume changes are probably produced by internal waves that developed on the steep temperature gradient located near the bottom of the tank during the product addition.

Distinct change in the temperature-compensated volume rate

In Fig. 7, a distinct change in the temperature-compensated volume rate was observed during the 29 August test between 19.0 and 23.5 h and 23.5 and 31 h. The rate increased from 0.38 L/h (0.099 gal/h) to 0.70 L/h (0.18 gal/h). We believe that this increase in rate is due to the presence of horizontal gradients in the rate of change of temperature between the centerline and the walls of the tank. This mechanism is illustrated in Fig. 9, which displays the time series of the thermistors located on the horizontal arms of Arrays A and B. A distinct shift in the rate of change of temperature is observed at 23.5 h; this coincides with the distinct change in the temperature-compensated volume time series. The difference in the rate of change of temperature observed before and after 23.5 h for the middle thermistors (Thermistors 21 and 25) on each horizontal arm is approximately 0.00175 °C/h. Assuming that this 0.00175 °C/h increase in rate affects 113,500 L (30,000 gal) of product, this would account for 0.21 L/h (0.055 gal/h) of the 0.32-L/h (0.085-gal/h) increase.

Uncompensated thermally induced volume changes

An attempt was made to explain and quantify the residual volume changes presented in Table 4. An analysis of each test is presented in [9]. This paper includes a brief discussion of the residual changes observed in the 29 August test. A portion of the error can be accounted for by the difference in the rate of change of temperature between the centerline and the walls of the tank. The temperature change measured at Thermistors 26 and 21 on Array A was 0.004 °C/h, while at Thermistor 27, located closest to the middle of the tank, it was 0.0022 °C/h. Similar differences were observed on Array B. Assuming that this 0.0018 °C/h increase in rate affects 113,500 L (30,000 gal) of product, this would account for 0.21 L/h (0.056 gal/h) of the 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. An analysis of the 27 August data, in which the upper thermistor (No. 10) was only 5.7 cm (2.25 in.) below the surface, showed a difference of 0.02 °C/h in the rate of change of temperature measured by this thermistor and the one located 31 cm (12 in.) below it. This suggests that additional thermistors are required in this region if the estimate of the volume changes in this layer is to be accurate. Assuming the same rate of change of temperature in the upper 11.5 cm (4.5 in.) of the product (7,258 L (1,915 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. These estimates of the measurement errors in the surface region and in the region between the centerline and wall of the tank account for only about half of the total residual volume change. However, they could easily be off by a factor of two. This factor-of-two uncertainty is derived from the lack of temperature measurements in these regions of the tank.

The additional residual volume changes could also be explained by condensation and by horizontal gradients in the rate of change of temperature along the long axis of the tank. An estimate of the condensation could not be made, but the temperature conditions measured at the vapor/liquid/wall interface are consistent with those that would produce condensation. Errors due to the horizontal gradient in the rate of change of temperature along the long axis of the tank were also examined. The temperatures measured by each thermistor on Array B were differenced with those measured by the thermistors on Array A that were located at the same height. The largest differences in temperature were generally less than $\pm 0.001\,°C/h$, 4 h or more after product additions or removals and were randomly distributed in the vertical. Thus, the sum of all temperature differences along the vertical axis was 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.

An analysis of the temperature-compensated volume data approximately 20 h after the product removal on 29 August and the product addition on 31 August showed that the residual volume changes had decreased to 0.036 and −0.043 L/h (0.009 and −0.011 gal/h), respectively. An analysis of the temperature data obtained on the horizontal arms of Arrays A and B showed that the gradient in the rate of change of temperature had completely dissipated by that time, suggesting that this gradient was the dominant error.

Instrumentation and ambient fluctuations

The minimum duration of a test depends on the magnitude and period of the instrumentation and ambient noise fluctuations. A leak detection test must be long enough that the trend in the temperature-compensated volume rate can be accurately estimated. The data in Fig. 7 suggest that a 4-h test would yield a good estimate of the trend. Previous calculations indicated that to meet the data quality objectives with the precision of the level and temperature sensors used in these experiments a test had to be at least 2 h long [12]. Thus, the ambient fluctuations would be the controlling factor in determining the appropriate duration of a leak detection test performed with these sensors. A 1-h test, typical of many tightness tests used on small tanks, would simply track the ambient volume fluctuations and would not yield a good estimate of the trend. A detailed discussion of how to estimate the minimum duration of a test based on the precision of the level and temperature sensors is presented in [11, 12]. 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.

Conclusions and recommendations

This study showed that the procedures currently used to compensate for temperature when testing 30,000- and 38,000-L (8,000- and 10,000-gal) tanks will not suffice when the tanks are as large as 190,000-L (50,000-gal). The most important cause of errors in testing large tanks with volumetric leak detection systems, which consist of a level or volume measurement system and a vertical array of temperature sensors, appears to be inaccurate temperature compensation. Five things are necessary for successful temperature compensation. 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 observed in the temperature-compensated volume 4 to 6 h or more after any product additions or removals can be averaged and (2) the precision of the temperature and level instrumentation 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 of the layers 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 height-to-volume conversion factor, and the volume of product in each layer of the tank.

Horizontal gradients in the rate of change of temperature between the centerline and the walls appear to be the controlling source of error in temperature compensation. A waiting period of at least 24 h is recommended so that these gradients have time to subside. If the initial temperature difference between the *in situ* product and that added or removed is greater than it was in the tests conducted as part of this study, a longer waiting period might be required. More data are required before the adequacy of a 24-h waiting period in such cases can be verified. The 24-h waiting period appears to be more than adequate for structural deformation of the tank to subside and for the violent temperature fluctuations that occur immediately after any transfer of product to or from the tank to dissipate. Unless the temperature is sampled with a horizontal array of temperature sensors 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. There are alternatives to direct measurement of the horizontal gradient. One is to conduct additional tests to determine if the rate of change of volume is approaching a constant value, and the other is not to begin a test until the thermal volume change in the tank as a whole, or in a single representative layer, is small enough that it cannot adversely affect the results of a test.

A total of at least 10 temperature sensors spaced vertically at 31-cm (12-in.) intervals or less is recommended; this recommendation assumes that the waiting period is at least 24 h. If more than 10 temperature sensors are available, these additional temperature sensors should be more closely spaced at the bottom of the tank and near the product surface, because in these two regions the rate of change of temperature and the vertical gradient in the rate of change of temperature are generally greater than they are elsewhere in the vertical. During the 24-h waiting period, the 31-cm (12.-in.) spacing used in these experiments was insufficient at times to accurately measure the rate of change of temperature near the bottom of the tank and near the surface of the product. If a waiting period shorter than 24 h is used, which may be possible, for example, if horizontal measurements of temperature are made as part of the test procedure, then a spacing of 15 cm (6 in.) or less is suggested.

The data collected in these experiments suggest that the minimum duration of a leak detection test should be at least 4 h so that the ambient volume fluctuations that occur in the tank can be averaged. The actual duration of a test might be longer if the precision of the instrumentation is less than it was in this study. In these experiments, however, the precision of the temperature and level sensors was sufficient to support a shorter test.

Ultimately, the performance achieved with a leak detection system is controlled by the precision of the instrumentation and the accuracy of estimating the constants. The best way to minimize the effect of instrumentation errors is to wait until the rate of change of temperature in the tank or in a layer is small. An uncertainty of 0.001 °C/h in the measurement of the average rate of change of temperature, which is typical of the types of uncertainties achieved during most leak detection tests, results in an error of 197 ml/h (0.052 gal/h) in a 190,000-L (50,000-gal) tank containing JP-4 fuel. This is large enough to exceed most detection thresholds used to conduct a tank tightness test. Assuming that 95% of the temperature changes can be compensated for, this means that a test should not be started until the rate of change of temperature in the tank is less than 0.02 °C/h, which is typical of the type of changes observed in tanks. An uncertainty of 5% in either the coefficient of thermal expansion or the volume of the product in the tank would result in a bias of 197 ml/h (0.052 gal/h). Clearly, temperature compensation that is sufficiently precise to meet the tank tightness regulatory standards (i.e., to detect a leak of 0.1 gal/h with a P_D of 95% and a P_{FA} of 5%) is difficult to achieve.

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

- Place the top and bottom temperature sensors approximately 8 cm (3 in.) from the product surface and from the bottom of the tank, respectively.
- Space the temperature sensors at intervals of 15 to 31 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 31 cm (6 to 12 in.) of product located immediately beneath the surface. (A 31-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 known. 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.
  (i) 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 0.05 gal/h in a tank containing JP-4 fuel, this would limit the rate of change of temperature to less than 0.008 °C in the largest layers of a 10.5-ft-diameter, 190,000-L (50,000-gal) tank divided into 10 layers.)
  (ii) 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 10.5-ft-diameter, 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 level sensors a precision of 0.00025 cm (0.0001 in.). The trade-offs in instrumentation precision and test duration are described in [12].
- 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*.

It must be emphasized that the conclusions and recommendations drawn from these experiments are based upon a very limited set of data. These recommendations, however, are based on the well-known and well-understood basic features of a volumetric test developed for smaller tanks (30,000 to 38,000 L (8,000 to 10,000 gal)); these are features that have been shown to be necessary for high performance through tens of evaluations of systems offered commercially and through many controlled experiments in underground test tanks. Whether the temperature-compensation procedure recommended for volumetric tests *conducted on 190,000-L (50,000-gal) tanks* is sufficient to meet the EPA's regulatory standard for a tank tightness test (or a monthly monitoring test) will not be known until a number of actual performance evaluations have been conducted on one or more systems that incorporate some or all of these procedures. Despite the fact that there were not enough data in this study to fully evaluate the effect of longer waiting periods, it is our opinion that a waiting period of at least 24 h is the key to high performance.

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