Journal of Hazardous Materials, 26 (1991) 261-300
Elsevier Science Publishers B.V., Amsterdam

Evaluation of volumetric leak detection methods used in underground storage tanks

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(Received March 19, 1990; accepted August 20, 990)

Abstract

In the spring and summer of 1987, the United States Environmental Protection Agency (EPA) evaluated the performance of 25 commercially available volumetric test methods for the detection of small leaks in underground storage tanks containing gasoline. Performance was estimated by means of an experimentally validated performance simulation. The simulation used (1) experimentally validated models of the important sources of ambient noise that control the performance of these methods, (2) a large database of product-temperature changes that result from the delivery of product at a temperature different from that of the product in the tank, and (3) a mathematical model of each test method to estimate the performance of that method. A major objective of this program was to quantify experimentally the major sources of ambient noise. This paper describes the results of these experiments and presents performance estimates for generic testing methods, which are typical of the methods evaluated, to illustrate the effect of these sources of ambient noise on performance. The experiments were performed at the EPA Risk Reduction Engineering Laboratory's Underground Storage Tank Test Apparatus in Edison, New Jersey.

Introduction

In the United States there are several million underground storage tanks containing petroleum fuels and chemicals. It is estimated that 10 to 25% of them may be leaking. This translates to up to one half million leaking tanks in the U.S. The contamination of groundwater that results from such leaks is a serious environmental threat and one that impacts public health directly, for in most states at least 50% of the potable water supply comes from underground wells. In 1984 (through the Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act of 1976), the U.S. Environmental Protection Agency (EPA) was charged with developing regulations for the detection of releases from underground storage tanks. The new regulations [1], released in September 1988, state that all volumetric tank tightness test

0304-3894/91/$03.50

methods must, within two years, have the capability of detecting leaks as small as 380 ml/h (0.1 gal/h) with a probability of detection of 95% and a probability of false alarm of 5%.

There are many commercially available methods for detecting leaks in underground storage tanks. Those which are the most widely used in the petroleum industry are in a category called volumetric tanks tests (also known as "precision", "tank tightness," or "tank integrity" tests). The premise of a volumetric tank test, and hence its name, is that any change in the volume of fluid within a tank can be interpreted as a leak. Detection of these leaks is difficult because there are many physical mechanisms which produce real or apparent volume changes that can be mistaken for leaks. Real volume changes are produced, for example, by thermal expansion or contraction of the production in the tank. The level changes of the product in the tank due to structural deformation of the tank walls and ends would be an example of an apparent volume change.

In 1986, the EPA initiated a program whose purpose was to evaluate the performance claims made by manufacturers of volumetric tank tests. The objectives of this study were to provide data to support the development of new EPA regulations, to define the performance of the current technology, to make recommendations to improve current practice, and to provide information that would help users select suitable leak detection systems. Participation in the program was voluntary. The manufacturers of 25 commercially available systems elected to participate. The evaluations were conducted at the EPA's Risk Reduction Engineering Laboratory (RREL) in Edison, New Jersey. An experimental setup consisting of one steel and one fiberglass tank was constructed especially for the evaluation. This Underground Storage Tank (UST) Test Apparatus, as it is called, permits the conduct of full-scale tank tests under controlled conditions. Leaks of different sizes can be simulated in the tanks, and control can be exercised over the temperature of the fluid in the tank and other factors that affect the performance of leak detection systems.

Prior to the EPA study, manufacturers commonly claimed that volumetric test methods could reliably detect leaks as small as 190 ml/h (0.05 gal/h). These claims were intended to satisfy the practice recommended by the national Fire Protection Association [2] for volumetric tests in underground storage tanks. This practice specified that a method should be able to detect leaks as small as 190 ml/h and should use a 190 ml/h threshold to detect them. In order to satisfy the practice, the method needed to compensate for all of the important sources of noise that controlled the performance of these methods.

The NFPA practice did not specify the statistical reliability required of the volumetric tests in terms of probability of false alarm (P_{FA}) and probability of detection (P_{D}) against this 190 ml/h leak rate. If the P_{FA} and P_{D} are not quantified, the performance of a volumetric test is unknown. With only a few exceptions, none of the manufacturers made a performance claim in terms of P_{FA}

and P_D or provided sufficient experimental evidence that could be used to make an estimate of performance in terms of P_{FA} and P_D. As a consequence, the performance of volumetric testing, which is the most commonly accepted way of determining the integrity of a tank, was unknown. In general, prior to the EPA program, the experimental evidence used to support performance estimates was limited.

The EPA study described in this paper presented the performance of the evaluated methods in terms of P_D and P_{FA} as a function of leak rate. The Edison experiments showed that the detection of leaks as small as 380 ml/h with a P_D of 95% and a P_{FA} of 5% represents a realistic performance goal in terms of the current technology; this led to the use of the 380 ml/h value as the performance standard in the EPA release-detection regulations for tank tightness testing [1]. A performance of 190 ml/h with the same 95% probability of detection and 5% probability of false alarm would be, at best, difficult to achieve.

The results of the EPA evaluation are presented in a two-volume report [3]. Volume I summarizes the evaluation results, as well as scientific findings about the ambient noise field in an underground gasoline storage tank. Volume II presents, in separate appendices, detailed reports describing the evaluation results of each of the 25 methods. A summary of the performance of each method evaluated in terms of leak rate, P_D and P_{FA} was published in two separate papers [4,5]. This paper summarizes the main scientific experiments and findings of the EPA research program. Additional information can be found in [6,7]. It is important to note that many of the manufacturers whose methods were evaluated in this research program have since made modifications to their methods based on the data presented herein and have reevaluated the performance of their systems. The performance of these modified systems show dramatic improvement, with most of the systems capable of meeting or exceeding the EPA regulatory standards.

Underground storage tank test apparatus

The underground storage tank (UST) test apparatus used in the evaluation is environmentally safe and was designed and built to evaluate the performance of in-tank leak detection systems. Construction was completed in August 1986. The test apparatus consists of two 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) underground storage tanks installed in a pea-gravel backfill material; one is a steel tank coated with plastic, and the other is a fiberglass tank. Two above-ground tanks are used to heat or cool product for simulation of a delivery to the underground tanks. With this combined apparatus, different product temperatures, product levels, and leak rates can be generated and accurately measured. This apparatus allowed the conduct of experiments designed to investigate each source of noise.

To address the overall project objective, a set of data quality objectives was established at the beginning of the program and was adhered to throughout the data collection. The data quality objectives were selected specifically to evaluate the 190-ml/h performance claim. The precision and accuracy of the product-level and temperature sensor systems used to collect data at the UST test apparatus were specified so that the performance of each test method could be evaluated at a leak rate of 190 ml/h with a probability of detection of 95% and a probability of false alarm of 0.1%, a more stringent requirement than either the draft (P_D of 99%, P_{FA} of 1%) or the final (P_D of 95%, P_{FA} of 5%) EPA release-detection standard. To meet this more stringent requirement, the precision of the instruments used to measure temperature and product level and the accuracy of the constants used to convert temperature and product level to volume must have a total uncertainty of less than 40 ml/h when the data are combined to estimate the temperature-compensated volume rate. The UST test apparatus instrumentation, calibration procedures, and data quality analyses after each test were designed to verify that the data were meeting the data quality objectives.

Volumetric tank tests

A volumetric tank test measures the change in the volume of product in the tank and attributes this change, once all other sources of noise have been accounted for, to a leak. Most methods measure changes in the level of the product and convert these to volume changes using a height-to-volume conversion factor. Others measure volume directly. The height-to-volume conversion factor, A_{eff}, that is used to convert level changes to volume changes is defined by

$$A_{eff} = \frac{\Delta V}{\Delta h}, \tag{1}$$

where Δh is the total level change that results from a given volume change, ΔV. A_{eff} is measured experimentally by inserting a solid object ("bar") of known volume, ΔV_{bar}, into the tank and measuring the level change that results.

A leak is defined in terms of flow rate in milliliters (or liters or gallons) per hour and can be negative or positive; that is, product can flow out of the tank or groundwater can flow into the tank. Once the flow rate has been measured by the test method, a decision must be made as to whether to declare the tank in question leaking or nonleaking. This is done by means of a statistical hypothesis test that determines whether the measured flow rate is statistically different from zero at a specified level of significance. In practice, this decision is usually made by comparing the flow rate to a predetermined threshold value.

Volumetric tank tests can be divided into two categories. In the first, the tank is filled to capacity, and in the second, the tank is partially filled. In filling a tank to capacity the operator does not stop until the level of the fluid reaches a specified level with the fill tube or within a standpipe located above grade; hence the term "overfilled" is applied to these tests. Overfilled-tank tests can be further categorized according to those conducted under constant or nearly constant hydrostatic pressure and those conducted under variable hydrostatic pressure. Hydrostatic pressure varies with any fluctuations in product level, groundwater level, or atmospheric pressure that occur during a test.

In a test conducted under constant or nearly constant pressure, product is added or removed in order to maintain a constant fluid level in the tank's fill tube or standpipe. To conduct a successful test, it is necessary, once a tank has been filled or after it has been topped off prior to testing, to observe a waiting period long enough to ensure that the tank has expanded to its maximum capacity. Then, if the fluid level is kept constant, the tank will neither expand nor contract during the test, and measured volume changes will accurately represent actual volume changes. If the fluid level is dropped within the fill tube or abovegrade standpipe prior to testing, a waiting period is also required to ensure that the tank has fully contracted. The time that it takes for the tank to deform will vary from one tank system to another.

When the product level during a test is variable, the pressure exerted on the walls and ends of the tank will change as the level changes. When such a test is conducted in an overfilled tank, the surface area of the product is extremely small — it is usually limited to the diameter of the fill tube and a number of other small openings such as the vent tube. Any volume changes will be seen as large height changes, even those due to a leak, will cause the tank to deform and its volume to change. Unless the deformation characteristics of the tank system being tested are known (this includes the backfill and surrounding soil) it is impossible to interpret the height changes in terms of volume changes. Even the experimentally measured height-to-volume conversion factor commonly used to convert level changes to volume changes does not properly include the effects of tank deformation. These deformation characteristics are not known at the time of the test, and it is impractical to measure them. There is, consequently, a high risk of error associated with variable-level tests.

Since the Edison experiments, many of the variable-level tests have been converted to constant-pressure tests. This has been accomplished by adding either of two features to the test: (1) releveling the product to maintain a constant level during the test or (2) increasing the surface area of the standpipe in which product level is measured.

When a test is conducted in a partially filled tank, only that portion of the tank that contains fluid is tested for leaks; the test cannot assess the integrity of that portion of the tank located above the product level. A test conducted in an overfilled tank, on the other hand, assesses the integrity of the entire tank.

The hydrostatic pressure is kept approximately constant during partially filled-tank tests because the surface area of the product is spread across the width and length of the tank. As a consequence, any level changes that occur during a test will be quite small, regardless of the size of the associated volume change. In partially filled-tank tests, the height-to-volume conversion factor can be used to convert level changes to volume changes. If a large volume of product is added or removed prior to beginning a test, a waiting period will also be required to ensure that the effects of deformation have subsided before the test is begun.

Sources of ambient noise

Detecting a leak by means of volumetric testing is an example of the common statistical problem of finding a signal in a background of noise. In this case, the signal is the volume change that is due to a leak, and the noise is the sum of all the volume changes due to factors other than a leak. Unfortunately, a leak is not the only physical mechanism responsible for changes in the level and volume of product. There are a number of physical mechanisms that can contribute to either real or apparent volume changes, whether the tank is leaking or not. The best-performing methods can reliably differentiate between these non-leak-related volume changes and an actual leak.

It is a common perception that if the equipment is working properly the test will yield th actual leak rate. In reality, there is always some variation in test results, and it is likely that even with the same test method a different flow rate will be obtained each time a test is conducted. Even a test on a nonleaking tank will generally yield a value different from zero. Variations in test results stem from three sources: (1) the equipment itself, (2) operational practice, and (3) environmental considerations such as thermal expansion and contraction of the product or structural deformation of the tank, and the way these and other environmental factors interact. For best results, the instrumentation noise should be at least a factor of three less than the environmental noise. This ensures that the instrumentation will not limit the detection of small leaks. Environmental noise is the more acute problem because it can be difficult to identify or to compensate for during a test, and it can be larger than the leak itself.

There are at least five sources of environmentally induced product-level or product-volume changes that are unrelated to a leak. These five sources are thermal expansion and contraction of product, structural deformation of the tank, expansion and contraction of trapped vapor, evaporation and condensation within the tank, and surface and internal waves. These ambient noise product-level or product-volume changes can be as large as or larger than the smallest leaks to be detected, and a compensation scheme that reduces their magnitude must be used if accurate detection of small leaks is to occur.

There are a number of effective ways to compensate for ambient noise. The five sources of ambient noise are by no means equal in their impact on the accuracy of a test. The first four are likely to have the most deleterious effects, because the error associated with them is large. The errors due to surface or internal waves can be minimized if the data are sampled temporally and/or spatially at a small enough interval.

Thermal expansion and contraction of the product

Temperature fluctuations cause expansion and contraction of the product. Expansion and contraction represent changes in volume that can easily be mistaken for a leak unless they are taken into consideration when overall volume changes are calculated. When product is added to the tank (for example, during a delivery or during topping to fill the tank to its maximum capacity), the temperature increases or decreases as the product seeks thermal equilibrium with the surrounding backfill, native soil, and groundwater. Similarly, newly added product seeks equilibrium with the product that is already in the tank, and vice versa. Thus, the largest rate of change of temperature occurs immediately following a delivery of product and decays over time. The large temporal fluctuations and horizontal gradients in the temperature field that occur after a delivery or topping are due to the mixing of two products. Until these inhomogeneities have had enough time to decay, accurate measurement of the average temperature changes with a single array of temperature sensors will be difficult. The importance of compensating for these average temperature changes cannot be overemphasized. The volume changes produced by expansion and contraction of the product are real, and may be as large as 4 L/h, but they are not in any way associated with a leak.

The UST test apparatus, equipped with three vertical arrays of thermistors separated horizontally, permits accurate measurement of the average rate of change of temperature of the product and vapor in the tank. The test apparatus thermistors are capable of sensing temperature changes of less than 0.001 °C. Those volume changes that occur as a result of thermal expansion and contraction of the product can be calculated by dividing the total volume into cells and taking the sum of volume changes produced in each individual thermistor cell i, i.e.,

$$\Delta V = \sum_{i=1}^{n} \Delta V_i = \sum_{i=1}^{n} C V_i \Delta T_i, \tag{2}$$

where ΔV is the total change in volume caused by temperature changes; ΔV_i is the volume change experienced in cell i; C is the coefficient of thermal expansion for the product; V_i is the volume of product in cell i; ΔT_i is the change in temperature in cell i; and n is the number of cells.

Because temperature compensation is such an important aspect of leak detection, ambient noise experiments were conducted at the UST test apparatus to characterize inhomogeneities of the temperature field of the whole tank.

This analysis included:

- generating a thermal-volume-fluctuation time series sampled once per minute for each thermistor array as well as for the average of the three arrays
- subtracting the average thermal-volume time series from each array's volume time series
- calculating the slope (i.e., volume rate) of the thermal-volume time series by fitting a least-squares line to 1-h blocks of data updated every minute
- differencing the volume-rate (slope) time series of each array from the average of all three arrays

The results of this analysis suggest that when testing is begun at least 4 to 6 h after product delivery, a single array of thermistors having a vertical spacing of 20 cm is sufficient to characterize the temperature field of the whole 30,000-L tank. In the first 4 to 6 h, large differences in temperature between the three horizontally spaced arrays are evident. In this interval, then, even three horizontally separated arrays are not sufficient to characterize the temperature field. After 6 h, the difference in the rate of change of temperature between arrays, expressed as a volume, is small. In the experiment on which this estimate is based, 15,000 L of product was added to a 30,000-L tank containing 15,000 L of product; actual times may vary depending on tank size and amount of product added. The results of the experiment are illustrated in Fig. 1 in a time series plot of residual fluctuations, or differences, in the rate of change of temperature volume between Arrays 2 and 3. (The added product was 5.6°C cooler than the *in situ* product). During the first 6 h, volume-rate differences

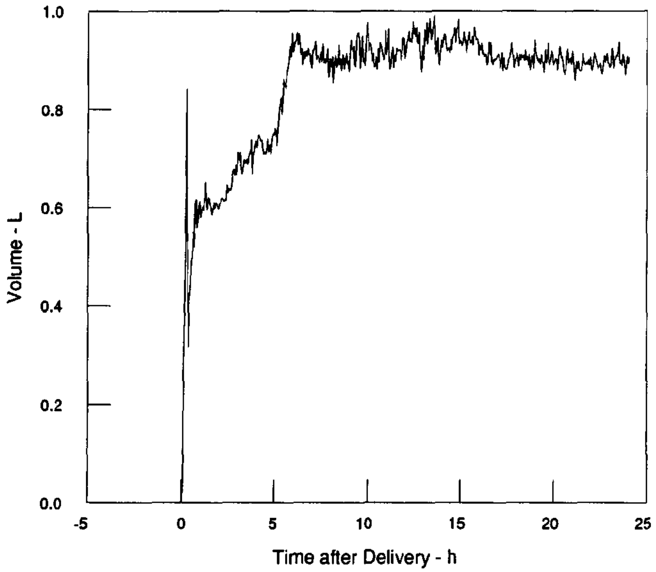

Fig. 1. Differences in residual fluctuations in root mean square temperature volume between Arrays 2 and 3 (28 October 1986).

larger than 500 ml/h and smaller than 100 ml/h were observed. Conducting a test during this period may lead to erroneous results. The temperature field is stable after 6 h, that is, after the horizontal temperature gradients along the long axis of the tank have become small.

Experiments were conducted in the fiberglass tank at the UST test apparatus to investigate the effects of topping on temperature compensation. Three vertical thermistor arrays were deployed to monitor the temperature field in the vicinity of the fill tube where the product was added. One array was inserted in the fill tube and the other two arrays were inserted on either side of it, approximately 75 cm away. This array configuration accounts for any horizontal gradients that might develop after topping. The tank was initially overfilled to a level within the fill tube more than 24 h before the start of the test. Approximately 19 L of product, either 7 °C cooler or warmer than the mean temperature of the product in the tank, was added to raise the level an additional 60 cm. It was anticipated that this product addition would effect a mean change in temperature of 0.004 °C for the product in the tank. Because the mean change in temperature of the product was so small, it would not significantly affect the mean rate of change of product temperature being driven by the mean temperature of the product in the tank and the mean temperature of the backfill and soil.

Several observations were made. First, the temperature field before topping exhibited a small but stable change in temperature. After the product had been added, the temperature field became highly disturbed for 2 to 3 h before re-approaching the pre-test temperature conditions. The temperature-volume fluctuations inferred by the two outer arrays were found to be similar to one another but different from those measured by the fill tube array. The symmetry was not perfect, probably because the addition of product sets up a flow in one direction or another. Third, the data suggested that an accurate estimate of the mean temperatures throughout the tank, required for thermal compensation, cannot be made until after the temperature field has stabilized. Fourth, if the temperature field is vertically undersampled, it is difficult to identify the time at which the inhomogeneities in the temperature due to topping have dissipated, because the inhomogeneities are not uniform from the top to the bottom of the tank.

Structural deformation of the tank

Whether it is constructed of steel or fiberglass, and whether it is embedded in a dense backfill or in a loose one that has more “give,”the tank itself expands and contracts in response to both level and temperature changes. This phenomenon is known as structural deformation. When the tank expands, the level of the fluid inside it goes down; conversely, when it contracts, the level goes up. The height changes produced by the change in the volume of the tank may also be mistaken for a leak. There are two types of structural deformation: (1) the *instantaneous* deformation that appears immediately after any change in product level and (2) the *time-dependent relaxation* of the tank. The volume change due to instantaneous deformation is accounted for when the height-to-volume conversion factor, A_{eff}, is measured experimentally. What is not accounted for in A_{eff} is the time-dependent relaxation of the tank. In order to do this, the amount of "give" of the tank, backfill and surrounding soil must be known. The length of time it takes for the tank to expand or "relax" to its maximum capacity must also be known. Generally, these values are *not* known during an actual test. However, the effects of structural deformation can be minimized by introducing a waiting period. The waiting period varies from one tank system to another. Efficient testing requires an analysis algorithm to determine when the effects of deformation have subsided. In the Edison tanks, time-dependent deformation took 12 hours or more to subside.

Instantaneous structural deformation

The height-to-volume conversion factor, A_{eff}, is defined by

$$A_{\mathrm{eff}} = A + A_{\mathrm{vp}} + A_{\mathrm{isd}}, \tag{3}$$

where A is the geometric cross-sectional area of the product surface and A_{vp} and A_{isd} are the volume changes per unit of product-level change produced by the compressibility of trapped vapor in an overfilled tank and the instantaneous structural deformation, respectively. It is not possible to distinguish the level changes due to the instantaneous expansion or contraction of any trapped vapor present in the tank from the level changes resulting from the instantaneous deformation. Therefore, it is not possible to measure A_{vp} and A_{isd} separately.

If there is no trapped vapor, $A_{\mathrm{vp}}=0$ and the contribution due to instantaneous deformation of the tank can be measured directly from eqn. (3) given that the surface area of the product is known or can be calculated and A_{eff} is measured experimentally. The volume changes due to instantaneous deformation, V_{bar}, which is derived from eqs. (1) and (3), are defined by

$$\Delta V_{\mathrm{isd}} = V_{\mathrm{bar}} - \Delta V_{\mathrm{eff}} - \Delta V_{\mathrm{vp}}, \tag{4}$$

where V_{bar} is the volume of the bar used in the height-to-volume conversion measurements, ΔV_{eff} is the measured volume change, and ΔV_{vp} is the volume change due to the compressibility of the trapped vapor.

An estimate of the instantaneous structural deformation was made from eq. (4); four days of experimental data were used to make this estimate, and it was assumed that the volume of the vapor pocket was known. Figure 2 shows that instantaneous structural deformation is directly proportional to change in pressure (product height). A_{isd} is estimated from the slope of the least-squares line as 35 cm^2. This value is very consistent with the values of A_{isd} calculated

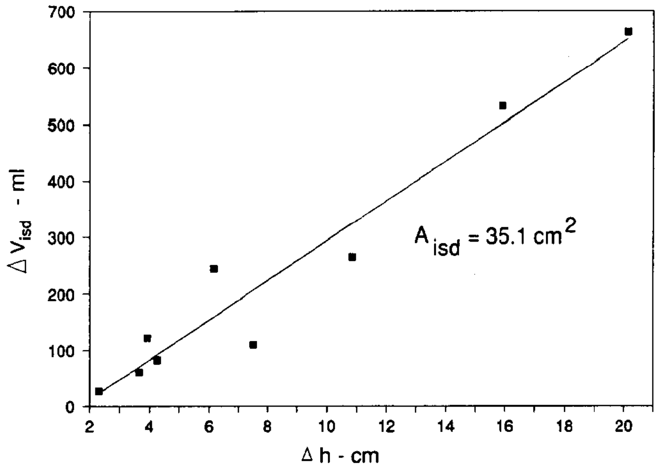

Fig. 2. Estimate of A_{isd} from data collected on 28–30 May and 6 June 1987.

for an overfilled tank in which the vapor pocket volume was 10 L (as described below in the section entitled *Expansion and contraction of vapor pockets*).

Variable-level tests

Even when expansion or contraction due to sudden, large, man-made changes in product level has reached its maximum, the tank continues to deform, expanding or contracting in response to every product-level change that occurs during a test. This occurs regardless of whether the change was produced by a leak or by one of the five environmental noise sources. It can be a special problem during a variable-level (i.e., variable-pressure) test if the tank/backfill/soil system is highly elastic *and* the tank is overfilled. In a case like this, interpretation of the results is difficult, even after sufficient time has elapsed to allow deformation from any initial product-level changes to subside, because the measured volume changes estimated from A_{eff} are always smaller than the actual volume changes. The reason for this is that any increase in product level at the start of a test causes the tank to expand in response to the increased pressure; product level then drops as a result of the expansion (deformation) of the tank; when the product level drops, the pressure is reduced and the tank contracts (deforms); when the tank contracts, the product level rises again at least part of the way back to where it was originally. The net result is that the level changes that actually occur are only a fraction of the level changes expected. This complex feedback mechanism is dependent on the tank/backfill/soil characteristics, which in actual practice are not known. Thus, A_{eff} cannot be used to convert level changes to volume changes. It is best, therefore, to avoid variable-level tests.

An exponential relaxation model, referred to as the Fill-Tube Dynamics

Model, is hypothesized as a way of describing the volume and product-level changes produced by tank deformation in an overfilled tank. For the specific case when a known amount of product, ΔV_p, is added instantaneously into the fill tube of an initially overfilled tank, the product-level time series for $t \geq t_0$ is

$$h(t)=\frac{\Delta V_P}{A_{\text{eff}}}+\frac{\Delta V_P}{A_{\text{eff}}}\left(\frac{K}{A_{\text{eff}}+K}\right)(\mathrm{e}^{-(t-t_0)/T_{\text{eff}}}-1), \tag{5}$$

where A_{eff} is the effective cross-sectional area of the product surface, K is the equilibrium elasticity of the tank/backfill/soil system, t_0 is the time at which the product level is changed, and the effective time constant of the tank is defined by

$$T_{\text{eff}}=T_C\frac{A_{\text{eff}}}{(A_{\text{eff}}+K)}, \tag{6}$$

where T_C is the hydrostatic-pressure relaxation time constant of the tank/backfill/soil system.

The first term in eq. (5) is the product-level change, which includes the effects of any trapped vapor and of the instantaneous deformation of the tank. The second term is the time-dependent relaxation due to tank deformation. The time it takes for the tank to deform is determined by T_{eff}, the effective time constant of the tank.

An experiment was conducted in the steel tank on 3 May 1987 to estimate K, T_C, T_{eff}, and A_{eff}. These data were selected for analysis because the thermally induced volume changes, which were less than 40 ml/h, as well as all other product-volume changes, were small enough to be negligible. The initial product level in the fill tube, before the start of the tests, was 30 cm above the top of the tank. A 5.045-L bar was used to displace this product. The rise and drop in the product level was approximately 38 cm, only 59% of the expected 62-cm change based on geometrical considerations. A_{eff} was estimated, from the 38-cm displacement produced by the 5.045-L bar, to be 132.7 cm^2. The measured value of A_{eff} was used to convert product-level changes in a 10-cm-diameter fill tube to product-volume changes. The product-volume data were detrended, and the model described by eq. (5) was fit to the data by means of a least-squares technique. The results are given in Table 1 and Fig. 3.

For the case in which the product level is instantaneously raised in the fill tube when the rate of change of volume in the tank is a constant, the product-level time series is given by

$$h(t)=\frac{\Delta V_p}{A_{\text{eff}}}+\frac{\Delta V_p}{A_{\text{eff}}}\left(\frac{K}{A_{\text{eff}}+K}\right)(\mathrm{e}^{-(t-t_0)/T_{\text{eff}}}-1)+\frac{C}{A_{\text{eff}}+K}(t-t_0), \tag{7}$$

where C is the flow rate produced by a leak and/or any other product-volume change. Equation (7) predicts the product-level changes that would occur in a

TABLE 1

Estimates of A_{eff}, T_C, T_{eff} and K made from measurements of product at a level within the 10-cm diameter fill tubes of the steel and fiberglass tanks at the UST test apparatus

Tank	A_{eff} (cm^2)	T_C (h)	T_{eff} (h)	K (cm^2)
Steel	132.7	3.0	1.6	117
Fiberglass	125.1	2.6	1.6	75

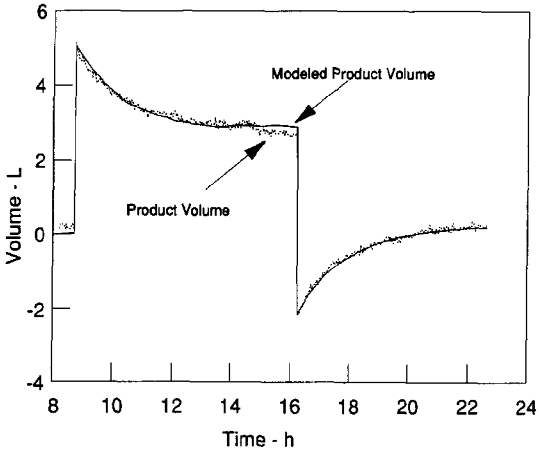

Fig. 3. Comparison of the measured and predicted volume time series for data collected on 3 May 1987 with product level in the fill tube of the steel tank at the UST test apparatus.

leaking tank, or a tank in which the product volume is changing, when a volumetric test is initiated by topping the tank. The product-level change consists of a large exponential change in the product level, followed by a linear rate of change.

Equation (7) was used to predict the product-volume changes in a 10-cm-diameter fill tube that are produced (1) by a 1-m product-level rise resulting from topping the tank immediately before the start of a test and (2) by a −1.2 L/h rate of change of volume during the test. The product-volume changes are shown in Fig. 4. A_{eff} is used to convert the product-level changes predicted by eq. (7) to volume changes. It is assumed that the volume change is produced by a leak, by thermal contraction of the product, or by a combination of these. No other volume changes are considered. The following values, typical of the steel tank at the UST test apparatus, were used in the calculations: $K=120$ cm^2, $T_C=3$ h, $T_{\text{eff}}=1.5$ h, and $A_{\text{eff}}=125$ cm^2. The predicted product-volume change, after several time constants, T_{eff}, have elapsed, is −0.61 L/h, only 51% of the actual −1.2 L/h volume rate. The dashed curve illustrates a −1.2-L/h

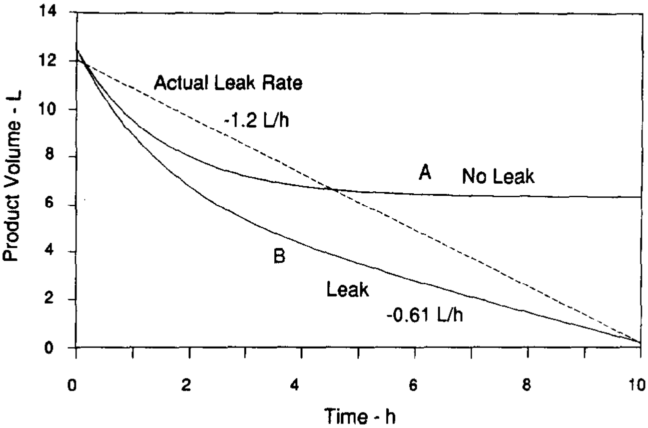

Fig. 4. Comparison of the Fill-Tube Dynamics Model predictions using eq. (4) for $A_{\text{eff}} = 125\ \text{cm}^2$, $K = 120\ \text{cm}^2$, and $T_C = 3\text{h}$.

volume rate. This deformation-induced effect could represent a large error in either the leak rate, the temperature-induced volume changes, or a linear combination of both. If the tank is not leaking, and the volume changes are produced only by temperature fluctuations, the temperature-compensated volume rate obtained by subtracting the measured volume rate of −0.61 L/h from the actual volume rate of −1.2 L/h should be +0.59 L/h instead of zero. For comparison, the product-level changes that are the result of deformation only are also shown in Fig. 4; the rate of change of volume after 4 to 6 h is approximately zero.

The two effects which occur after the tank has been topped are significant. First, if a test is conducted too soon after a product-level change, the measurement is typically dominated by the exponential volume change of the tank. In many methods an attempt is made, before starting a test, to wait until the large exponential decay has occurred. Many methods use a waiting period that is too short for these measured volume changes to become negligible. Second, it is mistakenly assumed that once the large decrease in product level typically associated with the exponential volume changes due to deformation becomes constant, an accurate test of the tank's integrity can be conducted. This is not true if K is approximately equal in magnitude to A_{eff}, because the linear product-level changes that occur after the exponential changes are only a fraction of the actual product-level changes that would occur if the tank were rigid and did not deform. The effect is particularly severe when the diameter of the fill tube is small, because in this case even large leak rates produce only small product-level changes. Equation (7) can be used to interpret this behavior. The second term in this equation approaches zero and the only time-dependent term is the third term. The height-to-volume conversion factor that needs to be used to convert level changes to volume changes when the time-dependent deformation is large is not A_{eff} but $(A_{\mathrm{eff}}+K)$.

Constant-level tests

Some methods measure volume changes directly by periodically adding or removing a measured amount of product to maintain a constant product level in the fill tube or an above-grade standpipe. Because product level is kept approximately constant, no significant additional deformation of the tank occurs during the test. The measured volume changes (converted from product-level changes by means of A_{eff}) represent the actual volume changes occurring in the tank.

The Fill-Tube Dynamics Model was extended to include the effects of periodically releveling the product in the fill tube every t minutes in the presence of a constant volume change, C, where C is the sum of a constant leak rate, LR, and any other constant product-volume change not related to a leak. The model includes the topping effect whereby a known amount of product is instantaneously added to the fill tube to attain a specified level for the test. The volume, V_{n}, at $\lambda = nt$ required to bring the product level to zero is given by

$$V_{\mathrm{n}} = -C\lambda + \left[\frac{\mathrm{KC}}{\mathrm{A_{eff}}+\mathrm{K}}(\lambda - \mathrm{T_{eff}} + \mathrm{T_{eff}}\mathrm{e}^{-\lambda/T_{\mathrm{eff}}}) - \left(\frac{A_{\mathrm{eff}}}{A_{\mathrm{eff}}+K}\right)V_{\mathrm{p}}(0)\,(1-\mathrm{e}^{-\lambda/T_{\mathrm{eff}}})\right]$$

$$\times\left(K + A_{\mathrm{eff}}\frac{\mathrm{e}^{-\lambda/T_{\mathrm{eff}}}}{A_{\mathrm{eff}}+K}\right)^{n-1} \qquad n \geq 1. \tag{8}$$

The derivation of eq. (8) is mathematically complex and only the result is given here. The total amount of product added to maintain a constant level in the fill tube is obtained by summing the V_{n} calculated from eq. (8) for all n. This is equal to the product-volume drop in a fill tube of very large diameter. If the releveling period is very much smaller than the effective time constant, eq. (8) is approximately by

$$V_{\mathrm{n}} \simeq -C\lambda - V_{\mathrm{p}}(0)\frac{\lambda}{T}\mathrm{e}^{-(n-1)\lambda/T}. \tag{9}$$

In practice, $V_{\mathrm{p}}(0)$ is unknown because the time history of past volume changes is unknown. It is assumed that the product level, $-h_0$ is constant (i.e., that there are no volume changes) for all time $t<0$, and that it is then raised a constant amount, h_0, at $t=0$. It can then be shown that

$$V_{\mathrm{p}}(0) = -Kh_0. \tag{10}$$

Thus, the volume change of the product at $t=0$ is dependent on the value of K, which is not known under most testing conditions.

If the product in the fill tube is releveled continuously, the volume changes will be equal to the leak rate after the deformation produced by an initial addition of product to the tank has ceased. The constant-hydrostatic-pressure time constant, T_C, governs the deformation. If the tank is releveled every 15 min, the time constant of the volume changes is approximately $1.14T_C$. This was obtained by solving eq. (8) and computing the time constant directly. Thus, the penalty for not releveling continuously is a small increase in the time required to test a tank.

Expansion and contraction of vapor pockets

In addition to their direct influence on the product, temperature fluctuations can also cause the expansion or contraction of vapor pockets that are almost always present after a tank has been filled to capacity. Here, though, temperature is not the sole influence.

Vapor pocket size can also be affected by atmospheric pressure and by pressure changes resulting from product-level changes. When the volume of the trapped vapor changes, there is a resultant change in the level of the product; this latter change may mistakenly be interpreted as a leak. Despite efforts to bleed the tank of trapped vapor, pockets large enough to adversely affect the outcome of a test may still be present. Vapor pockets in quantities as small as 40 L can influence a test result. It is virtually impossible to determine the exact size of vapor pockets because the effects of trapped vapor cannot be separated from the effects of instantaneous deformation of the tank. If the instantaneous deformation is negligible, or if the volume changes due to the instantaneous deformation are small in comparison to the volume changes produced by trapped vapor, it is possible to determine that trapped vapor is present. Based on the measurements made at the Test Apparatus, it should be possible to begin identifying the presence of trapped vapor when the total volume of trapped vapor is greater than 40 to 80 L. If vapor pockets of 40 to 80 L or more are shown to be present, or if for any reason (for example, if the tank is tilted) it is *suspected* that they are present, the tank and lines should again be bled; if vapor pockets are shown to be largely absent, testing may proceed.

Because the volume and location of the trapped vapor are usually unknown, it is nearly impossible to compensate for or even to estimate accurately the magnitude of the product-level (volume) changes produced by expansion and contraction of trapped vapor. Even if the location and the volume of the trapped vapor were known, it would be difficult to measure accurately the temperature and/or pressure of the trapped vapor. What is needed, then, instead of compensation, is a method of estimating the volume of trapped vapor. In this way, if the volume of trapped vapor were determined to be too large, an effort could be made to remove it, or a decision made not to conduct a test.

A set of experiments was designed and conducted at the UST test apparatus to estimate the volume of a known amount of trapped vapor in an overfilled tank by varying the pressure in a predetermined way. Two types of experimental configurations (Figs. 5 and 6) were used to conduct the experiments. In the first type, the tank was overfilled to a level within the fill tube, and an effort was made to remove all trapped vapor, as if a volumetric test were to be conducted. In the second, a sleeve was inserted into the fill tube of the tank to trap a known volume of vapor. For both configurations, a pressure change was pro-

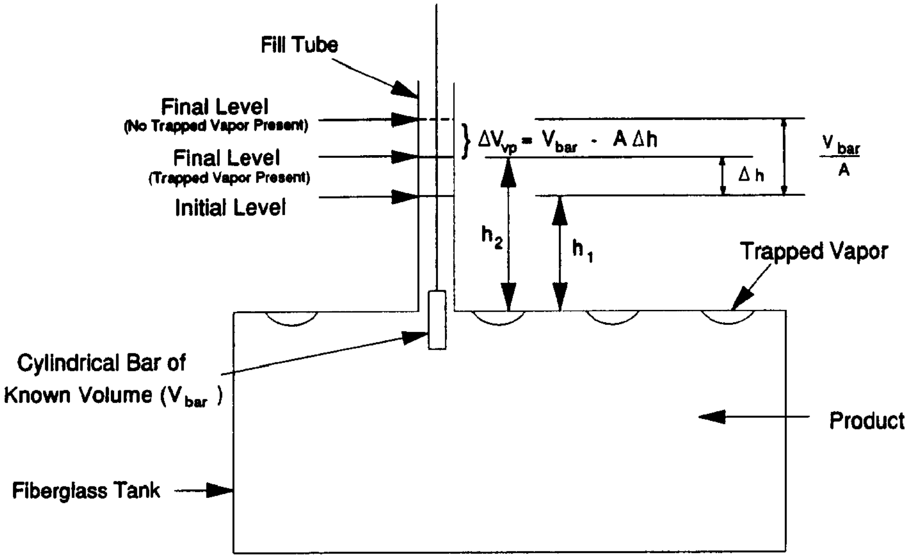

Fig. 5. Experimental configuration for trapped vapor tests in a well-bled fiberglass tank.

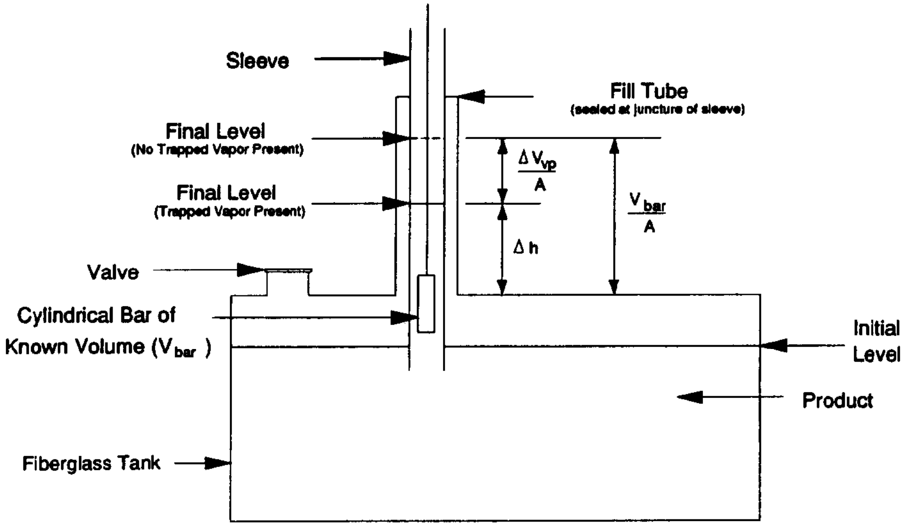

Fig. 6. Experimental configuration for the trapped vapor tests in the fiberglass tank.

duced by rapidly inserting a cylindrical bar of known volume into the tank. The height-to-volume conversion factor, A_{eff}, was computed directly from the bar volume, V_{bar}, and the measured product-level change, Δh. A_{eff} is controlled by the geometrical cross section of the free product surface, A, and the volume changes per unit of product-level change produced by the compressibility of the trapped vapor and the instantaneous structural deformation, A_{vp} and A_{isd}, respectively.

For a well-bled, overfilled tank containing small amounts of trapped vapor, the change in volume due to trapped vapor, ΔV_{vp}, can be estimated from

$$\Delta V_{\mathrm{vp}} = n V_{\mathrm{vp}} \ln\left(\frac{P_{\mathrm{A}} + \rho g \Delta h}{P_{\mathrm{A}}}\right), \tag{11}$$

where V_{vp} is the vapor pocket volume, ρ is the density of the product, g is the acceleration due to gravity, and n is a constant estimated to be unity. Equation (11) is derived from the pressure–volume relationship for a perfect-gas polytropic process, $PV^n = \text{constant}$. Because of the compression of the vapor and the instantaneous deformation of the tank, the measured volume change is less than would be expected given the geometrical considerations. The total volume changes due to instantaneous deformation and to vapor pockets are given by

$$V_{\mathrm{bar}} = A_{\mathrm{eff}} \Delta h + (A_{\mathrm{isd}} + A_{\mathrm{vp}})\left(\frac{V_{\mathrm{bar}}}{A} - \Delta h\right). \tag{12}$$

Validation of the model and accurate estimates of the volume of trapped vapor in the tank thus require that $A_{\mathrm{vp}} > A_{\mathrm{isd}}$. If the volume changes produces by the instantaneous structural deformation of the tank are large, neither the validation nor the method of making volume estimates will be accurate.

Trapped vapor in a well-bled tank

Many overfilled-tank tests were conducted to determine the bound on the instantaneous volume changes induced by vapor pockets and tank deformation. A special effort was made to remove all sources of vapor from the tank and associated piping by means of bleed valves that were placed at critical locations in the system. Table 1 summarizes the results of the tests in a well-bled, overfilled tank. Product-level changes were produced during a set of experiments conducted on 6 June 1987 by inserting and removing bars of different size (625, 953, 1551, and 2477 ml). The product-level measurements were made with a ruler to the nearest 3 mm.

Several observations about the data are noteworthy. It can be seen from Table 2 that the values of A_{eff} and $A_{\mathrm{isd}} + A_{\mathrm{vp}}$ are constant over the range of product-level changes. Since it can be shown from eq. (5) that A_{vp} is a constant over a wide range of pressure changes, it can be concluded that A_{isd} is also constant.

TABLE 2

Summary of the results of the 6 June 1987 overfilled fiberglass tank tests (product depth 335.3 cm)

Bar volume (ml)	Δh (cm)	A_{eff} (cm^2)	A (cm^2)	$A_{isd}+A_{vp}$ (cm^2)	V_{vp} for $A_{isd}=0$ (L)	A_{vp} for $V_{vp}=10$ L (cm^2)	A_{isd} for $V_{vp}=10$ L (cm^2)
626	5.20	120.2	81.1	39.0	55	7.0	32.0
953	7.77	122.7	81.1	41.6	58	7.1	34.5
1551	12.67	122.4	81.1	41.3	58	7.1	34.2
2477	20.40	121.4	81.1	40.3	57	7.0	33.3

TABLE 3

Summary of the trapped vapor tests conducted in the fiberglass tank on 5 June 1987[a]

Bar volume (ml)	Δh (cm)	A_{eff} (cm^2)	A (cm^2)	$A_{isd}+A_{vp}$ (cm^2)	V_{vp} (L)
1551	2.30	674.4	71.4	603.0	838
2477	3.65	678.6	71.4	607.0	345
5071	7.52	674.6	71.4	603.2	842

[a] Equation (8), with $n=1$, was used to do the calculations and it was assumed that atmospheric pressure was 13.9 m of gasoline. The product depth was 218.1 cm. An 821-L vapor pocket was trapped in the tank and fill tubes.

The results shown in Table 2 indicate that the maximum amount of vapor that can be trapped in the top of the tank is approximately 60 L; this assumes that the instantaneous structural deformation is zero. Other observations at the beginning of the program indicated that the tank should contain no more than 10 L of vapor. Assuming this to be the case, A_{isd} is estimated to be 35 cm^2.

Trapped vapor tests

An 821-L vapor pocket was trapped in the top of the tank by means of the sleeve shown in Fig. 6. Table 3 summarizes the results of these tests. Figure 7 illustrates the product-level changes produced by inserting and removing bars of different size (1551, 2477, and 5071 ml). Product-level changes induced by the exponential deformation of the tank can be seen where the two largest bars were inserted (Fig. 7). The three estimates of the 821-L vapor pocket are given in Table 3. The agreement is within the experimental error of the measurement. The two largest sources of error are the uncertainty in the volume of the trapped vapor and the contribution of the instantaneous deformation.

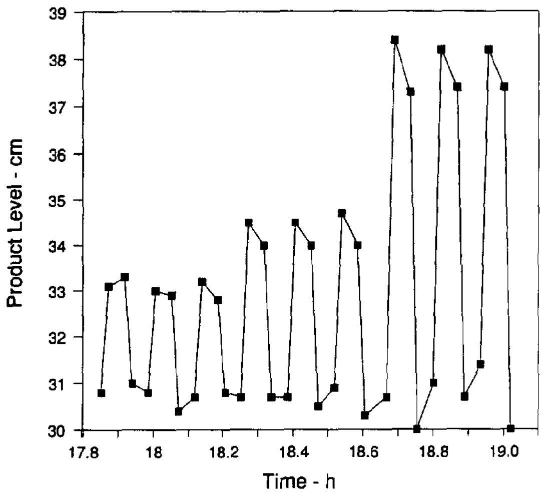

Fig. 7. Time series of the product-level changes in the sleeve of an underfilled fiberglass tank on 5 June 1987; product-level changes were produced by inserting three different-size bars (1151, 2477, 5071 ml).

Other factors

Unless a tank and its fill tube are completely filled and no air or vapor pockets are present, it is likely that, as temperatures change, fluid will evaporate from or condense on the free product surface or tank walls. This activity produces volume fluctuations that may be mistaken for a leak. A more detailed discussion is presented in [3].

Mechanical vibrations and other disturbances produce waves; these can be of two types: surface or internal. (In some instances, internal waves can produce surface waves.) Surface waves move along the exposed area of the product in a partially filled tank, causing a back-and-forth motion that is typically resonant along the longitudinal axis of the tank with periods that range from several seconds to ten or more. This seiching may be misinterpreted as changes in fluid level. Seiching may also occur in overfilled tanks if two openings are present. The period will be longer than in partially filled tanks. Internal waves, which are found in both filled and partially filled tanks, usually occur when there are temperature differences present, such as the boundary layer between resident and newly added product. The passage of an internal wave causes this boundary layer to undulate vertically so that a temperature sensor at a fixed location records the temperature changes associated with the wave rather than those responsible for volume changes. Internal waves with periods between 5 min and 30 min have been measured in tanks up to 37,850 L (10,000 gal). If the data are undersampled, i.e., if the sampling interval is greater than one-half of the period of the wave (Shannon theorem), aliasing occurs — the waves may appear to produce level or temperature changes, even though none exist. However, if the data are sampled frequently enough and are averaged, the problem is avoided.

Signal strength

The magnitude of the leak rate (i.e., the signal) depends on the hydrostatic pressure exerted on the hole. This differential pressure depends on the level of both the product and the groundwater during the test, the densities of the product and the groundwater, and the location of the hole. The main effect of groundwater is to modify (usually to decrease) the magnitude of the signal to be detected. The actual flow rate through the hole will also depend on the backfill material around the hole and the geometry of the hole.

The water table of the soil in which a tank is buried can vary in height depending on factors such as geographic location, season, and amount of precipitation. If a tank is leaking below the groundwater table, the height of the water table in relation to the tank has a direct effect on the flow rate measured during a test. If the water table is above the location of a hole or fissure in an underground tank, the groundwater exerts a pressure (hydrostatic) on that hole which counteracts the pressure exerted on the same hole by the fluid in the tank. There are many possible scenarios. Water can restrict the flow of product out of the tank; it can prevent flow entirely; or it can cause an inflow of water into the tank. As shown in Fig. 8, any of these scenarios can alter the rate of a leak. Whenever the groundwater is above a hole in the tank, it may cause even a large leak to go undetected. Since it is virtually impossible to determine the location of a hole in an underground tank, efforts must be concentrated instead on monitoring the groundwater level. This is accomplished by means of a "monitoring well" installed next to the tank and used to make measurements of the water table. It is important to be aware that when the water table is higher than the bottom of the tank, any tests for leaks will be less sensitive. The best test results are obtained when the water table is below the level of the tank. Flow through the hole is then unrestricted by groundwater.

How performance is defined for a test method

Performance is defined by the test method's probability of detection and probability of false alarm for each leak rate that the method claims to be able to detect. The probability of detection refers to the test's chances of correctly identifying a leaking tank comparing to its chances of failing to detect a leak that is actually present (error of the first kind). The probability of false alarm refers to a test's chances of reporting the presence of a leak when in fact none exists (error of the second kind). Given the foregoing statements, there are

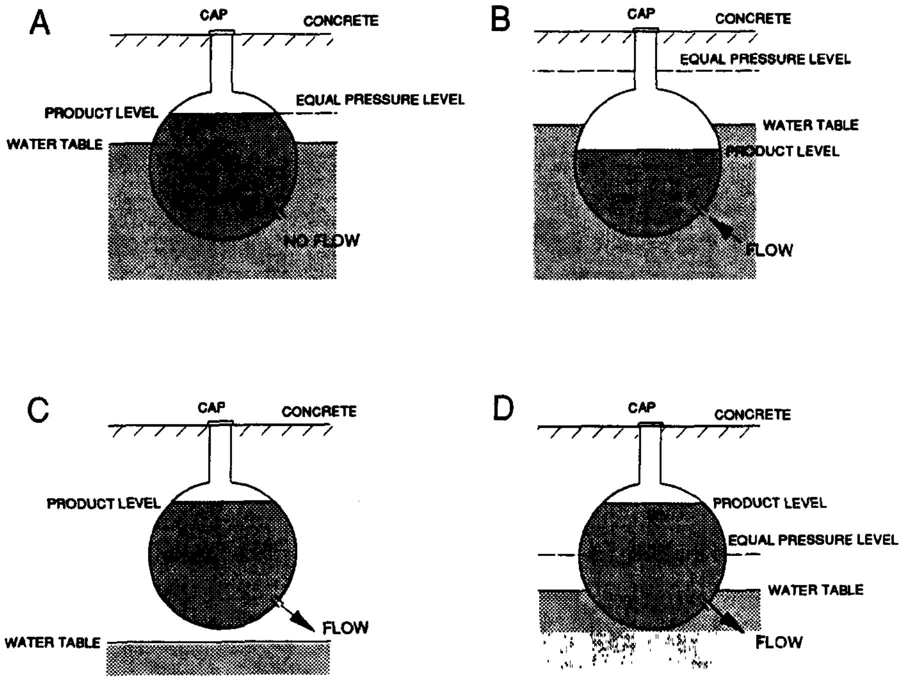

Fig. 8. Groundwater can affect the rate of flow through a hole in an underground tank. In (A), the pressure exerted by the product at the hole is exactly balanced by the pressure of the groundwater at the hole. Because the product is less dense than water, there is no flow in either direction even though the product is higher than the water table. In (B), the pressure exerted by the groundwater is greater than that of the product; therefore, water flows into the tank. In (C), since the water table is below the tank, there is no counter-pressure against the product at the hole; therefore, product flows out. Finally, in (D), the pressure exerted by the groundwater is less than that of the product; therefore, product flows out, but at a rate slower than shown in (C). The dotted line in each of the figures shows the product height required to produce an equal balance of pressure between the groundwater and the product.

four possible outcomes of a leak detection test: a correctly identified leak, a correctly identified tight tank, a false alarm, and a missed detection.

The performance of a detection system can only be determined once the fluctuation level (product-level or product-volume changes) at the output of the measurement system is known with and without the signal present. For any test method, the statistical fluctuation of the noise is observed in the histogram of the volume-rate results created by plotting the measured volume rates from a large number of tests conducted (1) over a wide range of conditions, (2) with many systems on one or more nonleaking tanks, and (3) by many different operators. The histogram indicates the probability that a particular volume rate will result from a test on a nonleaking tank. The histogram of the noise is developed experimentally. The histogram of the signal-plus-noise is usually developed from a model that indicates how the signal adds to the noise. It is usually assumed that the noise data are stationary (i.e., that the histogram of the noise does not change with time) and are spatially homogeneous (i.e., that the histogram of the noise obtained from one tank is not statistically different from the histogram obtained at another tank). This is not always true, and as a consequence, estimating performance is complicated.

The performance of a volumetric test method is estimated from the model shown in Fig. 9. If the calculated flow rate exceeds the threshold, it is assumed that a leak is present. This model assumes that the noise data are stationary and spatially homogeneous, that the noise histogram has a zero mean, and that the signal is additive with the noise. For rests conducted at a constant or nearly constant product level, the signal will be equal to the actual flow rate produced by a leak. However, if the product level is allowed to fluctuate during a test, the signal will be only a fraction, *k*, of the actual flow rate. Furthermore, the shape of the noise histogram may be different from the shape of the signal-plus-noise histogram. This model applies to all volumetric tests, providing that non bias exists. The standard deviation of the noise and the signal-plus-noise is a measure of the spread of the data and is directly proportional to performance. The smaller the standard deviation, the better the performance.

If the test method has a bias (i.e., if it is controlled by systematic errors), the histogram has a mean displacement. If the bias is large, it will generally control the performance of the method. A bias will result, for example, if a test is routinely conducted immediately after the level of product in the tank, fill tube, or standpipe has been raised, that is, if there is no waiting period to allow the product-volume changes produced by structural deformation to become small. If the bias cannot be quantified and removed, an accurate estimate of performance cannot be made.

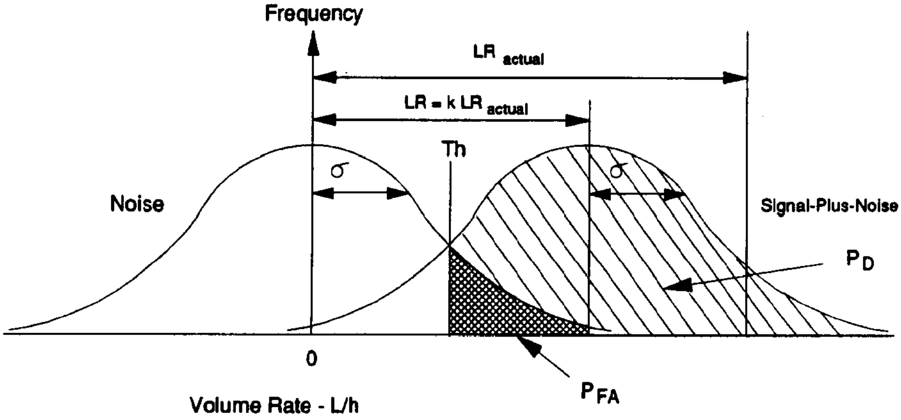

Fig. 9. Statistical model to estimate the accuracy of a volumetric leak detection system.

The P_D, represented in Fig. 9 by the hatched area, is defined as the fractional time the signal-plus-noise fluctuation will exceed the threshold. Clearly, if the threshold does not change, the P_D will be higher for larger leak rates. The P_{FA}, represented by the cross-hatched area, is defined as the fractional time that the noise fluctuation will exceed the threshold.

Both the P_D and the P_{FA} are dependent on the criterion for declaring a leak, that is, on the threshold value set by the manufacturer. If the calculated flow rate exceeds the threshold, it is assumed that a leak is present. Once this threshold value has been selected, the P_{FA} is established; it does not change, even if the leak to be detected is changed. The P_D, however, does change. The P_D increases as the leak to be detected increases. Stated simply, there is a better chance of finding large leaks than small leaks. The threshold can be changed in order to balance the P_D and P_{FA} in such a way that there is also an acceptable balance between economic and environmental risks. If the threshold is low (i.e., if very small leaks are to be detected), the probability of detection is high, but so is the probability of false alarm. On the other hand, if the threshold is high, there exists less chance of false alarm but also a greater probability of missed detections (because the P_D is lower). Any adjustment made to the threshold for the purpose of improving the P_D carries with it an increased risk of false alarm. Conversely, any adjustment made to the threshold for the purpose of lowering the P_{FA} automatically implies an increased risk of missed detections.

The most commonly used threshold is 190 ml/h. A threshold of 190 ml/h might yield high performance (e.g., a P_D greater than 99%) against a leak of 4 L/h, but low performance (e.g., a P_D less than 10%) against a leak rate of 95 ml/h. The 190-ml/h threshold is often confused with the leak rate to be detected, the P_D is only 50% against a leak of that size for a constant-level test. The EPA requires test methods to have a minimum detectable leak rate of 380 ml/h. In order for a test method to meet this requirement, its threshold must be *less* than 380 ml/h.

Choosing the right balance between the P_D and P_{FA} is a very difficult task. Missed detections result in the release of product into the ground and the consequential contamination of the nation's major source of potable water. False alarms lead to the expense of additional testing and/or the repair or replacement of tanks that are not leaking. It is fair to expect tank owners to interpret this balance in terms of financial considerations. The clean-up costs resulting from a missed detection must be weighed against the cost of unnecessary testing and repairs resulting from a false alarm. The EPA requires that tests be capable of detecting a leak with a probability of detection of 95% and a probability of false alarm of 5%. These, though, are only minimum standards, and the tank owner/operator may want better protection against the possibility of a testing mistake.

Evaluation approach

The performance of a leak detection system is determined from the histograms of the system and ambient volume-rate fluctuations in a nonleaking tank (i.e., noises) compiled for all conditions under which a test will be conducted, and from the relationship between leak rate and these volume rate fluctuations (i.e., signal-plus-noise). If the evaluation had included only a few test methods, each manufacturer could have been requested to perform a standard tank test for each ambient condition in the test matrix, and a histogram could have been generated from all of the volume rates measured [8–10]. However, because both the test matrix and the number of methods to be tested were large, this approach would have been too time-consuming and too costly to implement. In addition, this direct approach would not have provided any useful information either to assess the limits of the technology in general or to improve the performance of a given method. Instead, a novel approach, which does provide this information, was developed to perform the evaluation; this approach takes advantage of the common methodology of the majority of the volumetric test methods.

A three-step procedure was used to conduct the evaluations [3–7, 11–13]. The first step was to develop and experimentally confirm models of the important sources of noise that control the performance of each test method. If the total noise field is accurately modeled, the sum of the volume contributions from each noise source will be equal to the product-level changes in a nonleaking tank. As part of the modeling effort, a large database, reflecting the different product temperature conditions which could be experienced during field testing, was obtained at the test apparatus to simulate a test performed after a delivery of approximately 15,000 L of product at one temperature to a 30,000-L storage tank half-filled with product at another temperature.

The second step was to develop and validate, for each leak detection method, a model that mathematically described it. The test-method model includes the precision and accuracy of the instruments; the test protocol; the data collection, analysis and compensation algorithms; and the detection criterion. (The salient features of each test method can readily be found in the technical appendices to [3]). The model, in turn, was validated in two steps. First, each manufacturer was required to review the model for accuracy and to concur that it accurately represented the method before the evaluation was allowed to continue; and second, the manufacturer was required to participate in a three-day program of tank-test and calibration experiments at the UST test apparatus to validate the model. The manufacturer used his own crews and equipment for the three days of testing. Methods that were not operational at the time of the tests, or that were different from those with which their respective manufacturers had concurred, were not evaluated.

Finally, a performance estimate for each method was made by combining, in a simulation, the test-method model approved by the manufacturer, the product-level measurements estimated from the noise models, and the temperature database. The performance of a test method was evaluated by repeatedly simulating the conduct of a tank test in order to develop a histogram of the noise. Operational effects and deviations from the prescribed protocols during the three-day field testing program were also examined and discussed.

Two product-temperature databases were developed by experimentally generating a wide variety of temperature conditions that occur as a result of product delivery to the tank. One database corresponds to tests in which the product in the tank naturally attempts to come into thermal equilibrium with the surrounding backfill and native soil; the second corresponds to tests in which the product in the tank is deliberately mixed. Both databases were developed in the same way. Approximately 15 000 L of product that was either warmer or cooler than the resident product and the surrounding backfill was added to a half-filled 30,000-L tank. With each simulated delivery, the temperature field was measured over a period of 24 to 48 h, and temperature data were collected for a range of temperature differences of $\pm 10\,^\circ$C between newly added and *in situ* product. Because the added product circulates around the center of the tank, methods which do not have adequate vertical spatial coverage to measure temperature (e.g., those that have one temperature sensor located at the center of the tank) performed better in this evaluation than under the wider range of delivery conditions that occur in actual practice. The temperature database that was used in the evaluations was selected so as to give a normal distribution of the rate of change of volume over a 1-h period. The "unmixed" temperature database contained over 500 h of temperature and product-level data, and the "mixed" temperature database contained over 185 h of data.

Performance curves were generated that were based on the simulated noise and signal-plus-noise histograms. For high levels of performance, the P_{D} and P_{FA} are estimated from the tails of the histogram. With limited data, good estimates of the P_{D} and P_{FA} are sometimes difficult to make. In this study, the performance estimates were typically based on 50 to 200 independent realizations of the manufacturer's test. To reduce the uncertainty in the performance estimates at the higher P_{D} and lower P_{FA}, values, an exponential curve was fit to the tails of the histogram. The P_{D} and the P_{FA} obtained from the curve were used to estimate performance; an estimate of the uncertainty of the P_{D} and the P_{FA} was also made.

The performance is presented in three displays, the first of which is a plot of the probability of detection versus detection threshold for a family of leak rates with flow into and out of the tank (positive and negative volume rates). The second display is a plot of the probability of false alarm versus threshold. The third display shows the probability of detection versus the probability of false alarm for a family of leak rates. The third display is separated into two

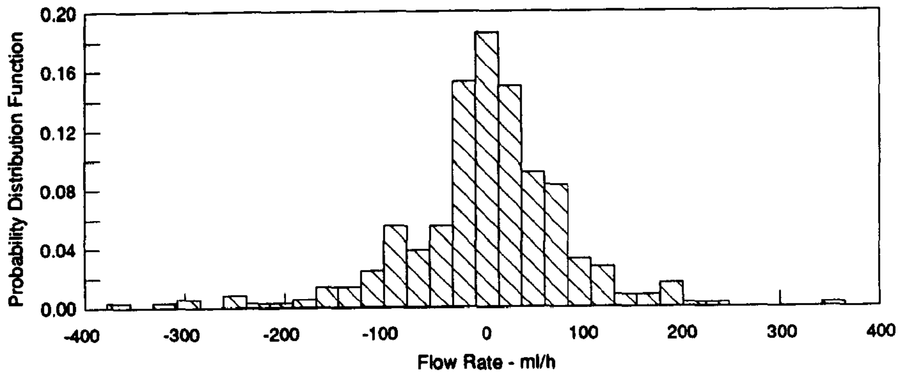

Fig. 10. Histogram of the noise generated for the five-thermistor test method.

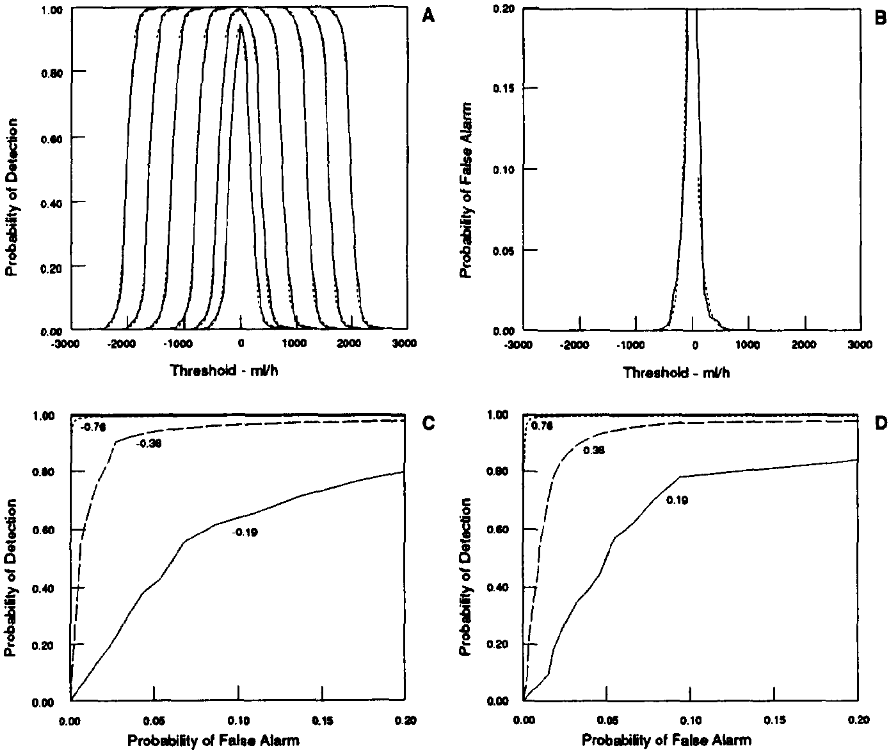

Fig. 11. Examples of performance curves for the five-thermistor test method.

plots, one for outflows and one for inflows. In this display, the mean of the noise histogram has been removed.

Examples of the noise histogram and performance curves illustrative of the output generated for each test method evaluated are shown in Figs. 10 and 11 for a hypothetical method that tests when product is near the top of the tank, using an array of five equally spaced, volumetrically weighted thermistors. It was assumed that the temperature and product-level sensors used by this method had sufficient precision to measure ambient product-volume changes that were less than 40 ml/h. The data were sampled once per minute and the duration of the test was 1 h. The only source of noise considered in the simulation was thermal expansion or contraction of the product.

An important distinction is made between evaluation and validation. A validated method is one whose performance can be reliably predicted under any conditions likely to be encountered when it is implemented in the field; it has been tested on large and small tanks and is known to have repeatable, predictable results. An evaluation is conducted using a subset of the variables used in validation. The results of the evaluation should, if a method has been correctly validated, fall within the range predicted by the validation. The EPA program was not meant to validate the performance of a test method. Rather, it was intended to estimate its performance under the conditions selected for the evaluation. These conditions were, however, fairly comprehensive.

Summary of evaluation results

Estimates of the potential performance of each test method were summarized in order to show the total number of methods meeting the detection standard of 380 ml/h with various probabilities of detection and false alarm. Table 4 shows the number of test methods attaining a certain P_D and P_{FA}, with each test method using its own detection threshold. For example, three of the test

TABLE 4

Summary of performance estimates[a]

P_D (%)	P_{FA} (%)	Number of methods having this P_D and P_{FA}
90-100	0-10	3
65-90	10-25	6
35-75	25-50	9
10-20	0-1	1

[a] Performance is expressed in terms of P_D and P_{FA} for the detection of a leak of 380 ml/h, each manufacturer using his own detection threshold. A P_D between 90 and 100% means that the probability of detection is more than 90% but is less than or equal to 100%, and so forth.

methods have a probability of detection greater than 90% with an accompanying probability of false alarm of 10% or less.

Table 5 summarizes potential performance in terms of the leak rate detectable with two different sets of P_D and P_{FA} (95% and 5% and 99% and 1%, respectively). Five test methods were able to detect leaks between 190 and 570 ml/h (0.05 and 0.15 gal/h) with the P_D of 95% and P_{FA} of 5% required by the EPA tank tightness regulations. One test method was able to detect a leak of the same size with the higher P_D of 99% and the lower P_{FA} of 1%. A total of eight methods evaluated could detect leaks of 950 ml/h (0.25 gal/h) or less with the P_D and P_{FA} specified by the regulations.

Table 6 gives another summary, an estimate of the performance that could be achieved with these methods after improvements had been made; these estimates are based on the experimental and theoretical work done during the program. Table 5 shows that, without modifications, many systems were not able to detect leaks smaller than 760 (±190) ml/h (0.20 (±0.05) gal/h). In

TABLE 5

Potential performance in terms of leak rate for two different sets of P_D and P_{FA}[a]

Detectable leak rate (ml/h)	Number of test methods able to detect this leak rate	
	With $P_D=95\%$, $P_{FA}=5\%$	With $P_D=99\%$, $P_{FA}=1\%$
190-570	5	1
570-950	3	5
950-1,320	1	2
1,320-2,080	1	2
2,080-2,840	1	0
2,840-3,600	3	2
3,600	5	7

[a] A detectable leak rate between 190 and 570 means that it is greater than 190 ml/h but is less than or equal to 570 ml/h, and so forth.

TABLE 6

Estimate of performance after two levels of modifications, expressed in terms of the smallest leak rate that can be detected with $P_D=99\%$ and $P_{FA}=1\%$

Detectable leak rate (ml/h)	Number of test methods able to detect this leak rate	
	After minor modification (protocol only)	After protocol and equipment modifications
190-570	6	12
570-950	13	7

Table 6, however, it is evident that with minor modifications, i.e., with protocol changes only, *all* the systems should be able to do at least as well as this; after both protocol and equipment modifications, the majority of systems should be able to detect leaks as small as 380 (±190) ml/h. Thus, for many methods, a significant increase in performance can be achieved by means of protocol changes alone. The actual performance improvement would depend, however, on the specific changes made by the manufacturer.

Generic performance calculations

Performance estimates were made in order to examine different approaches to temperature compensation and to examine the impact of deformation. The degree of temperature compensation achieved is dependent upon the extent of the vertical coverage of the temperature sensors. The impact of structural deformation on performance depends on the use of a waiting period after any product-level change.

Two calculations were made. The first, an estimate of the degree of temperature compensation that can be achieved with different measurement schemes, was derived from the product-temperature database. The second, an estimate of the systematic error that results from structural deformation as a function of the time constant (T_C) and elasticity constant (K) of the tank/backfill/soil system, was derived from a method with a vertical array of five thermistors, a configuration designed to compensate for thermally induced volume changes.

The analysis focused on overfilled-tank tests conducted when product level was within the 10-cm-diameter fill tube of a 30,000-L, 2.43-m-diameter tank containing unleaded gasoline. It was assumed that the precision of the product-level sensor was 0.25 mm, corresponding to a volume change of 0.002 L. This precision is an order of magnitude better than is necessary for the detection of a leak of 190 ml/h with a P_D of 99% and a P_{FA} of 1%. It was further assumed that the height-to-volume conversion factor was measured experimentally and that it includes the effects of instantaneous structural deformation and vapor pockets. Finally, it was assumed that the tank does not deform exponentially in response to a height change unless the deformation effects are specially included (in these tests, $K=0$ cm^2).

Six temperature-sensor configurations were used to illustrate the degree of temperature compensation that can be achieved as a function of vertical spatial coverage. For the structural deformation and trapped vapor configurations, an array of five thermistors, equally spaced and volumetrically weighted, was used to measure the average rate of temperature change in the tank. The temperature changes were converted to an equivalent volume. It was assumed that the volume of the product in the tank and the coefficient of thermal expansion were known perfectly. It was also assumed that the precision of the temperature measurement system was 0.001 °C, the actual precision of the thermistors used to collect the data at the test apparatus.

The data for each test method were collected and analyzed at a rate of 1 sample/min. A test duration of 1 h was used, and no test was begun until 12 h after delivery. No other product-level changes were induced before a test unless such was specifically stated. The temperature-compensated volume rate was calculated by subtracting the temperature time series from the product-level time series after each had been converted to an equivalent volume and a least-squares line had been fitted to the residual volume.

Temperature compensation

The six temperature-compensation schemes that were modeled are summarized in Table 7. In order that the performance estimates could be used to evaluate the temperature compensation scheme, no effect of structural deformation were included here. Schemes One, Three, Five and VWAT volumetrically weight the thermistor measurements for thermal compensation based on the circular geometry of the tank. Scheme AVGT uses the arithmetic mean of measurements from one array of submerged thermistors. The results are applicable equally to methods that overfill the tank without trapping vapor and to those that operate in a tank filled nearly to capacity. All temperature measurements were made when product level was near the fill hole, and all were made by Array 2 of the test apparatus thermistors.

A histogram and a set of performance curves were generated for each temperature compensation approach. To illustrate performance, the standard deviation of the noise and the signal-plus-noise histograms estimated from the histogram of the temperature-compensated volume rates is presented in Table 8. The leak rates that can be detected with a P_D of 99% and a P_{FA} of 1% are also summarized in Table 8. Figure 12 illustrates the change in the histogram for One, Five, and VWAT. The results suggest that performance improves with the number of thermistors and with volumetric weighting.

The results obtained with compensation schemes having three or fewer ther-

TABLE 7

Temperature compensation schemes

Method	Description
None	No temperature compensation
One	One thermistors located at the center of the tank
Three	Three thermistors
Five	Five thermistors
AVGT	Arithmetic average of all submerged thermistors
VWAT	Volumetrically weighted average of all submerged thermistors

TABLE 8

Standard deviations of temperature-compensated volume rate histogram and smallest leak rates detectable with a $P_D = 99\%$ and $P_{FA} = 1\%$ during a 1-h test

Scheme	Standard deviation (ml/h)	Detectable leak rate (ml/h)
None	789	3685
One	161	752
Three	112	523
Five	84	392
AVGT	30	140
VWAT	34	159

mistors should be interpreted cautiously. The product condition used in the Edison evaluation tends ot have some symmetry that will not always be encountered in the field. The results are somewhat dependent on the location of the thermistors relative to the initial and final volume of product in the tank after a delivery. If the *in situ* product at the time of delivery represented significantly more (or less) than half the capacity of the tank, differences of as little as 15 cm in the location of the temperature sensor and the product level (before the addition of product) could result in larger errors than those manifested in this study. To illustrate the magnitude of the error experienced with Scheme One (one thermistor), the location of the thermistor was moved first to $\frac{1}{4}$ and then to $\frac{3}{4}$ of the tank height. The results, designated by the height of the thermistor as a fraction of tank diameter and summarized in Table 9, suggest the performance that might be achieved if the tank were significantly more (or less) than half-filled at the time of delivery. It is evident that the performance was degraded severely in each case when the thermistor was at the $\frac{1}{4}$ or the $\frac{3}{4}$ positions.

Another calculation was made to estimate performance when a single thermistor is placed 30 cm above the mid-point of the tank. The standard deviation decreased from 161 ml/h when the thermistor was at the midpoint of the tank to 128 ml/h when it was 30 cm above the midpoint. There is very little difference between the two estimates. However, moving the thermistor up another 30 cm, i.e., 60 cm above the midpoint (equivalent to $\frac{3}{4}$ of the height of the tank), dramatically degraded the performance.

An estimate of performance was also made for the five-thermistor scheme after the array had been moved up by 20 cm, or one thermistor location, on Array 2. The standard deviation increased from 84 ml/h to 121 ml/h as a result of the change. Shifting the entire array up or down incrementally results in similar changes in the standard deviation. This change in the standard deviation is consistent with the experimental uncertainties of the temperature measurement.

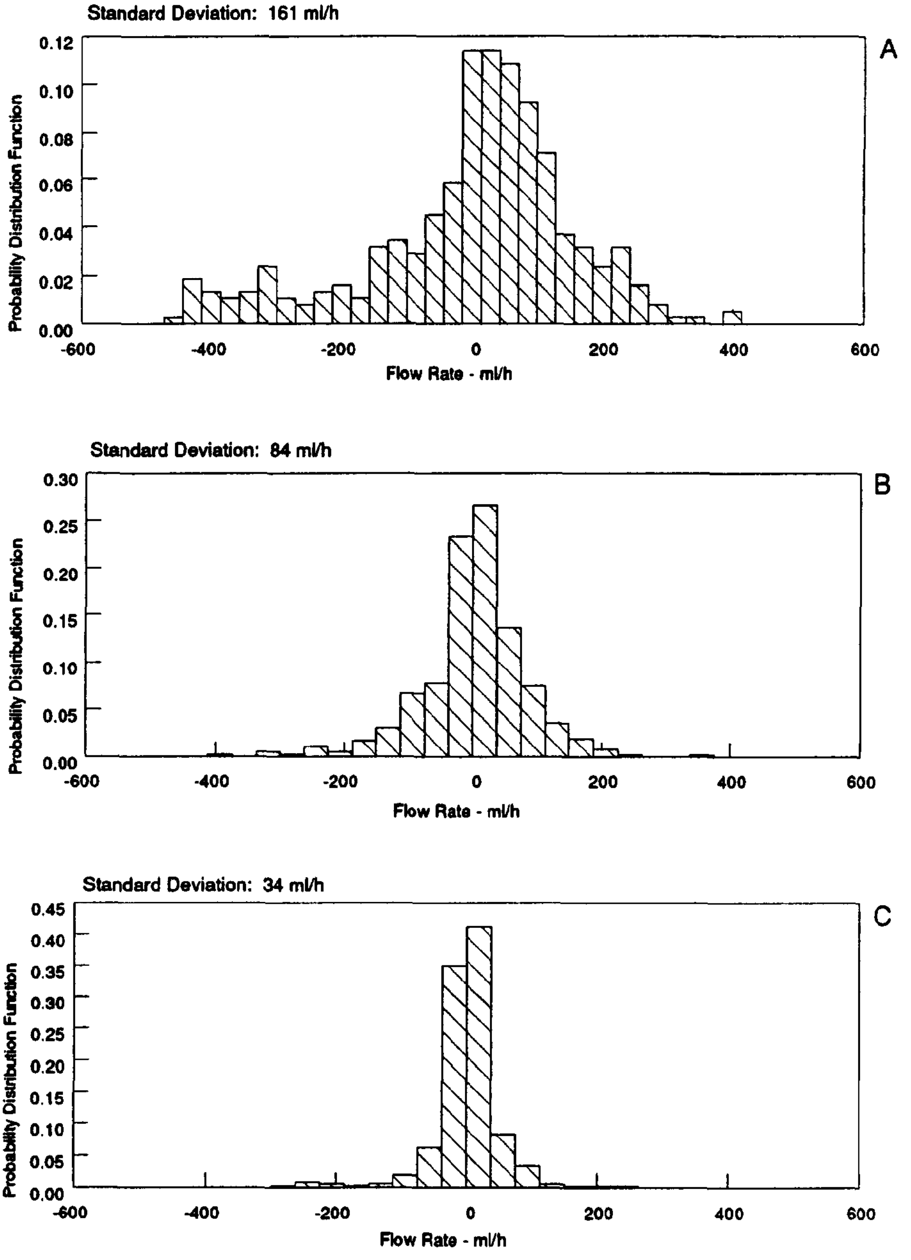

Fig. 12. Histograms of the noise compiled from overfilled, constant-head tank tests that compensate for thermal expansion and contraction of the product using (A) one temperature sensor located at the midpoint of the tank, (B) five equally spaced temperature sensors that are weighted volumetrically, and (C) eleven equally spaced temperature sensors that are weighted volumetrically. It is assumed that the tank does not deform (i.e., $K=0\ \mathrm{cm}^2$).

TABLE 9

Standard deviations and smallest detectable leak rates ($P_D = 99\%$ and $P_{FA} = 1\%$) for Scheme "One" with thermistor at different heights during a 1-h test

Fraction of tank height	Height (cm) from bottom of tank	Standard deviation (ml/h)	Detectable leak rate (ml/h)
$\frac{1}{4}$	61	934	4362
$\frac{3}{4}$	182	948	4427

The results indicate that temperature compensation is essential and that performance will improve with an increased number of thermistors. The results also suggest that it is possible to compensate for temperature sufficiently well to reliably detect leaks of 190 ml/h. Without compensation, only leaks of 4.75 L/h or larger are detectable with a P_D of 99% and a P_{FA} of 1%.

Results can be highly variable for any thermistor array which does not adequately cover the vertical extent of the tank. Since it is quite conceivable that temperature could be rising in the upper part of the tank and falling in the lower part, large errors can arise unless the temperature changes in both areas are monitored. A one-thermistor array will always have the potential for large errors because the measured temperature change is not representative of what is going on in the tank as a whole. In general, a three-thermistor array has the vertical coverage to avoid most of these problems, but the estimates can be poor under some conditions. A volumetrically weighted five-thermistor system is probably the minimum acceptable configuration for avoiding spatially induced errors. The magnitude of the compensation error, however, will continue to decrease with increased spatial coverage by the temperature measurement system.

Waiting periods

Because, for the wide range of tank/backfill/soil conditions among installed tanks, the probability distributions of the time constant, T_C, and the tank system's elasticity constant, K, are unknown, the full range of the effects of structural deformation was not included in the 25 test-method evaluations. The effects of deformation included in the evaluations were for a single tank/backfill/soil condition.

A theoretical estimate of the effects of structural deformation on performance was made from tests on a single tank. Another estimate was made by summing the results of tests on many tanks, each with different deformation characteristics. In all cases, the tanks were overfilled. The rate of change of the temperature-compensated volume in a nonleaking tank was estimated for cases when the only volume changes are produced by thermal expansion of the product and by structural deformation of the tank. Two calculations were made to estimate the effects, respectively, of starting a 1-h test immediately after topping the tank and of waiting 3 time constants (i.e., $3T_C$) before starting the test. These represent the extreme conditions, that is, cases for which there is now waiting period to allow for the stabilization of the large volume changes that occur immediately after any product-level change, and cases for which an adequate waiting period does exist.

The five-thermistor measurement system was used with varying values for T_C and K, and with $A_{\text{eff}} = A$ set to 82 cm^2. It was assumed that the initial product level in the fill tube was 15 cm above the top of the tank and that 8.2 L of product was added to the fill tube, an amount sufficient to raise the level 1 m if the instantaneous deformation and trapped vapor effects are not included.

It was assumed, for all calculations, that product-level changes are produced by the thermal expansion and contraction of the product and by the structural deformation of the tank.

Test starting immediately after topping

Histograms of the temperature-compensated volume rates were generated for increasing K (30, 60, 120 cm^2) for a time constant of the tank of 0.75 h. Figure 13 illustrates the effect of structural deformation on the result when $K = 120$ cm^2. Two observations are noteworthy. First, the histogram has a large nonzero mean, or bias, which suggests that most tests on a tight tank would result in a declaration that the tank is leaking; and second, the standard deviation is significantly larger than would be obtained if deformation were not occurring. Clearly, the test results are not predictable, and are dominated by the large change in product level that occurs immediately after topping the tank. The histogram of the temperature-compensated volume rate has a larger spread than that produced by thermal expansion or contraction of the product itself. Histograms were also generated for increasing T_C (0.5, 1, 3 h) with a tank elasticity constant of 120 cm^2. The results, shown in Table 10, indicate

TABLE 10

Standard deviations for a nonleaking tank immediately after topping ($K = 120$ cm^2, $A_{\text{eff}} = 82.0$ cm^2)

T_C (h)	Mean (ml) for test duration (h) of				Standard deviation (ml) for test duration (h) of			
	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0
0.5	−4000	−1200	−550	−550	527	506	508	530
1.0	−4500	−1800	−950	−550	236	510	512	546
3.0	−3250	−2000	−1450	−1000	585	532	535	557

that the mean changed but the standard deviation remained approximately the same.

Test starting three time constants after topping

Approximately 99% of the deformation will have occurred after three time constants. Therefore, if the total change in volume due to deformation is less than 4 L/h, the residual effects will be less than 40 ml/h, sufficiently small to allow a 190-ml/h leak to be detected.

Histograms were generated for increasing K (30 to 120 cm^2) and for increasing T_C (0.50 to 3 h). The results, shown in Table 11, were obtained with a 2-h test duration and a five-thermistor temperature-compensation scheme. The results obtained with a 1-, 3-, and 4-h test duration are almost identical to the results obtained with the 2-h test. The same conditions used to generate the histogram in Fig. 13 were used to generate the histogram in Fig. 14, except that the waiting period was three time constants or more. Unlike the case in which a test begins immediately after topping, the man of the histogram is approxi-

TABLE 11

Standard deviations for a nonleaking tank three time constants after topping ($A_{\text{eff}} = 82.0$ cm^2)

K (cm^2)	T_C (h)	Standard deviation (ml/h)
30	0.75	260
60	0.75	371
90	0.75	453
120	0.75	480
120	0.50	509
120	1.00	512
120	2.00	522
120	3.00	544

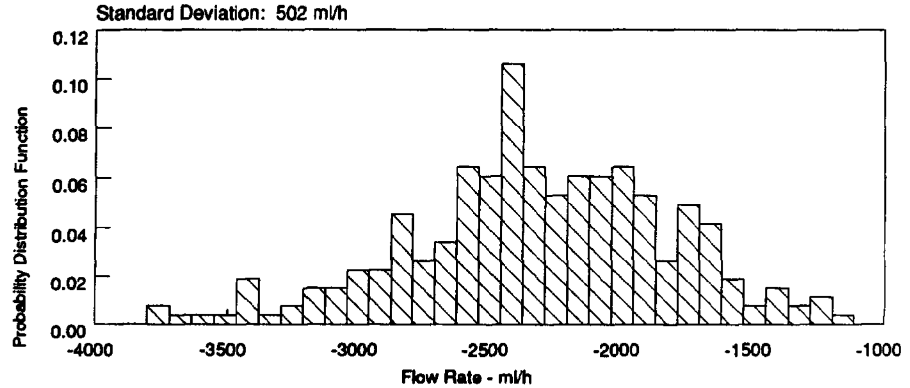

Fig. 13. Histogram of the noise generated from overfilled, variable-head tank tests conducted immediately after topping the tank (1-m product-level addition) for $T_C = 0.75$ h and $K = 120$ cm^2.

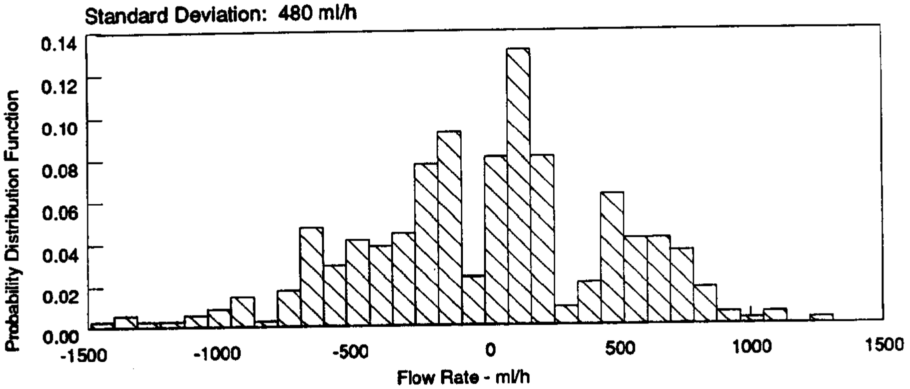

Fig. 14. Histogram of the noise generated from overfilled, variable-head tank tests conducted 3 time constants after topping the tank (1-m product-level addition) for $T_C = 0.75$ h and $K = 120$ cm^2.

mately zero when testing begins three time constants later. However, as before, the standard deviation increases with K.

Large values of K and T_C degrade the performance of a method which does not maintain a constant head during the test and many introduce a bias if the waiting period after topping is too short. In all cases, the spread in the histogram (i.e., standard deviation) of the temperature-compensated volume rates is greater than that achieved when the tank does not deform.

Features of volumetric system capable of reliable performance

Experimental studies at the UST test apparatus suggest that a test method having the characteristics described below should, with proper execution, meet or exceed the EPA regulatory requirements for testing tanks of approximately 40,000 L in capacity. Whether such a system does or does not meet the regulatory standard depends on the implementation of these features.

- There are 5 or more temperature sensors (or the equivalent).
- The temperature and level (or volume) sensors have a precision sufficient to measure volume changes of 95 ml/h.
- To minimize temperature instabilities, there is a waiting period of at least 6 h after a delivery of product.
- To minimize temperature instabilities, there is a waiting period of at least 3 h after topping the tank.
- Checks are made to identify the present of structural deformation and to wait for it to subside.
- There is a single threshold value used as a detection criterion.
- To avoid aliasing, data are sampled at intervals of 1 s in the case of a tank

that is partially filled or at intervals of 1 to 5 min in the case of an overfilled tank.

- Test length is between 1 and 2 h. Longer tests are required if the precision of the instruments is less than that given above.
- The test is conducted at a nearly constant hydrostatic pressure. For overfilled-tank tests this may require that the product be releveled at regular intervals during the test, or that the cross-sectional area of the measurement container be enlarged.

A reliable test method need not be identical to the system described above, nor contain the same features. In order to meet the regulatory requirements, a system need only be capable of detecting a leak of 380 ml/h with a P_D of 95% and a P_{FA} of 5%.

Conclusions

Five main conclusions are drawn from the Edison evaluations. First, at the time the EPA evaluations were done, performance was significantly less than what was claimed by most test-method manufacturers. Second, volumetric tank testing is complex, but test methods can achieve high performance if they follow the principles described above. Third, minor modifications should enable most test methods to significantly improve performance. Fourth, evaluation results should be presented in terms of probability of detection and probability of false alarm because this gives a quantitative estimate of performance. Finally, reliable tank testing takes time; appropriate waiting periods should always be observed.

The Edison experiments demonstrated that volumetric testing is sound in principle and that most test methods evaluated under the EPA program can achieve a high level of performance with only minor modifications. It is procedure that matters, and procedure can be changed. It was anticipated that once the recommended modifications have been made, most test methods will have performance levels that can meet the regulatory standards established by the EPA. Changes based on the Edison results have already been made to many test methods. Many of the manufacturers have reevaluated the performance of their modified systems and have achieved a performance that meets or exceeds the regulatory standards established by the EPA. The Edison results are approximately three years old, and any ranking of test methods based on them is now outdated. A similar evaluation today would probably yield an entirely different performance ranking. This is particularly true because simple procedural changes dramatically affect the performance estimates. For these reasons, the temptation to use only those methods that were ranked highest in this evaluation should be avoided.

If the performance ranking cannot be used, what was gained from the Edison experiments? The value of the experiments lies in the fact that all the test methods were evaluated under the same set of conditions, allowing the features common to reliable, high-performance tests to be identified.

High-performance test methods pay careful attention to:

- instrument calibration and maintenance,
- waiting periods after product delivery or product-level adjustments,
- vapor pocket removal (in tests on overfilled tanks),
- adequate spatial coverage by the sensors used to measure temperature.
- data acquisition, processing and analysis,
- maintaining a nearly constant hydrostatic pressure during the test,
- identical execution of each test (minimal operator influence).

A final comment is in order. The temptation to use only those methods evaluated in this study should be avoided. Any system that meets the EPA regulations and that has been satisfactorily evaluated should also be considered.

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