United States
Environmental Protection
Agency

Risk Reduction
Engineering Laboratory
Cincinnati Ohio 45268

Research and Development

EPA/600/S2-91/044 Sept. 1991

EPA

Project Summary

Volumetric Leak Detection in Large Underground Storage Tanks

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A set of experiments was conducted to determine whether volumetric leak detection systems presently used to test underground storage tanks (USTs) up to 38,000 L (10,000 gal) in capacity could meet EPA's regulatory standards (40 CFR Parts 280 and 281) for tank tightness and automatic tank gauging systems when used to test tanks up to 190,000 L (50,000 gal) in capacity. The experiments, conducted on two partially filled 190,000-L (50,000-gal) USTs at Griffiss Air Force Base in upstate New York during late August 1990, showed that a system's performance in large tanks depends primarily on the accuracy of the temperature compensation, which is inversely proportional to the volume of product in the tank. Errors in temperature compensation that were negligible in tests in small tanks were important in large tanks. The experiments suggest that volumetric systems now capable of meeting regulatory standards when used to test 30,000- to 38,000-L (8,000- to 10,000-gal) tanks will also meet these standards when used to test 190,000-L (50,000-gal) tanks if (1) the duration of the test is increased from 1 or 2 h to 4 h or more to ensure that the vertical gradients are accurately measured and to reduce the ambient and instrumentation noise, (2) the number of temperature sensors is increased from 5 to 10 or more so that the accuracy of estimating the average thermally induced volume change in the layer of product surrounding each sensor increases, (3) the waiting period after any addition or removal of product is increased from 6 to 24 h or longer so that the horizontal and vertical temperature gradients dissipate, (4) the average rate of change of temperature in any one layer or in the tank as a whole is small enough to allow accurate temperature compensation, and (5) an accurate experimental estimate of the constants necessary for converting level and temperature changes to volume is made. The experiments further suggest that a multiple-test strategy is required in order for such systems to meet the tank tightness regulatory standard.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The U.S. Environmental Protection Agency (EPA) regulation for underground storage tanks (USTs), published in the *Federal Register* (40 CFR Parts 280 and 281) on September 23, 1988, specifies the technical standards and a variety of release detection options for minimizing the environmental impact of tank leakage. With several exceptions, the shop-assembled tanks covered by the regulation range in size from small (a few hundred gallons in capacity) to very large, with no clearly defined upper limit. (Requirements for large field-erected tanks have not yet been established). The number of large tanks (defined here as those between

57,000 and 190,000 L (15,000 and 50,000 gal) in capacity) represents a small but important portion of the total tank population. This number is increasing because of the preference of tank owners/operators for a smaller number of larger tanks to meet storage needs. Many large-volume storage facilities have tanks that are nominally 190,000 L (50,000 gal) in capacity. Unfortunately, there is not enough information to help owners and operators of large tanks select a testing system that will be in compliance with the regulations. Furthermore, it is not known whether volumetric tests can achieve the same level of performance in large tanks as they do in smaller ones.

Objectives

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

Background

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

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

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

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

Conclusions

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

The following observations were made:

- Temperature fluctuations observed throughout the tank after approximately 38,000 L (10,000 gal) of product had been added or removed were too great, unless at least 4 h had elapsed, to permit an accurate leak detection test. (The addition of 38,000 L (10,000 gal) simulated a delivery of product to the tank.)
- Temperature fluctuations observed after the addition of approximately 19 L (5 gal) of product 25°C warmer or 8°C cooler than the in situ product were too great, unless 2 to 3 h had elapsed, to permit an accurate leak detection test. (The addition of 19 L (5 gal) simulated the topping of an overfilled tank.)
- The average rate of change of temperature between any two locations along the long axis of the tank, as measured by any two thermistors at the same height, but distanced horizontally, was less than 0.001°C/h beginning 4 h or more after product additions or removals. Furthermore, the mean temperature along the centerline of the tank was the same at each height, i.e., the horizontal gradient was negligible at the centerline.
- A horizontal gradient in the mean temperature was observed in the mid-region of the tank in the area between the centerline and the wall of the tank. The rate of change of temperature, as measured by three thermistors spaced at horizontal intervals of 30 cm (12 in.), was lower in the area of the centerline and higher in the area of the tank wall, an observation that is consistent with the physical process of heat transfer between the backfill surrounding the tank and the product inside it. The difference between the rate of change of temperature measured at the centerline of the tank and at locations off the centerline was large enough to suggest that a single vertical array is not sufficient for temperature compensation unless at least 18 h has elapsed since any product addition or removal. Additional horizontally oriented thermistors must be incorporated into the arrays to compensate for these temperature changes, or the test must not be started until the rate of change of temperature has subsided.
- The area near the bottom of the tank exhibited the largest vertical gradient and the greatest rate of change of temperature. In this region, a spacing of 30 cm (12 in.) between thermistors was not adequate, in the experiments conducted, for correct temperature compensation unless at least 10 h had elapsed since the last addition or removal of product.
- The temperature fluctuations that followed changes in product level in these experiments were so large that changes due to deformation were masked. As a consequence, none of the classical exponential level changes associated with tank deformation was observed in these experiments.
- Analysis of the level data revealed the presence of surface waves (seiches) having periods of 2 to 10 s and peak-to-peak amplitudes of 1 to 2 L. These waves were consistent with the fundamental and first harmonic of waves propagating along the long and short axes of the tank.
- Analysis of the temperature data revealed the presence of internal waves having periods of 3 to 30 min. These subsurface waves were large enough to produce periodic surface waves.
- Experimental estimates of the height-to-volume conversion factor were within 5% of the theoretical estimates made with a tank chart.
- When 10 h had elapsed after a product addition or removal, and thermistors spaced at 30-cm (12-in.) intervals were used for thermal compensation, the residual volume changes in each of three tests on nonleaking tanks were 0.36, 0.67, and -0.22 L/h (0.095, 0.177, and 0.058 gal/h) respectively. When 2 h had elapsed after topping and 20 h after a product addition or removal, residual volume changes in each of two tests were 0.036 and -0.043 L/h (0.0095 and -0.011 gal/h) respectively. These residual volume changes can be attributed to inadequate temperature compensation. (There was insufficient coverage near the surface of the product, at the bottom of the tank, and in the area between the centerline and the tank wall, all locations where large temperature gradients were present.) The effects of evaporation and condensation within the tank could not be quantified, but their contribution to the residual volume changes appears to be smaller than the errors in temperature compensation.

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

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

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

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

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

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

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

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

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

Recommendations

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

Temperature Compensation

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

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

- Place the lowest temperature sensor approximately 8 cm (3 in.) from the bottom of the tank and the uppermost sensor approximately 8 cm (3 in.) below the surface.
- Space the temperature sensors at intervals of 15 to 30 cm (6 to 12 in.) or less along the vertical axis of the tank; space the sensors at intervals of 15 cm (6 in.) or less in the bottom 46 cm (18 in.) of the tank and in the 15 to 30 cm (6 to 12 in.) of product located immediately beneath the surface. (A 30-cm (12-in.) spacing can be used if the rate of change of temperature between adjacent layers of product throughout the entire tank is nearly identical.)
- Partition the tank into layers, each of which is centered about a temperature sensor. Then calculate the volume of product in each layer.
- Wait at least 24 h for horizontal gradients in the rate of change of temperature to dissipate. (These horizontal gradients occur between the centerline and the wall of the tank.) Alternatively, measure these horizontal gradients directly, and do not attempt to compensate for temperature until they have dissipated. If the compensated volume rate exceeds the threshold, continue to test until the measured volume rate ceases to decrease and remains constant.
- Using real-time measurements, wait for the rate of change of temperature to diminish sufficiently that the maximum potential error in measuring the average rate of temperature for each test is small. The acceptable rate of temperature change depends on the number of thermistors, the precision of each thermistor, and the degree of compensation that can be achieved with the array of thermistors. A very conservative approach is to incorporate the following analysis tests.
  - Do not begin a test if the rate of change of temperature is great enough in any one layer to produce a volume change that will exceed the detection threshold. (When using a threshold of 0.19 L/h (0.05 gal/h) in a tank containing JP-4 fuel, this would limit the rate of change in temperature to less than 0.008°C in the largest layers of a 190,000-L (50,000-gal) tank divided into ten layers.)
  - Do not begin a test if the average rate of change of temperature throughout the tank is great enough to produce volume changes that exceed the threshold based on an average level of compensation to be achieved. (When using a threshold of 0.05 gal/h in a tank containing JP-4 fuel, this would limit the rate of change in temperature to less than 0.019°C throughout a 190,000-L (50,000-gal) tank if on average the method is able to compensate for 95% of the temperature changes.)
- Use the most precise temperature and level measurement systems available and calibrate them frequently and properly. It is recommended that temperature sensors have a precision of 0.001°C and the level sensors have a precision of 0.00025 cm (0.0001 in.).
- Check that all sensors function properly during a test. If a sensor malfunctions, the test should be repeated.
- Make sure the test is at least 4 h long so that ambient fluctuations will be properly averaged and will not affect the test. Longer tests may be required depending on the resolution and precision of the level and temperature sensors.
- Measure the coefficient of thermal expansion experimentally.
- Determine the height-to-volume conversion factor used to convert level measurements to volume measurements experimentally.
- Use a multiple-test strategy.

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

Evaluating a Volumetric Leak Detection System

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

The full report was submitted in fulfillment of Contract No. 68-03-3409 by Vista Research, Inc., under the sponsorship of the U.S. Environmental Protection Agency.

*U.S. Government Printing Office: 1992 — 648-080/60042

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The complete report, entitled "Volumetric Leak Detection in Large Underground Storage Tanks," (Order No. PB91-227942/AS; Cost: $23.00, subject to change) will be available only from:

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