United States
Environmental Protection
Agency

Risk Reduction
Engineering Laboratory
Cincinnati OH 45268

EPA/600/2-88/068a
November 1988

Research and Development

EPA

Evaluation of Volumetric Leak Detection Methods for Underground Fuel Storage Tanks

Volume I

EPA/600/2-88/068a
November 1988

EVALUATION OF VOLUMETRIC LEAK DETECTION METHODS FOR UNDERGROUND FUEL STORAGE TANKS

Volume I

by

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Contract No. 68-03-3409

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The information in this document, prepared by Vista Research, Inc., has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-03-3409 to CDM Federal Programs Corporation. It has been subjected to the Agency's peer and administrative review, and has been approved for publication. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

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

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

This document summarizes the results of an evaluation of 25 commercial, quantitative, in-tank volumetric methods for detecting small leaks in underground storage tank systems containing petroleum-derived fuels. The evaluation results and the basic information generated from this program will be useful to both government and industry personnel concerned with this aspect of preventing groundwater pollution.

For further information, please contact the Superfund Technology Demonstration Division of the Risk Reduction Engineering Laboratory.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Preface

This report presents the results of an evaluation by the U.S. Environmental Protection Agency (EPA) of the performance of 25 volumetric methods for detecting leaks in underground storage tanks containing motor fuels. The report is divided into two volumes. Volume I summarizes the evaluation results and the experimental work supporting the results, and Volume II presents the results of the evaluation performed for each method.

The field testing was done at EPA's Underground Storage Tank Test Apparatus located at the Risk Reduction Engineering Laboratory (RREL) (formerly the Hazardous Waste Engineering Research Laboratory) in Edison, New Jersey. With one exception, each method tested was used to perform a precision or tank tightness test. The performance of each test method is presented in terms of leak rate, probability of detection, and probability of false alarm. The results suggest that the performance claim of 0.19 L/h (0.05 gal/h) commonly made by the majority of the manufacturers is not being reliably met. The user of this report should be careful not to simply rank the methods according to the quantitative estimate presented, because with simple modifications, many of the methods can dramatically improve performance. Several methods have the capability to meet the EPA release detection regulations for tank tightness tests. Recommendations for improvement are made for each method. After improvements are made, it is anticipated that many more of the methods evaluated will meet the regulations.

Abstract

This report summarizes the results of the United States Environmental Protection Agency (EPA) research program to evaluate the current performance of commercially available volumetric test methods for the detection of small leaks in underground gasoline storage tanks. The evaluations were performed by the EPA at its Risk Reduction Engineering Laboratory (RREL) Underground Storage Tank (UST) Test Apparatus located in Edison, New Jersey.

The objectives of the program were to:

- o produce the technical data necessary to support the development of release detection regulations
- o define the current practice of commercially available systems
- o make specific recommendations to improve the current practice
- o provide technical information that will help users select suitable methods for testing the integrity of underground storage tanks

A unique approach to conducting the evaluation has made it possible to determine and resolve the technological and engineering issues associated with volumetric leak detection, as well as to define the current practice of commercially available test methods. The approach uses experimentally validated models of the important sources of ambient noise that effect volume changes in nonleaking and leaking tanks, a large database of product-temperature changes that result from the delivery of product to a tank at a different temperature than the product in the tank, and a mathematical model of each test method to estimate the performance of that method. The test-method model includes the instrumentation noise, the configuration of the sensors, the test protocol, the data analysis algorithms, and the detection criterion. This study and the ambient noise experiments contributed to a better understanding of the environmental factors that inhibit detection (temperature, structural deformation, trapped vapor, evaporation and condensation, and waves). These factors are now not only better understood but also better quantified. This knowledge is expected to lead to significant improvement in the performance of current and developing methods.

Twenty-five commercially available volumetric leak detection systems were evaluated. An estimate of the performance of each method was made in terms of the probability of detection and probability of false alarm against a 0.38-L/h (0.10-gal/h) leak rate using the detection threshold employed by each method at the time of the evaluation. Another set of performance estimates was made for each method in terms of the smallest leak rate that could be detected and still maintain a probability of detection and a probability of false alarm of 0.95 and 0.05, and 0.99 and 0.01. This performance estimate does not employ the manufacturer's detection

threshold; instead a threshold was selected which yields a probability of false alarm of 0.05 and 0.01, respectively. The leak rate measurable by these systems ranged from 0.26 to 6.97 L/h (0.07 to 1.84 gal/h), with a probability of detection of 95% and probability of false alarm of 5%. Five of the methods achieved a performance that was better than 0.57 L/h (0.15 gal/h), and a total of eight methods had a performance that was better than 0.95 L/h (0.25 gal/h). The leak rate measurable by these systems ranged from 0.47 to 12.95 L/h (0.12 to 3.42 gal/h) when the probability of detection increased to 99% and the probability of false alarm decreased to 1%. Only one of the methods achieved a performance better than 0.56 L/h, but five methods achieved a performance between 0.56 L/h and 0.95 L/h. The measured performance was considerably poorer than the often claimed 0.19 L/h (0.05 gal/h); this was probably a consequence of two factors: (1) the requirement that the detectable leak rate be framed in terms of a probability of detection (the probability that a test will result in the declaration of a leak when the tank is indeed leaking) and a probability of false alarm (the probability that a test will result in the declaration of a leak when the tank is tight); and (2) the fact that, in many instances, these measurements represented the first systematic evaluation of the test method (because, hitherto, no suitable test apparatus existed).

It is important to realize that, by and large, the performance of the methods evaluated here was limited by current protocol and practice rather than by hardware. Such limitations can be overcome by rather modest modifications to testing practice rather than by major system redesign. The results of tests at the UST Test Apparatus show that attention should be given to the following aspects of testing practice: waiting period after product delivery or adjustments to product level (e.g., topping); vapor pocket removal (in tests on overfilled tanks); adequate spatial sampling of the vertical temperature profiles of the product in the tank; length of tests; data acquisition, processing, and analysis; and maintaining constant product level. In the foregoing list of performance limitations, two of the items might require modifications to the measurement system itself. Modifications of the temperature and product-level measurement systems could require a more extensive development effort. As part of this study, an estimate was made of the potential performance that could be achieved by the various volumetric methods evaluated. The results showed that, with modifications, over 60% of the methods should be able to achieve a performance of between 0.19 L/h (0.05 gal/h) and 0.56 L/h (0.15 gal/h), and 100% should be able to achieve a performance of approximately 0.80 L/h (0.20 gal/h), given that a probability of detection of 99% and a probability of false alarm of 1% is to be achieved.

Leak detection technology is rapidly evolving. With the passage of federal legislation in 1984, the drafting of a proposed regulation by the United States Environmental Protection Agency in 1987, the development of numerous state and local UST programs, and the initiation of the Edison evaluation effort, the economic motivation for system improvements and technological discipline is increasing. Because the performance of individual test methods can be improved with minor modification, it is likely that most (including some of the worst-performing) methods will raise their performance to the level of the best-performing methods in the immediate future. These improvements are already known to be in progress. Consequently, by the time this report is published, its ranking of test methods will be obsolete, and the current ranking should not be used by itself for the selection of volumetric leak detection methods. The state of the art is not sufficiently developed for the ranking to be definitive, because simple modifications (many already under way) can change performance by a factor of 2 to 10, shifting the rank of a method from the bottom third to the top third. Selection of a method based simply on its ranking in this report, or worse yet, eliminating a method from consideration based on its current ranking, would be a mistake.

The current practice of precision leak testing is labor-intensive. The evaluations presented in this report reflect the performance of systems and crews that represent the best that the manufacturer has to offer. The performance of these systems can be significantly degraded by careless or inattentive application of the technology by operators. Complicated underground storage systems, such as those featuring tilted tanks, manifolded tanks, complicated piping, and tanks with vapor recovery systems, are commonly encountered in the field. If the operator does not discover these complications and take them into account the results can be further degraded. The dynamic technological environment makes the establishment of discipline in the practice more difficult. In this regard, the lettered appendices to this report (Volume II) should be of significant help to both the regulators and the users. Each appendix, describing the protocol and practice of a given method, represents the manufacturer's description of how a test is to be conducted. Operators should adhere to protocol, or, when deviating, should be sure that the change is such as to demonstrably improve performance (perhaps by following the specific suggestions given in the appendices). Increasing the waiting period after adding product to the tank is a typical example of such a change.

The regulatory and user communities will be besieged by new claims of improved performance from manufacturers. This report can be of value in estimating the impact of system improvements, but any new claims of improved performance, to be completely credible, must be supported, in most cases, by additional experimental and analytic evidence.

This report was submitted by Vista Research, Inc. in partial fulfillment of Contract No. 68-03-3409 with CDM Federal Programs Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from September 1986 to July 1987, and work was completed as of June 1988.

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Acknowledgments

This report was prepared for the U. S. Environmental Protection Agency (EPA) by Vista Research, Inc. under subcontract to CDM Federal Programs Corporation (CDM/FPC). Vista Research has performed this work under subcontract to and in conjunction with technical staff provided by CDM Federal Programs Corporation from February 1987 to the present, and by Enviresponse, Inc. prior to February 1987. The original program plan, developed by Vista Research, was completed in December 1984 under subcontract to IT Corporation. This work was performed under the auspices of the Risk Reduction Engineering Laboratory (RREL) of the Office of Research and Development (ORD) and of the Office of Underground Storage Tanks (OUST). Dr. Thomas R. Hauser, Director of RREL during this program, and Mr. Ronald Brand, Director of OUST, have actively supported this program.

Many individuals must be acknowledged for their energetic support and technical and administrative efforts in completing this complex project. This work would not have been possible without the sound technical guidance and technical review, enthusiastic encouragement, and vigorous support provided by Mr. John S. Farlow, Technical Project Monitor, and Chief of the Releases Control Branch (RCB), Superfund Technology Demonstration Division (STDD), RREL, and his staff. Mr. Robert Hillger contributed directly to this project in a variety of capacities. Mr. Anthony Tafuri served as Contract Project Officer. Dr. John E. Brugger, Chi-Yuan Fan, Richard Field, and Richard Griffiths also supported and reviewed this work. Mr. Ira Wilder, prior Chief of the RCB, and Mr. Ronald Hill, Director of the STDD, are acknowledged for their program support.

Mr. Ronald Brand and his technical staff at the Office of Underground Storage Tanks have been active participants and reviewers of the work. The efforts of David O'Brien, Michael Kalinoski, Steven Nacht, Steven Way, and Thomas Young are appreciated. Louise Wise and James McCormick have provided program direction and support during this work. In particular, the contribution made by Mr. Young must be singled out. He has been involved in an ongoing program of technical review, and has provided invaluable suggestions to focus the work, to improve it technically, and to better present it.

The Office of Environmental Engineering and Technology Demonstration of ORD has made valuable contributions to this effort. The contributions that have been made by Dr. John

Skinner, Director, and his staff, including Jay Benforado, David Berg, Alfred W. Lindsey, Charles Mitchell, and Burnell Vincent, are acknowledged. In particular, the efforts of Mr. Berg have been extremely important, and his contributions are gratefully acknowledged.

At the inception of this project a peer review of the proposed evaluation approach was conducted by the EPA and an external panel consisting of William E. Blain, Assistant Engineer, New York State Department of Environmental Conservation; Gerald L. Anderson, President, American Gas and Chemical Company, Ltd.; and Dr. Robert W. Coughlin, Professor and Head of the Department of Chemical Engineering, University of Connecticut. Their helpful comments are acknowledged.

The American Petroleum Institute (API), the Leak Detection Technology Association, and the Petroleum Equipment Institute, and their member organizations are gratefully acknowledged for their review and recommendations, particularly during the planning stage prior to the conduct of the evaluations. Many of their recommendations with regard to the Test Apparatus were implemented. In particular, Dr. Rudy White and Marc J. Meteyer of the API are acknowledged for their support and encouragement.

The authors and contributors to this report would like to acknowledge the project management and the administrative and technical support provided by CDM Federal Programs Corporation and Camp Dresser and McKee, Inc. (CDM). The development and experimental validation of the performance simulation, the conduct of the evaluations of the 25 commercial test methods, and the preparation of the final report were completed as part of the CDM/FPC contract. The Project Office on the contract was led by the Project Director, Mr. David F. Dolye, Senior Vice President of CDM; Dr. Myron Rosenberg, the Deputy Project Director, and Julia M. Nault of CDM, and Mr. William M. Kaschak of CDM/FPC actively supported the project team. The project team wishes to thank these individuals for their support throughout the conduct of this multi-company project. The support and encouragement of senior management, Mr. Thomas F. Cheyer, Senior Vice President of CDM, and Mr. William H. Parker III, Senior Vice President of CDM/FPC, are gratefully acknowledged. A special acknowledgment is made to Rosemary J. Ellersick of CDM/FPC and David Johnson, a member of her staff, for Quality Control and Quality Assurance support.

The authors and contributors would also like to acknowledge the contributions made by the management and technical staff of Enviresponse, Inc. The preliminary experiments conducted to design the UST Test Apparatus, the final design and construction of the UST Test Apparatus, the development and verification of the equipment and instrumentation, and the early work on the performance simulation were completed before February 1987. In particular, the contributions made by Mitchell D. Garber, Dr. A. C. Gangadharan, Stephen Sawyer, and Paul Faccone are acknowledged.

The preliminary design for the UST Test Apparatus was performed by IT Corporation. Messrs. John A. Broscious and Shahzad Niaki are acknowledged for their contributions during the formative stages of the project.

Dr. Harold Guthart, President of Vista Research, has been senior technical advisor for the program and Project Supervisor for all of the Vista Research work. The successful completion of this project would not have been possible without his support, encouragement, and technical input.

Preparation of this report represented a significant effort. Monique Seibel led the publication team, contributed to the technical writing of the report, and edited, illustrated, and organized it. Lisa A. Yurfest and Cynthia Komorowski did the word processing for the report. They were supported by Vivian A. Solis and George Koukoutsakis. Their efforts are sincerely appreciated.

The last and most important acknowledgment is extended to the participants in the evaluation program. The management, technical staff, and test crews who participated in this voluntary program were highly professional and cooperative throughout. Without their support, committment, and cooperation, this program would not have been possible. Thank you.

Dr. Joseph W. Maresca, Jr.
Vice President
Vista Research, Inc.

List of Abbreviations

A = Cross-sectional area of the product surface
A_{eff} = Effective cross-sectional area of the product surface
A_{LR} = Cross-sectional area of a hole in a tank
atm = Atmospheres
C = Volume rate
°C = Degrees Celsius
cm = Centimeters
ft = Feet
°F = Degrees Fahrenheit
g = Grams
gal = Gallons
h = Hours
Hz = Hertz
in. = Inches
$k = \beta$ = Fraction of true volume change
K = Elasticity constant
°K = Degrees Kelvin
kg = Kilograms
kHz = Kilohertz
L = Liters
lb = Pounds
LR = Leak rate (flow rate)
m = Meters
mb = Millibars
mg = Milligrams
MHz = Megahertz
ml = Milliliters
mm = Millimeters
ms = Milliseconds
μA = Microamperes
μm = Microns (micrometers)
μs = Microseconds
Ω = Ohms
P_D = Probability of detection

pdf = Probability density function
P_{FA} = Probability of false alarm
rms = Root mean square
s = Seconds
t = time
t_o = start time
T = Temperature
T_C = Time constant
T_{eff} = Effective time constant
Th = Threshold
TV = Temperature volume

API = American Petroleum Institute
ASTM = American Society of Testing Materials
ATGS = Automatic tank gauging system
EPA = Environmental Protection Agency
HWERL = Hazardous Waste Engineering Research Laboratory
LDTA = Leak Detection Technology Association
NBS = National Bureau of Standards
NFPA = National Fire Protection Association
PEI = Petroleum Equipment Institute
RREL = Risk Reduction Engineering Laboratory
UST = Underground storage tank(s)

List of Equivalent Units

1 millimeter = 0.04 inches	1 inch = 25.40 millimeters
1 centimeter = 0.39 inches	1 inch = 2.54 centimeters
1 centimeter = 0.033 feet	1 foot = 30.48 centimeters
1 meter = 3.28 feet	1 foot = 0.30 meters
1 gram = 0.035 ounces	1 ounce = 28.35 grams
1 kilogram = 2.21 pounds	1 pound = 0.45 kilograms
1 liter = 0.26 gallons (U.S.)	1 fluid ounce = 29.57 milliliters
1 milliliters = 0.03 fluid ounces	1 gallon (U.S.) = 3.79 liters

(degrees Celsius) 9/5 + 32 = degrees Fahrenheit
(degrees Fahrenheit -32) x 5/9 = degrees Centigrade

1 Introduction

This report summarizes the results of the United States Environmental Protection Agency (EPA) research program to evaluate the current performance of commercially available volumetric test methods that attempt to detect small leaks in underground gasoline storage tanks (UST).

1.1 Objectives

The specific objectives of the program were to produce the technical data necessary to support the development of release detection regulations; to define the current practice of commercially available systems; to make specific recommendations to improve the current practice; and to provide technical information that will help users select suitable methods for testing the integrity of underground storage tanks.

1.2 Regulatory Needs

Leaking underground storage tank systems represent a serious environmental threat. Estimates of the fraction of UST systems that are leaking range from 10 to 25% [1, 2]. Records from past release incidents indicate that, without the use of release detection, a release can become substantial before it is detected [3]. The 1984 Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act of 1976 have charged the EPA with developing regulations for the detection of releases from UST. The final version of the technical regulation was published in the Federal Register on 23 September 1988 [4]. The performance standard for volumetric testing requires that a method must be capable of detecting a leak rate of 0.38 L/h (0.10 gal/h) with a probability of detection of 0.95 and a probability of false alarm of 0.05.

Development of technically sound and defensible regulations requires that both the threat to the environment and the technological limits of release detection be known. The threat to the environment is extremely difficult to define because the transport, fate, and amount of petroleum that is hazardous to the environment are site-specific.

A performance standard that is based on the current technology will minimize the uncontrolled release of petroleum product. Unfortunately, the data required to formulate a realistic regulatory policy were incomplete or nonexistent before this study was undertaken. While many leak detection methods are available and can be used to detect small releases, the performance of these methods was unknown. Almost all of the volumetric test methods claim to meet the 190-ml/h (0.05-gal/h) practice recommended in the National Fire Protection Agency Pamphlet NFPA 329 [5], but very little evidence, theoretical or experimental, had been provided by the manufacturers to support these claims. The limited evidence available prior to the Edison evaluations [2, 6-8] suggested that the methods are not reliably meeting these claims, a fact that has been confirmed by this study. However, the study has also shown that, with relatively minor changes, many leak detection methods can meet the new regulatory requirements.

1.3 Volumetric Test Methods

Many types of commercial systems are available to detect leaks in underground storage tanks. In 1986, the EPA published a survey of available methods [1], grouping them into four categories: volumetric, nonvolumetric, inventory control, and leak-effects monitoring. For all the methods in the first three categories, tests are conducted inside the tank, while leak-effects monitoring is performed outside the tank.

Volumetric test methods were the first to be selected for evaluation because (1) these methods have the potential for detecting small leaks, (2) the measured quantity can be directly related to leak rate, (3) the main sources of testing errors were believed to be well known, even though the empirical data necessary to quantify and correct many of these errors did not exist, and (4) the technology was commercially available and widely accepted in industry. Volumetric methods that claim to meet the NFPA practice of 0.19 L/h (0.05 gal/h) are commonly known as "precision tests," "tank tightness tests," or "tank integrity tests." Some methods test in a partially filled tank, and others test in a tank overfilled into the fill tube or an above-grade standpipe.

A volumetric method measures the change in product volume that results from a leak in the tank; a leak can represent either the release of product from the tank or an inflow of groundwater into the tank. Most methods measure product level and product temperature. The product-level data are converted to product volumes, which are then temperature-compensated. Next, flow rate is calculated using one or more different analysis schemes. The flow rate is then compared to a threshold flow rate to determine whether the tank is leaking. If the flow rate exceeds the threshold, the tank is declared leaking. If not, the tank is declared tight. While the details of the actual instrumentation, measurement protocols, data reduction and analysis algorithms, and detection criteria differ from method to method, the testing approach is essentially the same for all methods.

1.4 Definition of Test Method Performance

The confident detection of very small releases represents a considerable technical challenge. Release detection is, by its nature, a statistical process. The uncertainty in release detection is a consequence of environmental factors, operational practice, and instrumentation precision and accuracy. Testing errors are manifested in one of two ways:

missed detections (leaking tanks declared to be tight) that result in the undiscovered release of product into the ground, or false alarms (tight tanks declared to be leaking) that lead to additional testing and may result in the needless and considerable expense of tank repair investigations and/or replacement.

A complete specification of system performance requires a description of the probability of detection (P_D) and probability of false alarm (P_{FA}) at a defined leak rate and also requires an estimate of the uncertainty of the P_D and P_{FA}. If, in addition, a frequency of testing is specified, then the limits of the threat to the environment, the confidence with which these limits can be met, and the costs associated with mistakes in testing can be defined.

The performance of each method evaluated is expressed as a leak rate at the product level at which the test was conducted. Some consideration was given to normalizing all results to the same hydrostatic head relative to a leak; this is impractical, because the hydrostatic pressure depends on the level of the product in the tank, the level of the groundwater outside the tank, and the unknown location(s) of the leak(s) in the tank. There is a set of conditions for each test method in which the hydrostatic pressure produced by the product in the tank and the groundwater outside the tank will prevent flow into or out of a tank, even if a hole is present. Proper interpretation of the test result is the responsibility of the test operator.

1.5 Evaluation Approach

The approach was designed to satisfy all four of the objectives listed above (Section 1.1).

1.5.1 Data Quality Objectives

To address the program objectives, 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 developed to evaluate the methods claiming to meet the 0.19-L/h (0.05-gal/h) practice recommended by the NFPA. The precision and accuracy of the product-level, product-temperature, and leak rate data collected at the UST Test Apparatus were sufficient to evaluate the performance of each test method at a leak rate of 0.19 L/h with the probability of detection of 0.99 and the probability of false alarm of 0.01 called for in the proposed UST regulations [3]. This level of performance requires that the one-standard-deviation uncertainty in the histogram of the volume rate results compiled from many tests of one or more nonleaking tanks be 0.04 L/h (0.01 gal/h) or less. The UST Test Apparatus instrumentation, the calibration procedures, and the data quality analyses after each test were designed to verify that the data were meeting these objectives (see Section 7).

1.5.2 Evaluation vs. Validation

An important distinction is made between evaluation and validation. The EPA evaluation program was not meant to validate the performance of a test method. Rather, it was intended to estimate the performance of a given system under the tank conditions selected for the evaluation. Ideally, the performance of each method submitted for evaluation has been validated by the manufacturer over the range of testing conditions for the method. Because the EPA recognized that most manufacturers participating in the program had not systematically evaluated or validated their methods, the test conditions selected for the evaluation were fairly comprehensive. The evaluation reported here was designed to verify the manufacturer's performance claim over a limited set of test conditions. A thorough discussion of the test conditions is presented in this report in order to help the reader interpret the applicability of the results.

1.5.3 Approach

The performance of a leak detection system was determined from the histograms of the noise (developed from the volume-rate fluctuations in a nonleaking tank compiled for all conditions under which a test had been conducted), and of the signal-plus-noise (developed from the relationship between leak rate and these volume-rate fluctuations). 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. 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 unique approach, which also provides this information, was developed to perform the evaluation; this latter approach takes advantage of the common methodology of the majority of the volumetric test methods. This approach was first formulated in [9] and is summarized in [10]. A detailed description of the evaluation protocol is given in [11].

A three-step procedure was used to conduct the evaluations. 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 to simulate a test performed after a delivery of approximately 15,000 L (4,000 gal) 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 model, in turn, was validated in two steps. First, each manufacturer was required to review the model for accuracy, make corrections to the model as necessary, and finally to concur that it accurately represented the method submitted for evaluation; and second, the manufacturer was required to participate in the Field Verification Tests, a three-day program of tank-test and calibration experiments at the UST Test Apparatus. The manufacturer used his own testing crews and test 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 using the test-method model approved by the manufacturer, the product-level measurements estimated from the noise models, and the temperature database. The performance of all test methods but one was evaluated against the same database of temperature conditions encompassing over 500 h of data. A special database of over 180 h was developed to evaluate the one method that continuously circulated the product in the tank during the test. Operational effects and deviations from the prescribed protocols during the Field Verification Tests were also examined and discussed.

1.5.4 Presentation of Results

The performance results are presented and discussed in four categories: underfilled-tank tests, overfilled-tank tests conducted at a nearly constant product level, overfilled-tank tests conducted at a variable product level, and tests for which no performance estimate was or could be made. The performance estimate was made for a 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) tank containing unleaded gasoline and assumes that the test procedure was followed precisely as specified by the manufacturer.

The performance of each method was obtained by combining several different calculations. First, a performance estimate was made for a single tank without any trapped vapor; it included the instrumentation noise, a wide range of temperature conditions, and one set of tank deformation characteristics. The performance of each method is presented in terms of the P_D and P_{FA} for leak rates between 190 ml/h (0.05 gal/h) and 5,000 ml/h (1.3 gal/h).

Second, the effects of structural deformation and trapped vapor were examined. For a wide range of petroleum storage facilities, neither the range of tank and backfill properties affecting the structural deformation of storage tanks nor the distribution of the volume of trapped vapor is known. For this reason, the effects of structural defomation and trapped vapor are discussed separately if they have a direct influence on the performance of a given method. An arbitrary selection of these conditions could have resulted, unfairly, in anomalously poor performance for many methods.

Third, the impact of the following variables was quantified: (1) operational effects such as topping off the tank before a test, which can impair effective temperature compensation and significantly increase structural deformation of the tank, and (2) protocol deviations such as waiting periods that are longer or shorter than specified for starting or ending a test, which can significantly change the deformation effects. Methods whose performance would be dominated by trapped vapor, deformation, and operational effects are identified in the report so that the performance, which is based primarily on the ability to compensate for product-temperature changes, can be properly interpreted. These effects are very important, since they are a prime cause of false alarms and missed detections.

1.6 Underground Storage Tank Test Apparatus

The evaluations were performed by the RREL at the EPA's UST Test Apparatus located in Edison, New Jersey. The Test Apparatus 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 (see Section 7). With this combined apparatus, different product temperatures, product levels, and leak rates can be generated and accurately measured. Thus, a wide range of tank testing conditions can be simulated.

1.7 Industry Participation

The only methods evaluated were those in-tank test methods that were capable of quantifying the flow rate produced by a leak in the tank. The EPA openly solicited all manufacturers of commercially available volumetric test methods to participate in the program. This was accomplished by public announcement in the Commerce Business Daily in July 1986 and with assistance from the American Petroleum Institute (API), the Petroleum Equipment

Institute (PEI), and the Leak Detection Technology Association (LDTA). Admission to this program was not closed until 1 April 1987, one month after the start of the Field Verification Tests.

Forty-three manufacturers and vendors of test methods originally indicated their desire to participate in this voluntary program. Twenty-five manufacturers completed the requirements necessary for evaluation. In fifteen of the methods evaluated, tests are conducted in an overfilled tank. In three of these methods, a constant head is maintained during testing. Of the remaining ten methods in which tests are conducted in an underfilled tank, the majority were automatic tank gauging systems (ATGS) for which a special protocol had been developed for this program. As a consequence, the performance of the ATGS evaluated as precision tests in this program may be different from the performance achieved when the same systems are operated as ATGS. A list of the twenty-five test methods and manufacturers that participated throughout the entire program is presented in Table 1.1.

Eighteen chose not to participate in the evaluation program. The reader should not assume that nonparticipation in the program is equivalent to poor performance. Manufacturers were not required to give reasons for not completing the program. About half of the 18 manufacturers who chose not to participate had been active at the beginning of the program, but dropped out because they were unable to complete the development and/or testing of their systems prior to the start of the Field Verification Tests. Several of the manufacturers in question missed their scheduled test times at the UST Test Apparatus because of development problems. Additional opportunities were provided, on a time-available basis, to accommodate the manufacturers' development efforts and still meet the EPA's deadline for completion.

Participation in the program involved a number of steps. First, manufacturers were required to execute a letter stating their desire to participate in the evaluation and their agreement to abide by its rules. Each company was required to designate a single contact for the exchange of technical and administrative information.

Second, each manufacturer was requested to answer a questionnaire that described specific aspects of the test method. This technical information was needed to describe the test method quantitatively; it included a claim of the precision and accuracy of the instrumentation, the configuration of the equipment deployed during a test, the specific procedure for conducting a test, the detailed data collection and data analysis procedures, and the criteria for determining whether a test was validly conducted and for declaring whether a tank is leaking.

Table 1.1. Participants Completing the EPA Volumetric Test Method Evaluation Program

Test Method Name	Test Method Manufacturer
AES/Brockman Leak Detecting System	Associated Environmental Systems Mr. R. Brockman (805) 325-2212
Ainlay Tank 'Tegrity Tester™	Soiltest, Inc. Mr. F.R. Kin (312) 869-5500
Automatic Tank Monitor and Tester (AUTAMAT)	Exxon Research and Engineering Co. Mr. D.B. Bolland (201) 765-3786
Computerized VPLT Tank Leak Testing System	NDE Technology, Inc. Dr. J.R. Mastandrea (213) 212-5244
DWY Leak Sensor	DWY Corp. Mr. J.W. Hamblen (715) 735-9520
EZY CHEK	Horner Creative Products, Inc. Mr. J. Horner (517) 684-7180
Gasoline Tank Monitor (GTM)	Tidel Systems Mr. M. Gregory (214) 416-8222
Gilbarco Tank Monitor	Gilbarco, Inc. Mr. M. Black (919) 292-3011
Inductive Leak Detector 3100	Sarasota Automations, Inc. Mr. R.P. Piccone (813) 366-8770
INSTA-TEST	EASI, Inc. Mr. C. Scafidi (219) 239-7003
Leak Computer	Tank Audit, Inc. Mr. D.E. Hasselmann (619) 693-8277
Leak-O-Meter	Fluid Components, Inc. Mr. M.M. McQueen (619) 744-6950
LiquidManager	Colt Industries Mr. C. Wohlers (813) 882-0663
LMS-750	PNEUMERCATOR Co., Inc. Mr. K. Slovak (516) 293-8450

Table 1.1 (concluded). Participants Completing the EPA Volumetric Test Method Evaluation Program

Test Method Name	Test Method Manufacturer
MCG-1100	L & J Engineering, Inc. Mr. L. Jannotta (312) 396-2600
Mooney Leak Detection System	The Mooney Equipment Co., Inc. (504) 282-6959
OTEC Leak Sensor	OTEC, Inc. Mr. J.W. Hamblen (715) 735-9520
PACE Leak Tester	PACE (Petroleum Association for Conservation of the Canadian Environment) Mr. P. Casson (416) 298-1144
Petro Tite	Heath Consultants, Inc. Mr. G. Lomax (617) 344-1400
Portable Small Leak Detector (PSLD)	TankTech, Inc. Mr. J.A. Carlin (303) 757-7876
S.M.A.R.T.	Michael & Associates of Columbia, Inc. Mr. M. Diimmler (803) 786-4192
Tank Auditor	Leak Detection Systems, Inc. Mr. W.E. Baird (617) 740-1717
Tank Monitoring Device (TMD-1)	Pandel Instruments, Inc. Mr. P. Lagergren (214) 660-1106
Tank Sentry II	Core Laboratories, Inc. Mr. M. Sullivan (512) 289-2673
TLS-250 Tank Level Sensing System	Veeder-Root Co. Mr. D. Fleischer (203) 527-7201

After technical interaction with the manufacturer's representative, a report describing each method as a mathematical model was generated; this model is a logical sequence of mathematical steps that can be (and were) implemented on a computer. The report is referred to as the "mathematical modeling report" or simply the "model report." A written concurrence with the test-method description, as presented in the mathematical modeling report, was required of each manufacturer. Some mathematical modeling reports contained information designated as proprietary, trade-secret, or company-confidential by the manufacturer. So as to prevent the unauthorized release of information, these reports are not available for public distribution by the EPA. Those nonproprietary aspects of the test methods necessary to interpret and understand the results of the evaluation are summarized in the appendix in Volume I and also in Volume II.

Each manufacturer was then invited to participate in the Field Verification Tests at the UST Test Apparatus in Edison, New Jersey. The Field Verification Tests consisted of two parts. First, a series of product temperature conditions was established; under each condition, a leak was simulated by withdrawing product from the Test Apparatus tank at a constant rate. Each manufacturer was asked to test the Test Apparatus tank for leaks by following his standard test protocol, using his own test crew and equipment. Second, the manufacturer's measurement system was calibrated to derive an estimate of its precision and accuracy. These tests and calibrations were used to validate the test-method model.

An evaluation report was prepared for every manufacturer who participated in the Field Verification Tests at the UST Test Apparatus. Each evaluation report is included as an appendix in Volume II of this report.

Finally, the manufacturers were asked to provide a written technical review of their respective appendices and to discuss these with the EPA and its contractor before publication of the final report. The manufacturer had three opportunities to review his evaluation while the final report was being prepared. Valid technical comments were incorporated in the final report.

The evaluation was conducted at no cost to the participants; however, travel and other expenses incurred by the participants during the program were not reimbursed by the EPA.

1.8 How to Use This Report

The body of this report summarizes the results of the evaluation. It contains a description of the approach used for the evaluations, a description of the performance model used to present the results, a summary of the performance currently being achieved by commercial systems, a quantitative description of the important sources of testing errors, and specific recommendations on how to minimize these errors and improve performance. Sections 2 and 3 summarize the main conclusions and recommendations of this research program. Section 4 gives an overview of volumetric tank testing, and provides basic information necessary to understand the other sections of the report. The performance of a test method is described in Section 5. Section 6 describes the simulation used to estimate the performance of the methods evaluated in this program. (Section 6.4 is highly technical and describes the ambient-noise-source models that were used in the simulation and that control the performance of a volumetric method.) Section 7 describes the UST Test Apparatus located in Edison, New Jersey, the data quality objectives, and the quality assurance and quality control procedures used during the collection and analysis of the experimental data. Section 8 presents important experimental and theoretical findings about the sources of ambient noise. Section 9 summarizes the protocol used to evaluate the performance of the 25 volumetric methods that participated in the program. In Section 10, several calculations are performed for generic test methods to illustrate how the performance of a volumetric method is affected by the sources of ambient noise, including how the performance of a method changes with the number of temperature sensors used to compensate for thermal expansion or contraction of the product. Section 11 summarizes the evaluation results presented for each method in Volume II of this report. Section 12 discusses how test methods can improve their performance.

The evaluation results for each method are presented in the lettered appendices to this report (Volume II). Each appendix is sufficiently detailed that the manufacturer, or the user, of the method can assess the performance results that are presented. Sections 1 and 2 of each appendix gives the name of the method and the manufacturer, and a description of the method that was evaluated. Section 3 presents the results of some limited field testing with the manufacturer's equipment and test crew, and Section 4 describes the validation of the performance model. Section 5 presents the performance results and gives suggestions for improving performance, in sufficient detail, it is hoped, for the user to determine whether the version of the test method being offered has been upgraded. The description of each method and the suggestions for improving performance are also found in the appendix in Volume I.

The report was prepared assuming the performance standard for tank tightness tests in the proposed rule [3], i.e., a method must be capable of detecting a leak rate of 0.38 L/h (0.10 gal/h) with a probability of detection of 0.99 and a probability of false alarm of 0.01. The tables summarizing performance in each manufacturer's appendix in Volume II of the report are presented for these values of P_D and P_{FA}. The final regulation [4] is addressed in the body of the report. The performance results summarized in the body of the report (Volume I) are given in terms of the P_D and P_{FA} achieved by each method against a leak rate of 0.38 L/h (0.10 gal/h) using the manufacturer's detection threshold employed at the time of the evaluation, and of the smallest leak rates that could be detected and still maintain a P_D of 0.95 and P_{FA} of 0.05, and a P_D of 0.99 and P_{FA} of 0.01. The latter estimates were made using thresholds that were different than those employed by the manufacturer in the evaluation.

The evaluation results are also summarized in [12, 13]. The first reference is a report being prepared by EPA's Center for Environmental Research Information (CERI), and the second reference is a professional society paper.

Both the body of the report and the appendices should be used to interpret the performance and the performance limitations of a particular test method. The description of the method given in each appendix in Volume II is an extremely important part of the evaluation. Any changes to the manufacturer's method may dramatically alter the performance results given in the appendix.

In accordance with the EPA guidelines applicable to ORD scientific and technical documents, all quantities in the report are presented in metric units and follow the standard format of the International System of Units (SI). Because it is common practice in the leak detection industry to present quantities in English units (e.g., gal/h) instead of SI units (e.g., L/h), three steps have been taken to help the reader to readily perform the conversions and to interpret and relate the quantities in SI units to the common practice. First, a List of Units and Conversions is presented in the front of the report. For more detail, the reader is referred to the Metric Practice Guide, ASTM [14]. Second, to facilitate the reading of the report, the SI quantities are followed by the English quantities in parentheses when they are first introduced in each chapter. Third, Table 1.2 presents the numbers most commonly used in this report in SI and English units.

Table 1.2. Commonly Used Quantities in English Units and SI Equivalents

English Units	SI Equivalents
0.05 gal/h	0.19 L/h (190 or 189 ml/h)
0.10 gal/h	0.38 L/h
0.20 gal/h	0.76 L/h
1 gal	3.8 L
8,000 gal	30,000 L
10,000 gal	38,000 L
0.001°F	0.0006°C

2 Conclusions

An important EPA-sponsored research program has been completed that has evaluated and made estimates of the performance of commercially available volumetric leak detection methods as they existed in the period March through July 1987. For each method evaluated, recommendations were made, as required, to improve performance. This two-year project has determined and resolved key technological and engineering issues associated with this type of leak detection. The following objectives were accomplished: (1) evaluation of the performance of 25 currently available volumetric systems for detection of leaks in underground gasoline storage tanks; (2) development of technical information important in the development of EPA's underground storage tank regulations; (3) development of specific recommendations that will allow manufacturers to improve the current practice of each method; and (4) development of basic information to assist the test users in selecting a method that meets EPA's new regulatory requirements for underground storage tanks. A summary of the key conclusions of this research project are provided below.

After minor modifications, most methods should meet EPA performance requirements. By and large, the leak detection systems evaluated were limited by protocol and current practice rather than by hardware. In general, such limitations can be overcome by rather modest modifications to testing practices; major equipment redesign is not necessarily required. As part of this study, an estimate was made of the potential performance that could be achieved by the various precision test methods evaluated. The results show that with modifications, 12 of the 19 methods (over 60%) that completed the evaluations should be able to achieve a performance between 0.19 L/h (0.05 gal/h) and 0.57 L/h (0.15 gal/h), and all 25 methods (100%) evaluated should be able to achieve a performance of approximately 0.76 L/h (0.20 gal/h). Some manufacturers are already using the results of this evaluation to improve practices and equipment to achieve the above performance levels, and are in the process of quantifying the performance actually achieved by the modified systems.

Presentation of evaluation results in terms of PD and PFA gives a quantitative estimate of performance. Twenty-five commercially available volumetric leak detection systems were evaluated. An estimate of the performance of each method was made in terms of the probability of detection and probability of false alarm against a 0.38-L/h (0.10-gal/h) leak rate using the detection threshold employed by each method at the time of the evaluation. Another set of performance estimates was made for each method in terms of the smallest leak rate that could be detected and still maintain probabilities of detection and false alarm of 0.95 and 0.05, and 0.99 and 0.01. This performance estimate does not employ the manufacturer's detection threshold;

instead a threshold was selected which yields a probability of false alarm of 0.05 and 0.01, respectively. The leak rate measurable by these systems ranged from 0.26 to 6.97 L/h (0.07 to 1.84 gal/h), with a probability of detection of 0.95 and probability of false alarm of 0.05. Five of the methods achieved a performance that was better than 0.57 L/h (0.15 gal/h), and a total of eight methods had a performance that was better than 0.95 L/h (0.25 gal/h). The leak rate measurable by these systems ranged from 0.47 to 12.95 L/h (0.12 to 3.42 gal/h) when the probability of detection increased to 0.99 and the probability of false alarm decreased to 0.01. Only one of the methods achieved a performance better than 0.57 L/h, but five methods achieved a performance between 0.57 L/h and 0.95 L/h. While these results are less than what is generally claimed by the manufacturers, the phenomena that degrade performance have been identified, and in most instances, the problems can be easily fixed. Six systems could not be evaluated under the conditions of this evaluation either because the manufacturer was unable to successfully conduct a tank test during a scheduled three-day testing period, because the measurement systems did not perform as described by the manufacturer, or (in one instance) because the Test Apparatus had not been properly configured for the tests. These six appeared to be either new systems or systems whose basic principles of operation were not yet fully understood by the manufacturer.

Tank testing is complex, but a high level of performance can be achieved if several key principles are followed. To avoid serious degradation of performance, several key factors must be accounted for when using any of the volumetric test methods. Those systems that did well in the evaluation had adequate spatial sampling of the vertical temperature profiles of the product in the tank; they incorporated adequate waiting periods after product delivery and/or topping the tank (in tests that overfilled tanks) to allow the spatial inhomogeneities in the product temperature field and the tank deformation to become negligible; they maintained a nearly constant hydrostatic pressure head during the test; they used an experimental estimate of the height-to-volume conversion factor; and they used sound data analysis algorithms and detection criteria. Performance of a test method suffered significantly whenever one of these aspects of testing was ignored or poorly implemented. In general, any method will perform poorly and provide results that are difficult to interpret if it: (1) fails to maintain a nearly constant hydrostatic head during the test; (2) does not accurately estimate the height-to-volume conversion factor; (3) tops the tank and begins to test almost immediately, or (4) waits an insufficient period of time after product delivery before beginning the test. Most manufacturers recognized the need to wait after a product delivery, but they did not appear to fully appreciate the magnitude of the degradation that occurs when the waiting period after topping (in methods that overfill the tank) is not long enough.

Current performance is significantly less than what is claimed by most manufacturers. Of the 25 commercially-available volumetric leak detection systems evaluated, most presently perform at a level that is considerably poorer than the common industry practice of 0.19 L/h (0.05 gal/h). This discrepancy between vendor claims and actual performance appears to be due to two reasons. First, in almost all instances, the measurements made by EPA under this project appeared to be the first systematic evaluation of each test method. Second, the performance estimates were formed in terms of a probability of detection and a probability of false alarm, a presentation that most manufacturers have not previously used to quantitatively describe performance.

Removal of vapor pockets is important to the performance of overfilled-tank test methods. Operationally, achieving a high level of performance with methods that overfill the tank requires the removal of trapped vapor before conducting a test; this is a necessary skill that, during this evaluation, was best demonstrated by the most experienced and best-trained test crews. Test methods designed for use in partially filled tanks are not subject to the effects of trapped vapor but can be affected by evaporation from the product surface and evaporation and condensation from the tank walls. Analysis of the evaporation and condensation data is incomplete. Based on a qualitative inspection of the test results, it is observed that when temperature conditions in the vapor space are relatively stable, the impact of evaporation and condensation on test performance is relatively small.

Constant-level testing is important with overfilled-tank test methods. A serious testing flaw was discovered in all methods which overfill the tank into a fill tube or standpipe and measure product-level changes. The error associated with this flaw was theoretically described and experimentally verified in this program. The flaw is easily eliminated by conducting the test at a nearly constant hydrostatic head. This can be accomplished by releveling the product in the fill tube and measuring volume directly, or by significantly increasing the cross-sectional area of the fill tube. The essence of the flaw is that the volume changes measured in the fill tube, after the waiting period designed for the observed deformation changes to subside, are reduced to an unknown fraction of the true volume changes. The flaw is a result of the fact that the tank structurally deforms continuously with any product-level changes in the fill tube. The contributions from all sources of volume change, including operator-induced and ambient product-level changes, are coupled and interact dynamically in a complex way to deform the tank. The volume changes due to leaks are similarly affected. The magnitude of the error depends on the cross-sectional area of the product surface, the elasticity properties of the tank-backfill-soil system, and the volume of trapped vapor.

Reliable tank testing takes time. The total time required for the methods evaluated at the UST Test Apparatus to complete a reliable tank test, from delivery of product to removal of the equipment from the testing site, is generally 12 to 24 h. The total duration of the test is controlled by the waiting periods after product delivery or topping the tank. The waiting periods can be shortened by incorporating data analysis algorithms into the test protocol. In this way the duration of the waiting periods can be estimated individually for each test.

3 Recommendations

Leak detection technology is rapidly evolving. With the passage of federal legislation in 1984, the drafting of national UST rules by EPA, the establishment of numerous state and local UST programs over the past several years, and the completion of this RREL research effort, the economic motivation for system improvements and technological discipline has been established. However, it is also clear that all the methods evaluated can be improved and that many of the methods need such improvement in order to satisfy the new EPA regulatory requirements given in [4]. The following recommendations are a direct outcome of the evaluation effort and are provided so that manufacturers, test users, and state and local regulators will be clearly informed as to what steps must be taken to make the necessary improvements.

Acceptable means are needed for evaluating anticipated improvements in performance. The results of this evaluation indicate that many manufacturers will have to make improvements to their systems in order to be able to meet the new EPA regulatory requirements. Others will make improvements to achieve a higher level of performance. The majority of these will be straightforward changes in how the method collects, analyzes, and interprets test data, compensates for temperature, accounts for tank deformation, and ensures that adequate waiting periods have elapsed. After these changes are made, many of the methods will meet the regulatory standard. However, this does not eliminate the need for verifying that the required performance improvements have been achieved.

To estimate the performance of a detection system, the histograms of the noise and signal-plus-noise need to be characterized. A complete performance evaluation includes the histogram of the noise, the conditions used to define the noise, the histogram of the signal-plus-noise (usually developed from the relationship between the signal and the noise), the performance in terms of the probability of detection, the probability of false alarm and the leak rate, and the uncertainty of the probability of detection and the probability of false alarm (i.e., the number of independent test conditions).

There are many different but viable approaches to estimating the performance of detection systems. For some of the methods evaluated an estimate of the performance achieved after improvements have been implemented can be calculated using information provided in this report. For the majority of methods, however, the need exists for experimental evidence before any new claims of improved performance can be fully supported. The necessary experimental data can be gathered from operational data collected at retail stations or test data collected on specially instrumented tanks. There are many acceptable approaches to evaluation that incorporate the principles used by the EPA at the Test Apparatus in Edison without the need for such a sophisticated facility. Acceptable methods of evaluation should be and are being developed by government, industry, and professional societies as guidance to manufacturers, users, and regulators whose responsibility it is to evaluate or interpret performance claims. Until such evaluation procedures are completed, it is strongly recommended that users employ only those test methods that have (at the minimum) adopted the procedural and equipment recommendations made in this report.

Two of the anticipated ramifications of this research project are rapid improvements in performance made by manufacturers and and increase in test users' and regulators' expectations concerning verification of future performance claims for all volumetric methods. Manufacturers of many of the methods that were evaluated by RREL have already begun to make the changes necessary to improve their systems' performance and to verify the new performance claims. This is a very encouraging development.

All volumetric test methods must account for and control the key sources of noise that impact performance. Reliably detecting small leaks in underground storage tanks is a technically challenging task. To achieve a high level of performance against leaks as small as 0.38 L/h (0.10 gal/h) requires:

- ***Sufficient waiting period after product delivery.*** Spatial inhomogeneities in the temperature field make the conventional approach to temperature compensation unacceptable for a period of up to 4 to 6 h after delivery. Tank deformation effects, however, may continue even longer. As with product delivery, a waiting period which minimizes these effects should be incorporated into the test protocol. The waiting period should be at least 6 h long unless validated analysis algorithms designed to minimize the waiting period are incorporated into the test protocol.
- ***Sufficient waiting period after topping.*** Several overfilled-tank test methods top the tank to a specified level immediately before testing. Although not much product is added compared to a product delivery, the resulting temperature and tank deformation effects can be significant. The horizontal temperature gradients that develop from topping last 2 to 3 h. The deformation effects can be large for a considerable period. A waiting period which minimizes these effects should be incorporated into the test protocol. The waiting period should be at least 3 h long unless validated analysis algorithms designed to minimize the waiting period are incorporated into the test protocol.

- o ***Sufficient waiting period after disturbing the vapor space in a partially filled tank.*** In some instances, it was observed that after a tank was opened to the environment the effects of evaporation and condensation of product remained large for 4 to 6 h. Additional analysis is required before a minimum waiting period can be recommended.
- o ***Adequate temperature compensation***. Leaks smaller than 3.8 L/h (1.0 gal/h) cannot be reliably detected without temperature compensation. To reliably detect 0.38 L/h (0.10 gal/h) leaks, a temperature array with at least five temperature sensors (or an averaging sensor with equivalent spatial coverage) appears to be necessary to adequately characterize the vertical temperature profile in the tank (for methods which do not circulate the product).
- o ***Testing at a nearly constant hydrostatic head.*** All tests should be conducted at a nearly constant hydrostatic pressure. Tests in partially-filled tanks are conducted at a nearly constant hydrostatic head but this is not true for overfilled-tank tests which measure product-level changes in a fill tube or standpipe. For accurate testing, these overfilled-tank tests should (1) measure volume directly by periodically releveling the product in the fill tube or standpipe, (2) enlarge the cross-sectional area of the measurement container, or (3) measure the elastic properties of the tank-backfill-soil system and incorporate them into the data analysis.
- o ***Approaching data collection and data analysis quantitatively.*** Reliable leak detection can be achieved by using simple, standard textbook data collection, reduction, and analysis algorithms. The effect of the data collection and data analysis algorithms needs to be understood, particularly when statistical tests are performed on correlated or aliased data.
- o ***Testing with calibrated measurement systems.*** To achieve a high level of performance in the field, the leak detection systems must be well maintained, properly installed, and regularly and accurately calibrated. Futhermore, it is highly desirable to include diagnostic calibration checks of the instrumentation as part of the test procedure.

Test users and regulators should require that the protocols developed for individual test methods be followed closely in the field by test operators. The evaluation of the volumetric test methods has shown that test operators must follow their own test method's protocol to achieve the level of performance that the method is capable of. Any deviations from the protocol will affect the performance of the method. It is recommended that once a test protocol is established and evaluated, it should be carefully followed for each test. It is particularly important to observe the specified waiting periods that are required to minimize the effects of temperature change and deformation that result when product is added to the tank. Moreover, any arbitrary judgments about the conduct of the test should be avoided.

Users of test methods should request from the manufacturer a written copy of the important features of the test method protocol. The user should also take time to observe whether those specifications are being following. Regulators should examine written protocols of methods that have been approved for use in their jurisdictions. If the method has been evaluated by the EPA, they should determine whether equipment and protocol changes have been made since the evaluation and should review the new performance claims.

Volumetric test methods should not be selected based solely on the ranking contained in this report. Because it has been shown that the performance of many of the individual test methods can be significantly improved with only minor modifications, some of the worst-performing methods are expected to raise their performance to the level (or beyond) of the best-performing methods in the immediate future. As a consequence, and because many methods have already incorporated many of the recommended changes for improvement, the current ranking of test method performance implied in this report is not particularly significant.

Manufacturers of volumetric test methods must closely heed the findings of this report to assure future compliance with the new regulatory requirements. Three of the methods were able to detect leaks of 0.38 L/h (0.1 gal/h) with a probability of detection of 0.95 and a probability of false alarm of 0.05. That means some additional improvements to many of the volumetric methods evaluated by RREL will eventually be needed in order for them to meet the new regulatory requirements for periodic tank tightness testing. Even the methods that meet the regulatory requirements may need improvement, because effects like topping the tank, which would degrade the performance of these methods, were not included in the performance estimates. These recommended improvements are often very simple to make but have been found to be critical to improving performance. Test users and state and local regulators will undoubtedly expect the improvements to be made. Under the new federal regulations, manufacturers of volumetric methods will have up to two years to demonstrate they have achieved the performance levels (specifically the P_D and P_{FA} values) required by the EPA.

4 Overview of Volumetric Precision Tank Testing

A volumetric leak detection system is designed to make an estimate of the total volume of product that is lost due to a leak over the duration of a test. For most tests, the volume lost is based on a change in product level. Tests may be conducted in a partially filled tank or in a tank overfilled into a fill tube that is connected to the tank or to an above-grade standpipe (see Figure 4.1). Two types of overfilled-tank tests are used. The most common one measures the product-level changes in the fill tube or standpipe, and the other periodically adds or removes product to maintain a constant product level during the test. Product level is measured using a variety of sensor systems.

Unfortunately, product-level fluctuations in a tank (the fundamental measurement) are also produced by numerous effects not related to a leak. These ambient fluctuations (i.e., ambient noise) can be as large as or larger than the smallest leaks to be detected. They may be caused by long waves in the tank which periodically move the product back and forth, primarily along the long axis of the tank (i.e., seiching); by volume changes produced by thermal expansion or contraction of the product; by evaporation or condensation at the product surface; by changes in the volume of the trapped vapor produced by temperature and pressure changes; and by changes, produced by structural deformation, in the volume of the tank itself. The accuracy, or "performance," achieved by a method usually depends on the magnitude of these fluctuations and on how well that method can minimize or compensate for these non-leak-related volume changes.

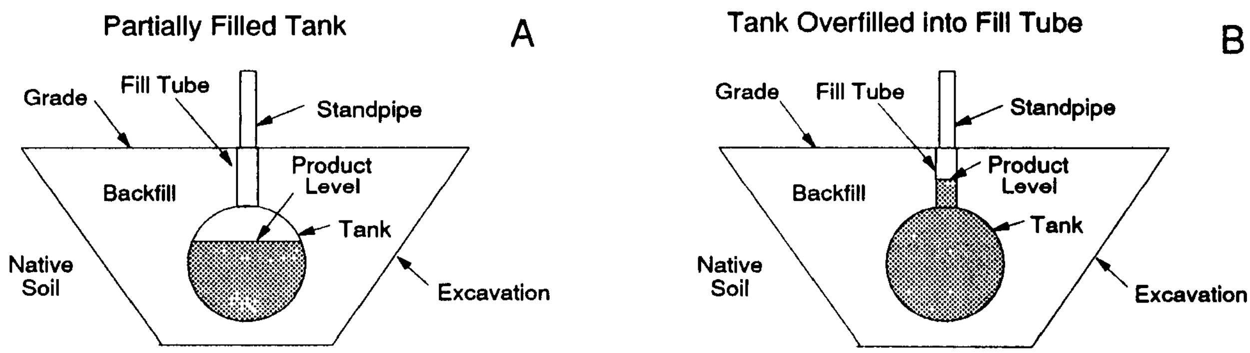


Figure 4.1. Cross-sectional view of an underground storage tank that is (A) partially filled and (B) overfilled into the fill tube.

The basic strategy in any volumetric test is as follows: (1) before taking measurements, observe appropriate waiting periods so as to avoid the problems associated with structural deformation of the tank and with the thermal instabilities that develop after product delivery or topping off the tank; (2) measure product-level change over the duration of the test; (3) measure product temperature over the same period; (4) properly sample and average the data so as to remove the effects of both surface and internal waves; (5) convert measurements to volume changes; (6) subtract out the thermally induced volume contribution; and (7) declare the tank leaking if the residual exceeds a specific threshold value. The basic assumptions are that vapor pockets have been removed, evaporation-condensation effects are small, and the groundwater table is below the bottom of the tank. Interpretation of the test result (i.e., the size of the leak) is discussed below.

4.1 Product-Level Fluctuations in an Underground Storage Tank

Product-level fluctuations in an underground storage tank can result from a leak as well as from a wide variety of other physical changes in the tank, product, or product surface.

4.1.1 Flow Rate Produced by a Leak

A leak may occur at any breach, hole, or loose fitting in an underground storage tank. Leaks near the top of the tank may occur because of missing bungs, or loose or broken joints where the piping is attached to the tank. A breach caused by corrosion or a crack in the tank material may occur at any location in the tank.

The performance of a test method is based simply on the ability of the method to measure the flow rate that occurs during a test. The flow rate through a hole depends, in general, on the hydrostatic pressure exerted on the hole, on the physical properties of the hole, and on sediment particulates in the tank and the backfill material outside the tank that may retard flow through the hole. The hydrostatic pressure is, in turn, a function of the level and density of product in the tank, the level and density of the groundwater table outside the tank, and the location of the hole. Flow through a hole could, under a different hydrostatic pressure, represent a larger or smaller leak rate than that measured during the test. Interpretation problems can be minimized by ensuring that the water table is below the bottom of the tank, as was the case during this evaluation.

A more detailed description of how the flow rate is affected by different combinations of product level and groundwater level is given in Section 4.7.

4.1.2 Apparent Flow Rate Produced by Non-Leak-Related Volume Fluctuations

Product-level fluctuations can affect the performance of a test method because they may be mistaken for (or interpreted as) a leak. The sources of these product-level fluctuations are:

- changes in the volume of the product and of air or vapor trapped in the tank

- o changes in the volume of the tank itself
- o product-level changes caused by surface and internal waves in the product

4.1.2.1 Changes in the Volume of Product and Trapped Vapor

Changes in the volume of product and trapped vapor are caused by any of several phenomena.

- o *Expansion and contraction of the product due to temperature changes.* Large volume changes result from thermal expansion and contraction because of three factors: the temperature changes in the tank may be large; the volume of the product in the tank is large; and the coefficient of thermal expansion of petroleum products is also large (nearly 4 to 7 times larger than that of water).
- o *Expansion and contraction of vapor trapped in the tank.* Product-level changes also result from the expansion and contraction of any trapped vapor and are a consequence of changes in vapor temperature, vapor pressure, atmospheric pressure, and product level. The magnitude of these volume changes is strongly dependent on the total volume of the vapor trapped in the tank. These changes occur only if the tank is overfilled for the test.
- o *Evaporation and condensation of product at the product surface and along the tank walls.* The volume changes due to this phenomenon can be important for tests conducted in a partially filled tank.

4.1.2.2 Changes in Tank Volume

The tank itself may undergo a change in volume during the test. The most important and least understood cause of such a change is structural deformation of the tank. Deformation, which occurs whenever the hydrostatic pressure relative to the bottom of the tank changes, consists of an instantaneous change in product level and a time-dependent relaxation of the tank-backfill-soil system (see Figure 8.15). Deformation can result in volume changes large enough to mask a leak, and, under some test conditions, can also affect the magnitude of the measured leak rate. For this reason, an understanding of the effects of structural deformation is essential.

A change in volume can also result from thermal expansion or contraction of the tank walls. This effect is not large unless the temperature changes are large. A simple calculation for a steel tank, assuming that the tank is a right regular cylinder, suggests that a 1°C change in temperature would result in a 0.30-L (0.08-gal) change in volume. This effect is most significant immediately after a delivery, when the temperature difference between the product in the tank and the backfill and *in situ* soil is largest.

4.1.2.3 Waves

Periodic product surface undulations can have several sources. A disturbance of the surface causes a seiching motion in the tank, meaning that product moves back and forth as a standing wave along either horizontal axis of the tank. The dominant seiche occurs along the long axis of the tank. Seiches, which can be quite large, occur mainly during partially-filled-tank tests, but can also occur during overfilled-tank tests if two product surfaces exist in the tank (e.g., fill tube and vent tube). The period of the standing waves in a partially filled tank may range from 2 to 10 s, depending on the geometry of the product surface. The presence of other wave motions in the tank (e.g., progressive waves) does not appear to be an important source of error.

Periodic surface undulations can occasionally be caused by internal waves, which are subsurface waves that can occur on a density gradient in the product. Since, for a given product, density is dependent mainly on temperature, these waves are typically found on temperature gradients. However, they may also occur at the boundary separating two products of different composition. Internal waves, which typically have a period of 5 to 20 min or longer in a 30,000-L (8,000-gal) tank, do not generally have a significant influence on the surface, but this is possible under some conditions. The presence of internal waves is more likely to impact temperature estimation. Undersampling the temperature data either spatially in the vertical field or temporally can lead to significant errors in estimating the thermal expansion of the product in the tank.

Waves should not affect the performance of a test method unless the data are undersampled, a situation which can lead to aliasing of the results. This error can be avoided if the data are sampled at least as often as one-half the period of the waves[1]. It is generally recommended that the data be sampled at one-third of the period. Thus, a 6-s period should be sampled at 2 s. Similarly, a 10-min internal wave would require that both the temperature and product-level measurements be sampled at 3.3 min. To accommodate both wave effects, a scheme that sampled the data at 2 s and averaged the samples to 3 min would suffice.

1. Waves in a half-filled 4,000-L (1,000-gal), 30,000-L (8,000-gal), and 80,000-L (20,000-gal) tanks typically have periods of approximately 3, 5, and 6 s, respectively.

4.2 Flow Rate Measurements during a Tank Test

An underlying assumption of a volumetric test is that product-level changes in a tank, whether produced by a leak or by any other volume change (such as the thermal expansion or contraction of the product), can be interpreted as product-volume changes. An accurate estimate of the height-to-volume conversion factor is required in order to convert the product-level changes to product-volume changes. The height-to-volume conversion factor is defined by

$$A_{eff} = \frac{\Delta V}{\Delta h} \tag{4.1}$$

where A_{eff} is the effective cross-sectional area of the product surface and ΔV is the volume change produced by a product-level change, Δh. A_{eff} may or may not be equal to the actual or geometrical cross-section of the product surface, A. If, in an overfilled-tank test, the instantaneous deformation of the tank is negligible, and if no vapor is trapped in the tank, then A_{eff} is the actual cross-sectional area of the product surface. If the tank deforms instantaneously, and if trapped vapor exists in the tank, then A_{eff} can be defined as the sum of the individual contributions to the effective surface area.

$$A_{eff} = A + A_{vp} + A_{isd} \tag{4.2}$$

where A_{vp} and A_{isd} are the volume changes per unit of product-level change produced by the compressibility of trapped vapor and the instantaneous structural deformation, respectively. Typically, A_{isd} and A_{vp} cannot be measured separately unless the volume of the trapped vapor is known. Eq. (4.2) indicates that A_{eff} can be interpreted as the sum of the individual contributions to A_{eff}. For partially-filled-tank tests, A_{eff} is usually equal to A and can be determined from the geometry of the tank, if it is well known. Because of the uncertainties in the tank geometry, particularly in the upper 10% of the tank, it is more accurate to measure A rather than to compute A from the manufacturer's tank chart relating the nominal volume of the tank with product level in the tank. For both overfilled-tank and partially-filled-tank tests, A_{eff} can be estimated from a simple measurement of the product-level change produced by inserting and removing a solid of known volume, e.g., a cylindrical bar.

In an overfilled-tank test, A_{eff} must be measured in order to account for the instantaneous structural deformation of the tank and the volume changes in the trapped vapor. A geometrical estimate will frequently lead to erroneous test results. Section 6 discusses the dynamics of product-level fluctuations within the fill tube or an above-grade standpipe and the impact of this phenomenon on system performance. For variable-head overfilled-tank tests, it has been shown that A_{eff} cannot be used to convert product-level changes to product-volume changes, and that the effective height-to-volume calibration factor is defined by $A_{eff} + K$, where K is the elasticity constant of the tank-backfill-soil system.

In a partially-filled-tank test (conducted with product level in the upper 10% of the tank) A_{eff} must also be measured, for two reasons. First, the geometry of the upper portion of the tank, which may be distorted during installation, is not known. Errors of 100% in estimating A_{eff} in the upper 5% of the two 30,000-L UST Test Apparatus tanks were typical, even though the tanks had been installed horizontally and the inside dimensions had been accurately measured. Second, it can be shown that a stick measurement of the mean product level required in order to use the tank chart to estimate A is not accurate enough if small leak rates are to be reliably detected.

4.3 Classification of Volumetric Test Methods

For the purpose of evaluating performance, volumetric test methods may be divided into two groups. The first group includes those methods in which the hydrostatic pressure is approximately constant throughout the test. For these tests, product-volume measurements can be readily interpreted from the product-level measurements. In this group are those methods that test in a partially filled tank, as well as those that test in an overfilled tank and periodically relevel the product at short intervals. A partially-filled-tank test is considered a constant-head test, because even large volume changes cause only small product-level changes in the tank. For example, a 0.76-L (0.20-gal) product-volume change will cause a change of only 0.013 cm (0.005 in.) in a partially filled tank, but the same volume addition in an overfilled tank will cause a product-level change of 10 cm (4 in.) in a 10-cm-diameter fill tube if the tank is rigid and contains no trapped vapor.

In the second group are tests which allow the product level in the fill tube to change; these do not maintain a constant hydrostatic pressure, and product volume cannot be interpreted from the product-level measurements unless the deformation characteristics of the tank-backfill-soil system are known.

4.4 Major Features of a Tank Test

A volumetric tank test has several major features that affect the performance of a given method. These features are presented in Figure 4.2. Not all methods include or adequately treat all of the features, and as a result performance is sacrificed. Some manufacturers have operating manuals with detailed instructions on how to conduct a test, but many do not.

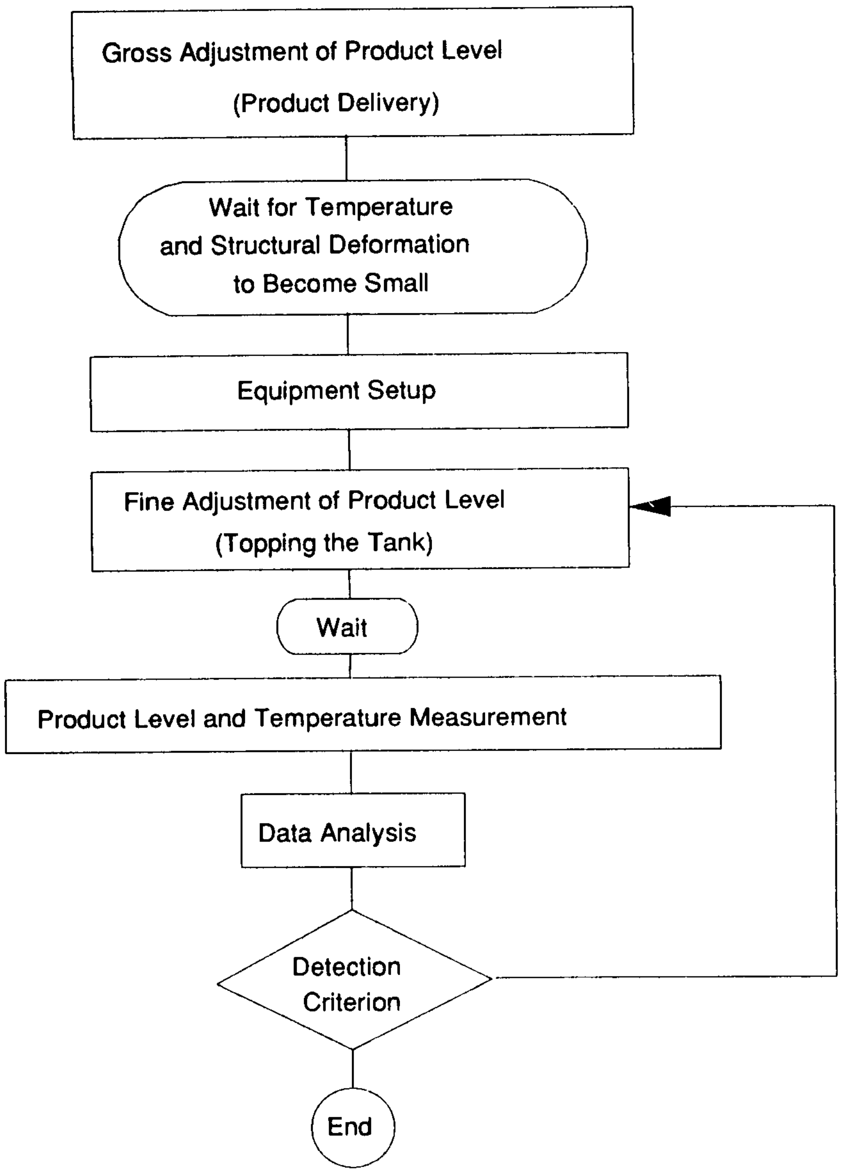


Figure 4.2. Overview of volumetric tank test procedure.

4.4.1 Product Delivery

The majority of volumetric test methods require that the test be conducted at a specified product level. Product is usually added in two steps to attain the required level. The first step is a gross adjustment and usually involves the delivery of a large amount of product to the tank, typically done the night before the test is to be conducted. Thousands of gallons of product may be added to the tank. The final level required for the conduct of a test is almost never attained in this first delivery. This is particularly true of tests that are conducted when the tank is overfilled because the person delivering product to the tank will not usually overfill it. Whether the level specified for a partially-filled-tank test is accurately attained as a result of a delivery depends on the accuracy of the predicted level of the product in the tank at the time the product is delivered, on the accuracy of the tank chart used to calculate the amount of product to be delivered to fill the tank, and on the accuracy of the volume estimate of product actually delivered. The second step is the fine adjustment required to attain the specified test level. This is usually done the next day, immediately before starting the test. The amount of product required to reach the test level may be several tens of liters. Both additions could be done at the time of the delivery if the test crew were present at that time and remained there to fine-tune the product level during the time required for the major temperature changes to dissipate. Such an approach would significantly decrease the time required to perform a test.

The addition of product has two effects on a test. First, the added product is likely to be at a temperature different from the original product in the tank and from the backfill and soil around the tank. This temperature difference results in large temperature changes in the product immediately after the delivery. The horizontal temperature gradients that develop during the period immediately following a delivery are large enough to prevent accurate temperature compensation. Second, the tank will deform as the product level in the tank changes. The product level (which affects the hydrostatic pressure in the tank) could change as much as 2.43 m (8 ft) in a tank 2.43 m in diameter. More typically, the product level will change 1 to 2 m. The structural deformation, which occurs nearly instantaneously in response to the addition of product, may be large (e.g., tens of liters). This deflection (what many people think of when structural deformation is discussed) is not what typically produces testing errors. The errors really result from the time-dependent relaxation of the tank as it tries to reach a geometric equilibrium with the backfill and soil surrounding it.

4.4.2 Waiting Period after Product Delivery

Most test methods, but not all, require a minimum waiting period after the product delivery and before the start of data collection. This waiting period is included in the test protocol to allow the temperature field in the tank to equilibrate and to allow the deformation effects to become small enough to be negligible. In general, most test methods require a waiting period of at least 4 to 6 h.

The performance of the methods presented in this evaluation depends on the manufacturer's observance of the minimum waiting period specified by the test protocol. If this period is too short to begin with, or if it is long enough in the protocol but arbitrarily shortened in the field, the performance of the method will decrease.

4.4.3 Equipment Setup

The time required to set up equipment varies among manufacturers. In general, it takes longer to prepare the tank for an overfilled-tank test than for a partially-filled-tank test because of the time required to completely seal the tank and bleed it of trapped vapor. The criterion for determining whether the tank is free of vapor is at best qualitative, and thus depends on the judgment of the test crew. The manufacturers and test crews with the most training and commercial tank testing experience were more proficient at removing trapped vapor than those crews with less training and experience.

4.4.4 Topping the Tank

The product level must be adjusted to the level required for the test. These adjustments are normally required for the overfilled-tank tests. Usually, the product level in the tank after a delivery is near the top of the tank (e.g., 10 cm), but is not in the fill tube. In comparison to the delivery the night before, only a small amount of product is needed to overfill or top the tank. Once product is at the level of the fill tube, the addition of 4 L (1.1 gal) of product could change the level up to 0.5 m (1.6 ft).

Note that large changes in the hydrostatic pressure occur when product level is being adjusted to the height specified for starting a test. The product-level changes during topping can be larger than those during the delivery process. In addition, the temperature changes following the topping can be as severe as those that follow a delivery. This addition of product disturbs the temperature field in the tank as a whole, as well as in the local area around the temperature measurement system located at the fill hole of the tank.

4.4.5 Waiting Period after Topping the Tank

Many manufacturers of overfilled-tank tests also specify that the test cannot begin immediately after the tank has been topped; this allows the structural deformation and inhomogeneities in the product-temperature field to become negligible and is usually the reason that a protocol may stipulate a waiting period. Those methods in which the tank is partially filled may also require a waiting period when the level is adjusted. Typically, a period no longer than 1 h is required by the tester.

The topping of the tank may be the single most influential factor affecting the performance of the test method. How long it takes to top the tank, as well as the waiting time after topping, is important. The evaluations conducted during this program were in strict accord with the operational protocol of the manufacturer. Because of the complexity of the deformation in an overfilled tank, any changes to the test protocol affect the results of a test. It is particularly important that the waiting time not be any shorter than the minimum specified by the manufacturer's test protocol.

4.4.6 Leak Detection Test

The test consists of collecting and storing the product-level and temperature data for analysis. Additional measurements are sometimes made by the manufacturer to interpret the test data.

4.4.6.1 Data Collection

Most of the manufacturers make a product-level measurement and a temperature measurement. A few of the methods measure change in volume or product mass. The leak detection tests vary from 1 to 12 h, although the data required to compute a leak rate may be as short as 15 min. The actual test duration is sometimes fixed by the test protocol and sometimes dependent on the collected data. The data sampling interval varies from less than 1 s to 12 h. Those manufacturers who do not specify a fixed test time usually terminate the test based on a measurement of the product-level and temperature fluctuations. Some of the criteria in the protocol are physically impossible to meet, while others are so stringent that a test could never be completed in any practical length of time. In these cases, the operator's decision to stop the test is often subjective. Most of the data are collected manually by reading an instrument or making a measurement, and the results are recorded on a data sheet. Some manufacturers have automated the data collection with the use of a computer.

4.4.6.2 Supplementary Measurements

There are two additional measurements commonly made to more accurately analyze the data. First, the majority of methods make a field estimate of the coefficient of thermal expansion of the product by making an API gravity measurement [15]. An average value of the coefficient for the type of product being tested (e.g., gasoline, diesel) is assumed if no measurements are made. Few of the manufacturers make a laboratory estimate of the coefficient. Although the error in estimating the coefficient could be 5 to 10%, this is usually not significant as compared to other errors presently found in the current practice.

Second, some manufacturers attempt to measure the height-to-volume conversion factor directly using a bar of known volume to displace the product level. If no measurement is made, the conversion factor is calculated from an estimate of the exposed product surface. This is done using a tank chart in the case of a partially-filled-tank test, and by measurement of the fill tube, vent, and other openings in the case of an overfilled-tank test.

4.4.7 Data Analysis

All of the manufacturers have well defined procedures for reducing the data, doing temperature compensation, and computing a volume rate. The data reduction may require averaging the data or resampling them at a different rate. In some instances, the temperature data are not sampled at the same rate as the product-level measurements.

Product-level changes are converted to product volume using a height-to-volume conversion factor. Some of the overfilled-tank methods that relevel the product make a direct measurement of the volume added to or removed from the fill tube.

The means for estimating thermal volume changes are more or less common to all methods. The algorithm estimates the mean rate of change of product temperature and converts the temperature change to a volume change. The majority of the manufacturers estimate the volume of the product in the tank from a tank chart, measure or assume a value of the coefficient of thermal expansion, and measure the rate of change of temperature.

The temperature-induced volume changes are then subtracted from the the product volume changes. These temperature-compensated volume fluctuations are then used to estimate the temperature-compensated volume rate. If the tank is leaking, the temperature-compensated volume is equal to the leak rate.

Some manufacturers do not use all of the data in a volume rate analysis. Some algorithms calculate a volume rate by subtracting end-of-test data from start-of-test data, and divide by the time that has elapsed between the two. Other algorithms add the cumulative volume changes to find the total volume change, and then divide by the test duration to get a rate. Finally, some manufacturers use a least-squares estimation approach to determine volume rate.

4.4.8 Detection Criterion

Most manufacturers use a single-threshold criterion for determining whether the tank should be declared leaking. If the temperature-compensated volume rate, when compared to the threshold volume rate, is greater than the threshold, the tank is declared leaking. The most common threshold is 0.19 L/h (0.05 gal/h) [5].

In a few cases, the detection criterion is very complicated and, in some instances, appears to be rather arbitrary. For some test methods, the criterion for declaring a leak is ambiguous when the temperature-compensated volume indicates that (a) the flow is into the tank, and (b) the groundwater table is below the bottom of the tank (or unknown but assumed to be below the bottom of the tank). In some instances the tank is declared tight, even though the threshold is exceeded. At other times, the data collection period is extended so that, in effect, another test is conducted.

In actual practice, the detection criterion may not be observed if the temperature-compensated volume rate is close to but exceeds the threshold, or if an extremely large value is obtained, suggesting that the test was faulty. Many test crews conduct a second test if the first exceeds the threshold by only a small amount; they declare the tank to be tight if the threshold is not exceeded in the second test. This particular multiple testing approach lowers the probability of false alarm but also lowers the probability of detection. If this unplanned retesting approach is repeated several times, the detection performance of a method having a high probability of detection from a single test would be lowered to an unacceptable level. The performance of the method depends on how many tests are conducted, and how the results from each test are used.

4.5 Time Required to Complete a Test

The time required to complete a test was defined as the total time that had elapsed between the arrival of the test crew at the storage facility and the final removal of the equipment from the tank. Delays in setting up the equipment, topping off the tank, and extending a test tend to increase the test time. On the average, the time required to set up the equipment and conduct a leak detection test is approximately 8 h; the time required for product delivery and the waiting period after the delivery will increase this time. This estimate is based on testing experience at the Test Apparatus.

4.6 Test Accuracy

The accuracy of a volumetric precision tank test can be altered significantly if the operator modifies the test procedure.

4.6.1 Performance of the Method

The performance of each method represents the capability of the method to detect a flow rate produced by a leak located somewhere in the tank. The probability of detection and probability of false alarm are determined for each flow rate. The measured flow rate cannot be properly interpreted in terms of potential environmental damage unless the hydrostatic pressure on the leak is known. The estimates made in this evaluation assume that the test crew follows the test procedures exactly as outlined by the manufacturer. If this is not done, the performance will be altered. In some instances, performance may actually improve as a result of delays in setting up and conducting a test. In most cases, the operator can degrade performance. Sometimes the errors are easily identified in a quality control/quality assurance audit, while in other cases, the effects are not known.

4.6.2 Operator Influences

Of the 25 test methods evaluated in the program, 19 involve the use of an operator to conduct a test. Tests with the other six methods are performed automatically once the equipment has been installed. For some methods, the role of the operator is simply to implement a well-structured test protocol. In other instances, the operator is allowed, or even required, to alter the protocol based on his own judgment; this is the more common situation. During the development of the mathematical model for each method, any operator judgments required to start or stop a test, or to interpret the results of the test, were quantified by the manufacturer. In most instances, the manufacturers had a great deal of difficulty doing this, or seeing the need to do it. Without quantitative judgments, however, the test method could not be evaluated.

The operator errors can be divided into four categories:

- improper setup of the test equipment or improper preparation of the tank before the test
- mistakes or carelessness in following the test protocol
- mistakes in recording the data or in performing the analysis
- deliberate changes to the test protocol based on operator judgments about the quality of the data or on real-time operator interpretation of the results

4.6.2.1 Improper Setup

The performance estimates made in this evaluation assume that the tank has been properly prepared for the test and that the equipment is properly set up. While there was difficulty with setting up equipment for some of the newer methods, this was, in general, not a major problem. Only for one of the methods was the crew unable to set up and conduct a test. The crew for another method was able to conduct one test, but did not believe that it was a valid one. Several other crews had instrumentation difficulties, but were able to correct the deficiencies and conduct tests.

Because trapped vapor can be a significant source of error in overfilled-tank tests, satisfactory removal of all trapped vapor is essential for an accurate test (see Section 8.2). It is the operator's responsibility to set up the test equipment without trapping additional vapor, and to properly remove from the tank, before a test is begun, any vapor that was already present. All the manufacturers claim that this can be satisfactorily done. They also claim to be able to recognize the presence of trapped vapor, even though they do not use a quantitative procedure. Tests conducted at the Test Apparatus also suggest that the effects of trapped vapor cannot be differentiated from the instantaneous tank deformation. If the tank did not deform instantaneously, it would be possible to measure the volume of trapped vapor, but since the tank does deform, any estimates of trapped vapor also include deformation effects.

4.6.2.2 Failure to Carefully Follow Test Protocol

The performance estimates assume that the test method is followed exactly. Failing to follow a certain aspect of the test protocol can seriously alter the expected performance of a test. The most common infraction of the protocol is the failure to observe specified waiting periods. The resulting error is subtle, and involves the time history of product-level changes in preparing for a test. Since future product-level changes depend on past ones, delays in testing, or not following the same procedure to add or remove product from the tank, will produce different results. (See Section 6.4). In some instances, the performance may improve as a result of delays in initiating testing.

4.6.2.3 Data Tabulation and Analysis Errors

The performance estimates assume that no errors occur in recording and analyzing the data. Many of the methods require the operator to read and manually record data. The calculations to estimate the temperature-compensated volume rate are often performed manually. Many of the test methods have detailed analysis sheets to help keep the operator from making mistakes.

The majority of the data recording errors and all of the calculational errors can be identified in a post-test data quality review. Whether a thorough data quality and analysis review is performed after the completion of a test is not known.

4.6.2.4 Arbitrary Changes to the Test Protocol Made by the Test Operator

As indicated in Section 4.6.2.2, any change to the test protocol will affect the performance of the method. While the operator should be required to make certain judgments (for example, whether the equipment is properly installed), any arbitrary judgments concerning the quality of the data as they are being collected, any changes in the length of the waiting periods, or any changes in the detection criterion should be avoided. These operator judgments are usually made because something about the test does not look right. However, in a validated system, these so-called problems have already been included in the performance estimate. If the problems are important to solve, the procedure should be included in the protocol and quantified as part of the validation. If not, the performance of the method will be affected, usually in an unknown way.

4.7 Groundwater Level Affects the Magnitude of the Leak Rate

The performance of a test method is based simply on the ability of the method to measure the flow rate that occurs during a test. Flow through the hole in the tank, whether this hole is large or small, can, under different hydrostatic pressures, represent a larger or smaller leak rate than that measured during the test. Interpretation of the environmental effects of a leak in the tank (i.e., the loss of product from the tank) requires more information than is known at the time of the test. The magnitude of the flow rate produced by a leak or hole in the tank is discussed below.

The relationship between the leak rate and the hydrostatic pressure is not well known. We could assume that the leak rate, LR, from a hole in the tank can be computed using the following relationship developed for flow from a free orifice:

$$LR = K_1 A_{LR} (2 g \Delta h)^{1/2} \tag{4.3}$$

where K_1 is a flow coefficient, A_{LR} is the cross-sectional area of the hole, g is the acceleration due to gravity, and Δh is the hydrostatic pressure head. The flow rate varies as the square root of the hydrostatic pressure head. This relationship is valid if the leak is large and the backfill does not inhibit flow through the hole in the tank. For small leaks or in cases when the flow is not free, as when improper backfill containing clay restricts the flow, a linear relationship might best describe the flow rate. In this case, the flow rate can be estimated by

$$LR = K_2 A_{LR} g \Delta h \tag{4.4}$$

where K_2 is a flow coefficient. Both relationships are probably valid for some tests. The actual flow rate will depend on the magnitude of the measured constant. However, no experimental evidence exists to validate either relationship. A 50% change in hydrostatic head will result in a flow rate that is 70% of the original flow rate for the free-orifice model, and 50% for the linear model. Regardless, the larger the hydrostatic pressure, the larger the leak rate.

The hydrostatic pressure, Δh, (i.e., the relative internal and external pressure at the location of the hole) has to be known in order to correctly interpret the flow rate measured during a test. Since the location of the leak is not typically known during an actual test, a quantitative estimate of Δh cannot be made. The test result that is simplest to interpret occurs when the groundwater level is below the bottom of the tank. If the tank has a leak, the flow rate measured during a test will at least be representative of the hydrostatic pressure exerted by the product; the flow rate measured at a lower product level will be less. This is not true if the groundwater level is above the bottom of the tank. It is also possible for the hydrostatic pressure exerted by the product inside the tank to equal the hydrostatic pressure exerted by the groundwater table outside the tank, producing a no-flow condition at the hole. This can occur because there is a density difference between the two fluids, even though the product and groundwater table are at different levels relative to the hole. For gasoline fuels, the no-flow condition occurs when the ratio of the groundwater level to product level is approximately 0.7, the ratio of the specific gravity or density of the two fluids. If the hydrostatic pressure inside the tank is greater than that outside the tank, product will flow out. Conversely, if the hydrostatic pressure is greater outside the tank, then water will flow into the tank. Thus, the magnitude of the measured leak rate during any one test might not be a good indication of the actual size of the hole in the tank or of the total loss of product that might occur during normal operations.

The underground storage tank geometry presented in Figure 4.3 can be used to derive the hydrostatic pressure exerted on a hole in the tank and to interpret the results of a test on a leaking tank. The hydrostatic pressure will depend on whether the hole is located above or below the product level, or above or below the groundwater level. When the hole is below the product level and groundwater level (Figures 4.3(a) and 4.3(b)), the hydrostatic pressure, expressed in terms of the product in the tank, is described by the following relationship:

$$\Delta h = h_{PL} - h'_{GWL} = h_{PL} - (h_{GWL} / S_{PL}) \tag{4.5}$$

where S_{PL} and S_{GWL} are the specific gravities of the product and the water, respectively, where h_{PL} and h_{GWL} are the levels of the product and groundwater, respectively, and $h'_{GWL} = h_{GWL}/S_{PL}$ is the equivalent pressure that is exerted by the groundwater in terms of product head when S_{GWL} is assumed to be 1.0. When $h'_{GWL} > h_{PL}$, the direction of the flow is into the tank, and when $h_{PL} > h'_{GWL}$, the direction of the flow is out of the tank. A no-flow condition exists when $h'_{GWL} = h_{PL}$. When the groundwater level is below the hole (Figure 4.3(c)), the hydrostatic pressure, expressed in terms of the product in the tank, is described by

$$\Delta h = h_{PL} - h_L \tag{4.6}$$

Finally, when the groundwater is above the hole and the product level is below it (Figure 4.3 (d)), the hydrostatic pressure, expressed in terms of the groundwater, is described by

$$\Delta h = h_{GWL} - h_L \tag{4.7}$$

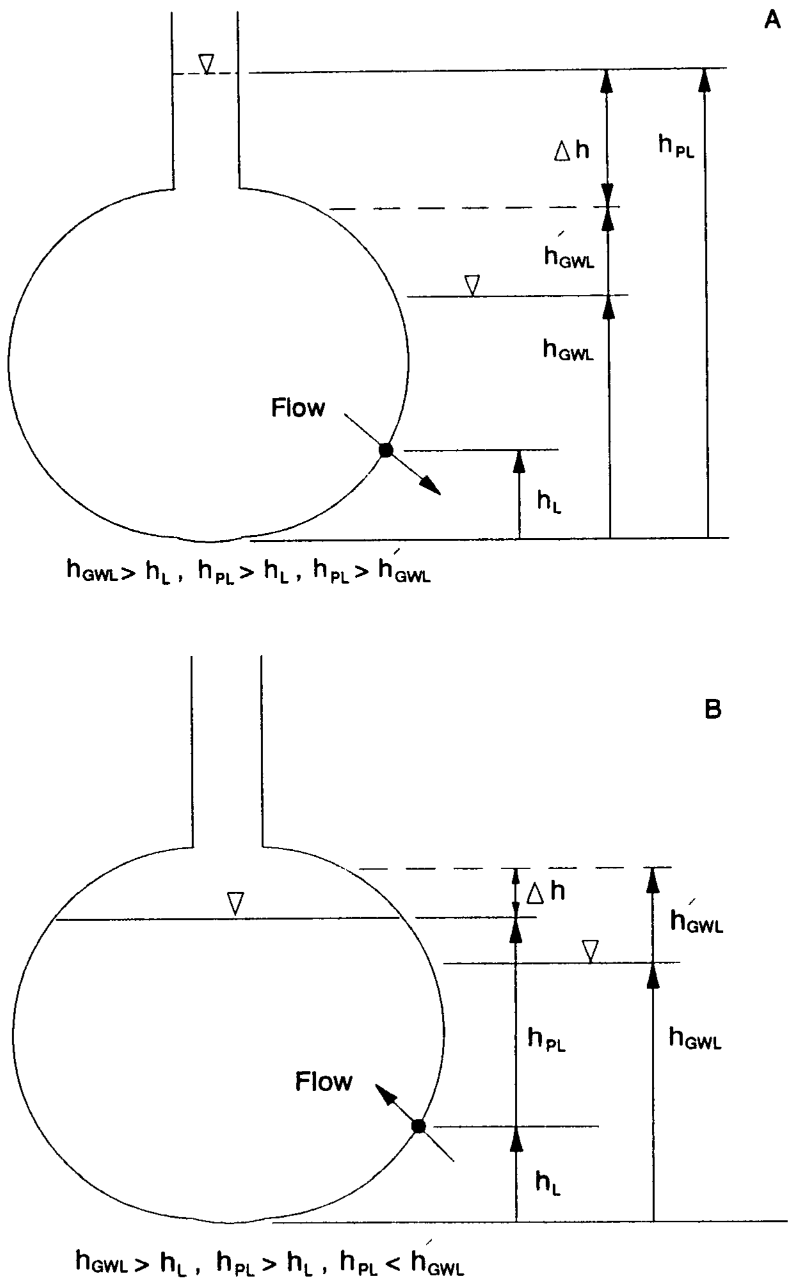


Figure 4.3. UST geometry showing hydrostatic-pressure relationships when (A, B) hole is below product and groundwater levels, (C) hole is above groundwater level and below product level, and (D) hole is above product level and below groundwater level.

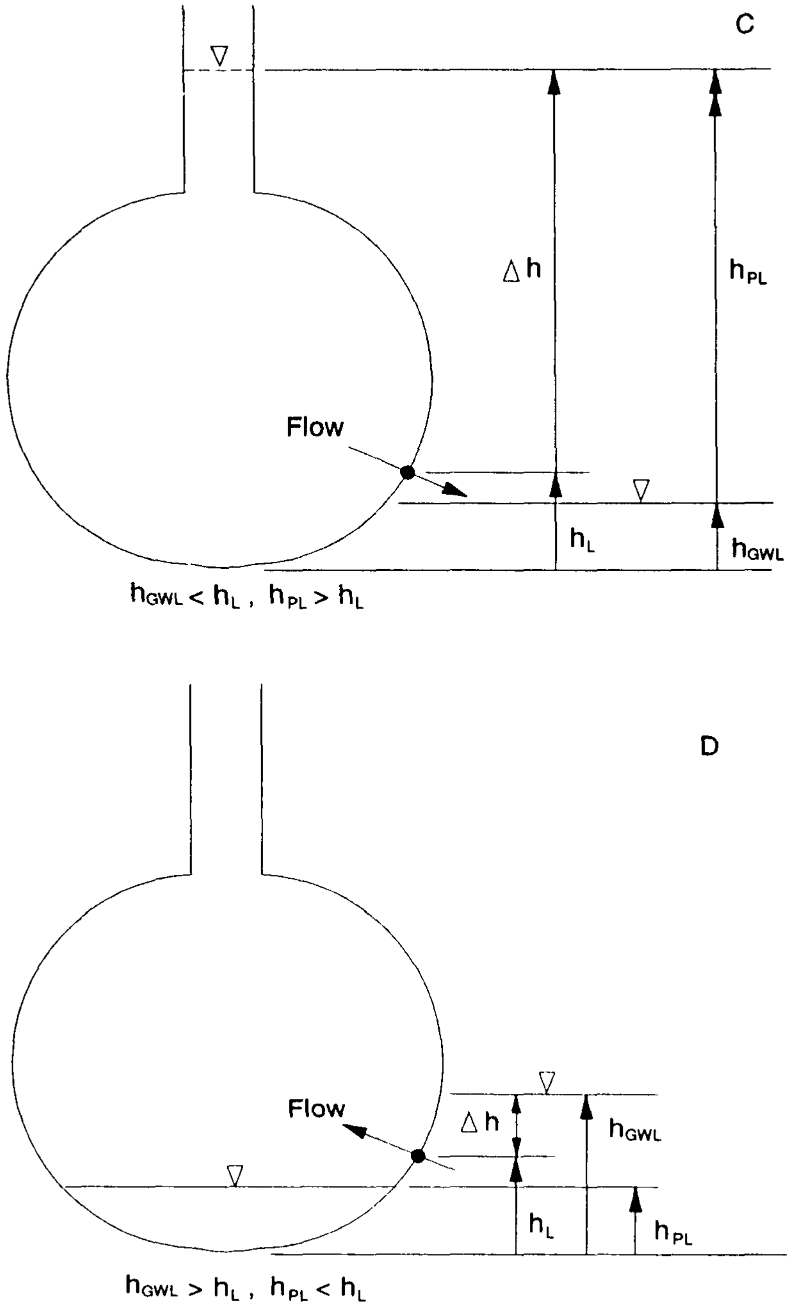


Figure 4.3 (concluded). UST geometry showing hydrostatic-pressure relationships when (A, B) hole is below product and groundwater levels, (C) hole is above groundwater level and below product level, and (D) hole is above product level and below groundwater level.

As a consequence, the performance of each test method is specified relative to the product level required to perform the test, and all flow rate measurements are referenced to this level. This approach yields a quantitative estimate of the method's ability to detect the flow rate. If the flow rate produced by the hydrostatic pressure is small, the leak may not be detected, even though the hole may be large.

Some methods attempt to conduct a test at two product levels, but this approach is not successful unless a large change in the hydrostatic pressure is induced. A 10% change in product level will produce a change in the flow rate of only 5 to 10%; in some cases, the flow rate will change by less than half of these percentages. In general, two-level tests have the disadvantage of either being long or being susceptible to other errors. The flow rate as measured by a test can not be easily interpreted in terms of the amount of product that could be lost to the environment, since it is impossible to predict the hydrostatic pressure on the hole in the tank unless the product level, groundwater table and hole location are known, as well as the relationship between leak rate and hydrostatic pressure.

Consideration was given to the idea of normalizing the results of each method to a standard product level so that the results of different methods could be compared directly. This idea was rejected because of the uncertainty in estimating the hydrostatic pressure exerted on the hole during an actual leak detection test and the relationship required to perform the normalization. Two methods with the same performance that are tested at different product levels can be subject to different flow rates from the same hole. Which method will work better depends on the hydrostatic pressure on the hole. In general, the high-product-level tests have larger flow rates than the low-level tests if the groundwater level is below the tank, or if the hole is below both the groundwater and product levels. As indicated before, the latter cannot be determined during a test because the location of the hole is generally unknown. If both the groundwater level and product level are above the hole, it is also possible that the hydrostatic pressure produced by a low-product-level test can be higher than that of a high-level test.

5 Performance of a Test Method

Detection of leaks in underground storage tank systems is an example of the classical statistical problem of finding a signal in a background of noise. In storage tank testing, the signal is the product-level or product-volume changes produced by a leak, and the noise is the sum of the product-level changes produced by the measurement system itself, by the environment, and by the operational practice. In a properly designed system, the noise introduced by the measurement system and the operational practices should be small compared to the environmental or ambient noise. The measurement system noise is easily controlled and should be designed to be smaller by at least a factor of 5 than the minimum signal to be detected. For some methods, the operational practice may significantly affect the magnitude of the ambient noise field. The impact of the operational practice can be minimized by proper test design.

The solution to the leak detection problem is straightforward and is accepted by the scientific and engineering communities. The same method used to evaluate the performance of a radar or sonar system, for example, can be (and is here) used to evaluate the performance of a leak detection system for an underground storage tank. Numerous descriptions of the statistical models used to analyze the data can be found in the scientific literature [e.g., 16-18]. Application of these models to underground storage tank leak detection systems was first described in [19, 20].

The performance of a test method is presented in terms of its probability of false alarm, or P_{FA} (the probability that a test will result in the declaration of a leak when the tank is tight), and its probability of detection, or P_D (the probability that a test will result in the declaration of a leak when the tank is indeed leaking), for a prescribed leak rate, LR.

The dominant sources of environmental or ambient noise are:

- *product temperature* (changes in product volume produced by temperature changes in the product)
- *vapor pockets* (changes in the volume of trapped vapor produced by temperature changes in that vapor due in turn to atmospheric and hydrostatic pressure changes, and by evaporation and condensation within the trapped vapor)
- *evaporation and condensation* (changes in product volume produced by evaporation from the product surface and condensation from the tank walls, and manifested as losses or gains of product)
- *structural deformation* (changes in the volume of the tank produced by changes in hydrostatic pressure on the tank prior to and/or during testing, e.g., product-level changes)

- *surface waves* (periodic product-level fluctuations that are unrelated to volume changes)
- *internal waves* (periodic subsurface temperature and/or product-level fluctuations that are unrelated to volume changes)

The first four sources of noise have temporal characteristics similar to those of the signal (i.e., linear changes). However, they may also have temporal fluctuations on scales different from those of the signal. Unless the tests are short, the temporal fluctuations of the surface and internal waves generally can be removed by appropriately sampling and filtering the data.

The ability to detect a signal is limited by that portion of the noise energy with the same characteristics as the signal (i.e., that portion which could be confused with the signal). For tank leaks, the signal in its simplest form is assumed to be a linear change of product level or product volume with time. The essential noise, therefore, is that which also leads to a linear change of volume with time. The portion of the noise that does not exhibit a linear change with time can be removed by averaging the data appropriately. A linear least-squares fit of volume as a function of time is one such method. The measurement made during a test may be either noise or the signal-plus-noise; unfortunately, it is not possible to separate the signal from the noise in a volume measurement alone, although measurements of other quantities may provide a separation.

Detection is usually accomplished by selecting a threshold level at the output of the measurement system. When the output exceeds the threshold, a signal is presumed to be present. The four possible outcomes of a leak detection test are presented in Table 5.1, where the test declaration is given on the vertical axis and the actual state of the tank is given on the horizontal

Table 5.1. Possible Outcomes of a Leak Detection Test

Measured Conditions	**Actual Conditions**	
	Leak	No Leak
Leak	Correct Declaration *(Leak)*	Incorrect Declaration *(False Alarm)*
No Leak	Incorrect Declaration *(Missed Detection)*	Correct Declaration *(Tight)*

axis. The two correct declarations are that the tank is accurately declared to be leaking or nonleaking. The two incorrect declarations are that a tight tank is declared to be leaking (i.e., a false alarm) and that a leaking tank is declared to be tight (i.e., a missed detection). For illustration, a measurement system's output for many tank tests is shown in Figure 5.1. The output fluctuates because of the random nature of the noise. If the signal (i.e., the leak) is much larger than the threshold, as it is for Tank C, it is not difficult to decide that the signal is present. But consider the measurements for Tanks A and B, which are leaking at the same rate. The noise fluctuation at A is large enough that the combination of signal-plus-noise exceeds the threshold. At B, the noise fluctuation is negative, and the resultant signal-plus-noise does not exceed the threshold. Thus, the presence of noise can sometimes enhance the detection of weak signals, but it may also cause the loss of a signal that would otherwise be detected, i.e., a missed detection.

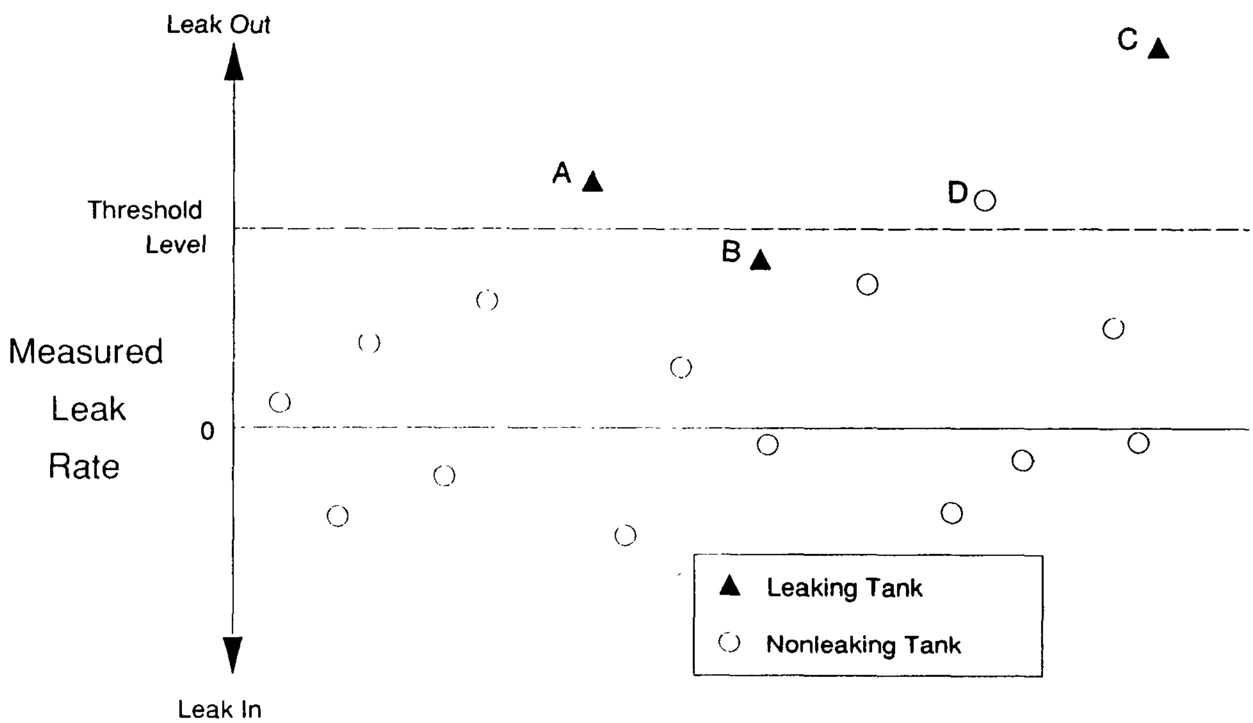


Figure 5.1. Typical measurement output for a sequence of tank tests. A and B are tanks leaking at the threshold rate. A is declared leaking and B is declared nonleaking. Tank C is leaking at a rate well above the threshold level, so there is no ambiguity in declaring it leaking. The open dots represent nonleaking tanks; one of them (D) has a noise fluctuation exceeding the threshold, producing a false alarm.

5.1 Signal

The signal is the rate of change of product level or product volume produced by a leak. The flow rate produced by a leak is assumed to be a constant (i.e., to be a linear change in volume with time) during the tests. For tests conducted at a constant hydrostatic pressure, the signal will be equal to the leak rate. Tests in partially filled tanks, or tests in overfilled tanks in which the product level is kept at a constant level by adding or removing a measured volume, are examples of constant-head tests. However, as is shown in Section 6.4.4, it is *not* true that the signal is equal to the leak rate if the product level is allowed to fluctuate during a test. Tests conducted in a tank overfilled into the fill tube or an above-grade standpipe, in which the product level changes, are examples of tests conducted under variable hydrostatic pressure. For these tests, the signal will be only a fraction, k, of the actual product level or product volume expected to be produced by a given leak rate. For constant-head tests the measured leak rate, LR, is equal to the actual leak rate, LR_{actual}. For variable-head tests, $LR = k\ LR_{actual}$. The volume changes caused by noise will be similarly affected, such that $VR = k\ VR_{actual}$, where VR_{actual} is a volume rate due to any noise source.

The specification of the weakest detectable signal is sometimes difficult because the criterion for deciding whether or not the signal is present (i.e., the threshold) may be hard to define. For example, weak signals, such as at B, would not be lost if the threshold were lower. However, too low a threshold increases the likelihood that a noise fluctuation alone will rise above the threshold and be mistaken for a real signal, such as the noise fluctuation at D, a false alarm. Conversely, too high a threshold means that signals might be missed. The selection of the proper threshold level is a compromise that depends on the relative importance of avoiding missed detections as opposed to the importance of avoiding false alarms.

5.2 Noise Histogram

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 performance analysis requires that the test sample consist of random, independent events. If there are no systematic errors in the measurement, the mean will not be statistically different from zero, and the *standard deviation* will reflect the uncertainty of the test method. It is usually assumed that the data are stationary (i.e., that the histogram of the noise does not change with time) and 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 more complicated.

The noise histogram can be described empirically or by a probability density function (pdf), both of which describe the fraction of the total number of occurrences of an event that appear in a defined interval. The likelihood of exceeding a specified noise level is described by the integral of the pdf (i.e., the area under the curve beyond the specified noise level[1]). Thus, if the area beyond some noise level is 0.25, for example, the probability of exceeding that noise level is 25%.

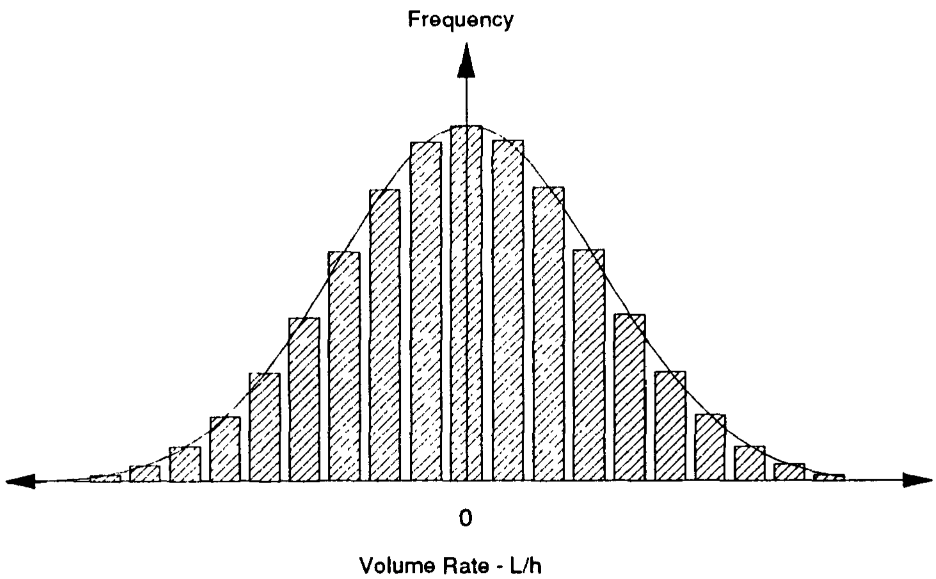


Figure 5.2. Normal probability model overlaid on noise histogram for a test method with a zero mean.

If the test method has no systematic errors, the mean of the histogram of the noise will not be statistically different from zero. This is illustrated in Figure 5.2, where it is assumed that the histogram follows a normal probability model. The probability of false alarm is determined from the noise histogram once the threshold leak rate has been selected. The P_{FA} is the portion of time that a noise fluctuation will exceed the threshold. This is computed as the area under the histogram beyond the threshold (Th), and is represented by the hatched area under the normal pdf shown in Figure 5.3. Mathematically, the probability of false alarm, also known as a false positive or a Type I error, is defined by

1. The entire area under the pdf is defined as unity.

$$P_{FA} = \int_{Th}^{\infty} f(x)\,dx \qquad (5.1)$$

For a given method's noise histogram, the threshold and P_{FA} are directly related. Once the threshold has been selected, the P_{FA} is automatically defined, and vice versa.

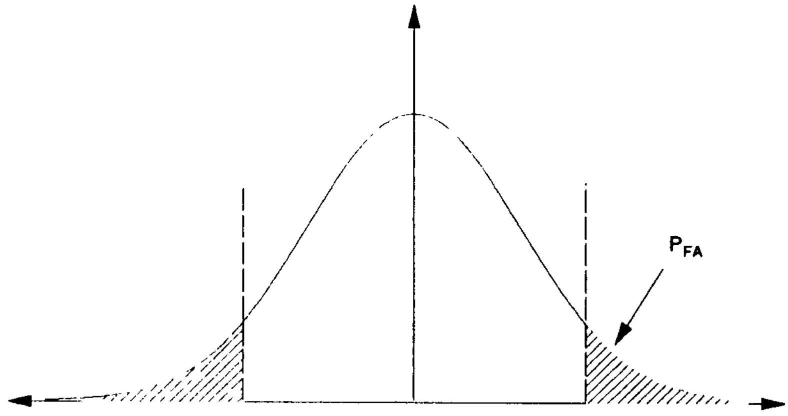


Figure 5.3. The probability of false alarm. The P_{FA} is the fractional time that a noise fluctuation will exceed the threshold (Th).

If the test method has a bias (i.e., if it is controlled by systematic errors), the histogram has a mean displacement, as shown in Figure 5.4. If the bias is large, it will generally control the performance of the method. A bias will result, for example, if a tank test is routinely conducted immediately after raising the level in the tank, fill tube, or standpipe without waiting for the product-volume changes produced by structural deformation to become small. This is particularly true if the time constant of the tank is several hours. In this case, the noise histogram will be shifted to negative volume rates (i.e., flow out of the tank). While the reason for the bias is known, it is difficult to quantify it because of the large number of tank combinations, backfill materials, and *in situ* soil conditions. If the bias cannot be quantified, the histogram may not be representative of the noise, and an accurate estimate of performance cannot be made. Many of the test methods evaluated in this study have a bias.

The effect of deformation on the overfilled-tank tests is illustrated in Figure 5.5. If no deformation were occurring, the histogram would be centered around 0. The bias is produced when the measurement is made during the steepest portion of the product-level fluctuations produced by the deformation (rather than later, after they have flattened out).

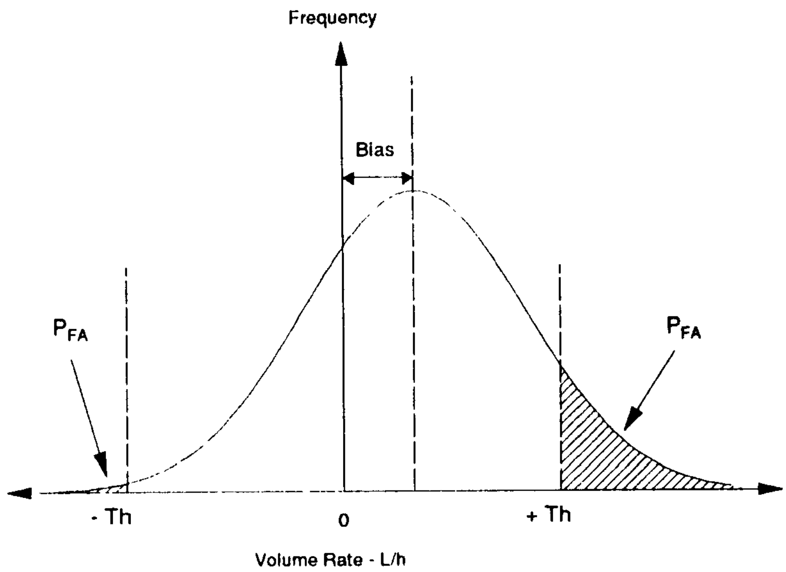


Figure 5.4. Noise histogram with a positive bias. The P_{FA} for a positive threshold (+Th) is larger than for a negative threshold (-Th).

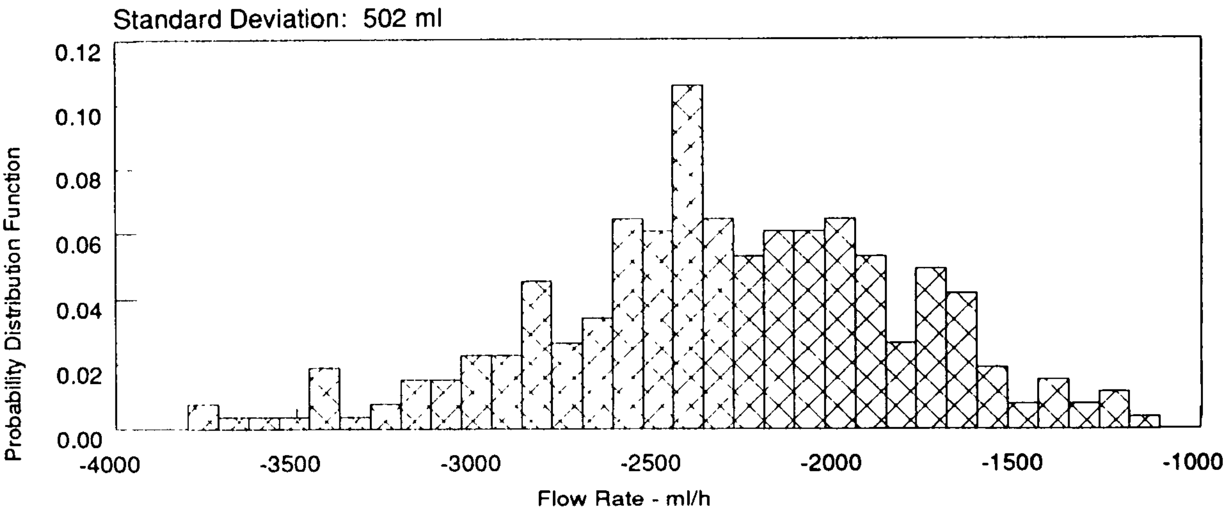


Figure 5.5. Illustration of the histogram of the bias produced by deformation-induced volume changes. The changes were produced during an overfilled-tank test and with no waiting period.

5.2.1 Overfilled-Tank Tests With Releveling/Partially-Filled-Tank Tests

In tests conducted with a constant hydrostatic pressure, the histogram of the noise is different from the histogram generated from variable-head tests, even though the product temperature and tank conditions are identical. In constant-head tests, the measured noise histogram, compiled from the temperature-compensated volume rates on one or more nonleaking tanks, is a good estimate of the actual noise histogram. This is not true if a test is conducted with a variable head in a tank that is subject to deformation.

5.2.2 Overfilled-Tank Tests with Variable Hydrostatic Pressure

In variable-head tests, the measured volume rate, VR, is only a fraction, k, of the actual volume rate, VR_{actual}. Thus, $VR = k\, VR_{actual}$, where $k = 1$ for constant-head tests and $0 \leq k < 1$ for variable-head tests. The mean and the standard deviation of noise histograms, compiled from the temperature-compensated volume rate for a nonleaking tank or tanks, are different for variable-head tests than for constant-head tests. The accuracy in measuring volume changes in a variable-head test depends on the deformation characteristics of the tank-backfill-soil system; these are described in Section 6.4.4.

The effect on the noise histogram, as well as the signal-plus-noise histogram, is illustrated below, assuming that (1) the characteristics of the noise histogram are described by its mean and standard deviation, and (2) only two sources of noise are present: thermal expansion and contraction of the product and one other source of noise. This mean rate of change of volume is defined by

$$\overline{VR} = k\,\overline{VR}_{actual} = k(\overline{TVR} + \overline{AVR}) \qquad (5.2)$$

where a bar over a quantity indicates a mean, where TVR is the rate of change of volume produced by thermal expansion or contraction of the product, and where AVR is the rate of change of volume produced by any other (or all other) source(s) of noise. The standard deviation, S, is given by

$$S_{VR} = \sqrt{S^2_{TVR} + S^2_{AVR}} \qquad (5.3)$$

where S_{TVR} and S_{AVR} are the standard deviations of the thermally induced volume changes and of other noise sources, respectively. The histogram of the thermally induced volume changes (estimated from temperature measurements) and of the measured volume changes, assuming that thermal changes are the only source of noise, is shown in Figure 5.6.

The histogram of the thermal changes (i.e., TVR) was simulated by assuming a normal distribution with $\overline{TVR} = 0$ and $S_{TVR} = 850$ ml/h, similar to the empirical histogram used in the performance estimates of the commercial methods. The mean of both histograms is zero since the mean of the TVR histogram is zero.

In principle, temperature compensation should reduce the standard deviation of the measured VR noise histogram and not change the mean. The mean and standard deviation of the temperature-compensated volume rate, TCVR, are given by

$$\overline{TCVR} = \overline{VR} - \overline{TVR} = (k-1)\overline{TVR} + k\,\overline{AVR} \qquad (5.4)$$

and

$$S_{TCVR} = \sqrt{S_{TVR}^2 + S_{AVR}^2} - S_{TVR} \qquad (5.5)$$

For constant-head tests, k = 1, and $S_{TCVR} = S_{AVR}$, but this is not true when deformation is important and k < 1. The temperature-compensated volume rate histogram for k = 0.6, assuming no other sources of noise, is shown in Figure 5.6.

5.3 Signal-Plus-Noise Histogram

In an actual test, the signal cannot be measured independently of the noise.

5.3.1 Overfilled-Tank Tests with Releveling/Partially-Filled-Tank Tests

For tests conducted with a constant hydrostatic pressure, the signal is assumed to be equal to the leak rate, and to be constant, independent, and additive with the noise. For a deterministic signal, the standard deviation of the signal-plus-noise is equal to the standard deviation of the noise. As a consequence, the performance can be estimated without making detailed measurements of the signal-plus-noise. The signal-plus-noise histogram has the same shape as the histogram of the noise but is displaced by the leak rate (e.g., Figure 5.7).

The magnitude of the leak signal is a function of the hydrostatic pressure on the hole (see Section 4). The level of the groundwater affects the size of the signal, but unless this level changes during the test, the noise is not affected. Changes in the groundwater level might be a problem during a heavy rainfall just before or during a test in a highly permeable soil or close to sea level near a tidal shore. However, during overfilled-tank tests in which the product level is not kept approximately constant, and the deformation is large, the groundwater level may indeed affect the size of the noise field as well.

5.3.2 Overfilled-Tank Tests with Variable Pressure

If a test is conducted with a variable head, the signal-plus-noise histogram must account for the deformation-induced changes. The volume change due to a constant leak rate affects only the histogram means derived in the analysis in Section 5.2.2. Eqs. (5.2) and (5.4), with a leak rate, LR, included, become

$$\overline{VR} = k(\overline{LR} + \overline{TVR} + \overline{AVR}) \qquad (5.6)$$

$$\overline{TCVR} = k\,LR + (k-1)\overline{TVR} + k\,\overline{AVR} \qquad (5.7)$$

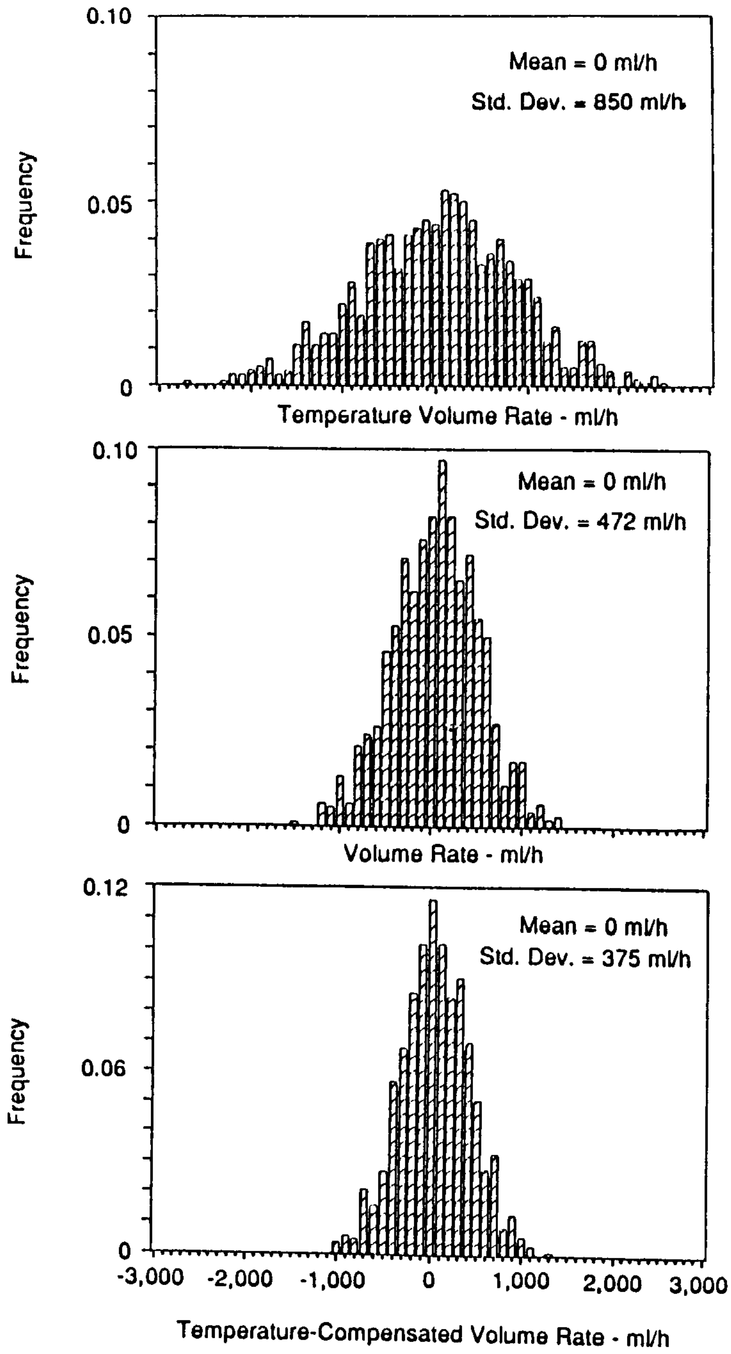


Figure 5.6. (A) TVR histogram estimated from product temperature measurements (the same for k = 1); (B) VR histogram for k = 0.6 without temperature compensation; and (C) VR histogram for k = 0.6 with temperature compensation. It is assumed that the only source of noise is the thermal expansion and contraction of the product, and that the mean of the thermal fluctuations is zero.

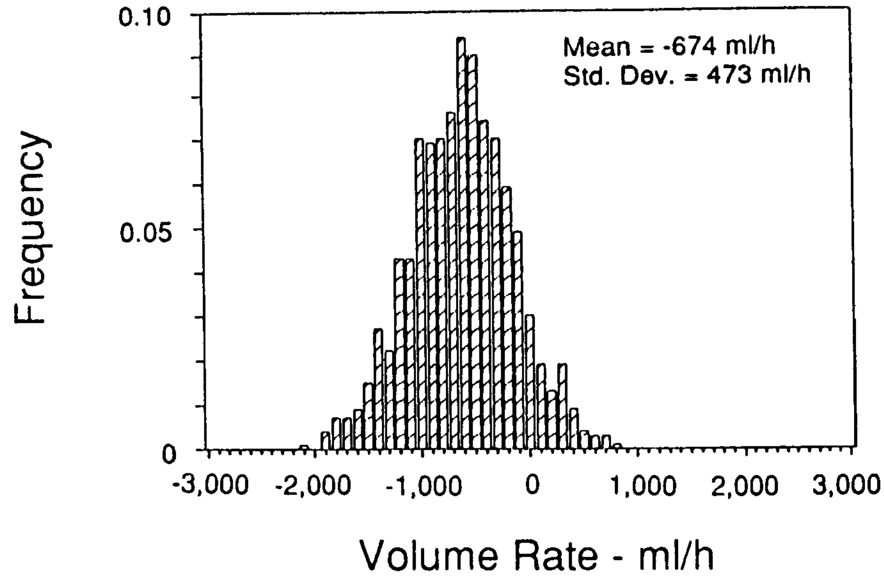


Figure 5.7. Comparison of the signal-plus-noise histogram for a -1.2-L/h leak rate and the noise histogram under the same product temperature conditions after temperature compensation. It is assumed that the only source of noise is thermal expansion or contraction of the product.

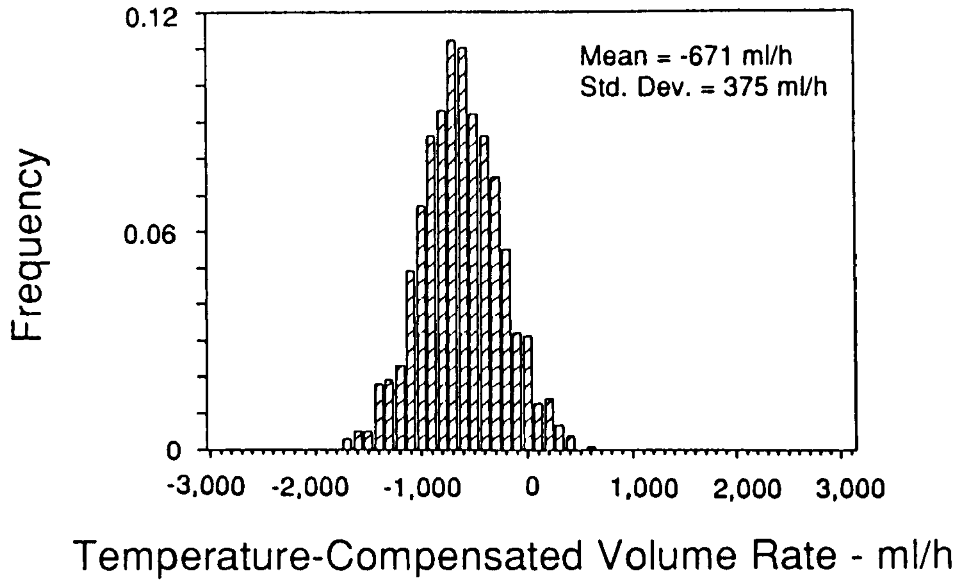


Figure 5.8. Comparison of the signal-plus-noise histogram for a -1.2-L/h leak rate and the noise histogram under the same product temperature conditions before temperature compensation. It is assumed that the only source of noise is thermal expansion or contraction of the product.

An example of the signal-plus-noise histogram for a -1.2-L/h leak with k = 0.6 (variable-head test), assuming the entire contribution to the noise is from thermally induced product-volume changes, is presented, before and after thermal compensation, in Figures 5.7 and 5.8. If the noise has a nonzero mean, the mean of the signal-plus-noise histograms will be different before and after temperature compensation.

For comparison, the histogram of the signal-plus-noise with k = 1.0 (constant-headtest) after temperature compensation would be identical to the leak rate (i.e., TCVR = LR and $S_{TCVR} = 0$). Before temperature compensation, TCVR = LR and $S_{TCVR} = S_{TVR}$.

5.4 Performance Model

The performance of a volumetric test method is determined from the histograms of the signal-plus-noise and the noise. For tests conducted under a constant hydrostatic pressure (e.g., partially-filled tank tests, or overfilled-tank tests which relevel), performance is estimated from the model shown in Figure 5.9. This model assumes that the data are stationary and spatially homogeneous, that the noise histogram has a zero mean, and that the signal is constant, equal to the leak rate, independent and additive with the noise. This model applies to all volumetric tests, providing that the systematic errors are small.

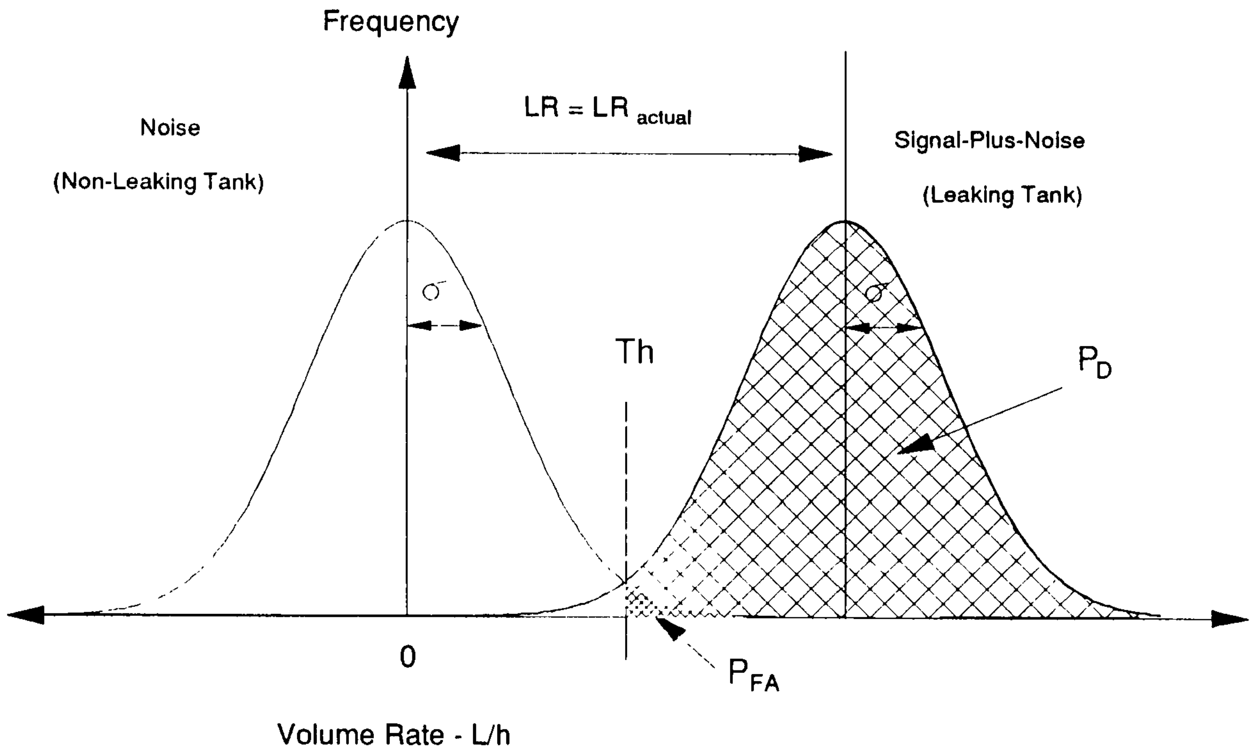


Figure 5.9. Statistical model to estimate the accuracy of a constant-head leak detection system.

Figure 5.9 shows the P_D, P_{FA}, Th, and the leak rate, LR, for the constant-head test (k = 1). Once Th has been selected, the P_{FA} is determined. The P_D is defined as the fractional time the signal-plus-noise fluctuation will exceed the threshold, and is represented by the hatched area. Clearly, if the threshold does not change, the P_D will be higher for larger leak rates. For tests conducted in an overfilled tank in which the product level fluctuates during the test, performance is estimated from the model shown in Figure 5.10. In this case, the leak rate determined by the signal-plus-noise histogram is not equal to the actual leak rate and the temperature-compensated noise histogram has a larger spread than it does for a constant-head test. As discussed in Sections 5.2.2 and 5.3.2, the noise and signal-plus-noise histograms, after temperature compensation, are impacted by the structural deformation of the tank. Since the noise histogram derived after temperature compensation has a larger standard deviation for variable-head tests (k < 1) than for constant-head tests (k = 1), the P_D will decrease and the P_{FA} will increase in comparison.

It is important to understand that the P_D, P_{FA}, Th, and LR are all interrelated; changing one parameter affects the value of one or more of the other parameters. If any two parameters are known, the others are fixed by the model. The choice of parameters affects the conclusions to be drawn from leak detection tests (i.e., the reliability of the test result). For a given leak, LR, choosing a high threshold, Th, gives an extremely small P_{FA} but results in a reduced P_D (i.e., the number of false declarations will be small, but the number of missed leaking tanks will be large). A low value for Th yields extremely large values for both the P_D, and P_{FA} (i.e., the number of leaking tanks detected will be large, but the number of false declarations will also be large). The benefits and costs associated with reducing the number of missed detections and false alarms can be balanced by judicious selection of the threshold.

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 (e.g., Figure 5.9). The smaller the standard deviation, the better the performance. The performance can be directly calculated from the standard deviation if (1) the noise is stationary, spatially homogeneous, and normally distributed with a zero mean, and (2) the signal is constant, equal to the leak rate, independent, and additive with the noise. For such conditions, the leak rate that can be detected with a $P_D = 0.99$ and a $P_{FA} = 0.01$ is 4.67 times the standard deviation. The threshold, established by the selection of a $P_{FA} = 0.01$, is 2.33 times the standard deviation. In this particular instance, the threshold is one half the leak rate because the P_{FA} plus the P_D is equal to 1. (However, this is not true in general.) Thus, a standard deviation of 0.163 L/h (0.043 gal/h) will result in the detection of a 0.76-L/h

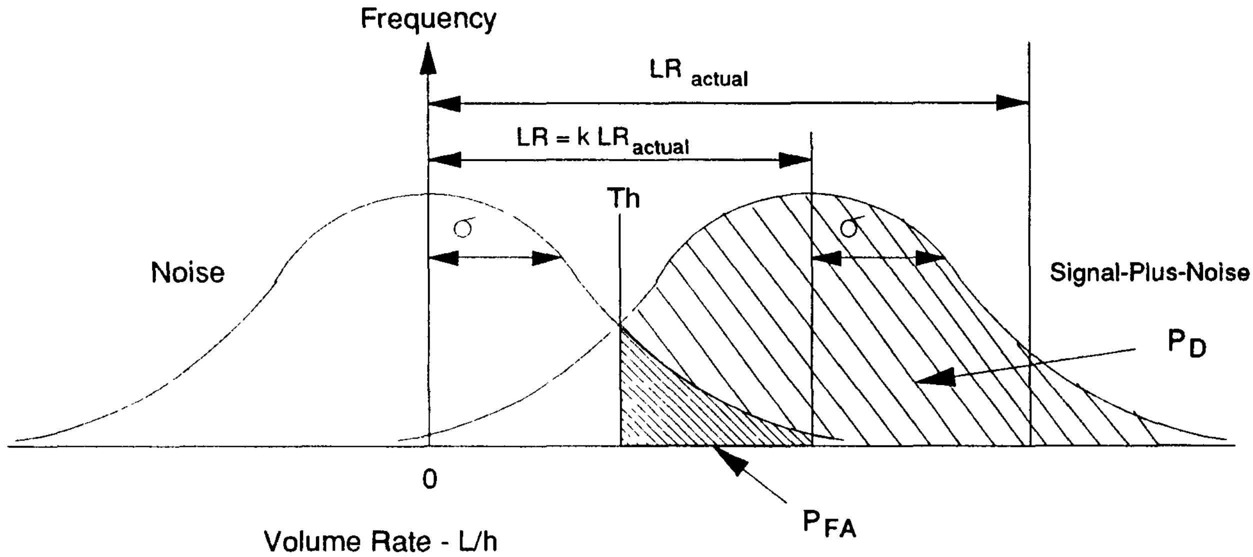


Figure 5.10. Statistical model to estimate the performance of a variable-head test. The same conditions apply for this model as for the constant-head model in Figure 5.9.

(0.20-gal/h) leak rate with a $P_D = 0.99$ and a $P_{FA} = 0.01$ for a threshold of $\pm$ 0.38 L/h (0.10 gal/h). The P_D is greater than 0.99 for leak rates of more than 0.76 L/h and smaller than 0.99 for leak rates less than 0.76 L/h.

In most of the methods evaluated here, the threshold has been set so as to be equal either to (1) the smallest leak rate detectable by the system or (2) the leak rate specified by regulatory policy or industrial practice. When the threshold is equal to the leak rate (common practice in the industry), the probability that a leak will be detected is only 50%. Typically, the methods evaluated here claim a high performance against leak rates of 0.19 L/h (0.05 gal/h), and yet they use a 0.19-L/h threshold to declare a leak. The threshold would have to be set to a value less than the minimum detectable leak rate in order for the probability of detection to be better than 50%.

Measurements of the ambient noise associated with underground storage tanks show fluctuations much larger than the smallest leaks to be detected (i.e., less than 0.76 L/h (0.20 gal/h)). In order to achieve satisfactory detection performance, the ambient noise fluctuation must be substantially reduced. The two approaches to noise reduction are (1) incoherent averaging, and (2) coherent cancellation or compensation. The goal of both approaches is to reduce the mean and standard deviation of the noise to zero.

Incoherent averaging reduces noise only if successive measurements contain substantially different noise fluctuations. The need to make many measurements spaced many hours apart makes incoherent averaging impractical as an approach to noise reduction.

Coherent noise cancellation can be effective and efficient, but its use requires an understanding (i.e., models) of the principal sources of noise as well as measurements of these sources of noise. In this process, the auxiliary measurements of the noise source are input to the model to predict volume changes which can then be removed from the measured volume change. The use of temperature sensors to estimate the thermal expansion or contraction of the product volume is an example of such a measurement. If the model is not known accurately, the procedure can be made data-adaptive, with the data themselves determining how the auxiliary measurements are to be manipulated before removal. However, this must be done with great care lest the data-adaptive procedure remove the signal along with the noise. Coherent noise cancellation, whether predictive or data-adaptive, can be accomplished readily with real-time algorithms and microprocessor hardware. Both the accuracy and adequacy of the noise-source measurements determine the effectiveness of the process; very large noise reductions are possible.

5.5 Multiple-Test Strategy

A properly designed multiple-test strategy can improve the performance of a volumetric test method in terms of P_D, P_{FA}, or both, over the performance obtained for a single test. The actual improvement depends on how many tests are conducted, how the data are analyzed, and whether the tests are independent. In the methods evaluated in this study, two types of analysis were used to implement a multiple-test strategy. Both attempt to reduce the statistical fluctuation of the histogram of the noise. The more common uses some form of an m-out-of-n approach, where n is the total number of tests and m is the number of times that the threshold is exceeded. The other calls for averaging the data from two or more tests before applying the detection criteria. If the multiple-test strategy is not properly designed, the performance achieved can be drastically different from what is expected or desired.

Substantial benefits can be achieved if the tests are independent and random. Because most multiple-testing strategies require that additional data be collected at the end or as part of a test, the results are not independent. Studies have shown that the statistical uncertainty obtained in a single test is *not* equal to the statistical uncertainty obtained from many different tests [8]. Uncompensated sources of noise result in systematic trends in the data which are not reduced by averaging. For example, if the temperature is only partially compensated for, the measured volume rate in a nonleaking tank will contain the effects of thermal expansion or contraction of the product in the tank. Two tests that are performed in close enough succession that the temperature field has not changed would result in approximately the same measured value. The second test would contain the same temperature-induced error as the first. No substantial benefits are gained from performing multiple tests if the errors are systematic and are large enough to dominate the random error. Multiple testing reduces only the random error, not the systematic error. Design of a multiple-testing strategy requires a thorough understanding of the testing system and the ambient noise associated with it.

The simplest multiple-test approach and one of the best is to average the measured volume rate results from one or more independent tests and use the average to determine whether the tank is leaking. Averaging will reduce the spread in the histogram of the data by the square root of the number of independent tests. If the tests are not independent (i.e., if the tests are correlated because of a systematic error), the reduction of the standard deviation will be less than the square root of the number of tests. Averaging will improve both the P_D and the P_{FA} over those obtained with a single test. Substantial improvements usually require that a large number of tests be conducted, even if the tests are independent.

Another tactic is to use an m-out-of-n approach. In this approach, two or more tests are conducted and a leak is declared if one, several, or all of the tests exceed the threshold. The m-out-of-n detection approach is more mathematically complex than the averaging approach, but is as easy to use. If the number of tests conducted is large, the m-out-of-n approach can result in substantial improvements in both the P_D and the P_{FA} If the number of tests is small, improvement may be seen in either the P_D or the P_{FA}, but not in both. An increase in the P_D over that obtained with a single test can be achieved, but at the expense of an increase in the P_{FA}. Likewise, the P_{FA} can be reduced below that obtained with a single test, but usually at the expense of a lower P_D.

The averaging and the m-out-of-n approaches are compared in Table 5.2 for a multiple-test strategy using two tests. In this example, it is assumed that the noise histogram compiled from many independent tests is normal, with a mean of zero and a standard deviation of S. Table 5.2 presents the the results of a detection system against a leak rate that is 2.33 times larger than the standard deviation by conducting two independent tests and declaring a leak if one, two or the average of the two tests exceeds the threshold. The threshold used to declare a leak is presented in terms of the standard deviation of the probability density function. The three thresholds selected result in a probability of false alarm of 0.1, 0.05, and 0.01 for a single test. For a standard deviation of S = 0.19 L/h (0.05 gal/h), for example, Table 5.2 gives the performance achieved by the three approaches against a 0.45-L/h (0.12-gal/h) leak rate using thresholds of 0.24, 0.31, and 0.45 L/h (0.064, 0.092, and 0.12 gal/h), respectively. The averaging improves both the probability of false alarm and probability of detection over that of a single test. The probability of detection is increased (i.e., it is greater than the P_D obtained with a single test, or that obtained by averaging two tests when a leak is declared as a result of either test exceeding the threshold), but at the expense of an increased probability of false alarm. Likewise, the probability of false alarm is less than the P_{FA} obtained with either a single test or by averaging two tests when both tests must exceed the threshold to declare a leak, but at the expense of a reduced probability of detection.

Table 5.2. Multiple-Test Performance Calculations for Two Tests*

	Single Test (m = n = 1)		m-out-of-n m = 1, n = 2		m-out-of-n m = 2, n = 2		Average of Two Tests	
Threshold	P_{FA}	P_D	P_{FA}	P_D	P_{FA}	P_D	P_{FA}	P_D
1.28 S	0.10	0.85	0.19	0.98	0.01	0.72	0.04	0.93
1.64 S	0.05	0.75	0.10	0.94	0.003	0.56	0.01	0.83
2.33 S	0.01	0.50	0.02	0.75	0.0001	0.25	0.0005	0.50

* The results are expressed in terms of the standard deviation S. The leak rate is 2.33 S. (Source: [21])

The m-out-of-n testing approach is less efficient than the averaging approach; more tests are required to achieve the same performance. While the m-out-of-n detection strategy is not as efficient as the averaging approach, one anomalously large test result will have less of an impact with the m-out-of-n approach than with the averaging approach. Averaging four independent tests will result in the same detection performance against a leak rate that is one half as large as one that can be detected in a single test. For a probability of detection of 0.99 and a probability of false alarm of 0.01, a test criterion which requires that the threshold be exceeded in three out of five tests reduces the standard deviation by a factor of 0.54.

5.6 Summary

The performance of a leak detection system governed by the performance model (Figures 5.9 and 5.10) can be determined from the histogram of the noise and from the quantitative relationship between the signal and the noise. The model assumptions about the signal and signal-plus-noise histograms have been verified using simulated leaks at the Test Apparatus. Using the commercial method's measurement system and following its prescribed test protocol, the histogram of its noise can be determined by compiling the volume rate results from a large number of tests in nonleaking underground storage tank systems over the range of conditions to which the leak detection system will be applied. The analysis was done not assuming a normal model. The measured data were used to estimate performance. Instead of repeating this extensive series of tests for each method, the data were collected once to create a temperature database. Then the response of each commercial method was determined using the same temperature database.

Throughout the report, performance is discussed in terms of the standard deviation of the noise. A large standard deviation reflects poor performance. This description was used for convenience to avoid displaying histograms and performance curves. It is particularly meaningful if the noise histogram is normally distributed.

6 Performance Simulation

In order to estimate the performance of a test method, it is necessary to generate histograms of noise and signal-plus-noise; these depend on the elements of the test method. For detection of leaks in underground storage tanks, the performance of a volumetric method can be estimated once the noise histogram has been characterized. This is possible because the signal can be assumed to be an additive linear change in volume with time, and because the product-level changes produced in a tank by the signal are predictable for both variable- and constant-hydrostatic pressure volumetric tests. Characterizing the noise histogram requires a substantial data collection effort. The noise is derived from the temperature-compensated volume rate estimates made from a volumetric test over a wide range of ambient test conditions.

A simulator, which mimics a test in an underground storage tank, was developed to estimate the performance of each volumetric test method against a given set of tank and temperature conditions. 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. When necessary (i.e., when data-dependent analysis and detection criteria were employed to declare a leak), the simulator was also used to develop a signal-plus-noise histogram.

To estimate performance, the simulation used an empirically derived database of product-level and temperature data developed for a 30,000-L (8,000-gal) underground storage tank backfilled with pea gravel and filled with a blend of unleaded gasoline. The test method was modeled in terms of the precision and accuracy of the instrumentation, test protocol (data collection procedure), data analysis, and detection criterion. The approach to temperature compensation was incorporated in the test protocol and data analysis. Many tests were then simulated, using the empirically derived database and the test method model to develop a noise and a signal-plus-noise histogram.

The performance simulation (summarized in Figure 6.1) has eight basic elements:

- o Experimental Data
- o Database Management
- o Temperature Database
- o Product-Level Database
- o Test-Method Model
- o Tank-Test Simulator
- o Noise and Signal-Plus-Noise Histograms
- o Performance Analysis

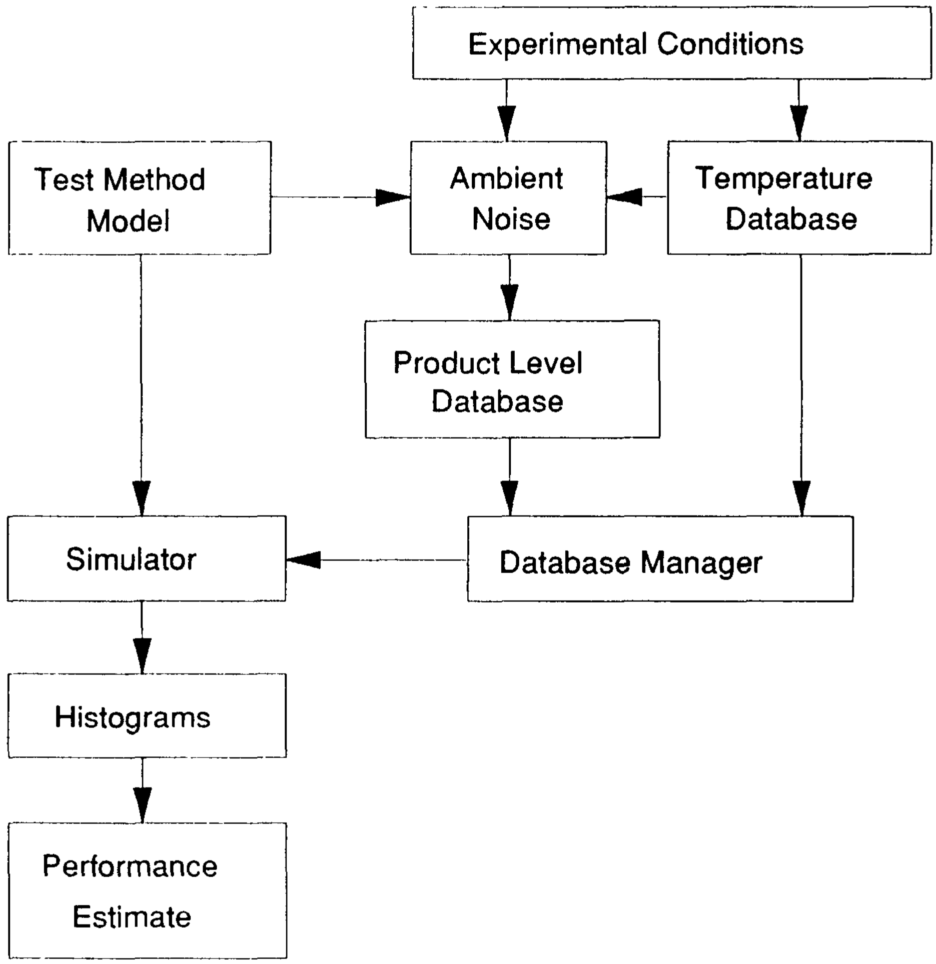


Figure 6.1. Flowchart of the performance simulation.

6.1 Experimental Data

Experimental data were used to generate a representative set of environmental conditions found in underground storage tanks. The temperature database was developed directly from a special set of experiments designed to emulate the delivery of product to a tank. The product-level database was developed from models of the ambient noise, the tank-backfill-soil conditions, and the instrumentation, measurement configuration, and protocol of the method. The models of the product-level or product-volume changes produced by each source of ambient noise that were used in the simulation were developed and validated with the data collected in a special set of ambient-noise experiments. The data were stored and manipulated using the database manager. The performance simulator specifies the test condition and accesses both the database manager and the test-method model to simulate a test. Histograms of the noise and signal-plus-noise were derived from the temperature-compensated volume-rate test results simulated for many tests and used to analyze performance.

The accuracy of the performance estimates is dependent on the accuracy of the test-method model, the accuracy of the product-level and temperature databases used to drive the simulation, and the number of tests used to derive the noise and signal-plus-noise histograms. Except for those methods which are affected by the ambient environment outside the tank, or which vertically integrate temperature using non-point-source sensors, the test-method model is simply a logical description of the instrumentation, test protocol, data analysis, and detection criterion. The temperature database was measured with thermistors that are calibrated to within 0.001°C. The product-level database was generated separately for each method using the applicable noise models, which predict the product-level or volume fluctuations in the tank. The ambient noise models used to predict product-level changes were validated during the ambient-noise experiments conducted at the Test Apparatus; the test-method model and, in particular, the temperature measurement approaches used by each method were validated during the Field Verification Tests.

6.2 Database Management

The temperature and product-level data were organized by means of a database management program that was used to store and manipulate data files for each individual tank-test condition. This database management program creates a separate binary file for each test run. The binary formatted run files provide efficient storage and rapid access.

Each binary run file, which has up to 64 channels of data, consists of a header record followed by the data records. Information describing the test run was recorded in the header, which also contains channel identification information describing the data type. The majority of the runs were 24 h in duration. The experimental data (e.g., product temperature), in engineering units, were added to the run file from ASCII LOTUS 1-2-3 importable files. The product-level and product-volume files were created in the program once the necessary experimental data had been added (e.g., temperature data are required in order to estimate the thermally induced volume changes). The test-method model was used to specify the geometry and tank deformation characteristics.

A variety of special utilities was developed for channel manipulation, perusal, and analysis. These utilities permit new channels to be created as functions of existing channels within the run file. They permit the data to be graphically displayed in either the time or frequency domain. In addition, it is possible to use these utilities to generate the data necessary for the evaluation or to conduct a special-purpose analysis. The noise-model realization software modules are a special class of the data manipulation routines. These modules are used to create the product-level or product-volume changes from the ambient noise models and the test-method model.

A database of product-level changes encountered during a wide range of test conditions was developed from the ambient noise models. The magnitude of the product-level fluctuations encountered during a tank test depends on several factors: the transfer of heat between the air, the ground, and the tank; the level and volume of product in the tank; the change in level of the product or groundwater immediately before or during the test; the elasticity and time constants of the backfill-soil surrounding the tank; and the volume of the vapor pockets trapped in the tank.

6.3 Temperature Database

To generate a useful temperature database, the volume fluctuations caused by thermal expansion of the product must be representative of the annual range of product-temperature changes that occur in the United States. As there was no existing information, a study was undertaken to estimate the range of temperature conditions that would be encountered throughout the 50 states [11]. It was determined from this study that the difference between the temperature of product to be added to a tank and the temperature of product in a tank is randomly distributed by geographical location, and that the range of temperature differences is between ±10°C.

Two temperature conditions were developed, one corresponding to tests that require the delivery of product to the tank and allow time for the temperature to come into equilibrium with the surrounding backfill, and a second one for tests that mix or circulate the product in the tank. This latter database was developed using a Petro Tite circulation pump, and was used to evaluate the Petro Tite method. Both conditions were developed by adding, to a half-filled 30,000-L tank, approximately 15,000 L of product that was either warmer or cooler than the resident product and the surrounding backfill. With each simulated delivery, the temperature field was measured over a period of 24 to 48 h, and temperature data were collected for the range of temperature differences of ±10°C between new and existing product. 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 nominal conditions used to develop the temperature database are summarized in Table 6.1, and the 1-h thermally induced volume changes are shown in Figure 6.2.

Table 6.1. Conditions Used to Create Temperature Database for the Steel Tank

Date	Δ Temperature (°C)
9/13/86	Ambient
9/20/86	8.3
9/22/86	2.8
9/27/86	-5.6
10/09/86	-11.1
10/10/86	Ambient
10/11/86	5.6
10/13/86	-2.8
10/14/86	Ambient
10/17/86	5.6
10/18/86	Ambient
10/19/86	2.8
10/25/86	-3.3
10/28/86	-5.6
10/29/86	Ambient
11/01/86	5.6
11/02/86	Ambient
11/04/86	8.0
11/05/86	Ambient
11/08/86	2.8
11/30/86	Ambient
1/23/87	Ambient
4/24/87	Ambient
7/27/87	-8.4
7/28/87	Ambient
7/29/87	-2.7
7/30/87	-2.2

The database contains over 500 h of temperature and product-level data. The temperature conditions identified as ambient denote that data collection was started a minimum of 24 h after the last product addition. The standard deviation of the data in Figure 6.2 is 848 ml/h, or 0.023°C/h in a 30,000-L tank. The temperature changes can be significantly larger in methods

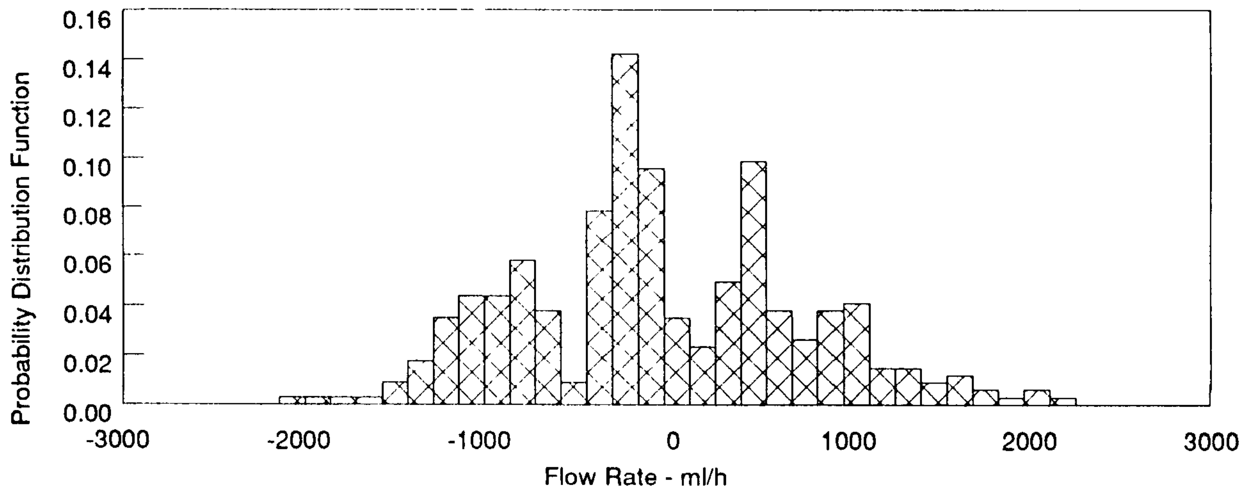


Figure 6.2. Histogram of temperature volume changes over a 1-h period 12 h after product was added to the tank.

which commence testing immediately after a delivery. The nominal conditions used to develop the mixed database are summarized in Table 6.3. The standard deviation of the mixed data, compiled from over 180 h of data, and shown in Figure 6.3, is approximately 2,000 ml/h, which is larger by more than a factor of 2 than the unmixed data. The reason for this is unknown, because the same nominal initial conditions were used to simulate the product delivery conditions. In part, the higher rate of product-volume change is due to heat generated in the tank during mixing.

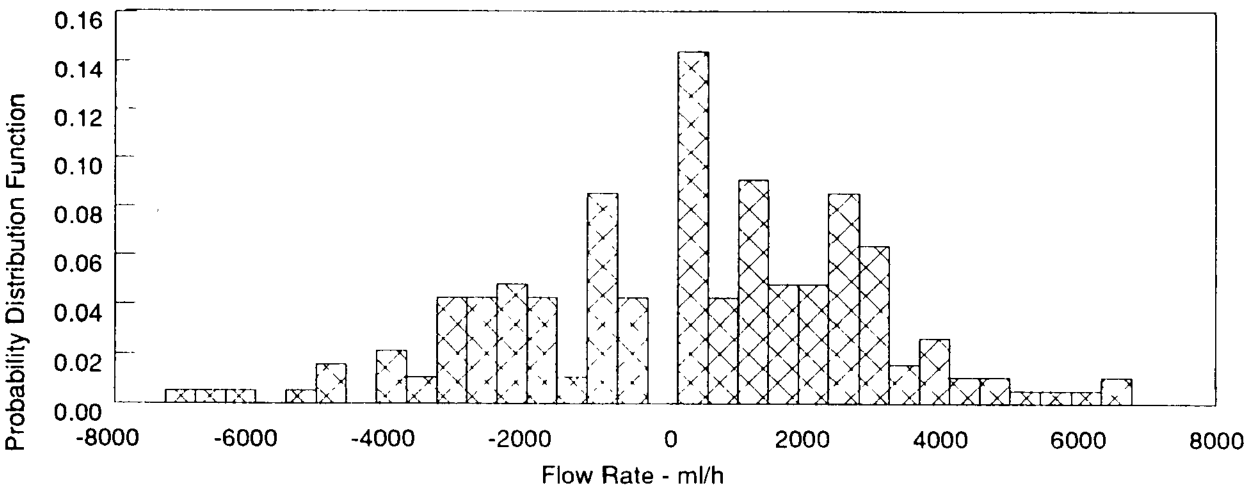


Figure 6.3. Histogram of the temperature changes in the circulated product temperature database.

Table 6.2. Nominal Run Conditions in the Circulated Product Temperature Database

Date	Tank	Δ Temperature (°C)
5/10/87	Steel	Ambient
5/11/87	Steel	-4.6
5/11/87	Steel	8.2
5/12/87	Steel	-4.6
5/10/87	Fiberglass	Ambient
5/11/87	Fiberglass	-3.6
5/11/87	Fiberglass	7.2
5/12/87	Fiberglass	-2.9
5/14/87	Fiberglass	-14.4
5/15/87	Fiberglass	Ambient
5/16/87	Fiberglass	7.78
5/18/87	Steel	Ambient
5/19/87	Steel	Ambient
5/20/87	Steel	Ambient
6/23/87	Fiberglass	Ambient
6/24/87	Fiberglass	-2.78
6/25/87	Fiberglass	2.78
6/26/87	Fiberglass	Ambient
6/27/87	Fiberglass	2.78
6/28/87	Fiberglass	2.78
6/30/87	Steel	2.78
6/30/87	Steel	-2.78
7/1/87	Steel	-5.56
7/2/87	Steel	5.56
7/2/87	Steel	-2.78
7/3/87	Steel	2.78

6.4 Product-Level Database

Product-level fluctuations depend on the ambient conditions in the tank, the tank-backfill-soil characteristics, and the test method. Using the test-method model and the ambient noise models, a product-level database was developed corresponding to each method. The test-method model specifies the system noise, the location and geometry of the product-level container, and the test protocol. The tank conditions were specified by experimental data. The ambient noise models describe the induced product-level fluctuations corresponding to each test method.

The physics of the ambient noise models are readily described mathematically. Because the product-temperature fluctuations that drive the models are difficult to predict theoretically, product-temperature fluctuations were measured.

It is possible to estimate the values of the tank-backfill-soil elasticity characteristics from the Test Apparatus data that is necessary to determine the effects of structural deformation. It is also straightforward to estimate trapped vapor pocket volume changes produced by pressure and temperature fluctuations when the volume of trapped vapor is known. Unfortunately, the range and distribution of values of tank elasticity and vapor pocket volume for installed tanks in the United States are not known.

The ambient noise models described below were used to estimate product-level and product-volume changes for calculation in the simulation. All of these models were validated with data collected during the ambient noise experiments at the UST Test Apparatus. Three of the sources of ambient noise result in product-volume changes: thermal expansion or contraction of the product, expansion or contraction of the trapped vapor, and surface losses or gains of product through evaporation and condensation. Changes in the volume of the container are described by structural deformation. Finally, surface and internal waves can induce estimation errors. The following sections describe the models developed for the simulation.

6.4.1 Thermal Expansion and Contraction of the Product

Those volume changes that occur as a result of thermal expansion and contraction of the product can be calculated as the sum of volume changes produced in each individual thermistor cell i, i.e.,

$$\Delta V = \sum_{i=1}^{n} \Delta V_i = \sum_{i=1}^{n} C V_i \Delta T_i \qquad (6.1)$$

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.

The temperature-volume time series is calculated using the data from three vertical thermistor arrays. The thermistors were spaced 20.3 cm (8 in.) apart, the lowest thermistor being 12.7 cm (5 in.) from the tank bottom. A thermistor cell is taken to be the longitudinal slab starting 10.2 cm (4 in.) below each thermistor and extending 10.2 cm above it. Of course, the lowest slab starts at the bottom of the tank, and the topmost slab ends at the gasoline surface. The change in volume for each slab was calculated by multiplying the first difference of the thermistor time series (or of the average of the three thermistors located at this slab level) by the coefficient of thermal expansion and by the volume of the slab. The temperature volume is thus represented by the sum of the changes in volume of all of the thermal cells.

The volume of a cell was computed by multiplying the length of the tank by the cross-sectional area between the top and bottom of the cell. By solving the integral equation representing this area, it can be shown that the formula for finding the area that extends from the bottom of the tank to a level, d, is:

$$\text{Area} = c\sqrt{2dr - d^2} + 2\left(\arcsin\left(\frac{c}{r} + \frac{\pi}{2}\right)\right)r^2 \tag{6.2}$$

where Area is the cross-sectional area below the product level, r is the radius of the tank, and $c = d - r$. Eq. (6.2) was supplemented by empirical measurements in the upper 15 cm of the Test Apparatus tanks.

6.4.2 Trapped Vapor

Trapped vapor can be a significant source of error in a volumetric test conducted in an overfilled tank. Air and vapor can be trapped in pipes, manways, and at the top of the tank, either because the tank is tilted or because it has an uneven top surface. The expansion and contraction of this trapped vapor, which are induced by changes in temperature, product level, or atmospheric pressure, will, in turn, induce changes in the product level. An estimate of the volume changes is made assuming that the air trapped by overfilling the tank is saturated with vapor. If dry air is mixed with product vapor, large pressure changes, and therefore large volume changes, will occur until the partial pressure of the trapped vapor mixture has reached a saturated state for the pressure and temperature in the vapor space. Because the partial pressure of gasoline is much larger than the partial pressure of air, even a small volume of trapped vapor can produce a volume change which is larger than the smallest leaks to be detected.

6.4.2.1 Expansion and Contraction of Trapped Vapor

To calculate the changes in volume of trapped vapor as a function of the temperature and pressure in the pocket, the air partial pressure, P_A, and the vapor partial pressure, P_V, are calculated as

$$P_A = Nk\frac{T}{V_{VP}} \tag{6.3}$$

$$P_V = P_o e^{-\frac{E}{kT}} \tag{6.4}$$

where N is the number of molecules, k is Boltzmann's constant, and E is the thermal energy. Then, the total pressure, P_T, is given by

$$P_T = P_A + P_V = Nk\frac{T}{V_{VP}} + P_o e^{-\frac{E}{kT}} \tag{6.5}$$

For small changes of P_T, Eq. (6.5) gives

$$\Delta P_T = Nk\left(\frac{\Delta T}{V_{VP}} - \frac{T\Delta V_{VP}}{V_{VP}^2}\right) + P_o e^{-\frac{E}{kT}}\left(\frac{E}{k}\frac{\Delta T}{T^2}\right) \tag{6.6}$$

After mathematical manipulations,

$$\frac{\Delta P_T}{P_T} = \left\{1 + \frac{P_V}{P_T}\left(\frac{E}{kT} - 1\right)\right\}\frac{\Delta T}{T} - \left(1 - \frac{P_V}{P_T}\right)\frac{\Delta V_{VP}}{V_{VP}} \tag{6.7}$$

The CRC Handbook of Chemistry and Physics [22] gives $P_V(T)$ for various C_7H_{16} and C_8H_{18} compounds. For T = 20°C, P_V is approximately 25 mm, and thus, for an extreme range of

$$\frac{E}{k} \sim 4500 \pm 300^\circ K,$$

$$\frac{\Delta V_{VP}}{V_{VP}} = (1.52 \pm .03)\frac{\Delta T}{T} - 1.03\frac{\Delta P_T}{P_T} \tag{6.8}$$

Eq. (6.8), then, describes the vapor pocket volume changes in terms of temperature and pressure for typical conditions at the UST Test Apparatus. Eq. (6.8) is not valid if the vapor is not saturated.

These same results can be obtained from the pressure volume and temperature volume for a perfect-gas polytropic process defined by

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n \tag{6.9}$$

and

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1} \tag{6.10}$$

where V_1 is the initial volume of the trapped vapor; V_2 is the final volume; P_1 is the initial absolute pressure and P_2 is the final absolute pressure; and T_1 is the initial temperature in °K and T_2 is the final temperature in °K. For a constant-temperature process (i.e., n = 1) Eq. (6.9) reduces to the perfect gas law. For a constant-pressure process (i.e., n = 0), Eq. (6.10) also reduces to the perfect gas law. The value of n is 1.4 for a reversible adiabatic change of a diatomic gas.

It is safe to assume that all overfilled tanks trap vapor. Eq. (6.8) was used to estimate the amount of vapor that will prevent the detection of a 0.19-L/h (0.05-gal/h) leak with a $P_D = 0.99$ and a $P_{FA} = 0.01$. To achieve detection performance requires that the change in volume of this vapor be less than 0.04 L/h (0.01 gal/h). Most temperature changes in an underground tank are less than 0.1°C/h. A 72-L (19-gal) vapor pocket would be required to produce a 0.04-L/h volume change. If the temperature changes are influenced by the ambient air (e.g., vapor trapped in an underground pipe located near the surface), vapor pockets that are much smaller in size can degrade detection performance because much larger temperature changes may occur. An atmospheric pressure change of 1 mb/h will produce a 0.04-L/h (0.01-gal) volume change in a 37.2-L (9.8-gal) vapor pocket. The atmospheric pressure calculations suggest that tests in overfilled tanks should not be conducted if the atmospheric pressure is changing rapidly. Against a 0.38-L/h (0.10-gal/h) leak rate, the allowable volume of trapped vapor would be twice as large as these estimates.

Small product-level changes in a fill tube or a standpipe will also produce large volume changes. A 2.5-cm/h (1-in./h) product-level change, which results in a 0.21-L/h (0.054-gal/h) change in volume in a tank that does not deform, will produce a change of 0.04 L/h if the volume of trapped vapor is 15.4-L (4.1 gal). For comparison, a 2.5-cm/h product-level change corresponds to a product-temperature change of only 0.005°C/h in a 30,000-L tank. Fortunately, these product-level-induced pressure changes can be entirely compensated for by using an experimentally measured height-to-volume conversion factor, A_{eff}, to interpret the product-level changes.

Vapor pocket volumes should be minimized. For reliable detection of a 0.19-L/h leak rate, it is recommended that the volume of trapped vapor be less than 50 L. Even an amount much smaller than 50 L can have significant consequences if tests are conducted before the partial pressure of the vapor has come into equilibrium with the tank environment.

6.4.2.2 Vapor Pocket Volume

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.

For a well-bled, overfilled tank containing small amounts of trapped vapor, Eq. (6.9) reduces to

$$\Delta V_{vp} = n V_{vp} \ln\left(\frac{P_A + \rho g \Delta h}{P_A}\right) \tag{6.11}$$

where V_{vp} is the vapor pocket volume, ρ is the density of the product, g is the acceleration due to gravity, and n = 1.03 for the model described by Eq. (6.8). 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

$$V_{bar} = \Delta V_{eff} + \Delta V_{isd} + \Delta V_{vp} = A_{eff} \Delta h + (A_{isd} + A_{vp})\left(\frac{V_{bar}}{A} - \Delta h\right) \tag{6.12}$$

where V_{bar} is the known volume of the cylindrical object used to displace product.

6.4.3 Evaporation and Condensation

When a tank is partially filled with product, there can be evaporation into or condensation from the vapor space. Assuming no exchange of vapor with dry air outside the tank, there are two ways in which evaporation and condensation can affect the measured liquid volume: (1) the amount of gasoline held in the vapor phase may change, and (2) condensate on the walls of the tank represents liquid that is not being measured. Equilibrium conditions are discussed first, followed by the more difficult (but more realistic) case of nonequilibrium conditions.

6.4.3.1 Equilibrium Conditions

The equilibrium condition exists when the partial pressure of gasoline in the air space equals the vapor pressure for the temperature at that point. The temperature is allowed to vary, though the prospect of maintaining the equilibrium condition with variable temperature is somewhat unrealistic. In practice, equilibrium will only be achieved if the saturated air is in close proximity to liquid at the same temperature, i.e., at the product surface or on tank walls wet with condensate. Recall also that gasoline is not a single compound, but a mixture of compounds.

First, consider the total volume of gasoline held in saturated vapor, which is one of the major factors in achieving the equilibrium condition. (Throughout this discussion, the quantity of gasoline is measured in equivalent condensed liquid volume, even though the gasoline may be in a gaseous state.) The density of gasoline in saturated vapor is derived from the gas law

$$PV = NkT \tag{6.13}$$

The density is

$$\rho = \frac{\mu}{A_o}\frac{N}{V} \tag{6.14}$$

where μ = molecular weight $\cong$ 114 g/mole and $A_O = 6.02\text{x}10^{23}$/mole. Substituting Eqs. (6.4) and (6.13) into Eq. (6.14) gives

$$\rho_V = \frac{\mu P_o}{A_o kT} e^{\frac{-E}{kT}} \tag{6.15}$$

$$= \frac{2.13 \times 10^5}{T} e^{-\frac{4500}{T}} \text{ g/ml}$$

for $E/k = 4500°K$ and $P_O = 1.55\text{x}10^{10}$ N/m^2, which are mean values for several C_7H_{16} and C_8H_{18} compounds for which $P_V(T)$ data are given in the CRC Handbook [22]. This compares to a liquid density $\rho_L = 0.746$ g/ml.

To calculate the density of saturated air, we must add the unsaturated-air density. Assuming the total pressure remains constant at $P_A = 1$ atm $= 1.01\text{x}10^5$ N/m^2,

$$\rho_A = \frac{\mu_A}{A_o kT}(P_A - P_V) \tag{6.16}$$

where $\mu_A = 29$ g/mole. Table 6.3 gives these values for a range of temperatures.

For typical temperatures, saturated air contains 0.1 to 0.3 L of gasoline for each 1,000 L of air. A representative condition of 15,000 L (4,000 gal) of air (a half-filled tank) corresponds to roughly 3.8 L (1 gal) of liquid in the vapor space. More importantly, this value changes by about 0.01 L/°C for each 1,000 L of air. The vapor space temperature is assumed to vary sinusoidally over a 24-h period, with an extreme-case magnitude of 1°C (as inferred from observations of vapor space temperatures in the Test Apparatus). This is equivalent to a vapor space temperature change of approximately 0.25°C/h. Combining these factors results in an apparent volume rate of about 0.04 L/h (0.01 gal/h), which is negligible. Thus, if the vapor stays in equilibrium, the amount and variation of gasoline held in the vapor phase should not be an important inhibition on leak detection. This condition is not apt to be experienced after product addition.

Table 6.3. Gas Phase Densities

Temperature (°C)	Density (g/L) of Vapor (ρ_V)	Density (g/L) of Saturated Air (ρ_A)	ρ_V/ρ_L (x10^4)
0	0.054	1.333	0.72
5	0.072	1.323	0.97
10	0.094	1.317	1.26
15	0.121	1.316	1.62
20	0.155	1.321	2.08
25	0.198	1.332	2.65
30	0.249	1.351	3.34
35	0.312	1.379	4.18

Second, consider the condensate clinging to the walls of the tank; this liquid is the other major factor in achieving the equilibrium condition. The amount can be highly variable. At one extreme, the tank walls will be dry if the wall temperature is greater than the product temperature (of course, it is the product temperature at the surface that is relevant). At the other extreme, with the tank walls cooler than the product, there will be condensation, eventually reaching an equilibrium with liquid dripping off at the same rate that vapor is condensing. For a tank 6.5 m long, with a 1.2-m radius, there will be 29 m^2 of wall area when the tank is half full. As an estimate, the maximum amount of liquid held on the walls would be approximately 0.2 mm thick (e.g., droplets 1 mm thick covering 20% of the surface). This number, which might easily be off by a factor of 2, yields approximately 6 L of liquid on the walls. The contribution of liquid from the tank walls to the equilibrium condition, then, could range from 0 to 6 L. The equilibrium state should be independent of temperature (or time) unless the temperature difference between the wall and the product changes sign. Note that if the walls are holding the maximum (constant) amount of liquid, there can still be substantial evaporation from the product surface, vapor transport to the walls, condensation on the walls, and dripping back into the tank.

6.4.3.2 Nonequilibrium Conditions

If the vapor space is out of equilibrium, either because dry air has been introduced to the tank or because the product temperature has changed with a new delivery, a significant volume change may result from the shifting amount of gasoline in the gaseous state. Depending on how extreme the starting condition is, there may well be a change of a liter or more in product volume as the vapor space comes into equilibrium. The time required for equilibration to take place is hard to predict; hence, volume rates are also hard to predict.

The temperature at the product surface is normally greater than or equal to the ground temperature. If the tank has been sitting for some time, the product temperature is observed to be the same as that of the ground. Recently added cool gasoline sinks to the bottom of the tank and does not influence evaporation and condensation, while recently added warm gasoline floats on top and is important. Consequently, attaining equilibrium usually means that product is lost to the vapor space rather than vice versa.

Because the upper tank walls respond slightly to diurnal temperature variations, they may become slightly warmer than the product at mean ground temperature. If the wall temperature exceeds the minimum or maximum product temperature during the day, the walls may be dry at one point and may carry the maximum condensate load at another, moving back and forth between these two extremes. Volume changes of several liters could result.

If recently added product is warmer than the ground, so that even with diurnal variations the wall temperature remains below the product temperature, the walls will maintain a maximum condensate load with no net effect on product volume. The evaporation from the product surface, condensation on the walls, and dripping back into the tank are part of the thermal equilibration process that moves heat from the warm product to the cooler tank walls.

One of the reasons that predicting the temporal evolution of the equilibration process is so difficult is that the density of the saturated air has a peculiar behavior with regard to temperature. The exact temperature depends on the vapor pressure curve for a particular product. When temperature increases, the air density drops, but the vapor pressure increases, replacing light air molecules with heavy gasoline molecules. At low temperatures, the vapor pressure is sufficiently low that the air dominates, but at higher temperatures, the gasoline dominates. This results in some unconventional effects. For example, if the product temperature is 13°C, there will be convection regardless of whether the walls are warmer than the product (and thus wet, allowing evaporation to occur) or cooler than the product. However, because the density of saturated air varies only slightly with temperature, convection will be relatively weak.

The above assumes that the air remains in saturated equilibrium as it moves from the region near the product surface to the wall. In actuality, if the air is moving into a warmer region, liquid may not be available for evaporation. Thus, while warm wet walls can cause convection, warm dry walls will lead to a stable, nonconvective vapor space.

Predicting the detailed process of equilibrium is very complicated. Even such a fundamental question as whether convection is occurring may not be knowable *a priori*, as it depends on the initial condition of condensate on the walls.

6.4.3.3 Summary

Gasoline in the gaseous state does not appear to present a problem except for the initial transients that appear when warm product has just been added. After these initial transients, the amount of condensate on the walls should remain stable. When the product surface temperature is near the tank wall temperature, the amount of condensate carried on the walls can vary by several liters depending on small diurnal temperature changes. This rate is effectively unpredictable.

6.4.4 Structural Deformation

Whenever the product level in the tank changes, the change in hydrostatic pressure causes the volume of the tank to change and therefore, the product level to change further. This expansion and contraction of the tank volume is strongly dependent on the compressibility of the backfill in the excavation and on the native soil surrounding the excavation. The deformation effects are particularly complex for tests conducted while product level in the fill tube or standpipe of an overfilled tank.

6.4.4.1 Product-Level Measurements in Overfilled Tanks under Variable Pressure

When product is brought into the fill tube (or into an above-grade standpipe) of an underground storage tank, the resultant increase in hydrostatic pressure causes the tank to expand. The increase in tank volume produced by this expansion lowers the product level in the fill tube. This drop in level decreases the hydrostatic pressure, and the tank will now relax towards an equilibrium level, one that is changing. Similarly, when product is removed from the fill tube, the decrease in hydrostatic pressure will cause the tank to contract, and the product level in the fill tube will rise.

An exponential relaxation model, referred to as the Fill-Tube Dynamics Model, is hypothesized to describe the volume and product-level changes produced by tank deformation in an overfilled tank. The model is mathematically derived first for the specific case of instantaneously adding a known amount of product, ΔV_P, into the fill tube of an initially overfilled tank, where the volume of the product in the tank, fill tube and standpipe, $V_P(t)$, is assumed to be greater than the volume of the tank, $V(t)$. This model describes the product-level changes produced by topping the tank, a procedure used by most methods in order to reach the product level required to start a tank test. (The model formulation does not include an estimate of the change in the leak rate produced by a change in the hydrostatic head.) This addition of product results in an instantaneous rise, Δh, in the product level in the fill tube that is mathematically described by $dh/dt = \Delta h\ \delta(t-t_o)$, where t_o is the time at which the product level is changed and $\delta(t-t_o)$ is the Dirac delta function. The model assumes an exponential increase in the volume of the tank itself. This is described by

$$V(t) = V_o + K\,\Delta h\left(1 - e^{-(t-t_o)/T_C}\right) \qquad (6.17)$$

for $t \geq t_o$ where V_o is the volume of the tank at time t_o; K is the equilibrium elasticity of the tank-backfill-soil system; and T_C is the hydrostatic-pressure relaxation time constant of the tank-backfill-soil system.

The rate of change of the volume of the tank with respect to time for $t \geq t_o$ is given by

$$\frac{dV(t)}{dt} = \frac{K\,\Delta h}{T_C}\, e^{-\frac{t-t_o}{T_C}} \qquad (6.18)$$

and $dV(t)/dt = 0$ for $t < t_o$.

The product-level changes in the fill tube are estimated by

$$h(t) = \frac{V_P(t) - V(t)}{A_{eff}} \qquad (6.19)$$

where $V_P(t) > V(t)$, and where A_{eff} is the effective cross-sectional area of the product surface. (See Section 4.2 and [23] for more detailed discussion.)

It is assumed that the volume changes produced by all product-level changes will add by linear superposition. This means that the total volume change can be computed by adding all of the individual volume changes produced by each instantaneous product-level change. This is given mathematically by the convolution integral

$$\frac{dV(t)}{dt} = \frac{K}{T_C}\int_{-\infty}^{t}\frac{dh(\tau)}{dt}e^{-\frac{t-\tau}{T_C}}d\tau \tag{6.20}$$

where τ is the time variable of integration. Eq. (6.20) can be expressed as

$$\frac{dV(t)}{dt} = \frac{K}{T_C}\left(\frac{dh(t)}{dt}*\psi\right) \tag{6.21}$$

where * indicates the convolution between dh(t)/dt and ψ, with $\psi = 0$ for $t < 0$ and $\psi = \exp(-t/T_C)$ for $t \geq 0$. Eq. (6.21) is substituted into the differentiation of Eq. (6.19) to obtain the rate of change of product level represented by

$$\frac{dh(t)}{dt} = \frac{1}{A_{eff}}\frac{dV_p(t)}{dt} - \frac{K}{A_{eff}T_C}\left(\frac{dh(t)}{dt}*\psi\right) \tag{6.22}$$

where

$$\frac{dV_P(t)}{dt} = \Delta V_P \delta(t-t_o) \tag{6.23}$$

Eq. (6.22) can be solved via Fourier Transform methods and integrated from $-\infty$ to time t to give the product-level time series for $t \geq t_o$,

$$h(t) = \frac{\Delta V_P}{A_{eff}} + \frac{\Delta V_P}{A_{eff}}\left(\frac{K}{A_{eff}+K}\right)\left(e^{-(t-t_o)/T_{eff}} - 1\right) \tag{6.24}$$

where the effective time constant of the tank is defined by

$$T_{eff} = T_C\frac{A_{eff}}{(A_{eff}+K)} \tag{6.25}$$

The product-level changes can be converted to product-volume changes by multiplying by the effective cross-sectional area, A_{eff}. The first term in Eq. (6.24) is the product-level change caused by the sum of the effects of the instantaneous deformation of the tank and of any trapped vapor. The magnitude of the instantaneous deformation is determined by the magnitude of the effective cross-sectional area of the fill tube. The second term is the 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. Eq. (6.25) suggests that the effective time constant is always shorter than the time constant in a constant-head test (i.e., time constant of the tank itself), and is a function of A_{eff} and the unknown elasticity constant, K, of the tank-backfill-soil system.

Table 6.4 presents the values of the effective time constant, T_{eff}, for different values of A_{eff} and K, where it can be assumed that A_{eff} is mainly a function of the fill tube cross-sectional area, A. The values of T_{eff} and K are within the range of values estimated experimentally for the steel and fiberglass tanks at the UST Test Apparatus. For fill tubes of small diameter, the deformation occurs very quickly in comparison to those with large diameters. The calculation suggests that a fill tube with a diameter of 81 cm (32 in.) has a time constant approximately equal to that of the tank.

Table 6.4. Estimate of How T_{eff} Changes with A_{eff} and K*

Effective Fill Tube Diameter (cm)	A_{eff} (cm^2)	K (cm^2)	T_{eff} (h)
10.2	81.1	120	0.40
10.2	81.1	60	0.57
10.2	81.1	30	0.73
10.2	81.1	15	0.84
5.1	20.3	120	0.14
20.3	324.3	120	0.73
40.6	1297.2	120	0.92
81.2	5188.7	120	0.98

* Eq. (6.25) is used to make the predictions, using T = 1 h for a 1-m rise in product level prior to starting a tank test.

The product level at infinity (i.e., many hours after the initial deformation) is given by

$$h(\infty) = \frac{\Delta V_p}{A_{eff} + K} \tag{6.26}$$

The total height change in the fill tube is interpreted in terms of the long-term height-to-volume conversion factor, (A_{eff} + K), rather than the short-term height-to-volume conversion factor, A_{eff}. An estimate of $h(\infty)$ cannot be made unless K, the elasticity constant of the tank system, is known. The total drop in product in the fill tube is

$$h(t_o) - h(\infty) = \frac{\Delta V_p}{A_{eff}} - \frac{\Delta V_p}{A_{eff} + K} \tag{6.27}$$

For small K, $[h(t_0) - h(\infty)]$ is approximately zero.

Eq. (6.22) can be generalized to predict the product-level changes produced by any type of product-volume change as opposed to just the instantaneous volume change used to derive Eq. (6.24). The product-level changes that result are given by

$$h(t) = \frac{V_p(t)}{A_{eff}} - \frac{K}{A_{eff}^2 T}\int_{-\infty}^{t} V_p(\tau) e^{-(t-\tau)/T_{eff}} d\tau \tag{6.28}$$

The product-volume changes in the fill tube can be estimated by multiplying Eq. (6.28) by A_{eff}.

Eq. (6.28) indicates that the product-level changes in the tank at any point in time are affected by the product-volume (or product-level) changes that occurred in the past. Thus, in order to interpret the current product-level changes in terms of volume, the past product-level changes must be known and included. It is also clear from Eq. (6.28) that the procedure for topping the tank will affect the product-level changes. The deformation of the tank and the resulting product-level changes will be different even if the same volume of product is added to the tank, but at a different rate or in different amounts. While in this case the product-level and product-volume changes were defined as zero for the period before the product was added, this is not necessarily true in other situations. It is important to follow the same topping procedure to maintain a predictable performance.

If the rate of change of volume of the product in the tank is a constant, C, then it can be shown that the rate of change of the product level in the tank is given by

$$\frac{dh(t)}{dt} = \frac{C}{A_{eff} + K} \tag{6.29}$$

where C is the flow rate produced by a leak or any other product-volume change. C is equal to the leak rate, LR, if all other volume changes are equal to zero. A negative leak rate or volume rate is defined as an outflow or a decrease in the volume of the product in the tank. In the fill tube, a leak which produces a constant rate of change of product volume produces a product-level change that cannot be estimated from A_{eff} unless K is zero. To estimate C using Eq. (6.29), an estimate of the long-term height-to-volume conversion factor, $A_{eff} + K$, is required. Since K is generally unknown during an actual test, C cannot be accurately estimated. If K is equal in magnitude to A_{eff}, the measured product-level change and, therefore, the product-volume change obtained by multiplying the product-level changes by the measured height-to-volume conversion factor may be too small by a factor of 2 or more. In a partially filled tank, the product-level changes can be directly related to volume by the height-to-volume estimated from a tank chart because (A_{eff} = A) >> K. For a partially filled tank, Eq. (6.29) reduces to

$$\frac{dh(t)}{dt} = \frac{C}{A} \tag{6.30}$$

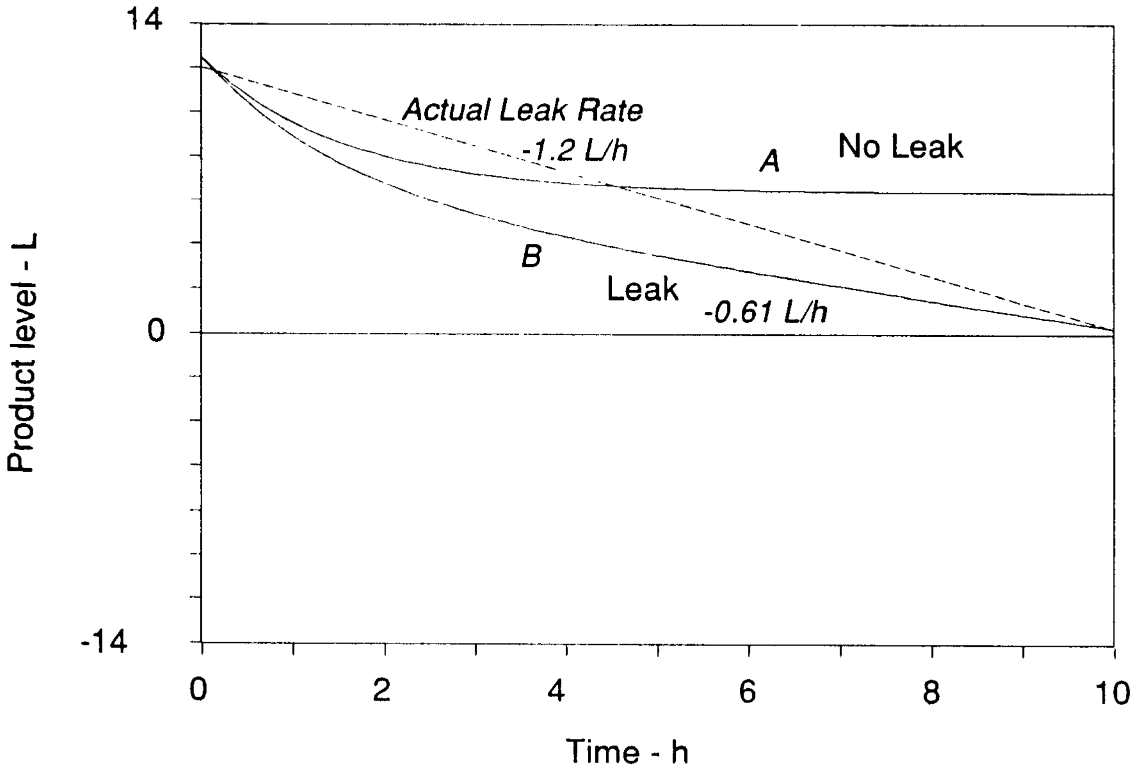
Eq. (6.29) also demonstrates that the effects of deformation are important and will occur even if there are no deliberate, operator-initiated product-level changes as assumed in the derivation of Eq. (6.24). Any change of volume, whether it be a leak or thermally induced expansion or contraction of the product, will affect the measured product-level changes similarly.

Finally, consider 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. This is described mathematically by

$$h(t) = \frac{\Delta V_p}{A_{eff}} + \frac{\Delta V_p}{A_{eff}}\left(\frac{K}{A_{eff}+K}\right)\left(e^{-(t-t_o)/T_{eff}} - 1\right) + \left(C\frac{(t-t_0)}{A_{eff}+K}\right) \tag{6.31}$$

Eq. (6.31) predicts the product-level changes that would occur in a 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. The linear rate of change predicted by Eq. (6.31) after several time constants, T_{eff}, have elapsed is identical to that of Eq. (6.29).

Eq. (6.31) was used to predict the product-volume changes in a 10-cm (4-in.)-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 Figure 6.4. The product-level changes are converted to volume changes using A_{eff}. The volume change is assumed to be produced by a leak, by thermal contraction of the product, or by a combination of these. No other volume changes are considered. Values of K = 120 cm^2, T = 3 h, T_{eff} = 1.5 h, and A_{eff} = 125 cm^2, typical of the steel tank at the UST Test Apparatus, were used in the calculations. 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 volume rate. For comparison, the product-level changes that are the result of deformation only are also shown in this prediction; the rate of change of volume is zero. This 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 changes, 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 would be +0.59 L/h instead of zero.



A: A_{eff} = 125 cm^2, K = 120 cm^2, T = 3 h, $C_{predicted}$ = C_{actual} = 0.0 L/h.
B: A_{eff} = 125 cm^2, K = 120 cm^2, T = 3 h, $C_{predicted}$ = -0.61 L/h, C_{actual} = -1.2 L/h.

Figure 6.4. Comparison of the Fill-Tube Dynamics Model predictions using Eq. (6.31) for different combinations of A_{eff}, K, and C. In a small-diameter fill tube, only a fraction of the actual leak rate is predicted. $C_{predicted}$ is estimated 3 or more time constants after the start of the test.

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. Many methods attempt, before starting a test, to wait until the large exponential decay has occurred. Second, it is mistakenly assumed that once the large decrease in product level 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 have occurred 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.

6.4.4.1.1 Product-Level Measurements in Overfilled Tanks under Constant Pressure

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. Because product level is kept approximately constant, no significant additional deformation of the tank occurs during the test. The measured volume changes (obtained by using A_{eff} to convert to product-level changes) represent the actual volume changes occurring in the tank.

The 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, or 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 at t = nt′ required to bring the product level to zero is given by

$$V_n = -C\lambda + \left[\frac{KC}{A_{eff}+K}\left(\lambda - T_{eff} + T_{eff}e^{-\lambda/T_{eff}}\right) - \left(\frac{A_{eff}}{A_{eff}+K}\right)V_p(0)\left(1-e^{-\lambda/T_{eff}}\right)\right]\cdot \left(K + A_{eff}\frac{e^{-\lambda/T_{eff}}}{A_{eff}+K}\right)^{n-1}, n \geq 1 \qquad (6.32)$$

The derivation of Eq. (6.32) is mathematically complex and only the result is given here. The analytical solution was compared to the numerical solution generated using Eq. (6.28) for verification. The total amount of product added to maintain a constant level in the fill tube is obtained by summing the V_n calculated using Eq. (6.32) for all n. This is equal to the product-volume drop in a fill tube of very large diameter; the drop would be estimated for the same parameters using Eq. (6.31). If the releveling period is very much smaller than the effective time constant, Eq. (6.32) is approximated by

$$V_n \cong -C\lambda - V_p(0)\frac{\lambda}{T}e^{-(n-1)\lambda/T} \qquad (6.33)$$

In practice, $V_p(0)$ is unknown because the time history of past volume changes is unknown. It is assumed that the product level, $-h_o$, 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_o at t = 0. It can then be shown that

$$V_p(0) = -Kh_o \quad (6.34)$$

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. The volume changes predicted by Eq. (6.32) are approximately equal to those shown in Figure 6.4 when Eq. (6.31) for the calculation made with $A_{eff} = 4560$ cm^2 >> K = 120 cm^2, providing that the product is releveled almost continuously. If the tank is releveled every 15 min, the time constant of the volume changes is approximately 1.14 T_C. This was obtained by solving Eq. (6.32) 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.

6.4.4.1.2 Summary

Any product-level change will deform the tank. Tests which allow the product level in the fill tube or in a standpipe to change freely may be subject to serious errors, because product-volume changes are not accurately estimated from the product-level changes in the fill tube using A_{eff} when K >> 0 cm^2 or when K >> A_{eff}. While T_C is also unknown, its exponential behavior is known, and an algorithm can be developed to minimize this effect by waiting for the volume changes to become negligible. The actual or true volume changes can be obtained by multiplying by the long-term volume-to-height conversion factor (i.e., A_{eff} + K) once the exponential changes induced by product-level adjustments necessary to start a test have become small. The magnitude of the error will depend on the elasticity of the tank. Since K is unknown, accurate estimates of the actual volume rate are difficult to make. If A_{eff} is not measured, then the error is larger yet. If K happens to be small compared to A_{eff}, the error is also small, but the tester has no way of knowing this.

The product-level fluctuations that occur in a volumetric test having a nearly constant hydrostatic pressure can be estimated by a simple sum of the individual contributions of each noise source. Product-level fluctuations can be converted to volume using the effective cross-sectional area of the product surface, A_{eff}.

6.4.4.2 Product-Level Measurements in Partially-Filled-Tank Tests

In partially-filled-tank tests conducted at a constant hydrostatic pressure, any change in product level causes the tank to deform. This deformation can be estimated using Eq. (6.35), except that the effective time constant of the tank is equal to T_C and the effective cross-sectional area can be estimated from the geometry of the tank and does not have to be measured. The deformation of a partially filled tank is estimated by

$$\Delta V = K \Delta h \left(1 - e^{-(t-t_0)/T_C}\right) \tag{6.35}$$

where $t \geq t_0$.

Except after product additions, structural deformation in partially-filled-tank tests is negligible. The height changes produced by temperature fluctuations, waves, or evaporation are very small when the tank is less than 90% filled.

6.4.5 Surface Waves

Changes in height caused by surface waves in the tank are sinusoidal, and can be modeled by

$$\Delta h(t) = B e^{-\frac{t}{T_w}} \cos(\omega t + \phi) \tag{6.36}$$

where Δh is the change in height, B is the initial magnitude of the height change, t is time, T_W is the decay constant, ω is the frequency of the surface wave, and φ is the phase at t = 0. In a tank, surface waves caused by external vibrations typically have a period on the order of 2 to 10 s. Surface waves have an impact on product-level data acquisition requirements.

6.4.6 Internal Waves

Large subsurface internal waves with periods on the order of several minutes to an hour or more propagating along a temperature (density) gradient are recorded as apparent fluctuations in the temperature of the product measured at any point affected by the wave. In some instances, these waves may result in surface disturbances. This noise source can be represented by a sinusoidal curve similar to the one described for surface waves. The period and amplitude are difficult to predict, and depend on the geometry of the tank, the density gradients in the tank and the generating force. The effect of internal waves in the simulation was incorporated as measured in the temperature database. Internal waves have an impact on thermal data acquisition requirements.

6.5 Test-Method Models

A mathematical model of each test method was developed from information provided by the manufacturer. A report summarizing the method, and including a description of the instrumentation, test protocol, data analysis, and detection criterion, was prepared and was given to the manufacturer for review and written concurrence.

With the ambient noise models and the experimental database, the test-method model generated the product-level database. A familiarity with the test configuration, system noise, and the test protocol was required in order to generate the product-level database, which was then input to the database manager. Finally, the product-level database was analyzed, using the method-specific data analysis algorithms to compute a temperature-compensated volume rate.

6.5.1 Instrumentation

The instrumentation used in each leak detection method was modeled with experimentally measured estimates of the resolution, precision and accuracy of the product-level and temperature measurement systems. The model reflects the number, the configuration, and the locations of the sensors. The system noise was added to the temperature and ambient noise database for use in the performance simulation.

6.5.2 Test Protocol

The method-specific test protocol reflects the conduct of the entire test, starting with product delivery and ending with the data necessary to compute the temperature-compensated flow rate. The test protocol includes the waiting periods after adding product to the tank, the data sampling, the test duration, and number of test periods required by the method (Figure 4.3). The test protocol also incorporates nonuniform and interactive sampling schemes, as well as test durations that are nonuniform or that are dynamically determined from the data.

6.5.3 Data Analysis

The data analysis algorithm for each leak detection method evaluated was identical to that specified by the manufacturer. The data analysis included the preparation of product-volume and temperature-volume time series, temperature-volume compensation schemes, and calculation of the temperature-compensated volume rate.

6.5.4 Detection Criterion

For each leak detection method, the method-specific detection criterion used to declare a leak was incorporated into its performance model.

6.6 Tank-Test Simulator

The tank-test simulator was used to mimic the conduct of a test of an underground storage tank. The simulator accesses the temperature and product-level databases, as well as the test-method model. The operator can specify which test method to implement, which part of the database to use, and how many tests can be conducted for each run file in the database.

The product-level time series is defined, in general, by

$$h(t) = \frac{K}{A^2 T_C} \int_{-\infty}^{t} V(\tau) e^{-\frac{(t-\tau)}{T_{eff}}} d\tau \tag{6.37}$$

$$V(t) = V_{SN}(t) + V_{AN}(t) + V_L(t) + V_{Protocol}(t) \tag{6.38}$$

where $V(t)$ is the volume change associated with product-level changes, $h(t)$; $V_{SN}(t)$ is the volume change associated with the product-level sensor system; $V_{AN}(t)$ is the product-level volume change associated with each of the six noise sources ; $V_L(t)$ represents the volume change associated with a leak; and $V_{Protocol}(t)$ represents product volume changes called for in the test protocol.

In a nonleaking tank, $V_L(t) = 0$. However, in general, $V(t)$ will not equal 0, because the combined system and ambient noise are statistically independent and will not sum to 0. The noise-compensated volume time series, $V_C(t)$, is defined by

$$V_C(t) = V(t) - V_{NC}(t) = V_{SN}(t) + V_{AN}(t) + V_L(t) + V_{Protocol}(t) - V_{NC}(t) \tag{6.39}$$

where $V_{NC}(t)$ are the volume change estimates inferred by the test method to compensate for the noise-induced volume changes.

The simulator then generates a histogram of the volume-compensated noise and, if desired, the signal-plus-noise. For the majority of the tests, only the noise histograms were generated.

6.7 Performance Analysis

The temperature-compensated volume rate data obtained for each simulated test were stored cumulatively in a file, ready for performance analysis. The histograms and cumulative distribution function of each test method were generated and displayed graphically.

The performance curves generated in this report were based on the measured noise and signal-plus-noise cumulative distribution functions. For high levels of performance, the probability of false alarm and the probability of detection are estimated from the tails of the cumulative distribution function. 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. For a few methods, the performance estimate was based on less than 50 test.

With this modest amount of data, it was difficult to make reliable estimates of the false alarm rate at 0.01 and the probability of detection at 0.99. The total number of realizations depended on the duration of the test. A model of the data can be used to estimate the cumulative distribution function more accurately.

An attempt was made to model the cumulative distribution functions with a normal model, which was calculated using the sample mean and standard deviation of the simulation results. In many instances, the model was in good agreement with the measured results. When there was poor agreement, it occurred because the tails of the measured histogram had not been modeled well by a normal distribution. In general, the normal model does not accurately describe the tails of the distribution. This is not unusual; a normal model usually predicts false alarm rates which are much lower than those observed.

An exponential function was fit to the data to more reliably estimate the tails of the cumulative distribution function at both the 0.99 and 0.01 and the 0.95 and 0.05 cumulative frequencies. This yields a better estimate than can be obtained by extrapolating the temperature-compensated volume rate with only one or two points. The model could also have been used to make performance estimates beyond the range of the data, but this was not generally necessary, nor was it desired. Several other functional forms were fit to the data, but the exponential curve provided the best fit.

In general, 20% of the data were used to fit the tails, 10% for each tail. The exponential model is given by

$$C(x) = D_0 + D_1 e^{-a(x)} \tag{6.40}$$

where C(x) is the cumulative distribution function, x is the temperature-compensated volume rate, D_O is the value of the cumulative distribution function at 0.90 and 0.10, D_1 is the amplitude of the exponential change, and a(x) is the rate of change of the cumulative distribution function. In some cases, less than 10% of the data were used to model the tails, and D_O changes appropriately.

A least-squares technique was used to estimate the uncertainty in the probability of detection and the probability of false alarm at 0.99 (or 0.95) and 0.01 (or 0.05) from the curve-fit coefficients. The resulting one-standard-deviation rms error of the P_D and P_{FA} was calculated and tabulated for each method.

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 mean of the noise histogram was removed for the third display (i.e., the bias was assumed to be zero), but the bias was included in the first two displays.

Three test results are summarized in the body of the report: (1) the performance of the method using the manufacturer's standard detection criterion (i.e., threshold) against a 0.38-L/h (0.10 gal/h) leak rate in terms of the P_D and P_{FA}, (2) the potenital performance that could be achieved with the method in terms of leak rate for a P_D of 0.99 and P_{FA} of 0.01, and a P_D of 0.95 and P_{FA} Of 0.05 after using a threshold defined by the P_{FA}. A more thorough presentation of results in given in the appendices in Volume II.

Examples of the performance curves illustrative of the output generated for each test method evaluated are shown in Figures 6.5 for a hypothetical test method which tests when product is near the top of the tank, using an array of five equally spaced, volumetrically weighted thermistors. The noise histogram is shown in Figure 10.1. 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 0.04 L/h (0.01 gal/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.

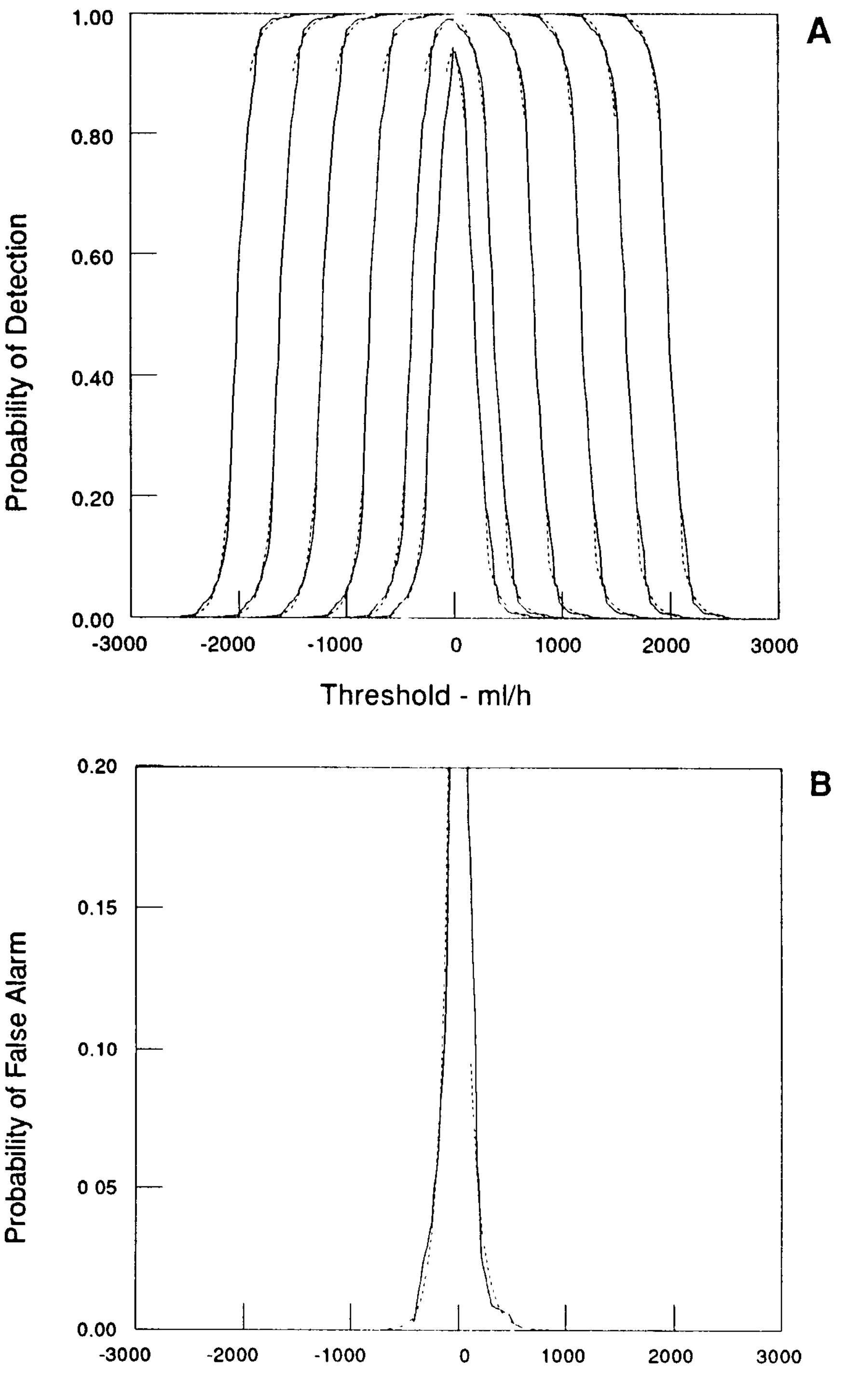
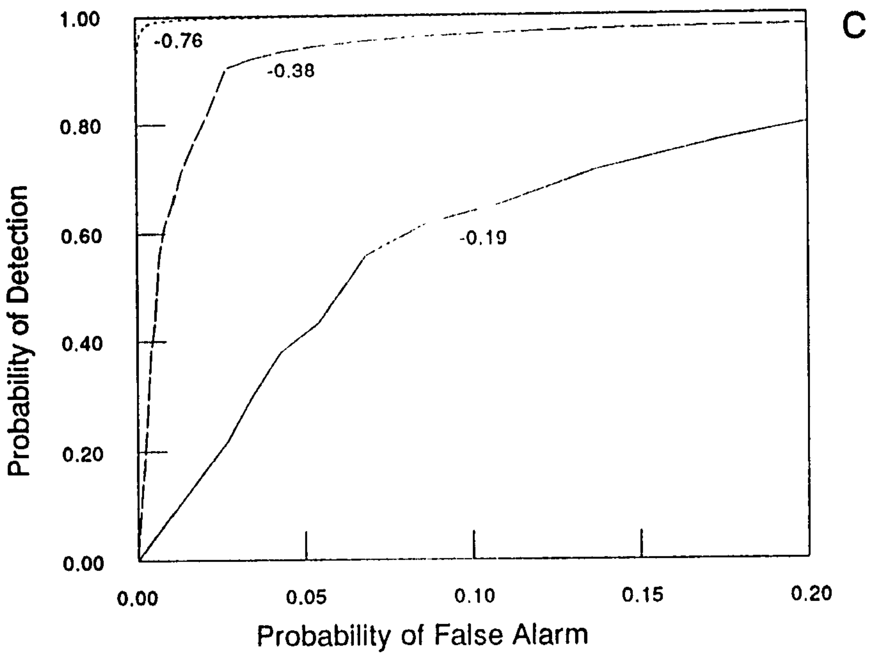


Figure 6.5. Examples of performance curves for a generic leak detection method. (A) P_D vs. Threshold, (B) P_{FA} vs. Threshold, (C) P_D vs. P_{FA} for flow out of the tank and (D) P_D vs. P_{FA} for flow into the tank.



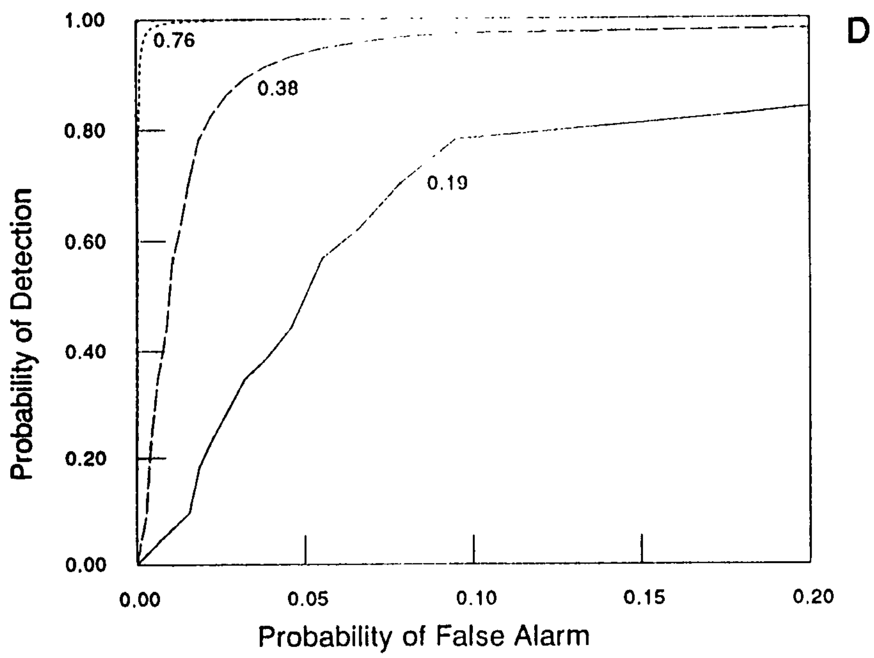


Figure 6.5,(concluded). Examples of performance curves for a generic leak detection method. (A) P_D vs. Threshold, (B) P_{FA} vs. Threshold, (C) P_D vs. P_{FA} for flow out of the tank and (D) P_D vs. P_{FA} for flow into the tank.

7 UST Test Apparatus and Quality Control of Measurements

All of the experimental data used to estimate the performance of the volumetric test methods were collected at the UST Test Apparatus. With this apparatus, full-scale tank tests can be conducted under controlled field conditions. The Test Apparatus can simulate the field delivery of product at temperatures different from that of the product stored underground. Leaks up to 8 L/h (2 gal/h) can be simulated in either the tank or its associated piping with an accuracy better than 0.04 L/h (0.01 gal/h). This is accomplished using a variable-speed pump. The apparatus can also evaluate the effects of subsurface water on test-method responses. In addition, vapor pockets of known size can be created in the tanks or in the associated piping such that, when the tank is filled, vapor is trapped at the top of the tank.

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 [24]. 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.

The majority of the commercially available test methods claim to detect leak rates as small as 0.19 L/h (0.05 gal/h). This claim satisfies the 0.05-gal/h recommended practice specified by the National Fire Protection Association in its Pamphlet 329 [5], which for many years was the only guidance available and thus became the nationally accepted standard for any method used to make a final determination as to whether a tank is leaking or not. The data quality objectives for this project were established to evaluate this common performance claim. Unfortunately, the process was not straightforward, because both the recommended practice and the performance claims are ambiguously stated. Because of the statistical nature of tank testing, a complete specification also requires that the probability of false alarm and the probability of detection and the uncertainty of each be included for the leak rate specified in the performance claim.

7.1 Test Apparatus

The UST Test Apparatus allows control to be exercised, as far as is practical, over the major factors that affect the accuracy of volumetric leak detection methods. The Test Apparatus is environmentally safe and permits the establishment of known test conditions in full-scale underground storage tanks. The Test Apparatus, shown in Figure 7.1, consists of the following major components:

- (1) 30,000-L (8,000-gal) steel tank
- (1) 30,000-L (8,000-gal) fiberglass tank

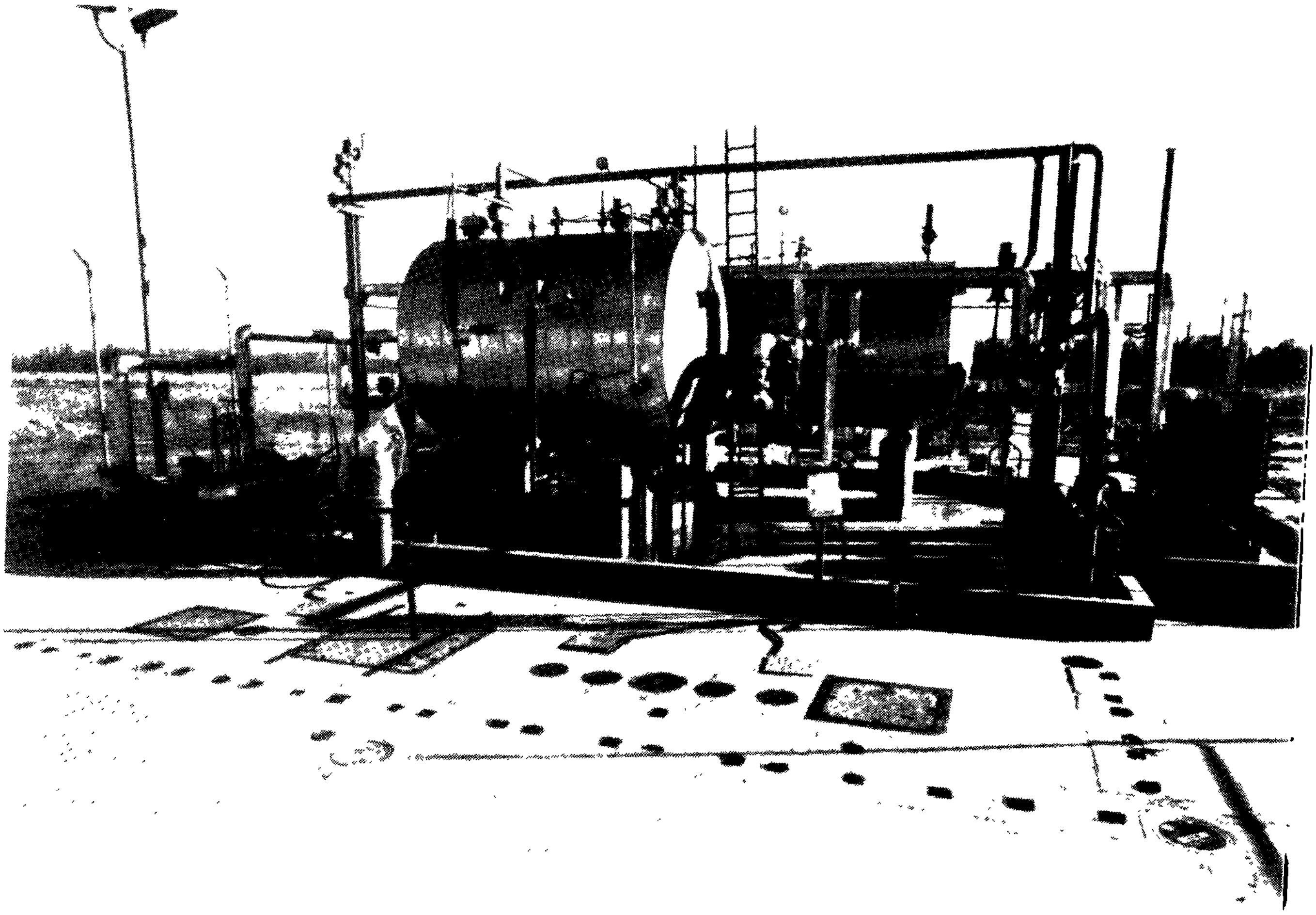


Figure 7.1. UST Tank Test Apparatus.

- Separate, synthetic-membrane pit liners to provide secondary containment for each underground tank and its associated underground piping
- (1) 11,500-L (3,000-gal) tank with heat exchange coils
- (1) 23,000-L (6,000-gal) tank with heat exchange coils
- (1) 154,000-Btu/h electric heater
- (1) 60,000-Btu/h chiller
- (2) 1,500-L/min (400-gal/min) transfer/circulation pumps
- Suction piping and pressure piping
- Monitoring wells both inside and outside the secondary containment of each tank

The two underground tanks adjacent to the above-ground equipment permit easy access for experimentation. Numerous tank penetrations, including manways, accommodate extensive instrumentation and permit maximum flexibility in experimental design. These penetrations also enable any of the commercial volumetric test methods to be used with either tank.

The secondary containment (synthetic membrane pit liner) surrounding each of the underground tanks serves three main purposes. It protects the environment from any unforeseen product release; in the event of a release, it allows the Test Apparatus personnel to determine whether the leak is in the tank or in the associated piping; and it permits, for test purposes, control of the water table surrounding the tank.

The field delivery of product at temperatures different from those of the product stored underground *in situ* can be simulated by extracting product from one of the underground tanks, heating or cooling it in one of the two above-ground tanks (in conjunction with the heater and chiller), and subsequently draining it back into the underground tanks before testing. The resulting internal temperature distributions produce a good test of thermal compensation techniques for leak detection methods.

The effects of subsurface water on test-method responses also can be evaluated in the Test Apparatus. The underground secondary containment liner can be deliberately flooded or drained at controlled rates that are representative of actual field situations. As a result, the effects of the water table elevation change on the structural deformation of the tank and of the thermal responses of the tank and the contained product can be evaluated.

Vapor pockets of known size can be created in the tanks or in the associated piping. The effects of these pockets on methods requiring tank overfilling before testing can be quantified over a wide range of vapor pocket sizes.

Other features of the Test Apparatus include the ability to withdraw product from the underground tanks by either above-grade (suction) or submerged (positive pressure) pumps. In addition, leaks can be induced in either of the tanks or in their associated piping at known, controlled rates over a wide range. These features facilitate the evaluation of each volumetric leak detection method's ability to differentiate piping leaks from tank leaks and allow verification tests to be conducted with a known leak rate.

The Test Apparatus design contains features that not only are directly applicable to the current evaluation program but also provide for considerable flexibility in anticipation of future possible areas of investigation. Among the areas considered are type of product; non-volumetric leak detection methods; and tank size, type of construction, and materials.

The Test Apparatus is situated to enable additional underground tanks to be added quickly (if needed), with minimal disruption of the existing equipment. It is anticipated that, at the minimum, a different tank capacity and a different type of construction (e.g., double-walled tanks) may be evaluated. The numerous monitoring wells, located both within and exterior to the secondary containments of each underground tank, and the numerous penetrations on each tank facilitate access so that additional test methods (such as those that identify leaks by other than volumetric means) can be evaluated readily.

7.2 Data Quality Objectives

The precision and accuracy of the product-level and temperature data collected at the UST Test Apparatus were specified so as to evaluate the performance of each test method at a leak rate of 0.19 L/h (0.05 gal/h) with a probability of detection of 0.95 and a probability of false alarm of 0.001 [11]. An estimate of the precision and accuracy of the measurement systems was made using the performance model shown in Figure 5.9. Assuming that the histograms of the noise and the signal-plus-noise are normally distributed, an estimate of the one standard deviation of the temperature-compensated volume rate needed to meet this performance specification was made. The standard deviation must be 4.76 times smaller than the leak rate to be detected in order to meet the probability of detection and probability of false alarm specified above. This corresponds to 0.04 L/h (0.01 gal/h) for a leak rate of 0.19 L/h. This means that the precision of the instruments used to measure temperature and product level, the accuracy of the constants used to convert temperature and product level to volume, and the number and spatial distribution of the sensors used to measure the temperature-compensated volume must have a total uncertainty of less than 0.04 L/h.

Precision is defined as the one-standard-deviation uncertainty in each successive measurement. The precision of the temperature and product-level data must be defined so that the rate of change of temperature and product level, after conversion to the rate of change of volume, is less than 0.04 L/h. To meet this objective, the temperature measurement system and the temperature calibrations were designed and implemented to ensure a precision of 0.001°C. For product-level measurements, a precision of 0.005 m for measurements made in a 10.2-cm (4-in.)-diameter fill tube and a precision of 0.0000013 m for measurements made in a half-filled, 30,000-L (8,000-gal) tank were required.

Accuracy (bias) is defined as the difference between the measured and the true value of a given quantity. The accuracy of the product-level measurement depends primarily on the magnitude of the error in estimating the volume of product in the tank and in estimating the height-to-volume conversion factor using a perfect tank chart (i.e., a table relating product depth to product volume). The degree of accuracy in using the product-level measurements to estimate a height-to-volume conversion factor from a tank chart is low, except when measurements are made when product level is in the upper 10 to 20% of the tank, where accuracy can be as exact as the precision requirements. Further errors can result from errors in the tank chart itself. A tank chart is usually developed for the nominal geometry of the tank. Any differences between nominal and actual dimensions that occur during fabrication of the tank, or any tilting of the tank or geometric distortion near the top or bottom that occurs during installation or use of the tank, will result in errors in the tank chart. In the upper 5 to 10% of the tank, an error of a factor of 2 can occur due to distortion. Because of errors in the tank chart, especially near the top of the tank, and because of the high degree of accuracy that is required when a tank chart is used to convert product-level measurements to volume, the height-to-volume conversion factor was measured directly in all experiments. The decision to measure the height-to-volume conversion factor eliminated the need to establish unusually stringent accuracy requirements that would be similar in magnitude to the precision requirements. These would have been difficult to achieve.

The accuracy of the product-level measurements was based upon the nominal accuracy specified by the manufacturer of the pressure sensor, *viz.*, 5 mm (0.2 in.), within the 0.04-L/h uncertainty necessary to detect a 0.19-L/h leak rate at the prescribed probabilities of detection and false alarm. There is no specific accuracy requirement for the temperature measurements. A value of 0.55°C (1°F) was selected for the air and ground temperatures. A value of 0.05°C was selected for the vapor and product temperatures so that profiles could be plotted without excessive deviations.

The precision and accuracy requirements, which are summarized in Table 7.1, were reevaluated in early January 1987 after a probability of detection of 0.99 and a probability of false alarm of 0.01 had been selected as the minimum acceptable testing errors in the EPA's proposed underground storage tank regulations [3]. The selection of a high probability of detection was based upon the EPA's desire to identify as many leaking tanks as possible. Since a false alarm does not result in environmental damage, the probability of false alarm was selected to maximize the number of test methods that could meet the performance standard and still provide a measure of protection from excessive testing errors to the owner or operator of an underground storage tank. The precision needed to satisfy this performance standard require that the standard deviation of the noise histogram be 4.67 times smaller than the leak rate to be detected. This is less stringent than originally estimated. Thus, the precision and accuracy requirements remained essentially the same, but the number of tests required to estimate a probability of false alarm decreased significantly.

Table 7.1. Specifications of the Apparatus Instrumentation

Sensor	Accuracy	Precision
Air Temperature	0.55°C	0.55°C
Vapor Temperature	0.55°C	0.55°C
Ground Temperature	0.55°C	0.55°C
Product Temperature	0.05°C	0.001°C
Product Level below Tank Top	0.005 m	0.0000013 m
Product Level above Tank Top	0.005 m	0.005 m

In its final version, the regulation stipulated a P_D of 0.95 and a P_{FA} of 0.05 [4]. The standard deviation of the noise histogram required to meet the final EPA regulation is 3.92 times smaller than the leak rate to be detected. The precision requirements for making temperature and product-level measurements are at their practical technological limits. The data quality objective represents the most stringent requirements on the data, because it assumes that the methods to be evaluated will meet the 0.19-L/h performance claim. In retrospect, neither the EPA regulation nor the performance achieved by the manufacturers required the data to meet this objective. For the majority of the evaluations performed in this program, the precision requirements specified here are 2 to 20 times more stringent than necessary.

7.3 Development of Data Quality Specifications

The data quality specifications are developed below.

7.3.1 Precision

The precision specifications are based on two criteria, referred to as *A* and *B*.

Criterion A. The uncertainty in the rate of change of the total volume times series (generated in the simulation by summing up to four ambient-noise volume time series collected at 1 sample/min over a 1-h period) is less than or equal to 0.04 L/h (0.01 gal/h) at any level in the tank.

Criterion B. The uncertainty in the rate of change of the temperature-compensated time series (generated from a two-point measurement of height and temperature over a 1-h period by the test method being evaluated) is less than or equal to 0.04 L/h at any level in the tank.

These criteria were selected because they represented a realistic range of noise and test-method conditions. If both criteria are satisfied, each test method can be evaluated, using the data collected in the apparatus, to within 0.04 L/h. The sensor precision required to satisfy *Criteria A* and *B* is presented in Tables 7.2 and 7.3, respectively.

Table 7.2. Precision of Each Sensor Required to Satisfy *Criterion A* in a 30,000-L (8,000-Gal) Tank (An instrument with an uncertainty of 0.0424 L (0.0112 gal) would result in an uncertainty of 0.000314 L/h (0.000083 gal/h) over a 1-h period.)*

Product Level	$S_{precision}$	
	Height	Temperature
Half-full 30,000-L tank	0.0000027 m (0.0424 L)	0.0021°C (0.0424 L)
Full 30,000-L tank (product level in 0.102-m (4-in.) diameter fill tube)	0.052196 m (0.0424 L)	0.0011°C (0.0424 L)

*Note: Using a 60-min time series wherein data are collected at 1 sample/min, an $S_{precision}$ of 0.0848 L (0.0224 gal) is required for a volume time series to satisfy the $S_{rate} = 0.04$ L/h (0.01 gal/h) requirement. Since there are up to four time series that may be added together, the required uncertainty in $S_{precision}$ for any one sensor is 0.0424 L (0.0112 gal). If the precision of the temperature and height sensors is specified as 0.001°C and 0.0000025 m, respectively, then the uncertainty in rate is less than 0.04 L/h (0.01 gal/h) at any product level.

The standard deviation of the volume rate can be estimated from the standard deviation of the slope, S_{rate}, of a least-squares line fit to a volume time series using

$$S^2_{rate} = \frac{nS^2_{precision}}{n(\sum t^2) - (\sum t)^2} \tag{7.1}$$

where $S_{precision}$ is the standard deviation of the ordinate (volume) about the regression line, n is the number of independent points, and t is the time of each volume sample. Eq. (7.1) assumes that the system noise of the height and temperature sensors is white. The precision ($S_{precision}$) can be estimated for each criterion using Eq. (7.1).

Table 7.3. Height Sensor Precision Required to Satisfy *Criterion B* in a 30,000-L Tank Given That Precision of the Temperature Sensor is 0.001°C*

Product Level	$S_{precision}$	
	Height	Temperature
Half-full 30,000-L tank	0.0000013 m (0.0201 L)	0.001°C (0.0178 L)
Full 30,000-L tank (product level in 0.102-m (4-in.) diameter fill tube)	0.002540 m (0.0201 L)*	0.001°C (0.0178 L)

* Calculated for a temperature-compensated volume rate of 0.0541 L/h (0.0143 gal/h)

Table 7.4. Uncertainty of the Temperature-Compensated Volume Rate Estimated Using the Temperature and Height Precision Specifications for a 1-h Measurement Period and a Rate of 1 Sample/Min

Height	Uncertainty (L/h)		
	One Thermistor	One Thermistor Array (12 sensors)	Three Thermistor Arrays (36 sensors)
Half-full 30,000-L tank	0.0000135	0.0000038	0.0000023
Full 30,000-L tank (product level in 0.102-m (4-in.) diameter fill tube)	0.0000178	0.0000051	0.0000030

The precision specification is the most crucial. Based on the two criteria, a temperature precision of 0.001°C and a height precision of 0.0000013 m are required. With this precision, the uncertainty in the temperature-compensated volume rate derived from a 1-h measurement of data collected at a rate of 1 sample/min is significantly better than 0.04 L/h (0.01 gal/h), even if only one temperature sensor (e.g., a thermistor) is used for compensation. Since 36 temperature sensors were used, the uncertainty of the rate was six times smaller. This is shown in Table 7.4, which presents the uncertainty in the temperature-compensated volume for measurements made in both half-full and full 30,000-L tanks using a single thermistor, one array of thermistors, and three arrays of thermistors.

7.3.2 Accuracy

The accuracy specifications are based on *Criterion C*, which states that the uncertainty in the product-level measurement required to estimate the product volume from a tank chart, and used in making an estimate of the thermally induced expansion or contraction of the product, results in a volume error less than or equal to 0.04 L/h due to a temperature change of 0.1°C/h.

The largest volume changes per unit of product-level change occur in a half-filled tank (where the surface area of the free product is largest in a horizontal right-regular cylindrical tank). This corresponds to a 157-L/cm (106-gal/in.) volume change in a half-filled 30,000-L tank containing gasoline. At this level, a 303-L (80-gal) error in the product volume results in a 0.04-L/h error due to a temperature change of 0.1°C/h. This corresponds to a product-level change of 1.3 cm (0.51 in.). The geometry of the UST Test Apparatus tanks was determined to an accuracy of 3.2 mm (0.125 in.) using a tape. A 3.2-mm error in tank dimensions results in an error of 95 L (25 gal), within the 303-L allowable error. *Criterion C* does not place any severe constraints on accuracy.

In general, the errors inherent in the tank chart itself can be large. The accuracy criterion, which was established assuming that the tank chart is accurate, was not required in order to estimate the height-to-volume conversion factor in the upper portion of the tank.

7.3.3 Representativeness

The performance estimates depend strongly upon the product-temperature changes that occur in a storage tank. Before the evaluations were started, a study was conducted to estimate the range of difference between the temperature of the product delivered to the tank and that of the *in situ* product and of the surrounding ground [11]. In all, 77 cities in the United States, including Hawaii and Alaska, were represented. The mean temperature difference during January was +3°C and during July -8.5°C. Based on this study, it was concluded that product-temperature changes caused by the addition of product at least 10.5°C warmer or cooler than the product in the tank would cover approximately 95% of the possible test conditions found nationally over the course of a year. During any one month, the 95% confidence intervals on the temperature differences were $\pm$ 5°C.

Product temperature conditions must be representative of conditions that would be found in the field during actual testing. Therefore, the data from which the temperature database was developed were collected at the Test Apparatus, and were generated assuming a uniform distribution of temperature differences between $\pm 10^{\circ}C$ so that the thermal changes expressed as a volume rate were approximately normally distributed with a standard deviation of 850 ml/h (0.225 gal/h).

Both of the 30,000-L tanks were used to collect the data at the Test Apparatus. In theory, the performance of a method should improve as tank capacity decreases, because, for example, the magnitude of the thermal expansion or contraction of the product also was shown to decrease as product volume decreased. Thus, the results of the evaluation are applicable to smaller-capacity tanks as well as to other tanks with similar diameters. The mean capacity of tanks in the United States is less than 23,000 L (6,000 gal) [2].

An extremely important source of noise is the deformation of the tank that may occur when product level is changed during test preparation and setup. The steel and fiberglass tanks were installed according to their manufacturers' specifications, and represent tanks which are relatively new (approximately one year old during the evaluations) and correctly installed. Since there are several hundred different types of tanks, different methods of installation, and different soils and backfill materials, the deformation characteristics of these particular tanks represent only one of a range of conditions found in the field. Available information [7, 25] suggests that the time constant of the tanks is similar to other measurements of time constants. Furthermore, since it is the backfill and *in situ* soil that seem to control the deformation of the tank walls, it is believed that the UST Test Apparatus tanks are at least typical of other new tank systems installed with a pea-gravel backfill.

The distribution of the volume of vapor trapped in an overfilled-tank test is also unknown. To obtain an accurate estimate of the trapped vapor distribution would require, as a minimum, basic information on the geometry of the tank as installed and feedback on how effectively the tank-test operators remove the vapor during the overfilling process. As a consequence, precise estimates are not available for incorporation in the performance evaluation. Qualitative estimates of vapor pocket effects, however, were developed and discussed based upon vapor bound estimates of the maximum size of vapor pockets which could be expected to exist.

The making of a complete performance estimate is hampered by the lack of information on the volume of trapped vapor and the time constant and tank elasticity constant for a representative national population of tanks. This is an obvious constraint that was known and planned for at the beginning of the program.

It should be noted that the above-ground piping system installed in the Test Apparatus is not typical of retail service stations. This was known and was also pointed out by test-method manufacturers, representatives of the petroleum industry and trade associations, and the EPA peer review panel. To avoid potential complications, none of the product transfer piping was included in the tests. The tank being tested was isolated from the above-ground tanks for the duration of the evaluations. All other aspects of the Test Apparatus were judged to be representative of a 30,000-L tank system that might be encountered in the field.

7.3.4 Completeness

The amount of temperature and product-level data required to validate the noise models and perform the evaluation was sufficient to meet the data quality objectives of the program.

7.3.5 Comparability

All data collected during the program were obtained at the UST Test Apparatus using automated data acquisition systems for data collection, calibration, and reduction. The data set that was collected is unique. For three of the methods, performance evaluations with these data were compared to field test evaluations of these same methods employed with different testing protocols. Agreement was within the experimental errors of the ambient noise field and the protocol differences [6-8, 21].

7.4 Instrumentation

Instrumentation used to gather data during the ambient noise experiments and to conduct the Field Verification Tests consists of several integrated systems designed to acquire highly precise measurements of product level and temperature in the underground tanks. A laser interferometer with two channels obtains detailed measurements of product-level changes. Absolute product level and atmospheric pressure are measured by separate pressure sensors. In addition, product temperatures are measured by means of 36 to 42 thermistors distributed vertically at three locations in each tank, seven thermistors distributed vertically in the ground near each tank, and one air thermistor. The temperature of the concrete pad and laser stand are also measured, as required, to support specific experiments.

The instrumentation was designed and calibrated so that the uncertainty in the volume fluctuations produced by the instrumentation itself was low enough to meet the data quality objectives. All instrumentation met the design specifications. Any individual sensor (e.g., a thermistor) which failed to meet specifications was not used in the analysis and was replaced at the next calibration. All instruments were calibrated on a regular schedule (usually monthly) according to the Quality Assurance Project Plan (QAPP) [16].

7.4.1 Laser Interferometer

7.4.1.1 Description

The laser interferometer measurement system is a highly precise instrument used to measure changes in the height of the product surface in a UST. The laser interferometer system consists of two elements: a laser interferometer mounted on a rugged adjustable stand, and two brass tubes inside of which are positioned floats containing corner-cube beam reflectors. The signal from the two interferometer channels is shown on two local displays which are in turn connected to a data acquisition computer so that long-term testing can be conducted. In operation, the laser measures changes in float position with respect to the interferometers mounted on the stand. The reference standard for these distance measurements is the wavelength of the laser light, which is very tightly regulated.

Product-level changes are measured simultaneously in both tubes, with one opened and one closed to the product in the tank. Product-level changes in the tube open to the tank are identical to the product-level changes in the tank, and thus are affected by all sources of noise and simulated leaks. Product-level changes in the closed tube are theoretically affected only by the thermal expansion or contraction of the product and by evaporation or condensation of the product.

Because the heat generated by the laser head and electronics is separated from the interferometers, the height measurements are very precise. The resolution and precision of the laser interferometer (according to its manufacturer's specification) are 0.025 and 0.043 μm, respectively. The laser is re-zeroed each time the power is turned on or off, or each time the laser display units are reset. As a consequence, the system is used to measure product-level changes but is not used to measure the depth of product in the tank. The product-level data are sampled at 200 Hz (200 samples/s), with a special-purpose data acquisition program (LIDAS) [26], written in Hewlett-Packard (HP) Basic, on an HP 9836 computer system that collects, downsamples, stores, and displays the data in real time. The data are transferred between the laser display units and the computer system via two binary-coded decimal (BCD) interface cards and two specifically designed 64-pin connecting cables.

7.4.1.2 Calibration

The performance of the interferometer system was verified in four separate tests, and was regularly checked during all experiments. First, the precision of the laser height measurement was determined to be 0.075 μm. This was determined from the white, high-frequency region of measured height change spectra obtained at a sample rate of 5 Hz with the laser.

Second, the float/tube assembly was checked for calibration by inducing height changes in the tube itself with precisely known volumes. This was accomplished by connecting the tubes so that, as measured by the laser, a cylinder of known volume inserted in one tube effects a displacement of one-half the volume in the other tube. The results of these tests suggested that, based upon the known geometry of the displacement volumes and of the brass tubes, the indicated volume change was well within the range of the experimental error of the expected responses.

Third, a similar calibration of the float/tube assembly conducted as part of each test consisted of repeatedly immersing a cylinder of known volume into the tank. The height change indicated by the laser system was then compared to the height change that would be expected based upon the previously measured tank geometry and measured absolute liquid level in the tank. Three different known changes in product height were induced in the half-filled steel tank and were measured by the interferometer to within 2 μm.

A fourth type of test was conducted periodically with both tubes open to the tank environment for 24 h. A high degree of coherence between the two channels was observed. Differential height changes observed between the two interferometers were caused by thermal expansion of the aluminum stand separating them and were compensated for by making use of the measured temperature of the laser stand.

7.4.1.3 System Checks Between Calibrations

The test of the laser interferometer height measurement system was made for each experimental run to determine whether the float/tube system was functioning properly. This was accomplished by inserting into the tank, and then removing, a solid object of known volume and measuring the resulting height change. The average height change for multiple in-and-out cycles was computed and compared to the tank calibration data for the mean product level in the tank. Typically, a 1,544-ml cylinder was used for the calibration check. The object was completely immersed for 90 s and then removed entirely for 90 s. Up to 10 cycles were made for each test run.

7.4.2 Pressure Measurement System

7.4.2.1 Description

Two pressure sensors were employed in the Test Apparatus. One sensor, located at the bottom of the tank being tested, was used to determine the mean level of product in the tank. This level was then converted, by means of a tank chart, to a mean volume of the product stored in the UST. The other sensor, located on the surface of the Test Apparatus, provided a detailed record of changes in atmospheric pressure. The piezo-resistive pressure transducers that were used to make the pressure measurements were selected because of their high resolution, long-term stability and stainless steel contact surface. Pressure and temperature were measured using two HP 3421A Data Acquisition/Control Units and an IBM AT computer system. Each HP 3421A unit scanned up to 30 channels of two-wire sensor data serially with a 5-1/2 digit multimeter. The data were transferred from the HP 3421A to the computer via an interface bus (HPIB). A modified version of the HP 3055S data acquisition software (TPDAS) [27] was developed for acquiring data with two HP 3421A units, and an IBM AT-compatible system was used for data collection.

7.4.2.2 Calibration

Calibration of the pressure sensor was accomplished monthly by putting a known pressure on the sensor and measuring the resistance. A known pressure was produced by inserting the pressure sensor into a long tube filled to a known level with liquid. The calibrations were performed over the entire measurement range (approximately 4 m for product and 1 m for atmospheric pressure) in either 15-cm (6-in.) or 30 cm (12-in.) increments, depending on the sensor being tested. The liquid levels were read visually to the nearest 0.5 mm, and the pressure readings were automatically recorded to the nearest 0.1 Ω. At each pressure, data were collected at 1 sample/min for a period of 7 min. Calibrations were performed using water. The gasoline calibration values were generated from those for water calibration, using the density measurements of the gasoline.

The precision of the pressure sensor was determined by the standard deviation of the ordinate about the regression line developed from 5-min averages of data at each pressure level. The accuracy, which depends on the accuracy of the density measurement and the accuracy of water levels in the calibration tube, was within 1 mm at the completion of the calibration.

7.4.2.3 System Checks Between Calibrations

Before and/or after each experimental run, a gauge-rod measurement of the mean product level in the tank was made and was compared to the pressure sensor measurements. These data were used to check the accuracy of the pressure sensor and to refine the calibration for each test, if necessary.

7.4.3 Temperature Measurement System

7.4.3.1 Description

The temperature-measurement system, which consisted of up to 51 two-wire, 30,000-Ω thermistors, two HP 3421A Data Acquisition/Control units, and an IBM AT-compatible computer system, measured product, ground, and air temperature. Two ultra-stable resistors were connected to each of the HP 3421A units to monitor the electronics.

Product temperature was measured using three vertical arrays of thermistors separated horizontally, permitting accurate measurement of the average rate of change of temperature of the product and vapor in the tank. The individual thermistors were spaced vertically at intervals of 20 cm (8 in.), with the bottom thermistor located 10 cm from the bottom of the tank. For each array, two thermistors were placed in the 10-cm-diameter fill tube, 10 cm and 46 cm, respectively, above the top of the tank. Up to 36 thermistors were used to measure the average rate of change of temperature of the product.

With three arrays it is possible to measure of the horizontal gradients in the temperature field along the long axis of the tank. Each array measures the temperature of approximately one third of the product volume. The average volume surrounding each thermistor level in a 30,000-L steel tank is given in Table 7.5. Thus, if the precision of the thermistor is 0.001°C, the uncertainty in the product-volume change caused by a temperature change in the vicinity of a thermistor, even one located at the middle of the tank, is small. The uncertainty for a thermistor located at the midpoint of a gasoline tank is 0.0019 L (0.0005 gal).

Table 7.5. Estimate of the Volume Surrounding Thermistor Levels in a 30,000-L Steel Tank 2.43 m in Diameter

Thermistor Number	Thermistor Height from Bottom (m)	(in.)	Volume Around Each Thermistor (L)	(gal)
1	0.102	4	1,204	318
2	0.305	12	2,112	558
3	0.508	20	2,605	688
4	0.711	28	2,915	770
5	0.914	36	3,108	821
6	1.118	44	3,199	845
7	1.321	52	3,199	845
8	1.524	60	3,108	821
9	1.727	68	2,915	770
10	1.930	76	2,605	688
11	2.134	84	2,112	558
12	2.337	92	1,204	318

An array of seven thermistors was used to measure the ground temperature. These data were used primarily to specify a test condition. The thermistors were placed in a steel tube so that they could be replaced if they failed. The tube was filled with sand and its top insulated from surface temperature changes.

Air temperature was measured using a single thermistor. The thermistor was located in a protected area, so that the sun did not shine directly on it.

A 30,000-Ω, two-wire thermistor was used to make all temperature measurements (ground, air and product). The thermistor, a thermally sensitive resistor, was designed to resolve temperature changes of 0.001°C and to begin sensing ambient temperature changes of 0.001°C (as opposed to sensing the temperature changes produced by the electronics), using the HP 3421A. This was accomplished by driving the thermistor with a constant current of only 10 µA. At this current, a resolution of 1 Ω was obtained with the HP 3421A. At 25°C, this corresponds to a resolution of 0.0008°C. The resolution increases for lower temperatures and decreases for higher temperatures (Figure 7.2). Each thermistor was placed in a stainless steel sheath, 0.038 m (1.5 in.) in length, which was then filled with epoxy. The time constant of the thermistors was only a few seconds. The data were collected at 1-min intervals, using the HP 3421A driven by an IBM AT compatible computer.

7.4.3.2 Calibration

The characteristics of the thermistors and the accuracy and precision of the system that measures temperature were estimated during calibration. Calibration of the thermistors includes:

- o developing a mathematical curve to define the resistance-versus-temperature characteristics
- o determining the precision and accuracy of the system that measures temperature

All calibration measurements were made using the entire array of thermistors, the two HP 3421A Data Acquisition/Control units, and the IBM AT compatible computer system.

Calibration curves were developed to convert the measured resistance to temperature over the expected range of temperatures to be encountered during the experiments (0 to 30°C). Figure 7.2 presents the nominal curve of resistance versus temperature for a 30,000-Ω thermistor. The relationship between temperature and resistance is highly nonlinear. The equation,

$$\frac{1}{T} = a_0 + a_1 \ln R + a_2(\ln R)^2 + a_3(\ln R)^3 \qquad (7.2)$$

where T is in degrees Kelvin and R is in ohms, has been determined to accurately represent the mathematical relationship between temperature and resistance for a negative-temperature-coefficient thermistor. The coefficients (a_i) were used to convert the resistance measurements made in ohms to temperature in degrees Celsius.

The calibration curves were developed by comparing the resistance measurements made by each thermistor to a reference thermometer, which was referenced to the triple point of water. Repeated measurements of the triple point of water can be made to within 0.0002°C. The reference thermometer, an HP Quartz thermometer, has a nominal accuracy of 0.04°C and a precision of 0.0001°C. The thermistor measurements were also referenced to two ultra-stable resistors, which indicates the presence of any drift in the electronics over time and permits the calibration curves of the individual thermistors to be adjusted accordingly. Resistors stable to 0.5 Ω or less are required; resistors stable to within 0.1 Ω were used.

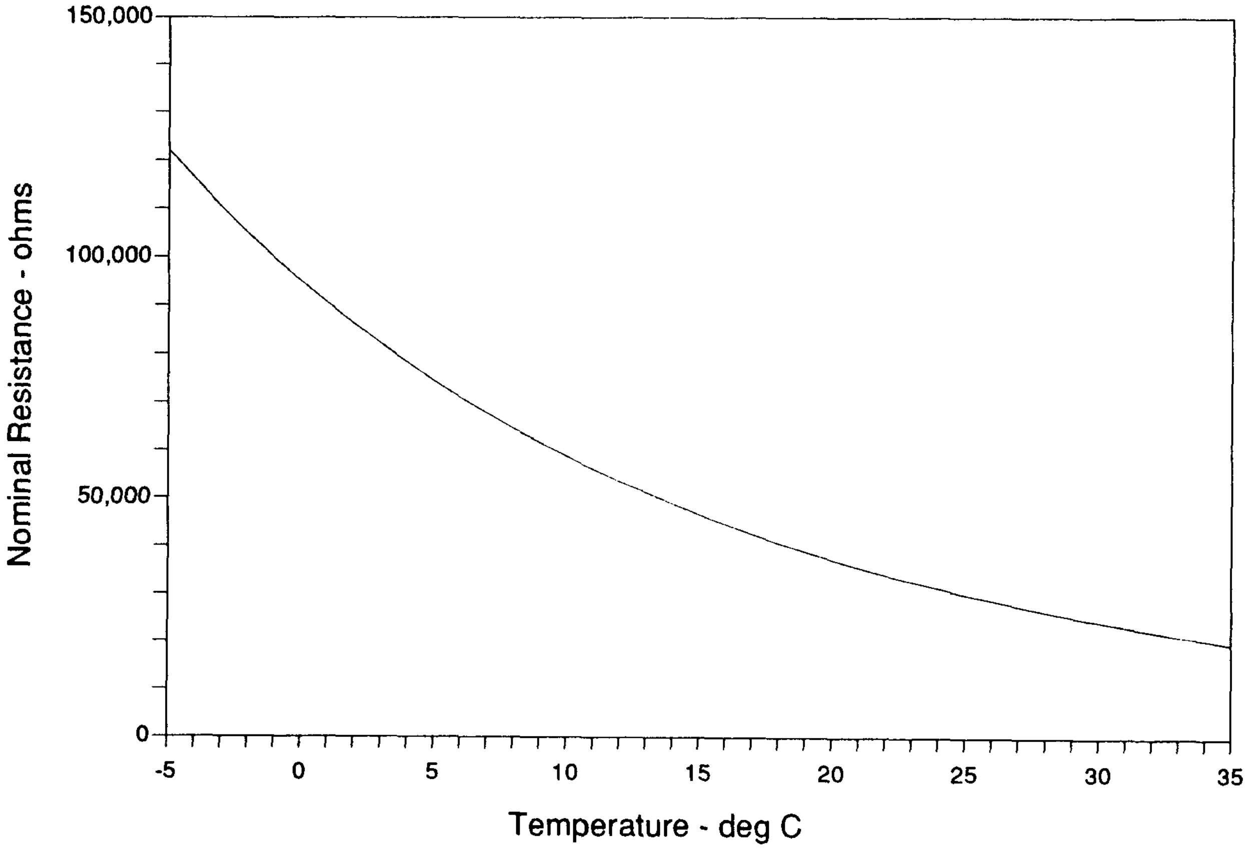


Figure 7.2. Nominal resistance-versus-temperature curve for a 30,000-Ω thermistor (YSI 44008).

The calibration procedure was performed monthly over the duration of the program. During the life of this project, three procedures were used for calibration. All involved placing all of the thermistors and the reference thermometer into an insulated constant-temperature water bath. The methods used to change the temperature of the bath evolved during the course of the program. In the first method, simultaneous measurements of resistance and bath water temperature were made for periods of 15 to 20 min at approximately 8 to 12 distinct bath temperatures. The bath temperature was changed or "stepped" in increments of approximately 2.5 to 5°C over the range of 0 to 30°C. The bath temperature was changed by adding warmer or cooler water to the existing bath. At each water bath, the temperature was allowed to reach thermal stability prior to collecting calibration data. This was accomplished by mixing the water thoroughly for 15 to 20 min before the calibration data were collected. The coefficients in Eq. (7.2) were estimated using a least-squares fit to the mean temperature and mean resistance at each nominal bath temperature.

An estimate of the accuracy, the inter-thermistor variability, was obtained by computing the standard deviation of the temperatures measured by all the thermistors for each temperature bath.

An estimate of the precision (or repeatability) of each thermistor was made for each bath temperature from the standard deviation of the ordinate (i.e., temperature) of a linear regression curve fit to the temperature and resistance data.

The procedure was improved in March 1987. Instead of sampling at 8 to 12 distinct temperature baths, an attempt was made to sample evenly throughout the temperature range. This was done primarily to reduce the manual input required to perform the calibrations and to reduce the risk of underdetermining the resultant curve fit. The procedure involved placing the thermistors and reference thermometer into an insulated ice-water bath and allowing a drift to ambient temperature to take place via conductive heat transfer. As the temperature of the water bath approached the ambient air temperature, the rate of temperature drift began to approach zero. At this point, it was necessary to add hot water (that is, to "step" the temperature bath as was done in the previously described calibration method) in order to collect data through the required temperature range. The resulting data set was then downsampled to produce a set containing approximately 250 data points. The coefficients of Eq. (7.2) were determined by a least-squares solution using the downsampled resistance-temperature data set.

The third method of thermistor calibration employs a microprocessor-controlled temperature bath that maintains a constant rate of change and that was first used in October 1987. The thermistors were placed, along with the reference thermometer, into an insulated water bath, which, in turn, was placed into a thermally controlled water bath. The insulated water bath drifted at a controlled rate of approximately 0.01°C/min through a range of 2.5 to 27.5°C. Once again, the resulting data set was downsampled to produce a set consisting of approximately 250 data points, and the coefficients of Eq. (7.2) were determined by a least-squares solution using the downsampled resistance-temperature data set.

When using either of the latter two calibration methods, an estimate of the precision of a thermistor is given by the standard deviation of the ordinate (i.e., temperature) of the regression curve fit of Eq. (7.2) to the temperature and resistance data calculated for each contiguous 0.1°C block of data over the entire temperature range. Two estimates of accuracy were made. To show the inter-thermistor variability, the first estimate was made, as before, by calculating the standard deviation of the temperatures measured by all of the thermistors at each of the 250 temperature points. The second estimate was made to determine the accuracy of each thermistor. This was achieved by computing the difference in the mean temperature between each 0.1°C segment of data and the calibration curve (offset).

Any thermistors that did not meet the precision and accuracy specifications over the entire temperature range (excluding calibration artifacts) were either physically replaced or were not used in the analysis. Typically, the thermistors that needed replacement had been identified before the monthly calibration. These thermistors, in addition to any that were suspected of poor performance, were replaced before the calibration. Thermistors that developed problems between calibrations were not used in the analysis, and their data were replaced by averaging the data from the thermistors vertically or horizontally bracketing them.

As a post-calibration analysis, the drift of the thermistors from the previous month's values was calculated for a nominal value of 25,000 Ω (nominal temperature of 25°C). This analysis gave an indication of how the performance of the thermistors had changed between calibrations.

7.4.3.3 System Checks Between Calibrations

Two checks of the temperature measurement system were made for each test. First, resistance measurements of the ultra-stable resistors during the thermistor calibration check were made throughout the test to determine whether there were electronic problems. If resistance changes of approximately 2 Ω occurred during any 1-h period, it was determined that the electronics were generating enough heat to affect the measurement of temperature of 0.001°C. If this occurred, the HP 3421A was replaced. In general, the electronics were robust and did not affect the temperature measurements. Second, a visual check of the time series of all of the thermistors was made after each test, also to identify any obvious problems. A more in-depth analysis was performed for thermistors which exhibited anomalous behavior.

7.4.4 Leak Inducement System

7.4.4.1 Description

Leaks were generated by withdrawing liquid from the tank (or adding it) using a variable-speed metering pump. The product was weighed and the leak rate calculated using the calibration curve. Leak rates can be resolved to 0.001 L/h or better. The magnitude of the leak was given by the slope obtained through least-squares regression analysis.

7.4.4.2 Calibration

Calibration of the leak inducement system was performed initially prior to installation, and was checked periodically during the test program. The initial calibration of the scale was performed by its manufacturer, using NBS traceable reference weights. The entire assembly (including scale, pumps, piping, and product-receiver tank) was calibrated upon its completion. NBS traceable weights were again used for this calibration. Readings were taken at increments covering the complete range of operating conditions. A calibration curve was then generated by means of a least-squares curve fit, and the precision and accuracy of the assembly were estimated.

The variable-speed metering pump, used to withdraw product from different locations in the apparatus, was initially calibrated with gasoline. The pump was operated at eight different speeds covering the entire anticipated operating range. For each speed, the discharge liquid was collected in a graduated cylinder for a period of 3 min. Five separate readings were made at each operating speed, and the results averaged to produce a single value. A least-squares curve fit to these data allowed the desired leak rate to be established subsequently during a particular test, while simultaneously allowing an estimate of the variance associated with pump performance to be made.

The accuracy of the pump's flow rate was checked by means of a high-precision industrial scale capable of resolving weight changes as small as 0.0001 kg (0.0002 lb). For the current set of tests, induced leak rates of unleaded gasoline ranging from 0.04 L/h to 7.6 L/h (from 0.01 gal/h to 2.0 gal/h) were anticipated. This corresponds to weight changes ranging from approximately 0.028 kg/h (0.062 lb/h) to 5.63 kg/h (12.4 lb/h). Based upon these flow rates, the most demanding precision required for the weighing apparatus occurs at the low flow rate of

0.04 L/h. Ideally, it is desirable to establish the flow rate within a 15-min measuring period. As a consequence, a precision of the weighing apparatus of approximately 0.0014 kg (0.003 lb) was required.

7.4.4.3 System Checks Between Calibrations

Calibration checks, also using NBS traceable reference weights, were performed periodically in order to ensure that the scale was functioning properly. Checks were made by placing known weights on top of the receiver tank and subsequently recording the scale response. Deviations from the known value of the indicated weight were used to identify potential scale problems, and to enable rapid corrective action to be taken.

7.5 Underground Storage Tanks

In order to convert product-level measurements to corresponding volume changes reliably, calibration was required for each tank. For the current tests, two means of determining the tank charts were devised. First, the inside dimensions of both the steel and fiberglass tanks were measured in detail after installation but before adding product. These measurements were used to calculate the volume of the tank as a function of height from the tank bottom. The results of these calculations were then compared with the manufacturer's tabulated values. Four measurements of diameter at 45° intervals around the longitudinal axis of the tank were made at each of ten axial locations. The measurements were made to the nearest 0.32 cm (0.125 in.), using a steel tape. A theoretical tank chart was generated to compute tank volume at any depth in the tank, assuming that the tank was a right regular cylinder. For the steel tank, for example, a diameter of 242.89 cm (95.625 in.) and a length of 649 cm (21 ft 3.5 in.) were used to generate the chart. The total capacity of the tank was estimated to be 30,107.8 L (7944 gal). An error of $\pm$ 0.32 cm (0.125 in.) in diameter would result in disparate tank volume estimates of 30,028.2 L (7923 gal) and 30,183.6 L (7964 gal), respectively. An error of $\pm$ 0.32 cm (0.125 in.) in tank length would result in tank volume estimates of 30,092.6 L (7940 gal) and 30,119.1 L (7947 gal), respectively. The maximum error in estimating tank capacity from these measurements is 95 L (25 gal).

Second (and in conjunction with these physical measurements), the laser interferometer was employed to determine a height-to-volume conversion factor for product at any level in the tank. This was achieved by measuring the gross level in the tank (either with the product pressure sensor or a dipstick) and then alternately inserting and removing a cylinder of known volume and noting the corresponding product-level changes. The largest uncertainty in the height-to-volume calibration factor occurs when product level is between 231.14 and 242.89 cm

(91 and 95.625 in.) in the tank. An extensive set of measurements at increments of 1.27 cm (0.5 in.) was made in order to generate an experimental curve. The theoretical and experimental height-to-volume curves for the steel tank are shown in Figure 7.3.

A height-to-volume calibration was performed routinely after each test run and was compared to the calibration factor that would be expected based upon the measured tank geometry and gross product level; this was done to verify that the laser interferometer measurement system was functioning properly and to obtain the actual height-to-volume conversion factor for that test run.

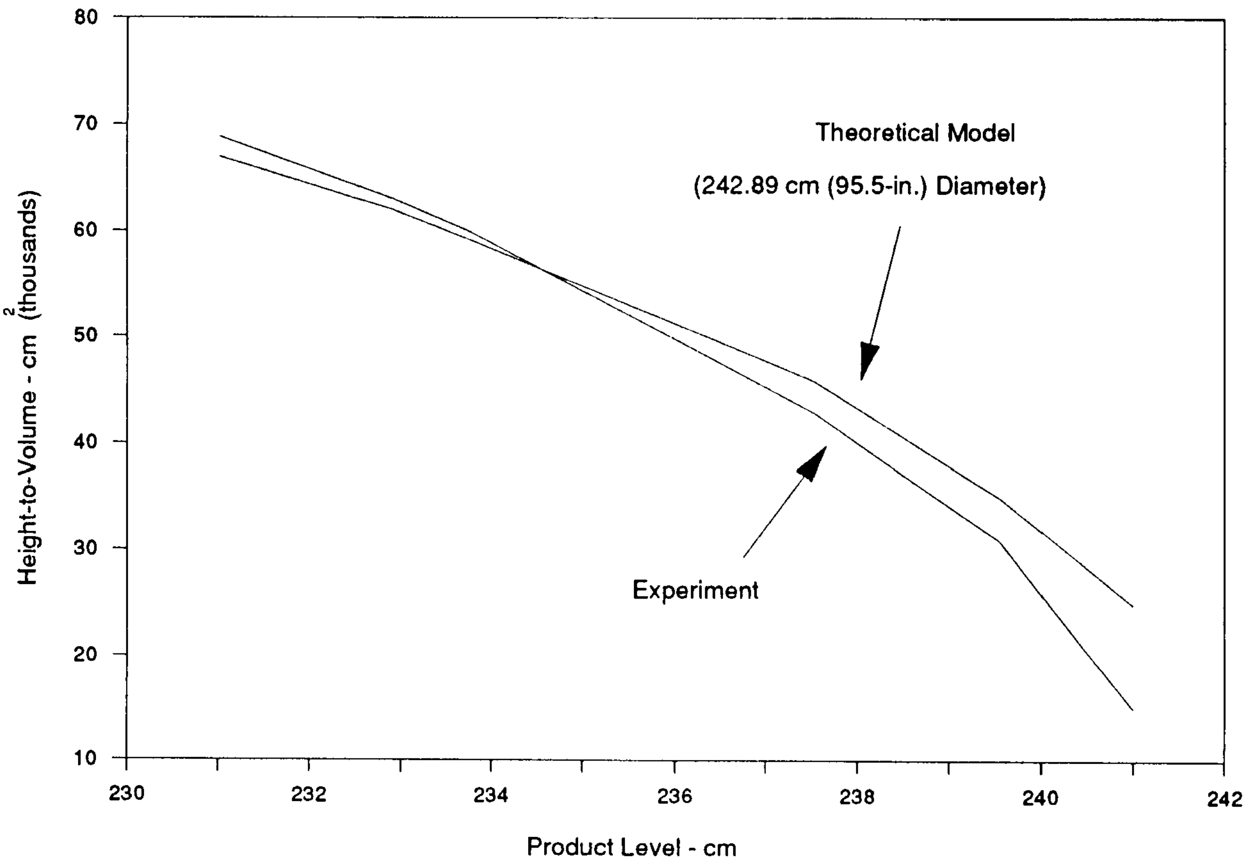


Figure 7.3. Experimental and theoretical height-to-volume conversion curves near the top of the steel tank. The experimental curve was obtained from the height displacement produced by a 1.544-L cylinder at each mean product level.

8 Ambient Noise Experiments

The objective of the ambient noise experiments conducted at the UST Test Apparatus was to support the test method performance evaluation and to validate the ambient noise models. Four of the ambient noise sources are, in one way or another, dependent on a temperature fluctuation. Temperature fluctuations in the product or in the vapor space are driven by a differential between the temperature of the backfill and soil and that of the product; this differential is incurred immediately after product addition. Neither surface-wave effects nor the most important structural deformation effects are not temperature-driven, and, after model validation, their impact can be assessed by exercise of the simulation. As a consequence, the Test Apparatus experiments were designed to sample the product temperature and level under a variety of conditions. The insights gained during the modeling and measurement program represent a significant contribution toward improving the performance of volumetric tank tests.

The emphasis of the ambient noise experiments was placed on the effects of product-temperature changes (including those that occur after product deliveries and topping the tank), structural deformation, and trapped vapor. Some of the effects of product temperature have been described previously in [28, 29], and some of the effects of tank deformation have been described in [23].

8.1 Product-Temperature Changes

Thermal expansion and contraction of the product in the tank can be inferred from a direct measurement of temperature using three thermistor arrays. In order to find the volume fluctuations produced by thermal fluctuations, it is necessary to make an accurate measurement of the product density. The coefficient of thermal expansion is determined in the laboratory from product density measurements as a function of temperature. The range of thermal product-volume fluctuations experienced by UST systems in the United States can be approximated by conducting experiments where the differential temperature between added and existing product is varied. The magnitude of the modeling error is estimated by overfilling the tank, removing any vapor pockets that may be present, waiting until structural deformation effects have become small, and comparing the measured volume changes to the modeled volume changes.

An analysis of the temperature fluctuation that occurs in an overfilled tank during the first 24 h after a delivery was performed using temperature data collected in the steel tank of the Test

Apparatus. To conduct each run, 15,000 L (4,000 gal) of product, at temperatures that were 0 to 10°C cooler or warmer than the temperature of the ground and of the *in situ* product, was added to the half-filled tank.

Thirteen 24- to 48-h tests were analyzed in order to characterize the temperature field and volume changes generated by temperature fluctuations. All tests were conducted with the fluid level between 233.7 and 238.8 cm (92 and 94 in.) in the 242.9-cm (95.6-in.)-diameter tank. Testing at this level permits the approximation of temperature changes in a full tank while simultaneously avoiding the incidental trapping of vapor pockets.

8.1.1 Product Temperature Analysis

Three analyses were performed. The first estimated and tabulated the magnitude of the thermal volume changes as a function of time after delivery. Temperature-volume changes were computed using the volumetrically weighted measurements from all submerged thermistors on the three vertical arrays. Results for data collected on 28 October 1986 are presented in Table 8.1 and Figure 8.1.

Table 8.1. Thermal Volume Changes Estimated from a 1-h Block of Data as a Function of Time after Delivery (28 October 1986)

Time (h)	Temperature Volume Change (L/h)
3	2.532
6	1.900
9	1.459
15	1.026
21	0.841

This analysis, which included all 13 tests, indicated that thermally induced volume changes are large even 24 h after product has been added to the tank, and that temperature compensation is necessary in order to conduct an accurate tank test. In the course of a 24-h test, uncompensated volume rates of 0.8 to 2.5 L/h were observed, as illustrated in Table 8.1.

The second analysis characterized the horizontal spatial inhomogeneities of the temperature field. The fundamental issue was whether one thermistor array is sufficient to characterize the temperature field of the whole tank. The analysis was conducted by:

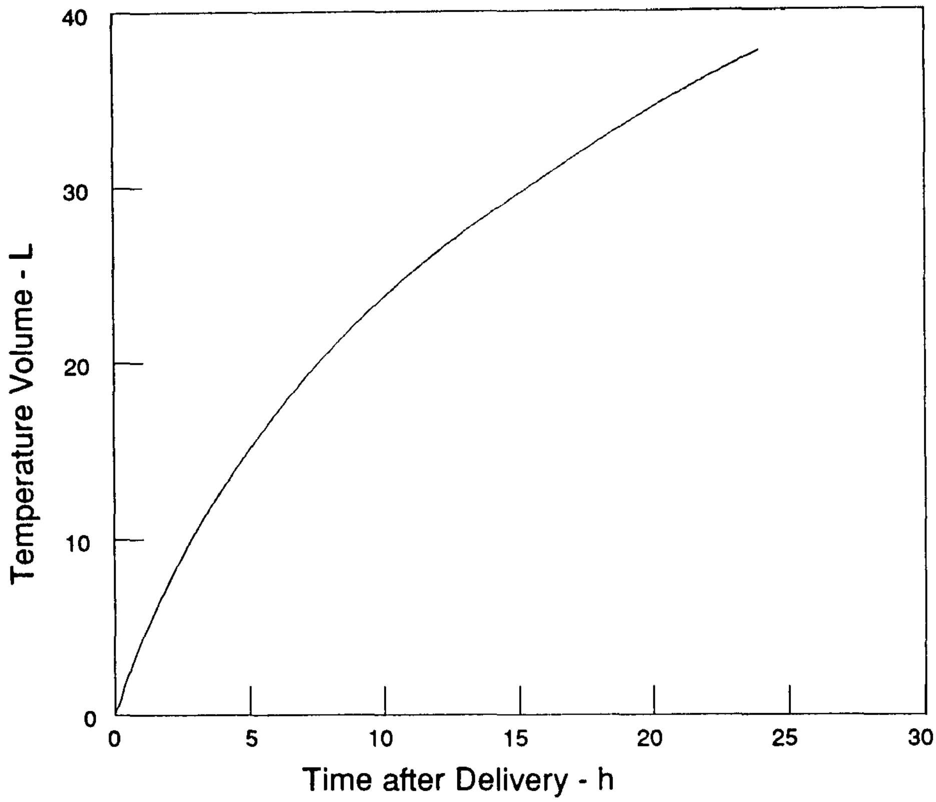


Figure 8.1. Temperature volume time series (28 October 1986).

- o 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
- o subtracting the average thermal volume time series from each array's volume time series
- o 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
- o differencing the volume rate (slope) time series of each array from the average of all three arrays

Results suggest that when testing is begun at least 4 to 6 h after product delivery, a single vertical 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, three arrays are not sufficient to characterize the temperature field. After 6 h, the differences in the rate of change of temperature between arrays, expressed as a volume, is small. This is illustrated in Figure 8.2 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 larger than 0.5 L/h and smaller than 0.1 L/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 become small.

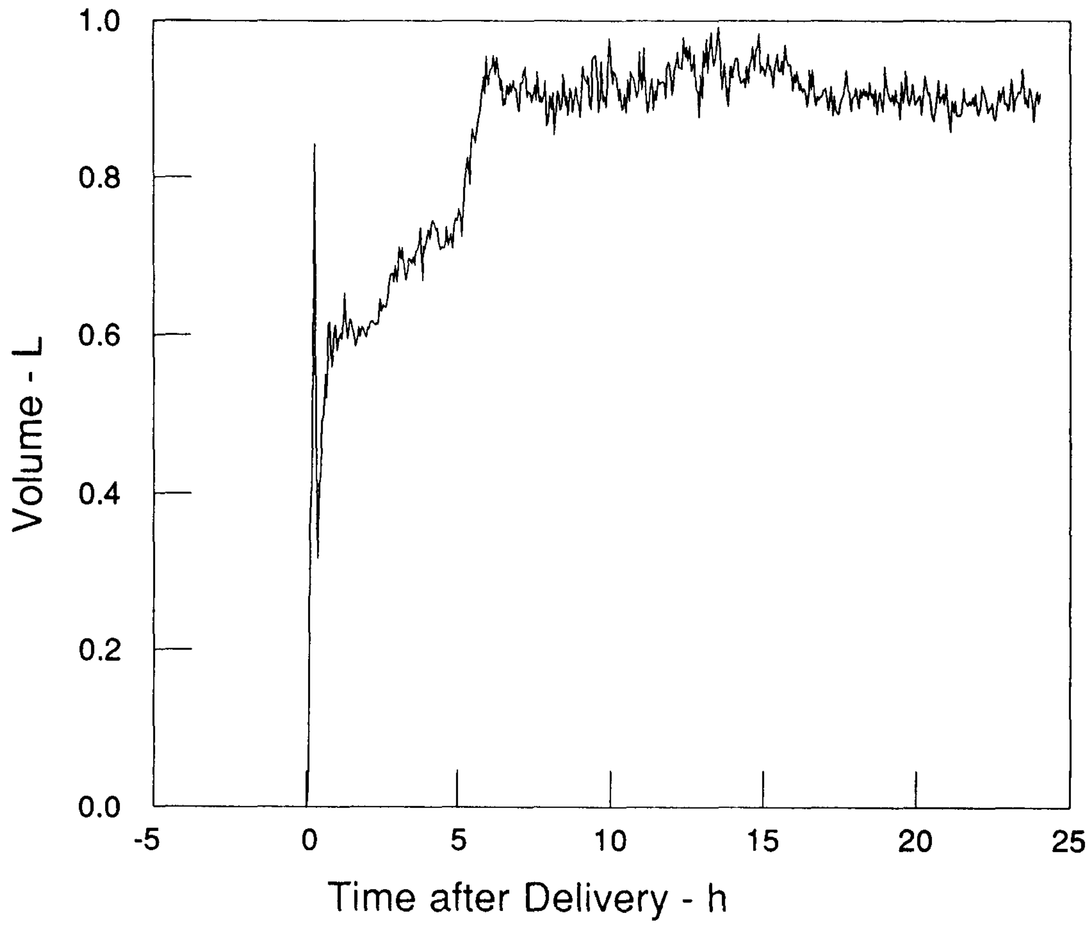


Figure 8.2. Differences in residual fluctuations in rms temperature volume between Arrays 2 and 3 (28 October 1986).

For this test, the average difference in slope for each array, after 6 h have elapsed, is summarized in Table 8.2. This analysis suggests that 6 h after product addition a single array can measure the temperature changes to within 0.04 L/h (0.01 gal/h), the precision required to reliably detect leak rates of 0.19 L/h (0.05 gal/h).

Table 8.2. Average Slope Differences for Three Thermistor Arrays

	Average Slope Differences		
Time (h)	**Array 1**	**Array 2**	**Array 3**
6	0.0099	0.0055	0.0154
8	0.0047	0.0078	0.0031
12	0.0089	0.0269	0.0181
16	0.0266	0.0114	0.0102
20	0.0083	0.0118	0.0201

A third analysis was undertaken to determine the adequacy of the 20-cm vertical separation of thermistors. The mathematical coherence between thermistor pairs was computed and the coherence measured to unity for frequencies less than 1/2 cycle per hour. The result is illustrated in Figure 8.3, which shows the data from two thermistors located near the middle of the tank. Because of the very high level of coherence for all fluctuations with frequencies lower than 0.02 cycles/min (periods longer than 5 min), it was concluded that a 20-cm spacing between thermistors provides an adequate characterization of the temperature field. Similar results were often observed for a 40-cm spacing. Even a 20-min spacing is not adequate when very steep gradients in the temperature field occur, or at boundaries between regions where temperature is increasing or decreasing.

These results have significant implications for tank testing. First, temperature compensation is essential to the conduct of an accurate tank test; without compensation, volume changes of 1- to 3-L/h were observed. Second, independent of structural deformation effects, a waiting period of at least 4 to 6 h after topping a partially filled tank is required before testing can begin. Third, for moderately severe initial thermal conditions, a single array of thermistors, at the fill hole, is sufficient for temperature compensation.

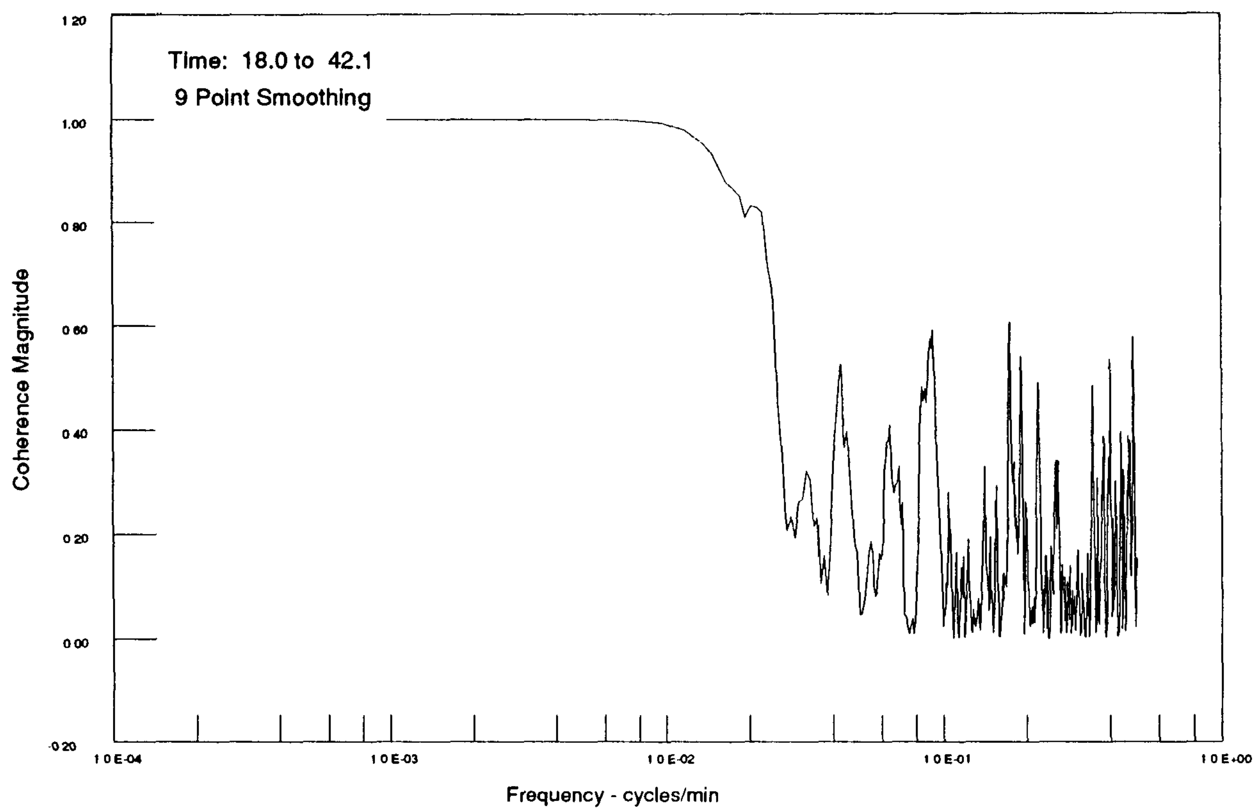


Figure 8.3. Coherence between two thermistors (18 and 19), located near the middle of the tank on Array 2 of the Test Apparatus. Twenty-four hours of data were used in the analysis. There are 7 degrees of freedom in the estimate.

8.1.2 Model Validation

To determine the thermally induced volume fluctuations in a tank, accurate estimates are necessary for the mean change of the temperatures, the coefficient of thermal expansion, and the total volume of product in the tank. The uncertainty in the computed thermal volume change depends on the spatial homogeneity of the product temperature and on the errors in measuring the aforementioned quantities. In a full 30,000-L (8,000-gal) tank, with thermistor precision equal to 0.001°C, the error in the thermal expansion coefficient is 0.000016/°C, and the error in volume is 95 L. The maximum error resulting from a 0.05°C/h change in temperature would be the 0.067-L/h (0.018-gal/h) error in the estimate of product-volume change.

The ability to compensate for thermally induced product-volume changes at the Test Apparatus was estimated from the residual fluctuations in the volume after the thermally induced volume changes had been subtracted. The product temperature experiments demonstrated that a single, vertical array of thermistors at the fill hole was sufficient to estimate the mean rate of change of temperature to within 0.04 L/h (0.01 gal/h). Figure 8.4 is an example of the residual fluctuations that remain after temperature compensation; these are approximately 0.04 L/h. The smallest residuals were obtained during overnight experiments. The residuals were usually manifested as linear trends.

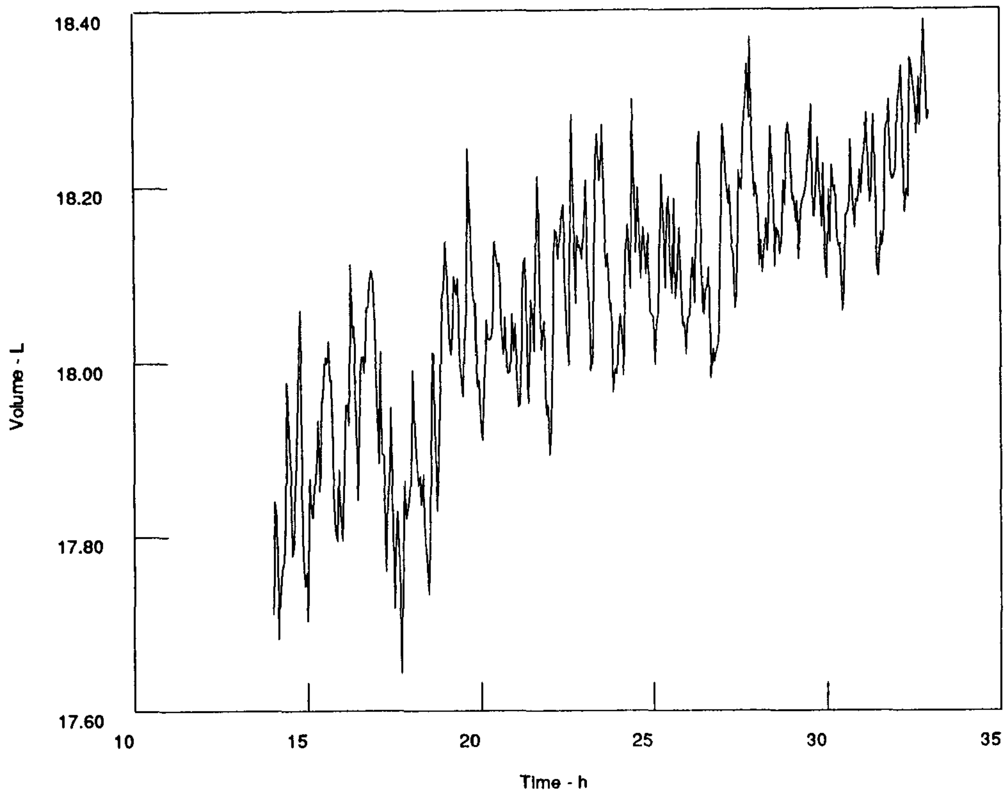


Figure 8.4. Residual fluctuations in volume after compensating for thermally induced product-volume changes.

8.1.3 Topping

In all methods in which the tank is overfilled, the filling process has two steps. The first is to fill the tank with sufficient product to raise the level as close to the top as possible, without letting the product rise into the fill tube. The exact level is variable depending on safety considerations and on the accuracy of the tank chart used to estimate the required volume of product. The second step is to top the tank to the product level required for the test. As little as 10 to 15 L (3 to 4 gal) or as much as 175 to 350 L (50 to 100 gal) may need to be added. Because the temperature of the added product is almost always different from the temperature of the product in the tank, the product added in the second step will affect the accuracy of the product temperature estimates required for temperature compensation as discussed below. The impact of topping the tank was observed frequently during the Field Verification Tests.

Experiments were conducted in the fiberglass tank to investigate the effects of topping. 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 (30 in.) 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 (5 gal) 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. This product addition would effect a mean change in temperature of 0.004°C for the product in the tank. It should not, however, affect the mean rate of change of product temperature being driven by the mean temperature of the product in the tank and the backfill-soil.

The results of adding cold and warm product to the tank are presented in Figures 8.5 and 8.6, respectively. Both plots display the temperature measured by 11 of the thermistors located on a single array at the fill tube for at least 0.5 h before topping and 4.5 h after topping. These thermistors are located 11 cm, 31 cm, 52 cm, 72 cm, 92 cm, 113 cm, 133 cm, 153 cm, 174 cm, 194 cm and 214 cm from the bottom of the tank. The mean temperature of the layer at each thermistor location was removed and plotted with an offset of 0.02°C greater than the layer below. This allows for the change in temperature at each layer to be compared to the others.

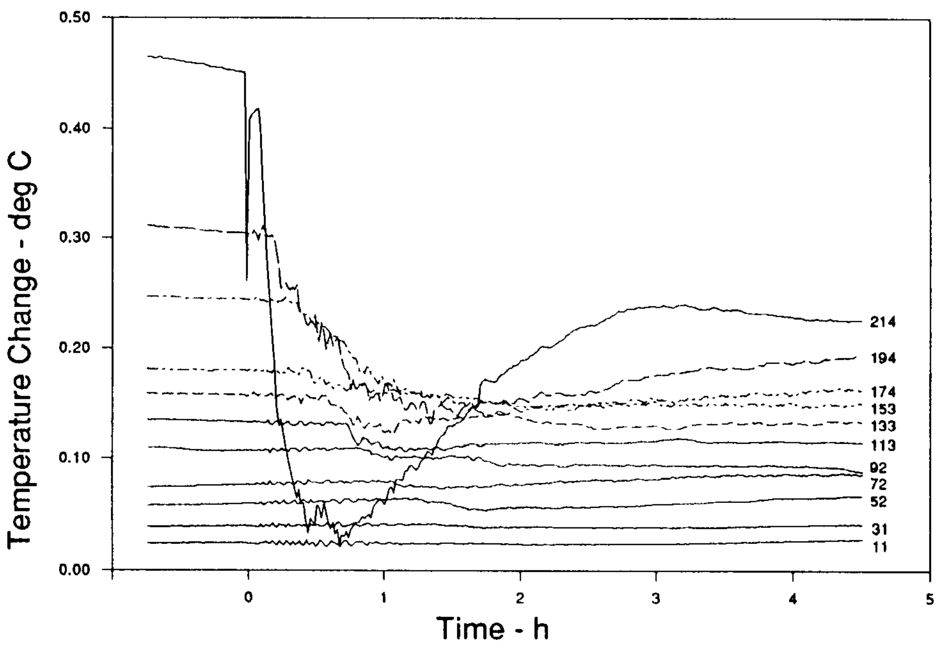


Figure 8.5. Effects of topping the tank with colder product, as represented by 11 thermistors located on an array at the fill tube of the Test Apparatus's fiberglass tank. The numbers next to each line indicate the height of the thermistors, in centimeters, from the bottom of the tank.

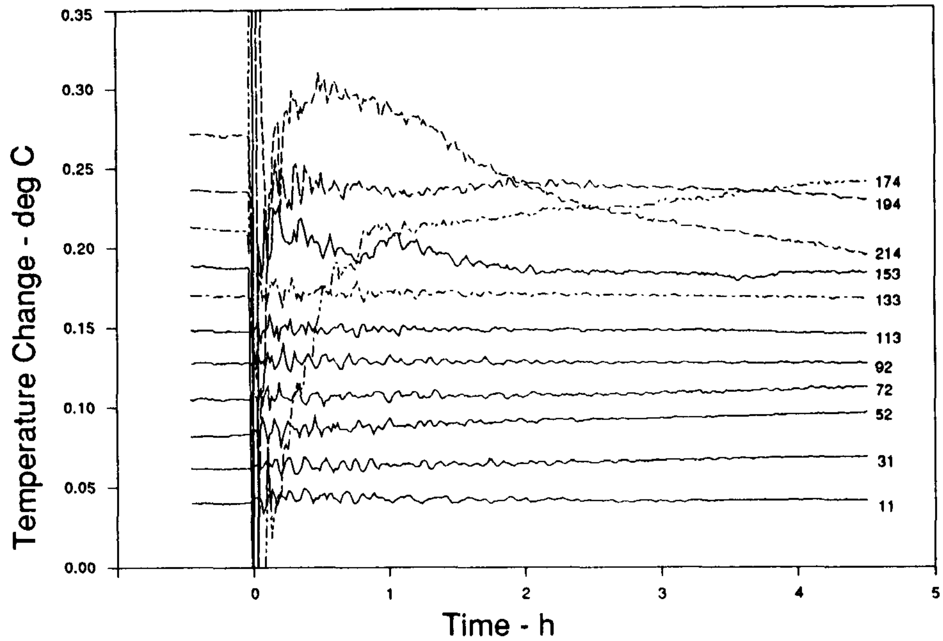


Figure 8.6 Effects of topping the tank with warmer product, as represented by 11 thermistors located on an array at the fill tube of the Test Apparatus's fiberglass tank. The numbers next to each line indicate the height of the thermistors, in centimeters, from the bottom of the tank.

Several observations about both tests are noteworthy. 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 pretest 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 rate of temperature 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 horizontal and vertical temperature gradients have dissipated. A minimum of five thermistors would be required in order to do this.

The temperature field changes with the addition of product that is cooler or warmer than the product in the tank. For both tests, the magnitude of the high-frequency fluctuations increases. The colder product (Figure 8.5) sinks and spreads out spatially at a level where the buoyancy forces balance the gravity forces. It took approximately 9 min after adding colder product for the bottom layer of the tank to be affected, as shown by the reaction of the thermistor located 11 cm from the bottom of the tank. The addition of colder product sets up a steep thermal gradient in the upper layers, probably from the entrainment of warmer product near the top of the tank down to layers which are cooler.

In Figure 8.6, it is observed that the force generated during the addition of warm product initially moves this warm product toward the bottom of the tank, but that warm product returns toward the top, where it heats the surface layers for a short period of time.

8.2 Trapped Vapor

A set of experiments was designed and conducted at the UST Test Apparatus to determine whether Eq. (6.8) is a satisfactory equation of state both for predicting pressure-related changes of volume in trapped vapor and for determining whether a method of estimating the volume of trapped vapor could be devised using the equation of state. The same basic experimental approach was used for both of the above objectives. The experiments were designed to estimate the volume of a known amount of trapped vapor in an overfilled tank by varying the pressure in a predetermined way. The experimental design, as well as interpretation of the data, were dependent on the magnitude of the instantaneous structural deformation of the tank. It was initially assumed that the instantaneous structural deformation was small. When it was found that this was not the case, many additional experiments were designed and conducted to estimate the magnitude of the instantaneous deformation in terms of $A_{i,sd}$.

8.2.1 Experimental Approach

A set of iterative experiments was designed and conducted to validate Eq. (6.11) and to develop and test a method of estimating the total volume of the trapped vapor in the tank. The approach was straightforward, but the experimental implementation and interpretation were not. Two types of experimental configurations (Figures 8.7 and 8.8) 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 produced 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. Validation of the model and accurate estimates of the volume of trapped vapor in the tank require that $A_{isd} << A_{vp}$ in Eq. (4.2) or $\Delta V_{isd} << \Delta V_{vp}$ in Eq. (6.12). If the volume changes produced by the instantaneous structural deformation of the tank are large, neither the validation nor the method of making volume estimates will be accurate.

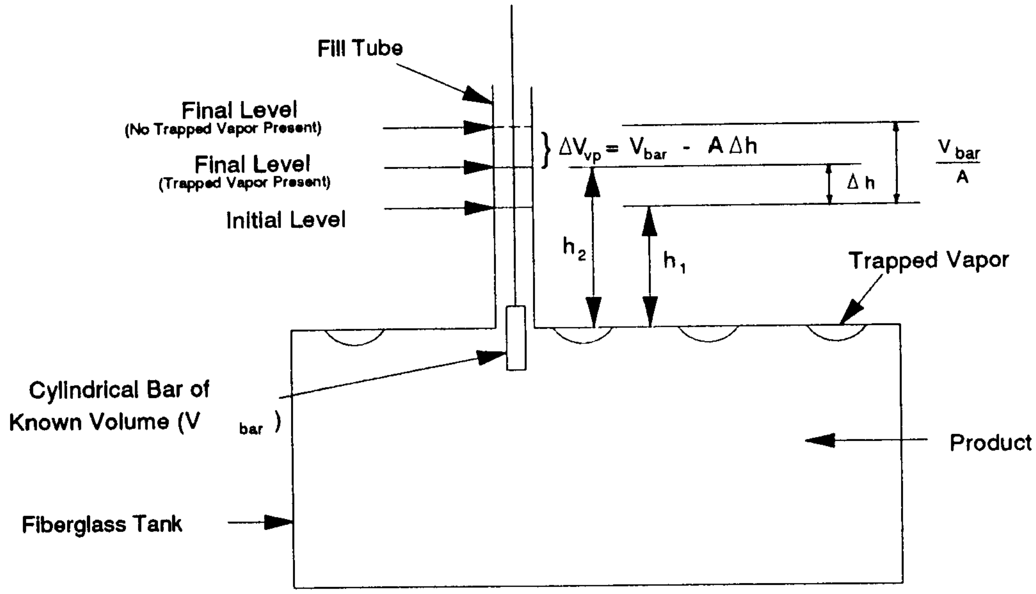


Figure 8.7. Experimental configuration for trapped vapor tests in a well-bled fiberglass tank. A cylindrical bar of known volume, V_{bar}, was used to raise the level of product.

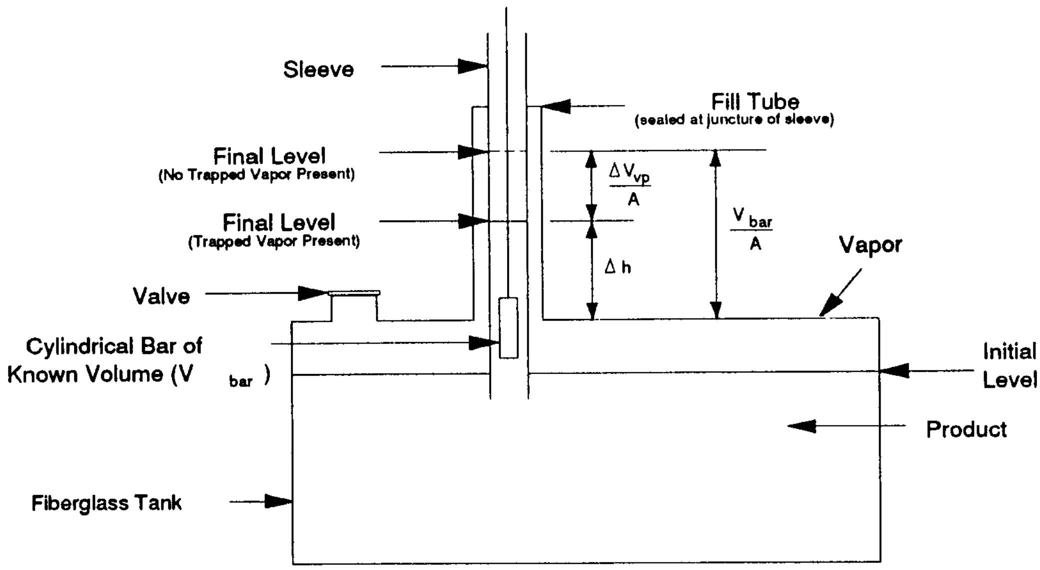


Figure 8.8. Experimental configuration for the trapped vapor tests in the fiberglass tank. A known amount of vapor was trapped using a sleeve that was extended into the tank. The volume of trapped vapor was estimated from an experimentally determined tank chart. It is assumed that the change in product level in the tank after a bar of known volume has been inserted is negligible. The valve is opened and closed to the atmosphere immediately before starting the test.

8.2.1.1 Procedure

Product-level changes produced by vapor pocket fluctuations can be measured by using the following procedure:

1) Fill the tank to a specified level so that the desired volume of vapor can be trapped in the tank.

2) Observe a waiting period that is long enough to ensure that the structural deformation effects resulting from filling the tank have become negligible.

3) For the configuration shown in Figure 8.7, overfill the tank with product to a level within the fill tube, while once again observing an adequate waiting period for structural deformation effects to subside.

4) For the configuration shown in Figure 8.8, insert a sleeve in the fill tube to trap the vapor.

5) For the configuration shown in Figure 8.8 only, open a bleed valve to allow the tank to come to atmospheric pressure; then close the valve and raise the product level in the sleeve.

6) For both configurations, insert a cylindrical bar of known volume into the tank through the fill tube to change the product level; then measure the product-level change.

In order to minimize the effects of the large product-level fluctuations and the exponential deformation of the tank that occur upon insertion of the bar, the following procedure was used: measure the product level; insert the bar over a 45-s period starting 15 s after the measurement; measure the product level 15 s after the bar has been inserted; measure the product level 2.5 min after the last measurement; wait 15 s and remove the bar slowly over the next 45 s; measure the product level; and vent the tank to the atmosphere in preparation for another cycle.

The tank was modified for these experiments so as to allow control of the size of the vapor pocket. A sleeve, extending 61 cm (24 in.) into the body of the tank, was inserted into the fill tube, which was then sealed at the juncture of the sleeve. The tank was then filled to a predetermined height below the top of the tank but above the bottom of the sleeve. Product levels for these experiments ranged from 200 to 232 cm (79 to 91 in.).

8.2.1.2 Experiments

In order to validate the model described by Eq. (6.11), the experimental configuration shown in Figure 8.8 was used. The experiment, which was designed to predict a known volume of vapor trapped in the tank, required that the values of n and V_{vp} be known, and that the volume change produced by the instantaneous structural deformation be small compared to the volume change of the vapor (i.e., $A_{isd} << A_{vp}$). Experiments were conducted to estimate the volume in the upper 15 cm of the tank; this was done in 1-cm intervals to account for any tilting or distortion of the tank geometry. Laboratory experiments were conducted to estimate the value of n for the product in the UST Test Apparatus tanks. To minimize the effects of the instantaneous structural deformation, a large vapor pocket was trapped for the experiment. The experiment was designed to limit the effects of A_{isd} to less than 5 to 10% of A_{vp}. To determine what size vapor pocket was required, a set of preliminary experiments was performed in a well-bled, overfilled tank using the configuration shown in Figure 8.7. The results of the experiment gave an upper bound on the value of A_{isd} or A_{vp}. Different bar sizes and different vapor pocket volumes were used. It was assumed that A_{isd} was a constant for small changes in the initial product level. This assumption was verified by inserting, at the same initial level, three or four bars of different volume to produce a product-level change. Eq. (6.11) was solved using a value of n = 1 and the volume of vapor estimated from the tank geometry. The volume change produced by the structural deformation was calculated by

$$\Delta V_{isd} = V_{bar} - \Delta V_{eff} - \Delta V_{vp} \tag{8.1}$$

8.2.2 Results

Although many vapor pocket experiments were conducted in both the fiberglass and steel tanks, the only results reported here are those from a limited number of experiments in the fiberglass tank.

8.2.2.1 Estimate of the Gas Constant

It was initially hypothesized that the volume changes produced by rapidly inserting the bar into the fill tube would occur adiabatically and that n (see Eq. (6.11)) would be equal to 1.4. A set of experiments was conducted in a rigid glass bottle to determine n. Figure 8.9 shows the experimental setup. The experiments were first conducted with water and then with the product used in the Test Apparatus tanks. A known volume of liquid was placed into a bottle of known volume. The liquid was then raised into the tube of known diameter by suction, while the vapor space was kept at atmospheric pressure. The level of the liquid was measured, and the suction pressure was released after the opening to atmospheric pressure had been sealed. The liquid in the tube fluctuated for several seconds until it reached a stable level. The level was then measured, and an estimate of n was made using Eq. (6.11). The results for water and gasoline are given in Table 8.3. The value of $n = 0.99 \pm 0.06$.

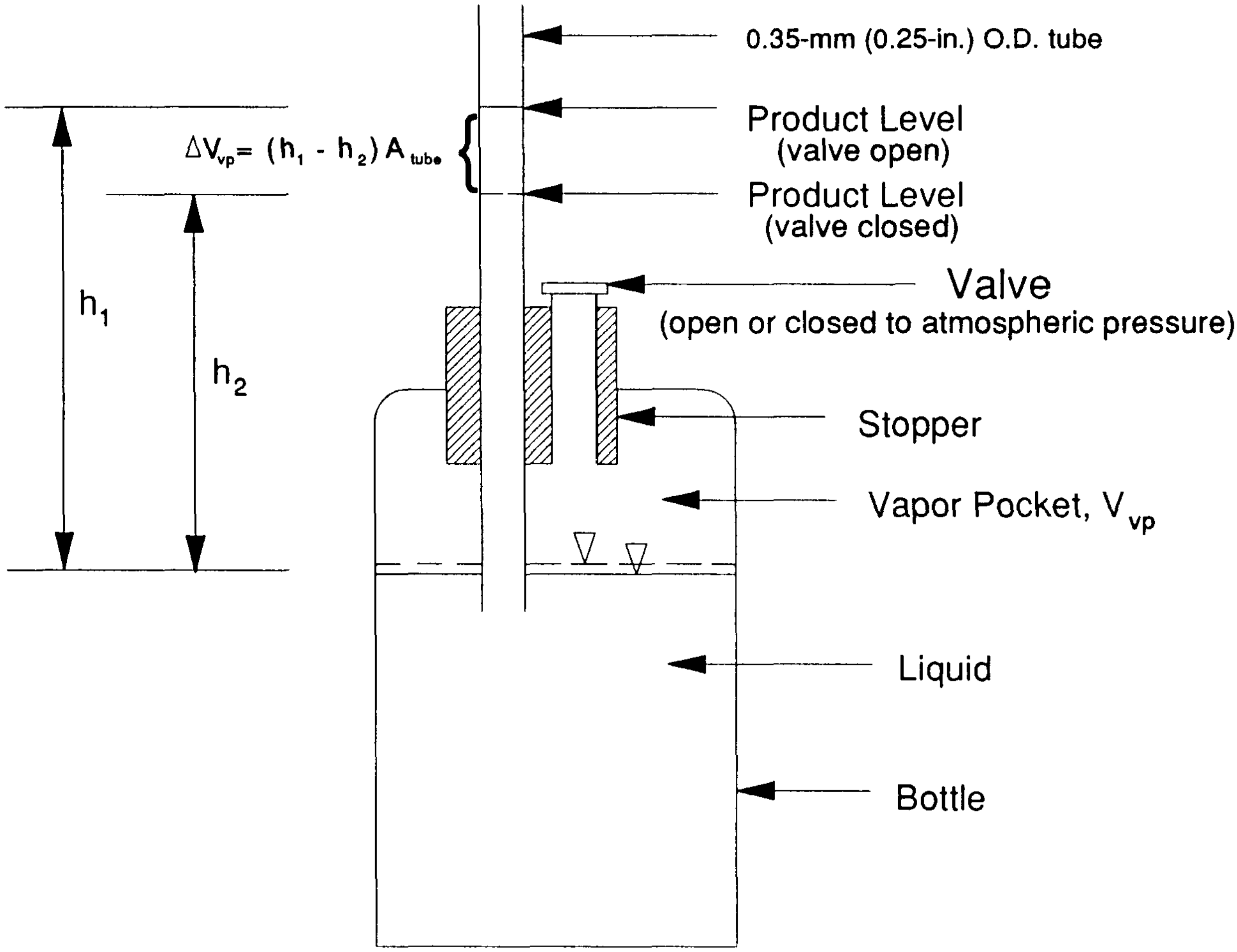


Figure 8.9. Experimental apparatus to estimate n. The initial pressure on the vapor pocket was atmospheric pressure, P_A. The change in the volume of the vapor pocket was estimated from the drop in product within the tube with cross-sectional area A_{tube}.

Table 8.3. Results of Laboratory Experiments to Estimate n (Bottle Volume = 803 ml)

Product	V_{vp} (ml)	Number of Tests	Mean n	Standard Deviation n
Water	179	6	1.017	0.021
Water	330	3	1.039	0.004
Gasoline	260	8	0.990	0.057

The results clearly indicate that n is closer to 1.0 than to 1.4, and that the process was not adiabatic. Also, the oscillating behavior after the suction pressure on the liquid in the tube had been released suggested potential measurement problems in full scale experiments. Furthermore, the product level in the tube began to rise as the partial pressure of the air-gasoline vapor increased.

8.2.2.2 Tests in Well-Bled Overfilled Tanks

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. The best that could be done was to reduce the vapor pocket to 10 L. However, the impact of this residual was determined to be negligible, as discussed in Section 6.4.2.

Table 8.4 summarizes the results of the tests in a well-bled, overfilled tank. This experimental configuration is shown in Figure 8.7. Figure 8.10 illustrates the product-level changes 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. The value of A_{eff} as a function of bar volume is shown in Figure 8.11.

Table 8.4. Summary of the Results of the 6 June 1988 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)
625	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

Several observations about the data are noteworthy. First, product-level changes induced by the exponential deformation of the tank can be seen where the two largest bars were inserted (Figure 8.10). Second, it can be seen from Figure 8.11 that the values of A_{eff} and $A_{isd} + A_{vp}$ are constant over the range of product-level changes. Since it can be shown from Eq. (6.11) that A_{vp} is a constant over a wide range of pressure changes, it can be concluded that A_{isd} is also constant. The uncertainty in the measurement is indicated by the spread in the individual values of A_{eff} for each bar.

The results shown in Table 8.4 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. Based on geometric considerations, it is estimated that the tank should contain no more than 10 L of vapor. If it is assumed that the quantity of trapped vapor is 10 L, A_{isd} = 35 cm^2.

The causes of trapped vapor were minimized in the Test Apparatus by paying careful attention to certain details. All manways were installed so as to prevent the trapping of vapor. All lips from fill tubes extending down into the tank were eliminated. Since the tank was installed horizontally, the only remaining variable that could be responsible for trapping vapor was the undulation of fluid in the top of the tank. A 1.25-cm (0.5-in.) layer of vapor along the surface would account for 19 L of vapor, but because of the irregularity of the surface, it is reasonable to assume that the amount of vapor actually trapped was less than 50% of this figure. The steel tank affords a more reliable estimate than does the fiberglass tank. In the former, water marks left near the top of the tank as a result of the water tests (conducted before the tanks were filled with product) are still visible; these show the exact location and quantity of the vapor pockets. Calculations in both the steel and fiberglass tanks suggest that it is possible that less than 10 L could be trapped.

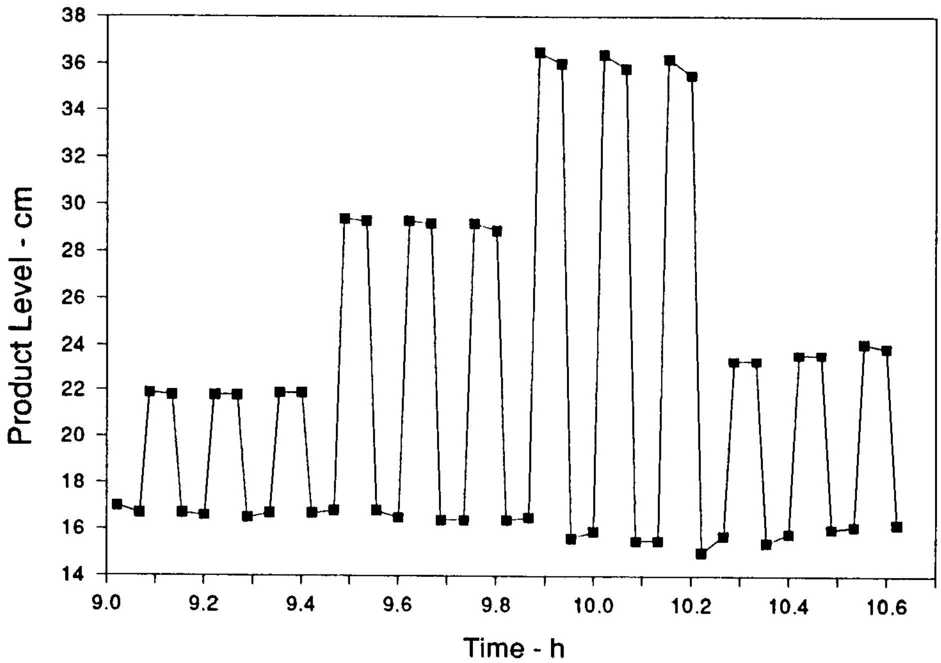


Figure 8.10. Time series of the product-level changes in the fill tube of an overfilled fiberglass tank on 6 June 1987, produced by inserting and removing four different- size bars (625, 953, 1551, and 2477 ml). The measurements were made with a ruler to the nearest 3 mm. The tank was well bled prior to testing in order to minimize the total volume of trapped vapor in the tank system. The initial product level was 335.3 cm above the bottom of the tank. The time interval between points is approximately 3 min.

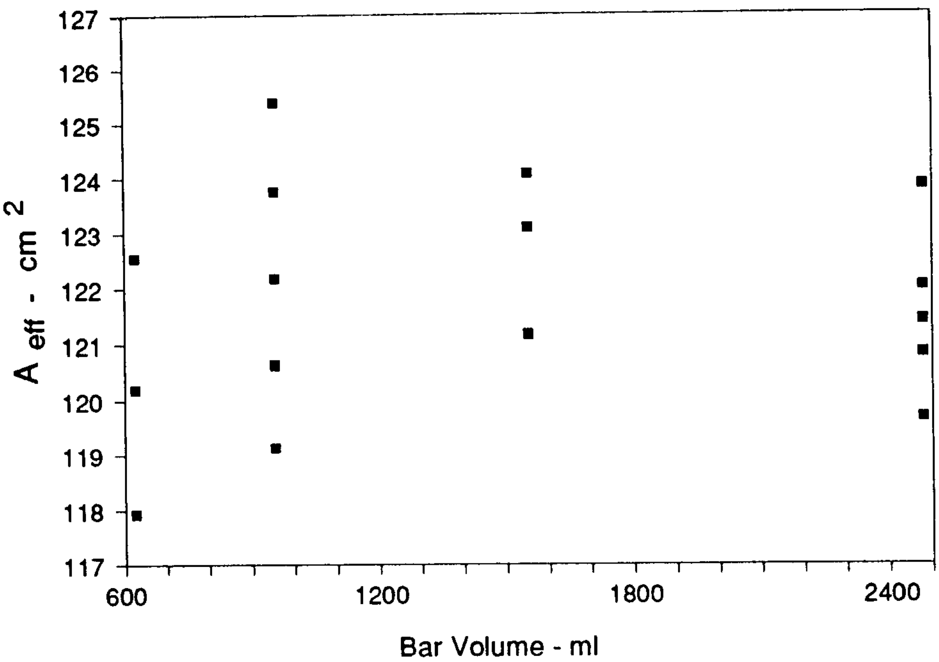


Figure 8.11. A_{eff} computed from the volume of the cylindrical bar, V_{bar}, and the measured product-level change data, Δh, obtained on 6 June 1987. The tank was well bled in order to minimize the total volume of trapped vapor in the tank system. The initial product level in the fill tube was 335.3 cm above the bottom of the tank.

If the maximum quantity (60 L) were trapped, the location of the vapor pocket would have to be in the upper 3 cm of the tank, and this, given the geometric considerations, is impossible. Similarly, to trap 60 L of vapor in a pipe would require that the status of a length of pipe 7.4 m long and 10 cm in diameter be unknown. Because all pipes have been filled with product and bled of trapped vapor through valves, it is unlikely that the piping conditions would be unknown to such a large extent.

After considerable experimentation, it was concluded that large changes in product level, since they are evidently not the result of trapped vapor, are due to the instantaneous deformation of the tank. Because the effects of trapped vapor and deformation are so similar, experiments were designed and conducted to estimate both.

8.2.2.3 Trapped Vapor Tests

An 821-L vapor pocket was trapped in the top of the tank using the sleeve shown in Figure 8.8. Table 8.5 summarizes the results of the tests. Figure 8.12 illustrates the product-level changes produced by inserting and removing bars of different size (625, 1551, 2477, and 5071 ml). The value of A_{eff} as a function of bar volume is shown in Figure 8.13.

Table 8.5. Summary of the Trapped Vapor Tests Conducted in the Fiberglass Tank on 5 June 1988*

Bar Volume (ml)	Δh (cm)	A_{eff} (cm^2)	A (cm^2)	$A_{lsd} + A_{vp}$ (cm^2)	V_{vp} (L)
625	0.82	765.0	71.4	693.6	963 **
1551	2.30	674.4	71.4	603.0	838
2477	3.65	678.6	71.4	607.0	845
5071	7.52	674.6	71.4	603.2	842

* The calculations were done by using Eq. (6.11) with n = 1 and assuming atmospheric pressure was 13.90 m of gasoline. The product depth was 218.1 cm. A 821-L vapor pocket was trapped in the tank and fill tubes.

** Values not used in the analysis

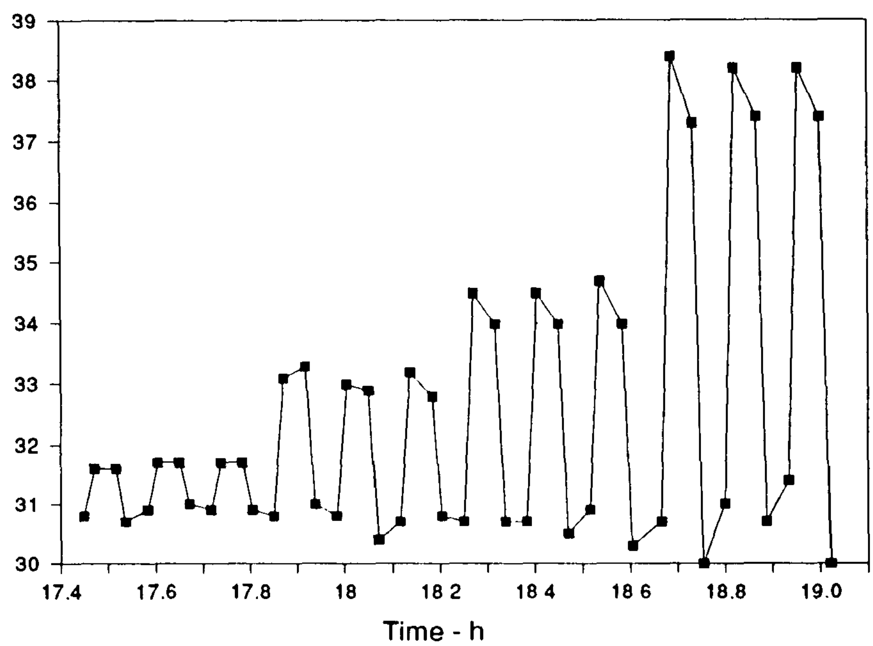


Figure 8.12. Time series of the product-level changes in the sleeve of an underfilled fiberglass tank on 5 June 1987; product-level changes were produced by inserting four different-size bars (625, 1551, 2477, 5071 ml). The measurements were made with a ruler to the nearest 3 mm. A vapor pocket of 821 L was trapped in the top of the tank for the measurements. The initial product level was 218.1 cm above the bottom of the tank. The time interval between points is approximately 3 min.

The observations made for the data shown in Figures 8.12 and 8.13 can also be made for the data from the 6 June 1987 overfilled-tank tests (Figures 8.10 and 8.11), except that the exponential deformation of the tank and/or vapor is more pronounced.

The data relevant to the smallest bar were removed from the data set, because the mean value of these data was different from that of the other three. The difference was probably due to the 35% relative error in measuring product-level changes (i.e., 0.3-cm error in measuring an 0.8-cm product-level change).

The three estimates of the 821-L vapor pocket are given in Table 8.5. 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. Assuming an error of 0.63 cm (0.25 in.) in measuring the absolute level of the product in the tank, there is a 50-L uncertainty in the volume estimate at 218 cm. An error of approximately 50 L, due to the instantaneous deformation of the tank, is estimated for $A_{isd} = 35$ cm^2.

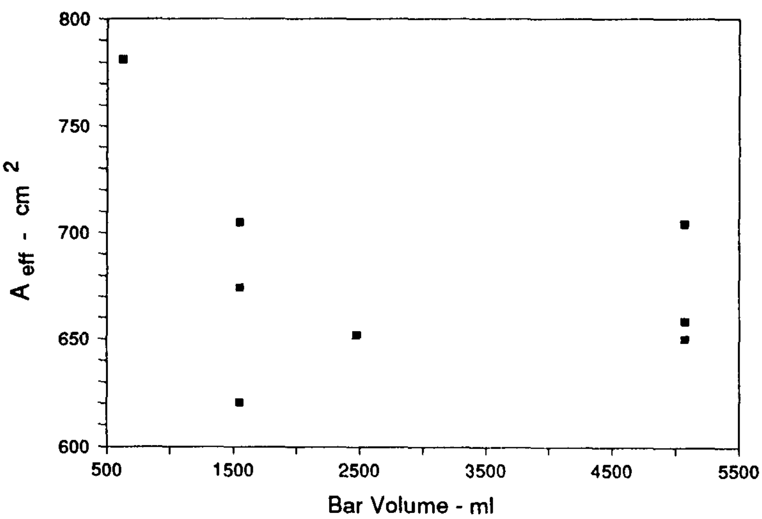


Figure 8.13. A_{eff} computed from the volume of the cylindrical bar, V_{bar}, and the measured product-level change data, Δh, obtained on 5 June 1987. An 821-L vapor pocket was trapped in the fiberglass tank. The initial product level was in the sleeve, 218.1 cm above the bottom of the tank.

8.2.2.4 Instantaneous Structural Deformation

An estimate of the instantaneous structural deformation was made, using the four days of experimental data presented in Table 8.6 (where h_o indicates initial product level) and assuming that the volume of the vapor pocket was known. Estimates of ΔV_{isd} were made for each vapor pocket and bar. Figure 8.14, a plot of the data, 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. The value of A_{isd} estimated from all experiments is 36 cm^2. This is very consistent with the value of A_{isd} calculated in an overfilled tank in which the vapor pocket estimate was 10 L.

Table 8.6. Summary of the Experimental Data Used to Estimate the Magnitude of the Instantaneous Deformation, A_{isd}

Date	h_o (cm)	V_{bar} (ml)	Δh (cm)	A_{eff} (cm^2)	Predicted V_{vp} (L)	Measured V_{vp} (L)	ΔV_{vp} (ml)	ΔV_{isd} (ml)
5/28	228.8	4021	15.90	252.9	254	207	2337	533
5/28	228.8	5071	20.14	251.8	253	207	2951	662
5/29	229.2	953	3.93	242.8	238	194	546	123
5/29	229.2	1544	6.14	251.2	250	184	853	246
5/30	229.6	952	4.25	224.2	212	184	561	84
5/30	229.6	2477	10.85	228.3	218	184	1426	266
6/5	218.1	5071	7.52	674.6	842	821	4416	111
6/5	218.1	2477	3.65	674.4	845	821	2150	63
6/5	218.1	1551	2.30	674.3	838	821	1356	28

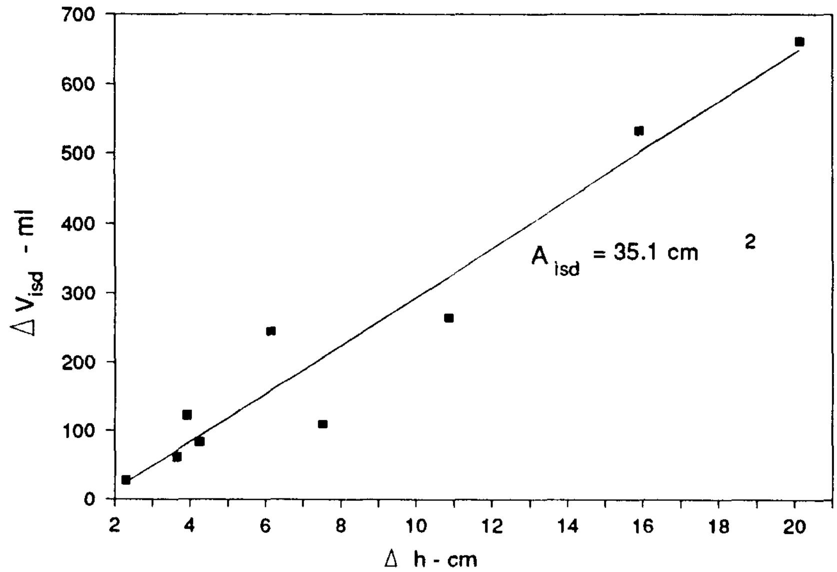


Figure 8.14. Estimate of A_{isd} from data collected on 28-30 May and 6 June 1987. The slope of the line is $A_{isd} = 35.1\ cm^2$.

8.2.3 Evaporation and Condensation

Because of the large pressure changes that occur as the vapor approaches partial-pressure equilibrium, large product-level changes can occur in the fill tube of an overfilled tank if the vapor is unsaturated. This effect was observed in field experiments conducted prior to the UST

Test Apparatus experiments [25], and in the laboratory experiments. An accurate volumetric test cannot be conducted unless the trapped vapor has approached an equilibrium condition. Available data suggest that this occurs in tens of minutes.

8.2.4 Experimental Estimates of A_{eff}

The presence of vapor affects the magnitude of A_{eff}. Table 8.7 gives the error that occurs in estimating product volume from product-level measurements when using the theoretical A rather than the measured A_{eff} height-to-volume calibration. The presence of even small amounts of trapped vapor can cause large errors in the volume estimates.

Table 8.7. Error in Estimating Product Volume from Product-Level Measurements If the Measured Height-to-Volume Calibration Factor, A_{eff}, Is Not Used (A 1000-ml bar was used to raise the product level in the fill tube.)

Trapped Vapor Volume (L)	A (cm^2)	A_{isd} (cm^2)	A_{eff} (cm^2)	A_{VP} (cm^2)	Height-to-Volume Error (%)
10	81.1	0	88.1	7.1	8.1
25	81.1	0	98.9	17.9	18.1
50	81.1	0	116.8	35.8	30.7
75	81.1	0	134.7	53.7	39.9
100	81.1	0	152.6	71.6	46.9
150	81.1	0	188.5	107.5	57.0
200	81.1	0	224.4	143.4	63.9

8.2.5 Summary

The experiments at the UST Test Apparatus suggest that unless it is very large, the volume of trapped vapor is difficult to estimate, because the effects of the instantaneous deformation of the tank can be large in comparison to the volume of trapped vapor. Using Eq. (6.11), it was estimated that the tanks at the Test Apparatus contained a maximum of 60 L of vapor, approximately 50 L more than were believed to be present on the basis of geometrical considerations and experimental analysis. Even though the volume of the trapped vapor cannot be accurately estimated with Eq. (6.11), such an approach is a good method of identifying a potential problem, because it yields an upper bound on the volume of trapped vapor. If the volume predicted by Eq. (6.11) is greater than 100 L, the presence of trapped vapor should be suspected.

The experiments also showed that a value of n = 1 should be used with Eq. (6.11) to estimate volume changes effected by pressure changes.

8.3 Structural Deformation

A series of experiments was conducted to validate the model of the product-level changes described by Eq. (6.24). The tank was overfilled to a level within the fill tube, and all known vapor was removed from the tank. The resulting product-level changes in the tank were monitored over the course of the subsequent 24-h period, until the effects of the exponential deformation and of the product-temperature changes could be assumed to be small. A bar was the inserted into the fill tube, instantaneously raising the product level; product-level and product-temperature changes were measured over the next 6 h. The experiment was designed so that all sources of noise except thermal volume changes could be made negligible.

8.3.1 Model Validation Results

An experiment was conducted in the steel tank on 3 May 1988 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 0.04 L/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 (15 in.), 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 product-level changes in a 10-cm (4-in.)-diameter fill tube were converted to product-volume changes using the measured volume of A_{eff}. The product-volume data were detrended, and the model described by Eq. (6.24) was fit to the data using a least-squares technique. The results are given in Table 8.8 and Figure 8.15.

Table 8.8. Estimates of A_{eff}, T_C, T_{eff}, and K made from the Product-level Measurements in the 10-cm-Diameter Fill Tube 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

Many different types of experiments were conducted to verify the theoretical relationships in Section 6.4.4, including releveling experiments. As expected, T_{eff} decreased as the diameter of the fill tube, A, decreased. T_{eff} was also shown to be a fraction of the actual time constant of the

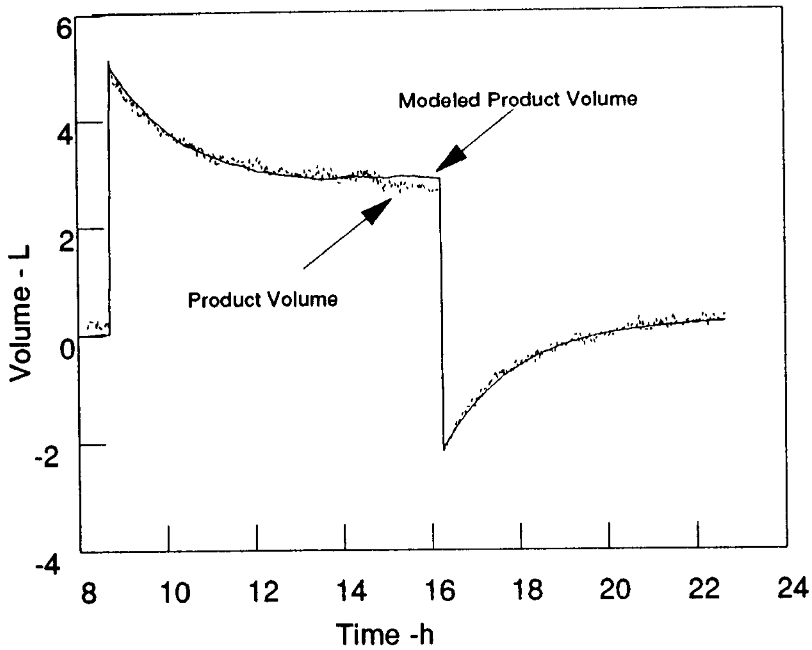


Figure 8.15. Comparison of the measured and predicted volume time series for data collected on 3 May 1988 in the fill tube of the steel tank at the UST Test Apparatus. A 5.045-L cylinder was used to raise and lower the product level in the fill tube instantaneously. The instantaneous product-level change was approximately 38 cm, only 59% of the expected 64-cm change.

tank, T_c, which controls the deformation for a constant head test. Finally, it was shown that the product-level changes predicted by Eq. (6.29) were controlled by a height-to-volume conversion factor, $A_{eff} + K$, that was dependent on the elasticity properties of the tank-backfill-soil system.

The experiments showed that K tended to decrease as product height above the bottom of the tank increased. The experimental estimates made for the steel tank showed that K was less than 15 to 30 cm^2 for product-level measurements made when product was 1.3 m above grade, but greater than 100 cm^2 for those made when product was in the fill tube but below grade. The data are not sufficient to generalize that the effects of deformation are small for tests that are conducted above grade. Neither are the data sufficient to generalize K and T_c for the wide range of tank, backfill, and soil conditions found nationally.

The experiments also showed that K changed as a function of the time of year. Experiments conducted 6 to 12 months after the initial ones resulted in different values of K, a finding which is consistent with the notion that K is strongly dependent on the elasticity properties of the backfill and *in situ* soil. The properties of the backfill and the native soil, particularly the consolidation of the soil, would be expected to change seasonally, as the temperature and water content changed.

8.3.2 Model Predictions of Product-Level Changes in the Fill Tube

The Fill-Tube Dynamics Model described by Eq. (6.31) and Eq. (6.32) was exercised to illustrate how the product level changed in the fill tube as a function of T_c, K, and A_{eff}. The constants used in the analysis cover the range of conditions measured in the steel and fiberglass tank experiments at the UST Test Apparatus.

8.3.2.1 Deformation Produced by Topping the Tank

Many overfilled-tank tests require that the tank be topped off before the test is started. This may involve adding tens of gallons of product to the tank to elevate the product into the fill tube and an additional gallon or two to attain a specified level within the fill tube. In addition, many tests require adjustments of the product level in the fill tube immediately prior to or during a test. While the volume changes are typically small, the resulting change in the hydrostatic pressure head may be large.

Eq. (6.31) was solved for a range of values of K and A_{eff} to illustrate the product-volume changes that are measured after topping, when the rate of change of volume in the tank is -1.2 L/h. The deformation of the tank associated with a 1-m increase in the product level within the fill tube was modeled. The initial product level was assumed to be above the top of the tank and was also assumed to be constant for the entire time prior to the simulation of a product addition to the tank (i.e., $V_p(t) = 0$ for $t < t_o$). The rate of change of volume estimated from the product-level changes after the large exponential changes have stabilized is presented in Tables 8.9 and 8.10.

Table 8.9. Effects of the Fill Tube Diameter on the Model Predictions*

Effective Diameter (cm)	A_{eff} (cm^2)	T_{eff} (h)	Predicted Volume Rate (L/h)	Actual Volume Rate (L/h)	Predicted: Actual	Temperature-Compensated Volume Rate (L/h)
2.5	5.1	0.04	-0.05	-1.2	0.04	1.15
5.1	20.3	0.14	-0.17	-1.2	0.14	1.03
7.6	45.6	0.28	-0.33	-1.2	0.28	0.87
10.2	81.1	0.40	-0.48	-1.2	0.40	0.72
15.2	182.4	0.60	-0.72	-1.2	0.60	0.48
20.3	324.3	0.73	-0.88	-1.2	0.73	0.32
25.4	506.7	0.81	-0.97	-1.2	0.81	0.23
50.8	2026.8	0.94	-1.13	-1.2	0.94	0.07
76.2	4560.4	0.97	-1.17	-1.2	0.97	0.03

* Estimates of how A_{eff} = A (i.e., the fill tube diameter) affects the product-volume changes predicted by Eq. (6.31), which are produced by a 1-m product-level rise resulting from topping the tank immediately before starting a test, and by a -1.2-L/h volume change resulting either from a leak or from thermal contraction of the product. The volume change and the temperature-compensated volume change were estimated after the exponential decay had become small. The predictions were made for K = 120 cm^2 and T_c = 1 h.

Table 8.10. Effects of Tank Elasticity on the Model Predictions*

K (cm^2)	T_{eff} (L/h)	Predicted Volume Rate (L/h)	Actual Volume Rate (L/h)	Predicted: Actual	Temperature-Compensated Volume Rate (L/h)
0	1.00	-1.20	-1.2	1.00	0.00
15	0.84	-1.01	-1.2	0.84	0.19
30	0.73	-0.88	-1.2	0.73	0.32
60	0.57	-0.69	-1.2	0.57	0.51
90	0.47	-0.57	-1.2	0.47	0.63
120	0.40	-0.48	-1.2	0.40	0.72

* Estimates of how K affects the product-volume changes in a 10-cm (4-in.)-diameter fill tube. The predictions were made for A_{eff} = 81 cm^2 and T_c = 1 h.

Tables 8.9 and 8.10 show that, as A_{eff} increases and K decreases, more accurate estimates of the actual rate of change of volume can be made. Because only the linear product-level changes (observed after several time constants, T_{eff}, have elapsed) are being analyzed (e.g., see

Figure 6.4), the results are independent of the time constant, T_c. A longer time constant would require a longer test. The results can be interpreted as either a measurement of a leak in the tank when all other volume changes are negligible or as an estimate of the temperature-compensated volume rate in a nonleaking tank. In the first case, the actual leak rate should be -1.2 L/h, and in the second case, the temperature-compensated volume rate should be 0 L/h.

8.3.2.2 Product-Level Changes that Occur During Releveling

Mathematically, the negative of the cumulative product-volume changes predicted by Eq. (6.32) for a volume rate, C, is nearly identical to the volume changes predicted by Eq. (6.31). This is true when (1) the cross-sectional area of the fill tube used to estimate product-level changes with Eq. (6.31) is large enough to approximate a partially filled tank (e.g., $A_{eff} = A > 4560\ cm^2$, which is equivalent to a fill-tube diameter greater than 76 cm), and (2) the releveling time interval is close to zero (e.g., $t' < 5$ min). An estimate of the time constant of the cumulative volume time series generated by adding the volume changes predicted by Eq. (6.32), as a function of the periodic releveling interval, t′, is presented in Table 8.11. The calculations were made for $K = 120\ cm^2$, $A_{eff} = 125\ cm^2$, $T_c = 1$ h, and $C = 0$ L/h. The time constant was estimated at the point at which 63% of the total product-volume change had occurred. Two points are noteworthy. First, the rate of change of volume approaches the leak rate after the initial exponential deformation has occurred. Thus, accurate tests can be conducted if the waiting period is sufficient for the deformation effects to subside. Second, the time constant is equal to the time constant of the tank, T_c, when the product is releveled continuously, and it increases if releveling is done at discrete intervals. The increase in the time constant, T_c, as a function of the releveling interval is given in Table 8.11.

Table 8.11. Time Constant of the Volume Time Series*

Releveling Interval (min)	Time Constant (h)
0	1.00
5	1.04
15	1.14
30	1.33
60	1.79

* The time constant was predicted using Eq. (6.32) as a function of periodic releveling interval, t′. The estimate was made using $K = 120\ cm^2$, $A_{eff} = 125\ cm^2$, $T_c = 1$ h, and $C = 0$ L/h.

8.3.2.3 Summary

Unless K is known, it is impossible to accurately estimate the rate of change of volume from product-level measurements made in the fill tube or standpipe during an overfilled-tank test. The theoretical and experimental analyses indicate that all volume changes are coupled in a complicated feedback mechanism.

The Fill-Tube Dynamics Model suggests that the rate of change of volume estimated from the measured product-level changes in an overfilled tank is in error, even if the measurement is made after the large changes initially produced by an addition of product to the tank have stabilized, and even if a measured height-to-volume conversion factor is used. The model calculations illustrate how T_c, K, and A_{eff} affect the estimate of product-volume changes in the fill tube. If K is large or if A_{eff}, controlled by the cross-sectional area of the fill tube and other openings in the tank, is small, large errors can be made in estimating the product-volume changes produced by a leak or by a temperature-compensated volume rate. The error can be minimized if K is small, A_{eff} is large, or the product is continuously releveled within the fill tube. Increasing the diameter of the container used to measure product-level changes and periodically releveling the product in the fill tube are two methods that can be implemented as a means toward conducting accurate tests. In both cases, a waiting period must be included in the test protocol to allow for the effects of tank deformation to become negligible. A variable level test can be accurately conducted if K is known. The value of K as well as T_C can also be measured empirically during a test, but the measurements are difficult and time-consuming to make.

The data collected at the UST Test Apparatus also suggest that K is small 1 m above grade, but the data from one set of tanks are insufficient to conclude that conducting a test while product level is well above grade will eliminate the problem.

8.4 Evaporation and Condensation

The effects of evaporation and condensation in a partially filled tank were not specifically investigated in this project. The data necessary to quantify the volume changes effected by evaporation and condensation were collected as part of another program, and the analysis is in progress. The residual volume changes were compensated for after product temperature changes had been compensated for. This was accomplished using all three Test Appartaus thermistor arrays, and was done 6 h or more after any disturbance to the tank. These residual volume changes were used to estimate the effects of evaporation and condensation. Preliminary analysis of a number of tests from the evaporation and condensation database suggests for partially filled tanks that the volume changes are generally small and may be within the experimental uncertainty of the temperature compensation estimates (0.04 L/h). No reliable quantitative estimate of the volume changes associated with evaporation and condensation over a wide range of tank temperature conditions has been made from the database.

Several observations were made during the UST Test Apparatus experiments. First, accurate temperature compensation of the product was not possible for approximately 6 h after any of the tank's fill tubes were opened.

Second, in experiments conducted in Test Apparatus tanks that were filled to within 15 cm of the top, the effects of evaporation and condensation were small (0.04 L/h) and were highly correlated with temperature.

Third, the volume changes associated with evaporation and condensation in a partiallyfilled tank were too complicated to predict using a simple physical model.

8.5 Surface Waves

Mechanical vibrations or other disturbances produce waves travelling along the product surface in a partially filled tank. These waves, which introduce a modulation of surface height, are resonant with the length of the tank. Their periodicity is also a function of the tank's dimension. Typically, waves caused by an external vibration have periods on the order of 2 to 10 s and amplitudes of 0.00127 to 0.0127 cm. A more detailed description of surface waves can be found in [19, 20, 25, 30].

8.6 Internal Waves

Internal waves usually occur whenever there is a density gradient present, such as the boundary layer between existing product and newly added product which is at a different temperature. These waves occur in both partially filled and overfilled tanks. They travel both longitudinally and latitudinally throughout the tank, below the product surface, with longitudinal waves being more significant. The internal waves are resonant in the tank, their periodicity being a function of the tank dimensions and the product density. The passage of the internal waves modulates the vertical position of the temperature gradient so that a sensor at a fixed position records a temperature change associated with wave phase rather than with any volume change.

Internal waves in a 30,000-L tank can have periods of several minutes to an hour or more; typically, these waves have periods of 5 to 20 min. An internal wave having an amplitude of

20 cm will produce a temperature change of 0.2°C if the temperature gradient is 1°C/m. These conditions can easily arise after a tank has been filled with product whose temperature differs from that of the *in situ* product [19, 25, 30].

8.7 Summary of Results from Ambient Noise Experiments

The major conclusions drawn from the ambient noise experiments are as follows.

- *Need for temperature compensation and adequate waiting periods.* Experiments to simulate the delivery of product at a temperature different from the tank's surrounding backfill and from the *in situ* stored product indicate that the thermal effects decay exponentially but are large enough, even 24 h after the delivery, to significantly impair a method's ability to detect small leaks unless the thermally induced volume changes are compensated for.

  When the vertical and horizontal distribution of the temperature was investigated, the results indicated that the volume-weighted temperature changes measured by a single array of thermistors at the fill hole of the tank would adequately compensate for the thermal changes in the product throughout the tank. The results also indicated that compensation when the product level was at the fill hole was not possible for at least 4 to 6 h after the delivery, but that after the waiting period, the rate of change of temperature could be measured with sufficient accuracy (with product level at the fill hole of the tank) to compensate to within 0.04 L/h. During the period immediately after topping, the effects of horizontal temperature gradients are too large to permit accurate thermal compensation for 2 to 3 h. The effectiveness of compensation after the horizontal gradients have stabilized depends on how well the temperature distribution is measured; compensation improves with increased spatial coverage, increased test time, and smaller sampling interval.

- *Expansion and contraction of trapped vapor.* It was found that the expansion and contraction of trapped vapor could be predicted using the perfect gas law with $n = 1$. Atmospheric pressure and product-level changes affect the volume of the trapped vapor, as do temperature changes. Efforts to develop a simple, practical method of measuring the amount of trapped vapor during a test were unsuccessful. The model can do no more than estimate an upper bound of the volume of trapped vapor, because the effects of trapped vapor can not be separated from the effects of instantaneous deformation. The tests on the UST Test Apparatus suggested that the effects of instantaneous deformation were equivalent to those produced by a vapor pocket of 50 L. Accordingly, a vapor pocket estimate of 100 L or more, derived by means of the perfect gas law, would indicate that trapped vapor is present in sufficient quantity to impact the performance of a test method. Even a small vapor pocket can be important if the product level in the fill tube is changing during the test. Holding the product level constant in the fill tube eliminates the impact of pressure changes induced by product-level changes.

- *Structural deformation.* Structural deformation of the tank leads to significant errors in precision testing. The product volume changes measured in the fill tube or standpipe during a variable-level overfilled-tank test cannot be accurately estimated unless the structural deformation properties of the tank-backfill-soil system are known. The product-level changes are produced (1) by the instantaneous deformation of the tank, and (2) by an exponential, time-dependent relaxation of the tank. Even after the exponential deformation has become small, the product-level changes resulting from all leak- and non-leak-related volume changes will continue to include the effects of the deformation. If a test is conducted during the exponential relaxation period, the measured volume rate may be large; it may introduce a negative bias (flow out of the tank), and will tend to suggest that the tank is leaking. If a test does not measure the instantaneous deformation of the tank, or if the test is conducted after the tank deformation has apparently ended (i.e., after the obvious exponential change), the measured volume rate will be only a fraction of the true volume rate. Fortunately, the combined effects of the instantaneous deformation and the trapped vapor can be measured during a test, and it is possible to wait, before starting a test, until the exponential product-volume changes become negligibly small. However, even after the product level has apparently come to equilibrium, the product-volume changes estimated from the measured product-level changes, using an accurately measured height-to-volume conversion factor, are always a fraction of the true volume changes; they depend in a complex way on the time and elasticity constants of the tank-backfill-soil system, the cross-sectional area of the product surface in the fill tube or standpipe, the instantaneous deformation of the tank-backfill-soil system, the volume of trapped air, and the previous temporal history of product additions to the tank. Although the product volume can be predicted using a convolution model of the height changes developed and validated during this program (i.e., the Fill-Tube Dynamics Model), it is necessary (albeit difficult) to measure the empirical deformation properties of each tank being tested. These properties vary with product level and can vary significantly from tank to tank. Some test results are unaffected by this effect of structural deformation, while others may be in error by a factor of 2 to 20.

- *Constant hydrostatic pressure.* In a test conducted under constant hydrostatic pressure, the product-level changes produced by structural deformation will eventually become small enough to be negligible. Releveling is one way to achieve a constant hydrostatic pressure in an overfilled-tank test. Another is to increase the effective surface area of the fill tube so that this area is much larger than the elasticity constant. The time constant of the tank will increase if releveling is not done continuously; a 15-min releveling period will increase the time constant by approximately 14%. Product must be added carefully during releveling so that the local temperature field around the sensors will not be disturbed.

- *Relationship between compressibility and hydrostatic pressure.* The experiments on the fiberglass and steel tanks at the Test Apparatus indicated that the compressibility of the tank and ground system decreased with increased head above the top of the tank, becoming negligible when product was approximately 1.3 m above tank top. The time and elasticity constants measured in the fill tubes of the steel and fiberglass tanks were (T_C = 3 h and K = 117 cm^2) and (T_C = 2.6 h and K = 75 cm^2), respectively. The fill tubes were 10 cm (4 in.) in diameter.

- *Height-to-volume conversion factor.* Accurate estimates of performance against small leaks require that the height-to-volume conversion factor be experimentally measured. This is essential for all methods that overfill the tank or conduct a test with product level within the top 10% of the tank. In overfilled-tank test, an error factor of 2 can occur if the calculated height-to-volume conversion factor, obtained from an accurate estimate of the area of the product surface and tank geometry, is used instead of the measured one. This error results from a combination of two factors: a volume change in any trapped vapor, and instantaneous deformation of the tank when the product level is changed. Even small amounts of trapped vapor have a significant impact on the magnitude of the height-to-volume conversion factor. In addition, because the geometry is not accurately predicted by the tank chart, the calculated height-to-volume conversion factor can be in error by a factor of 2 during a partially-filled-tank test in which the tank is filled to within 5 to 10 cm of the top. Furthermore, the precision of a stick measurement made when the product level in the upper 80 to 90% of the tank is generally not sufficient to estimate the conversion factor with the degree of accuracy needed to detect small leaks, even using a perfect tank chart.

- *Evaporation and Condensation in a Partially Filled Tank.* The impact of evaporation and condensation was not addressed in this program. The Test Apparatus experiments suggest that the effect of evaporation and condensation will degrade a method's ability to detect small leaks for up to 6 h after any of the apertures into the tank are opened. Preliminary analysis of some data obtained after all tank apertures have been closed for 6 h or more and after the vapor has stabilized suggests that the volume changes are small (e.g., approximately 0.04 L/h), but their impact on the reliable detection of leak rates between 0.19 L/h (0.05 gal/L) and 0.76 L/h (0.20 gal/h) has not yet been quantified.

9 Evaluation Protocol

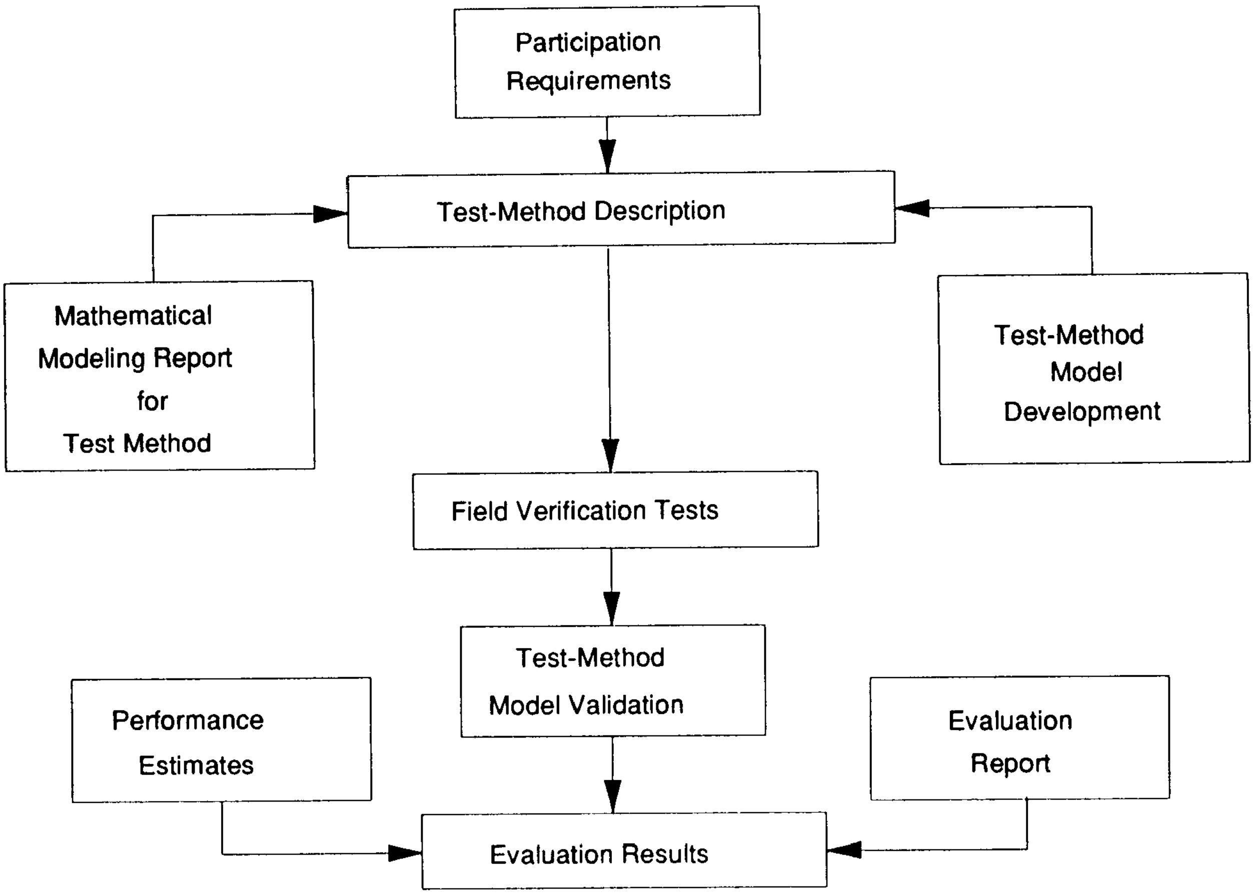


Figure 9.1 Flowchart of the evaluation protocol.

The protocol used to evaluate the performance of the volumetric test methods is summarized in Figure 9.1. As part of the participation requirements (which were summarized in Section 1.7), the manufacturer was asked to furnish a description of the test method. Based on this description, a computer model of the method was developed. In most instances, substantial interaction with the manufacturer was required in order to specify the method completely. The major features of the model were then described in a model report that was given to the manufacturer for review and written concurrence. Once written agreement had been obtained, the manufacturer was invited to participate in the Field Verification Tests at the UST Test Apparatus in Edison, New Jersey. The manufacturer was asked to use his method to test the Test Apparatus tanks under a variety of temperature and leak rate conditions during a three-day period. In addition, the precision of the manufacturer's product-level and temperature measurement systems was experimentally estimated. The data collected during the field tests were used to validate the model of the test method.

For each method, a performance estimate was made using the computer model of the method as input to the simulation. (A description of how the performance estimate was made with the simulation was given in Section 6.) It is important to understand that the performance estimate was not based on the data collected during the Field Verification Tests. Rather, as mentioned above, the Field Verification Test data were used to validate the test-method model that was used as input to the simulation. The performance of each method was presented in a set of three performance curves.

A 25- to 60-page report describing the results of the evaluation was prepared for each test method. The first draft was sent to the manufacturer for review and written comment. Each of the manufacturer's comments was then carefully reviewed for technical relevance by the EPA, and valid technical comments were incorporated in the report. Each manufacturer was then invited to participate in a half-day meeting to discuss his evaluation report and the potential for improvements to his system. The final version of the report was then sent back to the manufacturer for final review before publication. All of these reports appear as individual appendices in Volume II of this document.

Each appendix is divided into five sections. Section 1, a brief introduction, gives the name and manufacturer of the method evaluated. Section 2 describes the most important features of the manufacturer's instrumentation, the protocol used to conduct a test, the analysis algorithms, and the detection criterion. Sufficient descriptive material is presented to identify the major features of the method and to interpret the results of the evaluation; however, no confidential business information is included. Section 3 describes the results of the Field Verification Tests conducted by the manufacturer at the UST Test Apparatus in Edison, New Jersey, giving the results of actual tank tests conducted by the manufacturer's test crew and the conditions under which the tests were conducted. In addition, the results of a calibration of the manufacturer's product-level and temperature measurement systems are presented. The Field Verification Test data were used to validate the test-method model and to determine whether the manufacturer had actually followed the test protocol. Section 4 describes the validation of the test-method model. Section 5 presents the performance of the method and makes recommendations that might improve this performance. The performance was estimated from the results of a large number of tank tests simulated by using the test-method model and models of the ambient volume fluctuations that occur in a tank. A large temperature database, collected independently of the Field Verification Tests, was used as the primary input to the simulation. A list of the pertinent references is included with each appendix.

9.1 Test Method Description

With material furnished by the manufacturer at the commencement of the test program, including brochures, specification sheets, operational manuals, answers to a detailed questionnaire, and, usually, much discussion by telephone, a special modeling report was prepared that mathematically described each test method. The report described in detail the instrumentation, test protocol, data analysis (including temperature compensation) and detection criterion, as well as the mathematical algorithms developed to represent the method. In almost all cases, additional contacts with the manufacturer were required, either because important aspects of the method had not been specified or items in the questionnaire had not been answered completely. The manufacturer was required to review the report and concur in writing that it accurately represented his test method. The manufacturer was not permitted to participate in the Field Verification Tests in Edison, New Jersey, until this review and concurrence process was complete. Although it was time-consuming, this process (in general) went smoothly.

The model report served two important purposes. First, it clearly specified the important features of the method that was being evaluated. This was an important point, because many manufacturers had not specified their test procedures well, and this could have resulted in differing interpretations of test procedure. Since the performance is greatly affected by changes in test procedure, it is almost impossible to make a quantitative statement about performance unless the test procedure is well specified. It was concluded that many manufacturers had not had a structured procedure before this evaluation, and that, in many cases, they had not formalized their test procedures until this evaluation. For many manufacturers, specifying the procedure was difficult, because their operators were allowed to make a variety of judgments as part of, and during, the test. For example, a test might not be considered valid if the rate of change of temperature was "too great." While this was a valid approach, the criterion for what was "too great" was not well specified. It is obvious that performance would be better if the criterion were 0.01°C/h rather than 0.1°C/h, because the error in temperature compensation would then be smaller, given that the same degree of compensation was being achieved in all tests. It is equally clear that using a different criterion for each test in the field would also result in different degrees of performance. Thus, it was required that each manufacturer quantify these judgments as part of the test method. For the purposes of this evaluation, no changes to the method were allowed once the method had been defined in the model report and concurred with in writing by the manufacturer. It was important to adhere to this procedure, because some manufacturers were still attempting to make substantial changes to their methods, including instrumentation and important aspects of the protocol, as they were reviewing the final version of the report. This occurred frequently among the manufacturers of the newer methods, who viewed this evaluation as an opportunity for determining whether their methods were actually viable.

Second, the model report served as the basis of the computer code developed to model the method. (A general description of the model was presented in Section 6.5.)

Because some of the mathematical modeling reports include confidential information, they are considered proprietary, and are not available for public distribution by the EPA. The manufacturers, however, may distribute copies at their discretion. The modeling reports are referenced at the back of each appendix. A description of each method, which does not contain confidential information, is presented in Section 2 of each appendix in Volume II. This description is more than sufficient to identify the important features of the method and to interpret the results of a test performed with the method.

9.2 Field Verification Tests

Participation in the Field Verification Tests was a requirement for evaluation. The purpose of the tests was to

- o verify that the method existed and was operational,
- o verify that the major aspects of the test protocol were being followed,
- o estimate the precision and accuracy of the product-level and temperature measurement systems through calibration of the instrumentation, and
- o validate the model of the test method.

All field verification tests were conducted at the UST Test Apparatus over a three-day period during which it was planned that up to nine tank tests would be conducted by the manufacturer's test crew. For each method, three different temperature conditions were generated by the Test Apparatus engineers to simulate the delivery of product to the tank. In addition, leak rates up to 0.76 L/h (0.20 gal/h) were generated for some of the tests; however, no leak rates were induced for the first test after a product delivery. Such deliveries were simulated by adding product that differed in temperature from the product already in the tank. Except for temperature and leak rate, no attempt was made to change the test conditions. All valves connecting the piping with the tank were closed for the tests, so that only the tank was tested. No vapor pockets were created by the Test Apparatus engineers for any of the tests. There was no attempt or intention to trick the manufacturer or create conditions that were unusually severe or different from those normally encountered. The test conditions for individual manufacturers are given in Section 3 of each manufacturer's appendix (Volume II).

A new tank temperature condition was generated each day. Approximately 15,000 L (4,000 gal) of product was added to a half-filled tank containing, approximately, another 15,000 L of product. In the majority of cases, the tank temperature condition was prepared during the night before testing. Warm gasoline was added to cold; cold gasoline was added to warm; and gasoline at about the same temperature as that already in the tank was added. The difference in the temperature between the added gasoline and the ground was between ±10°C. The time series of the tank temperature conditions generated for individual manufacturers are presented in Section 3 of each manufacturer's appendix.

The performance estimates made for each method were not affected by the conditions generated during the Field Verification Tests, because a separate temperature database developed independently of the Field Verification Tests was used to evaluate all of the methods. However, the range of temperature conditions used in the Field Verification Tests was statistically similar to that of the database.

Two independent tests of the method, under the same temperature conditions, were planned for each day of testing. (Each *independent* test requires that either (1) the test crew remove their equipment from the tank and then set it up again before performing another test, or (2) that they start the test after creating a new product condition.) After each independent test had been completed and the manufacturer had reported a result, a second test was conducted by simply collecting another set of data over a similar period of time. This second test was not independent of the first. Time permitting, the manufacturer was then asked to conduct a second *independent* test. The same procedure was planned for the second day of testing, using a new temperature condition; one additional test sequence was planned on the morning of the third day of testing.

A detailed schedule was developed to conduct these tests. However, it became clear after the first few manufacturers had started testing that it would be difficult to conduct more than one independent test per day. Typically, four independent tests were conducted in all, one on the first day, two on the second, and one on the third. Setting up the test equipment on the first day generally took longer than anticipated, preventing the conduct of a second test on that day.

9.3 Test-Method Model Validation

The performance estimate made in this evaluation depends on the accuracy of the mathematical model of each manufacturer's test method. The model was developed by the EPA from information provided by the manufacturer, and was reviewed for accuracy and completeness and agreed to in writing by the manufacturer of the method. A systematic procedure was then used to validate the accuracy of the model.

With few exceptions, the model is a simple representation of the well-defined steps established by the manufacturer and followed by him to complete a test. The various parts of the model, including the time sequence for conducting a test, the data collection and reduction, the compensation measurements and analysis, the data analysis, and the criteria for a valid test and those for declaring a leak, were checked by hand and spreadsheet calculations for accuracy. The main uncertainties in the model are the actual (versus claimed) precision and accuracy of the instruments, the method of modeling the temperature measurement system when point sensors are not used, and operational effects. As soon as the field tests were complete, data from those tests were used to validate the model.

A four-step procedure was used to validate the test-method model used in the performance simulation. First, the tests were observed on a not-to-interfere basis by one or more of the Test Apparatus engineers to determine whether the test crew had used the equipment and followed the test protocol described in the model report. Most protocol deviations were identified during the post-test analysis after the tests had been completed. Second, the precision and accuracy of the product-level and temperature measurement systems were estimated experimentally during the third day of testing. Third, the software was validated using known inputs and outputs to ensure that it matched the test method described in the model report. This check was independent of the field tests. Fourth, validation was completed for the model of any method which did not use an array of point temperature sensors for the manufacturer's temperature compensation.

Not all of the 25 methods were evaluated. Two criteria were used for deciding whether to make a performance estimate: (1) the ability to obtain at least one valid test with a particular method, and (2) consistency between test results and expectations for the method. With regard to the former, it was assumed that a commercially available method should be able to perform one test in a 72-h period. Thus, any method that failed to perform at least once during the three days of testing was not evaluated. However, no manufacturer was eliminated from the evaluation simply because he had not brought a spare set of equipment (as specifically requested in the invitation letter) to use as a backup in case of instrument failure. The second criterion applied only to cases in which it was obvious that the manufacturer did not understand what his method was measuring, that is, when there was an error in the results that was many times larger than would have been expected based on individual errors in the measurement and compensation systems. Six methods were not evaluated: two methods failed to meet the first criterion, three methods failed to meet the second, and for one method the Test Apparatus was not properly configured for the tests. (In this last instance, a valve connecting the above- and below-ground tanks was not properly closed during many of the manufacturer's tank tests).

Once the test-method model had been validated, the manufacturer's temperature-compensated volume-rate test result was compared to that produced by the simulation in order to assess the operational effects, particularly the disturbance of the product's temperature field resulting from topping the tank before a test. Because the effects of temperature changes produced by topping the tank were large enough to produce highly erroneous results for a method that might otherwise achieve a high level of performance, these changes were not included in the simulation. It was assumed that as a result of this evaluation the manufacturer would either eliminate from his protocol the practice of topping the tank, or wait a minimum of 3 h or more for the resulting thermal effects to become small enough to be negligible. As a consequence, the performance estimate presented herein was considered invalid unless the manufacturer had incorporated these changes.

The test protocol specified by the manufacturer assumes that the test will proceed as prescribed. Unintentional delays in executing the test protocol were a common problem. To achieve accurate test results requires that the manufacturer wait long enough, after adjusting the level of the product in the tank, for the temperature inhomogeneities and the deformation effects to become small. Because of a variety of delays that arose in executing a test, some manufacturers whose protocol did not include an adequate waiting period accidentally realized the benefits of waiting. For the tests actually conducted at the Edison facility, delays such as problems in setting up equipment actually improved the accuracy of the test in some cases, and would have improved the performance estimate made in this evaluation. The model used to estimate performance assumes that the manufacturer's protocol is followed exactly as specified, even though it became clear during the Field Verification Tests that this was not always true. Consideration was given, for example, to including the effects of delay in the model and therefore in the performance estimates. This was not done, however, because it would have violated the protocol given by the manufacturer, and because it was extremely difficult to determine which delays were typical and which were not.

9.3.1 Adherence to Test Method

During the briefing conducted before any testing began, it was re-emphasized that unless the method described in the mathematical modeling report was followed, the evaluation would be invalid. It was stated that no tests would be conducted if the manufacturer had brought a different system to test, or had made major modifications to the protocol, analysis algorithms, compensation approach, measurement configuration, or instrumentation.

The manufacturers' test crews were asked to conduct their tests as they normally did. These crews, often consisting of senior management and senior technical staff (sometimes including the inventor of the system) as well as the designated test crew, were professional and cooperative. There was no intent on the part of the Test Apparatus engineers to police or interfere with the tests, even though the post-test interpretation of the manufacturers' data would have been much simpler if the Test Apparatus engineer had been able to make some additional measurements. The Test Apparatus engineer, whose main role was that of an observer, made sure that the Test Apparatus sensors were operating properly. He was available to answer questions for the test crew, but did not actively participate in any of the tests. No information regarding the nature of the test conditions (i.e., what temperature condition had been created or whether a leak had been generated for the test) was given to the test crew, so that this evaluation was equivalent to their testing one of their customers.

Deviations from the prescribed protocol were generally easy to identify during the post-test analysis. While some test procedures differed from agreed-upon protocols, no obvious intentional attempts by the manufacturers to make last-minute modifications were observed. In all instances the deviations that occurred were either unintentional (e.g., operational delays) or occurred because some part of the protocol did not work and could not have been followed. Some of the protocol deviations that were discovered during the tests were brought to the attention of the test crew. They were asked to describe what was being done, and the deviation was noted in the experimental logs. Operational delays and problems that occurred during the test were not considered protocol deviations.

The experimental logs, the Test Apparatus's and the manufacturer's raw temperature and product-level data, and the manufacturer's calculation data sheets and operational notes were all reviewed during and after the Field Verification Tests in order to identify any variances in the prescribed test protocol. The most common deviation involved the criteria for determining when the test was considered completed.

The Test Apparatus was general enough to permit all manufacturers to conduct their normal tests. No permanent modifications to the Test Apparatus were permitted. The Test Apparatus sensor systems functioned properly for the large majority of the tests. For a few of the methods tested, some problems with small but visible leaks in the above-grade thermistor connections occurred at the beginning of the tests. All Test Apparatus problems were fixed immediately, or the instrumentation was removed for the duration of the test. Test Apparatus problems and their impact on the manufacturers' tests are described in the appendices if they represented more than a simple delay in the test preparations.

Both the manufacturers' test crews and that of the Test Apparatus demonstrated professionalism in conducting the Field Verification Tests. The vast majority of the manufacturers' crews indicated that the tests had been fairly conducted, that the Test Apparatus crew had been helpful and had not interfered, that the nature of the tests was straightforward and typical of actual tank tests at retail service stations, and that the Test Apparatus was not as difficult to test as many of those they had previously performed at retail stations.

The validation procedure is discussed in Section 4 of each appendix in Volume II.

9.3.2 Instrument Precision and Accuracy

The manufacturer specified the precision and accuracy of the sensor systems used to collect the raw data. Typically, these included measurements of product level, product temperature, and product density. These were used as input to calculate product volume and volume change due to product-temperature changes, or temperature-compensated volume. The precision and accuracy of the sensor systems were determined from a calibration check performed during the Field Verification Tests. The measured precision and accuracy were used in the test-method model.

Several different methods were used to perform the calibration checks. The standard method used to calibrate the temperature measurement systems was to place the temperature measurement sensors in a controlled temperature bath. The temperature measured by the manufacturer's system was compared directly to the quartz thermometer used as a reference. Approximately 30 min of measurements were made in at least four different baths between 0 and 30°C; the temperature of the bath was allowed to drift slowly during each 30-min period. The calibration was performed to estimate the capability of the system to measure the rate of change of temperature. A least-squares line was fit to a scatter plot of the manufacturer's data and the reference data. The slope of the line indicates the accuracy of the system to measure absolute temperature changes, and the standard deviation of the manufacturer's temperature data about the line is a measure of the precision.

If the sensors were too large to be placed in the temperature bath, an alternate method was used to perform the calibration check. A direct comparison between the nearest Test Apparatus thermistor array and the manufacturer's temperature measurement system was made when horizontal temperature gradients in the tank were small enough to be negligible.

Two methods were used to check the precision and accuracy of the manufacturer's product-level measurement system. In the first method, where measurements were made in the tank, bars of different size were used to displace the product level. A bar was inserted in the product for 2 min and then removed for 2 min a total of 10 or more times. The precision was estimated from the standard deviation of the absolute value of the product-level changes after product-level trends had been removed from the data. The accuracy was determined by the mean height change. In the second method, which applied to those few instances where the first method could not be used, the manufacturer was asked to sample the data for several hours at a rate of 1 sample/min. The precision was then estimated from the white portion of the power spectrum obtained from the data.

9.3.3 Temperature Compensation

The manufacturer's temperature measurement or temperature compensation system was modeled using a linear combination of the Test Apparatus thermistors. If the manufacturer's system used point temperature sensors, the modeling validation was straightforward. If, however, the temperature measurements were made by a spatially integrating sensor, such as a thermistor strip or a tube filled with product, the temperature measurement sensor was modeled as a weighted average of the Test Apparatus thermistors. The model of these spatially integrating systems was based upon information provided by the manufacturer; if none was available, the manufacturer was asked to describe what he thought was being measured. The model was verified by the manufacturer as being representative of his system, and then was tested experimentally during the field tests. The validity of the models of spatially integrating temperature systems was not guaranteed; if the temperature measurement model could not be validated, no evaluation was performed. No attempt was made by the EPA to develop a more sophisticated physical model of the system, even though it was possible to do this. Four systems had temperature measurement models that could not be validated.

In some instances it was difficult to validate the spatially integrating temperature measurement models because of the 1-m horizontal spatial separation between the Test Apparatus thermistor arrays and the manufacturer's measurement system. Horizontal gradients in the temperature field were produced by topping product in the fill tube, or by addition of product to the tank to simulate a delivery. However, this difficulty was overcome in all cases.

9.3.4 Validation Procedure

The data collected during the Field Verification Tests were used to validate the model of the test method and assess the importance of operations on performance. The largest operational effects occurred whenever product was added to the tank and whenever delays in executing the protocol occurred. In some instances, operational effects actually improved performance. These operational effects are not included in the performance model. However, they may have a significant effect on performance and so are discussed separately in each appendix.

With the exception of the temperature compensation approach, the test-method model was simply a logical sequence of well-defined steps and algorithms to collect and analyze the data. The details of this procedure had already been presented in the model report. In what was essentially a computer-code validation, an effort was made to determine whether the algorithms produced the same answers as those prescribed by the manufacturer. The computer code was verified by using known input with known output. As part of the validation, the entire model code was exercised with complete sets of product-level and temperature data.

9.4 Evaluation Results

The evaluation results in each appendix are discussed in two parts. First, an estimate of performance is given, and second, recommendations for improving performance are made. These results are also summarized and discussed in Section 11.

The performance of each method was obtained by combining several different calculations. First, a quantitative estimate of performance was made for a single tank without any trapped vapor; it included the instrumentation noise, a wide range of temperature conditions, and one set of tank deformation characteristics. The performance of each method is presented in terms of the probability of detection and probability of false alarm for leak rates between 190 ml/h (0.05 gal/h) and 5,000 ml/h (1.3 gal/h). The performance estimate was made for a 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) steel tank containing unleaded gasoline, and assumes that the test procedure was followed precisely as specified by the manufacturer.

Second, quantitative estimates of the effects of structural deformation and trapped vapor on performance (presented in Sections 6, 8, and 10) were made over a wide range of conditions. The significance of these effects (discussed in Section 5 of each appendix) is that they can seriously degrade the estimates given by the performance curves. The effects of structural deformation and trapped vapor were not included in the performance curves, because for a wide range of petroleum storage facilities, neither the range of tank and backfill properties affecting the structural deformation of storage tanks nor the distribution of the volume of trapped vapor is known. For most methods, an arbitrary selection of these conditions could easily result in anomalously poor performance.

Third, operational effects were quantified. These effects include topping the tank before a test, which can significantly impair effective temperature compensation and significantly increase structural deformation of the tank. These operational effects can seriously degrade the estimates given by the performance curves.

The multi-step approach described above was taken because a majority of the methods are similarly influenced by deformation, trapped vapor, and operational effects. These three effects, which were noted during the actual field tests of each test method, result in large errors that could invalidate a test, yet they can be corrected by simple modifications to the protocol.

The part of each appendix describing performance improvements is brief. All methods can be improved to some degree. However, only those suggested modifications are given that can significantly improve the performance of a method. Many additional requirements which might produce incremental improvements of up to 10% were not mentioned. This does not imply that such changes are not warranted.

10 Performance of Canonical Test Methods

Most of the volumetric test methods are generically similar. They attempt to minimize the volume changes that occur in a nonleaking tank so that if a leak is present, these volume changes will be much smaller than those produced by the leak. Minimization of the volume changes (i.e., noise) is usually accomplished by temperature compensation and by including adequate waiting periods in the protocol.

Performance calculations are made in this section using a number of canonical methods which are representative of the 25 methods that have been evaluated. Each canonical method consists of product-level and temperature measurements that are combined to develop a histogram of the temperature-compensated volume rates. Unless specifically intended to demonstrate a deficiency, the canonical methods invoke sound operational, data collection, data analysis, and temperature-compensation practice. The results of the performance calculations made for these theoretical test methods are used (1) to help interpret the performance being achieved by the methods evaluated in this study, (2) to illustrate performance that can be achieved by such a method, (3) to illustrate the effects of the important sources of noise on performance so that design and performance improvements can be made, and (4) to estimate the practical technological limitations of volumetric tank testing.

Three calculations are made in this section. First, an estimate of the degree of temperature compensation that can be achieved with different measurement schemes is made using the product temperature database as a function of test duration. The degree of temperature compensation achieved is dependent on the ability of the temperature measurement system to estimate the average rate of change of temperature in the tank. There are six basic temperature measurement schemes employed by the methods evaluated. Second, an estimate of the volume changes that result from thermal expansion or contraction of trapped vapor is made using the temperature changes derived from the temperature database and measured by the thermistor located near the top of the tank. Third, 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 is made using a method with a vertical array of five thermistors to compensate for thermally induced volume changes.

10.1 Test Method Model Description

All calculations were performed using the basic test method described below, and the same temperature database used to evaluate the 25 commercial methods. Modifications were made to the method to illustrate specific effects on performance. Unless otherwise stated, all calculations were performed with this method.

The analysis was performed for overfilled-tank tests conducted in the 10-cm (4-in.)-diameter fill tube of a 30,000-L (8,000-gal), 2.43-m (8-ft) diameter tank containing unleaded gasoline. The precision of the product-level sensor was assumed to be 0.25 mm (0.01 in.), corresponding to a volume change of 0.002 L (0.0005 gal). This precision is an order of magnitude better than is necessary for the detection of a leak of 0.19 L/h (0.05 gal/h) with a P_D of 0.99 and a P_{FA} of 0.01. It is further assumed that the height-to-volume conversion factor was measured experimentally and 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 specifically included (i.e., for these tests K = 0 cm^2).

The six temperature sensor configurations given in Table 10.1 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 assuming that the volume of the product in the tank and the coefficient of thermal expansion were known perfectly. The precision of the temperature measurement system was assumed to be 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. The test duration was varied from 1 to 4 h, and no test was begun until 12 h after a 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.

10.2 Thermal Expansion and Contraction of the Product

All methods attempt to compensate for thermal expansion, either by measuring the rate of change of temperature directly and converting to the rate of change of volume, as described in Section 6.4, or by directly measuring the volume changes produced by temperature changes. The achievable performance depends on how accurately each approach measures the average rate of change of temperature of the product throughout the entire tank. Temperature compensation can be accomplished by means of a thermistor array placed at the fill tube of the tank, providing that (1) there is a waiting period to allow the horizontal gradients to dissipate after addition of product to the tank, and (2) any addition of product via the fill tube during the test does not adversely affect the temperature measurements. The product-level changes in the tank are estimated assuming that the only product-level changes present are caused by the thermally induced volume changes as determined from the three thermistor arrays in the tank.

10.2.1 Test Method Description

The six temperature-compensation schemes that were modeled are summarized in Table 10.1. In order that the performance estimates could be used to evaluate the temperature compensation scheme, no effects of structural deformation were included here. Schemes Cone, Thre, Five, and TVMT volumetrically weight the thermistor measurements for thermal compensation based on the circular geometry of the tank. Method 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, using Array 2 of the Test Apparatus thermistors.

Table 10.1. Temperature Compensation Schemes

Method	Description
None	No temperature compensation
One	One thermistor 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

10.2.2 Performance Results

A histogram and a set of performance curves were generated for each canonical method for test durations of 1, 2, 3, and 4 h. 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 10.2. The leak rates that can be detected with a P_D of 0.99 and a P_{FA} of 0.01 under the conditions in Table 10.2 are summarized in Table 10.3. As an example, the histogram and cumulative distribution function for the five-thermistor canonical method are shown in Figure 10.1 for a test duration of 1 h. Figure 10.2 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.

Table 10.2. Standard Deviations of Temperature-Compensated Volume Rate Histogram

Scheme	Standard Deviation (ml/h) for Test Duration (h) of 1.0	2.0	3.0	4.0
None	789	766	795	800
One	161	156	157	156
Three	112	106	105	105
Five	84	80	81	75
AVGT	30	35	35	31
VWAT	34	26	21	19

Table 10.3. Smallest Detectable Leak Rates with a $P_D = 0.99$ and $P_{FA} = 0.01$

Scheme	Detectable Leak Rate (ml/h) for Test Duration (h) of 1.0	2.0	3.0	4.0
None	3685	3577	3713	3736
One	752	729	733	729
Three	523	495	490	490
Five	392	374	378	350
AVGT	140	163	163	145
VWAT	159	121	98	89

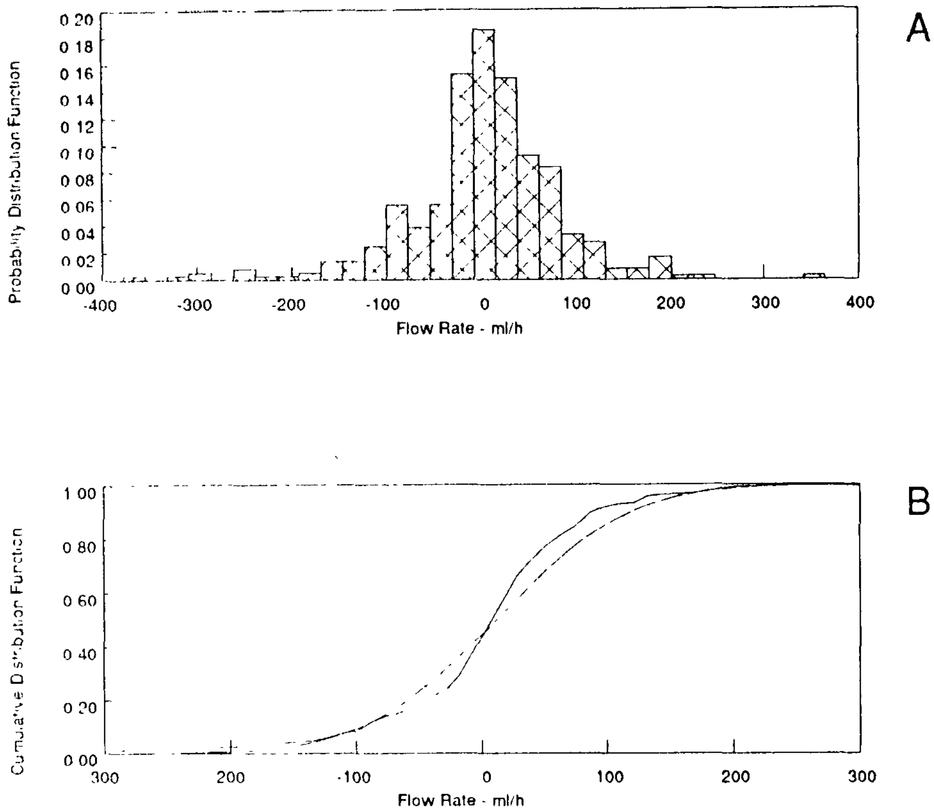


Figure 10.1. The histogram (A) and cumulative distribution function (B) for the five-thermistor method with a test duration of 1 h. The dotted line in (B) is a normal model generated with the mean and standard deviation of the histogram data.

The results of the compensation schemes having three or fewer thermistors should be interpreted cautiously. The product condition used in the Edison evaluation tends to 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 tank was not half-filled at the time of delivery, differences of as little as 15 cm (6 in.) in the location of the temperature sensor and the product level (before the addition of product) could result in larger errors than those manifest in this study. To illustrate the magnitude of the error for the one-thermistor case, the location of the thermistor has been moved to 1/4 and 3/4 of the tank height. The results, designated by the height of the thermistor as a fraction of tank diameter and summarized in Tables 10.4 and 10.5, suggest the performance that might be achieved if the product was not delivered to a half-filled tank. The performance is degraded severely for the 1/4 and 3/4 methods.

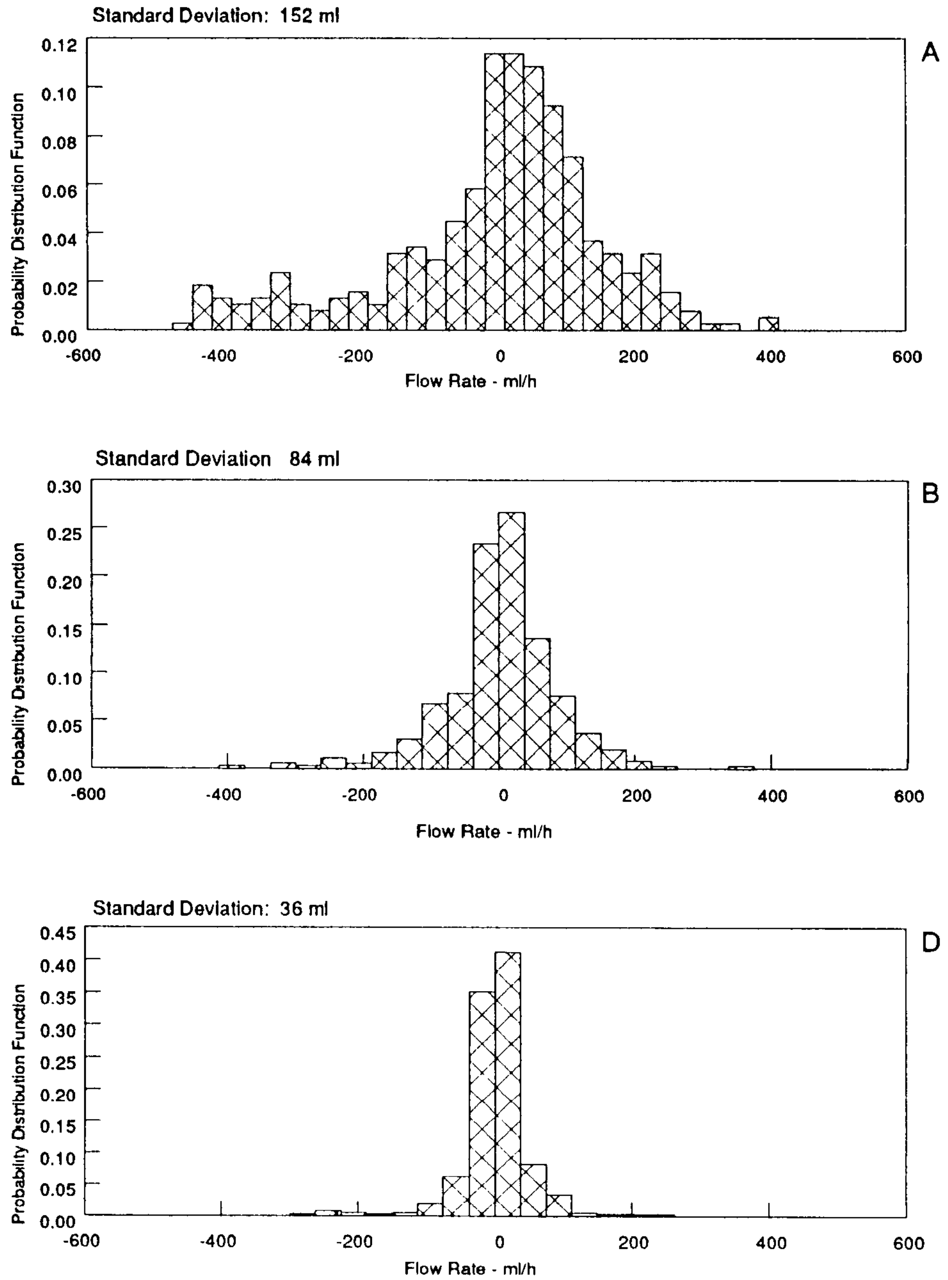


Figure 10.2. Histograms of the noise compiled from overfilled, constant-head tank tests that compensate for thermal expansion and contraction of the product using (A) one temperature sensor located at the midpoint of the tank, (B) five equally spaced temperature sensors that are weighted volumetrically, and (C) eleven equally spaced temperature sensors that are weighted volumetrically. It is assumed that the tank does not deform (i.e., $K = 0\ cm^2$). The standard deviations of the histograms shown in (A), (B), and (C) are 161 ml/h, 84 ml/h, and 34 ml/h, respectively. The histograms are compiled from estimates of the temperature-compensated volume rates for a 1-h test using thermistors with a precision of 0.001 °C. All product-level changes are measured in a 10-cm (4-in.)-diameter fill tube with a precision of 1 ml/h. The only product-level or product-volume changes are produced by the thermal expansion or contraction of the product.

Table 10.4. Standard Deviations for One-Thermistor Case at Different Heights

Method	Height (cm) from Bottom of Tank	Standard Deviation (ml/h) for Test Duration (h) of			
		1.0	2.0	3.0	4.0
1/4	61	934	939	947	954
3/4	182	948	952	958	962

Table 10.5. Smallest Detectable Leak Rates for One-Thermistor Case at Different Heights (P_D = 0.99 and P_{FA} = 0.01)

	Detectable Leak Rate (ml/h) for Test Duration (h) of			
Method	1.0	2.0	3.0	4.0
1/4	4362	4385	4422	4455
3/4	4427	4446	4474	4493

Another calculation was made to estimate the change in performance that would occur if one thermistor were located 30 cm above the mid-point of the tank. The standard deviation was reduced from 161 ml/h to 128 ml/h. Moving the thermistor up another 30 cm (3/4 method) dramatically changes the performance.

An estimate of performance was also made for the five thermistor method after moving the array up by 20 cm (8 in.), 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 array up and down by different amounts results in similar changes in the standard deviation. This change in the standard deviation is consistent with the experimental uncertainties of the temperature measurement.

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 0.19 L/h (0.05 gal/h). Without compensation, leaks of 4.75 L/h (1.19 gal/h) and larger are detectable with a P_D of 0.99 and a P_{FA} of 0.01.

The results also indicate that the increase in test duration did not, in general, improve the estimate of the mean rate of change of temperature in the tank. This result was initially puzzling, because it was contrary to previous experience [e.g., 6, 7]. This finding should be interpreted cautiously, since it does not necessarily indicate that a 1-h test will suffice. The level of electronic noise (including electronic drift) in most of the temperature measurement systems evaluated was higher than the noise level of the temperature measurement system used at the Test Apparatus, and the additional averaging gained from the longer duration of the test was needed for high performance. Also, if temperature fluctuations have periods of 20 to 30 min or longer, a test longer than 1 h is required to avoid aliasing the data. This is particularly true if the vertical temperature field is undersampled. For the most part, a 2-h test is long enough to avoid undersampling the temperature data.

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 of the temperature measurement system.

10.3 Trapped Vapor

It is difficult to estimate the impact of trapped vapor on an overfilled-tank test that is conducted under uncontrolled conditions, because the distribution of the volume of trapped vapor is unknown for the universe of installed tanks. If the volume of trapped vapor were known, it would be possible to develop a method of avoiding its effects, or perhaps a compensation scheme for minimizing them. Because of the instantaneous deformation of the tank, the effects of which are virtually undiscernible from those of trapped vapor, it is not possible to measure the volume of the vapor directly. Changes in the volume of the trapped vapor produced by hydrostatic (i.e., product-level) and atmospheric pressure changes can be minimized by using an experimentally determined height-to-volume conversion factor and conducting a test when the atmospheric changes are small.

A canonical method was used to estimate the important effects of trapped vapor. A five-thermistor measurement system was used to compensate for temperature. The precision of the product-level and temperature measurement systems does not affect the results.

Tests were simulated to estimate the effect of trapped vapor on test performance. Saturated vapor pocket volume changes were predicted using Eq. (6.8). The uppermost thermistor on the Test Apparatus thermistor array, located within 10 cm (4 in.) of the top of the tank, was used as input into the vapor model. Tests were simulated assuming a linear atmospheric pressure change of $\pm$ 0.5 mb/h. It was found that the vapor pocket volume changes induced by the combined effects of thermal and pressure changes are very small, less than 40 ml/h, for vapor pockets smaller than 200 L. The vapor pocket volume change caused by temperature fluctuation can be roughly estimated as 1 ml per liter of trapped vapor per degree Celsius change in mean vapor temperature. The change in vapor pocket volume due to pressure changes can be estimated as a 1.5-ml change in vapor pocket volume for every millibar change in vapor pocket pressure. Although the changes in vapor pocket volume should, in most cases, be relatively small during a test, the trapped vapor, if the initial volume is large, can be an important source of error unless it is included in the height-to-volume conversion factor. Furthermore, as discussed in Sections 6.4 and 8.2, even small vapor pockets can effect large changes if the vapor is unsaturated.

10.4 Structural Deformation

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 elasticity constant, K, are unknown, the full range of 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.

An estimate of the effects of structural deformation on performance was made for tests on a single tank and for tests on many tanks, all overfilled. The estimate was made of the rate of change of the temperature-compensated volume in a nonleaking tank 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., 3 T_C) before starting the test. These represent the extreme conditions, that is, cases for which there is no 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.

10.4.1 Test Method Description

The five-thermistor measurement system was used with varying values for T_C and K, and with A_{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 (2.2 gal) 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.

All calculations were performed assuming that product-level changes are produced by the thermal expansion and contraction of the product and by the structural deformation of the tank.

10.4.2 Product Volume Estimates in a Nonleaking Tank

The effects of structural deformation upon test performance were estimated for tests that start immediately after product volume adjustments are made and for tests in which a waiting period is observed after the tank has been topped.

10.4.2.1 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 10.3 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 in 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. The increase in the standard deviation with K is illustrated in Table 10.6. The standard deviation when K = 0 cm^2 is approximately 80 ml/h. 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 generated for increasing T_C (0.5, 1, 3 h) with a tank elasticity constant of 120 cm^2. The results, shown in Table 10.7, indicate that the mean changed but the standard deviation remained approximately the same. Figure 10.3 illustrates the effect on the mean and standard deviation as the time constant increases from 0.75 to 3 h. Clearly, the time constant controls the results.

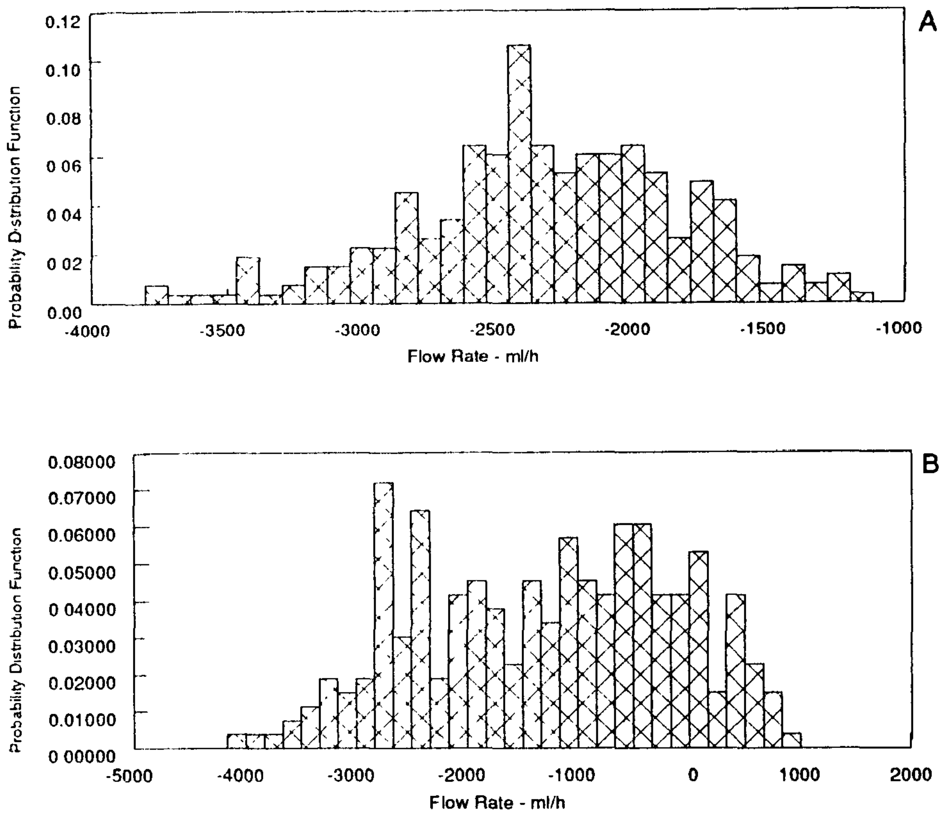


Figure 10.3. Histograms of the noise generated from overfilled, variable-head tank tests conducted immediately after topping the tank (1-m product-level addition) for (A) $T_c = 0.75$ h, K = 120 cm^2 and (B) $T_c = 3$ h, K =120 cm^2. The standard deviation of the histograms are 502 ml/h for (A) and 1160 ml/h for (B). The nonzero mean is produced by the exponential time-dependent structural deformation. The histograms are compiled from estimates of the temperature-compensated volume rates for a 1-h test with a method using five equally spaced thermistors having a precision of 0.001 °C. All product-level changes are measured with a precision of 1 ml/h in a 10-cm (4-in)-diameter fill tube. Other than deformation, the only product-level or product-volume changes are produced by the thermal expansion or contraction of the product.

Table 10.6. Standard Deviations for a Nonleaking Tank Immediately after Topping ($T_C = 0.75$ h, $A_{eff} = 82.0$ cm^2)

K (cm^2)	Standard Deviation (ml/h) for Test Duration (h) of 1.0	2.0	3.0	4.0
30	253	246	249	249
60	373	371	375	376
120	505	505	510	513

Table 10.7. Standard Deviations for a Nonleaking Tank Immediately after Topping ($K = 120\ cm^2$, $A_{eff} = 82.0\ cm^2$)

	Mean (ml) for Test Duration (h) of				Standard Deviation (ml) for Test Duration (h) of			
T_C (h)	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	536	510	512	546
3.0	-3250	-2000	-1450	-1000	585	532	535	557

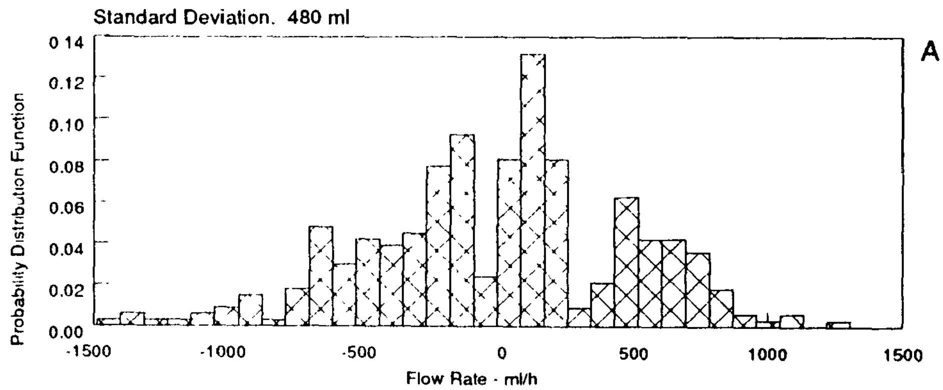
10.4.2.2 Test Starting 3 Time Constants After Topping

Approximately 99% of the deformation will have occurred after 3 time constants. Therefore, if the total change in volume due to deformation is less that 4 L/h (1 gal/h), the residual effects will be less than 0.04 L/h (0.01 gal/h), sufficiently small to allow a 0.19-L/h (0.05-gal/h) leak to be detected.

Table 10.8. Standard Deviations for a Nonleaking Tank 3 Time Constants after Topping ($A_{eff} = 82.0\ cm^2$)

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	0.5	509
120	1	512
120	2	522
120	3	544

The 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 10.8, were for a 2-h test duration and a five-thermistor temperature compensation scheme (Five). The results of using a 1-, 3-, and 4-h test duration are almost identical to the results of the 2-h test. The same conditions used to generate the histograms in Figure 10.3 were used to generate those in Figure 10.4, except that the waiting period was 3 time constants or more. The mean of the histogram is approximately zero, but the standard deviation increases with K and is approximately constant. The product-level and product-volume changes are smaller than those that would occur if deformation were not present, and as a consequence, the histogram of the temperature-compensated volume rates has a smaller spread than the original temperature volume histogram, but a larger one than the histogram for the case where deformation is not a problem. As K approaches 0 cm^2, the temperature-compensated volume rate histogram approaches the histogram generated without deformation (i.e., a standard deviation of approximately 80 ml/h). The effect of the increasing time constant is an increase in the duration of the test. The measured volume rate is controlled by K if the waiting period is sufficiently long for the exponential decay to stabilize.



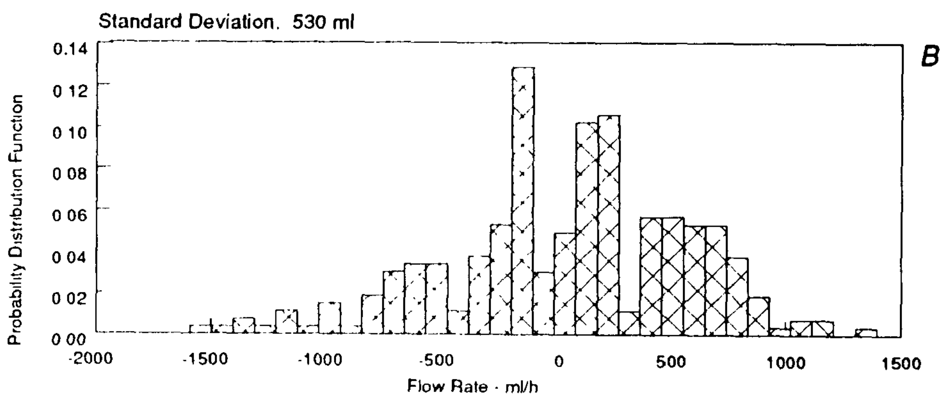


Figure 10.4. Histograms of the noise generated from overfilled, variable-head tank tests conducted 3 time constants after topping the tank (1-m product-level addition) for (A) $T_c = 0.75$ h, K = 120 cm^2 and (B) $T_c = 3$ h, K =120 cm^2. The standard deviation is 480 ml/h for histogram (A) and 530 ml/h for histogram (B). The means of the histograms are approximately zero, suggesting that the exponential time-dependent structural deformation effects have become small. The histograms are compiled from estimates of the temperature-compensated volume rates for a 1-h test with a method using five equally spaced thermistors having a precision of 0.001 °C. All product-level changes are measured with a precision of 1 ml/h in a 10-cm (4-in)-diameter fill tube. Other than deformation, only product-level or product-volume changes are produced by the thermal expansion or contraction of the product.

The performance estimates made in the appendices assumed one set of deformation characteristics. An estimate of performance was made for a uniform distribution of K between 0 and 120 cm^2 and T_C between 0 and 3 h for a 1-h test with a five-thermistor method. The wait time after topping was at least 3 time constants. One histogram of the temperature-compensated volume rates was generated for K and for T_C, respectively. The results, shown in Figure 10.5, show that the standard deviations were 410 ml/h when $T_C = 0.75$ h and K is uniformly distributed, and 514 ml/h when K = 120 cm^2 and T_C is uniformly distributed. Under these conditions, only leaks greater than 3.8 L/h (1 gal/h) could be detected with a probability of detection of 0.99 and a probability of false alarm of 0.01.

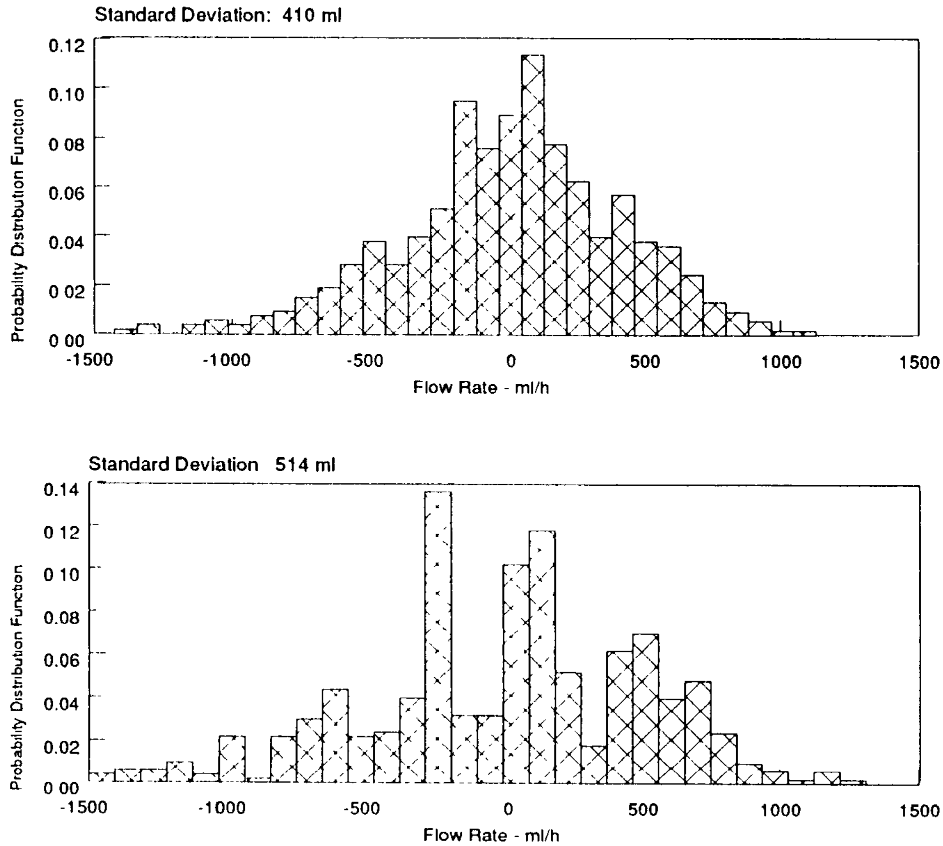


Figure 10.5. Histograms of the noise in overfilled, variable-head tank tests produced by a uniform distribution of (A) K (30, 60, 90, and 120 cm^2) with $T_c = 0.75$ h and (B) T_c (0.5, 1, 2, and 3 h) with K = 120 cm^2. It can be assumed that the waiting period after topping is long enough for the exponential time-dependent structural deformation effects to become small. The standard deviations of the histograms are 410 ml/h for (A) and 514 ml/h for (B). The histograms are compiled from estimates of the temperature-compensated volume rates for a 1-h test with a method using five equally spaced thermistors having a precision of 0.001 °C. All product-level changes are measured with a precision of 1 ml/h in a 10-cm (4-in)-diameter fill tube. Other than deformation, the only product-level or product-volume changes are produced by the thermal expansion or contraction of the product.

10.4.2.3 Summary

Large values of K and T_C degrade the performance of a method which does not maintain a constant head during the test and may 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.

The impact of deformation on the noise and signal-plus-noise histograms, and therefore on performance, was discussed in more detail in Section 5. Because it is impractical to measure K and T_C under actual field conditions, the results of tests conducted at a variable hydrostatic pressure must be considered suspect.

11 Performance of Commercial Test Methods

The performance of 25 commercially available volumetric test methods was evaluated by the EPA at the UST Test Apparatus. A description of each method and its performance are presented as a lettered appendix in Volume II. The appendices are listed in alphabetical order by the name of the method. The results are summarized in this section; for ease of reference, the description of each method and the recommendations for performance improvements are condensed into a single appendix in Volume I. These two sections are taken from the Volume II appendices. As summarized in Section 9.4, the evaluation results are presented and discussed in three subsections of each lettered appendix. In the first subsection, a quantitative estimate of performance is presented in tables and curves in terms of the probability of detection and probability of false alarm. These estimates do not include all of the sources of noise that control performance. Several sources of noise were not included because either the range of applicable conditions across the country was unknown and an arbitrary selection of conditions might have unfairly degrade the performance of some methods (e.g., the range of vapor pocket sizes), or the inclusion of a noise source had such a degrading effect on performance that it would have been difficult to interpret the result (e.g., topping the tank). The second subsection discusses the impact of the sources of noise which were not included fully in the quantitative estimate of the method, and the third section discusses the impact of operational practice on performance.

The performance estimate was made for a 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) tank containing unleaded gasoline, under the assumption that the test followed the manufacturer's specified procedure precisely. The conditions selected for evaluation, as estimated from empirical relationships developed in [11], represent a wide range of temperature conditions found throughout the United States. Tests conducted under more benign product temperature conditions and less elastic tank conditions would result in better performance.

The performance can be extrapolated to smaller-capacity tanks, to larger-capacity tanks with the same nominal diameter, and to other gasoline fuels. In principle, the results should also be applicable to other fuels, like diesel, providing that: the proper coefficient of thermal expansion for the fuel, as required for temperature compensation, is used; the evaporation and condensation characteristics of the fuel are not significantly different than they are for gasoline fuels; and the difference in density between gasoline and other fuels does not adversely impact either the test protocol or the deformation characteristics. Field evidence suggests that the performance of volumetric methods is different for diesel fuels than for gasoline fuels, being sometimes better and sometimes worse. A statistically significant bias has been identified for diesel fuels in tests that circulate and mix the product [8].

With one exception, all of the estimates were made using the temperature database, described in Section 6, that was collected independently of the Field Verification Tests. A smaller temperature database, in which the product was continuously circulated and mixed throughout the test, was developed using the Petro Tite circulation system, specifically to evaluate the Petro Tite test method. This database was generated using the same range of differences in temperature between the product in the tank and the product added to the tank, but the standard deviation of the histogram of the thermally induced volume changes for the mixed conditions was larger than for the nonmixed conditions; this suggests that the test conditions under which these methods were evaluated were more severe than the nonmixed test conditions. Whether this is true or not is uncertain, because the circulation does add heat to the product and increases the rate of change of temperature during the test.

11.1 How to Interpret Performance Results

The quantitative estimate of performance assumes that no trapped vapor is present (for methods that overfilled the tank), that all tanks have the structural deformation properties of one tank system, that the temperature field has not been disturbed by topping the tank, that the deformation effects produced by topping the tank were not included although specific product-level changes required by the protocol were, and that evaporation and condensation are negligible. The performance estimate further assumes that all tests are conducted precisely as prescribed by the manufacturer by a highly trained and competent test crew. The estimate does not, in general, include the uncertainty in the tank chart or coefficient of thermal expansion. The error introduced by using the manufacturer's tank chart for tanks at the Test Apparatus, and the coefficient of thermal expansion for the Test Apparatus tanks, however, are included in the performance estimates. The degradation in performance that occurs when these assumptions are violated is discussed in this section and in Sections 6, 8, 10, and 12.

The quantitative estimates of performance did not include the potential adverse effects of trapped vapor for overfilled-tank test methods, and of evaporation and condensation for partially-filled-tank test methods. These effects on performance are discussed in the second subsection of each lettered appendix and in Section 6.4 of the body of this report. The effects of trapped vapor were not included in the estimates because the distribution of the volume of trapped vapor in a tank depends on the tank geometry and the operator's expertise in overfilling and bleeding the tank; that is to say, the effects are unknown. It is assumed that the effects of trapped vapor will be minimal with experienced operators, and thus, this effect was not included in the performance estimate. This assumption is not always valid; the reader should understand that large testing errors can be made if vapor is trapped in the in the tank system. Because of the wide diversity of experience, even among operators of the same method, the performance of overfilled-tank tests presented in this report may be poorer than predicted. The effects of evaporation and condensation were not included because no simple model could be developed to predict their impact on performance; these effects are also operator-dependent. The magnitude of the effect depends on the change of the partial pressure of the gasoline vapor after the fill tube has been opened to the ambient environment for equipment setup and test preparations.

The quantitative estimates of performance for each method used one set of tank deformation characteristics. The estimates did not include a wide range of conditions because the nationwide distribution of tank-backfill-soil elasticity properties is unknown. This effect is also discussed in the second subsection of each lettered appendix and in Section 6.4.

The effect of all three sources of noise not included in the performance estimate is to increase the standard deviation of the noise and to introduce a bias for the deformation effects. The effects of trapped vapor and evaporation and condensation may also exhibit a systematic trend on a seasonal basis.

The performance estimates assume that the height-to-volume conversion factor, A_{eff}, is accurately estimated for each method. In general, this is true because most methods estimate A_{eff} experimentally. Any method that does not already do so can easily include this simple measurement in its protocol, and thus no manufacturer was penalized for failing to describe it in the protocol. It should be noted, however, that the estimates presented in this report could be in error by as much as 50% or more if this experimental measurement of A_{eff} is not implemented.

The performance estimates do not include the degradation in performance in overfilled-tank tests produced by topping the tank. Even when a level change was required, the spatial inhomogeneities in the temperature field produced by topping were not included. Again, to realize the performance presented in this report, changes must be made to many of the methods to account for the temperature and deformation effects of topping. It should be pointed out, however, that the deformation effects produced by the volume changes during the test (e.g., thermal expansion or contraction of the product) were included in the performance estimates. The effects of topping will have very little impact on test method performance if there is a waiting period of at least 2 to 3 h after adding product to the tank and before starting a test. Topping effects were not overly emphasized because the overall degrading effects of topping the tank are large enough to invalidate a test, and it is assumed that most manufacturers will change their protocol to minimize this problem.

The performance of each method should ultimately depend on how well the volume changes produced by thermal expansion or contraction of the product are compensated for and on the magnitude of the evaporation and condensation of the vapor from the product surface and tank walls. The effects of trapped vapor, structural deformation, and the spatial inhomogeneities in the temperature field produced by topping and delivery can and should be minimized.

Many of the methods evaluated exhibited a bias (i.e., a noise histogram with a nonzero mean that is statistically different than zero) in the noise histogram produced, in general, by the deformation of the tank. The magnitude of the bias for the test conditions used in the evaluation can be estimated from the data provided in the lettered appendices in Volume II. The bias is probably not as large as it might be under actual field testing conditions where the range of deformation conditions will be larger. The bias will change as the test conditions change. The performance estimates presented in Subsection 11.2 do not include the effects of the bias. In general, a method cannot be properly evaluated unless the bias can be quantified and removed. A performance estimate was made for all methods nonetheless. This assumes that the bias has been removed. This is essential to good performance, and it is assumed that all manufacturers will identify the reason for the bias and either quantify and remove it, or modify the method to eliminate its presence. The effects of the bias present in these data can be interpreted using the P_D-vs.-threshold and P_{FA}-vs.-threshold performance curves in the lettered appendices.

It cannot be emphasized enough that the results of this evaluation, particularly those shown in Tables 11.1, 11.3, and 11.5, should be used cautiously, because the majority of the test methods evaluated will probably have changes made since this evaluation. The detailed description of the performance of each method and the suggestions for improving performance can be found in the lettered appendices in Volume II as well as in the appendix in Volume I.

11.2 Performance Results

The evaluation results are summarized and discussed in four categories: (1) overfilled-tank test methods at variable head, (2) overfilled-tank test methods at constant head, (3) underfilled-tank test methods, and (4) those methods for which no estimates of performance could be made. The results of the quantitative estimates of performance for the first three categories are summarized in Tables 11.1, 11.3, and 11.5 (in Sections 11.2.1, 11.2.2, and 11.2.3). The results are presented in both SI and English units; Tables 11.1(a), 11.3(a), and 11.5(a) are in SI units and Tables 11.1(b), 11.3(b), and 11.5(b) are in English units. The tables include the mean and standard deviation of the noise histogram, the number of points in the histogram, the P_D and P_{FA} achieved with the method (using the manufacturer's standard detection criterion or threshold) against a 0.38-L/h (0.10-gal/h) leak rate, and the smallest leak rate that can be detected with (1) a P_D of 0.95 and P_{FA} of 0.05, and (2) a P_D of 0.99 and P_{FA} of 0.01. The latter two estimates are representative of capability, but are not actually being achieved because the manufacturer's standard detection threshold was changed to make these estimates. To make the two latter estimates, thresholds that would yield P_{FA}s of 0.05 and of 0.01, respectively, were derived from the noise histogram. The performance actually being achieved by these methods may be considerably different, because the actual threshold used by the manufacturer may be different. Additional factors, without which it is impossible to interpret the quantitative estimate of perfomance, are tabulated and presented for each category in Tables 11.2, 11.4, and 11.6. Of particular note is the length of the waiting time after topping. The six remaining methods could not be fully evaluated (see Section 11.2.4)

The leak rate measurable by these systems with a threshold established by a P_{FA} of 0.05 ranged from 0.26 to 6.97 L/h (0.07 to 1.84 gal/h), with a probability of detection of 0.95 and probability of false alarm of 0.05. Five of the methods achieved a performance that was better than 0.57 L/h (0.15 gal/h), and a total of eight methods had a performance that was better than 0.95 L/h (0.25 gal/h). The leak rate measurable by these systems with a threshold established by a P_{FA} of 0.01 ranged from 0.47 to 12.95 L/h (0.12 to 3.42 gal/h) when the probability of detection increased to 0.99 and the probability of false alarm decreased to 0.01. Only one of the methods achieved a performance better than 0.57 L/h, but five methods achieved a performance between 0.57 L/h and 0.95 L/h.

Over 90% of the methods evaluated claimed a performance of 0.19 L/h (0.05 gal/h), but none of the methods achieved this performance with a probability of detection of 0.99 and a probability of false alarm of 0.01. One of the methods (LMS-750 Leak Detection System) claimed a performance of 3.8 L/h (1.0 gal/h), and one method (TLS-250) claimed a performance of 0.76 L/h (0.20 gal/h), the latter with a P_D of 0.98 and a P_{FA} of 0.005. With this one exception, none of the methods either specified or attempted to support a P_D or P_{FA}

11.2.1 Overfilled-Tank Test Methods at Variable Head

In twelve test methods, the tank is overfilled to a level within the fill tube or an above-grade standpipe, and product-level changes are measured and converted to volume using a height-to-volume conversion factor. The major contributions to the noise are thermal expansion and contraction of the product, expansion and contraction of the trapped vapor (due to pressure, temperature, and evaporation and condensation within the vapor space), and structural deformation. Some of the methods use an experimentally determined height-to-volume conversion factor and others calculate it from an estimate of the product's surface geometry. All of the methods compensate for temperature and attempt to use one or more waiting periods to ensure that the temperature and deformation effects will become small. Trapped vapor may be a problem because it is difficult to estimate how much trapped vapor, if any, exists in the tank after it has been overfilled.

The performance of eleven methods is shown in Table 11.1. One method in this category (AUTAMAT) was not evaluated (see Section 11.2.4).

Table 11.1(a). Performance of Overfilled-Tank Test Methods at Variable Head (SI Units)

Test Method Name	Mean (L/h)	Standard Deviation (L/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (L/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (L/h)
AES/Brockman Leak Detecting System*	-0.167	0.910	112	0.45,0.34	6.79	12.95
Ainlay Tank 'Tegrity Tester	0.076	0.470	284	0.50,0.31	2.97	3.93
Computerized VPLT Tank Leak Testing System	0.023	0.230	99	0.66,0.19	1.08	1.84
EZY CHEK	0.048	0.184	399	0.86,0.15	0.62	0.93
Leak-O-Meter	-1.060	2.072	231	0.57,0.49	6.96	10.80
LiquidManager	0.307	0.168	79	0.80,0.14	0.75	1.25
Mooney Leak Detection System	-0.266	0.551	196	0.47,0.38	3.13	4.58
PACE Leak Tester	0.143	0.810	245	0.37,0.32	6.97	11.12
Portable Small Leak Detector (PSLD)	-0.192	0.871	135	0.63,0.32	3.05	5.60
S.M.A.R.T.	-0.033	0.366	81	0.58,0.32	2.25	3.43
Tank Auditor	1.048	1.107	207	0.57,0.43	6.27	12.52

*Data analysis algorithms for this method had to be modified in order to determine its minimum detectable leak rate.

The quantitative performance estimates made for variable head, overfilled-tank tests are affected by three factors: (1) the temperature and deformation effects produced by topping the tank, (2) the potential for trapping an unknown volume of vapor during a test, and (3) whether or not the height-to-volume conversion factor is measured experimentally or calculated theoretically from the tank geometry.

Table 11.1(b). Performance of Overfilled-Tank Test Methods at Variable Head (English Units)

Test Method Name	Mean (gal/h)	Standard Deviation (gal/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (gal/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (gal/h)
AES/Brockman Leak Detecting System*	-0.044	0.240	112	0.45,0.34	1.79	3.42
Ainlay Tank 'Tegrity Tester	0.020	0.124	284	0.50,0.31	0.78	1.04
Computerized VPLT Tank Leak Testing System	0.006	0.061	99	0.66,0.19	0.28	0.49
EZY CHEK	0.013	0.049	399	0.86,0.15	0.16	0.25
Leak-O-Meter	-0.280	0.547	231	0.57,0.49	1.84	2.85
LiquidManager	0.081	0.044	79	0.80,0.14	0.20	0.33
Mooney Leak Detection System	-0.070	0.146	196	0.47,0.38	0.83	1.21
PACE Leak Tester	0.038	0.214	245	0.37,0.32	1.84	2.94
Portable Small Leak Detector (PSLD)	-0.051	0.230	135	0.63,0.32	0.81	1.48
S.M.A.R.T.	-0.009	0.097	81	0.58,0.32	0.59	0.91
Tank Auditor	0.277	0.292	207	0.57,0.43	1.66	3.31

* Data analysis algorithms for this method had to be modified in order to determine its minimum detectable leak rate.

The effects of topping were not included in these evaluations, because the degradation that occurs from topping may be large (i.e., it may degrade the performance presented here by a factor of 2 or more) but is easy to correct. The degradation will be large if the product added to the tank is at a significantly different temperature than the product in the tank, or the level change is a large fraction of the tank diameter. The effects of topping can be avoided by waiting for the spatial inhomogeneities in the temperature field (e.g., Figures 8.5 and 8.6) and the product-level changes due to structural deformation to become negligible. The minimum waiting time may be different for each effect. The quantitative performance results presented here should not be considered valid if the waiting period is too short. Some methods use a dynamic analysis algorithm to minimize the waiting period for each test. If the algorithm does not result in a waiting period of 1 to 3 h or more, the method should be considered suspect.

After a tank has been topped, accurate temperature compensation is difficult to achieve unless a waiting period is observed; this is because topping produces spatial inhomogeneities in the product temperature field. A waiting period of at least 2 h, preferably 3 h, should be part of the test protocol. The errors in temperature compensation that would be produced by topping were not included in any of the performance estimates. Therefore, unless there is an adequate waiting period defined in the protocol, the actual performance of a method in the field can be significantly lower than that which is presented here. The methods subject to the effects of topping are identified in Table 11.2. The performance estimate made for any method that has a waiting period of at least 3 h would not be affected. All of the methods in this study, however, may be adversely affected because none has a 3-h waiting period.

Table 11.2. Factors That Affect the Performance of Overfilled-Tank Tests Conducted at Variable Head

Test Method Name	Waiting Period After Product Delivery (h)	Waiting Period After Topping (h)	H-to-V Conversion Factor[1]	Bias[2]
AES/Brockman Leak Detecting System	4	0	3	2
Ainlay Tank 'Tegrity Tester	8	2	4	1
Computerized VPLT Tank Leak Testing System	12	0	2	1
EZY CHEK	6	1	2	1
Leak-O-Meter	12	0.75	3	3
Liquid Manager	12	1	3	2
Mooney Leak Detection System	12	Variable[3]	1	2
PACE Leak Tester	12	0	3	2
S.M.A.R.T.	12	0	2	1
Tank Auditor	8	0	2	3

1 The numeral 1 indicates that the height-to-volume conversion factor has been theoretically estimated from the tank chart or the known geometry of the tank; 2 that it has been obtained by displacement of fluid using a solid of known volume; 3 that it has been obtained by displacement through addition or removal of product; and 4 that it has been obtained by means of a direct volume measurement.

2 The numeral 1 indicates a bias less than or equal to 100 ml/h; 2, greater than 100 but less than 400 ml/h; and 3, greater than 400 ml/h.

3 Stipulates a variable waiting period after tank has been topped.

Table 11.2 also shows the minimum waiting periods specified by each test method's protocol. The performance of methods which test within 4 to 6 h after a product delivery will also be affected by the spatial inhomogeneities of the temperature field. However, these effects are included in the performance estimates.

The effects of structual deformation are an important source of error in overfilled-tank test methods. These errors may occur whenever the product level in the fill tube or standpipe changes, specifically after a product delivery or topping of the tank, in tests which require measurements at two or more levels, or as a result of any product-level changes that occur during the test itself.

The performance of overfilled-tank test methods that allow the product level to change during the test is flawed because the induced product-level changes cause the tank to deform continuously, making conversion to true volume changes nearly impossible. The product-level changes measured during a test are either larger or smaller than expected. If the waiting period after topping the tank is too short (e.g., less than 2 to 3 h), the measured volume rate depends almost entirely on the product-level change due to the exponential changes caused by deformation. Such a measurement will tend to suggest that the tank is leaking. The effect of exponential changes is minimized if the time constant of the deformation is small or if the waiting period is long in comparison. If an adequate waiting period is used, the measured rate of change of product level (and product volume) will always be a fraction of the expected rate. Because the volume rate estimated for the product-temperature changes is not affected by the deformation effects in the fill tube, the temperature-compensated volume rate will always be in error. This flaw is subtle and not always apparent in field measurements, because the product-level changes will tend to approach a constant value. The error depends on the unknown structural deformation characteristics of the tank-backfill-soil system. The flaw can be minimized either by increasing the surface area of the product so that the hydrostatic pressure remains essentially constant during the test or by releveling the product in the tank.

The performance estimates were made using only one set of deformation characteristics. The value of K and T_C used in the analysis of each method is noted in each lettered appendix in Volume II. The values of K measured in the steel tank of the Test Apparatus indicated that K was smaller for tests conducted with the product level above grade than for tests conducted with the product level in the fill tube. As a consequence, the effects of deformation on the performance estimates made in Table 11.1 are less severe for above-grade tests than for below-grade tests. The time constant used in the analysis was typically 0.75 h, small enough (and deliberately selected for that reason) that a 2- to 3-h waiting period, approximately 3 time constants, would minimize the exponential deformation effects on performance. The time constant of the steel and fiberglass tanks was approximately 3 h, so that a minimum waiting period of 9 h or more might be required. Estimates of how T_C and K affect performance were given in Sections 6.4, 8.3 and 10.4.

The performance of any method is degraded when it does not conscientiously attempt to identify the exponential volume changes produced by structural deformation (i.e., those that result from changing the level of the product in the fill tube or standpipe) and wait for these to become small. The deformation effects produced by the product-level change required to top the tank were not included in these estimates. The 2- to 3-h waiting period required to minimize the spatial inhomogeneities in the product temperature field may not be long enough to minimize the effects of deformation. However, the methods in Table 11.2 that do not wait at least this long are affected by product temperature and may also be affected by deformation. In general, most methods unintentionally include a "start" waiting period because of the time it takes to top the tank. Unless it is sufficently long, minimum waiting period is no guarantee that deformation has subsided. Several of the methods incorporate an algorithm to identify and wait out the effects of deformation. The sensitivity of the methods to deformation can be assessed from the waiting periods observed after product delivery or topping. At the minimum, the waiting period must be at least as long as the one for product temperature disturbances (those produced by the addition of product), since the deformation effects may take longer to subside.

Large testing errors, 50% or more, even for well-bled tanks, can occur if the effects of the instantaneous tank deformation and trapped vapor are not included in the height-to-volume conversion factor, A_{eff}. A theoretical estimate of the cross-sectional area of the product surface, A, does not include these effects. Furthermore, accurate estimates of the cross-sectional area of the product surface area are difficult to make in operational practice because of the unknown presence of additional fill tubes and piping. Even when these are known to exist, their diameters may not be known. An experimental estimate of A_{eff} is therefore required. In addition, methods which determine A_{eff} by adding product to the tank may introduce spatial inhomogeneities in the temperature field. Because all methods can easily implement an experimental measurement of the height-to-volume conversion in their protocol, it was assumed in the performance estimate that all methods used an experimental estimate of A_{eff}. Table 11.2 indicates that only one method does not use an experimental measurement. In a case such as this, when the height-to-volume conversion factor is estimated only from the geometry of the tank, the performance estimates made in this report are likely to be in error by 50% or more. It is assumed that as a result of this evaluation all methods will implement the technique of experimentally estimating A_{eff}. A_{eff} is not a valid height-to-volume conversion factor if the product level is allowed to fluctuate in the fill tube or standpipe during the test; A_{eff} + K is the correct conversion factor. Since K is not usually known during a test and since K may be large compared to A_{eff}, large errors are possible in variable-level tests. If K is small compared to A_{eff}, then accurate tests can be conducted.

All of the overfilled-tank test methods have the potential for trapping vapor. The effects of trapped vapor were not included in the performance estimates because no severe problems are encountered unless (1) the effects of the trapped vapor (as well as the instantaneous deformation of the tank) are not included in the height-to-volume conversion factor, (2) the volume of trapped vapor is large, (3) large changes in atmospheric pressure occur during a test, (4) the temperature of the vapor is affected by ambient changes, or (5) the trapped vapor is not saturated. It was observed during the Field Verification Tests that the more experienced test crews did a better job in removing vapor from the tank before a test was begun. A method of estimating an upper bound on the volume of the trapped vapor is presented in Section 8.2 of this report.

The magnitude of the bias is also summarized in Table 11.2. To achieve the performance presented in Table 11.1, the bias must be identified and removed. Removal of a bias is a complex task. It cannot be correctly done simply by using the magnitude of the bias presented in this evaluation, because the magnitude of the bias may change with the testing conditions. Additional developmental work is required by the manufacturer.

In summary, the quantitative estimates of performance in Table 11.1 do not include the degradation in performance produced by topping; they do assume the benefits of an experimentally measured height-to-volume conversion factor. The errors produced by topping and by not measuring the h-to-v conversion factor directly can be corrected immediately, and it is assumed that they will be, because simple protocol changes are all that is necessary to do so. If these modifications have not been made, the performance estimate presented in Table 11.1 should be considered invalid. Even if the topping-related exponential deformation effects are properly handled, the potential for testing errors in the field is large (in the case of variable-level tests) because of the problems in making volumetric interpretations of the product-level measurements in the fill tube and standpipes. Reliable performance requires constant hydrostatic pressure. Significant improvements in performance would be realized if a waiting period were incorporated into the protocol after topping, if the test were conducted at a constant hydrostatic pressure head, and if an experimental estimate of A_{eff} were used to convert product-level changes to product-volume changes.

11.2.2 Overfilled-Tank Test Methods at Constant Head

In three of methods evaluated, the tank is overfilled and the volume of product necessary to maintain a constant level during the test is measured. The performance of these methods is presented in Table 11.3.

Table 11.3(a). Performance of Overfilled-Tank Test Methods at Constant Head (SI Units)

Test Method Name	Mean (L/h)	Standard Deviation (L/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (L/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (L/h)
Leak Computer	0.005	0.096	132	0.97,0.04	0.32	0.65
MCG-110	0.206	0.119	97	0.97,0.09	0.36	0.86
Petro Tite	0.002	0.209	25	0.79,0.21	0.80	1.11

Table 11.3(b). Performance of Overfilled-Tank Test Methods at Constant Head (English Units)

Test Method Name	Mean (gal/h)	Standard Deviation (gal/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (gal/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (gal/h)
Leak Computer	0.001	0.025	132	0.97,0.04	0.08	0.17
MCG-110	0.054	0.031	97	0.97,0.09	0.10	0.23
Petro Tite	0.000	0.055	25	0.79,0.21	0.21	0.29

Methods that overfill the tank and measure at a nearly constant product level are subject to the same effects as the overfilled-tank test with variable head, except that only the exponentially induced deformation of the tank is important. In addition, direct measurements of volume are made (i.e., the experimentally measured height-to-volume conversion factor is inherently known), so that an experimentally measured A_{eff} is not necessary. Table 11.3 should be interpreted using the data presented in Table 11.4.

Table 11.4. Factors That Affect the Performance of Overfilled-Tank Tests Conducted at Constant Head

Test Method Name	Waiting Period After Product Delivery (h)	Waiting Period After Topping (h)	H-to-V Conversion Factor[1]	Bias[2]
Leak Computer	Variable	Variable	4	1
MCG-1100	2	Variable	3	2
Petro Tite	0	Variable[3]	3	1

1 The numeral 1 indicates that the height-to-volume conversion factor has been theoretically estimated from the tank chart or the known geometry of the tank; 2 that it has been obtained by displacement of fluid using a solid of known volume; 3 that it has been obtained by displacement through addition or removal of product; and 4 that it has been obtained by means of a direct volume measurement.

2 The numeral 1 indicates a bias less than or equal to 100 ml/h; 2, greater than 100 but less than 400 ml/h; and 3, greater than 400 ml/h.

3 Product is circulated (5 to 8 min/1,000 gal at high level and 0 h at low level).

Several of the methods in Table 11.4 do not have a minimum waiting period specified in the protocol, but instead have an algorithm that analyzes the data, as they are being collected, to determine if the effects of thermal inhomogeneities and structural deformation have subsided. These methods are identified by the superscript 3. The thermal effect is also minimized in other methods that mix the product before or during the test. The success of these approaches can be assessed from the degree of temperature compensation achieved by each method during the Field Verification Tests; this is presented in the lettered appendices in Volume II.

11.2.3 Parially-Filled-Tank Test Methods

Ten of the methods that participated in the evaluation program routinely test in partially filled tanks. All of these tests are conducted at a specified product level which is less than 95% of the capacity of the tank. While the exact level is not critical, most of these tests require that product be added to the tank before a test is conducted. The addition of product will affect performance if the waiting period between the product addition and the start of the test is too short.

The major contributions to noise are instrumentation, thermal expansion and contraction of the product, evaporation and condensation from the product surface and tank walls, and structural deformation. The degrading effects on performance produced by the spatial inhomogeneities in the product temperature field and the structural deformation resulting from product delivery are included in these estimates. Because the test is conducted at a constant hydrostatic pressure, the measured product-level changes can be converted to product-volume change using a height-to-volume conversion factor. All of the methods compensate for temperature and attempt to wait for the deformation effects to become small. None of the methods listed in Table 11.5 compensates for evaporation and condensation of the product. In about half of the cases, better performance could be achieved if the system noise were lowered (i.e., if there were better precision of the product-level and product-temperature sensors).

Table 11.5(a). Performance of Partially-Filled-Tank Test Methods (SI Units)

Test Method Name	Mean (L/h)	Standard Deviation (L/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (L/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (L/h)
Gasoline Tank Monitor (GTM)*	0.105	0.408	13	0.73,0.21	1.35	1.91
Gilbarco Tank Monitor*	0.016	0.075	59	0.96,0.003	0.26	0.47
Inductive Leak Detector 3100	0.055	1.012	45	0.72,0.33	4.23	9.54
Tank Sentry II	-0.093	0.154	23	0.89,0.16	0.58	0.89
TLS-250*	-0.016	0.142	46	0.15,0.001	0.51	0.90

* In a precision test mode rather than in its normal operating mode as an automatic tank gauging system (ATGS)

The performance of five partially-filled-tank test methods is presented in Table 11.5. The remaining five (DWY Leak Sensor, INSTA-TEST, LMS-750, OTEC Leak Sensor, and Tank Monitoring Device (TMD-1)), could not be evaluated for the reasons discussed in Section 11.2.4.

The quantitative estimate of performance made for the methods in Table 11.5 do not include the effects of evaporation and condensation of product from the product surface and the tank walls. While these effects are believed to be small, the performance of all the methods presented here will be degraded somewhat. Preliminary estimates for a limited data set suggest that evaporation and condensation would affect the detectable leak rate presented in Table 11.5 by less than 0.19 L/h (0.05 gal/h), providing that the evaporation and condensation effects that occur whenever the tank is opened to the ambient atmosphere have ceased. No quantitative estimate of this latter effect has been made, but it was seen to be present each time the tanks at

Table 11.5(b). Performance of Partially-Filled-Tank Test Methods (English Units)

Test Method Name	Mean (gal/h)	Standard Deviation (gal/h)	Number	P_D and P_{FA} to Detect a 0.38 L/h (0.10 gal/h) Leak Rate (P_D,P_{FA})	Smallest Detectable Leak Rate for P_D=0.95 P_{FA}=0.05 (gal/h)	Smallest Detectable Leak Rate for P_D=0.99 P_{FA}=0.01 (gal/h)
Gasoline Tank Monitor (GTM)*	0.027	0.108	13	0.73,0.21	0.36	0.50
Gilbarco Tank Monitor*	0.004	0.020	59	0.96,0.003	0.07	0.12
Inductive Leak Detector 3100	0.015	0.267	45	0.72,0.33	1.12	2.52
Tank Sentry II	-0.024	0.041	23	0.89,0.16	00.15	0.23
TLS-250*	-0.004	0.037	46	0.15,0.001	0.13	0.23

* In a precision test mode rather than in its normal operating mode as an automatic tank gauging system (ATGS)

the Test Apparatus were opened to the ambient environment. Typically, a 6-h waiting period is required for the tank to reestablish a quasi-equilibrium condition after the it has been closed to the ambient environment. The performance of the methods given in Table 11.5 would probably be degraded if the waiting period were less than 6 h. The potential degradation in the performance estimate made here can be estimated from the minimum waiting periods after a product delivery that are included as part of the manufacturer's test protocol and that are given in Table 11.6.

Two of the methods evaluated are acoustic systems. Both are subject to a potentially large seasonal bias in the measurement of product level, because changes in product temperature, which affect the propagation of the acoustic signal, cannot be completely compensated for. This is best observed in [21].

The performance estimates for partially-filled-tank test methods do not include the uncertainty in the coefficient of thermal expansion; they do assume that the tank chart is sufficiently accurate to estimate the height-to-volume conversion factor accurately, a reasonable assumption when product level is not in the upper part of the tank.

The high level of performance achieved by three of these methods requires waiting periods of 18 to 24 h and test durations of 4 to 12 h. This represents a total test duration that is significantly longer than that of many of the other methods.

Table 11.6. Factors That Affect the Performance of Partially-Filled-Tank Tests

Test Method Name	Waiting Period After Product Delivery (h)	Waiting Period After Topping (h)	H-to-V Conversion Factor[1]	Bias[2]
Gasoline Tank Monitor (GTM)[3]	24	N/A	1	1
Gilbarco Tank Monitor[3]	18	N/A	1	1
Inductive Leak Detector 3100	3	N/A	1	1
Tank Sentry II	24	N/A	1	1
TLS-250	2	N/A	1	1

[1] The numeral 1 indicates that the height-to-volume conversion factor has been theoretically estimated from the tank chart or the known geometry of the tank; 2 that it has been obtained by displacement of fluid using a solid of known volume; 3 that it has been obtained by displacement through addition or removal of product; and 4 that it has been obtained by means of a direct volume measurement.

[2] The numeral 1 indicates a bias less than or equal to 100 ml/h; 2, greater than 100 but less than 400 ml/h; and 3, greater than 400 ml/h.

[3] Unknown magnitude of systematic error introduced by acoustic measurement of product.

11.2.4 Methods for Which No Performance Estimates Were Made

There were no performance estimates made for 6 of the 25 methods evaluated. Two of the six methods (INSTA-TEST and TMD-1) did not satisfactorily perform a valid test during the three days of the Field Verification Tests. Any method that could not complete a valid test during the three-day period was not evaluated; moreover, no data were obtained to validate the test method model. The temperature and product-level data obtained for three of the other methods (AUTAMAT, DWY Leak Sensor, and LMS-750) showed that the measurement systems were clearly not operating as the manufacturers had indicated; the models of these methods could not, therefore, be validated. The fourth method (OTEC Leak Sensor) could not be evaluated because the Tank Apparatus had not been properly configured for some of the tests. Typically, these were the methods that attempted to compensate for product-temperature changes without measuring temperature. In the case of these methods, the performance estimates made using the test method model would have been significantly better than what the field measurements indicated.

11.2.5 Summary of Test Results

The estimates of performance are summarized in Tables 11.7 and 11.8. Table 11.7 summarizes the methods' actual performance using the manufacturers' detection criteria. Table

11.8 summarizes performance using detection criteria that produce a probability of false alarm of 0.05 and 0.01. The performance results are expressed as the smallest leak rate that can be detected with probabilities of 0.95 and 0.99, respectively.

Table 11.7. Estimates of Test Method Performance In Terms of P_D and P_{FA} for the Detection of a Leak Rate of 0.38 L/h (0.1 gal/h) Using the Manufacturer's Detection Threshold

P_D	P_{FA}	Number of Methods Having P_D and P_{FA}
$0.90 < P_D \leq 1.00$	$0 < P_{FA} \leq 0.10$	3
$0.65 < P_D \leq 0.90$	$0.10 < P_{FA} \leq 0.25$	6
$0.35 < P_D \leq 0.75$	$0.25 < P_{FA} \leq 0.50$	9
$0.10 < P_D \leq 0.20$	$0 < P_{FA} \leq 0.01$	1

Table 11.8. Estimate of Test Method Performance in Terms of Leak Rate for Two Different Sets of P_D and P_{FA} Using the Detection Threshold Established by the P_{FA}

Detectable Leak Rate (L/h (gal/h))	Number of Methods Having This Leak Rate	
	P_D=0.95, P_{FA}=0.05	P_D=0.99, P_{FA}=0.01
0.19 (0.05) < LR ≤ 0.57 (0.15)	5	1
0.57 (0.15) < LR ≤ 0.95 (0.25)	3	5
0.95 (0.25) < LR ≤ 1.32 (0.35)	1	2
1.32 (0.35) < LR ≤ 2.08 (0.55)	1	2
2.08 (0.55) < LR ≤ 2.84 (0.75)	1	0
2.84 (0.75) < LR ≤ 3.97 (1.00)	3	2
3.97 (1.00) < LR	5	7

11.3 Instrumentation

For best performance, the instrument-system noise should be less than the ambient noise. The precision and accuracy requirements of the product-level and temperature measurement systems for the detection of a given leak rate are more stringent for the partially-filled-tank test methods than for the overfilled-tank test methods. For methods in which the tank is partially filled, the precision of the product-level measurements is generally marginal (as compared to the desired 1.3 μm) if detection of leaks as small as 0.19 L/h (0.05 gal/h) is desired. The specification for temperature is generally 0.001°C. If achieved, this is adequate to perform the temperature compensation necessary to detect 0.19-L/h leaks.

An analysis of the instrumentation system requirements for the Test Apparatus was presented in Section 7. A similar analysis should be done by each manufacturer to determine the limitations of the measurement system on performance. With few exceptions, the instrumentation specifications do not limit the performance of the methods evaluated.

An analysis of the instrumentation of each method was performed to determine the minimum leak detectable with a P_D of 0.99 and a P_{FA} of 0.01. Methods in which the tank is overfilled generally have more than adequate product-level precision.

The product-level and temperature measurement systems of all the methods evaluated in this study were calibrated during the Field Verification Tests. As a general rule, the product-level and temperature measurement systems did not meet their precision claims. The calibration performed at the Test Apparatus was the first for some of these instruments. Most methods specify either no regular calibration of the instruments or one that is not sufficient to verify precision properly. Calibrating the temperature measurement systems is particularly important, since a precision of 0.001°C is extremely difficult to achieve and maintain under field conditions.

11.4 Test Operations

All 25 of the test methods that were evaluated participated in the Field Verification Tests at the UST Test Apparatus in Edison, New Jersey. Each manufacturer was requested to test a tank with his own equipment and test crew, following his established protocol. The overall testing experience is summarized below; the specific experiences for each method are described in more detail in the lettered appendices (Volume II).

11.4.1 Setup

It generally took the manufacturers 1 to 2 h to set up the test equipment during the Field Verification Tests. As a rule, most manufacturers believed that the Test Apparatus tanks were easier to test than those encountered in the field. On several occasions, Test Apparatus failures (chiefly, minor leaks along thermistor cables) interfered with a few of the setup preparations; these problems were identified, as appropriate, in the individual manufacturer evaluations. Most of the test crews took longer than expected, given the schedules indicated in their protocols. Based on experience during the Field Verification Tests, it is evident that, generally, the test preparations and conduct of a test, not including the delivery and waiting period, would require that a service station be closed most of the business day.

11.4.2 Instrumentation

Several of the manufacturers had serious instrumentation problems. This was particularly true of systems which were in the development and testing phases, or which were one of a kind, or were not considered "off-the-shelf" systems.

11.4.3 Test Protocol

The majority of the methods that were evaluated followed their protocols reasonably well. The three most common violations of protocol were:

- not following a precise schedule in topping the tank
- not following (or not having) a well defined procedure for stopping a test
- not following (or not having) a well defined procedure for starting a test

11.4.4 Data Tabulation and Calculation

A few calculational and data tabulation errors were experienced during the Field Verification Tests, but this was not considered a major problem. Software errors were also identified during the model validation phase in several systems that collected data automatically. It must be assumed that the best test crews were asked to perform these tests, so that mistakes would be minimal. Furthermore, in many cases, high-level managers and executives (including the inventor or head engineer of the team that developed the system) were present for the tests; presumably, they checked the results. Whether errors in calculation or data tabulation are a significant problem in the field is unknown. Several testing organizations with quality assurance programs suggested that the error rate may be as high as 5%; however, they indicated that these errors could be identifed and corrected.

11.4.5 Arbitrary Operator Decisions

All of the test methods require one or more operators. In some methods, the role of the operator is simply to implement a well-structured test protocol. More commonly, the operator is allowed or even required to alter the protocol based on his own judgment. During the development of the mathematical model for each method, any operator judgments required to start or stop a test, or to interpret the results of the test, were quantified by the manufacturer. In most instances, the manufacturers had a great deal of difficulty either doing this or seeing the need to do it. Without quantitative judgments, however, the test method could not be evaluated.

The most important judgment concerns what the operator does when a tank is declared leaking. Usually, another test is conducted by simply continuing the data collection, and the tank is declared tight if the threshold is not exceeded in the second test. The ramifications of this approach are discussed in Sections 5 and 12.

11.5 Interpretation of the Evaluation Results

A set of test conditions was developed for this evaluation. The applicability of the results of the evaluation depends on whether the test conditions used and the performance estimates made in this evaluation are representative of those generally encountered at underground storage tank facilities.

The results of the evaluation are controlled by the temperature database and the elasticity constant of the steel tank at the Test Apparatus. The temperature conditions used in this study were generated from a climatic analysis (based on 77 cities located throughout the United States) of the difference in temperature between the product in the tank and that in the truck immediately prior to delivery. However, the value used for the elasticity constant is the only known value. It is anticipated that a wide range of tank deformation conditions will be encountered in the field. Section 10 describes a small study whose objective was to determine how performance is altered when different conditions are encountered. This study utilized generic methods representative of those evaluated in the larger study, and, using these generic methods, developed the performance norms described in Section 10. Results were compared on a relative basis.

The results obtained at the UST Test Apparatus were compared to field evaluations of three methods similar to the ones in this study [6-8, 21]. These field evaluations, which used data obtained at retail and industrial underground storage tank facilities, had already been made, or were being made at the time of this study. The protocols used by these methods were different, and the temperature conditions were less encompassing. All of the data were collected either (a) throughout the year in one state with a moderate climate (i.e., California), or (b) throughout the 50 states but during only one season (i.e., late spring and early summer). Nevertheless, the results of these field evaluations are consistent with the results obtained at the UST Test Apparatus and presented here.

11.6 Expected Performance after Modifications

Many of the methods that the EPA evaluated in this study are capable of significant performance improvements. A qualitative estimate was made of the performance that might be achieved by each method; the results are summarized in Table 11.9. The column labeled "After Minor Modifications" (e.g., changes relating to the sequencing and timing of data collection) shows that over 30% of the methods (6 out of 19) should be capable of achieving a high level performance against a 0.38-L/h (0.10-gal/h) leak. The last column, labeled "After Protocol and Equipment Modifications," shows that over 60% of the methods (12 out of 19) should be capable of achieving an equally high performance against a 0.38-L/h leak.

Table 11.9. Estimate of the Performance of Volumetric Test Methods Evaluated at the UST Test Apparatus after Two Levels of Modifications; Expressed in Terms of the Smallest Leak Rate That Can Be Detected with a P_D of 0.99 and a P_{FA} of 0.01

	Number of Test Methods Able to Detect This Leak Rate		
Detectable Leak Rate (L/h)	**Evaluation Results (Before Modifications)**	**After Minor Modification**	**After Protocol and Equipment Modifications**
$0.19 < LR \leq 0.57$	1	6	12
$0.57 < LR \leq 0.95$	5	13	7
$0.95 < LR \leq 1.32$	2	-	-

11.7 Selection of a Test Method

The performance statistics recorded in this report can be significantly improved through simple protocol and/or instrumentation modifications. Thus, while it may be possible to rank test methods according to the performance results obtained in this evaluation, it does not make sense to do so. Such a ranking will change as quickly as modifications are made. Furthermore, some modifications need to be implemented to achieve the results presented in this study.

A careful review of the instrumentation and protocol of the methods evaluated shows that those with the best performance are making optimum use of their instrumentation and testing approaches; their performance comes close to the technological limits. It is equally clear, based on their instrumentation and testing approaches, that the methods which were *not* in the upper third have the potential, as yet unrealized, to do better. Some methods performed more poorly than expected simply because of an easy-to-correct protocol error. After performance modifications have been made, many methods are expected to achieve performance levels that are more or less equal. A number of manufacturers have already begun making the suggested modifications. Thus, the temptation to rank these methods is premature, and should be avoided.

The effects of topping are not included in the evaluation of the overfilled-tank test methods. The majority of these methods do not utilize a waiting period that is adequate to avoid the degradation effects of topping. As a consequence, the performance of these methods may be significantly poorer than what is presented here. If an adequate waiting period were added to the methods' protocol, the results presented here would be representative of the methods' performance.

Before any method is selected, it is advisable that the entire performance evaluation report be read, including the appendices. The user needs to make an assessment about whether the method's protocol can be followed and whether it is particularly sensitive to operator influence or mistakes. The user also needs to determine whether the version of the method being offered is: (1) the original that was actually evaluated under this study; (2) an improved version that has also been evaluated under the same protocol used in this study (and whose performance can be compared on an equal basis with the 25 in the original evaluation); (3) an improved version that has been evaluated under some other protocol (and whose performance may not be comparable on an equal basis); or (4) an "improved" version that has not been evaluated (and whose performance is, therefore, not known).

12 Performance Improvements

Simple and low-cost modifications will permit many of the methods evaluated in this program to improve their performance dramatically. The determining factor in whether these modifications are simple to make, or can be done at low cost, is the method itself. The best candidates for such modifications are methods (1) in which the test protocol, data analysis, and detection criterion are implemented manually, (2) for which only a few prototypes exist, or (3) which are automated systems and can thus easily accommodate the required software changes. Even minor modifications to a method can be costly when a large number of systems that must all be upgraded exist in the field. For most methods, some changes are mandatory if a high level of performance against small leaks is desired. The suggestions for performance improvements made for each method and given in the appendices in Volume II are also included in the appendix in Volume I. The current section describes some of the more common problems in tank testing and suggests some simple ways to correct these problems.

12.1 Instrumentation

A well designed leak detection system should not be limited by its instrumentation. The technology of product-level and temperature measurement systems is sufficiently developed that the system noise can be designed to be less than the ambient or operational contributions to the noise field. In methods of testing in which the tank is overfilled, the instrumentation is generally more than adequate for the product-level and/or temperature measurements. However, for methods that test in partially filled tanks, in which the requirements on the product-level sensor system are 2 to 3 orders of magnitude more stringent, this is not always the case.

12.1.1 System Noise

The performance limit imposed by system noise should be estimated. An estimate of the noise level of each of the sensor systems is determined by measurements made in the same frequency band as the leak. Using system noise, one can determine the smallest leak rate that can be detected with the required probabilities of detection and false alarm. This is done by adding the variances of the equivalent volumes estimated from the product-level and product-temperature sensor systems. For example, a system that uses a product-level sensor with a standard deviation of 0.04 L/h (0.01 gal/h) and a temperature sensor suite with a standard deviation of 0.06 L/h (0.015 gal/h) would have a combined standard deviation of 0.068 L/h (0.018 gal/h) and would be able to detect a leak of 0.32 L/h (0.08 gal/h) with a P_D of 0.99 and a

P_{FA} of 0.01 in the case of a test conducted at a constant hydrostatic pressure. Thus, even with no sources of ambient or operational noise present, this system would not be able to detect leaks smaller than 0.32 L/h with equivalent reliability. This analysis assumes that the noise is white.

12.1.2 Sensor Geometry

For detection of leaks in underground storage tanks, it is necessary to estimate volume fluctuations due to thermal expansion or contraction of the product and to subtract them from the product volume estimate. It is essential to have well calibrated temperature sensors with sufficient spatial coverage to accurately estimate the mean rate of change of temperature. From a practical standpoint, it is possible to adequately cover the vertical temperature field by means of a temperature array containing point sensors. In general, the effects of horizontal variations were found to be small in if product has not been added less than 6 h before the test. While a 1- to 3-sensor array may obtain a high level of performance under some product-temperature conditions, the spatial coverage is not generally adequate, and large errors in estimating the temperature field will sometimes be made. To provide adequate spatial coverage to support a detectable leak rate of 0.38 L/h (0.10 gal/h) with a P_D of 0.99 and a P_{FA} of 0.01, and to ensure coverage at all product levels, at least five equally spaced thermistors, or methods which achieve a similar degree of averaging, are recommended.

12.1.3 Calibration

Since calibration is required in order to convert the output of the measurement system to engineering units, it is essential that all of the instrumentation be calibrated periodically, including off-the-shelf instrumentation which has already been factory- calibrated. The sensitivity of performance to thermal compensation makes the calibration of temperature sensors very important, particularly if a precision requirement of 0.001°C is to be met. While most instruments have linear calibration curves, the thermistors that many methods have incorporated into their systems do not. Thus, calibration is more difficult and requires enough data to develop a calibration curve.

12.2 Protocol

The performance of many of the methods evaluated in this study can be improved by modifying the test protocol. In general, protocol changes are the simplest type of changes to make. It should be noted, however, that many of these improvements require an increase in the total time required to complete a test, and will thus impact the amount of time that a retail station must remain closed for testing.

12.2.1 Groundwater Considerations

Correct interpretation of a test result (i.e., the temperature-compensated flow rate) depends on the level of the groundwater immediately outside the tank, because the groundwater level affects the rate of flow through a hole in the tank. Thus, in combination with the product level, the groundwater level affects the size of the signal to be detected, and, as a consequence, it is difficult to interpret the test results. When there is any suspicion that the ground water may be above the level of the tank, it is recommended that an estimate of the groundwater level be made before conducting any tests. It is also recommended that a formal procedure be included as part of all test methods to deal with groundwater if it is above the bottom of the tank. This recommendation is made because of the possibility that a no-flow or a low-flow condition could occur, in which case a leak might go undetected even by a reliable test method. Thus, when the groundwater level is high, it is recommended that the test be conducted at two levels (of product), or that the test be repeated at a later time, after the groundwater level has changed. When this is not possible, for example, in a tidewater area, test results should be viewed with caution.

Testing at two different product levels can be beneficial, but since any changes to the method can affect the performance, this approach needs to be designed, integrated into the test protocol, and evaluated properly. It is important to consider the effect on performance of the change in test protocol that results from adding or removing product from the tank for the purpose of changing the level, and of the new detection criterion required to interpret any two-level tests. An arbitrary change in the field in response to a high groundwater level will result in a test whose performance is unspecified.

The magnitude of the noise will also be affected if the groundwater level is actively changing during the test, and it is recommended that a test not be conducted under such conditions, which can alter the deformation of the tank and the rate of heat transfer between the product the backfill. The effects of a changing groundwater level were not fully quantified during the ambient noise experiments. One experiment that was performed indicated that large changes in product temperature occurred as the groundwater level in the backfill was lowered.

12.2.2 Height-to-Volume Conversion

The majority of the volumetric test methods measure product level and then convert level to volume using a height-to-volume conversion factor, A_{eff}. Some manufacturers use a theoretical estimate based on the geometry of the system, while others measure A_{eff} as part of the test protocol, using cylinder of known volume or a known amount of product to displace the product level.

In an overfilled-tank test, it is necessary to estimate A_{eff} in order to account for the effects of trapped vapor and the instantaneous structural deformation of the tank. Errors of 50% or more can result if A_{eff} is assumed to be equal to the area, A, of the free product surface. The calibration experiments necessary to estimate the height-to-volume conversion factor in an overfilled tank are not time-consuming and are easy to perform. For nearly contant level tests, the height-to-volume conversion factor is A_{eff}. For variable-level tests, K needs to be known, because the height-to-volume conversion factor is $A_{eff} + K$.

In a partially-filled-tank test it is commonplace to use the tank chart to estimate A_{eff}. Because, for a partially filled tank, A_{eff} is approximately equal to A, it is reasonable to estimate A_{eff} theoretically. Two errors are possible, however, either of which may be large enough to require experimental estimates. First, the tank chart may not constitute an accurate representation of the tank, because measurements are usually based on the nominal dimensions of the tank. Even if the tank chart has been developed from the measured dimensions of the tank, it is still possible that the theoretical estimate of A_{eff} near the top of the tank will be in error because of distortion or tilting of the tank that may have occurred during installation. Distortion near the top of the tank can lead to differences between the theoretical estimates of A_{eff} and the measured ones. Second, even if the tank chart is perfect, an accurate estimate of the actual depth of the product in the tank is a prerequisite for the proper use of the tank chart as a means of estimating A_{eff}. Typically, the depth of the product can be measured to within 0.25 cm (0.1 in.) with an instrument and to within 0.6 cm (0.25 in.) with a stick. In general, if reliable detection of leak rates as small as 0.19 L/h is desired, this measurement is not accurate enough to estimate A_{eff} in the case of a test that is conducted when product level is in the upper 80 to 90% of the tank. If the error is sufficiently large, it is recommended that A_{eff} always be estimated experimentally (by immersing a solid of known volume, measuring the height change, and calculating A_{eff} using Eq. (4.1)). As a check on the measurements, the experimental value should be compared to the theoretical one.

12.2.3 Product-Level Measurements During Overfilled-Tank Tests

Any volume changes that occur during a test will cause the tank to deform. If the product is maintained at a constant hydrostatic pressure during the test (this applies to both partially-filled-tank tests and to overfilled-tank tests in which product is releveled), a waiting period sufficient to allow the tank to deform is required.

On the other hand, if the test is conducted with a variable hydrostatic pressure, waiting for the structural deformation to subside is only a first step. Interpretation of the product-level changes after the initial exponential deformation has occurred requires a detailed knowledge of the time and elasticity constants of the tank-backfill-soil system. Because these variables are not known *a priori*, it is advisable to eliminate this method of collecting data. Accurate estimates of the product level are possible, but only if the elasticity constant, K, approaches zero.

12.2.4 Data Collection

Data collection is discussed in terms of sampling interval and test duration.

12.2.4.1 Sampling Interval

In the majority of the methods, data are undersampled, causing a phenomenon known as aliasing. This means that the high-frequency product-level fluctuations, which are not in the same frequency band as the leak signal, are manifested as low-frequency fluctuations in the frequency band of the signal. To avoid these effects, the data should be sampled at an interval which is at least 0.5 and preferably 0.33 of the period of the fluctuations in the tank, and then averaged. The significance of the aliasing depends on the sample interval and the magnitude and frequency spectrum of the fluctuations. Aliasing should be avoided or shown to be negligible.

Because the highest-frequency fluctuations (those with the shortest period) in a partially filled tank are produced by seiching of the product surface, the effects of aliasing can be easily avoided. These seiches or standing surface waves may have a period of 2 to 10 s in a 30,000-L (8,000 gal) tank, depending on the dimensions of the tank, the level of product in the tank, the free product surface at that level, and the density of the product and the vapor above it. To avoid aliasing the *surface-wave* data, the product level data should be sampled at time intervals of approximately 1 s.

In a 30,000-L tank, internal waves produce temperature and sometimes product-level fluctuations with periods between 3 and 60 min. Undersampling the thermal data equates to incorrect estimation of the rate of change of temperature, and thus can lead to inaccurate temperature compensation. In the 30,000-L Tank Apparatus tank, temperature fluctuations produced by internal waves typically had periods between 5 and 20 min. Predicting these periodic fluctuations is difficult. To avoid aliasing the *internal wave* data, a sample rate of 1 min should be sufficient.

To avoid aliasing when both internal and surface waves are present, product level and product temperature should be sampled at 1-s intervals and averaged to 1 min for analysis.

Alaising is a complicated phenomenon, and most methods which collect data manually will not be able to avoid this error. The error is generally small if the duration of the test is several hours. Even with alaising, these methods should be able to reliably detectleaks of 0.38 L/h.

12.2.4.2 Test Duration

The duration of the test has a direct effect on performance. Analyses of data from previous studies have shown that the longer the test duration, the higher the performance achieved [7, 19, 20]. Longer tests tend to reduce the random fluctuations of the noise if the number and location of the sensors are adequate.

An optimum test duration can be determined by collecting data over a 4- to 8-h period and then investigating the effect on performance of varying the test duration. This can easily be done during the manufacturer's field validation of the test method. For most of the methods evaluated in this study, a 1-h test is generally too short to obtain accurate results. Temperature-compensated volume fluctuations with periods between 30 and 60 min have been observed. A 2-h test is required to properly average out these effects. A 1-h test would suffice if, for example, the data were adequately sampled, the deformation effects had become negligible, and the product temperature field had been adequately sampled. The advantage of a longer test is that uncompensated noise can be averaged out.

12.2.5 Trapped Vapor

One of the sources of error in an overfilled-tank test is trapped vapor. Trapped vapor is a problem because its presence is difficult to detect. The release of bubbles or a sudden drop in product level are indicative that trapped vapor is present, but, in general, the volume of this trapped vapor is not easily ascertained. Even if the volume of the trapped vapor were known, it would be extremely difficult to compensate for the expansion and contraction of the vapor without detailed measurements of the temperature and pressure of this vapor, and it would be impossible to conduct a test if the volume of the vapor became too large. The best solution is to eliminate trapped vapor from the tank. This is best done during the initial preparations for a test.

A method, described in Section 8, was developed to estimate the volume of the trapped vapor. Unfortunately, because the volume changes caused by the instantaneous deformation of the tank are inextricably linked to those caused by trapped vapor, only an upper bound estimate of the amount of trapped vapor can be made. If A_{eff} is approximately equal to A, however, it can be assumed that the volume of trapped vapor is small.

It is recommended that this technique be used in all overfilled-tank tests in order to make an estimate of the volume of trapped vapor. The procedure, which can be completed within minutes, will not necessarily produce a good estimate of how much vapor is present, but it will indicate whether trapped vapor is largely absent. If the results of the procedure show that the volume of trapped vapor is large (e.g., 100 L), it should be assumed that trapped vapor is present, and appropriate action should be taken to remove it before a test is conducted. In the Test Apparatus tests, the volume of trapped vapor could not have exceeded 60 L, and was estimated to be about 10 L (even after extensive efforts to reduce it).

Regardless of the level of experience of the test crew, it is likely that some vapor will be trapped in the tank. As a consequence, the height-to-volume conversion factor must be measured experimentally, because small amounts of trapped vapor affect the magnitude of this factor.

During the course of these experiments at the Test Appartus, no detailed study was made of the product-level changes due to partial pressure changes in the tank before equilibrium has been reached. (This phenomenon was observed in the preliminary experiments leading up to the Test Apparatus experiments [25]). It is recommended that sufficient time be allowed after overfilling the tank for the trapped vapor to approach equilibrium with the temperature and pressure environment. In small containers (e.g., 1 L), this tends to occur over a period of minutes; thus, the time allowed for the structural deformation effects to become small (typically hours) should be more than sufficient to ensure that equilibrium has been reached.

12.2.6 Thermal Disturbance of the Vapor in a Partially Filled Tank

Any disturbance of the tank's thermal environment tends to degrade performance. Experiments in partially filled tanks at the Test Apparatus suggested that, for at least 6 h after opening the fill hole and preparing for a test, the temperature-compensated volume fluctuations were too large to permit a high level of performance against small leaks. The residual volume fluctuations evident in these experiments were probably caused by the escape of vapors when the fill tube was opened, and by the evaporation of product into the vapor space after the test was begun. For this reason, it is recommended that the test protocol specify that a waiting period be observed after test preparations have been completed.

12.2.7 Product-Level Changes

Any product-level changes will affect the thermal environment of the product and induce structural deformation of the tank.

12.2.7.1 Product Delivery

The term "product delivery," as used in this report, refers to the addition of very large amounts of product to a tank (usually the night before the test) to reach the approximate level needed for the test. Large horizontal temperature gradients develop during and after delivery. The data suggest that a minimum waiting period of up to 6 h is required before accurate thermal compensation in the tank can be achieved. The effects of structural deformation take at least 6 h to become small enough to be negligible.

Accurate tests of the tank cannot be reliably performed immediately following a delivery. Theoretically, when a method calls for circulating product in the tank, a test can be started as soon as the product is uniformly mixed. In reality, this may take several hours in a 30,000-L tank. Any method for which the manufacturer claims that a test can be started immediately following a delivery should be considered suspect.

12.2.7.2 Topping the Tank

Topping the tank, probably the largest source of error in overfilled-tank tests, is usually done the day of the test to bring the product to the exact level needed for the test. Like a delivery, it impairs accurate temperature compensation and induces structural deformation.

The effects of topping the tank, described in Section 8, are to disturb the local temperature field and to cause horizontal temperature gradients to develop in the tank. Thus, accurate temperature compensation is not possible for 2 to 3 h after topping, that is, until the disturbances have subsided.

Another more subtle effect was identified in methods that overfill the tank. The temperature of the product in the fill tube or above-ground standpipe is affected by the ambient changes in air temperature. If the product sinks, it can disturb both the horizontal and vertical distribution of temperature in the tank and the local temperature field around the sensors. The effect is similar to but not as severe as the effect induced by topping.

Unfortunately, the product-level changes (and the changes in hydrostatic pressure) that occur during topping are usually as large if not larger than those that occur during a delivery of product. While most protocols include a long waiting period after a delivery, in many cases no provisions are made for a waiting period after topping the tank. As a consequence, the effects of structural deformation may be large enough to seriously degrade the performance of a test. The length of the waiting period depends on the time constant and the magnitude of the deformation. Waiting 3 time constants will reduce the fluctuation level by 99%; this may or may not, depending on the magnitude of the deformation, be enough. It is hard to suggest a universally applicable waiting period because the deformation characteristics of individual tank-backfill-soil systems are unique. The available data at the Test Apparatus suggest that the waiting period should be a minimum of 6 h and can be as long as 24 h.

12.2.7.3 Releveling

In order to properly interpret volume changes, in the fill tube or standpipe of an overfilled tank in terms of volume changes, the product must be releveled during the test. If the releveling is not done carefully, the temperature field in the tank as a whole, as well as locally around the temperature sensors, can be disturbed when product is added to the tank. These effects can be minimized by releveling the product so that only very small amounts of product are added to the tank at any time and a thermal adjustment can take place. It is desirable to add product that is at approximately the same temperature as the product in the tank and to add it at a location that does not affect the local temperature field around the sensors. This might be accomplished by adding product through a tube that extends to the bottom of the tank.

12.2.8 Coefficient of Thermal Expansion

The accuracy of a temperature-compensation scheme depends in part on the accuracy of the coefficient of thermal expansion used to convert temperature to volume. Most tests either assume a coefficient for a given type of product (e.g., gasoline or diesel fuels), or measure the specific gravity of the product before or after a test and calculate the coefficient using the API tables. The tables are based on an average value of the coefficient generated from many different products. The uncertainty for the latter method can be estimated from the uncertainty of the coefficient in the tables for the measured specific gravity. In general, this uncertainty is approximately 5% providing the uncertainty of the measured specific gravity is small. The uncertainty for the former (the assumed value) also includes the change in the coefficient with specific gravity, which could result in an uncertainty of as much as 10% or more. While this error is very important for the detection of small leaks in large-capacity tanks, it was less significant than many of the other errors commonly encountered in volumetric testing.

12.3 Data Analysis

The need for adequate temporal sampling and averaging has already been noted. After data collection, the volume rate of change should be inferred from the temperature-compensated product-level time series (or mass time series) by a technique, such as least-squares, which estimates the linear trend in the time series.

12.4 Detection Criterion

The performance of a leak detection system is determined by the detection criterion, usually a threshold volume rate. Once the system performance has been determined for a particular criterion, this criterion should be used exclusively. If another criterion is substituted, the performance of the method is changed. Applying the given detection criterion leads to a known performance for the method, presumably established with an acceptable error rate in terms of the probability of missed detections and false alarms. If the error rate is unacceptable, the detection criterion should be changed, and the performance of the method should be determined again in light of the change(s).

The threshold is determined by the P_{FA}. To satisfy the $P_D = 0.95$ and $P_{FA} = 0.05$ requirements, a detection threshold of one half the desired detectable leak rate should be established; i.e., if the desired detectable leak rate equals 0.38 L/h (0.1 gal/h), the threshold for declaring a leak should be set to 0.19 L/h (0.05 gal/h). If a method claims a high performance against a leak rate, the threshold used to detect leaks should always be smaller than this leak rate by a factor of 2 or more. A high performance claim also implies that the precision of the leak detection system in the tank environment should be no larger than approximately 0.2 times the desired detectable leak rate.

12.5 Operator Influence

Because arbitrary changes to the protocol will alter performance, any method in which the operator is required to make judgments during the test is not recommended. This is particularly true if the operator adjusts the product level during the test or changes the sampling interval or the duration of the test by making arbitrary judgments about when to start and stop based on the specified detection criterion. Once the tank has been prepared for testing and the equipment has been properly set up, the test should be conducted exactly as specified. Changes should not be made during the test.

Special attention should be paid whenever any product-level adjustments are made. Since the magnitude of the volume changes due to deformation depend on the time history of the product level before the adjustments were made and on the details of how the product level is adjusted, it is recommended that all product-level adjustments be accomplished using a set, repeatable procedure.

A common field practice, not observed in the Field Verification Tests because of the requirement to follow the test protocol exactly, is to conduct more than one test consecutively if the measured volume rate is near, but exceeds, the threshold, or to arbitrarily declare the tank tight even though the threshold for flow into the tank is exceeded. Both pactices will lower probability of detection and may lead to a missed detection. The impact of the former depends on how the additional tests are interpreted with regard to the first and on whether the second test is independent or correlated with the first. If a multiple-testing procedure is desired, it should be incorporated into the test protocol and should be evaluated. In general, the number of tests should be fixed.

12.6 Multiple-Test Strategy

Some test methods employ a multiple-test strategy. Sometimes the multiple-test strategy is incorporated in the data collection and analysis, and sometimes it is incorporated into the detection criterion. As commonly practiced, the strategy is arbitrary and therefore has deleterious consequences on system performance. Also, the tests are not independent, and the expected improvement in P_D, P_{FA}, or both is not achieved because of the correlation between tests (e.g., systematic errors that remain essentially the same between tests). With a properly designed multiple-test strategy, however, improved leak detection performance can be achieved. As measured by leak rate, the system performance will improve for a constant P_D and P_{FA}.

To illustrate, let us propose to conduct five statistically independent tests of a tank. Let the tank be declared leaking if the detection threshold was exceeded in at least three of the five tests and declared tight if the threshold was exceeded in two or fewer tests. For this m-out-of-n strategy (where m = 3 and n = 5), the detectable leak rate is almost halved *vis-a-vis* the detectable leak rate of a single test, while the detection and false alarm probabilities remain at approximately 0.99 and 0.01, respectively. Such a result can be achieved only if the five tests are independent.

The multiple-test strategies utilized by the commercial methods can be improved. In general, the strategies are not properly designed, and therefore, the P_D and P_{FA} cannot be interpreted. Most methods use an m-out-of-n approach that reduces the P_{FA}; the P_D, however, is also reduced, sometimes in a substantial way.

Examples of strategies being used appear below.

- o The minimum volume rate out of two or more tests is used to determine whether the tank is leaking.
- o After the volume-rate threshold has been exceeded, an arbitrary number of tests is conducted, until such time as the measured volume rate fails to exceed the threshold.

These testing strategies are typically applied at the end of a test; they may be an inherent part of the test, or they may be used only because the test indicates the possibility of a leak. Most approaches are based on the assumption that the product-level changes in a nonleaking tank will become smaller with time. If this assumption is true, selecting the volume rate from the smallest or last test to determine whether the tank is leaking will lead to more accurate test results. If the noise has already decayed to a value small enough to be negligible, as required by most test designs, this approach will result in a substantial reduction in the P_{FA} but will also result in a P_D below that which would be obtained with a single test. If the number of tests that may be performed is large and/or not fixed, the P_D will approach 0.

It is difficult to interpret the impact of the multiple-test strategy on performance unless the tests can be shown to be independent (or the correlation between them is known) and unless the number of tests is fixed. The degree of performance achieved will depend strongly on the independence assumption. Most multiple-test strategies are implemented at the end of the first test. The second test is not apt to be independent of the first because of systematic errrors that are present during the first test and that are still present in the second test. The second test will not show a performance improvement if the first and second test both contain a vapor pocket large enough to impact performance. Neither will performance improve if uncompensated noise, such as evaporation and condensation, structural deformation, or thermal expansion and contraction of the product, is still present during the second test. It is easy to show statistically the dramatic improvement gained by using a multiple-test strategy; however, it is difficult to achieve this performance unless that test strategy is carefully designed and evaluated.

Achieving independence is difficult. One method of improving the chances of an independent test is to completely remove the equipment from the tank and perform another test. This may not always be sufficient if the same source of error persists for each test. For example, when vapor is trapped in a tilted tank during an overfilled-tank test, a nearly identical amount of vapor may be trapped during each succeeding test. For methods that overfill the tank, improving the chances of an independent test includes dropping the product level below the top of the tank before conducting another test. Chances improve if the second test is conducted on another day. Finally, if the first test is performed in an overfilled tank, the chances for independence improve if the second test is conducted when product level is near, but below, the top of the tank. Such an approach is impractical for many methods because of insufficient precision in the product-level instrumentation. In the latter approach there is the additional problem that the leak may not be located below the product level but in that section of tank or piping above the tank top. Finally, the impact on performance of any changes of product level prior to the conduct of additional tests must be carefully evaluated.

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Appendix

Descriptions of the 25 Test Methods Evaluated in the EPA Study and Suggestions for Improving the Performance of Each

(Source: Sections 2 and 5.2 of Each Appendix in Volume II)

A.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the AES/Brockman Leak Detecting System as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [A-1].

During the validation of the model, it was found that not all of the key features of the AES/Brockman system were in accord with the definitions in [A-1]. A discussion of the discrepancies is presented in Section A.4.

A.2 Improving System Performance

The AES/Brockman System as defined in [A-1] can realize performance improvements. The recommended changes include additional instrumentation, adjustments to the protocol, and a new leak-rate calculation algorithm.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 0-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

A.2.1 Instrumentation

The largest deficiency in the instrumentation is inadequate temperature compensation. A comparison of temperature volumes from the volumetrically weighted array with the manufacturer's estimate (see Figure B.3.4) shows that only in one case was there agreement between the two; i.e., the AES/Brockman estimate of temperature effects can contain large errors. This is caused by undersampling of the vertical temperature field, since the manufacturer measures the temperature at the base of the tank only. The manufacturer has observed that near the base of the tank the temperature changes at a greater rate than in the rest of the tank and, because of this, has incorporated a factor that serves to reduce the measured temperature volume. Although the present evaluation has not rigorously attempted to determine whether this temperature volume estimate is correct, a better estimate of the temperature effects might be obtained if the manufacturer included an array of thermistors. Since the AES/Brockman system is computer-based, incorporating the measurements from additional thermistors into the data analysis could be done with relative ease.

A.2.2 Protocol

The following protocol changes are recommended:

- Wait 6 to 12 h or longer after product delivery
- Relevel the product at 15-min intervals or less and record the volume changes
- Wait at least 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

The protocol employed by the AES/Brockman system involves large product-level adjustments each hour during a 3-h test. These adjustments are detrimental in two ways: (1) they cause measurable structural deformation effects, and (2) the added product disturbs the temperature field. It is recommended that the manufacturer consider raising the product once and performing the entire test at that level. Because the AES/Brockman system is computer-based, consecutive 1-h tests could be run to determine when structural deformation effects have subsided. Furthermore, if the manufacturer were to relevel product during the tests, underestimating the volume change due to the coupling of volumetric noise sources with structural deformation could be avoided. Both the coupling effects and the constant-level approach are discussed in detail in the body of the report.

A.2.3 Analysis

It is recommended that the manufacturer reexamine, as discussed above, the attempt to estimate the total temperature effect and that he remove TCC from the algorithm. This would require the incorporation of additional thermistors, since it is not evident that one thermistor located at the base of the tank is adequate to represent temperature.

The algorithm employed to evaluate the effects of structural deformation is not accurate and can cause gross errors in the measured leak rate results. The manufacturer would obtain better performance if he were to establish a method of determining, as a prerequisite for initiating a test, when structural deformation has become negligible. Performance would improve if the manufacturer removed the structural deformation estimate from the algorithm and calculated a thermally compensated leak rate. The criterion for determining whether a tank is leaking causes missed detections of leaking tanks, but at the same time, it greatly reduces the probability of false alarm. The implementation of this criterion therefore reduces the performance of the system. It is recommended that the criterion be removed from the analysis that determines whether a tank is leaking.

A.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

B.1 Ainlay Tank 'Tegrity Test Method Description

The Ainlay Tank 'Tegrity Tester is a volumetric tank tightness test which is conducted in an overfilled tank. The product level is allowed to vary depending upon environmental changes occurring in the tank, and no effort is made to maintain a constant level during the test, for which a threshold of 0.189 L/h (0.05 gal/h) is used. A tank is declared leaking if the thermally compensated flow rate is greater than this threshold. If the flow rate is less than the threshold, the tank is declared nonleaking.

B.1.1 Instrumentation

The Ainlay Tank 'Tegrity Tester uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of a slope tube indicator (manometer), and product temperature as determined by three temperature probes. The testing period of 1 h applies only to situations in which the capacity of the tank being tested is less than 37,800 L (10,000 gal). For tanks with a greater capacity, the increase in test duration is 15 min for every additional 9,450 L (2,500 gal). Test duration and sampling intervals are constant. The test is carried out in a storage tank that has been overfilled to a level within the fill tube.

Volumetric changes are determined by monitoring pressure changes in a tube inserted below product level in the tank's fill tube. Product height changes in the fill tube alter the amount of pressure required to force propane gas bubbles through the inserted tube, and these pressure changes are reflected as fluctuations in the height level of the water column in the slope tube indicator. Refer to the mathematical modeling report [B-1] for a schematic diagram of the Ainlay Tank 'Tegrity Tester.

Horizontal movement in the slope tube indicator corresponds to the changes in product level within the fill tube. Although a change in product level in the fill tube is barely noticeable, it causes exaggerated movement in the slope tube indicator, where it can be easily detected and measured.

The slope tube indicator consists of approximately 150 cm of clear plastic tubing coiled into a helix approximately 8 cm in diameter and 5 cm high. A 5-cm change in product level therefore produces a liquid movement of approximately 150 cm in the slope tube indicator.

Since volume change is shown directly on the slope tube indicator, product level is not used to determine volume change, and the device contains no scale. At the conclusion of the test, product is added to (or removed from) the tank by means of a graduated cylinder in order to return the slope tube indicator level to its starting point. The amount added (or removed) represents the gross volume change during the test period.

Temperature is measured with three thermistors (probes) placed at the vertical centroids of three volume slabs so as to have a weighting factor of 25% at the top, 50% in the middle, and 25% at the bottom. The input signal voltage from a thermistor is compared to the thermistor response data supplied by the thermistor manufacturer, and is encoded in a data logger. Calibration of the temperature sensors takes place before the first use of the instrument and is recommended at intervals of not more than one year. Precision and resolution of the sensors are those reported by the manufacturer. They were experimentally confirmed during the Field Verification Tests at Edison, New Jersey.

The volume change is determined by adding to or removing from the fill tube an amount of product sufficient to return the slope tube level to its starting point. This is done at the end of the test. The product is added by means of a graduated cylinder whose precision and resolution, as claimed by the manufacturer, are presented in Table B.1. This cylinder, with a capacity of 0.45 L, has numbered divisions every 0.038 L and five subdivisions between each numbered mark. The amount of product added or removed represents the gross change in volume during the test period.

Table B.1. Precision and Resolution of the Product Level and Temperature Measurement Systems

	Precision	Resolution
Product Level Measurement	0.0038 L	0.0076 L
Temperature Measurement	0.001°C	0.001°C

Three 6,000-Ω thermistors are used to measure temperature changes. The nominal temperature-resistance curve supplied by the manufacturer is used to convert from resistance to temperature. The resolution varies with temperature because the number of ohms per degree C is not constant. The resolution is less than 0.001°C for temperatures greater than 13.6°C. The temperature required for the calculations is represented by the difference between the temperatures at the beginning and end of the test. The thermistors have an operating range of -17 to 50°C.

B.1.2 Equipment Setup and Test Preparations

The manufacturer indicated that approximately 1 h would be required to set up the test equipment and prepare the tank for testing. The manufacturer requires that the tank be filled to a level within the fill tube the night before the test, but states that the test crew need not be present during the delivery of the product. Unless the crew is on site and personally supervises the overfilling of the tank, this requirement is unlikely to be met in actual tests. However, the crew must monitor product level to ensure that the product does not drop out of the fill tube and into the tank because of structural deformation and thermal contraction of the product, or overflow out of the top of the tank because of thermal expansion. If, in the absence of monitoring by the crew, such events do ensue, 38 to 380 L (10 to 100 gal) of product may need to be added to the tank immediately before the start of the test just to raise the product to the prescribed level within the fill tube.

B.1.3 Test Protocol

The test protocol requires at least an 8-h wait between the overfilling of the tank and the start of a test. If final topping off occurs immediately prior to the start of a test, an additional 2-h waiting period is required.

The test duration is 1 h in length, with temperature values being recorded at the beginning and end of the test period. For each of the three thermistors, data are recorded at the start and end of the test. In order to gauge temperature fluctuations, the operator also observes the temperature readings every 5 min on the field recorder during the test period. Based upon an undefined procedure, the operator utilizes this information to decide whether to continue the test. The basic parameters of the test protocol are summarized in Table B.2.

Table B.2. Important Parameters of the Ainlay Tank 'Tegrity Tester

Sample Period	60 min
Test Duration	60 min
Number of Samples per Sensor per Test	2
Test Start After Filling Tank	8 h
Test Start After Topping Off Tank	2 h
Test Type	Overfilled Tank

If, due to the height of the water table, the tank is sitting in water, compensation is made for the external pressure exerted by the water by fitting an extension to the fill tube and raising the level of product in the fill tube. This procedure is intended to neutralize the pressure effects of tank immersion in groundwater, and in effect restores dry tank conditions.

No compensation for evaporation is made, since experiments conducted by Ainlay showed an evaporation rate of less than 0.004 L/h in a fill tube at 23°C.

B.1.4 Data Analysis

The Ainlay Tank 'Tegrity Tester calculates a temperature-compensated volume rate for the single-point product-level and temperature measurements obtained at the beginning and end of the specified test period. Product-level measurements are converted to volume by adding sufficient liquid to the fill pipe to bring the slope tube manometer reading back to its starting point. The amount of liquid added is taken to be the volume change which occurred during the test.

Thermal expansion and contraction of the product is calculated from the volumetrically weighted thermistors placed in the tank. The volume change, ΔTV, is estimated using

$$\Delta TV = C_e V \Delta T \tag{B.2.1}$$

where the change in temperature, ΔT, is the volumetrically weighted value determined from the three thermistors, the total volume, V, is the tank volume as determined from the tank chart issued by the tank's manufacturer, and C_e is the coefficient of thermal expansion of the product. The value of C_e is determined immediately prior to a test by taking a sample of product and measuring its gravity with a hydrometer. The temperature of this sample is also measured, and the API gravity at 15.5°C calculated. The resulting value is then used, in conjunction with the API Tables, to determine the value of the coefficient.

Although the standard test duration is 60 min, the operator may terminate a test at any time if an irregular temperature profile is observed on the recorder. The criteria for establishing a definition of irregular temperatures are not available.

B.1.5 Detection Criterion

A leak is declared if the temperature-compensated volume rate exceeds 0.189 L/h (0.05 gal/h).

B.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the Ainlay Tank 'Tegrity Tester as it was evaluated and to interpret the results of the performance evaluation, it should be noted that the mathematical model of the system was developed based on the more detailed description of the test method provided in [B-1]. After it had been validated, this model was used to estimate the performance of the method.

B.2 Improving System Performance

The Ainlay Tank 'Tegrity Tester as defined in [B-1] can realize substantial performance improvements without hardware modification. The system could be further improved by additional instrumentation.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 2-h waiting period after topping may be too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. Thus, for many tests this effect is minimized by the 2-h waiting period required by the method. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer;The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

B.2.1 Protocol

The following protocol changes are recommended:

- o Wait 6 to 12 h or longer after product delivery
- o Sample the temperature data every 3 min
- o Relevel the slope-tube manometer at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

Releveling the product represents the most significant performance improvement that can be achieved by the Ainlay Tank 'Tegrity Tester. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 100%.

B.2.2 Analysis

It is recommended that the temperature-compensated volume rate be computed from the data taken at the recommended higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and 20 temperature measurements to estimate the thermal volume change, the performance could improve by as much as 100%.

B.2.3 Instrumentation

Performance improvement could be achieved by adding more thermistors to improve spatial sampling of the vertical temperature field. Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 30% performance improvement could be achieved by increasing the number of thermistors from three to five.

B.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

C.1 The AUTAMAT Test Method Description

The Automatic Tank Monitor and Tester (AUTAMAT) is a volumetric leak detection system

C.1.1 Instrumentation

The AUTAMAT system is designed so that the product level measured in a reference tube can be used as the thermal compensation for product-level changes measured in the tank. Both the product level in the reference tube and that in the tank are measured using absolute pressure sensors located near the base of the tank and offset vertically from one another by approximately 40 cm; a third absolute pressure sensor is used to measure and compensate for ambient pressure changes. The precision and resolution of the AUTAMAT system as given by the manufacturer are presented in Table C.1.

The reference tube, constructed of copper, has a diameter slightly smaller than the fill tube and is slightly shorter than the diameter of the tank. Another tube, smaller in diameter and approximately 1 m in length, is attached to the top of the copper reference tube. Inside the reference tube are four pieces of "deadwood" (material whose purpose is to displace volume) symmetrically located about the center of the tank in order to approximate the changing chord length across the tank's diameter.

A pressure sensor at the base of the tube monitors product level within the reference tube; another near the base of the tank monitors product level within the tank. A data set consisting of 10 samples gathered at a rate of 3 samples per second is collected every 2 min. The data are averaged and then stored for subsequent analysis. A graph of the product level in the fill tube versus that in the reference tube is displayed and updated during the test. This graph is used to determine whether the reference tube has come to equilibrium with the tank and whether structural deformation effects have ended.

Table C.1. Precision and Resolution of AUTAMAT Measurements as Specified by the Manufacturer

	Precision	Resolution
Product Level	0.05 cm	0.01 cm

C.1.2 Equipment Setup and Test Preparations

The setup of the AUTAMAT system and preparation for a test at the Edison facility typically took 1.5 h. This assumes that the product was at a satisfactory level prior to installation.

C.1.3 Test Protocol

Test protocol requires a wait of 12 h between filling the tank and starting the test. If more product must be added prior to the test, an additional waiting period of 1 h is necessary so as to allow structural deformation effects to subside. Additionally, a waiting period of 30 min is required, after the instrumentation is hooked up and started, for the temperature sensor to stabilize; the temperature sensor is used to compensate the pressure sensor electronics, and the 30-min waiting period may overlap with the other waiting periods. The 30-min waiting period may be lengthened if deemed necessary by the operator.

A complete data set consists of 61 data points collected at a rate of one every 2 min. A data point, which consists of 10 samples gathered at a rate of 3 samples per second, is collected every 2 min during the 2-h period.

The important features of the AUTAMAT system are summarized in Table C.2.

Table C.2. Important Aspects of the AUTAMAT Test Protocol

Sampling Period	2 min (average of 10 samples collected at 3 Hz)
Test Duration	2 h
Waiting Period after Product Addition	12 h
Wait after Sensor Installation	30 min
Test Type/Product Level	Overfilled Tank

C.1.4 Data Analysis

The concept underlying the AUTAMAT system is that thermal changes in the tank can be represented using a reference tube located in the tank. In order to best approximate the relative effects of temperature changes at different levels in the tank, the volume of the reference tube is varied as a function of depth so as to represent the varying chord length of the tank as a function of depth. With this approximation, the height changes in the reference tube are equated to thermal fluctuations in the tank, and these thermal fluctuations can be compensated.

C.1.5 Detection Criterion

A tank is declared leaking if the leak rate as determined by the AUTAMAT system is greater than a threshold of +/- 0.189 L/h (0.05 gal/h). If the leak rate is less than the threshold, the tank is declared nonleaking.

C.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the AUTAMAT system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [C-1].

C.2 Improving System Performance

The AUTAMAT system can realize improvements by changing the data analysis. In addition, the system employed in the field can be improved by correcting the errors that affect temperature compensation.

C.2.1 Protocol

The protocol as defined in [C-1] does not give the operator a systematic method of determining whether structural deformation is occurring. The AUTAMAT method, which is computer based, could include specific criteria for making such a determination. It is recommended that a specific criterion be employed in order to standardize implementation of the method in the field. The criteria should include sufficient time for the probe to stabilize, for the temperature field to stabilize, and for structural deformation effects to subside.

C.2.2 Instrumentation

To determine why the measured temperature was not representative of the tank, it would be necessary to fully evaluate and analyze the instrumentation. It is recommended that the manufacturer determine exactly what the temperature probe is measuring. An empirical study could also help determine (1) what waiting period is necessary to obtain equilibrium and (2) the thermal conditions that cause the probe to incorrectly estimate temperature. In order to empirically determine what the sensor is actually measuring, the manufacturer might attach sets of thermistors inside and outside the probe. Comparison of these sets of thermistors would present an independent validation of the assumption that the probe is representative of the overall tank temperature. Furthermore, by experimenting with different product temperatures and ambient temperatures, the manufacturer could obtain useful data that would aid in determining the time necessary to achieve equilibrium, and in understanding the lag that might be present between temperature changes outside and inside the tube. Permanent instrumentation as described above would allow the manufacturer to determine whether the sensor had reached equilibrium with the product.

C.2.3 Analysis

A major improvement which can be made in the data analysis concerns the conversion of height changes to volume changes. As described in [C-1], the method assumes that the height measurements can be converted to volume by multiplying by the measured equivalent cross-sectional area of all risers from the tank. When conversion is done in this manner, an error results that is caused by the coupling of the volumetric noise sources with the deformation of the tank. As a consequence, the volumetric estimation is grossly underestimated.

There are two approaches to correcting this error: (1) it can be minimized by testing with a large cross-sectional area at product level; or (2) it can be virtually eliminated by releveling the product and tracking the volume added and subtracted. A discussion of this error, and of corrective action to be taken, is presented in the body of this report.

D.1 The VPLT Test Method Description

The VPLT system is an HP 9807 computer-based leak detection system which calculates a thermally compensated leak rate. The system also compensates for vapor pockets, structural deformation, ground water effects, pressure changes, and evaporation. Data on product temperature, air temperature, product level, and ambient pressure are collected during a test. If the VPLT system detects a leak in the full system test, further testing is done to determine the location of the leak. The VPLT system employs an extensive set of test procedures which address numerous conditions that may be encountered in the field. For this program, only one specific protocol has been evaluated. The system is capable, according to the manufacturer, of detecting leaks as small as 189 ml/h (0.05 gal/h).

D.1.1 Instrumentation

Two independent methods of measuring product level are used: an electromechanical sensor which floats directly on the product surface, and a gauge pressure sensor, referenced to ambient pressure, located within 10 cm (4 in.) of the product level. Although data are collected from both sensors, the data used for the calculations are primarily those from the electromechanical sensor. The pressure sensor is used as an independent measurement in order to avoid false results due to equipment failure. In the case where the product level is elevated above grade a third sensor, whose purpose, again, is only to determine whether there are any equipment failures, is used to determine product-level change (the product is observed in the fill tube extender).

Both product-level sensors are calibrated prior to a test to determine the height-to-volume scale factor, HtoV. This is performed by inserting a bar of known volume into the liquid. The pressure transducers are calibrated every six months for pressure and temperature sensitivity versus sensor output. Another pressure sensor measures changes in the ambient (atmospheric) pressure.

For a 30,000-L (8,000-gal) tank, product temperature is measured using an array of five thermistors equally spaced at 48.6-cm (19.1-in.) intervals, with the first thermistors located 24.3 cm (9.5 in.) from the base of the tank. The resolution and precision of the sensors, as reported by the manufacturer, are summarized in Table D.1.

Table D.1. Precision and Resolution of VPLT System Sensors

	Precision	Resolution
Electromechanical Level Measurement	2.54 μm	2.54 μm
Pressure Measurement	4.0 μm	4.9 μm
Temperature Measurement	0.00006°C	0.00006°C

D.1.2 Equipment Setup and Test Preparations

Tank preparation and instrumentation deployment typically require about 1 h to complete, and are relatively straightforward. Instrumentation is generally installed at the fill hole, and the tank is overfilled nearly to grade prior to initiating preliminary calibration checks and establishing the stability of the tank. Considerable efforts are expended to ensure that all accessible trapped vapor is vented. In addition, a sample of product is extracted from the tank to enable API hydrometer measurements and expansion coefficient determinations to be made.

D.1.3 Test Protocol

The significant features of the VPLT test method are summarized in Table D.2.

Table D.2. Important Aspects of the VPLT Test Protocol

Sampling Period of Temperature Sensor	3 min (30,000-L tank)
Sampling Period of Product Level Sensor	3 min (30,000-L tank)
Test Duration	2 h (nominal)
Number of Samples per Sensor per Test	41 (nominal)
Waiting Period after Addition	12 h
Test Type/Product Level	Overfilled Tank

Testing with the VPLT system can be done using either of two approaches. The first approach, not evaluated in this report, is to mix product in the tank for approximately 1.5 h before performing the test. If the temporal gradient of any of the thermistors is greater than 0.056°C/h, the mixing must continue for an additional 30 min. The existence of this approach was not indicated or described to the EPA until two days before the manufacturer was to arrive for the Field Verification Tests, and, due to scheduling constraints inherent in the overall test program, has not been evaluated. The second approach is to fill the tank prior to testing and not mix the product. It is claimed that with this approach, a test can normally be completed within 3 to 5 h of filling the tank.

The test protocol that was evaluated requires that the tank be filled a minimum of 12 h prior to the test. A test pipe adapter is attached to the fill tube(s) so that product level can be brought 5 to 7 cm above grade. If the groundwater level is too high, product is raised above grade to counteract any masking effects which may occur due to the additional pressure of the groundwater. The manufacturer then attempts to remove any trapped vapor pockets. A product sample is taken and a hydrometer measurement made to determine the specific gravity of the product being tested. The specific gravity, measured to three significant figures, and the temperature of the product are entered into the computer where they are converted to the coefficient of thermal expansion of the product. Nominally, the test lasts 2 h, with the second hour of data being used to determine the reported leak rate. This test period, however, may be extended if either the geometry band (for unknown volume in the tank and piping) or structural deformation effects indicate that a longer test is necessary. Details of the test protocol are included in [D-1].

The presence of structural deformation is determined by whether the leak rate over a 60-min period (calculated every 3 min) is within a range of +/- 0.01 gal/h; unless it is within this range, the tank is not considered stabilized. The VPLT system determines the presence of vapor pockets by detecting oscillatory movement in pressure level and leakage rate plots. If the oscillatory behavior has a peak value exceeding 0.189 L/h in the leak rate values, it is concluded that an excessively large vapor pocket is present, and attempts are made to remove it. If this occurs, the product level is lowered until the vapor pocket is located and released.

D.1.4 Data Analysis

The VPLT system incorporates an averaging technique into its leak rate calculations in order to reduce random sensor noise. No more than five data points are incorporated into the average. The algorithm differentiates between the first-hour and post-first-hour testing. The second hour is defined so that in the averaging technique five samples each are used for both the new and the old values.

The VPLT system uses five methods of determining a leak rate. The leak rate reported by the test, however, is determined by means of the averaging technique combined with the temperature stratification compensation, using data from the primary (electromechanical) sensor. The other four methods are used as a comparison. The leak rate calculated with the secondary sensor (pressure sensor) is used as a check on the primary sensor. If the values do not fall within a range of +/- 0.01 gal/h, both sensors are checked.

Using a 1-h average of the data collected over the last hour of the test, the system computes a temperature-compensated volume rate from the product pressure and temperature measurements. Thermal compensation is performed by volumetrically weighting the readings from the five thermistors:

$$\Delta TV = \sum_{i=1}^{5} C_e V_i \Delta T_i \qquad \text{(D.2.1)}$$

where ΔTV is the change in volume, C_e (the coefficient of thermal expansion of the product) is determined from hydrometer readings, V is the volume of fluid, and ΔT is the change in temperature of that fluid volume.

Using the temperature and time-averaging technique, the leak rate is calculated. Over any time interval in the test (not to exceed 1 h), a temperature-and-pressure-compensated volume change is calculated. The compensated volume change over the time interval represents the calculated leak rate for that sample. Because the pressure is defined as the differential pressure in the model, ambient pressure effects are automatically compensated for. The VPLT system actually incorporates two absolute pressure sensors, measuring atmospheric and in-tank pressure, and compensates for atmospheric changes numerically. The temperature volume and pressure values are obtained by using the averaging technique outlined above. Although a leak rate is calculated at every sample period, the leak rate reported by the test is the one obtained during the last 1-h period.

If the leak rates calculated over a 1-h period do not fall within an error band of +/- 0.0378 L/h (0.01 gal/h), the test must continue because the tank has not stabilized sufficiently. The test does not end until a 1-h period of leak-rate data falls within this range. If this occurs before 2 h of testing have been completed, the test continues to the 2-h mark. If all criteria are met, the test is considered successful.

D.1.5 Detection Criterion

A leak is declared if the compensated volume rate for the last hour of testing is greater than a threshold of 0.189 L/h (0.05 gal/h). This flow rate is based on the volume rate recommended by NFPA. If the flow rate is less than the threshold, the tank is declared nonleaking. An inflowing compensated volume rate exceeding the threshold is considered to indicate an inconclusive test.

D.1.6 Mathematical Model

While the description provided in Section D.2 is sufficient to identify the key features of the VPLT system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that the mathematical model of the system was based on the more detailed description of the method provided in [D-1]. After it had been validated, the model was used to estimate the performance of the method.

D.2 Improving System Performance

The Computerized VPLT Tank Leak Testing System system could realize performance improvements without making any hardware modifications.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. A waiting period after topping is required to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. The effective waiting period for this method is determined by an analysis algorithm; the effectiveness of this algorithm was not evaluated.

A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

D.2.1 Protocol

The manufacturer of the Computerized VPLT Tank Leak Testing System could improved its performance by introducing a waiting period of 3 to 6 h or longer after topping off the tank, thus reducing errors due to structural deformation and to the destruction of a stable temperature field. Instead of allowing the product level to drift, the manufacturer could periodically adjust product level. This would remove the error present in interpreting product-level changes.

D.2.2 Detection Criterion

The convergence criterion should be revised. The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

E.3 The DWY Leak Sensor Test Method Description

The DWY Leak Sensor is a volumetric leak detection system capable, according to the manufacturer, of detecting leaks as small as +/- 0.189 L/h (0.05 gal/h) that occur in the walls or product distribution lines of an underground storage tank. For the performance results described in this report, it was employed as a precision (volumetric) leak detection test operating in an underfilled tank.

E.1.1 Instrumentation

The DWY Leak Sensor uses two measuring devices, a float and a detector rod, both of which measure product level, to estimate a temperature-compensated flow rate.

The position of the float, which is measured over a period of time, is related to the volume changes by means of the phenomenon that supports a buoyant object in a liquid. The float assembly is dependent on the size and type of the tank. A float shell is selected from a group of shells of varying length suitable for a variety of tank sizes. The float length and weight are chosen based on the diameter of the tank, the height of product in the tank, and the density of the test product. These measured values are determined prior to a test.

The detector rod assembly consists of a photoelectric cell and a float attachment hinge. The float movement forces an ink solution into or out of the photocell, and the resulting change in light transmittance in the photocell causes a voltage drop across the cell. This voltage change, which is a function of the product-level change, is measured by a voltmeter that has been calibrated prior to the test.

Volumetric changes are determined by monitoring product height changes with the float. The float senses these liquid-level changes in the tank, and the detector rod measures the relative position of the float with respect to the rod. The data are recorded on a strip chart.

The DWY Leak Sensor compensates for thermal effects by taking advantage of the natural temperature compensation inherent in the specifically designed float. This phenomenon is established by the relationship that exists between the temperature and three other factors, namely, liquid density, liquid volume, and liquid buoyancy forces (which are a function of density). A change in temperature (thus a change in volume) can therefore be exactly offset by density (buoyancy) changes providing that the floating object (i.e., float) is at a point in the tank where the volumetric and density changes caused by the temperature variations have an equal effect.

The manufacturer's claimed precision and resolution of these measurements are summarized in Table E.1, and were experimentally verified at the UST Test Apparatus in Edison, New Jersey during the Field Verification Tests.

Table E.1. Manufacturer's Precision and Resolution Claim for the DWY System Measurements

	Precision	Resolution
Product Level	0.0005 cm	0.0005 cm

E.1.2 Equipment Setup and Test Preparations

The manufacturer indicated that it would take approximately 1 h to install the equipment and prepare for the start of the test. This assumes that the product level is satisfactory for the conduct of a test.

E.1.3 Test Protocol

The important features of the DWY test protocol are summarized in Table E.2. Test protocol requires that the tank be filled to 50% to 82% of capacity. There is a waiting period of at least 6 h between the filling of the tank and the start of a test (i.e., calibrations), so as to allow the temperature of the product in the tank to stabilize. During the 1-h period immediately preceding data collection a 1/3-hp pump is used to spray product into the vapor space in order to saturate it. The 1-h period is the approximate time required to complete this procedure in a 30,000-L (8,000-gal) tank. Instrumentation warm-up and calibration also take place during this time. Calibration and testing continue at 1-h intervals until two consecutive readings give the same calculated (leak rate) result, or until a 4-h maximum test period has been completed.

Table E.2. Important Aspects of the DWY Test Protocol

Sampling Period	1 h
Test Duration	4 h (maximum)
Waiting Period after Addition	6 h
Test Type/Product Level	Underfilled Tank/50% to 82% of capacity

E.1.4 Data Analysis

A thermally compensated volume change is computed from the change in the height of a weighted float immersed at the null point of the tank where thermal changes are exactly offset by buoyancy forces. Data are obtained by sampling once per hour over the duration of the test. The voltage change over the 1-h period is converted to volume by multiplying by a conversion factor determined from the calibrations made before the test.

A tank chart, supplied by the tank manufacturer, is used to convert product-level measurements to volume. Height-to-volume conversion is accomplished by using linear interpolation between pairs of data points tabulated at 2.54-cm (1-in.) intervals of tank depth.

All tests are considered successful providing that data are collected for the entire duration of the test period, and that the appropriate initial waiting period is observed. A test is considered successful when two consecutive 1-h tests give the same calculated result, or when the 4-h maximum test period has been completed. The reported leak rate is that computed over the last 1-h testing period.

E.1.5 Detection Criterion

A leak is declared if the thermally compensated volume rate derived for the test period exceeds a threshold of +/-0.189 L/h (0.05 gal/h). If the flow rate is less than the threshold, the tank is declared nonleaking.

E.1.6 Mathematical Model

While the description provided in Section E.2 is sufficient to identify the key features of the DWY system as it was evaluated, and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [E-1]. After it had been validated, this model was used to estimate the performance of the method.

E.2 Improving System Performance

A systematic investigation of the DWY system should be made. There are two sources of error that should be investigated: the implementation of the float system for temperature compensation and the effect of spraying product into the vapor space before the test. Theoretically, the float system should behave as predicted, but whether it actually does is unknown. The Test Apparatus experiments suggests that any disturbance to the product or vapor immediately before a test can result in large testing errors; such disturbances should be avoided.

F.1 The EZY CHEK Test Method Description

The EZY CHEK leak detection system estimates a temperature-compensated volume rate from measurements of product level and product temperature. This is an overfilled-tank test. Although test length is considered constant, the sampling interval can vary. The manufacturer of the EZY CHEK leak detection system claims the ability to detect leak rates of 0.076 L/h (0.02 gal/h).

F.1.1 Instrumentation

Volumetric changes are determined indirectly with a pressure sensor, calibrated before and after each tank test, that measures the pressure required to force air bubbles into the product. A simple calibration performed for each test relates the observed value (lines on a chart recorder) to the apparent change in volume using a cylinder of known volume (0.19 L (0.05 gal)). Because the measurement is made in a standpipe (fill tube extender) located above ground, the tank must be overfilled to a level within the fill tube. It should be noted that, in normal situations, product is added until it is approximately 50.8 cm (20 in.) above grade in the standpipe.

Temperature is measured using a temperature averaging probe consisting of platinum sensing wire encased in a coiled spring of plastic tubing. The coil is wound more tightly toward the center of the probe, thus weighting the temperature of the measured product more heavily toward the center of the tank. A quantitative description of the higher density of coils toward the center is presented in Appendix B of the technical memorandum on the mathematical model [F-1].

Both temperature and volumetric data are sampled at 15-min intervals. The temperature data, obtained from a digital multimeter, are digitized with an integration time of 30 to 45 s, while the volumetric data, obtained from a chart recorder, are manually digitized. The chart recorder is circular and has 29 divisions per inch. Because the recorder and pressure gauge have a combined range of 2.5 cm (1 in.) of water, the bubbler height must be adjusted and the chart pen repositioned if the height change is greater than 2.5 cm. A 2.5-cm change equals approximately a 463-ml change in volume in a 15-cm (6-in.) diameter standpipe.

According to the EZY CHEK representative, a 22-line change is nominally observed for a 0.19-L calibration rod for a tank with a 5-cm (2-in.) diameter vent and a 10-cm (4-in.) diameter fill tube. Taking into account that the chart recorder is read to a resolution of 1/2 line, a resolution of 0.004 L would be obtained.

The precision of the sensor is 0.013 cm (0.005 in.) for water. For gasoline, the precision is 0.018 cm (0.007 in.) due to the lower density of that fluid. Precision and resolution calculations for product-level measurement are presented in Table F.1. The model of the method assumed a 5-cm diameter vent and 15-cm diameter standpipe.

Table F.1. Precision and Resolution of the EZY CHEK Leak Detection System as Specified by the Manufacturer

	Precision	Resolution
Level Measurement	0.004 L	0.004 L
Temperature Measurement	0.001°C	0.0006°C

F.1.2 Equipment Setup and Test Preparation

For a 30,000-L (8,000 gal) tank there is a 6-h minimum wait required between the filling of the tank and the commencement of the test. After this wait, the tank is topped off, the standpipe is filled with product, and testing begins immediately. A test is not complete unless 2 h of "good" data are obtained [F-1].

F.1.3 Test Protocol

The important features of the EZY CHEK test method are summarized in Table F.2. The test is conducted 6 h after a product addition and lasts for a period of 2 h. The temperature data are collected manually at a 15-min interval. The fluid-level data are recorded on an analog chart recorder.

Table F.2. Important Aspects of the EZY CHEK Test Protocol

Sampling Period	15 min
Test Duration	2 h
Waiting Period after Addition	6 h
Test Type/Product Level	Overfilled Tank/Above Grade

F.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product-level and product-temperature measurements using an average of the data obtained during the last hour of the test.

The thermal expansion and contraction of the product, ΔTV, is estimated using

$$\Delta TV = C_e V \Delta T \qquad (F.2.1)$$

where the rate of change of temperature, ΔT, is estimated from the thermal probe, the total volume, V, of the product in the tank is given as the capacity of the tank, and a value of the coefficient of thermal expansion, C_e, is calculated by measuring both the specific gravity and the temperature of the product and using an ASTM petroleum measurement table.

A test is considered successful if the eight values for the measured change in volume are within +/- 0.024 L of each other and the eight values for the measured temperature change per 15-min period are all within +/- 0.003°C of each other.

F.1.5 Detection Criteria

The tank is declared leaking if both of the following criteria are met: (a) the test is successful (valid), and (b) the leak rate is greater than 0.19 L/h and represents an outflow. An inflow of 0.076 L/h or greater is considered an inconclusive test.

F.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of EZY CHEK as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [F-1]. After it had been validated, this model was used to estimate the performance of the method.

F.2 Improving System Performance

The EZY CHEK system defined in [F-1] can realize performance improvements. One involves a change in protocol and the other a change to the analysis algorithm.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 1-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

F.2.1 Protocol

The following protocol changes are recommended:

- o Wait 6 to 12 h or longer after product delivery
- o Relevel the product at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period
- o Sample the temperature data every 3 min

The performance of the EZY CHEK system is significantly affected by (1) the lack of an adequate method for avoiding systematic errors due to structural deformation and (2) a time period inadequate for the temperature field to stabilize after product delivery. After product delivery a period of 6 to 12 h or longer is necessary to allow the temperature field to stabilize. The manufacturer should stipulate this in his protocol. Furthermore, he must ascertain whether the measured flow rate is being significantly affected by the systematic error resulting from structural deformation. The problem here lies in having, *a priori*, an adequate estimate of the time and tank elasticity constants of the tank in order to determine the length of time necessary to allow tank deformation effects to become negligible. A general discussion of methods to determine whether structural deformation has subsided is presented in the body of the report. It is recommended that the manufacturer increase the waiting period after topping off the tank in order to allow the temperature field to stabilize. Finally, the manufacturer could remove the possibility of misinterpreting height changes by releveling during a test and keeping track of the amount of product added and removed for the volume measurements.

Releveling the product represents the most significant performance improvement that can be achieved by the EZY CHEK system. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 50%.

F.2.2 Analysis

The averaging scheme used by the manufacturer results in a first-value-subtracted-from-last-value algorithm. The EZY CHEK analysis therefore makes only partial use of the available data, utilizing only the first and last measurements of the 1-h analysis period, and failing to utilize those collected at each 15-min interval. Intermediate measurements presently have no other value than to allow the operator to spot any change in the rate of temperature or volume. By performing a least-squares fit of the data collected over a 2-h period, the manufacturer could reduce the instrumentation limitation of his system to a standard error of 18 ml/h, thus reducing the instrumentation-limited detectable leak rate to 84 ml/h with a $P_D = 0.99$ and a $P_{FA} = 0.01$. By increasing to the recommended sample rate and using a least-squares linear analysis, the manufacturer could further decrease the instrumentation limitation to a standard error of less than 6 ml/h and improve the detectable leak rate to 30 ml/h with a $P_D = 0.99$ and $P_{FA} = 0.01$. This procedure could improve performance by as much as 125%.

F.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

G.1 The Gasoline Tank Monitor (GTM) Test Method Description

The Gasoline Tank Monitor (GTM) is an automatic tank gauging system capable, according to the manufacturer, of detecting leaks as small as 3.785 L (1.0 gal) when operated in a precision test (shutdown) mode. This is the minimum volume loss the GTM system can detect over the duration of a test (i.e., this is the threshold value for which the system is programmed); thus, for the 10-h test specified by test protocol, the minimum detectable flow rate would be 0.379 L/h (0.10 gal/h). The monitor, consisting of a tank sensor and a remote control console, is mounted permanently in the tank, and can perform a leak detection test when dispensing operations have ceased. For the tests described in this appendix, the GTM was employed as a volumetric test method using the protocol outlined in [G-1] and summarized below. The protocol of the GTM system employed as a volumetric test is different from that used when the system is in an automatic tank gauging mode.

G.1.1 Instrumentation

The GTM system uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of an acoustic device (ultrasonic transducer), and product temperature as determined by a temperature probe (bimetallic coil).

Volumetric changes are determined by monitoring fluctuations in product level (height) with an ultrasonic transducer that has been excited by a 4-μs voltage pulse to produce a 250-kHz incident signal, and recording them on an 8031 microprocessor. The resonant characteristic of the transducer creates an envelope-shaped waveform that propagates through a 5.08-cm (2-in.) diameter fiberglass tube containing a fixed reference target, a bimetallic coil having a position that is a function of temperature, and a third target consisting of the liquid/air surface boundary. Each of these targets produces a reflected wave that is received by the transducer. The microprocessor records height changes digitally.

The transducer output, shaped by a threshold detection circuit to produce a pulse, is detected by a precision rectifier/low-pass filter circuit, the leading edge of the output pulse identifying that of the reflected signal envelope. A programmable timer with a 4-MHz reference clock that begins counting when the transducer is energized is used to measure the round-trip travel time of the acoustic wave. The round-trip travel time for each echo is stored by the microprocessor. Echoes from the fixed reference target and the liquid surface boundary are used to calculate the product level, and the echoes from the reference target and the bimetallic coil reflector are used to calculate the distance between the transducer and the coil reflector. As the product level or temperature changes, so does the travel time of the acoustic signal. This distance, in turn, is used to calculate the temperature of the product in the vicinity of the coil.

Temperature is determined by using the ultrasonic transducer to monitor the position of a bimetallic coil. The angular movement of the coil is a function of its temperature. The nominal temperature-displacement curve supplied by the manufacturer is used to convert from angular displacement to temperature. The bimetallic coil has an operating range of 4 to 38°C (40 to 100°F). Its resolution, which varies with temperature because the number of angular degrees per degree Celsius is not constant, is less than 0.06°C for temperatures less than 38°C. The bimetallic coil is located approximately 4.5 cm from the bottom of the tank.

Product temperature data, like height data, are sampled continuously between the start and end of the test, and are used to determine the change in temperature, which will in turn be used in the thermal compensation calculations.

The claimed precision of these measurements is summarized in Table G.1, and was experimentally verified at the UST Test Apparatus during the field verification tests.

Table G.1. Manufacturer's Precision and Resolution Claim for the GTM System Measurements

	Precision	Resolution
Product Level	0.0254 cm	0.0254 cm
Temperature	0.06°C	0.06°C

G.1.2 Equipment Setup and Test Preparations

The GTM system sensor can be installed permanently in the tank via a 7.6-cm (3-in.) or 10.2-cm (4-in.) riser located at the top of the tank. Installation of the sensor on the Test Apparatus, along with the associated temporary wiring to the console, required approximately 1 h. Assuming the proper liquid level had been established in the tank, testing could then have commenced immediately.

G.1.3 Test Protocol

Employing a tank test in its volumetric mode requires that the tank be filled to between 50% and 95% of capacity, with a minimum product height of 45.7 cm (18 in.). Because the tank's temperature field may be significantly disturbed by the addition of product to attain this level, a waiting period of 24 h after filling must be observed. After this wait, a test may be initiated. The total test duration is specified as 24 h. The significant aspects of the test protocol are summarized in Table G.2.

Table G.2. Important Aspects of the GTM Test Protocol

Sampling Period	1 s
Test Duration	24 h
Waiting Period after Addition	24 h
Test Type/Product Level	Underfilled Tank/50% - 95% of capacity

G.1.4 Data Analysis

Volume and temperature are calculated from an average of 32 measurement samples obtained for each second of the test. The volume rate and temperature-volume rate are then calculated, and a thermally compensated volume rate is continuously developed during each second of the test. The total leak rate for the test period is calculated from the sum of the temperature-compensated volumes divided by the total test time.

A tank chart, supplied by the tank manufacturer, is used to convert product-level measurements to volume. Height-to-volume conversion is accomplished by using linear interpolation based on a 32-point table.

Thermal expansion or contraction of the product, ΔTV, is estimated from

$$\Delta TV = C_e V \Delta T \qquad (G.2.1)$$

where the temperature change, ΔT, is estimated from the output of the ultrasonic detector; the total volume, V, of the product is estimated from a product level measurement; and a value of the coefficient of thermal expansion, C_e, for gasoline is determined, by the operator, from the American Petroleum Institute (API) type-6B algorithm which is incorporated in the GTM console. In order to use this algorithm, a measurement of the API gravity of the product must be made and the value centered into the console.

All tests are considered successful providing that data are collected for the entire duration of the test period, and that the appropriate initial waiting period is observed.

G.1.5 Detection Criterion

A leak is declared if the thermally compensated volume rate exceeds a threshold of 0.189 L/h (0.05 gal/h). If the flow rate is less than the threshold, the tank is declared nonleaking.

G.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the GTM as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [G-1]. After it had been validated, this model was used to estimate the performance of the method.

G.2 Improving System Performance

The GTM system can realize performance improvements by making changes to the instrumentation, protocol, analysis, and detection criterion.

G.2.1 Instrumentation

Probably the largest sources of errors are due to inadequate measurement of the vertical temperature field. This source of error is two-fold:

- o The distance between the reference fiducial and the surface produces a systematic error in the estimation of the product height. This error has not been quantified for this evaluation, but it will control performance. It can result in a large systematic error.
- o The performance of the Gasoline Tank Monitor is also limited by its point-source temperature system. By increasing the number of temperature probes between the tank bottom and product surface the temperature field could be better estimated.

The change in performance as a function of the number of thermistors (temperature probes) on a vertical array is discussed in the body of the final report. Substantial improvement occurs when additional thermistors are used, allowing better sampling of the temperature field.

G.2.2 Analysis

The Gasoline Tank Monitor system could improve performance further by performing a least-squares regression on the data. This could significantly alleviate the problem associated with aliasing internal waves, and makes maximum use of the information obtained from the data sampling. Refer to the main body of the report for a discussion of performance as a function of sampling and test duration.

G.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

H.1 The Gilbarco Tank Monitor Test Method Description

The Gilbarco Tank Monitor is an automatic tank gauging system capable, according to the manufacturer, of detecting leaks as small as 0.757 L/h (0.20 gal/h) when operated in a precision test (shutdown) mode. The monitor, consisting of a tank sensor and a remote control console, is mounted permanently in the tank, and can perform a leak detection test when dispensing operations have ceased. For the tests described in this appendix, it was employed as a volumetric test method using the protocol outlined in [H-1] and summarized below. The protocol of the Gilbarco Tank Monitor employed as a volumetric test is different from that used when it is in an automatic tank gauging mode.

H.1.1 Instrumentation

The Gilbarco Tank Monitor system utilizes three types of sonic measurements to determine the temperature-compensated volume rate: fuel surface ("1"), calibration reflectors (fiducials) ("2"), and water ("3"). The measurements are taken using the sequence 1, 2, 1, 3, 1, 2, 1, 3..., etc., with a time differential of approximately 70 ms between each measurement.

Volumetric changes are determined by monitoring fluctuations in product level (height) with an ultrasonic transducer that has been excited by a voltage pulse nominally of 465 ns to produce a 1.1-MHz incident signal, and digitally recording them on a microprocessor. The resonant characteristic of the transducer creates an envelope-shaped waveform that propagates through the product, which contains several fixed reference targets (fiducials). These fiducials are attached to a vertical aluminum rod at equally spaced intervals of 30.5 cm (12 in.), beginning 30.5 cm from the tank bottom. A second medium consisting of the liquid/air surface boundary serves as the variable target. Each of these targets (i.e., the fixed targets and the liquid/air surface) produces a reflected wave that is received by the transducer.

The transducer output, shaped by a threshold detection circuit to produce a pulse, is detected by a precision rectifier/low-pass filter circuit. The leading edge of the output pulse identifies the presence of the reflected signal envelope. A programmable timer with a 19.66-MHz reference clock that begins counting when the transducer is energized is used to measure the round-trip travel time of the acoustic wave. The round-trip travel time for each echo is stored by the microprocessor. Echoes from the fixed reference fiducials and the liquid surface boundary are used to calculate the product level, while temperature is calculated using the echoes from the bottom and top fiducials. It should be noted that the word "top" refers to topmost *submerged* fiducial.

The product height is measured by means of an ultrasonic transducer located 15.2 cm (6 in.) from the tank bottom. The round-trip travel time of the reflected acoustic signal is used to monitor the liquid surface. The travel time of the acoustic signal changes in proportion to the product-level changes. The operating range of the product level-measurement device is from 19 to 320 cm (7.5 to 126 in.).

Temperature is also measured by using the ultrasonic transducer, which is used to monitor the acoustic velocity changes. (Acoustic velocity is determined by measuring the round-trip time for sound to travel from the the transducer to the highest reflector that is submerged at least 2.54 cm below the product surface.) The nominal temperature curve supplied by the manufacturer is used to convert the velocity of the acoustic signal to temperature. The resolution is less than 0.0006°C for temperatures greater than 38°C, varying with temperature because the velocity of sound per degree Celsius is not constant. The nominal operating range of temperatures is -32 to 38°C (0 to 100°F).

Product temperature data, like height data, are sampled continuously between the start and end of the test, and are used to determine the change in temperature, which in turn is used in the thermal compensation calculations.

The manufacturer's claimed precision and resolution for these measurements, summarized in Table H.1, were experimentally verified at the UST Test Apparatus in Edison, New Jersey during the field tests of the Gilbarco system.

Table H.1. Manufacturer's Precision and Resolution Claim for the Gilbarco Tank Monitor System Measurements

	Precision	Resolution
Product Level	0.000254 cm	0.000178 cm
Temperature	0.001°C	0.0006°C

H.1.2 Equipment Setup and Test Preparations

Under actual field conditions, the sensor is installed permanently in the tank via a 10-cm (4-in.) riser located at the top of the tank. Installation of the sensor in the Test Apparatus tank, along with the associated temporary wiring to the console, required approximately 2.5 h. Assuming the proper liquid level had been established in the tank, testing could then have commenced immediately.

H.1.3 Test Protocol

Employing a tank test in its volumetric mode requires that the tank be filled to between 80% and 95% of capacity. Because the tank's temperature field may be significantly disturbed by the addition of product to attain this level, a waiting period of 18 h after filling is specified. After this wait, a test may be initiated. The total test duration is specified as 5 h. The significant aspects of the test protocol are summarized in Table H.2.

Table H.2. Important Aspects of the Gilbarco Tank Monitor Test Protocol

Sampling Period	7 to 8 s
Test Duration	5 h
Waiting Period after Addition	18 h
Test Type/Product Level	Underfilled Tank/80% to 95% of capacity

H.1.4 Data Analysis

Volume and temperature are calculated from 50 measurement samples obtained for each hour of the test. The volume rate and temperature volume rate are then calculated, and a thermally compensated volume rate is developed for each hour of the test. The total leak rate for the test period is calculated from the sum of the hourly temperature-compensated volumes divided by the total test time.

A tank chart, supplied by the tank manufacturer, is used to convert product-level measurements to volume. Height-to-volume (HtoV) conversion is accomplished by using linear interpolation between pairs of data points tabulated at 2.54-cm intervals of tank depth.

Thermal expansion or contraction of the product, ΔTV, is estimated from

$$\Delta TV = C_e V \Delta T \qquad \text{(H.2.1)}$$

where the temperature change, ΔT, is estimated from the output of the ultrasonic detector; the total volume, V, of the product is estimated from a product-level measurement; and a value of the coefficient of thermal expansion, C_e, for gasoline is furnished by the petroleum company.

All tests are considered successful providing that data are collected for the entire duration of the test period, and that the appropriate initial waiting period is observed.

H.1.5 Detection Criterion

A leak is declared if the thermally compensated volume rate for the test period exceeds a threshold of +/- 0.189 L/h (0.05 gal/h). If the flow rate is less than the threshold, the tank is declared nonleaking.

H.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the Gilbarco Tank Monitor as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [H-1]. After it had been validated, this model was used to estimate the performance of the method.

H.2 Improving System Performance

The Gilbarco Tank Monitor system can realize performance improvements. These involve changes to the analysis and detection criterion, and are discussed below.

H.2.1 Instrumentation

The main source of error is the measurement of product level. By judicial selection of the depth of the product relative to the reference fiducial, this error has been minimized. This effect has not been thoroughly investigated and the magnitude of this error is not known.

H.2.2 Analysis

The Gilbarco Tank Monitor accurately measures a vertical average of the temperature field. A weighted average would improve performance. A discussion of the performance improvements achieved by using a volumetrically weighted average of temperature is given in the main body of the report.

The Gilbarco Tank Monitor system could improve performance by performing a least squares regression on the data. This makes maximum use of the information obtained from data sampling.

H.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

I.1 The Inductive Leak Detector 3100 Test Method Description

The Inductive Leak Detector 3100 is a system that provides inventory reconciliation (automatic tank gauging) and is capable, according to the manufacturer, of detecting leaks as small as +/- 0.189 L/h (0.05 gal/h) when operated in a precision test (shutdown) mode. The monitor, consisting of two tank sensors (product height and temperature) and a remote control console, is mounted permanently in the tank, and can perform a leak detection test when dispensing operations have ceased. For the tests described in this appendix, it was employed as a volumetric test method using the protocol outlined in [I-1] and summarized below. The protocol of the Inductive Leak Detector 3100 employed as a volumetric (precision leak) test is different from that used when the system is in an automatic tank gauging mode.

I.1.1 Instrumentation

The Inductive Leak Detector 3100 system when in leak check mode utilizes two measuring devices to estimate a temperature-compensated flow rate. Product level is determined by means of a digital rule and float, and product temperature is determined by a temperature probe. Temperature is measured by means of a single resistance temperature detector (RTD) placed 87.6 cm (34.5 in.) from the bottom of a 244-cm (96-in.) diameter tank.

A Minco resistance temperature detector (RTD) is used to measure temperature changes. The RTD has an operating range of -40 to 100°C (-40 to 212°F). The nominal temperature-resistance curve supplied by the manufacturer is used to convert from ohms to temperature. The resolution is less than 0.17°C for temperatures less than 0°C, varying with temperature because the number of ohms per degree Celsius is not constant.

Volumetric changes are determined by monitoring fluctuations in the product level (height). The product-level sensor consists of a float device riding the product surface, and is attached to a digital rule that senses the product-level fluctuations due to the motion of the surface waves. These height changes are digitally recorded on a microprocessor.

Product-temperature data, like height data, are sampled continuously for 1 min at the start and end of the test, and are used to determine the change in temperature, which will in turn be used in the thermal compensation calculations.

The claimed precision and resolution of these measurements are summarized in Table I.1, and were experimentally verified at the UST Test Apparatus in Edison, New Jersey during the Field Verification Tests.

Table I.1. Manufacturer's Precision and Resolution Claim for the Inductive Leak Detector 3100 System Measurements

	Precision	Resolution
Product Level	0.254 cm	0.127 cm
Temperature	0.17°C	0.17°C

I.1.2 Equipment Setup and Test Preparations

The sensor is installed permanently in the tank via a 10-cm (4-in.) riser located at the top of the tank. Installation of the sensor on the tank, along with the associated temporary wiring to the console, required approximately 1 h. Assuming the proper liquid level had been established in the tank, testing could then have commenced immediately.

I.1.3 Test Protocol

Testing a tank in the volumetric test mode requires that the tank be filled to approximately 93% of the tank diameter (97% of tank capacity for a tank 243.84 cm in diameter). Because the tank's temperature field may be significantly disturbed by the addition of product to attain this level, a waiting period of 3 h after filling must be observed. After this wait, a test may be initiated. The total test duration is specified as 10 h. The significant aspects of the test protocol are summarized in Table I.2.

Table I.2. Important Aspects of the Inductive Leak Detector 3100 Test Protocol

Sampling Period	10 s (first and last minute only)
Test Duration	10 h
Waiting Period after Addition	3 h
Test Type/Product Level	Underfilled Tank/93% of tank diameter

I.1.4 Data Analysis

Volume and temperature are calculated from 14 measurement samples (seven each from the first and last minutes) obtained from each sensor. The volume rate and temperature volume rate are then calculated, and a thermally compensated volume rate developed for each test.

A tank chart, supplied by the tank manufacturer, is used to convert product-level measurements to volume. Height-to-volume conversion is accomplished by linear interpolation between pairs of data points tabulated at 2.54-cm (1-in.) intervals of tank depth.

Thermal expansion or contraction of the product, ΔTV, is estimated from

$$\Delta TV = C_e V \Delta T \tag{I.2.1}$$

where the temperature change, ΔT, is estimated from the output of the temperature probe, the total volume, V, of the product is estimated from a product-level measurement, and a value of the coefficient of thermal expansion, C_e, for gasoline is furnished by the petroleum company.

All tests are considered successful providing that data are collected for the entire duration of the test period, and that the appropriate initial waiting period is observed.

I.1.5 Detection Criterion

A leak is declared if the thermally compensated volume rate for the test period, Δt, derived from Eq. (I.2.2), exceeds a threshold[1] of +/- 0.189 L/h. If the flow rate is less than the threshold, the tank is declared nonleaking.

$$\text{Flow rate} = \frac{\Delta V - \Delta TV}{\Delta t} \tag{I.2.2}$$

I.1.6 Mathematical Model

While the description provided in Section I.2 is sufficient to identify the key features of the Inductive Leak Detector 3100 as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [I-1]. After it had been validated, this model was used to estimate the performance of the method.

I.2 Improving System Performance

The Inductive Leak Detector 3100 system can realize performance improvements if changes are made to the instrumentation, test protocol, analysis, and detection criterion. Since the system is limited by the system noise changes to the instrumentation are highly recommended.

I.2.1 Instrumentation

Probably the largest source of error is due to inadequate temperature compensation, a result of improper determination of the vertical temperature field. The change in performance as a function of the number of thermistors (temperature probes) on a vertical array is discussed in

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1 Currently the Inductive Leak Detector 3100 system does not set a threshold to declare a tank leaking or nonleaking, but reports a leak rate. The threshold value of 0.189 L/h conforms to the current NFPA standard and is used as the detection threshold for the purposes of this report.

the body of the final report. Substantial improvement occurs when additional thermistors are used, allowing better sampling of the temperature field. In addition, improving the precision of the temperature sensors will substantially improve performance.

Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 50% performance improvement (assuming thermistors with better precision) could be achieved by increasing the number of thermistors to five.

I.2.2 Protocol

The following protocol changes are recommended:

- Wait 6 to 12 h or longer after product delivery
- Sample the temperature data every 3 min

Increasing the minimum waiting period after a product delivery could further improve the Inductive Leak Detector 3100 system. The thermal effects of a delivery are minimized only because the current protocol stipulates a long test duration. The test results are influenced also by the effects of unknown temperature changes due to horizontal gradients, as well as by structural deformation effects, as discussed in the main body of the report.

I.2.3 Analysis

The performance of the Inductive Leak Detector 3100 system could be improved by increasing the sample rate over the duration of the test rather than taking the first and last minute of data and performing a least-squares regression. This could significantly alleviate the problem associated with aliasing internal waves and maximize the information obtained from the data sampling. Refer to the body of the report for a discussion of performance as a function of sampling and test duration.

I.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly. This is also discussed in more detail in the body of the report.

J.1 The INSTA-TEST System Test Method Description

The INSTA-TEST system is a volumetric leak detection system which, for this evaluation, was employed strictly as a test of the tightness of underfilled tanks.

J.1.1 Instrumentation

The INSTA-TEST leak detection system measures the differential change in pressure obtained by comparing open and closed tubes placed in the tank. The tubes are made of copper and are 1.90 cm in diameter and approximately 3.3 m long. They are inserted into the tank through the fill tube before a test. The top of each copper tube is open, as is the base, which is within a few inches of the center line of the tank. After installation is completed, the base of one tube is closed, preventing any product from entering. The system remains in this condition for a variable time period, at the end of which the tops of both tubes are closed and connected via a differential pressure transducer that permits comparison of their respective pressures. The base of the closed tube is then opened, and the pressure change resulting from the level changes in the open and closed tubes is read from a digital meter. This change in pressure is converted to volume using a scale factor determined during a previous calibration. Since thermal compensation is performed physically by the integration of temperature in the closed tube, no calculations are performed.

Test length is determined as a function of tank size and product level. The precision and resolution of the INSTA-TEST system, as given by the manufacturer, are presented in Table J.1.

Table J.1. Precision and Resolution of INSTA-TEST System as Specified by the Manufacturer

	Precision	Resolution
Product Level	34.2 μm	10.2 μm

J.1.2 Equipment Setup and Test Preparations

The manufacturer did not specify the amount of time usually required for installation of the equipment and test preparations.

J.1.3 Test Protocol

The important features of the INSTA-TEST test method are summarized in Table J.2. Test protocol requires that product be added to the tank at least 1 h prior to testing. For a precision test, the tank must be approximately 95% full. In order to avoid transient effects, the actual differential pressure measurement is made approximately 2 min after the tube is opened. The sensor's electronics have an integration period of 10 s.

Table J.2. Important Aspects of the INSTA-TEST System Test Protocol

Test Duration	Variable
Waiting Period after Addition	1 h
Test Type/Product Level	Underfilled Tank/95% of tank capacity

J.1.4 Data Analysis

A thermally compensated volume change is computed from the change in pressure resulting from the level changes in the open and closed tubes. The pressure change is converted to volume using a previously determined calibration factor. Thermal compensation is performed physically by the integration of temperature in the closed tube and, as a result, no direct temperature measurements or calculations are performed.

J.1.5 Detection Criterion

A tank is declared leaking if the flow rate as determined by the test is not equal to 0.0 ml/h.

J.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the INSTA-TEST system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [J-1].

J.2 Improving System Performance

No recommendations for improving system performance were made as part of this evaluation.

K.1 The Leak Computer Test Method Description

The Leak Computer system, designed to function in an overfilled tank, measures changes in product volume and product temperature in order to determine a volumetric flow rate. Changes in product volume are determined by measuring the amount of product that is added or removed to keep the product level in the fill tube constant. The amount of product added or removed is determined by the change in weight (mass) of a supply of product maintained outside the tank (approximately 13.2 L (3.5 gal)), while a control loop using two optical detectors determines the time at which this addition or removal takes place.

K.1.1 Instrumentation

An array of three thermistors, volumetrically weighted by a factor of 15%, 70%, and 15%, respectively, is used to determine a weighted average of the product temperature.

The volume of the tank is determined from the tank manufacturer's strapping table, which specifies that the coefficient of thermal expansion used in the thermal compensation calculations for gasoline is 0.0012402/°C (0.000689/°F). When a test is performed, the measured volume changes are compensated for thermal expansion prior to calculating a leak rate. The precision and resolution of the temperature and volume measurement systems as given by the manufacturer are presented in Table K.1.

Table K.1. Precision and Resolution of the Leak Computer System as Specified by the Manufacturer

	Precision	Resolution
Volume Measurement	10.0 ml	3.3 ml
Temperature Measurement	0.0017°C	0.0005°C

K.1.2 Test Protocol

Test protocol does not require a waiting period between the filling of the tank and the start of a test, but the duration of a test must be at least 70 min. Volume and temperature data are digitally recorded at a rate of 120 samples per cycle. The cycle period, approximately 50-70 s in length, remains constant for the duration of a test. The test is finished either when the standard deviation of the leak rates is less than 0.189 L/h (0.05 gal/h) or when the following criterion is satisfied 10 times consecutively: the standard deviation of 30 leak rates is less than half of the last leak rate determined. Table K.2 lists the important aspects of the test protocol.

Table K.2. Important Aspects of the Leak Computer Test Protocol

Sampling Period	between 50 and 70 s (120 samples averaged per 50 to 70-s cycle)
Test Duration	70 min (minimum)
Wait Period	0 h
Test Type/Product Level	Overfilled Tank/Constant (Below Grade)

K.1.3 Data Analysis

Thermal expansion and contraction of the product is calculated from the volumetrically weighted thermistors placed in the tank. The volume change is estimated using

$$\Delta TV = C_e V \Delta T \qquad (K.2.1)$$

where the change in temperature, ΔT, is the volumetrically weighted value determined from the three thermistors, the total volume, V, is the tank volume as determined from the tank chart issued by the tank's manufacturer, and C_e is the coefficient of thermal expansion of the product.

Thermal volume changes calculated from temperature measurements are subtracted from the volume changes determined by measuring the amount of product added or removed.

K.1.4 Detection Criterion

The manufacturer considers the test result to represent the actual leak rate with a 95% confidence interval less than or equal to the leak rate. The tank is declared leaking if the leak rate exceeds 0.189 L/h.

K.1.5 Mathematical Model

While the description presented in Section K.2 is sufficient to identify the key features of the Leak Computer as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description provided in [K-1]. After it had been validated, the model was used to estimate the performance of the method.

K.2 Improving System Performance

The manufacturer of the Leak Computer system can improve performance by making changes to the protocol, the detection criterion, and the instrumentation.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. A waiting period after topping is required to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. The effective waiting period for this method is determined by an analysis algorithm; the effectiveness of this algorithm was not evaluated.

A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected.

Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

K.2.1 Protocol

It is recommended that the manufacturer reassess the ability of the waiting period algorithm to differentiate between the effects of structural deformation and a leak.

K.2.2 Instrumentation

Performance improvement could be achieved by adding more thermistors to improve spatial sampling of the vertical temperature field. Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 30% performance improvement could be achieved by increasing the number of thermistors from three to five.

K.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

L.1 The Leak-O-Meter Test Method Description

Leak-O-Meter is a precision tank testing device capable, according to the manufacturer, of detecting leaks as small as 189 ml/h (0.05 gal/h). The apparatus, attached to the fill tube of a tank, functions when dispensing operations have been suspended. For the tests described in this report, the system was employed using the protocol described in [L-1] and summarized below.

L.1.1 Instrumentation

The Leak-O-Meter system determines a thermally compensated flow rate by measuring volumetric fluctuations and temperature. The precision and resolution of the Leak-O-Meter measurement system, as given by the manufacturer, are presented in Table L.1. Volumetric fluctuations are measured directly with a flow transducer having a range of 60 L/h and located in an extension of the fill tube. The transducer is calibrated by injection of a known amount of liquid before and after each test, and has a reported response time of 5 s. The tank is overfilled to a level approximately 1.22 m above grade. The sensor used to measure temperature consists of a single thermistor from which readings are sampled digitally at 25-s intervals; these are displayed on a chart recorder.

Table L.1. Precision and Resolution of the Leak-O-Meter System as Specified by the Manufacturer

	Precision	Resolution
Volume Measurement	0.00061 L/h	0.00378 L/h
Temperature Measurement	0.01°C	0.001°C

L.1.2 Equipment Setup and Test Preparations

The manufacturer indicated it would take approximately 45 min to install the Leak-O-Meter equipment and calibrate the device. This assumes that the product level is satisfactory for the conduct of a test.

L.1.3 Test Protocol

The important features of the Leak-O-Meter test method are summarized in Table L.2. Incorporated within the test are a 12-h wait after product addition and a maximum test duration of 129 min consisting of three 43-min tests. The test may be shorter than the nominal 129 min if the data collected over the first 86 min agree within 10%. There is also a waiting period after topping the tank which corresponds to the time it takes to install and set up the Leak-O-Meter system, nominally 45 min.

Table L.2. Important Aspects of the Leak-O-Meter Test Protocol

Sampling Period	25 s
Test Duration	129 min (maximum)
Waiting Period after Filling the Tank	12 h
Waiting Period after Topping Off	45 min (approximate)
Test Type/Product Level	Overfilled Tank

L.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product's flow rate and temperature measurements. For each test, data are collected in three sets. Each set, following identical procedures for data collection and analysis, is comprised of three individual tests during which temperature data are monitored continually. A detailed flowchart of the data analysis algorithm is given in [L-1]. The rate of temperature change is estimated from the average temperature change measured over a 15-min period, during which only temperature data are recorded. The data are then used to estimate the thermal rate of change for the entire set. The rate of thermal volume change is estimated by the coefficient of thermal expansion (C_e) and the volume of the tank (V_{tank}). C_e is determined by measuring both the specific gravity and the temperature of the product, using ASTM tables D1250-80; tank volume is determined from the manufacturer's tank chart. If the estimate of the thermal rate of change (TLR) differs by more than 25% from the value determined during the test, the TLR value is updated. Flow-rate data are collected for 6 min after the end of the 15-min period, and the average value is used as the volumetric flow rate. After a 5-min wait, the same sequence is repeated a second and then a third time. The three measured flow rates, subsequently compensated for thermal effects, are then averaged to yield the leak rate for that set.

For each set, the thermistor is deployed at a different location in the tank. During Set A, the thermistor is positioned at two-thirds of the tank height as measured from the bottom; during Set B it is positioned at one-half the height of the tank; and during Set C at one-third. If the thermally compensated leak rates determined during Set A and Set B do not agree within 10%, then Set C is performed. If the leak rates determined for two of the three sets are not within 10% of one another, the sequence must be repeated until the percentage criterion is satisfied. The leak rate reported at that point is an average of the two closest leak rates. The thermal compensation is estimated using

$$\Delta TV = C_e V \Delta T \tag{L.2.1}$$

where the rate of change of temperature, ΔT, is estimated from the thermistor data; the total volume of the tank, V, is estimated from a tank chart; and a value of the coefficient of thermal expansion, C_e, for gasoline is estimated from the API tables.

L.1.5 Detection Criterion

A leak is declared if the measured temperature-compensated volume rate exceeds +/- 189 ml/h.

L.1.6 Mathematical Model

While the description provided in Section L.2 is sufficient to identify the key features of the Leak-O-Meter as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [L-1]. After it had been validated, this model was used to estimate the performance of the method.

L.2 Improving System Performance

The Leak-O-Meter system as defined in [L-1] can realize performance improvements with changes to the system protocol and analysis procedure. By also making minor hardware modifications, the system performance could be markedly improved.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 0.75-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

L.2.1 Protocol

The following protocol changes are recommended:

- o Sample the temperature data every 3 min
- o Relevel the product at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

The performance of the Leak-O-Meter system as modeled is significantly affected by deformation effects. Accurate measurement of volume changes in the fill tube requires releveling of the product during a test and an adequate time for the deformation effects to become negligible.

Releveling the product represents the most significant performance improvement that can be achieved by the Leak-O-Meter system. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 100%.

The Leak-O-Meter system samples at only three locations in the tank and provides the option of accepting data from only two of the three locations. In order to thermally compensate to the degree claimed by the manufacturer, the tank must be sampled at more (at least five) vertical locations in the tank for shorter periods of time.

L.2.2 Analysis

The present method of estimating leak rates depends exclusively upon operator intervention and interpretation of the collected data. The Leak-O-Meter system could benefit greatly from the introduction of digital data collection and processing equipment. The flow meter presently used in the Leak-O-Meter system appears to display a noisy signal. This situation could also be improved if a digital-signal processing scheme were implemented.

It is recommended that the temperature-compensated volume rate be computed from the data taken at the recommended higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and 20 temperature measurements to estimate the thermal volume change, the performance could improve by as much as 100%.

L.2.3 Instrumentation

Performance improvement could be achieved by adding more thermistors to improve spatial sampling of the vertical temperature field. Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 30% performance improvement could be achieved by increasing the number of thermistors to five.

L.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

M.1 The LiquidManager Test Method Description

LiquidManager is a precision leak detection device capable, according to the manufacturer, of detecting leaks as small as 38 ml/h (0.01 gal/h) in the absence of noise sources other than thermal noise. This capability, when factored for other uncompensated noise sources, will allow for the detection of leaks of 189 ml/h (0.05 gal/h). The unit is installed in an unsealed fill tube from which any drop tube that might have been present has been removed.

M.1.1 Instrumentation

The LiquidManager leak detection system measures the change in product level and compensates for thermal fluctuations. The precision and resolution of the LiquidManager measurement system as given by the manufacturer are presented in Table M.1. The LiquidManager measures fluid level by measuring the natural period of oscillation resulting from the combined buoyancy and gravitational forces exerted on a probe ("displacer") that is submerged to its midpoint in the product. The period is inversely related to the square root of the total vertical force on the probe. The probe location is adjusted for fluid-level changes so as to keep the period of oscillation constant. Product level is sampled at a frequency of 1 Hz.

The temperature measurements are made by raising and lowering a thermistor through the product throughout the test. The initial and final temperature values, which are the only values used in the leak rate calculations, are obtained by holding the thermistor stationary for 90 s at the center of each of 17 equally spaced segments as it gradually ascends from the base of the tank to the top. (Its initial position is actually 25.4 cm (10 in.) from the base of the tank, and its final position is 25.4 cm from the top.) Temperature data are read at a sample rate of 8 Hz. The temperature probe is said by the manufacturer to have a response time constant of 1 s.

Table M.1. Precision and Resolution of the LiquidManager System as Specified by the Manufacturer

	Precision	Resolution
Product Level	0.25 mm	0.15 mm
Temperature	0.001°C	0.0005°C

M.1.2 Equipment Setup and Test Preparation

The installation of the LiquidManager precision tank testing device at the Edison UST facility took up to 1.5 h. This assumes the product was at a satisfactory level for testing.

M.1.3 Test Protocol

The important features of the LiquidManager system are summarized in Table M.2. The LiquidManager method requires that the tank be filled to a level within the fill tube at least 12 h prior to the start of the test. At the end of this 12-h period, product is added until a pressure of just under 0.35 kg/cm^2 (5 psi) is attained at the base of the tank, and at the end of another 1-h waiting period the product level is lowered to obtain 0.28 kg/cm^2 (4 psi) at the base of the tank; both pressure levels are determined according to a set of relations developed by the manufacturer. No additional product-level changes are required, and after a 15-min period has elapsed, the test may start. Test duration for a 243.8-cm (96-in.) diameter tank is approximately 92 min; this comprises 16 min for temperature data collection prior to the 1 h of product-level measurements, and 16 min at the end of these measurements.

Table M.2. Important Aspects of the LiquidManager System Test Protocol

Sampling Period	0.125 s
Test Duration	92 min
Waiting Period After Addition	12 h
Test Type/Product Level	Overfilled Tank/Above Grade

Prior to the start of a test, LiquidManager checks the thermal stability of the tank. If the standard deviation of the temperature measured over the 90-s period at each segment is greater than 0.01°C, the test is delayed an additional 15 min.

M.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product-level and product-temperature measurements. The level measurements used for the calculations are an average of the first and last 40 samples collected over the 1-h test period. As the product-level sensor has a sampling rate of 40 Hz, the 40 sample segments of data represent the first and last 40 s of the 1-h test period. The temperature data, which are collected prior to and after the 1 h of product-level sensor data, represent temperatures at 17 equally spaced points beginning 25.4 cm from the tank bottom and ending 25.4 cm from tank top. The temperature sensor stabilizes at each of the 17 locations for 90 s and collects data at an 8-Hz sample rate. An average of the last 30 samples, representing 3.75 s of data, of each 90-s period is used in the calculations. The two sets of temperature data points are then volumetrically weighted and differenced to give an estimation of the average overall temperature change of the product in the tank, ΔT. The thermal expansion or contraction of the product, ΔTV is estimated using

$$\Delta TV = C_e V \Delta T \qquad (M.2.1)$$

where V is the total volume of product in the tank and C_e is the coefficient of thermal expansion for gasoline furnished by the manufacturer.

A height-to-volume (HtoV) calibration is conducted with a known volume at the 0.28-kg/cm^2 level prior to and after each test. By using the known exposed surface area and the HtoV factor obtained during calibration, an estimation of vapor pocket size is made. The product level sensor data in conjunction with the HtoV conversion factor are used to estimate the gross volume change.

M.1.5 Detection Criterion

A leak is declared if the measured temperature-compensated volume rate exceeds +/- 189 ml/h (0.05 gal/h).

M.1.6 Mathematical Model

While the description provided in Section M.2 is sufficient to describe the key features of the LiquidManager system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [M-1]. After it had been validated, this model was used to estimate the performance of the method.

M.2 Improving System Performance

The LiquidManager system can realize performance improvements by changing the protocol of the test.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 1-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

The performance of the LiquidManager system can be affected to varying degrees by volume changes due to structural deformation. Because structural deformation effects vary between tanks, an adequate quantitative estimate is difficult to ascertain. It is therefore recommended that the LiquidManager utilize a method for maintaining a constant product level during the test period while keeping other protocol requirements the same.

M.2.1 Protocol

The following protocol changes are recommended:

- Relevel the product at 15-min intervals or longer and record the volume changes
- Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

Releveling the product represents the most significant performance improvement that can be achieved by the LiquidManager system. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 80%.

M.2.2 Analysis

It is recommended that the temperature-compensated volume rate be computed from the data taken at the higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and at least 20 temperature measurements were used to estimate the thermal volume change, the performance could improve by as much as 100%.

M.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

N.1 LMS-750 Test Method Description

The LMS-750 is a leak detection system capable, according to the manufacturer, of detecting leaks as small as approximately 3.785 L/h (1 gal/h). The LMS-750 system measures product level and temperature in order to determine a temperature-compensated leak rate. The test length is constant, as is the sampling period.

N.1.1 Instrumentation

The LMS-750 system uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of the Pneumercator Direct Lift Model 2-412 level sensor, and product temperature as determined by two thermistors located at 33% and 66% of the tank height.

Volumetric changes are determined by monitoring fluctuations in product level using a float device. A data set containing 48 readings is collected every 26 s and recorded. The 48 readings are averaged, and the average recorded as the representative value of each data set.

Product temperature is recorded using two thermistors located at 33% and 66% of the tank height (0.80 m and 1.6 m, respectively, from the bottom of the tank). As with product-level data, temperature sensors are sampled 48 times every 26 s, and an average is calculated to represent that data set.

The precision and resolution of the LMS-750 measurement system, as specified by the manufacturer, are given in Table N.1.

Table N.1. Manufacturer's Precision and Resolution Claim for the LMS-750 Measurements

	Precision	Resolution
Level Measurement System	0.06 cm	0.06 cm
Temperature Measurement System	0.2°C	0.2°C

N.1.2 Test Protocol

The important features of the LMS-750 test method are summarized in Table N.2. The test protocol defined by the manufacturer in [N-1] and followed in this evaluation requires that the product level be brought to approximately 90% of tank capacity a minimum of 2 h prior to testing. The test, 6 h in length, is begun as soon as the equipment is installed.

Table N.2. Important Aspects of the LMS-750 Test Protocol

Sampling Period	26 s
Test Duration	6 h
Waiting Period after Addition	2 h
Test Type/Product Level	Underfilled Tank/90% capacity

N.1.3 Data Analysis

Product level and temperature are sampled 48 times every 26 s, and an average is calculated to represent that data set. The average of each product-level data set is converted to a volume by multiplying the height value by a scale factor (HtoV), which is determined from a tank chart. This volume is compensated for thermal effects using the temperature data collected during the test.

Thermal expansion or contraction of the product, ΔTV, is estimated from

$$\Delta TV = C_e V \Delta T \qquad \text{(N.2.1)}$$

where C_e is the coefficient of thermal expansion, V is the volume of product in the tank, and ΔT is the change in temperature.

Six temperature-compensated values from six data sets are used to perform a least-squares linear fit. A coefficient of determination (the square of the correlation coefficient) is calculated in order to determine whether the data collected for that group of six sets are acceptable or not. These calculations are performed every hour, producing six leak rate values. An average temperature-compensated value of the six data sets represents a 2.6-min group, if the data are acceptable. Otherwise, the value for that group is replaced with the value of the most recent group. The difference between the temperature-compensated volume at the beginning and end of each hour results in the leak rate for that hour. The average of the six values at the end of the test is reported as the final leak rate.

N.1.4 Detection Criterion

A tank is declared leaking if the flow rate as determined by the test is greater than a threshold of +/- 3.785 L/h (1 gal/h). If the flow rate is less than the threshold and the coefficient of determination is greater than 0.85, the tank is determined to be leaking. At these low flow rates, no rigid specification of the leak rate is made but, rather, a recommendation is made to perform a precision volumetric test to confirm the indication. If the leak rate is less than 3.785 L/h but is not zero, and if the coefficient of determination is less than 0.85, the test is considered invalid.

N.1.5 Mathematical Model

While the description provided above is sufficient to identify the key features of the LMS-750 as it was evaluated, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [N-1].

N.2 Improving System Performance

The LMS-750 system can realize significant performance improvements if instrumentation capabilities are enhanced.

Changes to the test protocol and the data analysis algorithm could also result in an improved ability to detect small leaks. These improvements, which may require substantial modifications, should be approached from the standpoint that they will have to comply with regulatory standards which may be promulgated in the future.

N.2.1 Instrumentation

The precision of both the temperature and height sensors can be significantly improved. Based upon the calibration analyses performed during the Field Verification Tests, a volume rate no smaller than 8.7 L/h could be detected with a P_D of 0.99 and a P_{FA} of 0.01. Improving the height precision (or the volume rate attributable to height precision) by a factor of 2 could reduce the minimum detectable leak rate by roughly half, bringing the expected performance into relatively close agreement with the current claim of 3.875 L/h. This reduction in detectable leak rate may also be achieved by raising the level at which the test is conducted so that the free surface area (and thus the height-to-volume coefficient) is reduced by half. This practice would not be inconsistent with conducting a test with the tank at full capacity, provided that a reasonable degree of confidence in the height-to-volume coefficient can be maintained.

N.2.2 Test Protocol

Errors due to structural deformation and inadequate temperature compensation can be minimized by increasing the waiting time between filling the tank and initiating a test. Obviously, the optimum waiting time for structural deformation will be site-specific. However, analyses conducted at the Test Apparatus suggest that thermal compensation will be difficult to achieve sooner than 12 h after product addition.

The 2-h waiting period after topping may be too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. The 2-h waiting period is long enough to minimize the temperature-induced effects for many testing situations. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

N.2.3 Analysis

The effect of the analysis algorithm employed by the LMS-750 as defined in [N-1] is difficult to ascertain without performing the simulation, but a few generalizations can nevertheless be made. By performing replacement of uncorrelated data as defined in [N-1], the system may be removing data and possibly degrading performance by effectively reducing the system resolution. It is recommended that the LMS-750 system not replace data, but rather employ either an averaging or least-squares type of analysis over all data collected. The manufacturer should also be aware that the algorithm for declaring whether the tank is leaking is biased in that it declares that an inflow is not a leak.

N.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

O.1 The MCG-1100 Test Method Description

The MCG-1100 is a volumetric leak detection system capable, according to the manufacturer, of detecting leaks as small as 151 ml/h (0.04 gal/h). The MCG-1100 method determines a thermally compensated leak rate in an overfilled tank. Product level is above grade and is maintained constant during a test.

O.1.1 Instrumentation

The MCG-1100 system utilizes a microprocessor-based data acquisition system to digitally monitor product level and temperature. The precision and resolution of the MCG-1100 measurement system, as given by the manufacturer, are presented in Table O.1. The product-level measurement system, situated outside the tank, consists of three interconnected units: the level-control chamber, the fill chamber, and the by-pass chamber. The level-control chamber is attached directly to the tank by means of a fill tube extension so that product may be filled to a level above grade. Both the fill chamber and the by-pass chamber are connected by means of tubing to the level-control chamber and electronically to the MCG-1100 electronics box.

The level-control chamber is set up so that product is continually released into the by-pass chamber at a predetermined rate. If the product level decreases, the float in the level-control chamber opens a passage allowing product to enter from the fill chamber. A needle valve is manually set to a predetermined minimum flow rate, allowing product to flow from the level-control chamber to the by-pass chamber. The minimum flow rate is determined from temperature measurements taken prior to the test.

Product level is measured both in the fill chamber and the by-pass chamber by a sensing board, located on the outside the chambers. This board monitors the movement of a magnetic float in response to level changes the chambers. Temperature is measured using five thermistors located at the volumetric centers of five equal volumes.

Table O.1. Precision and Resolution of MCG-1100 Measurements

	Precision	Resolution
Product Level	3.17 mm	3.17 mm
Temperature	0.0028°C	0.00056°C

O.1.2 Equipment Setup and Test Preparations

The test crew typically took 1.5 h to set up the equipment and prepare for the first stage of the test protocol. This assumes that the product level is satisfactory for the conduct of a test.

O.1.3 Test Protocol

The important features of the MCG-1100 test protocol are summarized in Table O.2. Test protocol requires that the tank be filled up to the base of the fill tube a minimum of 2 h prior to testing. Upon the arrival of the test personnel at the site, the product level is brought above grade in two stages. In the first stage, the tank is filled to 38 cm (15 in.) above grade. Product level is then observed to assure that the tank has stabilized. The tank is considered stabilized if the level does not drop below 10 cm (4 in.) above grade in the ensuing 30-min period. If it does, the level is again raised to 38 cm above grade and monitored. This step is repeated until the level remains above 10 cm for a period of 15 min. In the second stage, product is brought to a level 122 cm (48 in.) above grade and is monitored for a minimum of 1 h. If the level drops below 107 cm above grade, product is added to bring the level back to 122 cm. To complete the second stage, the change in volume for each of three consecutive 15-min periods must be less than 0.3785 L (0.1 gal). Otherwise, additional waiting periods in increments of 15 min ensue until such time as the change-in-volume criterion has been satisfied. Once the second stage is completed, normally within 1 to 3 h from the start of the first stage, the level is brought to 46 cm (18 in.) above grade. A 15-min wait ensues, and the test may then commence.

Table O.2. Important Aspects of the MCG-1100 System Test Protocol

Sampling Period	1 h
Test Duration	1 h
Waiting Period after Addition	2 h
Waiting Period after Topping Off	Variable
Test Type/Product Level	Overfilled Tank/Constant (Above Grade)

O.1.4 Data Analysis

A thermally compensated volume rate is computed from the product-level and product-temperature measurements sampled at the beginning and end of the 1-h test. Each sample comprises five measurements averaged over a 2-s period. The measured level changes are converted into volume changes by multiplying by the cross-sectional area of each chamber.

The thermal expansion and contraction of the product, ΔTV, is estimated using

$$\Delta TV = C_e V \Delta T \tag{O.2.1}$$

where the rate of change of temperature, ΔT, is estimated from the volumetrically weighted average of five thermistors; the total volume, V, of the product in the tank is determined using a tank chart; and a value of the coefficient of thermal expansion, C_e, for the product is determined using the specific gravity measured with a hydrometer and adjusted to 15.6°C (60°F) using API Table VI-B. The leak rate, LR, is calculated from

$$LR = \Delta VF - \Delta VB - \Delta TV \qquad (O.2.2)$$

where ΔVF is the rate of change of volume in the fill chamber, ΔVB is the rate of change of volume in the bypass chamber, and ΔTV is the thermal expansion and contraction of the product as calculated in Eq. (O.2.1).

The flow rate from the level-control chamber to the by-pass chamber is determined using thermal data obtained during the first 15 min of the 30-min period prior to the test. The flow rate is manually set to a rate 20% greater than the expected thermal change as estimated using Eq. (O.2.1) for the 15-min period. The flow rate setting is not to be less than 75.7 ml/h.

The test is successful if the set flow rate to the by-pass chamber is not less than the measured thermal change. Unless this criterion is satisfied, the test is not valid and must be performed again.

O.1.5 Detection Criterion

A leak is declared if the measured temperature-compensated volume rate for the test period exceeds +/- 151 ml/h (0.04 gal/h).

O.1.6 Mathematical Model

While the description provided in Section O.2 is sufficient to identify the key features of the MCG-1100 as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical mode of the system was developed based on the more detailed description of the test method provided in [O-1]. After it had been validated, this model was used to estimate the performance of the method.

O.2 Improving System Performance

The two major problems that exist in the MCG-1100 system, as it was evaluated, can be remedied through protocol adjustments and require no changes to the instrumentation. An improvement in performance can also be achieved by making alterations to the analysis.

O.2.1 Protocol

The following protocol changes are recommended:

- o Wait 6 to 12 h or longer after product delivery
- o Sample the temperature data every 3 min

- o Relevel the product at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank and maintain constant product level during the waiting period

The 2-h time period between product delivery and the start of a test is not long enough for the tank to become thermally quiet, thus precluding adequate thermal compensation. Experiments at the Test Apparatus have shown that a period of up to 12 h is required before a system can adequately perform thermal compensation. It is evident, therefore, that significant improvement could be obtained by lengthening the waiting period before a test.

The largest error present in the MCG-1100 system is the systematic error caused by structural deformation. Raising the product level and then lowering it so that deformation effects cancel out may work for some tanks, but because there is no systematic approach to verifying that the cancellation has occurred, the system is very susceptible to deformation effects arising from the large level changes. If the protocol were adjusted so that product level was raised once and then kept constant, it would be necessary only to determine when deformation effects from the initial product-level change had subsided. A detailed analysis of the data over a sufficient period of time would be required to ascertain the relaxation constant of the tank so that an appropriate waiting period could be defined. Available data suggest that a period of 4 h would be required for stability to be achieved in the Test Apparatus tank. Distortion of the tank's temperature field, caused by topping off the tank, could also be diminished by an appropriate waiting period.

O.2.2 Analysis

It is recommended that the temperature-compensated volume rate be computed from the data taken at the recommended higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and 20 temperature measurements to estimate the thermal volume change, the performance could improve by as much as 100%.

O.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

P.1 The Mooney Test Method Description

The Mooney Leak Detection System estimates a temperature-compensated volume rate from measurements of product level and product temperature in an overfilled storage tank. Test length (1 h) and data sample rate are constant.

P.1.1 Instrumentation

Volumetric changes are determined by measuring product height changes with a mechanic's ruler. A known volume of product (0.47 L (0.125 gal)) is added to the tank before the test in order to empirically determine the scale factor relating change of product level to change of volume. Height measurements are then made at 15-min intervals by inserting the ruler into the product and recording the results.

Temperature is measured by five thermistors placed at the volumetric vertical centers of five equal volumes. The thermistors are checked in a bath to determine that the resistance values are in the right range, but they are not calibrated. The ohmmeter is checked with a 10,000-Ω plug.

The precision and resolution of the Mooney measurement system as given by the manufacturer are presented in Table P.1.

Table P.1. Precision and Resolution of the Mooney System as Specified by the Manufacturer

	Precision	Resolution
Height Measurement	0.05 cm	0.05 cm
Temperature Measurement	0.0014°C	1 Ω at 720 Ω/°C

Both volumetric and temperature data are sampled at 15-min intervals. The product height is measured with the mechanic's ruler twice at each 15-min mark, with the two samples taken 1 min apart; after each sample has been read by two test personnel, the four readings are averaged. The temperature data are read as the resistance from a digital ohmmeter.

P.1.2 Test Protocol

Test protocol requires a 12-h wait between the filling of the tank and the commencement of the test. It may be necessary to add product to the tank in order to raise the liquid level to the top of the fill tube. In such cases, an additional waiting period of 5 min per 2.54 cm (1 in.) of added head is required after topping off the tank. This waiting period is not to exceed 30 min unless the change in product level is greater than 0.318 cm (0.125 in.) during the last 10 min of the waiting period, in which case an additional waiting period of 15 min is required. Salient aspects of the test protocol are presented in Table P.2.

Table P.2. Important Aspects of the Mooney System Test Protocol

Sample Period	15 min
Test Length	1 h
Number of Samples per Test	5
Test Start after Filling Tank	12 h
Test Start after Topping Off Tank	Variable (5 to 54 min)
Test Type	Overfilled Tank

P.1.3 Data Analysis

Data are obtained by sampling every 15 min for 1 h, thereby collecting five data points per sensor per test. Only product level and temperature data are collected. Product level is sampled twice at the 15-min mark. Temperature and product-level data are differenced to obtain the change in quantity of fluid per 15-min sampling interval.

Compensation for evaporation effects is performed by measuring the evaporation of product from an evaporation cup placed in the fill tube. The amount of change in product level within the evaporation cup is used to compensate for evaporation effects.

The coefficient of thermal expansion (C_e) is obtained from the station owner and is verified by determining C_e from a specific gravity measurement and the manufacturer's tables; the volume of the tank is determined from a tank chart. The change in volume due to thermal effects is calculated and is then subtracted from the measured volume change for each period, as shown in the equation

$$\text{Thermal volume change} = \Delta TV = \Delta T C_e V \qquad (P.2.1)$$

where ΔT is the change in temperature, C_e is the coefficient of thermal expansion, and V is the volume of product in tank at beginning of test. The average compensated change in volume per 15-min period is shown by

$$\Delta V_{comp} = \Delta V_{measured} - \Delta TV \qquad (P.2.2)$$

$$\Delta V_{compavg} = \sum_{i=1,4} \frac{\Delta V_{comp(i)}}{4} \qquad (P.2.3)$$

P.1.4 Detection Criterion

If the leak rate as determined by the test is within +/- 0.076 L/h (0.02 gal/h) of the 0.19-L/h (0.05-gal/h) leak rate criterion, it is possible that the tank is leaking, and another test is required for confirmation. If the average of the two tests is greater than 0.19 L/h, the tank is considered leaking.

P.1.5 Mathematical Model

While the description provided in Section P.2 is sufficient to identify the key features of the Mooney System as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [P-1]. After it had been validated, this model was used to estimate the performance of the method.

P.2 Improving System Peformance

The Mooney Leak Detection System as defined in [P-1] can realize substantial performance improvements without hardware modification.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 5-min to 54-min waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

P.2.1 Protocol

The following protocol changes are recommended:

- o Sample the temperature data at least every 3 min
- o Relevel the product at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

Releveling the product represents the most significant performance improvement that can be achieved by the Mooney Leak Detection System. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 80%.

P.2.2 Analysis

It is recommended that the temperature-compensated volume rate be computed from the data taken at the recommended higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and 20 temperature measurements to estimate the thermal volume change, the performance could improve by as much as 100%.

P.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

Q.1 The OTEC Test Method Description

The OTEC Leak Sensor is a volumetric leak detection system capable, according to the manufacturer, of detecting leaks as small as +/-0.189 L/h (0.05 gal/h) that occur in the walls or product distribution lines of an underground storage tank. For the performance results described in this report, it was employed as a precision (volumetric) leak detection test operating in an underfilled tank.

Q.1.1 Instrumentation

The OTEC Leak Sensor uses two measuring devices, a float and a detector rod, both of which measure product level, to estimate a temperature-compensated flow rate.

Calculations show that the buoyant force acting on a partially submerged object will be independent of changes in liquid density if the ratio of displaced volume to displaced surface is equal to the ratio of total liquid volume to total liquid surface. A float that is tapered at the upper end can be submerged so as to match the volume-to-surface ratio in a horizontal cylindrical tank filled to any level. Changes in buoyant force on such a float will therefore reflect changes in tank inventory, since the buoyant force is independent of density.

The position of the conical float, which is measured over a period of time, is related to the volume changes by means of the phenomenon that supports a negatively buoyant member in a liquid. The float assembly is dependent on the size and type of the tank. A conical float shell is selected from a group of floats of varying length suitable for a variety of tank sizes. The conical float's length and weight are chosen based on the diameter of the tank, the height of product in the tank, and the density of the test product. These measured values are determined prior to the test.

The detector-rod assembly consists of a photoelectric cell and the conical float attachment. The movement of the conical float forces an ink solution into or out of the photocell, and the resulting change in light transmittance in the photocell causes a voltage drop across the cell. This voltage change, which is a function of the product-level change, is measured by a voltmeter that has been calibrated prior to the test.

Volumetric changes are determined by monitoring product height changes with the conical float. The conical float senses these liquid-level changes in the tank, and the detector rod measures the relative position of the float with respect to the photocell. The data are recorded on a strip chart.

The manufacturer's claimed precision and resolution of these measurements are summarized in Table Q.1, and were experimentally verified at the UST Test Apparatus in Edison, New Jersey during the Field Verification Tests.

Table Q.1. Manufacturer's Precision and Resolution Claim for the OTEC Sensor Measurements

	Precision	Resolution
Product Level	0.0001 cm	0.0005 cm

Q.1.2 Equipment Setup and Test Preparations

The manufacturer indicated that it would take approximately 1 h to install the equipment and prepare for the start of the test. This assumes that the product level is satisfactory for the conduct of a test.

Q.1.3 Test Protocol

The important features of the OTEC test protocol are summarized in Table Q.2. Test protocol requires that the tank be filled to 50% to 100% of capacity. There is a waiting period of at least 4 h between the filling of the tank and the start of a test (i.e., calibrations), so as to allow the temperature of the product in the tank to stabilize. If the tank is not filled to capacity, a 1/3-hp pump is used to spray product into the vapor space in order to saturate it during the 1-h period immediately preceding data collection. The 1-h period is the approximate time required to complete this procedure in a 30,280-L (8,000-gal) tank. Instrumentation warm-up and calibration also take place during this time. Calibration and testing continue at 1-h intervals until two consecutive readings give the same calculated (leak rate) result, or until a 3-h maximum test period has been completed.

Table Q.2. Important Aspects of the OTEC Test Protocol

Sampling Period	1 h
Test Duration	3 h (maximum)
Waiting Period after Addition	4 h
Test Type/Product Level	Underfilled Tank/50% to 100% of capacity

Q.1.4 Data Analysis

A thermally compensated volume change is computed from the change in the height of a weighted float immersed at the null point of the tank where thermal changes are exactly offset by buoyancy forces. Data are obtained by sampling once per hour over the duration of the test. The voltage change over the 1-h period is converted to volume by multiplying by a conversion factor determined from the calibrations made before the test.

A tank chart, supplied by the tank manufacturer, is used to convert product-level measurements to volume. Height-to-volume conversion is accomplished by using linear interpolation between pairs of data points tabulated at 2.54-cm (1-in.) intervals of tank depth.

All tests are considered successful providing that data are collected for the entire duration of the test period, and that the appropriate initial waiting period is observed. A test is considered successful when two consecutive 1-h tests give the same calculated result, or when the 3-h maximum test period has been completed. The reported leak rate is that computed over the last 1-h testing period.

Q.1.5 Detection Criterion

A leak is declared if the thermally compensated volume rate derived for the test period exceeds a threshold of +/-0.189 L/h (0.05 gal/h). If the flow rate is less than the threshold, the tank is declared nonleaking.

Q.1.6 Mathematical Model

While the description provided in Section Q.2 is sufficient to identify the key features of the OTEC system as it was evaluated, and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [Q-1]. After it had been validated, this model was used to estimate the performance of the method.

Q.2 Improving System Performance

The OTEC system was not evaluated because the above-ground tanks used to heat and cool product was left open during the Field Verification Tests. Nevertheless, a systematic investigation of the OTEC system should be made. There are two sources of error that should be investigated: the implementation of the float system for temperature-compensation and the effect of spraying product into the vapor space before the test. Theoretically, the float system will be subjected to errors whenever the rate of change of temperature is not vertically uniform. Experimental data taken during the ambient noise experiments at the Test Apparatus suggest that any disturbance to the vapor space during a partially filled test can degrade performance unless these efects are allowed to subside. The effect of spraying product into the vapor space was not evaluated.

R.1 The PACE Test Method Description

The PACE Leak Tester is a volumetric test capable, according to the developer, of detecting leaks as small as 0.237 L/h (0.063 gal/h). The PACE apparatus is temporarily installed at the fill hole of a tank. The test is normally conducted only when dispensing operations have been suspended. For the tests described in this report, the protocol in [R-1] was employed.

R.1.1 Instrumentation

The PACE Leak Tester system uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of a dip-tube manometer, and product temperature as determined by three temperature probes.

Volumetric changes are determined by monitoring product-level changes in a dip tube. This measuring device consists of two units: a dip tube mounted in the tank, and a measuring rule (dipstick) located inside the dip tube. The dip tube, measuring approximately 150 cm in length and 2.54 cm in diameter, is welded into a cap that has been threaded to fit the fill tube in such a way that the dip tube extends approximately 5 cm above the top of the fill tube. The dip tube extends below the product level in the tank, and product-level changes are measured on the dipstick.

Once the tank has been filled to within 30 to 45 cm of the top of the fill tube, all vents and openings to the tank are sealed except for the fill hole fitted with the dip tube. This creates a vapor space between the product level and the cap. The dip tube now provides the only access to the storage tank during testing, and sealing the system in this manner causes the dip tube to behave like a manometer. Any product-level changes within the tank produce an amplification of the height change in the dip tube, a phenomenon due to the pressure difference between the atmosphere and the vapor space in the fill tube.

To determine height changes, product level is monitored by means of the dipstick. This is accomplished by notching the dipstick and measuring the distances between notches at the conclusion of the test.

Temperature is measured with three thermocouples (probes) placed at the vertical centers of three equal volumetric slabs at the dip tube location.

A height-to-volume (HtoV) calibration, performed just before the start of a test, is done by removing a known volume of product from the fill tube (0.237 L) and measuring the corresponding height change.

The stated precision and resolution of the measurement systems used in the PACE Leak Tester are summarized in Table R.1.

Table R.1. Precision and Resolution of PACE Measurements

	Precision	Resolution
Product Level Measurement	0.318 cm	0.159 cm
Temperature Measurement	0.006°C	0.006°C

R.1.2 Equipment Setup and Test Preparations

Equipment deployment in the tank, because of the nature of the test, requires extensive purging and bleeding of vapor from the tank risers. Normal equipment installation requires approximately 1 h, after which calibration checks and testing may be initiated. This assumes that a product level satisfactory to testing has been established.

R.1.3 Test Protocol

The important features of the PACE Leak Tester are summarized in Table R.2. The test is carried out in a storage tank that has been overfilled into the fill tube. It consists of three half-hour segments (experiments), resulting in a total test duration of 1.5 h.

An experimental leak rate (flow rate) is obtained for each experiment (i.e., each segment). At the conclusion of the test (i.e., 1.5 h from the start), the three experimental flow rates are statistically analyzed to arrive at a flow rate for the test. The test duration, experiments, and sampling intervals are constant.

Test protocol requires a wait of at least 12 h between the filling of the tank and the start of a test. Prior to testing, the tank is filled to a level within 35 to 40 cm of the top of the fill tube.

Table R.2. Important Aspects of the PACE Leak Tester

Sampling Period	30 min
Test Duration	90 min
Waiting Period After Addition	12 h
Test Type/Product Level	Overfilled Tank/Below grade

R.1.4 Data Analysis

A temperature-compensated volume rate is computed from the measured height and temperature data. The measured height changes are converted to gross volume changes by the calibration tests which are performed prior to each 0.5-h experiment. For each experiment, the thermal volume change calculated from the measured temperature change is computed. The thermal expansion and contraction of the product, ΔTV, is estimated from

$$\Delta TV = C_e V \Delta T \qquad (R.2.1)$$

where the rate of change of temperature, ΔT, is estimated from the three thermistor arrays; the volume, V, of the product in the tank is estimated from the developer's tank chart; and the value of the coefficient of thermal expansion of the product, C_e, is 0.00108/°C (0.00060/°F). This volume is then subtracted from the gross volume change to obtain a temperature-compensated volume rate. The procedure is repeated for each of the three experiments. The results of the three experiments are then analyzed statistically to determine whether the test is successful and, if so, the mean and standard deviation of the leak rate.

R.1.5 Detection Criterion

A leak is declared if the mean flow rate (i.e., the temperature-compensated volume rate) is greater than 0.237 L/h. If the flow rate is less than this value, the tank is declared nonleaking.

R.1.6 Mathematical Model

While the description provided in Section R.2 is sufficient to identify the key features of the PACE Leak Tester as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method in [R-1]. After it had been validated, the model was used to estimate the performance of the method.

R.2 Improving System Performance

The PACE Leak Tester system defined in [R-1] can realize performance improvements. These improvements are discussed in terms of changes to the instrumentation, protocol and data analysis.to not appear to validate these predictions.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 0-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

R.2.1 Instrumentation

The largest source of error is the volumetric noise created by excessive structural deformation. This is a direct result of the small diameter of the fill tube. While decreasing the tube diameter tends to increase the gain of the height measurement, it also increases the magnitude of changes in the hydrostatic head, which increases the structural deformation and volumetric noise. At some point, the volumetric noise increases so much that the gain in the height measurement does nothing to increase the performance of the system.

If the developer were to use a larger tube diameter, such as 7.6 cm, volumetric noise would be greatly reduced, while an acceptably small level of instrumentation noise would still be maintained. Using the parameters from Section R.5.3.1 with a 7.6-cm diameter tube, the standard error in the volume measurement is 7.29 ml/h. This gives a minimum detectable leak rate (based on instrumentation) of 163 ml/h, 2 ml/h greater than with the 2.54-cm diameter tube. Although, due to the same interaction, error will still be present, the developer can eliminate or minimize it by keeping product level constant. This approach is discussed in the body of this report.

Performance improvement could be achieved by adding more thermistors to improve spatial sampling of the vertical temperature field. Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 30% performance improvement could be achieved by increasing the number of thermistors from three to five.

R.2.2 Protocol

The following protocol changes are recommended:

- Sample the temperature data every 3 min
- Relevel the product at 15-min intervals or less and record the volume changes
- Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

Releveling the product represents a significant performance improvement that can be achieved by the PACE Leak Tester. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 80%.

The PACE Leak Tester system could be further improved by increasing the sample rate for temperature measurements. This would ensure that internal waves in the tank were not being aliased into the measurement. Sampling temperature every 3 min is recommended in the case of 7-min internal waves.

In addition to more frequent temperature sampling, there could be an extra waiting period of 4 h after the height calibrations are performed. Topping off the tank prior to testing may cause the local temperature field (below the fill tube) to become unrepresentative of the rest of the tank. This requires an additional wait of 4 h after topping off the tank.

R.2.3 Analysis

It is recommended that the temperature-compensated volume rate be computed from the data taken at the recommended higher sample rates using least-squares techniques. If four volume measurements were used to estimate the volume-rate change and 20 temperature measurements to estimate the thermal volume change, the performance could improve by as much as 100%.

R.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

S.1 The Petro Tite Test Method Description

The Petro Tite leak detection system uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of a graduated cylinder, and product temperature as determined by a temperature probe. For a 30,000-L (8,000-gal) storage tank, the testing period consists of four phases with a total duration of 400 min. Test duration and sampling intervals are constant. The test is carried out at two levels in a storage tank that has been overfilled into the fill tube extender so that the product level is approximately 70 cm above grade in the first level and 30 cm above grade in the second. These levels are dependent on the height of the water table and relative height of the fill tube extender (standpipe) above grade. If the water table is high enough that it exerts pressure on the tank, enough product is added to bring the level in the fill tube to the equivalent of dry soil conditions.

S.1.1 Instrumentation, Equipment Setup and Test Preparations

The precision and resolution of the Petro Tite measurement system as given by the manufacturer are presented in Table S.1.

Table S.1. Precision and Resolution of the Petro Tite System as Specified by Manufacturer

	Precision	Resolution
Level Measurement	0.00095 L	0.0189 L
Temperature Measurement	0.000031°C	0.000031°C

There are four phases in a Petro Tite Test: (1) create circulation in the product to produce a uniform temperature throughout the tank; (2) sample the product to obtain a coefficient of thermal expansion; (3) perform the high-level test; and (4) perform the low-level test.

13.1.1 Phase 1 - Circulation

During the first phase of the Petro Tite test, a circulating (jet) pump draws product by means of a suction tube from an area at least 15 cm (6 in.) below the top of the tank. The product is discharged, under pressure of approximately 1.76 kg/cm^2 (25 psi), through a discharge hose into sections of tubing which have been coupled together to form an outlet nozzle at the bottom of the tank. This nozzle is adjusted so as to be above any water at the bottom of the tank and below any drop tube that may be present. The nozzle is directed at a 45° angle upwards from the center line of the longitudinal axis of the tank. This suction and nozzle system creates a vortex-like swirling motion in the tank in an attempt to produce a uniform (homogeneous) temperature throughout its contents. At the same time, the operator is making visual observations for above-grade and gross system leakage. The duration of this phase is based on the viscosity and volume of product in the tank, i.e., 5 to 8 min per 3,800 L (approximately 5 min for light fuels such as gasoline and 8 min for heavy fuels such as diesel) or until predictable thermal readings are achieved. After the completion of Phase 1, circulation continues throughout the duration of the test.

13.1.2 Phase 2 - API Sample

The second phase requires the operator to obtain a sample of the product, which is tested for the purpose of determining its coefficient of expansion. During this phase the jet pump is shut down for approximately 30 s to prevent air from being sucked in by the pump while the sample is being removed through a bleed valve.

13.1.3 Phase 3 - High-Level Test

The third phase requires the operator to take periodic thermal and product-level measurements based on the diameter of the tank, as shown in Table S.2. During this phase the operator is making visual observations for changes or fluctuations in product volume due to structural deformation, thermal stabilization due to circulation (Phase 1) and/or vapor pockets. The sampling interval is every 15 min, so for a large tank requiring 12 measurement readings, Phase 3 could last as long as 3 h.

Table S.2. Number of Readings Required for High-Level Test

Tank Diameter (m)	Number of Readings
1.22	4
1.63	4-6
1.83	6
2.13	6-8
2.44	8
2.59	8-10
2.74	10
3.05	10-12
3.25	12

13.1.4 Phase 4 - Low-Level Test

At the start of the low-level test, which is Petro Tite's precision test, the product level in the fill tube extender is dropped to approximately 30 cm above grade, with product volume and thermal changes being recorded every 15 min. Volumetric changes are determined by monitoring the product height changes in the fill tube extender. This is done by means of a 3.785-L (1-gal) graduated cylinder that measures the amount of product added or drained to maintain a constant product level.

S.1.2 Test Protocol

Test protocol requires that the tank be filled to a level above grade so as to achieve the same testing conditions as for dry soil. The procedure for achieving the correct height is based on the external pressure exerted on the tank by the surrounding water table; nominal testing pressure is 0.28 kg/cm^2 (4 psi). There is no waiting period between the filling of the tank and the commencement of a test. Important aspects of the protocol are shown in Table S.3.

Table S.3. Important Aspects of the Petro Tite Test Protocol

Sampling Period	15 min
Duration of Equipment Setup	15 min
Duration of Phase 1	Variable within 5 to 8 min per 3,800 L
Duration of Phase 2	Variable
Duration of Phase 3	60 to 180 min
Duration of Phase 4	60 min
Total Test Duration	400 min
Number of Samples per Sensor per Experiment	2
Test Start after Filling Tank	0 min
Waiting Time after Product Addition	0 min
Test Type/Product Level*	Overfilled Tank/Constant

*Product level is kept constant during any one phase of testing

S.1.3 Data Analysis

A thermally compensated volumetric flow rate is computed from the product-level and product-temperature measurements obtained by sampling once every 15 min. One data point is collected for each sensor at the start of the test and one at the end. Temperature and volume are differenced to obtain the change in volume and change in temperature per sampling interval, with the result representing the total change in temperature and volume through the duration of the experiment.

The coefficient of thermal expansion is determined by the operator from API gravity tables, and the tank volume from strapping charts. Change in volume is calculated according to the equation

$$\text{Thermal volume change} = \Delta TV = C_e V \Delta T \qquad (S.2.1)$$

where C_e is the coefficient of thermal expansion of the test liquid, V is the volume of product in the tank at the start of the test, and ΔT is the change in temperature.

The flow rate reported as the test result is the sum of four consecutive experimental flow rates, each of which represents the thermally compensated volume change divided by the duration of the experiment as shown in the equation

$$LR = \frac{\Delta V - \Delta TV}{\Delta t} \qquad (S.2.2)$$

where LR is the flow rate, ΔV is the change in product volume, and Δt is the duration of the experiment (15 min).

S.1.4 Detection Criterion

A tank is declared leaking if the flow rate as determined by the test is greater than a threshold of -0.189 L/h (0.05 gal/h). If the flow rate is greater than the threshold and is also positive, the test is considered invalid, since the nature of the test design precludes the detection of inflowing (positive) leaks.

S.1.5 Mathematical Model

While the description provided in Section S.2 is sufficient to identify the key features of the Petro Tite system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [S-1]. After it had been validated, this model was used to estimate the performance of the system.

S.2 Improving System Performance

The Petro Tite system could realize performance improvements if alterations were made to the test protocol and data analysis. No major design modification is required.

S.2.1 Protocol

The manufacturer could improve the performance of the Petro Tite system by lengthening the high- and low-level tests. Structural deformation of the tank can cause testing errors. The duration of the high-level tests is too short, unless the tank elasticity constant of the tank is small, as it was for the Test Apparatus tanks. This is also true of the low-level tests. If the tank elasticity constant were larger, as may be the case with other tanks, deformation could affect the test results. The effects of structural deformation had only minimal impact on this evaluation.

S.2.2 Data Analysis

Using least-squares techniques to estimate the leak rate would maximize the information obtained from the 15-min sample interval.

S.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

T.1 The PSLD Test Method Description

The PSLD system measures product level, product temperature and ambient pressure, which are combined to determine a volumetric leak rate. The PSLD system is a self-contained unit which is deployed by a technician in a customer's tank for data collection and is retrieved the following day for analysis. The technician at the site conducts no analysis of test data. Rather, the raw data are transmitted to a central processing facility where a staff of technical analysts examine the results in detail. As such, no on-site operator intervention is required.

When the PSLD system is used to monitor product level, product may be added or removed during the data collection period, but the leak rate is determined during a "quiet" period. When the PSLD system is used as a precision leak test, however, product additions and deletions are not allowed during the test period. It is the latter mode which this evaluation addresses. The manufacturer describes this as an overfilled or nearly filled tank test. Although test length is variable this evaluation is for a 4-h test. The manufacturer of the PSLD system did not claim a detectable leak rate.

T.1.1 Instrumentation

The product-level measurement system consists of a 4.445-cm (1.750-in.) diameter float located inside a 4.458-cm (1.755-in.) diameter fiberglass tube. Conversion from height to volume is performed using the combined cross-sectional area of all open surfaces when the tank is overfilled, and the area at product level as obtained from a numerical integration of the tank dimensions when it is underfilled.

The temperature measurement system, nominally used in a 30,000-L (8,000-gal) tank, incorporates 16 RTD temperature sensors spaced at intervals of 20.32-cm (8-in.) on a 3.05-m (10-ft) rod. Temperature sensors are thus found both in the product and in the vapor space up to the top of the fill tube.

An absolute pressure sensor is located near the top of the fill tube in order to measure ambient pressure changes.

Table T.1 lists the instrumentation precision and resolution of the PSLD as given by the manufacturer.

Table T.1. Instrumentation Precision and Resolution as Given by the Manufacturer

	Precision	Resolution
Level Measurement	0.0013 cm	0.000254 cm
Temperature Measurement	0.0014°C	0.00277°C

T.1.2 Test Protocol

Test protocol specified for this evaluation requires that product be added immediately prior to the test to a level approximately 30.5 cm (12 in.) above the base of the fill pipe (as measured by a stick). The temperature of the product deposited is measured to within 0.5°C. Normally, a sample of product is subjected to a chromatographic analysis in order to evaluate the constituent properties of the fluid. The results are then used to determine the coefficient of thermal expansion, the bulk modulus, the coefficient of heat transfer, and the specific heat of the fluid being tested. The analysis to determine the leak rate is performed later, and a report is subsequently sent to the customer. For the Field Verification Tests, however, the sample analysis was performed prior to the tests so that the final leak rate could be calculated at the site.

An instrumentation check is conducted immediately preceding the test, which then proceeds in the following sequence. At a point 34 min after the start of the test, 550.6 ml (1 pint) of product are removed. At the end of the next 30-min period another 550.6 ml are removed; this is repeated twice more at intervals of 30 min. At the end of the fourth 30-min mark, 189 L (50 gal) are removed to bring the product to a level approximately 5.1 to 10.2 cm (2 to 4 in.) below the fill tube. Product level is then measured by means of a dipstick, and data are collected for a period of 1 h before the test is stopped.

The important features of the PSLD test method are summarized in Table T.2.

Table T.2. Important Aspects of the PSLD Test Protocol

Sampling Period	1 min
Test Duration	4 h
Waiting Period After Addition	0 h
Test Type/Product Level	Overfilled/Nearly filled Tank

T.1.3 Data Analysis

Rather than supplying the algorithms for obtaining the leak rate, the manufacturer supplied a "black box" set of code which was incorporated into the simulation for the evaluation of the PSLD method.

The PSLD system collects data at a rate of 10 Hz. The data are then filtered and wild points are removed. In the mathematical model of the system, however, data are sampled at a rate of 1/60 Hz, and the filtering scheme is not included.

T.1.4 Detection Criteria

A tank is declared leaking if the flow rate as determined by the test is greater than a threshold of +/- 0.189 L/h (0.05 gal/h). If the flow rate is less than the threshold, the tank is declared nonleaking.

T.1.5 Mathematical Model

The description provided above is sufficient to identify the key features of the PSLD system as it was defined by the manufacturer. The extensive number of product-level changes specified by the manufacturer were not included in the evaluation. The simulation was performed as an underfilled tank test because (1) the manufacturer did not follow his specified protocol during the Field Verification Tests, and (2) the code supplied by the manufacturer would have seen all of these product-level changes as possible leak rates.

T.2 Improving System Performance

Given the length of the PSLD test and the number of thermistors, the precision of the instrumentation in the PSLD system should have performed much more accurately than was observed. Therefore, it is suggested that there may be a problem in the data analysis. Because no information was supplied by the manufacturer concerning the algorithm employed to determine the leak rate, it is not possible to make specific suggestions for improving performance. However, general suggestions are made based on data obtained at the Test Apparatus and on the results of a canonical method study described in Section 10 of the report.

Since it appears that the PSLD system can be used as an overfilled-tank test, it is suggested that the manufacturer examine the discussion in the body of this report that deals with the error due to interaction of the volumetric noise sources in the fill tube. This causes the conversion from height to volume to be in error, even if a calibration is performed prior to the test. This evaluation did not examine the performance of the PSLD system as an overfilled-tank test.

T.2.1 Protocol

The following protocol changes are recommended:

- o Wait 6 to 12 h or longer after product delivery
- o Relevel the product at 15-min intervals or less and record the volume changes
- o Wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

Releveling the product represents the most significant performance improvement that can be achieved by the PSLD system. Releveling removes the deleterious effect of dynamic structural deformation described in Section 6 of the report. Eliminating the dynamic structural deformation would improve the performance of the system by approximately 100%.

T.2.2 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

U.1 The S.M.A.R.T. Test Method Description

The S.M.A.R.T. system determines a volumetric leak rate by measuring product-level change in an overfilled tank. The manufacturer assumes that temperature effects are automatically compensated for by the fact that pressure is measured from the base of the tank. The test length is variable within a maximum of 3 h.

U.1.1 Instrumentation

A differential pressure sensor located 7.62 cm (3 in.) from the base of the tank is used to measure changes in product level, accomplished by measuring the change in pressure needed to force air into the product. The change in pressure is converted to a volume change using a scale factor, HtoV, calibrated prior to the test. Since the manufacturer states that the measured pressure change is physically compensated for temperature effects, no temperature data are collected. The S.M.A.R.T. system contains another pressure sensor, located at the base of the tank, which is used to determine the ingress of water when the system is used as a tank monitor, but which is not incorporated in the precision leak detection calculations. Precision and resolution of the sensor as reported by the manufacturer are presented in Table U.1.

Table U.1. Precision and Resolution of the Product-Level Measurement System as Claimed by the Manufacturer

	Precision	Resolution
Product Level	0.019 cm	0.0254 cm

U.1.2 Equipment Setup and Test Preparation

Test protocol requires that the tank be filled to a level within the fill tube 12 h prior to the test. If, after the 12 h have elapsed, product level has dropped below the fill tube, more product can be added to the tank without an additional waiting period before the start of the test.

U.1.3 Test Protocol

The important features of the S.M.A.R.T. test method are summarized in Table U.2. The product level data are collected at non-periodic intervals during each hour, but the only data employed in the leak rate calculations are those collected at each hourly interval.

Table U.2. Important Aspects of the S.M.A.R.T. System Test Protocol

Sampling Period	1 h
Test Duration	1 h
Test Start After Filling Tank	12 h
Test Type/Product Level	Overfilled Tank/Below Grade

U.1.4 Data Analysis

The test lasts 1 to 3 h, with the difference between the first and last values over a 1-h period used to determine volume change for that period. If the absolute leak rate calculated during the first hour is greater than 0.189 L/h (0.05 gal/h), the test will continue for another hour. If the absolute leak rate calculated during the second hour still exceeds 0.189 L/h, the test will continue one more hour. In this case the leak rate determined during the third, or final, hour is the one reported as the test result. If the leak rate determined during either the first or second hour is less than 0.189 L/h, the leak rate determined during that hour is the one reported.

U.1.5 Detection Criteria

The tank is declared leaking if the absolute value of the calculated leak rate is greater than 0.189 L/h.

U.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the S.M.A.R.T. system and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [U-1]. After it had been validated, this model was used to estimate the performance of the method.

U.2 Improving System Performance

The S.M.A.R.T. system as defined in [U-1] can realize performance improvements. If the present approach is to be followed, a major change to protocol or instrumentation will be required, as discussed below. Another alternative would be to abandon the attempt to do automatic thermal compensation and to make temperature measurements instead. For a discussion of system performance for a range of methods measuring height in the fill tube and of the role of an array of thermistors, refer to the canonical study discussed in the body of the report.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

U.2.1 Protocol

The performance of the S.M.A.R.T. system can be improved by establishing a method for determining the length of the waiting period after topping off the tank. An adequate waiting period will ensure that the effects of structural deformation are negligible. While no algorithm for determining the length of the waiting period is presented here, a general discussion of structural deformation and how to determine its magnitude is presented in the body of the report.

U.2.2 Temperature Compensation

The claim that temperature compensation occurs automatically is incorrect when pressure measurements are made with the product at a level in the fill tube. The error is best illustrated by example. The following analysis is performed assuming that the temperature, density, and rate of temperature change throughout the tank are uniform. When measurements are made in a fill tube with a diameter of 10.16 cm, a temperature change of 0.01°C results in a level change of approximately 4.5 cm (362.4 ml). Because of the large volume of gasoline in a full tank, and the relatively small cross-sectional area of the fill tube, temperature changes result in large hydrostatic head changes compared to the small change in product density. In this example, with the initial product level 3 m above the pressure sensor, the measured gauge pressure changed by a factor of 0.015, and the density changed by a factor of 0.0000125. This demonstrates that the S.M.A.R.T. pressure measurements are not automatically compensated for temperature effects. Automatic temperature compensation is better approximated when the product level is below the fill tube. For example, at a level of 236 cm in the steel tank of the Test Apparatus, a 0.01°C change in temperature results in a product-level change of approximately 0.004 cm. Assuming the change could be measured precisely, the curvature of the tank walls would induce a 150-ml apparent product voidage error. At mid-tank, a 0.01°C change in temperature results in a product-level change of 0.0003 cm and an error of 133 ml. These estimates do not include any coupling effects due to structural deformation. This simple analysis indicates that thermal compensation cannot be performed by measuring pressure at the base of the tank when the product is in the fill tube. The induced error in automatic compensation can be reduced, but not eliminated, by testing in a partially filled tank.

If the automatic thermal compensation approach is to be retained, product level must be below the fill tube when test measurements are made. Given this situation, the S.M.A.R.T. system would be limited by its instrumentation resolution for a 1- to 3-h test. To improve performance the test could be lengthened or the instrumentation improved. If the test were lengthened, data could be averaged, thereby reducing the need for better instrumentation. The longer the test, the less stringent the resolution requirement becomes. Although the assumption that thermal compensation occurs automatically when pressure measurements are made is an erroneous one, the error is minimized when product is below the fill tube during testing.

U.2.3 Analysis

Because of the assumption that thermal compensation is automatic, system performance would not be improved by making changes in the analysis. If the protocol were changed such that the product level was below the fill tube during testing, a recommendation could be made that a more sophisticated algorithm (such as a least-squares fit) be employed to determine the flow rate.

U.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

V.1 The Tank Auditor Test Method Description

The Tank Auditor Leak Detection System is a precision volumetric leak detection system capable, according to the manufacturer, of reliably detecting leaks as small as 189 ml/h (0.05 gal/h). The test equipment is temporarily installed in a tank in order to perform the measurements. The test is done in an overfilled tank, and the resulting test data, obtained during a period in which dispensing operations have been suspended, are used to determine a temperature-compensated volume change in the tank.

V.1.1 Instrumentation

The Tank Auditor system gives computerized temperature and height measurements. The precision and resolution of these measurement systems, as reported by the manufacturer, are summarized in Table V.1. Product level is measured by monitoring the movement of a small buoyant displacer suspended in the liquid. The movement of this displacer is converted, via an RF transducer, to an electrical signal which can then be recorded. The magnitude of the transducer output is directly related to the motion of the displacer. Product level is converted to volume by inserting a bar of known volume into the product and recording the displacer/transducer response.

Temperature is measured by a single quartz thermometer probe located at the geometric vertical center of the tank during testing. The probe is suspended in the tank via a thin, weighted cable, and is not rigidly located spatially in the tank. The probe, consisting of a precisely manufactured quartz crystal, has a frequency of oscillation that is a precise function of temperature. Changes in product temperature result in changes in probe oscillation frequency, which are then converted and recorded by appropriate electronics.

Table V.1. Resolution of the Tank Auditor Leak Detection System

	Precision	Resolution
Level Measurement System	0.0133 cm	0.0018 cm
Temperature Measurement System	0.001°C	0.0001°C

V.1.2 Equipment Setup and Test Preparations

On the first day of testing, preparation of the tank and setup of the equipment took approximately 2 h. Progressively less time was required on subsequent days, as the test crew became more familiar with installation requirements for the test tank. On the second day, these preparations took 1 h, and on the third, 30 min. Preparation time included tank level adjustments required prior to initiating a test.

V.1.3 Test Protocol

The test consists of two phases. During the first phase, product-level and temperature measurements are made over a period of 1 h. During this period, total system integrity is tested, and the presence of leaks, tilting of the tank, vapor pockets, and tank deformation ascertained. After this time, the product level is reduced to approximately 2.5 cm above the tank top, and another 30 min of data are recorded. The low-level testing confirms the presence of vapor pockets, tilting, and leaks. The important features of the Tank Auditor Leak Detection System are summarized in Table V.2.

Table V.2. Important Aspects of the Tank Auditor Leak Detection System

Sampling Period	2 s
Test Duration	1.5 h
Test Duration of Phase II	0.5 h
Waiting Period after Addition	8 h
Test Type/Product Level	Overfilled Tank

V.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product-level and temperature measurements made during each phase of testing. For a complete test, a least-squares linear regression is performed on both the temperature and level measurements in order to assess the rate of change of the variables. Height changes measured during a test are converted to volume by means of periodic calibrations performed using displacement bars of known volume.

The change in volume due to thermal fluctuations is calculated by the equation

$$\Delta TV = C_e \, V \Delta T \qquad \text{(V.2.1)}$$

where ΔTV is the change in volume due to temperature change; the coefficient of thermal expansion of gasoline, C_e, is determined by API hydrometer measurements made on a sample of product removed from the tank; the volume of product in the tank, V, is determined by the tank manufacturer's chart; and the change in temperature, ΔT, is that measured by the temperature probe in the tank.

The compensated volume rate is calculated by subtracting the calculated thermal volume change from the gross volume change as indicated by the corresponding product height measurement, after converting that height to volume via the appropriate height-to-volume calibration coefficient.

V.1.5 Detection Criterion

A leak is declared if the calculated temperature-compensated volume rate exceeds a threshold of -189 ml/h (-0.05 gal/h). If the compensated volume rate is less than the threshold, the tank is declared nonleaking.

V.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the Tank Auditor Leak Detection system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [V-1]. After it had been validated, this model was used to estimate the performance of the method.

V.2 Improving System Performance

The Tank Auditor system could realize significant performance improvements without any hardware modifications.

The effects of topping are not included in the quantitative performance estimates made for this method, and as a consequence, the actual performance that would be achieved during actual testing would be less than the estimates presented in this evaluation. The 0-h waiting period after topping is too short to minimize the impact of the (1) spatial inhomogeneities and (2) structural deformation produced by the addition (or removal) of product to reach the level required to begin the test. A waiting period of at least 2 to 3 h is required to minimize the spatial inhomogeneities in temperature. This period is long enough to minimize the effects of a 7°C difference in temperature between the product in the tank and the product used to top the tank. A longer period may be required to minimize the deformation-induced product-level changes. This can present operational problems, because the time required to minimze the effects of deformation in some tanks may be 1 to 5 times (or more) longer than the time required to wait for the temperature effects to stabilize. The time constants of the Test Apparatus tanks, for example, are 2 to 3 h, which means that the minimum waiting period would be 6 to 9 h or longer; the waiting period would be longer if the deformation effects were large and more than three time contants were required for them to become small compared to the smallest leak to be detected. Since the temperature and deformation effects associated with topping are independent of each other, the protocol and/or analysis algorithm use to minimize this effect must address each disturbance. A single waiting period based on a maximum disturbance would adequately address the temperature instability. However, this may not suffice for the deformation effect.

V.2.1 Protocol

The recommended protocol changes incorporate procedures that were followed during the Field Verification Tests. A standardized test protocol should be developed that eliminates operationally induced variation in test performance.

The following protocol changes are recommended:

- wait 6 to 12 h or longer after product delivery
- relevel at 15-min intervals or longer and record the volume changes
- wait 3 to 6 h or longer after topping off the tank, and maintain constant product level during the waiting period

The system could be vastly improved by introducing a waiting period after the tank has been topped off with product. The volume measurement calibrations would be more accurate if performed at the end of this waiting period. The two-phase test protocol was not conducted during the field tests. If the two-level test is reinstituted, a waiting period should be introduced between the test phases to allow the tank to deform after the product level has been lowered.

Periodic product releveling would minimize the error associated with the coupling of temperature volume and structural deformation. Because the volume measurement system has limited dynamic range, a virtual releveling was performed between tests during the field testing. Instead of allowing the product level to drift, the manufacturer could periodically readjust product level. This would remove the error present in interpreting product-level changes.

V.2.2 Analysis

A longer test period would improve the estimation of temperature-volume changes. The spatial decorrelation distance is as short as 20 cm when temperature trends less than 15 min in duration are being measured.

V.2.3 Instrumentation

Performance improvement could be achieved by adding more thermistors to improve spatial sampling of the vertical temperature field. Based upon studies of canonical methods presented in Section 10 of the report, it is estimated that a 50% performance improvement could be achieved by increasing the number of thermistors from one to five.

V.2.4 Performance Estimate Based on the Field Verification Tests

Assuming that the the standard deviation of the field tests reflects the performance of a modified Tank Auditor without bi-level testing, and that the criteria for test success could be better defined, the performance of the system as field-tested would be much better than that of the system defined by the manufacturer in the mathematical modeling report [V-1]. The minimum leak rate detectable by the modified system is estimated to be 2.4 L/h (0.63 gal/h), with a P_D of 0.99 and a P_{FA} of 0.01.

V.2.5 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

W.1 The TMD-1 Test Method Description

The TMD-1 is a volumetric leak detection system capable, according to the manufacturer, of detecting leaks as small as 0.189 L/h (0.05 gal/h) which can occur in an underground storage tank.

W.1.1 Instrumentation

The TMD-1 system is composed of an In-Tank Emulator (ITE), which is used to determine the loss or gain of fluid in the tank. The function of the TMD-1 is to measure the level of fluid in the ITE, which is done by means of an HP 5528A laser interferometer. The TMD-1 makes no direct temperature measurements except to predict evaporation effects; this is done at the beginning of a test. The TMD-1 method employs a constant sampling rate with a variable test length. The test must be at least twice the length of the longest period observed in the data by the operator. For the purpose of the mathematical model, it is assumed that this period is 10 min. Therefore, the test must last 20 min.

The ITE, inserted in the tank through the fill tube, consists of a closed tube containing a fluid with a low coefficient of thermal expansion (0.00004/°C) and a density of 0.84 gm/cc. A flexible pac, or bladder attached to the bottom of the ITE tube expands and contracts in such a way as to mimic the pressure (height) changes in the surrounding product. Due, however, to its low coefficient of thermal expansion, the fluid in the ITE expands and contracts only minutely in response to thermal fluctuations. Thus, the system is effectively a U-tube device sensing pressure at the base of the tank. The sensor is designed to measure changes of product mass, since level changes due to thermal expansion and contraction of product in the tank are expected to be compensated automatically by the associated change in product density (i.e., pressure change). The laser interferometer system measures the fluid level inside the ITE tube. The sum of evaporation effects subtracted from the product-level change measured in the ITE predicts the volume change or leak. The claimed precision and resolution of the system are given in Table W.1.

Table W.1. Precision and Resolution of TMD-1 System as Specified by the Manufacturer

	Precision	Resolution
Level Measurement	12.7 μm	63.5 μm

Data are collected at a rate of 20 Hz and smoothed using an 11-point smoothing window. This is done by means of a simple moving average, using the statistical software package developed by Statistical Graphics Corporation (SGC). After collection and smoothing of the data, these SGC routines fit a third-order polynomial, an exponential, and a linear equation to the data by least-squares methods. The mean percentage error (MPE) and the mean absolute percentage error (MAPE) from the first two forms (exponential and third order) are used to determine whether the data are good; errors must be within +/- 0.5% and 1.00%, respectively, in order for the data to be considered acceptable. If, within the 20-min test length, the data are determined not to be good, no conclusions can be drawn and the test must be repeated.

W.1.2 Equipment Setup and Test Preparations

Equipment setup normally requires approximately 2 h. After this time, testing may begin, assuming that the proper level has been established in the tank.

W.1.3 Test Protocol

Test protocol requires that the tank be filled to 95% of capacity at least 12 h prior to testing. The liquid level in the tank is determined manually by means of a dipstick. This liquid level is used to determine a trigger value in length units. If the absolute slope of the product-level change is greater than this value, the tank may be leaking. If the slope is within a range of +/- 20%, the average of the tests is reported; otherwise the leak rate of the second test is reported. It is important to note that the data are not acceptable unless the MAPE and MPE values for each leak rate are within the prescribed limits.

The important features of the TMD-1 test are given in Table W.2.

Table W.2. Important Aspects of the TMD-1 Test Protocol

Sampling Period	0.05 s
Test Duration	Variable (1-2 h)
Waiting Period After Addition	12 h
Test Type/Product Level	Underfilled/95% filled tank

W.1.4 Data Analysis

Prior to conducting a set of tests, the expected evaporation rate (ER) is calculated. ER is then subtracted from the rate of volume change measured to determine the final leak rate.

As noted previously, three different curves are fit to the data collected. The first two, a third-order polynomial and an exponential, determine whether the data are good. The third curve, a linear equation, determines the rate of height or product-volume change. If the data are determined to be good at the end of a 20-min test, the linear equation is fit and a leak rate is determined. If the data are not good, the test is repeated until acceptable data are obtained. Once the data are considered acceptable, a leak rate is calculated and compared to the threshold value or trigger rate. As described in [W-1], if the value is within +/-20% of the trigger rate, the test is performed again, this time at a test duration of 1.5 times the original test (30 min). Again the leak rate is calculated. If both leak rates are within the range of +/- 20%, the average of the two is reported; otherwise the second leak rate is reported.

W.1.5 Detection Criterion

A tank is declared leaking if the flow rate as determined by the test is greater than 0.189 L/h (0.05 gal/h). If the leak rate is less than the threshold, the tank is declared nonleaking.

W.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the TMD-1 as it was evaluated and to interpret the results of the performance evaluation, it should be noted that the mathematical model of the system was based on the more detailed description of the test method described in [W-1]. After it had been validated, this model was used to estimate the performance of the method.

W.2 Improving System Performance

No recommendations for improving system performance were made as part of this evaluation.

X.1 The Tank Sentry II Test Method Description

The Tank Sentry II is a precision volumetric leak detection system capable, according to the manufacturer, of detecting leaks as small as 189 ml/h (0.05 gal/h). The sensor consists of a level measuring device and a temperature measurement system. The test is conducted in a nearly full tank in which dispensing operations have been suspended.

X.1.1 Instrumentation

The Tank Sentry II leak detection system uses two measuring devices to estimate a temperature-compensated flow rate: product level as determined by means of a dip-tube manometer and product temperature as determined by a temperature probe.

Volumetric changes are determined by monitoring pressure changes with a dip-tube pressure sensor (manometer). This measuring device consists of two units: a dip tube mounted in the tank and a reference cell mounted on a work station close by. The dip tube is inserted below the product level in the tank and is matched with a similar external device connected to a micrometer mounted in the reference cell. Product-level changes in the tank alter the pressure required to force gas bubbles through the dip tube. To monitor these changes, the pressure exerted on the dip tube is compared, by means of a sensitive differential pressure (DP) transducer at a zero differential pressure, to the pressure exerted on the reference-cell probe. The reference-cell duplicates the pressure changes of the dip tube in the tank. When the reference-cell probe is at the same depth as the dip tube, the DP transducer meter reads zero (null point). The depth of the reference-cell probe is measured with a micrometer.

Product level is monitored by the DP transducer to determine height changes during the test, and a hard copy is generated on a strip chart for backup and verification purposes. The depth changes measured between the start and end of the test (i.e., between the initial and final readings on the micrometer attached to the reference cell) represent the total height change during the test period.

Temperature is measured with a thermocouple (probe) placed at the vertical volumetric center of the product in the tank. The resolution and precision of the instrumentation are summarized in Table X.1.

Table X.1. Precision and Resolution of the Tank Sentry II System as Specified by the Manufacturer

	Precision	Resolution
Product Level	0.0025 cm	0.00025 cm
Temperature	0.06°C	0.06°C

X.1.2 Equipment Setup and Test Preparations

Equipment setup in the tank prior to a test is relatively straightforward, and does not require extensive tank preparation. In general, test equipment can be deployed in an hour or two, barring unforeseen instrumentation difficulties.

X.1.3 Test Protocol

The important features of the Tank Sentry II Leak detection system are summarized in Table X.2.

Table X.2. Important Aspects of the Tank Sentry II Test Protocol

Sampling Period	12 h
Test Duration	12 h
Waiting Period after Addition	24 h
Test Type	Filled Tank
Product Level	Below Top of Tank

Test protocol requires a wait of at least 24 h between the filling of the tank and the start of a test. The tank is filled to a level just below the fill tube (within a few centimeters of the top of the tank), thus keeping the surface area to a minimum.

Product temperature data are sampled only at the start and end of the test in order to determine the change in temperature, which is used in the thermal compensation calculations. The product level (height) data are also sampled in this manner.

X.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product-level and product-temperature measurements made at the beginning and end of the test period.

A tank chart supplied by the tank manufacturer is used to convert product-level measurement to volume. Conversion is accomplished by interpolating between points on the chart.

X.1.5 Detection Criterion

A tank is declared leaking if the leak rate as determined by the test is greater than a threshold of +/- 0.189 L/h. If the leak rate is less than the threshold, the tank is declared nonleaking.

X.1.6 Mathematical Model

While the description provided in Section X.2 is sufficient to identify the key features of the Tank Sentry II leak detection system as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [X-1]. After it had been validated, this model was used to estimate the performance of the system.

X.2 Improving System Performance

The performance of the Tank Sentry II system could be improved by making minor changes. Refer to the body of the report for further discussion of improving system performance.

X.2.1 Instrumentation

Changing to at least five relatively inexpensive thermistors similar to those used on the Test Apparatus would significantly improve system performance, both in terms of spatial resolution in the tank and improved sensor resolution and precision.

X.2.2 Protocol

Due to large errors in the tank chart when the product level is within a few centimeters of the top of the tank, height-to-volume calibrations should be done prior to conducting a test to better determine any volume change.

X.2.3 Analysis

By increasing the sample rate and performing a least-squares regression on the data, the Tank Sentry II system could significantly alleviate the temperature compensation problem associated with aliasing internal waves.

X.2.4 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly.

Y.1 The TLS-250 Tank Level Sensing System Test Method Description

The TLS-250 Tank Level Sensing System is an automatic tank gauging system capable, according to the manufacturer, of detecting leaks as small as 757 ml/h (0.20 gal/h) with a probability of detection of 0.98 and a probability of false alarm of 0.005. It is usually permanently installed in the tank, and it can perform a leak detection test when the dispensing operations are closed. For the tests described in this report it was employed as a volumetric test using the protocol described in [Y-1] and summarized below. The protocol of the TLS-250 system employed as a volumetric test is different than the one used when the TLS-250 is permanently installed in the tank.

Y.1.1 Instrumentation

The TLS-250 system gives computerized measurements of product level and product temperature. The precision and resolution of the TLS-250 measurement system as given by the manufacturer are presented in Table Y.1. Product level is measured using an eight-section cylindrical capacitance sensor that is tubular in shape. Its hollow center permits a temperature probe to be suspended within the sensor and also provides an exit for the sensor's wiring. The capacitance of the vapor space and of the product are measured *in situ* prior to testing. Given these values and the distance between the capacitor plates, the dielectric constant for both media can be estimated. The dielectric constants are then used to calculate height changes in the tank.

Temperature is measured using one thermistor located inside a sealed glass tube approximately 2.43 m in length, with the thermistor positioned about 1.1 m from the bottom. The glass tube is sheathed in an open-ended aluminum tube of the same length. The manufacturer describes the effective temperature weighting function as a half sine wave with the peak at the 40% volume level. This function is an approximation determined empirically, and has not been rigorously tested by the manufacturer.

Table Y.1. Resolution and Precision of the TLS-250 System as Specified by the Manufacturer

	Resolution	Precision
Level Measurement	0.0025 mm	0.0025 mm
Temperature Measurement	0.006°C	0.006°C

Y.1.2 Equipment Setup and Test Preparations

The manufacturer indicated that it would take approximately 1 h to install the equipment and prepare for the start of the test. This assumes that the product level is satisfactory for the conduct of a test.

Y.1.3 Test Protocol

The important features of the TLS-250 test protocol are summarized in Table Y.2. The test consists of two phases, the first being a 2-h minimum waiting period between the delivery of product to the tank and the start of data collection, and the second being the 8-h duration of the data collection. The data are collected at a sampling interval of 0.67 s and averaged to obtain a 1-h sample. Although the minimum duration of a test is 5 h, the maximum is not fixed by the manufacturer; it is usually determined by the number of hours for which normal dispensing operations cease each day.

Table Y.2. Important Aspects of the TLS-250 System Test Protocol

Sampling Period	1 h (average of 0.67-s samples)
Test Duration	8 h
Waiting Period after Product Addition	2 h
Test Type/Product Level	Underfilled Tank/80% of capacity

Y.1.4 Data Analysis

A temperature-compensated volume rate is computed from the product-level and product-temperature measurements using a 1-h average of the data obtained during the first and last hour of the test. A tank chart furnished by the manufacturer is used to convert the product-level measurements to volume. Height-to-volume conversion is accomplished using curvilinear interpolation between 20 pre-loaded tank-specific calibration points. The data that are entered represent 5% height increments across the diameter of the tank. These points can be automatically generated from a single volume and diameter input for a steel tank (assuming a right regular cylinder), or from the calibration points for a fiberglass tank with rounded ends, or by entering all 20 points as obtained from a tank chart or on-site strapping tests.

The thermal expansion and contraction of the product, ΔTV, is estimated using

$$\Delta TV = C_e V \Delta T \qquad (Y.2.1)$$

where the rate of change of temperature, ΔT is estimated from the one thermistor probe; the total volume, V, of the product in the tank is estimated from a product-level measurement; and a value of the coefficient of thermal expansion, C_e, for gasoline is furnished by the manufacturer.

All tests are considered successful providing that product-level and temperature data are collected for the entire duration of the test.

Y.1.5 Detection Criterion

A leak is declared if the measured temperature-compensated volume rate exceeds +/- 568 ml/h (0.15 gal/h). Based upon this criterion, the manufacturer claims that a leak of 757 ml/h (0.20 gal/h) can be detected with a probability of detection of 0.98 and a probability of false alarm of 0.005.

Y.1.6 Mathematical Model

While the description provided above is sufficient to identify the key features of the TLS-250 as it was evaluated and to interpret the results of the performance evaluation, it should be noted that a mathematical model of the system was developed based on the more detailed description of the test method provided in [Y-1]. After it had been validated, this model was used to estimate the performance of the method.

Y.2 Improving System Performance

The performance of the TLS-250 system can be improved by means of changes to the instrumentation and the protocol.

Y.2.1 Instrumentation

Probably the largest source of error is inadequate temperature compensation, a result of undersampling the vertical temperature field. The change in performance as a function of the number of thermistors on a vertical array is discussed in body of the final report. Substantial improvement occurs when additional thermistors are used, allowing better sampling of the temperature field. In the Field Verification Tests, the TLS-250 temperature measurement system did not perform as the manufacturer indicated. The empirical measurements made during the Field Verification Tests suggest that the system behaved more like a single point sensor rather than the sinusoidal probe indicated by the manufacturer. It is recommended that the characteristics of the probe be quantified.

Y.2.2 Protocol

The TLS-250 system could be further improved by increasing the minimum waiting period after a product delivery. At present the thermal effects of a delivery are minimized only because the current protocol stipulates a long test duration. The test results are also influenced by the effects of the unknown temperature changes due to horizontal gradients, as well as by structural deformation effects. A longer waiting period after product delivery would ensure that effects of thermal changes and of structural deformation have subsided.

Y.2.3 Detection Criterion

The probability of false alarm is determined by the threshold. The manufacturer should determine what probability of false alarm is desired and adjust the threshold accordingly. Improved probability of detection can be attained by decreasing the threshold (i.e., increasing the probability of false alarm).

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