# ESTCP
# Final Report

## Validation of the

# Low-Range Differential Pressure (LRDP) Leak Detection System

## for Small Leaks in Bulk Fuel Tanks

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

## Executive Summary

The Naval Facilities Engineering Service Center (NFESC), Port Hueneme, California, and its industrial partners, Vista Research, Inc., and Vista Engineering Technologies, L.L.C., have demonstrated and validated (DEM/VAL) an innovative mass-based leak detection system for *bulk* underground storage tanks (USTs) containing petroleum fuels. The *Low-Range Differential Pressure (LRDP)* system is a computer-controlled system that can reliably detect small leaks in bulk USTs ranging in size from 50,000 gal to 12,500,000 gal. As part of this project, it has been evaluated for performance by an independent third party in a 122.5-ft-diameter, 2,100,000-gal tank following EPA's standard test procedures. The LRDP meets the monthly monitoring and annual precision (tightness) test regulatory compliance guidelines established by California using either a 10-h (overnight) or 24-h test.

This project was performed under the *Environmental Security Technology Certification Program (ESTCP)*. The objective of the ESTCP is to demonstrate and validate innovative environmental technologies that are needed to address the environmental objectives of the Department of Defense (DoD), that are cost effective, and that will be ready for the development of commercial products and services at the completion of the DEM/VALs. All of the objectives of the project have been met, and the LRDP is ready for commercial use. Both (1) on-line, permanently installed monitoring systems and (2) tightness testing services using the LRDP can be obtained commercially through Vista Research, Inc.

The LRDP system achieves a very high level of performance against small leaks because of its high precision (0.0002 in.) and its accurate methods of compensating for the thermal expansion and contraction of the fuel, the instrumentation, and the tank. Because of its innovative design, the LRDP achieves this high level of precision and accuracy with an off-the-shelf, industrial-grade differential pressure sensor. Thus, the LRDP not only delivers high performance, but it is also rugged and field-worthy.

The LRDP system is fully automatic and is comprised of (1) an innovative in-tank level sensing unit, (2) an embedded remote test controller to collect and analyze the data from a test, and (3) a host computer to initiate, report, and archive the results of a test. A test can be initiated by an operator or can be automatically scheduled for a future date and time. The in-tank sensor can be installed through a standard 8-in.-daimeter opening without removing fuel from the tank. The electronics meet Class 1, Div. 1 standards. The LRDP system is compatible with the DoD Fuels Accounting System (FAS) and can be integrated with FAS to test the tanks in a fuel farm or a bulk storage facility.

The in-tank sensor is comprised of (1) a vertical reference tube that spans the full usable height of the tank, (2) a sealed, bottom-mounted container that houses all of the level-measurement sensors, and (3) a special bellows-mounting system that is used to attach the system to the top of the tank. The reference tube is shaped so that it has a cross-sectional area that is proportional to the cross-sectional area of the tank as a function of depth. Except for 50,000-gal USTs and the 12,500,000-gal Red Hill tanks, all of the DoD's bulk USTs have vertical walls, and therefore, the reference tube has a constant cross-sectional area. A valve at the bottom of this tube allows fuel from the tank to enter or leave. When the tank is to be tested for leaks, the valve is closed, thus isolating the fuel in the reference tube from that in the tank. As the level of liquid in the tank fluctuates, the level of liquid in the closed reference tube mimics it—except when the change in level is due to a leak. High precision is achieved because the dynamic range of the differential pressure sensor only needs to accommodate the differences in level between the reference tube and the tank and not the full height of the tank. The very small differences between the changes in level (pressure) in the tank and those in the tube are detected by a differential pressure sensor that is located in the sealed container at the bottom of the tube. Thus, the differential pressure sensor makes a direct measurement of the change in level that is due to a leak, if one is present. Because the differential pressure is housed at the bottom of the tank, where it is not subject to ambient air conditions, it avoids a common problem of other mass-based leak measurement systems—thermally induced drift of the pressure sensor. In addition, the special bellows-mounting system removes any thermally induced vertical movement of the tank, the manway, or the in-tank sensor. The LRDP system is self-calibrating, and its performance and functionality can easily be checked between tests any time the valve is in the open position.

The performance of the system was independently evaluated for a 10- and a 24-h test by Ken Wilcox Associates, Inc. (KWA), a nationally recognized third-party evaluator, using a variety of detection thresholds that were selected (1) to maintain a low probability of false alarm, (2) to optimize performance against certain target leak rates, and (3) to meet or exceed known regulatory requirements. The performance was determined

experimentally and was reported in accordance with the guidelines set forth in "Alternative Test Procedures for Evaluating Leak Detection Methods: Evaluation of Bulk Field-Constructed Tanks," a standard test procedure for bulk underground tanks that is approved by the National Work Group on Leak Detection Evaluations (NWGLDE), an EPA-sponsored oversight group. A leak detection method cannot be used unless the evaluation has been approved by this group. The evaluation consisted of 12 tests conducted on a 122.5-ft-diameter, 2,100,000-gal bulk underground storage tank containing jet fuel and located at the Navy's Point Loma Fueling Facility, San Diego, California. The tests were conducted over a wide range of temperature and induced leak conditions beginning on March 22, 2000 and ending on June 8, 2000. Neither the temperature conditions nor the leak rates were made available to NFESC until the test results had been generated and the evaluation report prepared.

The LRDP is currently listed by the NWGLDE and is approved for use in California based on a third-party evaluation previously conducted at NAS North Island on an 88-ft-diameter tank. The results of the current ESTCP evaluation, conducted on the 122.5-ft-diameter tank at Point Loma, a much larger tank than the one used in the North Island evaluation, have been submitted to the NWGLDE for review and update of the previous listings. The results of the KWA evaluation (which are presented in this report) indicate that a single 10-h test with the LRDP-10 can detect a leak of 1.14 gal/h with a probability of detection ($P_D$) of 95% and a probability of false alarm ($P_{FA}$) of 5% in a 122.5-ft diameter tank. The performance of the LRDP-10 scales with the product surface area of the tank and improves as the tank diameter decreases. The LRDP-10 can detect leaks as small as 0.2 gal/h in a single test in a 51-ft-diameter tank; by averaging four tests, a 0.2-gal/h leak can be detected in a 73-ft-diameter tank with the same probabilities of detection and false alarm. The performance improves with a 24-h test. The LRDP-24 can detect a leak of 0.69 gal/h with a $P_D$ of 95% and a $P_{FA}$ of 5% in a 122.5-ft diameter tank; when the 12 monthly tests are averaged together, the system has the capability for detecting leaks as small as 0.2-gal/h. The LRDP-24 can detect leaks as small as 0.2 gal/h with the same $P_D$ and $P_{FA}$ in a 66-ft-diameter tank with a single test and in a 93-ft-diameter tank by averaging four tests together. The LRDP-10 and the LRDP-24 are the only in-tank, on-line monitoring systems that can meet both Option 7 and Option 10 of the California regulatory guidelines for underground bulk storage tanks.

A DEM/VAL of the LRDP system configured to test 50,000-gal underground storage tanks was performed at Hunter Army Airfield. For these tests, the reference tube was shaped to match the cylindrical cross-section of the tank as a function of depth. While a third-party evaluation was not performed, it was clear from the results of the DEM/VAL tests that the LRDP could meet the 0.2-gal/h monthly monitoring regulatory requirements with an 8-h test.

Many important improvements to the LRDP previously evaluated at NAS North Island have been made under this ESTCP project. As a consequence of these improvements, the LRDP is ready for implementation throughout the DoD. Some of these improvements are:

- The notebook computer and data acquisition system were replaced with field-worthy embedded controller, which collects data, evaluates data quality, analyzes test results, and stores the results.
- The system was made fully automatic, and the software was made easy to use. The electronics are housed in an explosion proof container and meet Class 1, Div 1 Standards.
- The system was originally approved as a portable system and can now also be used as a stand-alone system for on-line, real-time, in-tank monitoring.
- The in-tank sensor unit was redesigned for easy installation and now fits into a standard 8-in. diameter opening and a tank of any diameter and any product depth.
- The LRDP can be easily interfaced with base fueling operations, including the FAS, and can be used for both leak detection and inventory monitoring
- The evaluated performance of the LRDP is 20% better than originally determined in the first evaluation, and the performance limitations (e.g., a 24-h waiting period) have been removed.
- A leak detection test can be conducted with the LRDP using either a 10-h or a 24-h test.

The LRDP has several significant cost advantages over other internal and external technologies. The cost advantages are realized because of the extremely high performance of the LRDP and the low probability of false alarm, the on-line monitoring capability of the LRDP when permanently installed in a tank, the capability of the system to conduct a short test (an overnight test), and the low recurring costs associated with testing. For each tank brought into compliance, the LRDP can realize cost savings over other mass-based methods in terms of installation and testing of $250,000 or a factor of 3 over a 10-year period. The cost savings realized by the LRDP over an in-tank tracer method can be well over $1,000,000 or a factor of 12 over a 10-year period. This can result in savings of up to several tens of millions of dollars for each DoD fuel storage facility. The savings of the LRDP compared to other mass-based systems would result in a payback of less than three years. This payback is less than one year when compared to an in-tank tracer method. The cost of a tracer method is expensive because of the high recurring cost of testing. The costs of other mass-based methods are high because of lower performance and the inability to meet both the monthly monitoring and annual precision regulatory requirements with an on-line system. In addition to the installation and operational cost savings, the LRDP has the potential to save DoD many hundred of millions of dollars in terms of clean-up and tank replacement cost avoidance.

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## Acronyms

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|---|---|
| AST | Aboveground storage tank |
| CERF | Civil Engineering Research Foundation |
| CERL | Construction Engineering Research Laboratory (Army) |
| DESC | Defense Energy Support Center (DESC) |
| DoD | Department of Defense |
| EPA | Environmental Protection Agency |
| ESTCP | Environmental Security Technology Certification Program |
| EvTEC | Environmental Technology Evaluation Center |
| I/F | Interface |
| MDLR | Minimum Detectable Leak Rate |
| MODBUS | Industrial Networking System that uses RS232 Serial Master-Slave Communications |
| NAS | Naval Air Station |
| NFESC | Naval Facilities Engineering Service Center |
| NWGLDE | National Work Group on Leak Detection Evaluations |
| $P_D$ | Probability of Detection |
| $P_{FA}$ | Probability of False Alarm |
| $P_{MD}$ | Probability of Missed Detect |
| PLC | Programmable Logic Controller |
| PSA | Product surface area |
| RTD | Resistance Temperature Device |
| TLR | Target Leak Rate |
| UST | Underground Storage Tank |
| VR | Volume Rate |

# Acknowledgments

The LRDP team would like to acknowledge and thank the fuel farm directors and their staff at the Point Loma Fuel Terminal, the Hunter Army Airfield, the Defense Energy Office, Los Angeles (San Pedro), and the NAS North Island for making their facilities available for the DEM/VALs of the LRDP system, and for coordinating and supporting the DEM/VALs. We would also like to acknowledge the input and support of the Defense Energy Supply Center (DESC) and Endress+Enhauser Coggins Systems. Ken Wilcox Associates, Inc., performed the third-party evaluation of the LRDP. The LRDP was initially developed by NFESC and Vista Research with funding from the Pollution Abatement Ashore Program, which is sponsored by the Environmental Protection, Safety and Occupational Heath Division (N45) of the Chief of Naval Operations, and from Vista Research. The work described in this report was funded through the Environmental Security Technology Certification Program (ESTCP) and is entitled, "Validation of the Low Range Differential Pressure (LRDP) Leak Detection System for Small Leaks in Bulk Fuel Tanks." A full list of contacts is included in Section 8 of this report.

The LRDP team would like to especially thank Dr. Jeffrey Marqusee and Dr. Robert Holst for their support.

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# 1.0 Introduction

The *Low Range Differential Pressure (LRDP)* system is an innovative technology that was developed for the reliable detection of small fuel leaks in the *bulk* underground storage tanks (USTs) that are owned or operated by the Department of Defense [1-2]. If a tank is leaking, the LRDP quantitatively measures the leak rate in gallons per hour, the quantity of regulatory interest. The LRDP system can be used to test tanks ranging in capacity from 50,000 gallons to 12.5 million gallons and will work for tanks with vertical and/or curved walls. The LRDP is a fully automatic, mass-based system, which is easy to install and use. The LRDP system can be permanently installed in a tank and used for on-line monitoring and precision (tightness) testing. It can also be used as a portable system for periodic testing of any tank in the fuel farm. The duration of a test can be either 10 or 24 h depending on the size of the tank and the performance required.

The LRDP, which is shown in Figure 1, is the only in-tank system that has the performance to address both the monthly monitoring and annual precision test leak-detection regulatory requirements for bulk USTs [3-5] without requiring the installation, operation and cost of a second system. Not only is the LRDP the only system that can cost effectively meet both requirements, it can meet these requirements with a very low probability of false alarm. *It is also the only system that can conduct an overnight test.* The technology is not site-specific, and the performance of the technology is not affected by site geology or topographic factors. The system can be implemented in a bulk tank of any size and of any configuration. It can also be readily integrated into the DoD tank farm Fuel Accounting System (FAS) and other fuel management and handling systems.

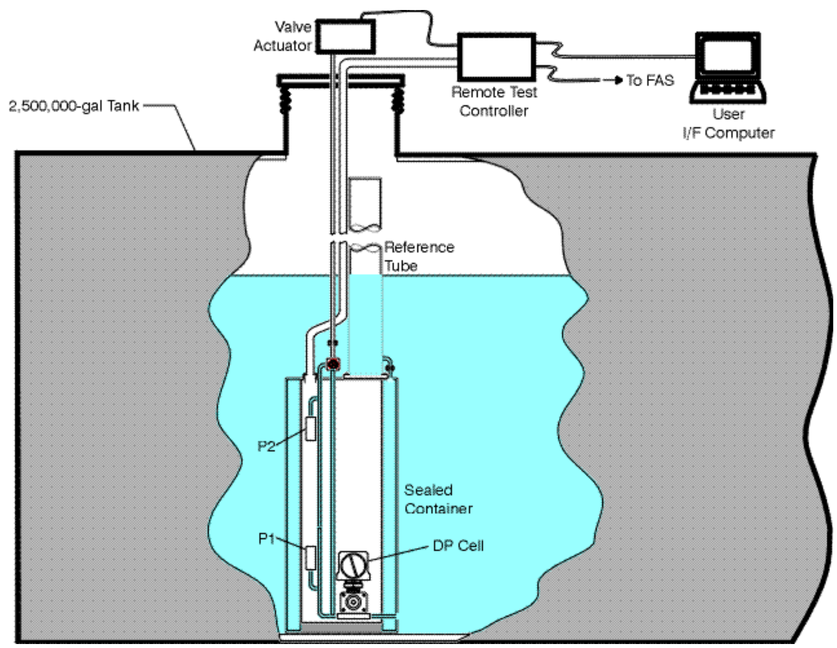


**Figure 1.** Low-Range Differential Pressure (LRDP) system for bulk USTs.

The LRDP technology also provides facility operators with valuable tank replacement and clean-up cost avoidance information, because the probability of a missed detection, the probability of a false alarm, and the confidence intervals on the measurement of the flow rate due to a leak are known for the LRDP. With this information, an estimate of the life-cycle cost of the technology can be made. Significant cost savings can be realized, because the performance of the LRDP is high, and the recurring costs associated with operation of the system are low.

As part of the *Environmental Security Technology Certification Program (ESTCP),* the LRDP technology was demonstrated and validated (DEM/VAL) in two 2,100,000-gal, field-erected, bulk USTs and in a 50,000-gal, shop-fabricated UST, all owned and operated by the DoD. One of the bulk USTs was located at the Point Loma Fuel Terminal, San Diego, California, and the other was located at the San Pedro Fuel Facility, Defense Energy Office, Los Angeles. The DEM/VAL conducted on the 50,000-gal UST was conducted at the Hunter Army Airfield (a sub-unit of Fort Stewart), Savannah, Georgia. These technology demonstrations were performed by the Naval Facilities Engineering Service Center (NFESC), Port Hueneme, California, the U. S. Army's Construction Engineering Research Laboratory (CERL), Champaign, Illinois, and their industrial partners, Vista Research, Inc., Sunnyvale, California, and Vista Engineering Technologies, L.L.C., Kennewick, Washington. The ESTCP is a corporate DoD program that promotes innovative, cost effective environmental technologies through demonstration and validation at DoD sites. This project was performed as part of the *Compliance* ESTCP Thrust Area under *Improved Leak Detection and Prevention Technologies for Underground Storage Tanks (USTs) and Underground Pipelines*. The main points of contact for this project are listed in Appendix A.

The objective of the DEM/VAL conducted at the Point Loma site was to obtain an independent third-party evaluation of the performance of the LRDP as an on-line monitoring and precision test leak-detection system. This evaluation was originally planned for the San Pedro site, but a small flow across the pipeline valve prevented the evaluation from being conducted at this site. However, the limited number of tests conducted at San Pedro indicated that the LRDP had the capability for meeting the regulatory requirements for precision testing and monthly monitoring.

Before a method can be used, it must be evaluated for performance by an independent third party and listed by the National Work Group on Leak Detection Evaluations (NWGLDE). The evaluation was performed by Ken Wilcox Associates, Inc. (KWA) at the Point Loma site. The evaluation was conducted in a 122.5-ft-diameter bulk UST in accordance with a standard test procedure following EPA guidelines that was developed specifically for bulk storage tanks [6, 7]. This procedure was reviewed and approved by the NWGLDE, a national group of regulators, which is sponsored by the EPA, to simplify the certification of leak detection methods by the states. The NWGLDE reviews the third-party evaluations of leak detection methods for completeness and accuracy. If the evaluation is complete and accurate, the NWGLDE will list the method. This listing allows the states, which develops a list of approved methods that can be used for leak detection in their state, to approve methods without extensive review. If the method is not listed by the NWGLDE, the states will not approve or use the method. The listing gives a description of the method, its performance, and the limitations on its use.

The results of this performance evaluation for an overnight test (10 h) and for a 24-h test have been submitted for review and update of the current LRDP listings by the NWGLDE so that the system can be used by the states to address their leak detection regulatory requirements [8-15]. A draft of the updated listing is presented in Appendix B. The performance of the system is presented in terms a probability of detection ($P_D$) of a given target leak rate (TLR) in gallons per hour and a probability of false alarm ($P_{FA}$), where the $P_D = 95\%$ and the $P_{FA} \leq 5\%$. The TLR is usually specified by the regulatory requirements and may be different from state tot state. The TLRs are typical 1, 2, or 3 gal/h for monthly monitoring and 0.2 gal/h for precision testing.

The objective of the DEM/VAL conducted at the Hunter Army Airfield site was to demonstrate the technology in a 50,000-gal UST with cylindrical walls. This DEM/VAL consisted of a limited number of tests showing that the system was capable of meeting the EPA's regulatory requirements for monthly monitoring at 0.2-gal/h. A third-party evaluation was not performed for this type of UST. If the LRDP is to be used for testing cylindrical USTs, a third-party evaluation will be required.

This technology has been successfully transferred to industry. Leak-detection products and services based on this technology are commercially available through Vista Research, Inc.; these products and services include (1) on-line, permanently installed monitoring systems and (2) tightness testing services. Product description and product specification sheets are included in Appendix C.

### 1.1 Problem

The DoD owns and operates over 300 bulk USTs. They range in size from 100,000 gal to over 4,000,000 gal, and have diameters up to 135 ft. Over half of these bulk USTs are located in California. The DoD also owns twenty 12,500,000-gal USTs in Red Hill, Hawaii. In addition, the DoD owns and operates many thousands of *large* shop-fabricated USTs (e.g., 50,000-gal) throughout the country. Until recently, unlike the small USTs found at petroleum service stations, the bulk tanks had no regulatory requirements for periodic leak detection. The federal regulations deferred bulk USTs from the regular annual tightness test or monthly monitoring tests that other smaller USTs must undergo. However, various states have implemented regulations or testing guidelines, which have the strength of regulations, for bulk USTs. This presents a unique problem for DoD, because DoD is the only owner of bulk USTs. Because of increasing remediation and cleanup costs due to tank leakage and the implementation of regulatory guidelines and requirements, the DoD is in need of one or more leak detection systems to meet their environmental needs.

Prior to the start of this ESTCP project, the only system that could meet the Federal UST regulatory requirements was a tracer method in which a unique tracer could be added to the fuel. However, the cost of using this technology is very expensive, even for a single annual tightness test, and is not cost effective for monthly monitoring. The use of other types of tracer methods, which use one or more constituent components of the fuel as tracers, do not work, because the background contamination results in too many false alarms. While acoustic systems have application for aboveground storage tanks (ASTs), they have not been used for bulk USTs and do not have the performance to meet regulatory guidelines for bulk USTs. Volumetric systems, comprised of level and temperature sensors like those used on the smaller USTs at petroleum service stations, cannot adequately compensate for the thermal expansion and contraction of the fuel to be considered. While statistical inventory reconciliation methods are approved and widely used at service stations, their performance, even for these small tanks, is suspect by the regulatory community. Regardless, of performance, the fuel farm UST systems are not adequately configured for leak detection, and it would be very expensive to retrofit the fuel farm to implement this approach.

The technology of preference for DoD's bulk UST owners and operators is an in-tank, mass-based system. The performance of a conventional mass measurement system, however, is seriously limited by three factors and cannot be used to address the regulatory guidelines for both monthly monitoring and periodic precision testing unless these limitations are fully addressed. The first limitation is that a conventional system, which uses a differential pressure sensor with sufficient dynamic range to measure level changes over the full vertical extent of the tank, lacks the *precision* required to detect small leaks unless special-purpose, delicate and expensive sensors are used. The second limitation is that, in a tank with a variable cross-sectional area, thermal influences can cause large changes in volume, which are not compensated by a differential pressure sensor. The third limitation is the errors produced by the thermal expansion or contraction of both the instrumentation and mounting system.

The LRDP system was developed to address these limitations. The reference tube addresses the first limitation, and a "shaped" tube addresses the second limitation; the bottom-mounted sensors and the special bellows mounting system used in the LRDP system described below address the third limitation.

### 1.2 Background

The LRDP system was developed to address the requirements for leak detection specified in the Navy's Environmental Quality Research and Development Requirement No. 2.iii.2.a "Improved Leak Detection and Prevention Technologies for Underground Storage Tanks (USTs)." The LRDP system provides the DoD a method of leak detection for bulk USTs that

- will be in compliance with local, state and federal regulatory requirements,
- has with sufficient performance to detect a leak, if one were to occur, so that the environmental damage and the costs associated with cleanup and remediation could be minimized,
- is reliable enough to be used, because it does not have false alarm problems and could be used without any significant impact to operations, and
- is very cost effective, because it can be installed, operated, and maintained over time less expensively than other technologies, and could be effectively used to minimize the cost of cleanup and remediation by early detection of and quantification of the size of a leak. An estimate of the cost savings associated with the use of this technology is between $500 M and $1 B.

All four of these objectives are based on the performance of the method, and the LRDP system has more than sufficient performance to meet the compliance, detection, operation, and cost objectives required of a leak detection technology needed to satisfy DoD's environmental needs.

The LRDP, shown in Figure 2, was originally developed for detection of leaks in the world's largest USTs [2]. The 20 Red Hill tanks, which are owned and operated by the U. S. Navy, are buried over 100 ft deep in the hills above Honolulu, Hawaii and contain 12.5 million gallons of fuel. Each tank is 100 ft in diameter and 250 ft in height. In 1996, an LRDP was installed in one of the Red Hill tanks (Tank 16) for demonstration purposes. (Another LRDP has recently been installed in Tank 9 (March 2001) and a third-party evaluation has been completed [16]).

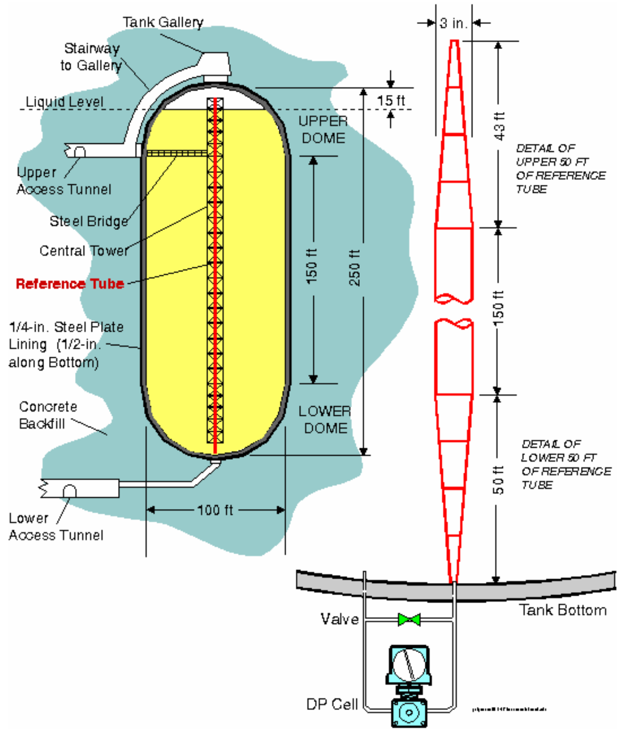


**Figure 2.** LRDP system with a tapered tube installed in a 12,500,000-gal Red Hill UST.

While waiting for fuel to be added to Tank 16 at Red Hill, a second LRDP was built and installed in a 88-ft-diameter, 600,000-gal UST at the NAS North Island Fuel Farm. The first implementation of this system, which is shown in Figure 3, was developed for cylindrical tanks with vertical walls and evaluated for performance by KWA in a 600,00-gal UST at the NAS North Island Fuel Farm in 1998. The LRDP was listed by the NWGLDE for use as a precision leak-detection system for bulk USTs using either a 24- or 48-h test, a waiting period of 24 h, and an average of a set number of tests (1, 4 or 5 tests) [1, 5]. The performance estimates made in this third-party evaluation were contaminated by a small inflow (~0.1 gal/h) that occurred during the evaluation; this inflow introduced a small bias and degraded the performance of the system over what it should have been. Even so, the performance was excellent and more than sufficient to meet regulatory requirements for both monitoring and precision testing. The limitations and constraints imposed on the use of the LRDP by the NWGLDE as a result of this first evaluation were addressed and eliminated in the evaluation described in this report.

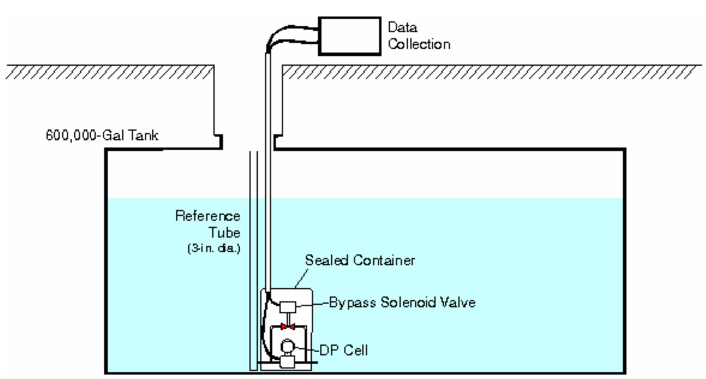


**Figure 3.** Engineering Prototype of the LRDP system for bulk USTs

The main difference between the LRDP system installed at NAS North Island and the one used in this evaluation is the size and location of the sealed container at the bottom of the reference tube. The measurement sensors in the sealed container were the same for both systems. Since the fuel in both versions of the reference tube extended from the bottom of the tank to the product surface and had an identical cross-sectional area, identical performance is expected and was verified by a side-by-side comparison of the improved version of the LRDP system evaluated during the Point Loma DEM/VAL.

### 1.3 Objectives of the Demonstration

The objective of this ESTCP project was to demonstrate and validate (DEM/VAL) a reliable, cost-effective leak-detection system for monthly monitoring and periodic precision testing of the *bulk* underground storage tanks (USTs) with vertical walls that are owned and operated by the DoD. This project was an expansion of the previous testing and regulatory approval obtained in California for the LRDP on an 88-ft-diameter bulk UST at NAS North Island [1]. The present tests were designed to demonstrate the system on larger tanks and to obtain regulatory approval for use of the system as an on-line monitoring system and with a test duration of 24 h and a second test duration shorter than 24 h (i.e., 10 h). The output of the project is an alpha-prototype of the LRDP leak detection system (1) that is ready for pre-production testing by industry and (2) that has been evaluated for performance by an independent third party following a *standard test procedure* developed by the EPA and approved by the NWGLDE. The third-party evaluation will be submitted to the NWGLDE for review and inclusion on a national list of leak detection methods, which are ready for use by the states. An additional objective was to demonstrate that the LRDP system also can be used to test the smaller, 50,000-gal underground storage tanks with curved walls.

Unlike many other environmental technologies, the approach to DEM/VAL is prescribed by the EPA. In 1988, the EPA developed a set of standard test procedures for estimating the performance of various types of leak detection methods. In 1996, a standard test procedure was prepared for mass-based or volumetric leak detection methods for bulk USTs [6]. The results are presented in terms of a volumetric target leak rate (TLR) in gallons per hour, a probability of detection ($P_D$), and a probability of false alarm ($P_{FA}$). The regulatory requirements of each state are specified in terms of $P_D$, $P_{FA}$, and TLR, where the state sets the TLR, and at a minimum, the $P_D$ must be equal to or better than 95% and the $P_{FA}$ must be less than or equal to 5%. The standard test procedure for mass-based systems allows for the scaling of performance for vertical-wall USTs with surface areas up to 250% of the surface area of the UST used in the evaluation. The standard test procedure places a number of constraints on the scaling of performance. First, the performance of the method could not be scaled to a target leak rate less than 0.2 gal/h, and second, the smallest UST that the method is approved for use has a capacity of 50,000 gal.

### 1.4 Regulatory Requirements

The UST regulation, issued in 1988 by the EPA, *deferred* the requirements for testing bulk or field-erected USTs for leaks [3]. The main reason for the deferral of field-erected USTs was the lack of any technologies in 1988 that could reliably test these large tanks for leaks. Only the shop-constructed USTs, which are typically used at service stations and have capacities of 50,000 gal or less, were strongly regulated. In contrast, the large field-erected USTs, which have capacities between 100,000 to 12,500,000 gal, did not need to meet the rigorous leak-detection performance standards for monthly monitoring or annual tightness testing established for small USTs [3].

The performance of a leak detection system with a $P_D$ = 95% for a specified TLR and a $P_{FA}$ = 5% is called the minimum detectable leak rate (MDLR), where the MDLR equals the specified TLR. This jargon should not be confused with the smallest leaks that can be detected. Leaks smaller than the TLR can be detected, but the $P_D$ may be less than 95% (even if the threshold is not changed) or the $P_{FA}$ may be less than 5% (by changing the threshold). While many leak detection systems are operated at this level of performance, the chief advantage of computing the MDLR for each method, even if they are not operated at this level, is that the performance of different methods can be easily and directly compared.

The UST regulation, which was required to be implemented by the states, requires that all regulated USTs be tested for leaks on a *monthly* basis with a leak detection system capable of detecting a leak as small as 0.2 gal/h with a probability of detection ($P_D$) of 95% or greater and a probability of false alarm ($P_{FA}$) of at 5% or better. Between the issuance of the UST regulation on 22 December 1988 and the 10-year period that allowed for tank owners to meet the UST upgrading requirements (by 22 December 1998), tightness (or precision) tests of the USTs were allowed in lieu of the monthly monitoring. While the testing schedule prescribed by the EPA regulation allowed intervals of up to 5 years between tests, most states required *annual* tightness testing if this option was selected by the tank owner. To meet the regulatory requirements for a tightness test, a leak detection system capable had to be capable of detecting a leak as small as 0.1 gal/h with a $P_D \geq 95\%$ and a $P_{FA} \leq 5\%$. During this 10-year period, the states struggled with how to test bulk USTs and what performance standards should be required. Until the mid- to late-1990s, bulk USTs were rarely tested for leaks; large inventory imbalances were the primary mode for identifying a leak. The volumetric systems that were typically used to meet the performance standards required for the small regulated USTs found at service stations could not meet these same standards on the bulk USTs. The LRDP, a mass-based system, was developed in response to the need for detection of leaks in bulk USTs owned by the Department of Defense (DoD).

During the late 1990s, California, where the majority of all of DoD's bulk tanks are located, developed regulatory guidelines for testing bulk tanks. Since the DoD owns almost all of the bulk USTs in the United States, the California guidelines were mainly prepared for DoD compliance.

The basic option for testing USTs, regardless of size, is to meet the 0.2-gal/h monthly requirement in the EPA UST regulation. This option, included by California as Option 1, is overly stringent and does not have a low enough $P_{FA}$ for routine monitoring. As a consequence, California developed other options that included a precision test at 0.1 gal/h, which is not realistic for testing bulk USTs [4].

Two of the ten testing options (Options 7, 10) developed by California were based on the input from discussions from NFESC and Vista Research and the results of the first third-party evaluation of the LRDP [4] conducted at North Island. Both of these options required monthly monitoring and a periodic precision test. These performance guidelines are stringent, consistent with bulk operations, and achievable. These two guidelines are summarized in Table 1. The other options are variances of the UST leak detection performance standards issued for the small USTs found at service stations and are not generally consistent with the design and operation of bulk USTs. The State of California requires that each leak detection system be third-party evaluated, be approved and listed by the NWGLDE, and be approved and listed on the California list.

As will be discussed in Section 5, the LRDP meets all of these standards. However, any leak detection system that can meet Option 1 can also meet Options 7 and 10, so Option 1 would not be the first choice by the fuel farm operator unless such level of protection is really needed or the standard can be met with a much lower $P_{FA}$ than 5%. Furthermore, the LRDP system is the only on-line monitoring mass-measurement system that can meet both the monthly monitoring and precision testing guidelines in Options 7 and 10 for all bulk USTs owned by DoD.

**Table 1.** California Testing Options for Bulk USTs [4]

| California Testing Options | Monthly Monitoring Test | Precision (Tightness) Test |
|---|---|---|
| **Option 1** | | |
| Target Leak Rate – gal/h | 0.2 gal/h | |
| $P_D$ - % | $\geq$ 95% | |
| $P_{FA}$ - % | $\leq$ 5% | |
| Testing Schedule – years | 1 month | |
| | | |
| **Option 10** | | |
| Target Leak Rate – gal/h | 0.3 to 1.0 gal/h | 0.2 gal/h |
| $P_D$ - % | $\geq$ 95% | $\geq$ 95% |
| $P_{FA}$ - % | $\leq$ 5% | $\leq$ 5% |
| Testing Schedule – years | 1 month | 1 year |
| | | |
| **Option 7** | | |
| Target Leak Rate – gal/h | 1.0 to 2.0 gal/h | 0.2 gal/h |
| $P_D$ - % | $\geq$ 95% | $\geq$ 95% |
| $P_{FA}$ - % | $\leq$ 5% | $\leq$ 5% |
| Testing Schedule – months | 1 month | 6 months |

Because of the particularly high performance achieved by the LRDP, the State of California would not allow the system to be used as designed (Version a in the NWGLDE listing), even though it met these performance guidelines. The State limited the target leak rate to twice the minimum detectable leak rate (MDLR) achieved by the system (Versions 1.1a or 1.2a). For most UST sizes, the $P_{FA} << 5\%$ for the LRDP.

### 1.5 Improvements to the LRDP Evaluated at NAS North Island

The work was accomplished in the following four tasks:

- Task 1 - Prepare and execute work plan
- Task 2 - Design, assemble, integrate and checkout alpha prototype
- Task 3 - Conduct system DEM/VAL and evaluation testing at selected DoD installations
  Task 4 - Prepare technology transfer package and implementation plan

All four tasks were successfully completed; the technology has been transferred to industry and is being offered commercially to address DoD's bulk UST environmental needs.

Four testing methods of the LRDP system were evaluated for performance. For each method, one of four thresholds can be used to detect a specific target leak rate (TLR) or to operate with a specific $P_{FA}$. The TLR is usually specified by the regulatory agency. The $P_D$ = 95% for all thresholds and all methods used by the LRDP. The list distinguishes each threshold by a unique version number. Table 2 summarizes the four methods. Two of the methods require only one test, and two of the methods require the averaging of up to 12 tests. The name of the method contains the duration of the test in hours and the number of tests to be averaged. The LRDP-10 is implemented with a 10-h test, and the LRDP-24 is implemented with a 24-h test. The LRDP-10-n is a test that requires the averaging of "n" tests. The number of tests to be averaged depends on the required performance. This type of method is normally used to meet the 0.2-gal/h precision (tightness) test requirement for the larger tanks owned by DoD. Any or all four of these methods can be used in combination to address regulatory requirements. For example, the LRDP-10 might be used to address the monthly monitoring requirement, and the LRDP-24 might be used to address the precision test requirement.

**Table 2.** Summary of the Four Methods of the LRDP System for Bulk Tanks

| Name of Test Method | Type of Test | Test Duration | Number of Tests Averaged Together |
|---|---|---|---|
| LRDP-10 | Monitoring, Precision[1] | 10 h | 1 test |
| LRDP-10-n | Precision[1] | 10 h | $1 < n \leq 12$ tests |
| LRDP-24 Version A | Monitoring, Precision[1] | 24 h | 1 test |
| LRDP-24-n Version A | Precision[1] | 24 h | $1 < n \leq 12$ tests |

[1] Can be used to address the regulatory standards for a 0.20-gal precision test, when the monthly monitoring requirement is 2.0 gal/h or less.

Many important improvements to the LRDP evaluated at NAS North Island have been made under ESTCP. As a result of these improvements, the LRDP is ready for implementation throughout the DoD. However, none of these improvements effected any changes to those parts of the system that control performance. For example, the same differential pressure sensor was used in both systems. Some of these improvements are:

- The notebook computer and data acquisition system were replaced with a field-worthy remote test controller, which collects data, evaluates data quality, analyzes test results, and stores the results.
- The system was made fully automatic, and the software user interface was made easy to use.
- The system was originally approved as a portable system and can now also be used as a stand-alone system for on-line, real-time, in-tank monitoring.
- A special set of data quality indices were developed and tested to insure the reliability of each test result.
- The in-tank sensor unit was redesigned for easy installation and now fits into a standard 8-in. diameter opening of a tank of any diameter and any product depth.

- The LRDP can be easily interfaced with base fueling operations, including the FAS, and can be used for both leak detection and inventory monitoring
- The evaluated performance of the LRDP is 20% better than originally determined in the first evaluation, and the performance limitations (e.g., a 24-h waiting period) have been removed.
- The monthly monitoring regulatory guidelines can be met with the LRDP using a 10-h test, which is short enough to be conducted overnight. For many of DoD's bulk USTs, the LRDP also be used to address the precision testing guidelines with a 10-h test. The LRDP can be used to address the precision testing guidelines for the remaining bulk USTs with a 24-h test.
- The electronics are housed in an explosion proof container and meet Class 1, Div 1 Standards.
- With changes to the design of the reference tube, the LRDP was adapted for use in testing 50,000-gal USTs and other USTs with curved walls.

The main attributes of the LRDP system are summarized below:

- The LRDP is directly inserted into a standard 8-in.-diameter opening in the tank that is being tested or monitored.
- The LRDP can be used to perform a leak detection test without removing fuel from the tank.
- The LRDP can be used to test USTs with both vertical and curved walls.
- The output of a leak detection test is easy to interpret, because it is a direct measurement of the leak rate in gallons per hour, the quantity of regulatory and engineering interest.
- Because the LRDP system is a mass-based system, it inherently compensates for the thermal expansion or contraction of the fuel in the tank during a test. Furthermore, accurate tests can be initiated without a long pre-test waiting period that are needed by other systems to allow the horizontal temperature gradient to stabilize throughout the tank.
- The special mounting system eliminates thermally induced movement of the reference tube during a test.
- Thermally induced drift of the differential pressure sensor is virtually eliminated, because it is mounted in a sealed container at the bottom of the tank.
- Because the differential pressure sensor used to measure level (volume) changes in the tank needs a dynamic range of only 1 in. (rather than the total height of the tank, like other mass-based systems), the LRDP has the precision (0.0002 in.) to detect very small leaks in large-diameter tanks.
- The system is self-calibrating, and the performance and functionality of the LRDP can easily be checked between leak detection tests.

## 1.6 Report Organization

This report is organized following the ESTCP final report outline. Section 2 provides a description of the technology. Section 3 describes the sites/facilities where the DEM/VALs were conducted, and Section 4 describes the demonstration approach. Section 5 presents the results of the DEM/VALs and the performance of the LRDP. Section 6 presents a cost assessment of the technology. Section 7 describes the regulatory interactions. Section 8 describes how the technology can and is being implemented. Section 9 describes the lessons learned that might be useful for other demonstrations, and Section 10 briefly summarizes the results of the project.

# 2.0 Technology Description

A description of the LRDP is presented below.

## 2.1 Description

The LRDP system is a mass-based, leak-detection system for use in bulk USTs containing petroleum fuels. If a tank is leaking, the LRDP quantitatively measures the leak rate. The LRDP system can be used to test tanks ranging in capacity from 50,000 gallons to 12.5 million gallons and will work for tanks with vertical and/or curved walls. Its modular design makes it easy to install in a tank of any depth or diameter. It can be installed through a standard 8-in.-diameter opening without removing any fuel from the tank. The LRDP system can be permanently installed in a tank and used for on-line monitoring and precision (tightness) testing. It can also be used as a portable system and be moved from tank to tank for periodic testing of any tank in the fuel farm. The former is the preferred configuration, because of the regulatory requirements for monthly monitoring. A test can be completed in 10, 24, or 48[1] hours. Better performance is achieved as the duration of the test is increased. For almost all applications, a 10- or 24-h test is sufficient; a 48-h test can be used if enhanced performance is needed.

The LRDP can be used to test all three types of large, regulated, fuel USTs owned by the DoD: (1) bulk, field-erected USTs with vertical walls, (2) very large bulk USTs like those at Red Hill, and (3) large, shop-constructed cylindrical USTs (e.g., 50,000-gal tanks). The largest bulk USTs owned by DoD have diameters of ~134 ft and capacities of 2,000,000 to 4,000,000 gal. The largest USTs are located in Red Hill and have a capacity of 12,500,000 gal; these tanks are 250 ft in height and 100 ft in diameter; the top and bottom 50 ft of the tank is dome shaped. The 50,000-gal USTs are nominally 10.5 (to 12.0) ft in diameter and 77.2 (to 59.0) ft in length.

The pre-production prototype of the LRDP system, developed in this ESTCP project and shown in Figure 4, is a fully automatic, computer-controlled system. It is comprised of (1) an in-tank level sensing unit, (2) a local embedded remote test controller to implement a test and to collect and analyze the data from a test, and (3) a host computer to initiate, display, report, and archive the results of a test. The level-measurement sensor is an industrial differential pressure (DP) sensor that is located in a sealed container at the bottom of the in-tank sensing unit. A test is initiated by an operator using the host computer. The remote test controller, located in close proximity to the tank, automatically operates the LRDP system. A test report is generated upon completion of the test. The LRDP system is compatible with the DoD Fuels Accounting System (FAS) and can be integrated with FAS to test the tanks in a fuel farm or bulk storage terminal.

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[1] A 48-h test was evaluated for performance at NAS North Island. The performance obtained for the 24-h test in the second evaluation conducted as part of this ESTCP project was better than that obtained for the 48-h test in the first evaluation. This result is a consequence of contamination of the first results with a small inflow that occurred during the evaluation. If a 48-h test were performed, it would have better performance than a 24-h test. It should only be used, however, if the results of the 24-h test are inconclusive and better performance is needed. Although better performance will be achieved with a 48-h test, the performance claim can be no better than the 24-h test, unless it is re-evaluated.

The in-tank level sensing unit of the LRDP system that has been designed for tanks with vertical walls (that is, upright cylinders with flat bottoms) is comprised of the following:

(1) a **reference tube** that extends from the top to the bottom of the tank

(2) a **valve**, located near the bottom of the tank, with which to open and close the tube

(3) a **sealed container** mounted at the bottom of the reference tube

(4) a **differential pressure sensor**, mounted in a sealed container located at the bottom of the tank, that measures the *difference* between the level of liquid in the tank and that in the reference tube

(5) two **pressure sensors**, mounted in the sealed container, that can be used to measure the level and specific gravity of the fuel in the tank

(6) a **temperature sensor**, mounted on the differential pressure cell in the sealed container, that can be used to compensate the differential pressure sensor or the pressure sensors for temperature, and/or to measure the temperature of the fuel at the bottom of the tank

(7) **electrical wires** (4-20 ma contained in a sealed conduit) that connect the bottom-mounted sensors to the data acquisition system outside the tank, and

(8) a special bellows-mechanical **mounting** system to eliminate thermal movement of the reference tube and transducer enclosure.

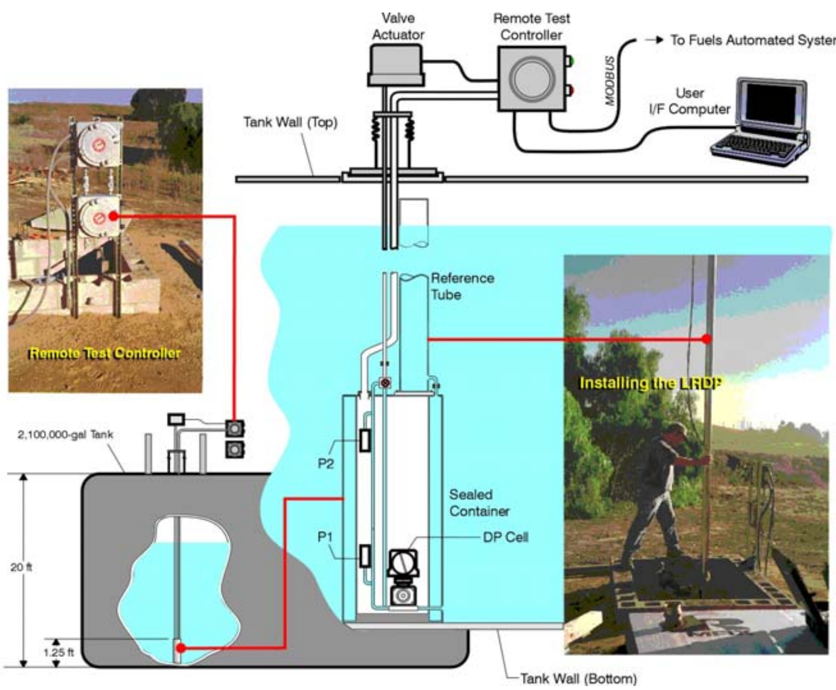


**Figure 4.** LRDP system used in the ESTCP bulk UST DEM/VALs.

The fuel in the tank is allowed to enter or leave the reference tube through a valve located at the bottom of the tube. The valve is opened and closed electronically (a function that can also be done manually). Except for a test, the valve is left in the open position. This allows fuel from the tank to enter the reference tube until the level of liquid is the same in both. When the valve is open, i.e., when the level of liquid in the tube is identical to that in the tank, the precision and accuracy of the LRDP system can be checked. When the tank is to be tested, the valve is closed, isolating the fuel in the tube from the fuel in the rest of the tank. With the exception of a level change due to a leak, the level of the fuel in the reference tube mimics the level of the fuel in the tank. The DP sensor measures the difference in the levels of fuel between the reference tube and the tank. If the *rate of change* of the level in the tank (which can be expressed in terms of gallons per hour based on a height-to-volume conversion from the tank's strapping table) exceeds a pre-set detection threshold, the tank fails the test.

### 2.2.1 Sources of Noise

Ambient noise—real and apparent volumetric changes not associated with a leak—may, unless compensated, mask the presence of a leak or look like a leak. The LRDP compensates for the important source of ambient noise. Since it is known that the reference tube is not leaking, and since level changes in the tube mimic those in the tank, the ambient noise is removed from the test result. Because the LRDP is a mass-based system, it compensates automatically for the greatest source of noise—the level (volume) changes produced by thermal expansion and contraction of the fuel. Note that this approach must be modified for tanks with curved walls (e.g., horizontal cylinders, or vertical cylinders with spherical tops and bottoms). To address this type of tank, the LRDP system incorporates a second design in which the constant-diameter reference tube is replaced by a variable-shaped tube that mimics the cross-sectional changes in the tank's geometry [17]. Such a reference tube was used to test the 50,000-gal USTs during the Hunter Army Airfield DEM/VAL.

High performance is achieved with the LRDP system, because the novel design of the in-tank sensing unit results in (1) a very high precision for making level measurements with an off-the-shelf differential pressure sensor and (2) effective compensation of the thermally induced changes of the fuel, the sensors, the tank, and the mounting system. For bulk tanks, both high precision and effective compensation is required to meet regulatory guidelines.

**Table 3.** Illustration of the Magnitude of the Sources of Errors in a 122.5-ft-Diameter Bulk UST Containing 2,100,00 gal of Fuel

| | **Level Change** (in.) | **Temperature Change** ($^{o}$C/h) | **Volume Change over 24 h** (gal) | **Volume Error 24-h Test*** (gal/h) | **MDLR** 24-h Test** (gal/h) |
|---|---|---|---|---|---|
| Precision | 0.001 | | 1.50 | 0.062 | 0.22 |
| Thermal Expansion or Contraction of Jet Fuel | | 0.01 | 504.00 | 21.00 | 75.39 |
| 6-in. of exposed manway by air temperature | | 0.10 | 22.04 | 0.92 | 3.30 |
| DP sensor by fuel temperature | | 0.01 | 17.63 | 0.73 | 2.64 |
| DP sensor/electronic equipment by air temperature | | 0.10 | 176.33 | 7.35 | 26.38 |
| Total without Thermal Expansion or Contraction | | | | 7.44 | 26.71 |
| **Total** | | | | **22.28** | **79.99** |

* Assumes 24 degrees of freedom in regression line. ** TLR for a $P_D$ = 95% and a $P_{FA}$ = 5%.

Table 3 illustrates, for the conditions given, the magnitude of the errors in a 122.5-ft diameter UST and the MDLR that would result if these errors were not compensated. These conditions are modest and do not represent extreme conditions. Unless these thermally induced sources of noise are compensated by the leak detection system, leaks as small as 0.2 or even 1.0 or 2.0 gal/h would be masked by these large volume changes and would not be detected. Conversely, unless these volume changes are not compensated, they might be confused with a leak and lead to false declarations (i.e., false alarms). It is the latter that tends to plague systems and results in a loss of confidence in the system and ultimately in not using the system by fuel farm operators.

As can be seen in Table 3, any one of the errors, if not compensated, can be large enough to prevent the method from meeting the regulatory requirements. For example, if a method has a precision of 0.001 in., this results in a volume change of 1.50 gal over a 24-h period in a 122.5-ft-diameter tank. This assumes that a regression line is fit to data in and that there are 24 degrees of freedom. Assuming this was the only error, the method would have a MDLR of 0.22 gal/h.

In a tank with a capacity of 2,100,000 gal, a 0.01$^{o}$C/h change in temperature results in a 21.00 gal/h volume change. If this thermally induced volume change is not compensated to within 0.01$^{o}$C/h, then the error would be too large to use this approach for leak detection. This is the main reason mass-based systems, rather than volumetric (level and temperature) systems, are used for bulk USTs. A mass-based system compensates this error directly as part of the measurement. Even if a volumetric system can compensate to 0.001$^{o}$C/h, a performance of 7.54 gal/h would result, which is also too large for routine use.

Exposed parts of the tank upon which the leak detection system is mounted will change elevation by thermal expansion and contraction of the mounting system. Diurnal temperature swings of over 15 $^{o}$C are not uncommon. An estimate of the thermally induced level change based on a temperature difference of 2.4$^{o}$C over a 24-h period (0.1$^{o}$C/h) on an exposed section of manway of 6 in. results in 0.92 gal/h error. This error is quite common for improperly mounted systems and would prevent the reliable detection of leaks of 3.3 gal/h if there were no other errors. As shown in Table 3, the thermally induced changes in a differential pressure cell or it electronics can result in apparent height changes that are also very large if not compensated.

All of these potential sources of error must be reduced or compensated to about a third of the target leak rate required for regulatory compliance. In California, this means that monitoring methods must compensate to within 0.3 gal/h to meet a monthly monitoring requirement of 1.0 gal/h and to within 0.06 gal/h to meet a periodic (semi-annual or annual) precision test of 0.2 gal/h. The LRDP compensates for over 98% of all of the thermally induced changes listed in Table 3, and because of the reference tube, the LRDP can achieve a very high precision with a DP sensor (0.0002 in.).

**Figure 5.** In-tank portion of the LRDP system for a bulk UST with vertical walls.

### 2.2.2 Reference Tube

The key components of the in-tank sensing unit are a reference tube that spans the full usable height of the tank and a sealed container at the bottom of the tube (and tank) that houses the measurement sensors. Unlike most other mass-based systems, the LRDP

**Figure 6.** Shaped reference tube used
UST.

system does not require a high-precision DP sensor nor does it require special compensation for changes in the temperature of the pressure sensor itself. Instead, the precision of the LRDP is controlled by the reference tube. The reference tube, because it greatly reduces the dynamic range over which measurements must be made, increases the precision of the DP sensor significantly - 100 to 3,000 times in comparison to systems without a reference tube. This allows the LRDP system to employ an off-the-shelf, inexpensive, and rugged DP sensor instead of a special purpose, expensive and delicate one. An industrial grade DP sensor, which is manufactured by Rosemount, is located in the sealed container and measures the change in level between the fuel inside the reference tube and in the tank.

A straight, constant diameter tube is used to test tanks with vertical walls (Figure 5), and a geometrically shaped tube is used to test tanks with curve walls (Figure 6). For bulk tanks with straight walls, the reference tube has a diameter of 3.5 in. For tanks with curved walls, the tube is shaped so that the product surface area at any depth changes in the same proportion in the tube and in the tank [17]. A shaped reference tube is needed for 50,000-gal horizontal tanks and for the 12.5-M-gal tanks at Red Hill. If the tube is not shaped appropriately, the thermally induced volume changes of the fuel cannot be accurately compensated. This is true for both mass-based and volumetric systems. The errors can be large enough to prevent the system from meeting the regulatory guidelines. In the Red Hill tanks, for example, the tapered tube eliminates an error of 20 gal/h that would otherwise be present in the measurement. Such errors can occur even when the rate of change of temperature is extremely small (e.g., $0.0023^{o}C/h$, as it was in this estimate).

**Figure 7.** Bottom container of the LRDP housing the sensor systems.

The same shaped reference tube can be used for all tanks with the same diameter, regardless of capacity. For best accuracy, the design of the tube should change as the diameter of the tank changes. For 50,000-gal tanks two reference-tube designs would cover the range of tank diameters (generally 10.5 to 12.0 ft) found in commercial and DoD tanks.

### 2.2.3 Measurement Sensors in a Bottom-Mounted Sealed Container

All of the measurement sensors are located in a special sealed container at the bottom of the tank (Figure 7). This container is 18 in. in height and 6.8 in. in diameter. The sealed container is actually comprised of a cylinder within a cylinder. The inside cylinder is dry and contains a differential pressure sensor, one or two pressure sensors, and a temperature sensor attached to the differential pressure sensor. The annular space that exists between the inner and outer cylinder contains fuel and communicates with the fuel in the reference tube attached to the top of this bottom module. As an extension of the reference tube, the cross-sectional area of the annular space also changes in the same proportion as the product surface area in the tanks changes. If the tank has vertical walls, then the cross-sectional area of the annular space does not change. If the walls of the tank are curve, then a special spacer bar is inserted into the annular space whose volume changes with depth so that the cross-sectional area of the annular space changes appropriately with depth. A spacer bar, whose volume is constant with depth, can be used to reduce the cross sectional area in the annular space if a reference tube with a smaller diameter than 3.5-in. is used. These spacers are made of aluminum to reduce weight. To avoid the possibility of leakage, the bottom of the container is welded closed.

The DP sensor is the main sensing element of the LRDP. It measures the difference in level of the fuel in the reference tube and in the tank. The DP sensor measures the change in level between the fuel inside the reference tube and in the tank. The two sensing ports of the DP sensor are at the same elevation. One of the ports communicates directly with the fuel in the tank. The other port communicates with the fuel in the annular space. As stated above, an industrial grade differential pressure sensor, which has a long-term demonstrated track record of performance, can be used in the system, because the measurement configuration only requires measurements to be made over the small differences in height that may occur in the reference tube and in the tank during a test. The differential pressure sensor is set to operate over a height range of $\pm$0.5 in. of fuel; the same dynamic range was used for the Red Hill tank. This configuration increases the precision of the differential pressure measurement by a factor of at least 150 over a system that does not use a reference tube. Because of the small dynamic range of the measurement, the precision of measuring level is 0.0002 in., where the precision is defined as the one-standard deviation of the measured level fluctuations (Figure 8).

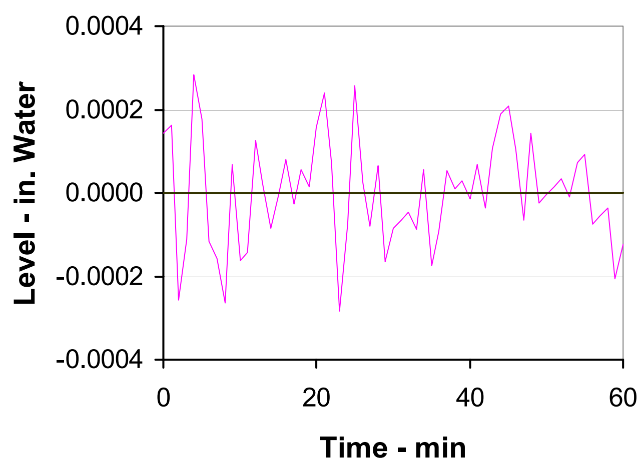


**Figure 8.** A time series of the LRDP illustrating that the precision is 0.0002 in.

A temperature sensor (RTD) is attached to the body of the DP sensor. It can be used to compensate for any thermal changes of the sensor if they become large. None of the field demonstrations and evaluations conducted to date has required such compensation, because the sealed container housing the sensors is located in a nearly constant temperature bath (i.e., the fuel in the bottom of a tank). While 0.01$^{o}$C/h changes in the fuel temperature are large enough to produce volume changes of the fuel that mask a leak, such temperature changes are too small to affect errors in the DP sensor measurement. Temperature changes of several degrees per hour or more are required to introduce errors that may impact the accuracy of the DP sensor measurements. The temperature sensor mounted on the DP sensor can also be used to obtain an estimate of the mean temperature of the fuel in the tank.

One or two absolute pressure sensors may be located in the sealed container. If one pressure sensor is located in the container, then the level of the fuel in the tank can be measured and used for inventory control purposes. If two pressure sensors are installed in the container, then in addition to the level measurement, either the specific gravity of the fuel can be measured, or the level of any water at the bottom of the tank can be measured. The former measurement is made with the two sensors communicating with the fuel in the tank and separated by 16 in. The latter measurement is made by placing one of the sensors at a depth near the bottom of the tank, so that it is located in the water when water is present.

### 2.2.4 Mounting of the In-tank Sensor Unit

The reference tube and its connection into the annular space extends from the bottom of the tank to a level that is higher than the maximum level at which the tank is to be tested. The top of the reference tube must be able to communicate freely with the vapor space. Many years of experience has indicated that any leak detection system with a level sensor needs to rest on the bottom of the tank. Thus, the reference tube should be installed such that it rests on the bottom of the tank. Suspending the reference tube (or a level sensor from the top of the tank) introduces errors due to the thermal expansion and contraction of the staff, chain or tube used to suspend the level sensor. Problems are also encountered when the system is rigidly attached to a manway plate at the top of the tank, because the manway plate can raise (or lower) the reference tube due to thermal expansion or contraction. As shown in Figure 9, the mounting system is comprised of a 4-in. diameter cap in the manway of the tank, a bellows to prevent thermal movement, and a motor to open and close the valve. The bellows mounting system eliminates the thermal movement of the tank or manway

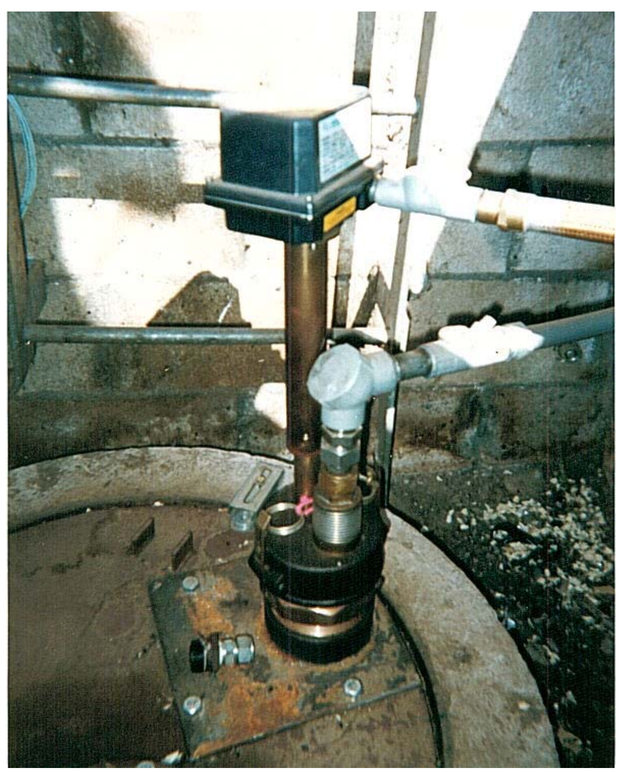

**Figure 9.** Mounting system for a permanently installed LRDP in a bulk UST.

subject to ambient air temperatures. While thermally induced level changes of several thousandths of an inch can introduce large test errors, the bellows system allows for level changes of many hundredths of an inch (0.03 to 0.06 in.) before any errors are introduced.

### 2.2.5 Remote Test Controller

The remote test controller, shown in Figure 10, is located near each tank to be monitored and contains a microprocessor, a disk, a temperature sensor, and a stable resistor. The remote test controller can collect up to 8 channels of data, but more channels can be added, if required. Once a test is initiated from the host computer, the microprocessor collects, analyzes, outputs, and stores the data and the results. The analysis not only includes a computation of the measured volume rate, which is equal to the leak rate, if a leak is present, but also includes a comprehensive set of quantitative data quality indices (DQIs) that automatically assess the quality of the data before the data are used to complete a test. Up to 50 tests can be conducted and stored without downloading the data. The power supply and sensor electronics are also located in the controller unit. Because of the temperature sensitivity of the pressure sensors and the large swings that can occur in the ambient temperature during a test, a temperature sensor and a stable resistor are installed in the controller for compensation. Only one, either the stable resistor or the temperature sensor, is needed for compensation. However, both have been demonstrated as effective in this project.

**Figure 10a.** Photograph of the remote test controller.

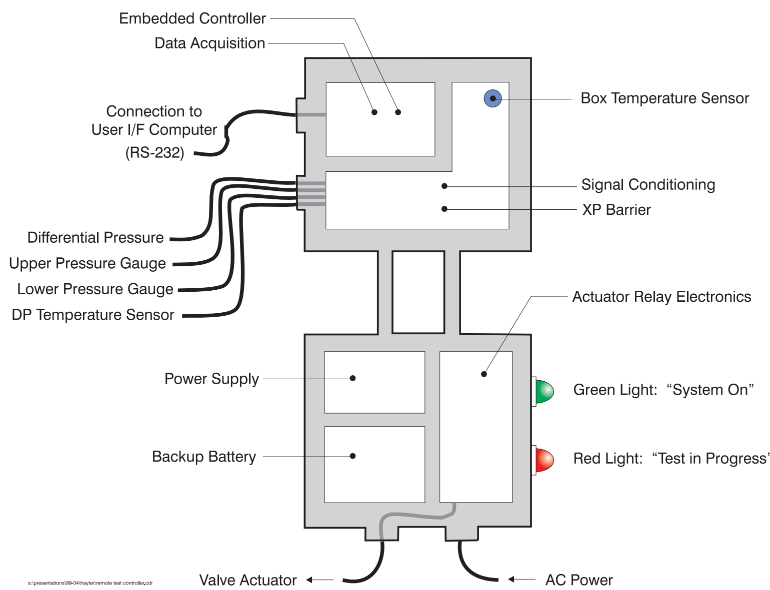


**Figure 10b.** Schematic of the remote test controller.

### 2.2.6 Software

The host computer is used to initiate a test with its user-friendly Graphical User Interface (GUI) developed in a Windows 98 platform. Appendix D shows seven of the user screens. The first screen (Figure D-1) allows the operator to conduct a leak detection or review the results of previous leak detection tests.

The next screen (Figure D-2) asks what type of test will be conducted (a 10-, 24-, or 48-h test), the duration of the waiting period after the final tank operations have been terminated, the start of the test, and the threshold criterion. The current date and time is also given for information. The software is set up to operate using Version 1.1a of the LRDP system [8-15]. Once the tank diameter is specified and the type of the test is selected, the threshold criterion and the waiting period change accordingly. If a longer waiting period or a different threshold is desired, it can be entered directly.

The screen shown in Figure D-3 can be used to initiate a test now or to schedule one for a later time. Before a test can be started, it is imperative that the tank is isolated from its associated piping. A special reminder screen (Figure D-4) is displayed before a test can be initiated to make sure that the operator has shut all of the valves necessary to perform a leak detection test.

A test is initiated by clicking on the Start/Schedule Test button. One a test is initiated, no further action is required by the operator. Output of a time history of the data from any of the sensors can be displayed during the test. This screen also contains the relevant information about the test being conducted, including the start and stop time.

The next screen (Figure D-6) shows an output report from a leak detection test. This report can be printed and is sufficient to address all of the typical reporting requirements of the state and local regulating agencies.

The screen shown in Figure D-7 summarizes the results of previous tests and allows the user to obtain the test reports from any previous test. This screen is particularly useful when addressing the monthly monitoring requirement or when averaging data.

### 2.2.7 Conduct of a Test

A test consists of a waiting period (between the last transfer into and out of the tank and the start of a test) and the test itself. The waiting period used in these evaluations was 2 h. This waiting period is not necessary from a performance stand point, but practically, it insures that the tank has been prepared for a test, i.e., all valves have been closed and any drainback or disturbance from pumps etc. have been minimized. The basic procedure for conducting a test is described below.

- Specify what type of test will be conducted (i.e., the test duration) and what waiting period will be used. There are two standard tests: (1) the LRDP-10, comprised of a 2-h waiting period and a 10-h test, and the LRDP-24, comprised of a 2-h waiting period and a 24-h test.
- Specify the threshold to be used in determining whether or not the tank passes or fails the test
- The valve at the bottom of the reference tube is automatically left open between tests and the level of the fuel in the tube should be at the same level as the fuel in the tank

- If the LRDP is being inserted into the tank for a test, allow the reference tube to fill up with fuel so that the fuel in the tube and in the tank is at the same level
- Close the valve to isolate the fuel in the reference tube from the fuel in the tank
- Begin collecting data with the LRDP. The data collected during the waiting is not used in the analysis. The data collected following the waiting period is used in the analysis.
- Generate a time series of the difference in the level changes in the tube and the tank using the pressure measurements obtained with the DP sensor. Level measurements are obtained by dividing the pressure measurements by the specific gravity of the fuel (e.g., 0.82).
- Convert the level time series to a volume time series using the height-to-volume conversion (HVC) factor for the tank. For a 122.5-ft-diameter tank, the HVC factor is 7,347 gal/in.
- Apply a set of Data Quality Indices (DQIs) to the volume time series to determine if the data collected is of sufficient quality to be used in a test. If a data quality problem is encountered during the first half of a test, the test is automatically extended by a time interval equal to half the test duration. If a problem is encountered during the second half of the test, the test is automatically repeated. The test operator can abort the test at any time if there is not enough time to complete the tests before normal operations begin. Thus, the test may be extended either 12 or 24 h for a 24-h test, or 5 or 10 h for a 10-h test, depending on which half of the test data is of poor quality. If the test is extended, at present, the software only allows an extension equal to the duration of the test. If the extended test data fail the DQI tests, then another test can be initiated immediately or at a later time.
- If the data fail the DQI tests, then the output of the test is *Inconclusive* and must be repeated.
- If the data pass the DQI tests, then the rate of change of volume is computed by fitting a regression line to the volume time series data
- The measured volume rate is compared to the detection threshold to determine whether the test is a *Pass* or a *Fail*. The tank passes the test if the measured volume rate is less than or equal to the threshold. If the tank fails the test, the tank and the test data should be checked for problems, and then the tank should be re-tested. A leak rate is only printed out if the tank fails the test.

### 2.2.8 Data Quality Indices

Before a test is begun, the operator should verify that the valves required to isolate the tank from its associated piping are closed and that the level of the fuel in the tank is below the top of the reference tube (which is usually above the maximum safe operating level of the fuel for the tank).

A number of data quality tests were developed and incorporated into the data acquisition and analysis software to identify potential problems that might occur during a test. These data quality problems were identified using previous data collected with the LRDP. One of the data quality tests is designed to determine if a pump is turned on during a test (Figure 11). Two pump signatures are shown in Figure 11. A test should not be conducted if product is being removed or added to the tank.

Another data quality test is designed to determine if there is a step discontinuity in the data (Figure 11). Such discontinuities might occur, for example, if a product sample is obtained during the test, or if the tank is opened during a test.

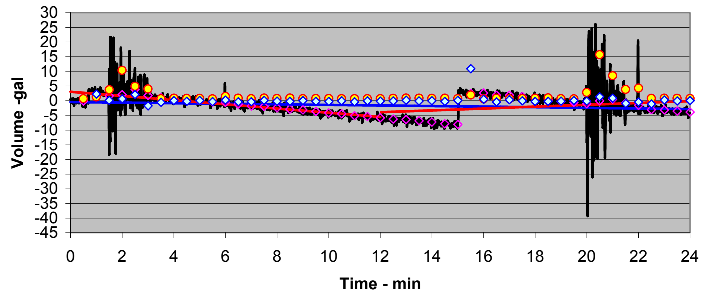


**Figure 11.** Example of the results of the data quality indices identifying that a pump was turned on during a test.

Another data quality test is designed to determine if there are any data dropouts or wild points in the data set (Figure 11). Still another data quality test is designed to determine if the fluctuations in the level are too large for analysis. Strong winds, internal waves, and other physical factors might produce such fluctuations. A data quality test is also designed to determine if there are any inflows during a test.

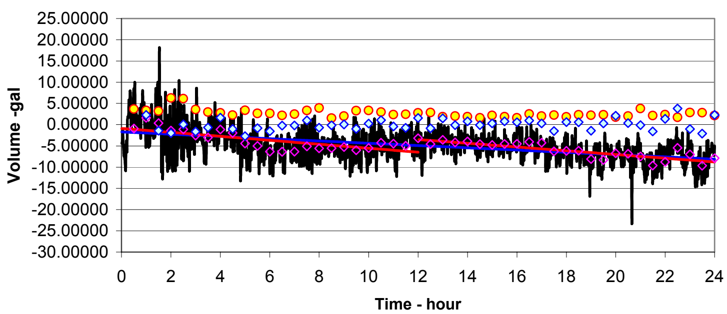


**Figure 12.** Example of the results of the data quality indices identifying a problem with the stability of the data trend.

Another data quality test is also used to determine if the data set is sufficiently stable to draw a conclusion. A non-stationary leak, structural deformation of the tank, evaporation or condensation, or a particularly strong thermal affect might produce an unstable data set. All of these data quality indices are set at the time the LRDP is installed and should not be changed unless the number of inconclusive tests is too high. Figure 12 shows a data set with stability problem in which the trend for the first half of the test is different than for the second half of the test.

During the evaluation, the data quality indices were set sufficiently high so that all of the data would be of sufficient quality to use except for very extreme problems. This was required to minimize the time required to complete the evaluation. It was justified because many of the problems that might be encountered operationally would not be encountered during a controlled evaluation (e.g., a transfer during the middle of a test).

### 2.2.9 Summary

In summary, the LRDP is designed to easily and accurately compensate for the major sources of noise that might occur during a leak detection test. Accurate compensation is obtained because the LRDP is specifically designed to compensate for each source of noise without the need for arrays of temperature sensors or delicate and expensive level sensors. As a consequence, all of the sensors are off-the-shelf, commercially available sensors that have a proven track record of performance. The reference tube, the bellows mounting stand, and the bottom-mounted sensors are the key elements that lead to high performance. Other mass-based systems do not work as well because the sensors are mounted at the top of the tank and are subject to large diurnal swings in the ambient air temperature, are very delicate and expensive to achieve the level of precision required to conduct a test, and may require the use of nitrogen gas.

## 2.2 Strengths, Advantages, and Weaknesses

The LRDP system is ready for *Full-Scale Implementation*. It has the following advantages over other technologies that might be used for leak detection in large tanks:

- The LRDP is a mass-based technology, which is a preferred technology of the owners and operators of DoD bulk USTs.
- The LRDP can be used to perform a leak detection test without removing fuel from the tank.
- The LRDP system can be installed through a standard 8-in.-diameter opening in the tank.
- The LRDP can be used to test USTs with both vertical and curved walls. The DEM/VALs were conducted in a bulk UST with vertical walls and a 50,000-gal UST with curved walls. In another evaluation, the LRDP was used to test bulk USTs with both vertical and curved walls. For tanks with curved walls, a special shaped reference tube needs to be constructed.
- The LRDP has the best performance and the shortest test time (10 h) of any mass-based technology. It is the only system that conduct a test in less than 24 h.
- The output of a leak detection test is easy to interpret, because it is a direct measurement of the leak rate in gallons per hour, the quantity of regulatory and engineering interest.
- The system is constructed of off-the-shelf sensors and components that have a proven track record of high performance, excellent reliability, and low maintenance.
- The LRDP can be used as a portable system for performing a precision test as part of a leak detection testing service or permanently installed in the tank for automatic tank gauging operations including monthly monitoring and precision testing.
- The LRDP system has been successfully demonstrated in a variety of operational DoD tanks.
- The LRDP system has been evaluated for performance and is listed with the National Work Group on Leak Detection Evaluations, a nationally recognized, regulatory group that allows the local and state regulatory agencies to select methods for their use.
- The LRDP system is the only mass-based system that can meet both the monthly monitoring and the semi-annual or annual precision test regulatory guidelines in California.
- The LRDP system is approved for use in California.
- The recurring cost of using and maintaining the LRDP are significantly lower than tracer methods and other mass-measurement methods. Because the LRDP system is a mass-

based system, it inherently compensates for the thermal expansion or contraction of the fuel in the tank during a test. Furthermore, accurate tests can be initiated without a long pre-test waiting period.

- The mounting system eliminates thermally induced movement of the reference tube during a test.
- Thermally induced drift of the differential pressure sensor is virtually eliminated, because it is mounted in a sealed container at the bottom of the tank.
- Because the differential pressure sensor used to measure level (volume) changes in the tank needs a dynamic range of only 1 in. (rather than the total height of the tank, like other mass-based systems), the LRDP has the precision (0.0002 in.) to detect very small leaks in large-diameter tanks.
- The system is self-calibrating, and the performance and functionality of the LRDP can easily be checked between leak detection tests.
- The sensors used to measure differential pressure, pressure, and temperature are robust and have been used commercially in the pipeline leak detection systems that Vista Research has been selling for many years.
- The LRDP system can be modified for testing aboveground storage tanks (ASTs).

The main limitation of the method is that all of the valves in the fuel facility that isolate the tank from its associated piping must seal completely; if these valves do not completely seal, the LRDP system will detect this flow. This is not usually a problem for monitoring, because the monitoring standards are high enough to accommodate small flows across the valve. For precision tests, however, the valves must seal completely. If the tank fails a test (either a monitoring or precision test), a detailed inspection of the tank and pipe valves is performed next assuming this is the reason for the failed test, and if necessary, valve blinds are installed to complete the test. In many instances, closing the valves tighter is all that is needed. The magnitude of this problem is not known for bulk tanks, but it is the same problem encountered and successfully addressed for routine monitoring of underground storage tanks at service stations.

## 2.3 Factors Influencing Cost and Performance

Unlike remediation technologies, the performance of an LRDP is essentially independent of the site and the facility, because through the third-party evaluation, the performance is estimated over a range of conditions that the system will operate. While these conditions may not include the extremes, they are sufficient to identify performance problems that might be encountered under more challenging conditions. The main factor influencing the performance of the LRDP system (and other mass-based systems) is the size of the tank. The performance of the LRDP scales with the product surface area (tank diameter squared) in a prescribed way as determined by the third-party evaluation [6].

The main sources of problems during a test are operational ones. It is important that the tank is completely isolated from the associated piping, i.e., all valves are completely sealed, before a test is initiated. It is also important that any drainback of fuel into the tank has ceased before a test is initiated.

The LRDP is designed to fit into a standard 8-in.-diameter opening in a tank. The initial purchase cost, the installation cost, and the cost of operational use and maintenance are not affected by site parameters or site geology. This assumes that electrical power is available at each tank and that communication cable has already been installed between each tank and the building where the host computer is located. This assumption is valid, because systems used to acquire inventory level data are currently being used at each site. The cost differential between an LRDP in a bulk UST with a small height (e.g., 13 ft) versus a large height (e.g., 25 ft) is insignificant and is attributed to the cost of a longer reference tube.

# 3. Site/Facility Description

An overview of the sites/facilities used in the two demonstration and validation (DEM/VAL) tests are described below. For more details, please see the ESTCP Demonstration Plan [18].

## 3.1 Background

Two types of DEM/VALs were planned. The first, and most important, was to evaluate the performance of the LRDP in a large diameter bulk UST with vertical walls following a nationally accepted standard test procedure [6]. Since the leak detection system is not affected by soil conditions and site geology, and the evaluation procedure only requires that a tank that which is not leaking, the most important criterion in selecting a DEM/VAL site is to select a site with a suitable tank that can be used in the evaluation. Two criteria were used in selecting a site. First, it was desired to perform the DEM/VAL in a tank with a large enough diameter to address all of the tanks used by DoD. Second, it was desired that no inflow or outflow due to leaking valves or drainback from piping occur during the evaluation. Both problems interfered and degraded the results of the North Island evaluation, and the estimate of system performance from the evaluation did not reflect the true performance of the system. If there were no inflows, the evaluated performance would have been at least a factor of two better than determined from the evaluation. Initially, a bulk UST at the San Pedro Fuel Farm was selected for the DEM/VAL. After a series of tests in the tank, it was found that a small uncontrolled outflow existed due to a faulty valve. Because this outflow could not be measured independently, the DEM/VAL was moved to the Point Loma site, because it met the site selection criteria and the facility expressed an interest in using the system.

The second DEM/VAL was to demonstrate that the LRDP could be used for leak detection in a 50,000-gal horizontal tank with curve walls. While not considered a bulk UST, these large tanks are usually found at bulk fueling facilities and are used for storage of fuel before transfer into a hydrant pit or a loading rack. These tanks are found at almost every military facility. The Hunter Army Airfield site was selected for the DEM/VAL because this is typically the largest tank found at Army sites and there was on-site support and interest in fielding a DEM/VAL.

## 3.2 Site/Facility Characteristics

Brief descriptions of the Point Loma and Hunter Army Airfield DEM/VAL sites are given below.

### 3.2.1 DEM/VAL 1: Point Loma Fuel Terminal (Third-Party Evaluation in a Bulk UST)

The Point Loma Fuel Terminal stores and supplies fuel to other facilities in the area (e.g., the NAS North Island). The facility is located in San Diego, California, and has over 30 bulk USTs.

The evaluation was conducted in Tank 175, because it was one of the largest field-erected bulk USTs owned or operated by DoD and the valves isolating the tanks had just been replaced and were expected to seal tightly. Also, the configuration of the tanks and their associated piping was easy to verify whether or not the valves sealed. Finally, the configuration afforded several ways to insure that the tanks were isolated from the piping.

Figure 13 shows the location of Tank 175. This tank is located in a hillside and stores 2,100,000 gal of JP-5 fuel. Fuel is pumped into the tank to fill it and the removal of fuel from the tank is accomplished by gravity. The tank is 122.5 ft in diameter and 23.5 ft in height. The tank is buried about 5 ft below the surface of the ground. The product surface area (PSA) of the tank is 11,786 $ft^2$. Level changes in this tank are converted to volume changes using a height-to-volume conversion (HVC) factor of 7,347 gal/in.

**Figure 13.** Tank 175 at the Point Loma Fuel Terminal.

### 3.2.2 DEM/VAL 2: Hunter Army Airfield (50,000-gal UST)

There are 30 shop-fabricated 50,000-gal USTs at the Hunter Army Airfield (a sub-unit of Fort Stewart). Each of these tanks are nominally 10.5 ft in diameter, 80 ft in length, and are made of 3/8-inch thick welded steel. The tanks originally had a cut-back asphalt coating and, in 1986-87, were lined inside with a 10-mil thick epoxy coating. Impressed current cathodic protection systems were installed at the tank batteries in 1978. Figure 14 shows the location of Tank 45, the 50,000-gal UST used in the DEM/VAL.

**Figure 14.** Tank 45 at the Hunter Army Airfield.

The thirty 50,000 gal USTs are arranged in three batteries of ten tanks each, at Pumping Stations #3, #4, and #5. The pumping stations are located in the Helicopter Landing and Parking Area. The tank batteries are about 1500 feet west of the Base Operations Building #1252 and are identified as structures #8080, #8082, and #8084. These tanks were installed in the 1952-53 time period.

Until 1996, the tanks were used to store JP5.  In 1996, the facility converted to JP8.  Neither the tanks nor the piping have ever had a discovered leak.  Each 10-tank battery has a 6-inch diameter manifold connected supply pipeline and a 12-inch diameter discharge piping system running to the aircraft fueling area.  An internal inspection, in 1997, of three selected tanks revealed the interior coating to be intact, with no signs of deterioration or significant corrosion.

# 4.0 Demonstration Approach

As stated above, two types of demonstrations were conducted. The first and most important was an evaluation of the performance of the technology following a standard test procedure used and approved by the regulating community for bulk USTs [6]. The second was a demonstration of the system on a 50,000-gal tank commonly found at bulk fueling facilities. This second demonstration consisted of a few tests to demonstrate that the system had the performance capability to meet the 0.2-gal/h monthly monitoring regulatory standard. For more details, please see the ESTCP Demonstration Plan [18].

## 4.1 Performance Objectives

The performance objectives of the DEM/VALs are established by the regulatory guidelines for detection of leaks in bulk USTs. Since there are no national regulatory compliance standards for bulk USTs, the California regulatory guidelines were adopted as the basis for the performance objectives of this project, because they are practical and the most stringent standards. These guidelines indicate that the leak detection system must be evaluated for performance by an independent third-party following a standard test procedure [6]. The results of this evaluation must be reported in terms of a $P_D$ of the target leak rate (TLR) and a $P_{FA}$. As stated above, the TLR is specified by the regulatory agency and at a minimum the $P_D$ must be equal to or better than 95% and the $P_{FA}$ must be less than or equal to 5%. The DEM/VAL at the Point Loma Fuel Terminal followed this standard test procedure. The performance objective of the DEM/VAL conducted on the 50,000-gal USTs at Hunter Army Airfield was to show that the results of several tests had the capability for detecting leaks of 0.2-gal/h, the regulatory standards for these tanks. This was accomplished by conducting a few tests and showing the results were not statistically different than the evaluation results. The evaluation results indicated that the LRDP would be able to detect a TLR = 0.2 gal/h with a $P_D$ = 95% and a $P_{FA}$ = 5%.

## 4.2 DEM/VAL 1: Point Loma Fuel Terminal (Third-Party Evaluation in a Bulk UST)

A third-party evaluation of the LRDP was conducted by Ken Wilcox Associates, Inc. (KWA). The output of the evaluation is the TLR that can be detected with a $P_D$ = 95% and a $P_{FA}$, which must be less than or equal to 5% for the system to be used. The LRDP leak detection system was designed for use in petroleum fuel tanks, but can be used for other hazardous substances. This section describes the sampling/data-collection procedure used in the evaluation, the physical set-up and operation of the facilities and equipment needed to conduct the evaluation, the conditions in the evaluation, and the output from each test conducted.

### 4.2.1 Evaluation Procedure

The LRDP was evaluated in accordance with the protocol described in the report "Alternative Test Procedures for Evaluating Leak Detection Methods: Evaluation of Bulk Field-Constructed

Tanks" [6]. This 1996 protocol was updated in 1999 for mass-based bulk leak detection systems and adheres to the guidelines specified in EPA's standard test procedures for determining and reporting the performance of leak detection systems. The update allows the performance results to scale with the product surface area of the tank and averaging of the test results to improve performance. This protocol has been approved by the NWGLDE, and has been accepted by federal, state and local regulatory agencies as the means for demonstrating the performance of bulk tank leak detection systems. This protocol is also in accordance with the evaluation protocol and reporting procedures specified in the ASTM standard practice (E-1526-93) [7].

The UST regulation for USTs requires that the performance of any leak detection that is used for testing a tank be evaluated for performance following a standard test procedure. The states, which implement the regulation, require an independent third party to perform the evaluation. The leak detection systems used for the small USTs found at petroleum service stations are evaluated in testing facilities owned and/or operated by the third-party evaluator. For systems used in bulk USTs, an operational facility must be used because no bulk test facilities exist. When an evaluation is completed, it is submitted to the NWGLDE for review and certification that it has been properly evaluated. Properly evaluated leak detection systems are then added to a list for use by the states when approving leak detection methods for use in their states. For most of the states, if a method is listed, it can be directly approved. For a limited number of states, like California and Florida, a more detailed review may be required.

As shown in Table 4, the evaluation protocol requires that 12 tests be conducted at four different leak rates and under variable fuel temperatures. The tank is emptied to 50% of capacity and refilled back to approximately 95% to produce (1) temperature conditions typical of

**Table 4.** Standard Test Schedule

| Test Prep | Test No. | Pair No. | Set No. | Nominal Leak Rate | Nominal Temp Diff |
|---|---|---|---|---|---|
| Trial run | - | - | - | 0.00 | 0 |
| Empty to 50% | 1 | 1 | 1 | LR1 | T1 |
| then refill to 95% | 2 | 1 | 1 | LR2 | T1 |
| Empty to 50% | 3 | 2 | 1 | LR4 | T2 |
| then refill to 95% | 4 | 2 | 1 | LR3 | T2 |
| Empty to 50% | 5 | 3 | 2 | LR1 | T3 |
| then refill to 95% | 6 | 3 | 2 | LR4 | T3 |
| Empty to 50% | 7 | 4 | 2 | LR2 | T4 |
| then refill to 95% | 8 | 4 | 2 | LR3 | T4 |
| Empty to 50% | 9 | 5 | 3 | LR4 | T5 |
| then refill to 95% | 10 | 5 | 3 | LR1 | T5 |
| Empty to 50% | 11 | 6 | 3 | LR3 | T6 |
| then refill to 95% | 12 | 6 | 3 | LR2 | T6 |

operational conditions during fuel deliveries and transfers and (2) the type of wall deformation that might occur as a result of a level change. Typically, the rate of change of temperature depends on the temperature difference between the fuel in the tank and the backfill and soil around it. For the purposes of the evaluation, a temperature condition, as reported on a given test, is equal to the difference in temperature between (a) the fuel in the tank and (b) the fuel brought into the tank during filling operations. (It is assumed that the temperature of the fuel in the tank *before* such a transfer is approximately the same as that of the backfill and surrounding soil.) For each test, the third-party evaluator induces leaks of a pre-determined size, all *unknown* to the testing party. At the end of the 12-test sequence, the testing party submits its estimates of the leak rates, and the testing party's data are analyzed in accordance with statistical guidelines provided in the evaluation protocol [6].

Neither the LRDP or any of the equipment used in the evaluation produce any contaminants. The product removed from the tank to simulate a leak flows through clean tubing into a clean barrel. Since the fuel is not contaminated, it is normally returned to the tank after the test. Thus, there is no test process waste, other than that resulting from final cleaning of the tube and barrel.

The test results will qualify the system for use in bulk USTs with any commercial petroleum product of grade number 2 or lighter. For other liquids, some component materials may need to be changed for chemical compatibility.

The evaluation protocol requires that performance be presented in terms of the leak detection system's $P_{FA}$ and its $P_D$ against a specified TLR. The performance is estimated directly from the histogram of the noise and the histogram of the signal-plus-noise. In general, the noise histogram is estimated from a statistical compilation of the results of many leak detection tests on a non-leaking tank. These tests are conducted over a wide range of ambient thermal conditions and induced-leak conditions such as might be expected during routine testing. For mass-based systems, where the signal (volume changes) produced by the leak are additive with the noise, the signal-plus-noise is then a shifted replica of the noise histogram. The shift (or mean) of the signal-plus-noise histogram is equal to the TLR. The histograms are generally displayed in terms of their cumulative frequency distributions (CFDs).

The performance of the LRDP system was estimated using a student-t probability model for the histograms. More detailed descriptions on how to estimate performance can be found in the standard test procedure [6]. Because mass-based systems test at a constant pressure, the signal-plus-noise histogram can be generated directly from the noise histogram by adding the leak rate of interest to the test results. This is possible, because the volume changes due to a leak are additive with those due to noise.

This is not true of all leak detection systems. With non-mass-based (and non-volumetric) systems, for example, the signal-plus-noise histogram must be generated experimentally for each and every leak rate for which the probability of detection is desired.

Unlike remediation methods, once a leak detection method is evaluated in a tank, similar performance can be expected in other tanks provided that they are not too big and the main source of noise, thermal expansion and contraction of the fuel, is not too much larger than the conditions used in the evaluation. For in-tank volumetric methods, mainly used to test the small USTs found at service stations, at least two constraints were placed on the use of the system. First, the system could not be used to test a tank that was any larger than 150% of its volume. Second, the system could not be used to test a tank when the difference in the temperature of the fuel and the ground was greater than 150% of the average temperature condition used in the evaluation. The only performance that could be claimed by the manufacturer of the system was the one that was evaluated, regardless of the size of the tank or temperature conditions under which it would be used. If a larger tank was to be tested, then another third-party evaluation had to be performed.

For bulk USTs using a mass-based system, these constraints were modified to accommodate the differences between mass and volumetric methods. The temperature constraint was eliminated, because it does not affect the performance of a mass-based system. The tank-size limitation was modified, because the performance of a mass-based system does not scale with the volume of the fuel in the tank; it scales with the product surface area. Because of the limited number of bulk USTs and the wide range of tank sizes, the NWGLDE increased the multiplier from 150% to 250%. If the evaluation tank was properly selected, than once evaluated, it could be used to test any tank within the DoD. The use of the 150% constraint would have meant that at least three or four evaluations would have had to be conducted to cover all of the tanks. Because of the large range of tanks to be tested, the NWGLDE required that the performance of the method be scaled by the product surface area. Thus, for tanks larger than the one used in the evaluation, the performance of the method would be worse than that achieved in the evaluation, and for tanks smaller than the one used in the evaluation, the performance would be better. The NWGLDE also limited the TLR to no less than 0.2 gal/h, regardless of scaling. This scaling can be technically justified and has been experimentally verified for mass-based systems, but not for volumetric methods.

KWA conducted its third-party evaluation of the LRDP system at the Point Loma Fuel Terminal, on a 122.5-ft-diameter, 2,100,000-gal bulk UST. This tank was selected because it was one of the largest diameter tanks owned and operated by the DoD, and the valves that are used to isolate the tank from its associated piping were new, double-block valves that sealed tightly. The tank contained jet fuel with a specific gravity of approximately 0.82. The tank was approximately 23.8 ft in height. The tests were conducted between 87 and 90% of capacity, the maximum safe operating level for the tank. Several additional tests were conducted at 50% capacity to demonstrate that the performance does not vary with product depth.

The evaluation was done in accordance with the EPA guidelines described above. With a mass-based system like the LRDP, there is no real need to induce leaks during an evaluation, because, as stated above, volume changes due to a leak are simply additive with those due to noise (for example, thermal expansion or contraction of the fuel). Induced leaks are included in the evaluation, because they are required by the protocol to create a blind testing situation and to ensure that the system actually responds to a leak.

### 4.2.2 Evaluation Tank

The evaluation was conducted at the Point Loma Fuel Facility over a three-month period beginning on March 22, 2000 and ending on June 8, 2000. The tank used in the evaluation is located on a hillside and stores JP-5 fuel. The fuel is pumped into the tank to fill it and the removal of fuel from the tank is accomplished by gravity.

The evaluation was performed in an operational 2,100,000-gal steel-lined concrete tank containing jet fuel. The tank was 122.5 ft in diameter and 23 ft-5 in. in height. Figure 13 showed the location of the tank in the side of a hill.

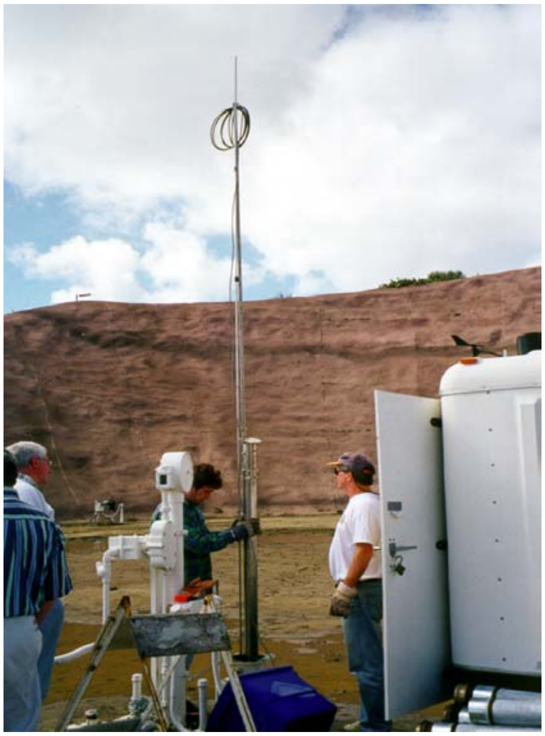

**Figure 15.** Installation of the LRDP in the Point Loma tank.

The LRDP was installed in the tank and checked out on 15-17 February 2000. Representatives from NFESC, KWA, Vista Research, and Vista Engineering were present. A two-person team is needed to install the system. The total installation time is less than 4 h. The LRDP was installed in an 8-in. opening (Figure 15). The LRDP used at North Island and KWA's level gauge and RTD array were installed in a 22-in.-diameter manway located about 10 ft away from the 8-in. opening. The peristaltic pump used to induce leaks in the tank was also located in this manway.

Level changes in this tank can be converted to volume changes using a height-to-volume conversion factor of 7,347 gal/in. Testing during the evaluation was accomplished by KWA personnel following the LRDP testing procedures specified by NFESC and Vista Research. Leak simulations and fuel deliveries were also defined by KWA. The LRDP data were collected by KWA. The output of each test was automatically output from the system. The results from additional test durations were also output from a worksheet used by KWA using the same analysis procedure as used in the system. The evaluation was interrupted, as required by fuel farm personnel, to support military and fuel operations. Delays of one or more days to a week or more sometimes occurred in executing the evaluation protocol.

For comparison purposes, the LRDP evaluated in an 88-ft-diameter tank at NAS North Island (Figure 3), was also installed in the tank through a 22-in.-diameter manway near the 8-in. opening. This was done to demonstrate that the performance of the modified version of the system developed under this ESTCP project was no different than the system evaluated previously. The level data obtained with both systems, as expected, were nearly identical.

Leaks were induced by KWA through the manway. For each test, the volume rate measured by the LRDP system was compared to the leak rate induced by KWA. Twelve tests were conducted. There was a total of six fuel transfers. Fuel was transferred from other tanks in the fuel farm. The temperature of the received fuel and the fuel in the tank was measured for each test. Tests were conducted with the tank at approximately 90% full with additional tests conducted at 50% full. The induced leaks were monitored by KWA throughout the three-month evaluation.

The induced leaks were produced by pumping fuel out of the tank with a peristaltic pump. Nominal leak rates of 0.4, 0.8, and 2.0 gal/h were randomly induced during the evaluation. Neither the nominal nor actual leak rate was made known to NFESC or Vista until many months after the evaluation had been completed and the final evaluation report was prepared. Leak rates were calculated from the total mass of fuel removed from the tank during the test and the density of the fuel that was measured with an analytical balance in a laboratory. The mass of the fuel removed from the tank was measured by pumping the fuel into a barrel hanging from a load cell. The uncertainty in the induced leak rates was less than 0.01 gal/h. During each test, KWA also verified the magnitude of the induced leak rate by measuring the pump rate with a graduated cylinder and a stop watch.

Fuel levels and fuel temperatures were electronically monitored by KWA throughout the evaluation using a level gauge and an RTD array. This allowed KWA to record and document the exact times and temperatures of the fuel deliveries. The temperature array consisted of RTDs located in the bottom 50% of the tank.

### 4.2.3 Evaluation Conditions and Test Results

The test conditions and results obtained during the evaluation are summarized in Table 5. Column 1 gives the test number, and column 2 gives the date and time that each test was started. The level change due to the delivery of fuel to the tank prior to the start of the test is shown in column 3, and the temperature condition (the difference in temperature of the fuel in the tank and

**Table 5.** Summary of the Test Results and Induced Leak Rates for the LRDP Systems

| Test No. | Test Start (d/m/y (hhmm)) | Level Change due to Delivery (in.) | Temperature Condition[1] (°F) | Fuel Depth (%) | KWA Nominal Induced Leak Rate[2] (gal/h) | KWA Actual Induced Leak Rate[2] (gal/h) |
|---|---|---|---|---|---|---|
| 1 | 03/22/00 1539 | 116.0 | 0.2 | 90 | -0.3 | -0.327 |
| 2 | 03/23/00 1736 | N/A | N/A | 90 | 0.0 | 0.000 |
| 3 | 03/27/00 1519 | 113.4 | -0.2 | 89 | -0.4 | -0.444 |
| 4 | 03/28/00 1728 | N/A | N/A | 89 | -0.8 | -0.824 |
| 5 | 04/05/00 1715 | 106.0 | -0.6 | 87 | -1.0 | -1.040 |
| 6 | 04/06/00 1919 | N/A | N/A | 87 | 0.0 | 0.000 |
| 7 | 04/18/00 1614 | 111.3 | -0.2 | 89 | -0.8 | -0.765 |
| 8 | 04/19/00 1740 | N/A | N/A | 89 | -0.2 | -0.170 |
| 9 | 04/27/00 1308 | 63.6 | 1.4[3] | 90 | -2.0 | -1.934 |
| 10 | 05/11/00 1500 | N/A | | 88 | -2.0 | -1.820 |
| 11 | 05/12/00 1731 | 110.3 | N/A | 88 | 0.0 | 0.000 |
| 12 | 06/07/00 1557 | 109.4 | -0.5 | 88 | -2.0 | -1.845 |
| | | | -0.2 | | | |

1 A negative temperature condition means that the fuel in the tank was colder than the fuel in the tank and the surrounding ground.
2 A negative value indicates a leak out of the tank.
3 Test 9 was initiated 70.6 h after the transfer was completed so it was not used in the temperature differential calculations. A test was not conducted before Test 9.

the fuel delivered to the tank) is shown in column 4. The depth of fuel in the tank during the test, the nominal induced leak rate, and the actual leak induced by KWA as part of the evaluation are shown in columns 5 through 7, respectively. As shown in Table 5, the temperature conditions ranged from –0.6° F to +1.4° F. Fuel deliveries ranged from 463,662 gal (a level change of 63.6 in.) to over 845259 gal (a level change of 260 in.). The leaks induced by KWA, nominally 0, [0.2, 0.3, 0.4], [0.8, 1.0], and 2.0 gal/h, ranged from 0.0 gal/h to 1.94 gal/h.

A more detailed summary of the test conditions and the results are presented in Tables 6-8. Tables 7 and 8 show the volumetric errors for both the LRDP-10 and LRDP-24.

### 4.2.4 Comparison of the LRDP Evaluated at NAS North Island and the LRDP Evaluated Under ESTCP

To show that the performance of the system was unaffected by the changes to the LRDP system under ESTCP, leak detection data were simultaneously obtained using the LRDP tested at North Island and the LRDP used in the ESTCP evaluation. Figure 16 shows a comparison of the two data sets offset by a constant of 0.002 in. for display purposes. The estimated volume rate determined by each LRDP is different by 0.01 gal/h.

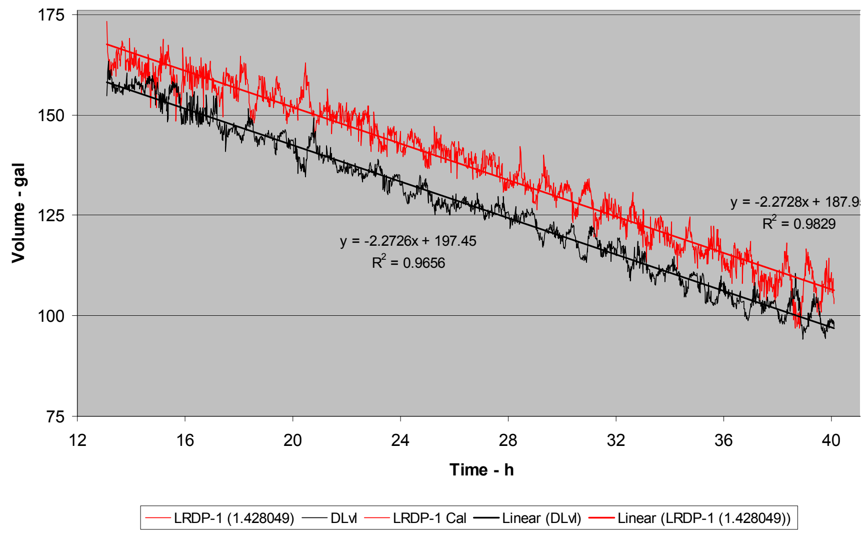


**Figure 16.** Comparison of the LRDP data obtained with the engineering prototype of the LRDP and the LRDP evaluated in the ESTCP project.

**Table 6.** Summary of the Evaluation Temperature Conditions

| Test No. | Delivery Start Time | Delivery End Time | Delivery Fill Time | Before Fill Level (50%) (inches)* | After Fill Level (inches) | Before Fill Volume (50%) (gallons) | After Fill Volume (gallons) | Start Temp (deg F) | End Temp (deg F) | Calculated Delivery Temp | Delivery Temperature Differential |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3/22/2000 11:30 | 3/22/2000 15:31 | 1/0/1900 4:01 | 144.0 | 260.0 | 1,049,354 | 1,894,613 | 64.4 | 64.2 | 64.0 | 0.2 |
| 3 | 3/27/2000 11:00 | 3/27/2000 15:18 | 1/0/1900 4:18 | 144.0 | 257.4 | 1,049,354 | 1,875,455 | 64.4 | 64.5 | 64.7 | -0.2 |
| 5 | 4/5/2001 8:22 | 4/5/2001 17:15 | 1/0/1900 8:53 | 144.0 | 250.0 | 1,049,354 | 1,821,852 | 64.6 | 65.1 | 65.7 | -0.6 |
| 7 | 4/18/2000 11:00 | 4/18/2000 15:30 | 1/0/1900 4:30 | 144.0 | 255.3 | 1,049,354 | 1,860,590 | 65.4 | 65.5 | 65.8 | -0.2 |
| 9 | 4/25/2000 12:59 | 4/25/2000 14:29 | 1/0/1900 1:30 | 196.5 | 260.1 | 1,431,905 | 1,895,567 | 65.8 | 65.4 | 64.0 | 1.4 |
| 11 | 5/11/2000 10:34 | 5/11/2000 14:53 | 1/0/1900 4:19 | 144.0 | 254.3 | 1,049,354 | 1,853,303 | 65.8 | 66.2 | 66.7 | -0.5 |
| 12 | 6/7/2000 12:08 | 6/7/2000 15:54 | 1/0/1900 3:46 | 144.0 | 253.4 | 1,049,354 | 1,846,380 | 68.0 | 68.2 | 68.3 | -0.2 |

(1) Height-to-volume = 7,287 gal/in. (2) Tank Capacity = 2,098,708 gal. (3) Tank Height = 288 in.

* Tank operator stated that the level was dropped to 50% operational level before each delivery.

**Table 7.** Final Results for the Evaluation of the LRDP-10 at Point Loma

| Test No. | New LRDP Filename | Transfer Prior to Test | Nominal Leak Rate (gal/h) | Induced Leak Rate (gal/h) | Waiting Period (h) | EVR (gal/h) | Actual VR (gal/h) | VR Error (gal/h) |
|---|---|---|---|---|---|---|---|---|
| 1 | Tnk175_3_22_2000_15_39.dat | | | -0.327 | 1.87 | -0.179 | -0.327 | -0.148 |
| 2 | Tnk175_3_23_2000_17_36.dat | Yes | 0.3 | 0.000 | 0.00 | 0.470 | 0.000 | -0.470 |
| 3 | Tnk175_3_27_2000_15_19.dat | | 0.0 | -0.444 | 2.00 | -1.142 | -0.444 | 0.698 |
| 4 | Tnk175_3_28_2000_17_28.dat | Yes | 0.4 | -0.824 | 0.00 | -0.908 | -0.824 | 0.0838 |
| 5 | Tnk175_4_5_2000_17_15.dat | | 0.8 | -1.040 | 10.00 | -0.724 | -1.040 | -0.316 |
| 6 | Tnk175_4_6_2000_19_19.dat | Yes | 1.0 | 0.000 | 0.00 | -0.059 | 0.000 | 0.059 |
| 7 | Tnk175_4_18_2000_16_14.dat | | 0.0 | -0.765 | 10.00 | -1.014 | -0.765 | 0.249 |
| 8 | Tnk175_4_19_2000_17_40.dat | Yes | 0.8 | -0.170 | 0.00 | -0.566 | -0.170 | 0.395 |
| 9 | Tnk175_4_27_2000_13_8.dat | | 0.2 | -1.934 | 3.00 | -2.194 | -1.934 | 0.260 |
| 10 | Tnk175_5_11_2000_15_0.dat | | 2.0 | -1.820 | 1.95 | -1.797 | -1.820 | -0.023 |
| 11 | Tnk175_5_12_2000_17_31.dat | Yes | 2.0 | 0.000 | 2.00 | -0.238 | 0.000 | 0.238 |
| 12 | Tnk175_6_7_2000_15_57.dat | Yes | 0.0 | -1.845 | 2.00 | -1.786 | -1.845 | -0.060 |
| | | | | **Mean = 2.24** | | | | **Mean = 0.080 gal/h** |
| | | | | **Median = 1.98** | | | | **Standard Deviation = 0.317 gal/h** |
| | | | | | | | | **N = 12** |
| | | | | | | | | **dof = 11** |
| | | | | | | | | **MDLR = 1.140 gal/h** |
| | | | | | | | | **n needed for 0.2 gal/h = 32.5** |
| | | | | | | | | **$t_B$ = 0.878** |

**Table 8.** Final Results for the Evaluation of the LRDP-24 at Point Loma

| Test No. | New LRDP Filename | Transfer Prior to | Nominal Leak Rate (gal/h) | Induced Leak Rate (gal/h) | Waiting Period (h) | EVR (gal/h) | Actual VR (gal/h) | VR Error (gal/h) |
|---|---|---|---|---|---|---|---|---|
| 1 | Tnk175_3_22_2000_15_39.dat | Yes | 0.3 | -0.327 | 1.87 | -0.327 | -0.327 | 0.000 |
| 2 | Tnk175_3_23_2000_17_36.dat | | 0.0 | 0.000 | 0.00 | 0.232 | 0.000 | -0.232 |
| 3 | Tnk175_3_27_2000_15_19.dat | Yes | 0.4 | -0.444 | 2.00 | -0.726 | -0.444 | 0.282 |
| 4 | Tnk175_3_28_2000_17_28.dat | | 0.8 | -0.824 | 0.00 | -1.072 | -0.824 | 0.248 |
| 5 | Tnk175_4_5_2000_17_15.dat | Yes | 1.0 | -1.040 | 2.00 | -0.832 | -1.040 | -0.208 |
| 6 | Tnk175_4_6_2000_19_19.dat | | 0.0 | 0.000 | 0.00 | 0.081 | 0.000 | -0.081 |
| 7 | Tnk175_4_18_2000_16_14.dat | Yes | 0.8 | -0.765 | 12.00 | -1.053 | -0.765 | 0.288 |
| 8 | Tnk175_4_19_2000_17_40.dat | | 0.2 | -0.170 | 0.00 | -0.453 | -0.170 | 0.283 |
| 9 | Tnk175_4_27_2000_13_8.dat | | 2.0 | -1.934 | 3.00 | -2.162 | -1.934 | 0.228 |
| 10 | Tnk175_5_11_2000_15_0.dat | Yes | 2.0 | -1.820 | 1.95 | -1.834 | -1.820 | 0.014 |
| 11 | Tnk175_5_12_2000_17_31.dat | | 0.0 | 0.000 | 2.00 | -0.190 | 0.000 | 0.190 |
| 12 | Tnk175_6_7_2000_15_57.dat | Yes | 2.0 | -1.845 | 2.00 | -1.997 | -1.845 | 0.152 |
| | | | | **Mean = 2.24** | | | | **Mean = 0.097 gal/h** |
| | | | | **Median = 1.98** | | | | **Standard Deviation = 0.192 gal/h** |
| | | | | | | | | **N = 12** |
| | | | | | | | | **dof = 11** |
| | | | | | | | | **MDLR = 0.690 gal/h** |
| | | | | | | | | **n needed for 0.2 gal/h = 11.9** |
| | | | | | | | | **$t_B$ 1.750** |

### 4.3 DEM/VAL 2: Hunter Army Airfield (50,000-gal UST)

A DEM/VAL of the LRDP was conducted on a 50,000-gal UST at the Hunter Army Airfield, Savannah, GA (part of Fort Stewart). The specific objectives of the DEM/VAL, the physical set-up and operation, and the sampling/data-collection procedure are described below.

The primary objective of the test was to demonstrate that the system could be used to test horizontal tanks for leaks. A special reference tube, whose cross-sectional area changed as a function of depth was used instead of a constant-diameter tube. Other objectives of the DEM/VAL were to

- demonstrate that the LRDP could measure the level of the fuel in the tank to the nearest 1/8 in. for inventory control and reconciliation,
- validate the deployment procedure that was developed to insure that all air was adequately bled from the tubing in the sensor system, and
- demonstrate that the LRDP could be used as a portable system for performing an annual precision test of the tank.

In a vertical right regular cylinder, the free surface area of the fuel is constant regardless of level. In a tank with curved walls, however (e.g., a horizontal cylinder, or a vertical cylinder with a spherical top and bottom), the free surface area varies as a function of level. In this type of tank, a DP sensor will not completely compensate for the thermal expansion or contraction of the fuel. To address this type of tank, the LRDP system incorporates a second design in which the cylindrical reference tube is replaced by a variable-shaped tube that mimics the cross-sectional changes in the tank's geometry as a function of depth [17]. This shaped reference tube, which is shown in Figure was used instead of the constant-diameter tube used for bulk USTs.

**Figure 17.** Installation of the LRDP in the 50,000-gal UST.

The DEM/VAL was conducted between 29 November and 2 December 1999. The tank contained 38,100 gal (74% of capacity) for these tests. Figures 17 and 18 show the LRDP being installed in the tank through the standard 8-in.opening in the tank. The LRDP can be installed in less than four hours by a single person.

Three types of tests were conducted to meet the objectives stated above. The first was to demonstrate that the level of the fuel in the tank could be measured and used for inventory purposes. The second was to show that the system would respond if a known volume of product were to be removed or added to the tank. The third was to demonstrate that the LRDP had sufficient performance to meet the 0.2-gal/h monthly monitoring regulatory standard.

**Figure 18.** Top of the being installed in an 8-in.opening in a 50,000-gal UST.

A 24-h test was conducted on November 19, 1999 to determine whether or not the tank was leaking. Having determined that the tank was tight, a demonstration of the system was conducted for site personnel on November 20, 1999. After the demonstration, additional data were collected with the LRDP; a total of 74 h of data were collected. Analyses were then performed to make an estimate of performance of the LRDP for use in 50,000-gal USTs using test durations of 8 h and 24 h.

To satisfy the 0.2-gal/h monthly monitoring regulatory standard, the LRDP would have to be able to detect a leak of 0.2 gal/h with a $P_D$ = 95% and a $P_{FA} \leq 5\%$. This performance is achieved if the standard deviation of the error in the tests used in an evaluation is less than or equal to 0.06 gal/h. If only a single test was conducted, the error in this test would have to be less than 0.10 gal/h, as determined by a hypothesis test using a student's t distribution at a level of significance of 0.05.

**Table 9.** Summary of the Test Results for the LRDP Systems in a 50,000-gal UST at Hunter Army Airfield

| Test No. | Test Start (mm/dd/yy hhmm) | Induced Leak Rate (gal/h) | 8-h Test VR* (gal/h) | 8-h Test VR Error (gal/h) | 24-h VR* (gal/h) | 24-h Test VR Error (gal/h) |
|---|---|---|---|---|---|---|
| 1a | 11/19/99 1155 | 0.000 | -0.087 | -0.087 | 0.014 | 0.014 |
| 1b | 11/19/00 1939 | 0.000 | 0.027 | 0.027 | | |
| 1c | 11/20/99 0339 | 0.000 | 0.123 | 0.123 | | |
| 2a | 11/20/99 1604 | 0.000 | -0.049 | -0.049 | 0.010 | 0.010 |
| 2b | 11/21/99 0004 | 0.000 | 0.051 | 0.051 | 0.010 | 0.010 |
| 2c | 11/21/99 0804 | 0.000 | 0.042 | 0.042 | -0.008 | -0.008 |
| 2d | 11/21/99 1604 | 0.000 | -0.037 | -0.037 | | |
| 2e | 11/22/99 0004 | 0.000 | 0.013 | 0.013 | | |
| 2f | 11/22/99 0804 | 0.000 | 0.014 | 0.014 | | |
| 2g | 11/22/99 1604 | 0.000 | -0.080 | -0.080 | | |
| 2h | 11/23/99 0004 | 0.000 | 0.010 | 0.010 | | |
| 2I | 11/23/99 0804 | 0.000 | -0.025 | -0.025 | | |
| 2j | 11/23/99 1604 | 0.000 | 0.066 | 0.066 | | |

* VR = Volume Rate

The 98 h of data collected during the November 19, 1999 and November 20, 1999 tests were grouped, and as shown in Table 9, the data were analyzed in 8 h and 24 h segments to make an estimate of performance.

A full-scale evaluation was not performed, because the scaled results of the bulk UST evaluation indicates that this level of performance would easily be achieved by the LRDP in a 50,000-gal UST. As a consequence, only a few tests were performed and a statistical comparison was made. If the LRDP were to be used to test these USTs, it would have to undergo a complete third-party evaluation.

### 4.4 Other Field Tests in Bulk USTs with the LRDP

It was originally intended to verify that the system was functional and then to evaluate the performance of the LRDP in a 132.5-ft-diameter, 2,100,000-gal bulk UST at the DEO-LA San Pedro Fuel Farm. The first objective was addressed, but the second objective could not be addressed because of a valve or valves that did not completely seal.

The San Pedro fuel farm is located about 1.5 miles NW of the West Basin of Los Angeles Harbor. Tank #5, which was been selected for the demonstration tests, contained jet fuel and was 20 ft in depth. It had extensive leak testing within the past two years and does not have any known leaks.

The LRDP was installed in the tank on January 1999, and an extensive set of field measurements were made until May 1999. A small flow across the valve (outflow) of approximately 0.1 gal/h was observed that was believed to be due to valve leakage. The specific source of this small flow could not be identified, and it was determined that the evaluation should be performed on another tank in which the valves were known to be tight, as required by the evaluation protocol. Such a problem existed during the first evaluation of the LRDP at North Island and led to artificial constraints being placed upon the operational use and performance of the system by the NWGLDE. Additional discussion can be found in Section 9.

# 5.0 Performance Assessment

The performance of the LRDP system was assessed for its suitability for both monthly monitoring and for annual or semi-annual precision (tightness) testing. The results of the third-party evaluation conducted by KWA on the Point Loma bulk UST are presented and discussed below. Section 5.1 summarizes the results of the previous evaluation, and why a second third-party evaluation was conducted. Section 5.2 describes the various methods evaluated. Section 5.4 describe the data measured with the LRDP system and summarizes statistically the individual test results tabulated in Table 7 for the LRDP-10 and Table 8 for the LRDP-24. Estimates of the performance of the LRDP-10 and LRDP-24 are presented in Sections 5.4 for a single test. The enhanced performance achieved when two or more tests are averaged together is presented in Section 5.5 for the LRDP-10-n and the LRDP-24-n, where n is the number of tests averaged together. Section 5.6 summarizes the results for different thresholds and $P_{FA}$s (Versions 1.0a, 1.1a, and 1.2a). The applicability of the results and how to use the LRDP is meeting regulatory requirements are presented in Sections 5.7 through 5.10. Section 5.10 describes the results of the DEM/VAL at Hunter Army Airfield on a 50,000-gal UST.

The only difference in the test protocol between the LRDP-10 and the LRDP-24 is the duration of the test. The 10-h test duration required by the LRDP-10 allows for monitoring tests to be conducted during an overnight period. The same type of monitoring test can be accomplished with the LRDP-24 using a 24-h test, but with a significantly better probability of false alarm against the same target leak rate, or a significantly better capability for detecting smaller leaks for the same probability of false alarm. As predicted by theory, the performance of the LRDP-24 in terms of detectable leak rate is 70% better than the performance of the LRDP-10. As shown below, however, both systems have sufficient performance to meet the regulatory standards for testing bulk tanks.

## 5.1 Results of the First LRDP Evaluation

The performance of the LRDP system depends on the diameter of the tank, the duration of the test, and the number of tests averaged together. The LRDP was previously evaluated for performance by Ken Wilcox Associates. This evaluation was performed in an 88-ft-diameter UST at the NAS North Island Fuel Farm. Some degradation of performance occurred because of fuel drainback into the tank during the evaluation. Such degradation is not representative of the method, but rather the evaluation conditions. A data quality index was used to identify the presence of drainback (inflow) and to determine when it was small enough to begin a test. The average waiting time required to wait until the drainback was small was 24 h. Thus, a waiting period of 24 h was specified by the NWGLDE. Even though the drainback was small after 24 h (less than 0.1 gal/h), it degraded the performance by at least a factor of two over what should have been the outcome of the evaluation. This assessment could be made because of several back-to-back tests with and without leaks in which the volume rate difference between these tests was equal to the induced leak to within 0.03 gal/h.

Even with this degradation, the LRDP still achieved excellent performance. The performance achieved with the LRDP for a 24- and a 48-h test indicated that with a single test the LRDP could detect leaks as small as 0.46 and 0.38 gal/h, respectively, with a probability of detection of 95% and a probability of false alarm of 5%. By averaging 4 or 5 tests together, the performance improved by a factor of 2 or more for both methods.

The main problem with this evaluation was the limitations placed on the LRDP that were technically unnecessary. These limitations included a 24-h waiting period (when none is actually required) and the inclusion of a 0.1-gal/h bias (due to the inflow and not the system) in the use of a threshold for conducting a precision test at 0.2 gal/h. While this bias does not impact a monitoring test at 1, 2 or 3 gal/h, it would impact a precision test. In addition, the inflow prevented the evaluation of the LRDP for a test duration shorter than 24 h.

Since the LRDP did not automatically report the test result at the conclusion of a test, the system was not approved for stand-alone monitoring. Instead, the analysis was automatically performed in a spreadsheet at the completion of a test. This latter constraint is not significant, because all the criteria could be met for monitoring provided that an operator start and stop a test, and then imported the data into a spreadsheet for analysis.

The LRDP was re-evaluated for performance during this ESTCP project to

- eliminate the unnecessarily long waiting period imposed by the regulators,
- obtain approval to operate the system as an automatic monitoring system,
- obtain a more accurate estimate of performance that was not degraded by uncontrolled, nonleak-related inflows and outflows during the test, and
- obtain approval for a test that could be conducted in less than 24 h (i.e., overnight).

All of these objectives were met in the second evaluation conducted under ESTCP.

The LRDP was operated in a fully automatic monitoring mode and was evaluated for test durations of 10 h and 24 h. A waiting period of 2-h was used just be sure that all operations had ceased before a test was begin.

The results of the first evaluation were listed by the NWGLDE for test durations of 24 and 48 h [19-26]. The new results are being submitted for approval for a 10- and 24-h test [8-15]. There are presently 12 approved ways to implement a leak detection test with the LRDP system that change only in terms of test duration, testing frequency (monitoring or tightness regulatory requirements), number of tests averaged together, and probability of false alarm [5]. The performance and operation of the system were designed to meet the California regulatory guidelines for bulk tanks [5], but have general application for all states. The system is currently approved by the NWGLDE for

- use as a portable system with a 24- and 48-h test (LRDP-24 or LRDP-48) [19-22],
- averaging multiple tests together (e.g., 4 or 5 tests) for increased reliability and/or increased detection sensitivity LRDP-24-5 or LRDP-48-4) [23-26],

- a variety of monthly monitoring (0.3-1.0, 1.0-2.0, and 2.0-3.0 gal/h) and precision testing (0.2 gal/h) regulatory options, and
- all vertical-walled tanks with capacities greater than 50,000 gal and diameters less than 140 ft.

When the results of the third-party evaluations performed under ESTCP are listed by the NWGLDE, the LRDP system will be approved for

- use as a stand-alone, in-tank monitoring system or as a portable system with a 10- and 24-h test (LRDP-10 or LRDP-24) [8-11],
- averaging multiple tests together (e.g., where the number of tests is less than 12) for increased reliability and/or increased detection sensitivity LRDP-10-n or LRDP-24-n) [12-15],
- a variety of monthly monitoring (0.3-1.0-2.0, 2.0, and 2.0-3.0 gal/h) and precision testing (0.2 gal/h) regulatory options, and
- all vertical-walled tanks with capacities greater than 50,000 gal and diameters less than 194 ft.

## 5.2 Methods Evaluated

As described in Table 1, four LRDP test methods were evaluated: (1) LRDP-24, (2) LRDP-24-n, (3) LRDP-10, (4) LRDP-10-n. Methods (3) and (4) allow individual test results from up to 12 tests to be averaged together before applying a threshold. As done in the first evaluation, for each of these test methods, the performance was estimated for four thresholds. As a consequence, for each method, there are four "versions" of the KWA evaluation report and four versions of the method. An "a" in the version number is used to differentiate the LRDP-24 evaluated at North Island from the LRDP-24 evaluated at Point Loma. The Point Loma results will replace the previous results for the LRDP-24. The LRDP-10 is a new method. Although this is a new method, a version number of "a" is also used to indicate it was evaluated at Point Loma.

The performance was estimated for four thresholds to allow the method to be used as needed to satisfy regulatory and operational requirements and for direct comparison of the performance to other methods. The basic version, called ***Version a***, sets the threshold to insure that the $P_D$ = 95% against the target leak rate and that the $P_{FA}$ is as small as possible and less than or equal to 5%. In this case, the TLR and $P_D$ (= 95%) can be the same for any tank diameter. However, if the threshold is selected in this way, the $P_{FA}$ will be different for each tank diameter, which is acceptable provided that the $P_{FA} \leq 5\%$. This method is used for the small regulated USTs found in petroleum service stations and is how the LRDP was intended to be used. However, the NWGLDE would not let us use this approach for a number of reasons. First, the performance of the LRDP was too good, and the NWGLDE, comprised of regulators from states with bulk USTs, were concerned that leaks smaller than the threshold would go undetected, because they knew that the method had the performance to detect them using a smaller threshold. Second, they did not want the $P_{FA}$ to be different for every tank tested, because they thought it would be confusing to tank owners. They wanted the $P_D$ and $P_{FA}$ to be the same for every tank and to allow the TLR to change.

Version 1.0a, which was reported previously to the NWGLDE for a 2.0 and 3.0 gal/h leak as Version 1.0, is reported here for leaks of 1.65 and 2.40 gal/h for the 24-h test and leaks of 1.90 and 2.40 for the 10-h test. These TLRs were selected because it allowed the LRDP to address the 0.3-1.0-, the 1.0-2.0-, and 2.0-3.0-gal/h monthly monitoring standards for all tank sizes. In this method, the NWGLDE required that a TLR be selected for the evaluation tank. This TLR would then be scaled for the tank being tested, keeping the $P_D$ and $P_{FA}$ the same for tanks of different product surface areas. This method is different than "Version a," because the selected TLR changes with tank diameter, but the $P_{FA}$ remains the same. In Version a, the TLR can be the same for all tank diameters.

Version 1.1a is intended for use in California. For this version, the TLR for the evaluation tank was selected so that it is less than or equal to twice the MDLR. For the LRDP-24, a TLR of 0.95 gal/h was selected, and for the LRDP-10 a TLR of 1.65 gal/h was selected. Both TLRs are less than 2 * MDLR[1]. These TLRs are less than 2 * MDLR and were selected, because this choice of TLRs allows the LRDP to be used to address Option 7 or 10 of the California regulatory guidelines for monthly monitoring.

In Version 1.2a, the threshold was selected to give the MDLR, the smallest leak rate that could be detected in a given tank and still insure a $P_D$ = 95% and a $P_{FA}$ = 5%. The MDLR is useful, because it is a simple way to compare the performance of different methods.

Ken Wilcox Associates, Inc., has prepared four evaluation reports (LRDP-24, LRDP-24-n, LRDP-10, LRDP-10-n) [8-11]. These reports include Version a of the standard EPA Results Form. The performance that corresponds to the other three threshold selections are presented in four more KWA reports that include only the Results Forms and the Method Description Forms for versions V1.0a, V1.1a, and V1.2a [12-15]. As state above, these performance results are reported identically to the results determined from the North Island evaluation. This was done purposefully so that it should be straightforward for the NWGLDE to review and approve these updated results.

The performance results scales with the square root of the number of tests, n, averaged together, and linearly the product surface area (PSA), which can also be expressed in terms of tank diameter (D). The formula used to compute the threshold and TLR for a particular tank size are presented in Appendix E for Version a and Appendix F for the other three versions. Examples of the results for all four versions are presented in Appendices G – J.

### 5.3 Results of the Leak Detection Tests

An example of the level data measured with the LRDP in Test 10 for a 10-h test and a 24-h test is shown in Figures 19 and 20, respectively. The tests of the LRDP-10 were initiated at the same time as those of the LRDP-24. The induced leak rate was 1.82 gal/h, and the leak rate measured by the LRDP-10 was 1.80 gal/h and the LRDP-24 was 1.83 gal/h.

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[1] A TLR = 2 * MDLR for the LRDP-24 would equal 1.38 gal/h (2 * 0.69 gal/h), and a TLR = 2 * MDLR for the LRDP-10 would equal 2.28 gal/h (2 * 1.139 gal/h).

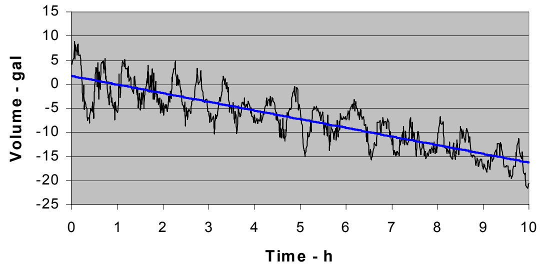


**Figure 19.** Level data obtained with the LRDP-10 system for Test 10.

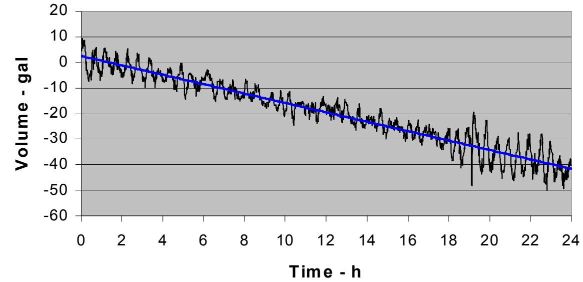


**Figure 20.** Level data obtained with the LRDP-24 system for Test 10.

The waiting period was initiated at 1500 on 11 May 2000, and the test started 2 h later at 1700. The precision of the data (i.e., the standard deviation of the data about a regression line fit to the data) is less than 0.0003 in. The data do not exhibit any evidence of ambient diurnal temperature effects on the differential pressure sensor or the reference tube mounting system. The linearity of the 24-h data in Figure 20 suggests that the volume rate estimated with these data should be about the same for both the 10-h and 24-h test periods.

A 1-h periodicity is observed in the level data obtained for this test and several other tests. In some tests this periodicity was 2 to 3 h. This periodicity is consistent with the presence of internal waves in the tank. This periodicity was not observed in the San Pedro data shown in Figure 21. It is likely that the geometry of this specific tank is such that a resonance condition is sometimes established. The amplitude of these fluctuations observed during the other 11 tests ranged from a factor of three higher and lower. These fluctuations do not affect the results of either the 10- or 24-h tests. The main effect is that a test must include 3 to 5 cycles to achieve a stable performance. If the evaluation had been completed in the tank at San Pedro, it is likely that a 4- to 8-h test would have been evaluated.

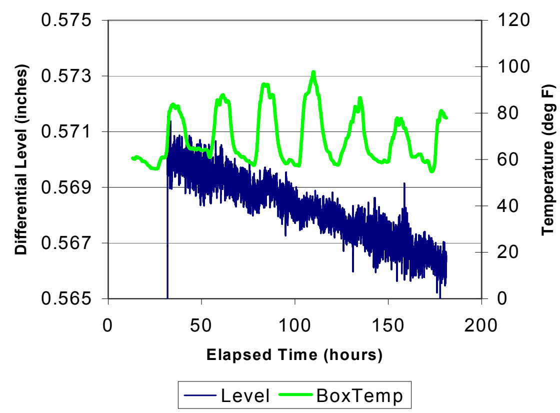


**Figure 21.** Level data obtained with the LRDP system over a 96-h period in a 132.5-ft-diameter tank at San Pedro.

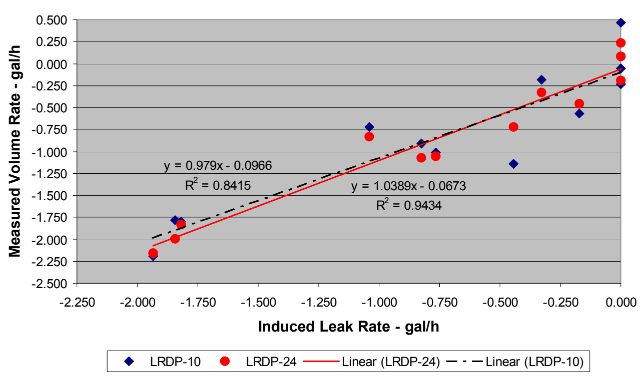


**Figure 22.** Least-squares lines fitted to the test results of the LRDP-10 and the LRDP-24.

The results of the leak detection tests for the LRDP-10 and the LRDP-24 were tabulated in Tables 7 and 8. These test results are presented graphically in Figures 22 and 23 for the LRDP-10 and the LRDP-24. Each test result is plotted against the leak induced for that test. In Figure 22, the test results measured by the LRDP systems appear on the y-axis, while the KWA-induced leak rates appear on the x-axis. A least-squares line has been fitted to the results of the tests with each LRDP system. The slope of the line is nearly 1.0 (1.039 for the LRDP-10 and 0.979 for the LRDP-

24); this indicates that the volume changes due to the induced leaks are additive with any other volume changes in the tank. The intercepts for the LRDP-10 and the LRDP-24 systems, -0.097 and -0.067 gal/h, respectively. A statistical hypothesis test at a level of significance of 0.05 shows that the intercepts are not different from zero.

This is more easily seen in the error plot shown in Figure 23. The error plotted on the y-axis is the difference between the induced leak rate and the leak rate measured by the LRDP system for both test durations. The mean and standard deviation of the test results for each system, after the induced leak has been subtracted out, are summarized in Table 10. The standard deviation of the 10-h test is nearly 70% larger than the standard deviation of the 24-h test, which is consistent with expectation.

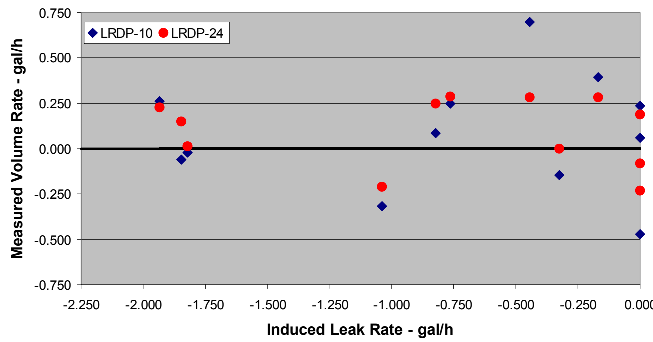


**Figure 23.** Difference between the induced leak rate and the volume rate measured with the LRDP-10 and the LRDP-24.

**Table 10.** Mean and Standard Deviation of the Difference between the Measured Leak Rates (Test Results) and Induced Leak Rates for the LRDP-10 and LRDP-24

| Type of LRDP System | Number of Tests | Mean Volume Rate (gal/h) | Standard Deviation (gal/h) |
|---|---|---|---|
| LRDP-10 | 12 | 0.080 | 0.318 |
| LRDP-24 | 12 | 0.097 | 0.192 |

A two-sided statistical hypothesis test, as required by the evaluation protocol, was performed to determine if the mean was statistically different from zero. The results of a two-sided Student-t test conducted at a level of significance of 0.05 was that the mean could not be distinguished from zero. The critical Student-t statistic is 2.20 and the computed statistics for the LRDP-10 and the LRDP-24 were 0.878 and 1.750, respectively. This means that the mean computed in the evaluation does not have to be included in the threshold as a system bias. This is significant, because the mean was shown to be statistically significant in the first evaluation. Even though the NWGLDE recognized that this non-zero mean was produced by nonleak-related inflows and was not a bias of the method, they were requiring that the threshold include the mean, which when used would have resulted in an unacceptably high probability of false alarm. The present evaluation shows that the bias computed in the first evaluation was not real.

Figure 24 shows the cumulative frequency distributions (CFDs) of the test results, with the dashed line denoting the LRDP-10 and the solid line denoting the LRDP-24. These CFDs were generated after the induced leak rate and the

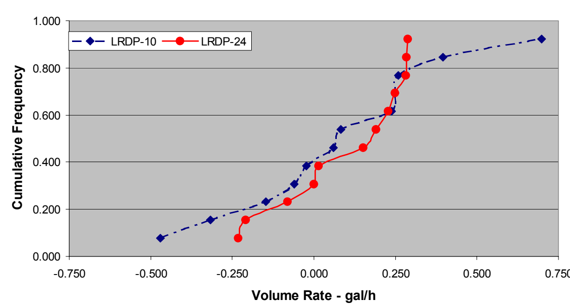


**Figure 24.** Cumulative frequency distributions of the test results in a 122.5-ft-diameter bulk UST after the volume changes due to the induced leak were removed.

mean inflow had been subtracted. Based on the CDF of the LRDP-10 and the LRDP-24, a threshold set at volume rates greater than –0.5 and –0.25 gal/h, respectively, would have resulted in no false alarms during the evaluation.

The difference in performance between the LRDP-10 and the LRDP-24 can be attributed to one or two of the evaluation tests. If the LRDP-10 measured the same result as the LRDP-24 for Tests 2 and 3, the mean and standard deviation of the LRDP-10 would be 0.066 gal/h and 0.226 gal/h, respectively, which means the performance of the LRDP-10 is similar to the LRDP-24 for most tests. Although its quoted performance is not nearly is good, in operation, it will give similar results for 80% of the tests conducted.

The LRDP was also evaluated for an 18-h test with a 6-h waiting period. The mean and standard deviation was 0.080 gal/h and 0.198 gal/h, respectively. The performance of the LRDP using this test protocol is nearly the same as LRDP using a 24-h test with a 2-h waiting period and would result in a MDLR of 0.713 gal/h, as compared to an MDLR of 0.690 gal/h for the 24-h test. While the difference between the LRDP-24 and the LRDP-18 was only 0.02 gal/h, a 12-test average would not quite meet the 0.20-gal/h precision test standard with the LRDP-18 for the evaluation tank. For this reason and because the total test time for both methods is about the same and a 24-h test has already been approved by the regulators, only the 10-h and 24-h test protocols were evaluated.

### 5.4 Performance Estimates for a Single Test (LRDP-10 and LRDP-24)

Estimates of the performance of the LRDP-10 and the LRDP-24, in terms of $P_D$ and $P_{FA}$, were generated for the evaluation tank from the standard deviation of the test results given in Table 10. The formula for computing performance is presented in Appendix E. In Table 11, the thresholds used for detection were selected so as to maintain a $P_D$ of 95% and a $P_{FA}$ of 5%. As stated above, for such a threshold, the resulting leak rate is called the minimum detectable leak rate (MDLR).

**Table 11.** Performance Estimates for the LRDP-10 and the LRDP-24

| Type of LRDP System | Threshold (gal/h) | Leak Rate (gal/h) | Probability of False Alarm (%) | Probability of Detection (%) |
|---|---|---|---|---|
| LRDP-10 | 0.570 | 1.14* | 5.0% | 95.0% |
| LRDP-24 | 0.345 | 0.69* | 5.0% | 95.0% |

* For these thresholds, the leak rate is also referred to as the minimum detectable leak rate (MDLR).

The performance of these two systems against larger leaks in the evaluation tank is shown in Table 12. The thresholds set for these performance estimates were selected so as to maintain a $P_D$ of 95% and to make the $P_{FA}$ as small as possible. In order for the LRDP-10 to maintain a $P_D$ = 95% against a leak rate that is larger than 1.14 gal/h and still have a $P_{FA} \leq 5\%$, the threshold should be less than the leak rate by 0.57 gal/h or more and no smaller than 0.57 gal/h. In this case, a threshold anywhere from 0.57 to 1.43 gal/h could be used if the leak rate is 2.0 gal/h. Similarly, in order for the LRDP-24 to maintain a $P_D$ = 95% against a leak rate that is larger than 0.69 gal/h and still have a $P_{FA} \leq 5\%$, the threshold should be less than the leak rate by 0.345 gal/h or more and no smaller than 0.345 gal/h. In this case, a threshold anywhere from 0.345 to 0.655 gal/h could be used if the leak rate is 1.0 gal/h.; a threshold anywhere from 0.345 to 1.655 gal/h could be used if the leak rate is 2.0 gal/h. Because the evaluation is based on only 12 tests, the $P_{FA}$ is reported as very much less than 1% (<< 1%) if the calculated $P_{FA}$ is a factor of ten or more smaller than 1.0%. Additional performance results as a function of TLR and tank diameter are presented in Appendices I and J.

**Table 12.** Performance Estimates for the LRDP-48 and the LRDP-24 against Larger Leaks

| Type of LRDP System | Threshold (gal/h) | Leak Rate (gal/h) | Probability of False Alarm (%) | Probability of Detection (%) |
|---|---|---|---|---|
| LRDP-10 | 1.43 | 2.0 | <<1.0% | 95.0% |
| LRDP-10 | 0.93 | 1.5 | 0.7% | 95.0% |
| LRDP-24 | 1.655 | 2.0 | <<1.0% | 95.0% |
| LRDP-24 | 1.155 | 1.5 | <<1.0% | 95.0% |
| LRDP-24 | 0.655 | 1.0 | <1.0% | 95.0% |

The smallest leak rate that is detectable in the evaluation tank with a 24-h test with a $P_D$ = 95% and a $P_{FA}$ = 5% was 0.69 gal/h This scales to a detectable leak rate of 0.36 gal/h in an 88-ft-diameter tank, the diameter of the bulk UST used in the first evaluation at North Island. In the previous evaluation, the MDLR for a 24- and a 48-h test was 0.45 gal/h and 0.38 gal/h respectively. Thus, once the inflow problems experienced during the first evaluation are eliminated, the LRDP-24 performs slightly better than the LRDP-48 evaluated at North Island.

### 5.5 Performance Estimates for More than One Test (LRDP-10-n and LRDP-24-n)

The performance of the LRDP-10 and the LRDP-24 (or any leak detection system) can be improved significantly by combining the results of two or more tests. Averaging two or more test results before applying the threshold will improve *both* the probability of detection and the probability of false alarm over that obtained for a single test. Performance improves as the number of tests averaged together increases. The performance will depend on the test duration and the number of tests, n, averaged together. For example, the performance of the LRDP-10-4 is a factor of 2.0 (square root of 4) times better than a single 10-h test with the LRDP-10; the LRDP-10-4 uses a test duration of 10 h and averages four 10-h tests together.

The performance of the LRDP-10-n and LRDP-24-n systems, where n is the number of independent tests averaged together, is obtained using the *standard deviation of the mean* test result, $S_m$, of the LRDP-10 and LRDP-24 systems. The standard deviation of the mean test result can be determined from the standard deviation of the single-test results, S, computed in the third-party evaluation. Once the standard deviation of the mean test result is known, the performance of the mean (average) test result (in terms of $P_D$ and $P_{FA}$) can be computed using the same methods as for the single test results.

For independent tests, $S_m$ of the LRDP-10 and LRDP-24 is obtained from S and the number of tests, n, averaged together. The standard deviation of the mean, $S_m$, is given by

$$S_m = S /(n)^{0.5} .$$

For the LRDP-10 and the LRDP-24, values of n that yield an MDLR of 0.2 gal/h or less were purposely selected. This equates to a system capable of detecting a 0.2-gal/h leak with a $P_D$ = 95% and a $P_{FA} \leq 5\%$. In this way, the LRDP-10 and the LRDP-24 could meet the annual testing requirements for bulk tanks established by the state of California. Table 13 summarizes the mean and standard deviation of the mean test result for the LRDP-10-n and the LRDP-24-n for different values of n in the evaluation tank. Table 14 summarizes the performance in terms of the MDLR.

**Table 13.** Mean and Standard Deviation of the Difference between the Measured Test Results and Induced Leak Rates for the LRDP-10-n and LRDP-24-n for n = 4, 6, and 12

| Type of LRDP System | Number of Tests Averaged Together | Mean Volume Rate (gal/h) | Standard Deviation of the Mean (gal/h |
|---|---|---|---|
| LRDP-10-1 | 1 | -0.080 | 0.3175 |
| LRDP-10-4 | 4 | -0.080 | 0.1588 |
| LRDP-10-6 | 6 | -0.080 | 0.1296 |
| LRDP-10-12 | 12 | -0.080 | 0.0917 |
| LRDP-24-1 | 1 | -0.097 | 0.192 |
| LRDP-24-4 | 4 | -0.097 | 0.096 |
| LRDP-24-6 | 6 | -0.097 | 0.0784 |
| LRDP-24-12 | 12 | -0.097 | 0.0055 |

**Table 14.** Performance Estimates Made for the LRDP-10-n and the LRDP-24-n Systems

| Type of LRDP System | Threshold (gal/h) | Leak Rate (gal/h) | Probability of False Alarm (%) | Probability of Detection (%) |
|---|---|---|---|---|
| LRDP-10-1 | 0.57 | 1.14 | 5.0% | 95.0% |
| LRDP-10-4 | 0.285 | 057 | 5.0% | 95.0% |
| LRDP-10-6 | 0.233 | 0.465 | 5.0% | 95.0% |
| LRDP-10-12 | 0.165 | 0.329 | 5.0% | 95.0% |
| LRDP-24-1 | 0.345 | 0.690 | 5.0% | 95.0% |
| LRDP-24-4 | 0.173 | 0.345 | 5.0% | 95.0% |
| LRDP-24-6 | 0.141 | 0.282 | 5.0% | 95.0% |
| LRDP-24-12 | 0.100 | 0.199 | 5.0% | 95.0% |

The average test result is important because it allows the same in-tank leak detection system to meet both the 0.3-1.0 or 1.0-2.0-gal/h monthly monitoring and the 0.2-gal/h annual leak testing requirements established by the state of California for bulk tanks. All of the LRDP systems can easily meet the monthly testing requirements with a very low probability of false alarm (<1%).

With averaging, all of the bulk USTs owned or operated by the DoD can also meet the precision test requirements.

## 5.6 Formula to Compute the Threshold and Target Leak Rate as a Function of Tank Diameter for the LRDP-10 and LRDP-24

The performance of a leak detection system can be affected by the size and geometry of the tank. This relationship is not quantitatively understood for volumetric methods, but is predictable for mass-based systems. For most mass-based technologies, performance is related to the surface area of the fuel in the tank (but not the volume of fuel in the tank).

The evaluation protocol specifies that the threshold for declaring a leak must be adjusted when testing tanks that are smaller or larger than the tank used in the evaluation. For a mass-based system, the threshold and the TLR are obtained from the ratio of the surface area of the tank being tested and the surface area of the tank used in the evaluation.

According to the evaluation protocol [6], the maximum tank size to which a mass-based method may be applied is determined by the surface area of the tank and is limited to two and one-half times the surface area of the tank used in the evaluation. Since the surface area of the 122.5-ft diameter, 2,100,000-gal tank used in this evaluation is 11,756 ft$^2$, the LRDP-10 and the LRDP-24 can be used to test tanks with diameters up to 193.4 ft. The maximum tank capacity (in terms of volume of fuel in the tank) that can be tested with the LRDP systems is not constrained by the evaluation and will depend on the height of the tank.

As discussed previously in this report, the NWGLDE would not list the LRDP using a threshold established to maintain a $P_D$ = 95% against the target leak rate. Instead, thresholds were selected against two leak rates using a set $P_{FA}$ and a $P_D$ = 95% (Version 1.0a), a TLR less than or equal to 2 * MDLR using a set $P_{FA}$ and a $P_D$ = 95% (Version 1.1a) , and the MDLR (Version 1.2a). Tables 15 and 16 present the formula for computing the thresholds and target leak rate as a function of tank diameter, D, (or product surface area) and number of tests, n, averaged for the LRDP-10 and LRDP-24, respectively. The tables also gives the largest tank diameter for which the MDLR is 0.2 gal/h or less. The formula are based on a product surface area for the 122.5-ft-diameter evaluation tank of 11,786 ft$^2$. A more complete set of formula for these versions are presented in Appendix F.

**Table 15.** Formula to Compute the Threshold and Target Leak Rate as a Function of Tank Diameter for the LRDP-10

| Method | Tank Diameter | Target Leak Rate |
|---|---|---|
| (Probability of detection of 95% with a probability of false alarm of 5%) Version 1.2a | *For tank diameters less than 51.3 ft* | 0.20 gal/h |
| | *For tank diameters (D in ft) up to 193.7 ft* | (3.14*(D*0.5)$^2$/11,786)*1.139 gal/h |
| | *For tank diameters D = [2,635.0*(n)$^{0.5}$]$^{0.5}$ (LRDP-10-n)* | 0.20 gal/h (average of 1 < n ≤ 12 tests) |
| (Probability of detection of 95% with a probability of false alarm of 0.29%) Version 1.1a | *For tank diameters (D in ft) up to 193.7 ft* | (3.14*(D*0.5)$^2$/11,786)*1.653 gal/h |
| | *For tank diameters D = [1,817.3*(n)$^{0.5}$]$^{0.5}$ (LRDP-10-n)* | 0.20 gal/h (average of 1 < n ≤ 12 tests) |
| (Probability of detection of 95% with a probability of false alarm of <0.15%) Version 1.0a | *For tank diameters (D in ft) up to 193.4 ft* | (3.14*(D*0.5)$^2$/11,786)*(2.0-0.569) gal/h |
| | *For tank diameters (D in ft) up to 193.4 ft* | (3.14*(D*0.5)$^2$/11,786)*(3.0-0.569) gal/h |

**Table 16.** Formula to Compute the Threshold and Target Leak Rate as a Function of Tank Diameter for the LRDP-10

| Method | Tank Diameter | Target Leak Rate |
|---|---|---|
| (Probability of detection of 95% with a probability of false alarm of 5%) Version 1.2a | *For tank diameters less than 66.0 ft* | 0.20 gal/h |
| | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11,786)*0.69$ gal/h |
| | *For tank diameters $D = [4,349.7*(n)^{0.5}]^{0.5}$ (LRDP-24-n)* | 0.20 gal/h (average of $1 < n \leq 12$ tests) |
| (Probability of detection of 95% with a probability of false alarm of 0.48%) Version 1.1a | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11,786)*0.946$ gal/h |
| | *For tank diameters $D = [3,172.4*(n)^{0.5}]^{0.5}$ (LRDP-24-n)* | 0.20 gal/h (average of $1 < n \leq 12$ tests) |
| (Probability of detection of 95% with a probability of false alarm of <0.003%) Version 1.0a | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11,786)*(2.0-0.345)$ gal/h |
| | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11,786)*(3.0-0.345)$ gal/h |

Tables 17-19 further summarize the results of the evaluation. Table 17 gives the MDLR for n = 1, 4, 6, and 12 for three tank sizes. This table also presents the results from the previous evaluation for comparison. A more complete presentation of the results for these versions are presented in Appendices G and H.

**Table 17.** Example of the MDLR in gal/h ($P_D$ = 95% and a $P_{FA}$ = 5%) as a Function of Tank Diameter

| Method | PD-% | PFA-% | Target Leak Rate - gal/h 122.5 ft | 88 ft | 60 ft |
|---|---|---|---|---|---|
| | for tank diameters of | | | | |
| **LRDP-10** | 95% | 5% | **1.14** | 0.59 | 0.27 |
| **LRDP-10-4** | 95% | 5% | 0.57 | 0.29 | 0.14* |
| **LRDP-10-6** | 95% | 5% | 0.46 | 0.24 | 0.11* |
| **LRDP-10-12** | 95% | 5% | 0.33 | 0.17* | 0.08* |
| **LRDP-24** | 95% | 5% | **0.69** | 0.36 | 0.17* |
| **LRDP-24-4** | 95% | 5% | 0.35 | 0.18* | 0.09* |
| **LRDP-24-6** | 95% | 5% | 0.28 | 0.15* | 0.07* |
| **LRDP-24-12** | 95% | 5% | 0.20 | 0.10* | 0.05* |
| **LRDP-24*** | 95% | 5% | 0.89 | 0.46 | 0.21 |
| **LRDP-48*** | 95% | 5% | 0.74 | 0.38 | 0.18* |

* Although the computed MDLR is less than 0.20 gal/h, the performance of the system must be reported and the system operated at 0.20 gal/h.

Table 18 gives the largest tanks in which the LRDP-10, LRDP-10-n, LRDP-24, and LRDP-24-n can meet the precision test TLR requirement of 0.20 gal/h with two different $P_{FA}$s. Table 19 gives the largest tank diameters in which the LRDP-10 and the LRDP-24 can meet the monthly monitoring standards of 0.3-1.0, 1.0-2.0, and 2.0-3.0 gal/h. Also, Table 18 shows that an annual precision test can be conducted in any tank with a diameter of less than 51 ft with a $P_{FA}$ = 5%, which covers over 50% of the bulk USTs. The LRDP-10 can also be used to meet the precision requirement using a single test at a $P_{FA}$ = 0.3% for all tanks with diameters less than 43 ft. Table 19 shows that the LRDP-10 can be used to address the 0.3-1.0-gal/h and the 1.0-2.0-gal/h monthly monitoring requirement for tanks with diameters up to 95 and 135 ft. respectively, with a very low $P_{FA}$ (0.3%). This covers the full range of bulk USTs owned or operated by the DoD.

**Table 18.** Largest Diameter Tank in which a 0.20 gal/h Leak Rate Can Be Detected as a Function of the Number of Tests Averaged Together*

| Method | $P_D$ | $P_{FA}$ | TLR-gal/h | For Tank Diameters ≤ | | | |
|---|---|---|---|---|---|---|---|
| | | | | n=1 | n=4 | n=6 | n=12 |
| **LRDP-10-n** | 95% | 5.0% | 0.20 | 51 ft | 73 ft | 80 ft | 96 ft |
| **LRDP-10-n** | 95% | 0.3% | 0.20 | 43 ft | 60 ft | 67 ft | 79 ft |
| **LRDP-24-n** | 95% | 5.0% | 0.20 | 66 ft | 93 ft | 103 ft | 123 ft |
| **LRDP-24-n** | 95% | 0.5% | 0.20 | 56 ft | 80 ft | 88 ft | 105 ft |

*$P_D$ = 95% and a $P_{FA} \leq$ 5% for the LRDP-10, LRDP-10-n, LRDP-24, and LRDP-24-n as a Function of Tank Diameter and Averaging (n = 1, 4, 6, 12)

As shown in Table 19, with the LRDP-24, the 0.3 – 1.0-gal/h monthly monitoring requirements can be addressed for all but a few of the largest bulk USTs owned by DoD. The advantage of using the 0.3 – 1.0-gal/h criterion is that only a single precision test at 0.2 gal/h is required each year. Table 19 shows that the LRDP-24 can be used to address the 0.3 – 1.0-gal/h and the 1.0 – 2.0-gal/h monthly monitoring requirement for tanks with diameters up to 126 and 178 ft. respectively, with a low $P_{FA}$ (0.5%). This covers the full range of bulk USTs owned or operated by the DoD. Also, Table 18 shows that an annual precision test can be conducted in any tank with a diameter of 66 ft with a $P_{FA}$ = 5%, which covers over 50% of the bulk USTs. If a precision test is conducted with the LRDP-24, then all of the 88-ft-diameter tanks at the North Island fuel farm can be tested in compliance with California regulations by conducting a precision test four times a year.

**Table 19.** Largest Diameter Tank in which Various Leaks Can Be Detected as a Function of Target Leak Rate*

| Method | $P_D$ | $P_{FA}$ | Tank Diameters for TLRs in gal/h | | | | |
|---|---|---|---|---|---|---|---|
| | | | **for TLR in gal/h =** | 0.30 | 1.0 | 2.0 | 3.0 |
| **LRDP-10** | 95% | 0.3% | | 52 ft | 95 ft | 135 ft | 165 ft |
| | | | **for TLR in gal/h of** | 0.30 | 1.0 | 2.0 | 3.0 |
| **LRDP-24** | 95% | 0.5% | | 69 ft | 126 ft | 178 ft | 218 ft |

*$P_D$ = 95% and a $P_{FA} \leq$ 5% for the LRDP-10 and the LRDP-24

## 5.7 How to Use the LRDP System

The LRDP system gives the tank owner or operator great flexibility in developing a testing strategy for meeting the monthly monitoring and the precision test regulatory requirements. The overnight testing capability of the LRDP-10, the high performance of the LRDP-24, and the capability for averaging tests together allow a testing strategy to be developed that includes both methods. A testing strategy, which is both cost effective and minimizes disruption to operations, can be developed. Tables 18 and 19 suggest how the system may be used; also see Appendices G - J for more detail. The detailed calculations can be made using the formula in Tables 15 and 16; Appendices E and F give additional detail.

Appendices G and H present the results for the LRDP-10 and the LRDP-24, respectively, for all four versions of each method (a, 1.0a, 1.1a, and 1.2a) for a sufficient number of TLRs to design a testing strategy without using the equations in Appendices E and F. The four tables in each appendix present the target leak rate, threshold, standard deviation, $P_D$ and $P_{FA}$ for specific target leak rates of interest and specific tank diameters of interest. These results will indicate which size tanks can be tested with the LRDP-10 and the LRDP-24 to meet the 0.2, 0.3-1.0, 1.0-2.0, and 2.0-

3.0 gal/h precision and monthly monitoring standards. The table also indicates how many tests need to be averaged to detect 0.2 gal/h. The standard deviation, which is used to estimate the performance, is also shown. Appendices I and J present the results for the LRDP-10 and the LRDP-24, respectively, for Version a, as a function of tank size, for the TLRs of interest (0.2, 0.3, 1.0, 2.0, and 3.0).

The guiding principle that should be used when developing a testing strategy is to minimize the probability of a false alarm. Any $P_{FA}$ that is less than 1% will suffice, but it is highly desirable to have the $P_{FA}$ < 0.1%. Experience shows that the $P_{FA}$ computed using a normal distribution, as required by the EPA standard test procedures, is reasonably accurate for estimating the $P_{FA}$ at 5% but results in a lower than observed $P_{FA}$ for $P_{FA}$s < 1%. A $P_{FA}$ of about 0.01% really results in a $P_{FA}$ of about 0.1%.

The performance of the 10-h test is sufficiently good that almost all of the monthly monitoring tests, regardless of tank size, can be conducted using a 10-h test. For tanks with diameters less than 51 ft, the 10-h test could also meet the 0.2-gal/h precision testing criterion established by the State of California. By averaging 4 tests together tanks as large as 73 ft in diameter could be test. When the LRDP was used for monitoring at 1.0, 2.0 or 3.0 gal/h, both tests had a $P_{FA}$ < 0.3% for all tanks owned or operated by DoD.

All three of the testing options described in Table 1 can be used. As indicated by Tables 18 and 19, for the smaller bulk USTs, the LRDP-10 or LRDP-24 to meet the 0.2-gal/h monthly monitoring requirement outright. However, it is probably more cost efficient and less disruptive to operations for 12 monthly tests to be performed using the 0.3 – 1.0-gal/h monthly monitoring option and one annual test at 0.2 gal/h than 12 monthly tests at 0.2 gal/h. This latter approach minimizes the potential for false alarms and provides excellent environmental protection well within the regulatory standards. If this latter approach is used, small valve weeps would not interfere with the monthly monitoring testing. For the largest DoD bulk USTs, the only available strategy may be to use the LRDP-24 and test at 0.2 gal/h.

The exact option to select for the tank owner/operator to use will depend on the size of bulk USTs at the facility. The provider of the LRDP can help the tank owner/operator design a testing program that is best for the facility. The first step in the design process is to determine which LRDP system can be used for monitoring and which LRDP system can be used for precision testing with the fewest tests to be averaged and the lowest $P_{FA}$ that can be used. Once this is completed, a test protocol which is uses the minimum number of testing combinations (methods and versions) should be selected. The added time required to design the testing program in the beginning will have great benefits once it is implemented.

### 5.8 Results of the DEM/VAL of the LRDP in a 50,000-gal UST

The LRDP was successfully demonstrated at the Hunter Army Airfield in a 50,000-gal UST. All of the DEM/VAL objectives were met. First, it was demonstrated that the LRDP can be used as a portable leak detection system. The system was unpacked, pressure tested, installed and bled in less than a day. Also, the system was removed from the tank and packed up in less than a day. Though there were two people on-site at all times, for this size of system, a single person could easily install, bleed and remove the system.

Second, upon installation, the level of the product in the tank was measured with the LRDP. The level measured with the LRDP was within 0.1 in. of the level measured with a tape measure. This is within the 1/8 in. (0.125 in.) regulatory requirement for inventory level measurements.

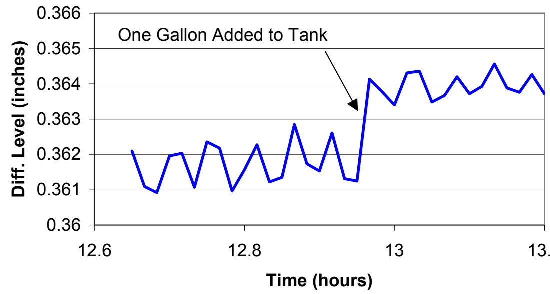


**Figure 25.** Height-to-volume calibration level data in a 50,000-gal UST.

Third, a calibration check was performed next to verify that the height-to-volume conversion factor to use for the testing. This was accomplished by adding a gallon of fuel and measuring the level change with the LRDP. As shown in Figure 25, this addition was easily measured by the LRDP. At 74 % capacity, a one gallon volume change is equivalent to approximately a 0.002 in. level change.

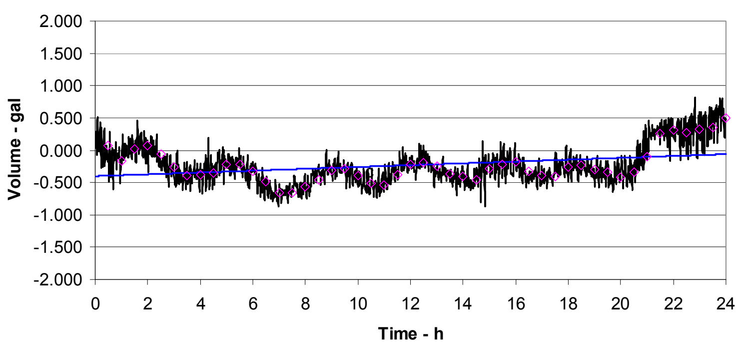


**Figure 26.** Volume data from a 24-h leak detection test with the LRDP-24.

Fourth, four 24-h leak detection tests were conducted. The first two tests showed an inflow of ~ 0.25 gal/h. Upon further investigation, it was found that the system had not been properly bled. When this problem was corrected, the tank was tested with the LRDP for leaks using a target leak criterion of 0.1 gal/h. The test result was a PASS, because the measured volume rate of 0.014 gal/h was less than a threshold of 0.05 gal/h. The final leak detection test was the demonstration of the system for the Hunter personnel. A 74-h data set was obtained (Figure 27). The data in Figures 26 and 27 were post analyzed to evaluate the performance of the system using shorter test periods. The results are tabulated in Table 9 for test durations of 8 h and 24 h. These preliminary results show that a leak rate criterion of 0.2-gal/h should be achievable in 50,000-gal tanks with only an 8-h test period. The results are presented graphically in Figure 28, and the statistics are summarized in Table 20 for both test durations.

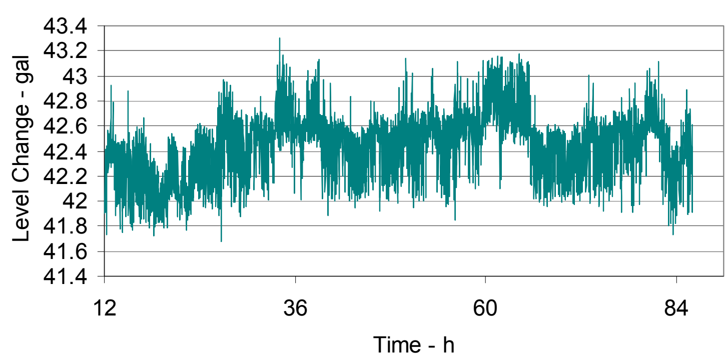


**Figure 27.** Volume data obtained from 74-h of measurements with the LRDP.

**Table 20.** Estimate of performance for the LRDP made for an 8-h and a 24-h test duration on a 50,000-gal UST.

| **Performance Parameters** | **8 h** | **24 h** |
|---|---|---|
| **November 19-20, 1999 Data** | | |
| **Test Duration – h** | | |
| **Mean – gal/h** | 0.000 | 0.006 |
| **Standard Deviation – gal/h** | 0.047 | 0.010 |
| **Count** | 13 | 4 |
| **Threshold – gal/h** | 0.084 | 0.023 |
| **MDLR –gal/h** | 0.168 | 0.047 |
| | | |
| **Precision Test MDLR – gal/h** | 0.200 | 0.200 |
| **Precision Test Threshold –gal/h** | 0.116 | 0.177 |
| **Precision Test $P_{FA}$** | 1.5% | < 0.001% |

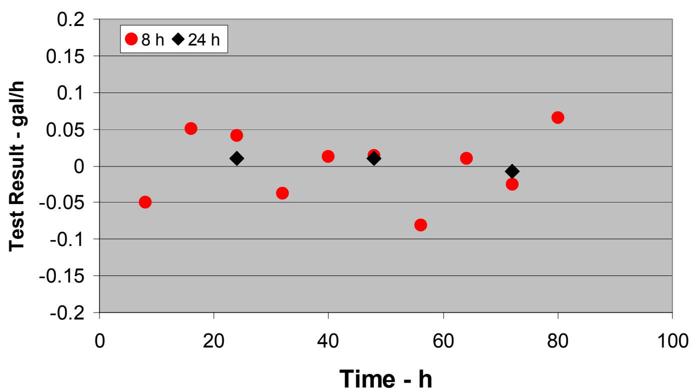


**Figure 28.** Estimate of performance made for the LRDP in a 50,000-gal UST.

This demonstration provided an opportunity to learn additional information regarding the deployment of the LRDP. First, the importance of properly "bleeding" the system was demonstrated. Bleeding the system refers to the act of purging any air-bubbles that may be trapped in the LRDP tubing and which may contribute to erroneous level measurements. Originally, it was thought that adequate purging would take place if the system was installed in a near-full tank with the reference tube valve closed. When the LRDP is resting on the bottom, with the reference tube empty, the valve is then opened so that the fuel will rush through the plumbing and fill the tube. The head of fuel in a near-full tank was thought to be adequate to flush out any air bubbles. Two subsequent 24-h tests showed substantial level trends on the order of +0.4 gal/h and +0.2 gal/h, respectively. Because the tank was completely isolated from the fuel lines and a test for water infiltration was negative, we knew that the tank had no actual inflow and that the system results were erroneous.

To address this problem, the system was repurged. The procedure was to close the valve, fill the reference tube to the top, pull the system up through the riser just to the point where the valve is still below the fuel surface, and open the valve so the fuel column in the reference tube will rush back through the plumbing until the DP cell reading is within 0.5 inches. Next, the valve is closed and the system is lowered to rest on the bottom. The valve is then opened to allow the fuel to rush back into the plumbing to fill the reference tube. This procedure was performed twice, and the volume rate obtained in a subsequent 24-h test was 0.014 gal/h.

The need to perform extensive bleeding of the LRDP is a key finding of this DEM/VAL. The current design for the LRDP maintains the reference tube isolation valve in the open position when a test is not being conducted. It is possible that air bubbles may have gotten into the system when the tank was drained and the system was not effectively bled during the subsequent fill. A standard procedure for bleeding the system, including valve control logic changes, was implemented prior to the installation at Pt. Loma.

We also found that not having the system mounted permanently made it susceptible to a noise level of a factor of 2 to 3 times higher than expected. This was due to two factors: (1) the system "rocked" a bit due to the curved bottom of the tank, and (2) any motion of the conduit due to wind/bumping/etc. induced this rocking motion. We showed that this problem existed by "jiggling" the conduit manual and then noting that the LRDP did not return to the exact previous position (before rocking), resulting in a step of 0.001 inch, or 0.5 gallons. This problem can be alleviated by shaping the bottom of the LRDP to better fit the bottom of the tank.

An oscillation with a 2 to 3 h period is also present in the data collected during the first week of the installation (Figure 26). The peak-to-peak amplitude of this oscillation is about 0.001 inches or about 2 to 3 times the amplitude of the random background noise. While the source of this oscillation is unknown, this periodicity is consistent with those of internal waves. The oscillation was not present in later data sets, such as the 74-h data set. In addition, there is a small diurnal component to the signal that does not get compensated, on the order of 0.001 in. This may be due to thermal effects on the conduit that cause the LRDP to "rock", as discussed previously.

### 5.9 Results of the DEM/VAL of the LRDP in a 132.5-ft Diameter Bulk UST at San Pedro

Figure 21 showed a 74-h data set obtained in a 132.5-ft diameter bulk UST at San Pedro. Superimposed on the level data is the temperature of the electronic package located in the embedded controller. This figure illustrates a number of important characteristics of the LRDP system. First, the diurnal temperature changes observed in the embedded controlled are not present in the compensated level data. This indicates that the compensation algorithm is effective. Second, the random fluctuations about the mean level change is representative of the system noise and the random background noise. For these data, the fluctuation level is 0.005 in., which is somewhat higher than the precision of the level measurement capability of the system. Third, the mean trend suggests an outflow from the system of 0.1 gal/h, which is most probably associated with a valve that did not fully close. The tank is located at the top of a hill and product transfers are made under gravity flow from the tank.

**Table 21.** Summary of the Results of Eight 24-h Tests with the LRDP in the San Pedro Tank after the Mean Flow Was Removed.

| Test Duration (h) | Tank Diameter (ft) | Number of Tests | Leak Rate (gal/h) | Probability of False Alarm (%) | Probability of Detection (%) |
|---|---|---|---|---|---|
| 12 | 132.5 | 18 | 0.46 | 5.0% | 95.0% |
| 24 | 132.5 | 8 | 0.26 | 5.0% | 95.0% |
| 12 | 88 | 18 | 0.133 | 5.0% | 95.0% |
| 24 | 88 | 8 | 0.069 | 5.0% | 95.0% |

A preliminary estimate of performance was made using the data obtained during the system checkout (Table 21). The performance estimate was made eight 24-h tests and assuming that the valve flow leakage was zero. The performance obtained indicated that the LRDP could be used to test the largest diameter bulk USTs owned and operated by the DoD. The performance obtained, when scaled for comparison of the previous evaluation results in an 88-ft-diameter tank, was over twice as good as obtained in the first evaluation. The results also suggested that a test duration that was shorter than 24 h would be possible. The MDLR determined from a sample of eight 24-h tests was 0.26 gal/h in the 132.5-ft diameter tank and 0.15 in the 88-ft-diameter tank. The tests conducted at San Pedro were a precursor to the Point Loma evaluation, and the results of the measurements made at San Pedro justified switching sites to complete the evaluation.

# 6.0 Cost Assessment

This section summarizes the cost and cost savings achievable with the LRDP for testing bulk USTs. This section also compares the cost of the LRDP to other in-tank mass-based systems and external systems such as tracer-based systems. The cost advantages of the LRDP are realized because of the extremely high performance of the LRDP, the on-line, monitoring capability of the LRDP when permanently installed in a tank, the capability of the system to conduct a short test (an overnight test), and the low recurring costs associated with routine testing to address regulatory requirements.

Two DEM/VALs of the technology were conducted. The cost of these DEM/VALs are summarized in Table 22. The first DEM/VAL was to install an LRDP system in a 2,100,000-gal bulk UST (Tank 175) at the Point Loma Fuel Terminal, San Diego, California, and to conduct a third-party evaluation to determine performance. The second DEM/VAL was to conduct a series of tests with the LRDP in a 50,000-gal shop-fabricated UST (Tank 45) at Hunter Army Airfield, Savannah, Georgia. With the exception of the reference tube, the same LRDP system was used for both DEM/VALs. The DEM/VAL costs include an initial site visit, installation, checkout, and removal of the equipment, and conduct of the DEM/VAL (data collection, analysis, and briefing of the results). The DEM/VAL at Point Loma required the collection of data over a 2-month period to check out the system and over a 3-month period to conduct the third-party evaluation. The DEM/VAL at Hunter was only a demonstration of the technology and was completed in less than two weeks.

**Table 22.** Summary of the Costs of the Two DEM/VALs of the LRDP System

| DEM/VAL | Cost of the DEM/VAL | Cost of the Third-Party Evaluation | Total |
|---|---|---|---|
| Point Loma Fuel Facility | $75,000 | $45,000 | $120,000 |
| Hunter Army Airfield | $25,000 | N/A | $25,000 |
| **Total** | **$100,000** | **$45,000** | **$145,000** |

Section 6.1 summarizes the estimated cost of the LRDP, and Section 6.2 compares the approximately cost of other in-tank mass-based methods and tracer-based methods to the LRDP system. Section 6.3 discusses the potential cost avoidance savings associated with the use of a reliable leak detection system like the LRDP. Finally, Section 6.4 summarizes the approximate cost of the parts used to manufacture the LRDP.

## 6.1 Cost Performance

The total life-cycle cost of leak detection includes the following items:

- ***Cost of Regulatory Compliance:*** Purchase, installation, and operation of a leak detection system (direct and recurring costs)

- – Purchase price of the leak detection system (direct cost)
- – Installation of the system (direct cost)
- – Training (direct and recurring cost)
- – Maintenance (recurring cost)
- – Cost of testing in meeting regulatory compliance requirements (recurring cost)
- – Cost of shutting down operations for testing (recurring cost)
- – Cost of false alarms (recurring cost)
- – Cost of missed detections (recurring cost)

- ***Cost Avoidance***
  - ***Fines and Shutdown of Operations:*** Costs associated with fines for not being in compliance and the cost impact on operations and operational readiness. (direct cost)
  - ***Tank Replacement Cost Avoidance:*** Pre-mature replacement of tanks (direct cost)
  - ***Remediation/Cleanup Cost Avoidance:*** Clean-up costs due to lack of testing or testing mistakes (direct cost)
- ***Commercialization and Technology Transfer Cost:*** Commercialization of the pre-production system (direct cost)

It is possible to make an estimate of all of these costs, because the performance of the leak detection system is known through the third-party evaluation. The $P_D$ and $P_{FA}$ allow estimates of the cost of testing mistakes, remediation, and tank replacement to be made. The *cost of regulatory compliance* is described below; the costs associated with *cost avoidance* and *commercialization and technology transfer* is described in Section 6.3.

Regulatory compliance will include the costs associated with the purchase, installation, and use of a leak detection system. It is estimated that the DoD owns or operates approximately 300 bulk UST with capacities greater than 100,000 gal. The life-cycle cost of a leak detection technology is comprised of the elements in Table 23. The Startup costs are fixed costs associated with the purchase, installation, and operator training. The Operational and Maintenance costs are also fixed and are small for the LRDP. The recurring costs associated with Compliance Testing and Test Mistakes are very small. Once the LRDP is permanently installed, a test can be initiated by pressing a start button.

In general, it is not the direct costs that control the price of a leak detection system. Rather, the recurring costs of monthly monitoring and annual precision testing tend to control. For poor performing systems with a higher than desired $P_{FA}$, the cost of testing increases, because

- additional tests with the same system or another system will have to be conducted to distinguish false alarms from leaks,

- site investigation may be required in terms of monitoring wells or uncovering of buried tanks to determine whether or not the tank is actually leaking,

- such false declarations may have to be reported to regulatory authorities with all the ramifications of such a report, and

- the activities required to determine whether or not a failed test is a false alarm will shutdown facility operations until the false alarm can be resolved.

If the $P_{FA}$ is unacceptably too high, operational experience indicates that fuel farm personnel often do not operate or trust the equipment, and thus, leaks may go undetected. This can be very costly because of the remediation costs associated with undetected leaks.

**Table 23.** Compliance Monitoring Technology Costs for the LRDP on a Per Tank Basis

| **Direct Environmental Costs** | | | | **Recurring or Variable Environmental Costs** | | | |
|---|---|---|---|---|---|---|---|
| **Startup** | | **Operation & Maintenance** | | **Compliance Testing** | | **Testing Mistakes** | |
| Equipment Cost | $40,000 | Equipment Cost | $40,000 | Equipment Cost | $40,000 | FA Mitigation<br>Remediation | $40,000<br>$750,000 |
| **Activity** | **%** | **Activity** | **%** | **Activity** | **%** | **Activity** | **%** |
| Facility preparation, mobilization | $4,000 (10%) | Labor to operate equipment | $4000 (10%) | Monthly monitoring | $400 (1%) | False alarms ($P_{FA}$ =< 0.1%) | $40 (0.1%) |
| Equipment Design | $4,000 (10%) | Utilities | $800 (2%) | Annual precision testing | $400 (1%) | Missed detections* | $938 (0.125%) |
| Equipment purchase | $40,000 (100%) | Consumable and supplies | $400 (1%) | Facility shutdown costs for testing | $1,200 (3%) | | |
| Installation | $8,000 (20%) | Equipment maintenance | $2,000 (5%) | | | | |
| Training of Operators | $2,000 (5%) | Training of operators | $800 (2%) | | | | |
| **Total** | **$58,000 (145%)** | **Total** | **$8,000 (20%)** | **Total** | **$2,000 (5%)** | **Total** | **$978** |

* It is assumed that the $P_D$ = 95% against a TLR = 0.2 gal/h and the number of leaking tanks is 10% of the 300 bulk USTs owned by the DoD. It is further assumed that all of the tanks are tested at a TLR of 0.2 gal/h, and as a consequence of testing at such a small leak rate, the remediation average remediation costs are assumed to be 25% of the average remediation costs.

Table 23 summarizes the costs associated with regulatory compliance with the LRDP. A Parts List for the LRDP is presented in Section 6.3. The purchase price of an LRDP assumed for this estimate is based on the purchase of 10 to 20 in-tank sensor units. Table 23 presents the cost model in terms of a percentage (%) of the equipment purchase price. The costs of false alarms and missed detections are based on an assumed price for additional testing ($500) and an average remediation cost ($750,000 per incident). The average remediation cost is based on 890 remediation jobs performed by the Navy. These two costs are indicated in the table heading. It is assumed that the $P_{FA}$ is less than 0.1%, and that the probability of a missed detection is $P_{MD} = 1-P_D = 5\%$ for a target leak rate of 0.2 gal/h. It is further assumed for this computation that 10% of all of the bulk USTs owned by the military are leaking. Because small leaks can be detected with the LRDP, the large average cost of remediation can be greatly reduced; for this calculation, it is assumed that the cost of remediation is 25% of the average cost.

An important cost is the cost of shutdown associated with testing and testing mistakes (false alarm investigations). Since the military is not selling fuel commercially, any short-term or permanent shutdown of fueling operations is difficult to quantify in terms of dollars. However, it is unacceptable to shutdown military operations, or to seriously impact operational readiness. An estimate of $40,000 for a False Alarm mitigation was used in Table 23, resulting in a $40 per tank cost at a $P_{FA}$ of 0.1%. The total cost per tank is $69,000. A cost comparison of the LRDP and tracer and other mass-measurement systems is given in Section 6.2.

### 6.2 Cost Comparison to Conventional and Other Technologies

The LRDP has several significant cost advantages over other technologies. The cost advantages are realized because of the extremely high performance of the LRDP, the on-line monitoring capability of the LRDP when permanently installed in a tank, the capability of the system to conduct a short test (an overnight test), and the low maintenance and recurring costs associated with the system and the testing. The monthly monitoring and precision testing requirements in California, for example, indicate that at least 12 and more likely 13 tests need to be conducted each year just for regulatory compliance, and one of these tests must be conducted at 0.2 gal/h. Only a permanently installed system can cost-effectively address such regulatory monitoring requirements. A number of the in-tank mass-based systems that are commercially available cannot be permanently installed in a tank and used for monitoring. The number of tests to be conducted each year will be increased (1) if the leak detection system is susceptible to false alarms, or (2) if tests need to be repeated, because they are too long and must be prematurely terminated or because they interfere with operations.

An estimate of the cost savings realized by the LRDP over two other methodologies is shown in Tables 24 through 27. Method 1 represents a tracer method with a high recurring cost of Compliance Testing. Method 1 assumes that a tracer must be added to the tank; no cost estimate is provided for tracer methods that use constituents in the fuel as tracers, because their performance has been found to be unacceptable. Method 2 is an in-tank mass-based method with the capability to only meet the monthly monitoring requirements. No other permanently installed in-tank, mass-based system besides the LRDP has the capability to meet the annual 0.2-gal/h performance standard. No specific commercial methods are identified by brand name here, but the cost savings achieved with the LRDP over a tracer method is due to the small recurring cost of testing with the LRDP and over the other permanently installed in-tank methods is due to the fact that the LRDP can be used to meet the annual precision test as well as the monthly monitoring tests. The best way to interpret the tables is to examine the relative cost savings between the LRDP and the other methods. The calculation uses the fixed Start-up costs and the recurring Compliance Testing costs from Table 23 for the LRDP.

The cost comparison calculation is done as follows. First, it was assumed that the Startup and O&M costs are the same for all methods. Established price lists for bulk leak detection systems are not generally available, because most product sales or testing jobs are performed under a unique contract bid. In many instances, the purchase price of the equipment or of the testing depends on the number of tanks that need to be tested. Therefore, it is difficult to make an estimate of the cost of other methods besides the LRDP. Historically, because the price of leak detection equipment and testing with the equipment tends to be market driven rather than cost driven, it is safe to assume that the price of all methods will be similar. This computation assumes $75,000, which is higher than anticipated for the LRDP and is probably lower than anticipated for Methods 1 and 2. This estimate includes the one-time purchase of the equipment for $40,000 (same as for the LRDP), as well as the operation and maintenance cost, the cost of testing and testing mistakes. The one-time purchase of equipment can be as high as $75,000 for mass-based systems. Second, the real cost savings of the testing tends to be controlled by the recurring cost of testing or the cost of additional testing because of lack of capability of the method to satisfy both the monthly monitoring and the annual precision test. The estimate assumes that 12 monthly tests and one annual precision at 0.2 gal/h are conducted each year. Third, there are significant cost savings associated with cost avoidance and remediation/cleanup because accurate and reliable leak detection is being performed. It is safe to say that the DoD would realize significant cost savings (many hundreds of millions of dollar) if any leak detection system was installed and used. If a reliable and accurate leak detection system is used, these savings can be a factor of 2 to 5 greater. These latter cost savings are not included in this calculation. Fourth, this cost comparison does not include the costs of Testing Mistakes. The number of tests to be conducted each year will be increased (1) if the leak detection system is susceptible to false alarms, or (2) if tests need to be repeated, because they are too long and must be prematurely terminated or because they interfere with operations.

Table 24 summarizes the cost of the initial purchase and installation of the leak detection system, the cost of performing 12 monthly tests, and the cost of performing an annual precision test. It is assumed that Methods 1 and 2 have the capability for performing the monthly monitoring test, but only Method 1 also has the capability for performing the annual test. It is assumed that Method 2 must use Method 1 to perform the annual precision test. It is also assumed that the recurring cost of testing is high for Method 1 as compared to the LRDP and that the recurring cost of testing is the same as the LRDP for Method 2. Table 25 summarizes the total cost of meeting the regulatory

**Table 24.** Comparison of the Cost of Testing in Dollars ($) with Monthly Monitoring and an Annual Precision Test for Each Bulk UST for the First Year

| | Purchase of System | Monthly Monitoring | | | Precision Test | Total |
|---|---|---|---|---|---|---|
| | Initial Purchase for One UST | Conduct of a Single Test | Cost of 12 Monthly Tests | Cost of Monthly Monitoring for First Year | Annual Cost of Precision Test | Cost of Compliance for Year 1 |
| **Method 1** | 75,000 | 10,000 | 120,000 | 195,000 | | 195,000 |
| **Method 2** | 75,000 | 240 | 2,880 | 77,880 | 25,000 | 102,880 |
| **LRDP** | 75,000 | 240 | 2,880 | 77,880 | | 77,880 |
| **Method 1/LRDP** | | | | | | 2.5 |
| **Method 2/LRDP** | | | | | | 1.3 |

requirements for a single bulk UST for all three methods. Clearly, the recurring cost of Method 1 dominates the cost of testing. Table 26 summarizes the cost for a fuel farm containing 15 bulk USTs, and Table 27 summarizes the cost for all 300 tanks throughout the DoD complex.

The ratio of the cost of each method relative to the LRDP are given in the tables. The savings of the LRDP compared to Method 1 would result in a payback period of less than one year, and the savings compared to Method 2 would result in a payback period of approximately three years, even without including the savings due to fewer tank replacements and lower remediation costs.

Table 22 summarizes the total cost of meeting the regulatory requirements for a single bulk UST for all three methods. Clearly, the recurring cost of Method 1 dominates the cost of testing. Table 23 summarizes the cost for a fuel farm containing 15 bulk USTs, and Table 23 summarizes the cost for 300 bulk USTs. *When Methods 1 and 2 are compared to the LRDP, the cost of the other methods is a factor of 3 to 12 higher than the LRDP.*

**Table 25.** Comparison of the Cost of Testing in Dollars ($) with Monthly Monitoring and an Annual Precision Test for Each Bulk UST Over 1, 3, 5 and 10 Years

| Testing Method | Total Cost of Compliance for | | | |
|---|---|---|---|---|
| | First Year | Three Years | Five Years | Ten Years |
| **Method 1** | 195,000 | 435,000 | 675,000 | 1,275,000 |
| **Method 2** | 102,880 | 158,640 | 214,400 | 353,800 |
| **LRDP** | 77,880 | 83,640 | 89,400 | 103,800 |
| **Method 1/LRDP** | 2.5 | 5.2 | 7.6 | 12.3 |
| **Method 2/LRDP** | 1.3 | 1.9 | 2.4 | 3.4 |

**Table 26.** Comparison of the Cost of Testing in Dollars ($) with Monthly Monitoring and an Annual Precision Test for 15 Bulk USTs Over 1, 3, 5 and 10 Years

| Testing Method | Total Cost of Compliance for | | | |
|---|---|---|---|---|
| | First Year | Three Years | Five Years | Ten Years |
| **Method 1** | 2,925,000 | 6,525,000 | 10,125,000 | 19,125,000 |
| **Method 2** | 1,543,200 | 2,379,600 | 3,216,000 | 5,307,000 |
| **LRDP** | 1,168,200 | 1,254,600 | 1,341,000 | 1,557,000 |
| **Method 1/LRDP** | 2.5 | 5.2 | 7.6 | 12.3 |
| **Method 2/LRDP** | 1.3 | 1.9 | 2.4 | 3.4 |

**Table 27.** Comparison of the Cost of Testing in Dollars ($) with Monthly Monitoring and an Annual Precision Test for 300 bulk USTs Over 1, 3, 5 and 10 Years

| Testing Method | Total Cost of Compliance for | | | |
|---|---|---|---|---|
| | First Year | Three Years | Five Years | Ten Years |
| **Method 1** | 58,500,000 | 130,500,000 | 202,500,000 | 382,500,000 |
| **Method 2** | 30,864,000 | 47,592,000 | 64,320,000 | 106,140,000 |
| **LRDP** | 23,364,000 | 25,092,000 | 26,820,000 | 31,140,000 |
| **Method 1/LRDP** | 2.5 | 5.2 | 7.6 | 12.3 |
| **Method 2/LRDP** | 1.3 | 1.9 | 2.4 | 3.4 |

## 6.3 Cost Avoidance

The magnitude of the cost savings that can be realized by minimizing testing mistakes, managing tank replacement efforts and minimizing remediation/cleanup efforts through early detection of a release is a direct function of the use and performance of the leak detection system. If the equipment is used frequently and the performance is high (i.e., the probabilities of false alarm and missed detection are low), then the integrity of the tanks can be verified periodically and do not need to be routinely replaced. They can continue to be used with confidence that they are not leaking, and if a leak develops, that it will be quickly detected. This reduces the volume of fuel released into the ground and the scope and cost of the cleanup. The high performance of the LRDP means that the number of false alarms and missed detections will be much smaller than other technologies. Furthermore, the high performance of the LRDP allows the probability of false alarm of the system to be set to a very low level without sacrificing the detection of small leaks. The other mass-based systems and some tracer-based approaches do not have the performance to operate with a low probability of false alarm. In addition, other mass-based methods must operate at a higher target leak rate. The total cost savings that can be realized by implementing a reliable leak detection program can be $500 million to $1 billion dollars. These cost savings are described below.

***Fines and Shutdown of Operations.*** The cost of testing more than offsets the cost of the fines that may be levied if the tanks are not tested within the specified regulatory guidelines and are out of compliance. Fines may be $25,000 per day per facility, or more. Ultimately, if the bulk USTs are not in compliance, fuel operations can be shut down. Since the military is not selling fuel, any permanent or short-term shutdown of fueling operations is difficult to quantify in terms of dollars. However, it is unacceptable to shutdown military operations, or to seriously impact operational readiness. Because the LRDP has the performance to perform both the monthly monitoring and the annual precision test, it is the most cost effective way to be in compliance. Because in many instances, an LRDP test can be performed in 10 h rather than the 48 or 72 h required by other methods, the impact on shutdown is significant.

***Tank Replacement Cost Avoidance.*** Most bulk USTs are expensive to replace; the costs per tank can be tens of millions of dollars. Replacement costs can be minimized, avoided, or delayed by using accurate and reliable leak detection. There are two types of tank replacement programs. First, the DoD has considered simply replacing all of the bulk USTs with bulk ASTs. The costs associated with such an approach would be well over $400,000,000. Such an approach can be avoided or minimized. It assumes that there are no accurate or reliable methods of leak detection, which is not true. Second, the DoD will need to replace or retrofit tanks as required for safe storage. The use of accurate and reliable leak detection can justifiably and safely avoid premature replacement of tanks. The cost savings associated with the use of leak detection is very large. For example, the U. S. Army has estimated that it would cost over $10,000,000 just to replace the 50,000-gal USTs at the Hunter Army Airfield (without testing equipment or testing services) as opposed to $3,100,000 for implementation of a testing program with the LRDP over a 10-year period. For our calculations, we assumed that the cost of replacement is $5 per gallon of stored fuel.

***Remediation/Cleanup Cost Avoidance.*** The cost of remediation and cleanup are by the largest costs associated with leaking tanks and clean-up cost avoidance can be the most significant cost savings realized with the purchase, installation and use of reliable leak detection. It is difficult to estimate the portion of the costs associated with clean-up that can be avoided, but it is significant.

The Navy has 659 future LUFT sites to clean up and has estimated that the total cost will be $890,000,000. Early detection of leaks can significantly reduce the total cost of cleanup because the concentration and areal extent of the plume is smaller than it would be if the leak was not detected early.

***Commercialization and Technology Transfer.*** The costs associated with technology transfer and commercialization have been minimized for the LRDP, because the third-party evaluation has already been completed and submitted to the NWGLDE for review and approval, and one company, Vista Research, has already commercialized the pre-production system. The former is a significant barrier (both in cost and time) for entry into the marketplace, and the later can take many years for industry to commit the resources needed for commercialization.

## 6.4 Cost of the Parts to Manufacture the LRDP

Table 28 summarizes the cost of the parts to assemble an LRDP.

**Table 28.** Parts List for the LRDP

| System | Item | Specification | Vendor | Price/ea | Qty | Total Price |
|---|---|---|---|---|---|---|
| **In-Tank** | | | | | | |
| | Differential Pressure Sensor | | Rosemount | $1,568 | 1 | $1,568 |
| | Pressure Sensors | | Pressure Sys. | $680 | 2 | $1,360 |
| | Indelas Electrical Actuator | | Flow Soln. | $252 | 1 | $252 |
| | RTD and Transmitter | | Omega | $173 | 1 | $173 |
| | Bellows (1) | | | $86 | 1 | $86 |
| | Bellows (2) | | | $181 | 1 | $181 |
| | SS Tubing (1) | | Peterson&Marsh | $273 | 1 | $273 |
| | SS Tubing (2) | | Peterson&Marsh | $635 | 1 | $635 |
| | Flanges, Ring, Cover | | Premier Tool | $1,410 | 1 | $1,410 |
| | Valve | | RS Crum | $130 | 1 | $130 |
| | | | | **Subtotal:** | | **$6,068** |
| **Above-Tank** | | | | | | |
| | DM6430X PC104 DAQ | -40 to 85 deg C | RTD | $845 | 1 | $845 |
| | SKH486DX100 PC104 CPU | Ext. Temp. | RTD | $1,296 | 1 | $1,296 |
| | 72Mbyte Disk-On-Chip (M-systems) | Normal Temp. | AtOnce | $683 | 1 | $683 |
| | Explosion Proof Box | N/A | Appleton | $580 | 2 | $1,160 |
| | 24 Volt Power Supply (chg to 25V) | -10 to 71 deg C | Acopian | $205 | 1 | $205 |
| | ASTEC DC-DC (AA258024L0505) | -25 to 70 deg C | Bell Industries | $83 | 1 | $83 |
| | RTD and Transmitter | | Omega | $173 | 1 | $173 |
| | Voltage Reference (AD586) | 0 to 70 deg C | Newark | $13 | 1 | $13 |
| | Red LED (XP) | | Miller Wholesale | $69 | 1 | $69 |
| | Green LED (XP) | | Miller Wholesale | $85 | 1 | $85 |
| | XP Barrier | | R. Stahl | $153 | 4 | $612 |
| | Battery (Gell Cell) | | Newark | $10 | 2 | $21 |
| | Labor to Drill Holes in XP boxes | | Danco Machine | $300 | 1 | $300 |
| | | | | **Subtotal:** | | **$5,545** |
| | **Misc. Electrical** | | | | | **$644** |
| | **Misc. Mechanical** | | | | | **$2,692** |
| | | | | **Total Parts:** | | **$14,951** |

# 7.0 Regulatory Compliance

The DoD owns and/or operates almost all of the bulk USTs in the United States. While the leak detection requirements for bulk USTs (i.e., field erected USTs) were deferred in EPA's UST regulation issued on 22 September 1988, many of the states have or are in the process of requiring testing of such tanks. California is a major example, but the bulk USTs in New York, Michigan, Maine, and Florida also require that these tanks be tested routinely for leaks. It is not surprising that the members of the NWGLDE for bulk USTs are comprised of senior and active regulators from each of these states. The NFESC team has had major interactions, meetings, and discussions with the members of the NWGLDE, both as work group representatives and as regulators. The process for obtaining approval of the LRDP-24 and the LRDP-48, based on the LRDP evaluated North Island, took over 18 months of frequent interactions. A number of important issues were derived from these interactions. The NFESC team took a lead role in these discussions and was responsible for many of the major regulatory changes that took place and allowed for DoD tanks to be in compliance.

A new evaluation protocol was developed for mass-based leak detection systems, because of real differences between volumetric leak detection systems and mass-based leak detection systems. The NFESC team, in conjunction with KWA, took a lead role in developing and technically supporting these changes. The basic evaluation procedure comprised of conducting 12 blind tests did not change. Nor did the evaluation conditions change. What did change was how to report and apply the results of the evaluation. The new evaluation procedure

- increased the range of tank sizes (diameters) for which the results of the evaluation would apply,
- acknowledged the concept that mass-measurement systems compensate for the thermal expansion and contraction of the fuel in the tank and the performance and
- acknowledged that the performance of mass-measurement systems scale with the surface area of the product in the tank and not the volume of the product in the tank,
- allowed the performance to scale with tank size (more specifically, the surface area of the product in the tank),
- limited the scaled performance of the method to no less than 0.2 gal/h,
- allowed two or more tests to be averaged together to improve performance, and
- limited how the threshold used to declare a leak could be set.

The new evaluation procedure increased the ranged of USTs for which the evaluation was valid from 150% of the surface area of the product in the tank to 250% of the product surface area of the tank. This had significant positive ramifications. This meant that if an evaluation was performed in a tank with a diameter of 88 ft or greater, the leak detection system could be used to test all of the tanks owned and operated by DoD without having to be reevaluated. Before this change, the same system would have had to be evaluated a total of three times to cover the range of bulk USTs owned by DoD. Since the number of tanks is limited to 300, vendors would not have found it cost effective to have the evaluations conducted and a large number of DoD tanks would go untested and be out of regulatory compliance. The NFESC team provided analysis and technical arguments to support this increase to 250%.

The new evaluation procedure acknowledged that the volume of product in the tank does not affect the result of a leak detection test with a mass-measurement system. Rather, the performance was affected by the surface area of the product in the tank. This was important, because, previously, the applicability of the evaluation was determined from the volume of product in the tank. This was also important, because, at the time, the NWGLDE was considering the option of scaling the performance of the evaluated method so that it could be used to test smaller and larger tanks than the one used in the evaluation. The NFESC team was the first group to make this argument with the regulators and provided experiment evidence, theory, and analyses to support this premise.

The new evaluation procedure allowed the performance of the evaluated method to scale with the product surface area of the tank, provided that the target leak rate of the scaled performance was not less than 0.2 gal/h. Thus, any tank that had a product surface area that resulted in a scaled target leak rate less than 0.2 gal/h would be tested at 0.2 gal/h. There was no upper bound on performance except that the largest tank for which the evaluation was applicable was set at 250% of the product surface area of the tank used in the evaluation. The NFESC team provided experiment evidence, theory, and analyses to support this performance scaling.

The new evaluation procedure acknowledged that averaging test results would increase performance for methods whose results were random, additive, and independent, and accepted the approach for computing the performance without having to be reevaluated. The NFESC team played the primary role in advancing this methodology. Its acceptance meant that a mass-based measurement system could be used for both monthly monitoring and annual precision testing for high performing systems, even if the tank being tested is too large for the method to meet the 0.2-gal/h target leak rate criterion in a single test.

The new evaluation procedure also established limitations on how some of the methods could be used. For small USTs found at service stations, the threshold of the leak detection system was selected to operate with at the MDLR = 0.2 gal/h (i.e., $P_D$ = 95% for a TLR = 0.2 gal/h and a $P_{FA}$ = 5%), or with a threshold that was set so that the $P_D$ = 95% for a TLR = 0.2 gal/h and the $P_{FA} <$ 5%. The performance of the LRDP was deemed to be too good by the NWGLDE to operate in this latter manner, because the threshold that would be used to detect a leak rate of 2 gal/h with a $P_D$ = 95% would be 1.9 gal/h. The regulators were afraid that smaller leaks would go undetected using such a threshold and limited the target leak rate to no larger than twice the MDLR. Practically, this prevented the LRDP from using the 3 gal/h monitoring standard in California, because its performance was too good, but allowed poor or marginal methods to use this standard. This NWGLDE-imposed usage limitation is unfortunate because it did not allow the LRDP to be operated as it was originally intended. It is also the reason that Versions 1.0, 1.1, and 1.2 exist. The performance of the LRDP is sufficiently good, however, that this regulatory limit does not impact its use. The NWGLDE also felt that the use of this approach for selecting a threshold would be confusing to tank owners because the PFA would change for every tank size tested (even though the $P_{FA}$ was always less than 5%). They agreed that a threshold could be selected that was less than 5% provided that the target leak rate would scale with tank size. The NWGLDE developed a table to show examples of the performance of the method when testing different size tanks. This table was added to the standard results form of the third-party evaluation.

In addition to the changes to the evaluation protocol, the NFESC team helped developed two California leak detection standards for bulk USTs. In 1998, California developed a number of regulatory leak detection guidelines for the owners and operators of bulk USTs. The original guidelines were based on the target leak rates (0.1 and 0.2 gal/h) being used for 10,000-gal USTs at service stations. For monthly monitoring purposes, California developed a target leak rate of 1 to 2 gal/h and 2 to 3 gal/h to accommodate the performance of the one evaluated mass-based leak detection system, provided that a 0.1-gal/h precision (tightness) test be conducted annually or bi-annually by another method. There were several problems with this approach. First, the guidelines do not acknowledge the differences between the small USTs found at service stations and the large infrastructure USTs found at bulk fueling facilities. Second, the emphasis on the use of a target leak rate of 0.1-gal/h was misguided, because even at service stations, this standard is difficult to meet. The NFESC team proposed that several guidelines be developed that replace the annual precision test at 0.1 gal/h with an annual precision test at 0.2 gal/h. This is significant, because a high performance mass-based leak detection system, like the LRDP, can be operated at 0.2-gal/h. The two guidelines presented in Table 1 (options 7 and 10) were the result of the interactions.

Finally, before the first evaluation was conducted, the NFESC team had several meeting with the NWGLDE and the California regulators to inform them of the evaluation procedure and to insure that the procedure being followed was acceptable. The evaluation procedure and reporting procedure followed at Point Loma is identical to that approved by the NWGLDE and various state regulatory agencies for the first evaluation.

The NFESC team has worked closely with the NWGLDE and the state regulators to insure that the DEM/VALs conducted to evaluate the performance of the LRDP would be acceptable. This interaction has also played a very significant role in the acceptance of the LRDP, development of new ways to use bulk UST leak detection systems, development of better ways of evaluating and reporting the results of a third-party evaluation, and development of regulatory guidelines.

# 8.0 Technology Implementation

## 8.1 DoD Need

As stated in the introduction, the DoD owns and/or operates almost all of the bulk USTs in the United States. While the leak detection requirements for bulk USTs (i.e., field erected USTs) were deferred in EPA's UST regulation issued on 22 September 1988, many of the states have or are in the process of requiring testing of such tanks. California has developed a set of regulatory guidelines for testing bulk USTs. Other states, like New York, Michigan, Maine, and Florida also require bulk USTs to be tested. The requirement for testing may cost many tens to hundreds of millions of dollars, depending on the testing approach used. The use of the LRDP, because of its ability to address the monthly monitoring and the annual precision testing with the same system, can realize significant cost savings for the DoD.

## 8.2 Transition

The LRDP is ready for commercialization. The drawings, specifications, and software screens are described in Appendices C and D. A workshop was conducted by the Environmental Technology Evaluation Center (EvTEC) of the Civil Engineering Research Foundation (CERF) with representatives present from the petroleum industry, the Defense Energy Support Center (DESC), the U. S. Air Force, Army, and Navy, and technical experts to introduce the technology and to describe the advantages of the system for regulatory compliance [27]. The LRDP was also submitted for an R&D 100 award.

The LRDP already has regulatory approval, and the evaluation conducted as a DEM/VAL at Point Loma has been submitted for approval by the NWGLDE in April 2001. Since this submittal parallels the previous submittal, no significant technical acceptance problems are anticipated. As of this publication date, the third-party evaluation is still under review by the NWGLDE. If the LRDP is used to test 50,000-gal USTs or tanks with curved walls for regulatory compliance, another third-party evaluation will have to be conducted.

Vista Research has commercialized the LRDP. Product description and specification sheets are included in Appendix C. Immediate commercialization of this technology has been possible, because industry was involved during the demonstrations and the bulk storage tank facilities had a real need to be in regulatory compliance.

# 9.0 Lessons Learned

Generally, the demonstrations of the LRDP at the three sites went smoothly. It is important that the site selected for the demonstration will be adequate for demonstration and validation and that the owners and/or operators of the site are interested in participating in and the outcome of the demonstration, because of the time and effort required to conduct a DEM/VAL. The LRDP teams received excellent support at all three sites.

One problem was encountered during the demonstrations that is specific to the performance evaluations of in-tank leak detection systems. The third-party evaluation was originally scheduled to be conducted at the San Pedro Fuel Farm. The valves on the bulk UST selected for the evaluation at the San Pedro fuel farm did not completely seal. This allowed a very small flow (~ 0.1 gal/h) to occur. Such flows are too small to interfere with monthly monitoring tests that might be conducted on a tank, because the monitoring standards require that the threshold be set to detect the much larger leaks of 1 or 2 gal/h, and the performance of the LRDP is easily capable of detecting such leaks. However, this problem could have had significant impact on the conduct of a precision test in which the leak to be detected is of similar magnitude. For the conduct of the annual precision test, the valves might need to be sealed more tightly or replaced with new valves, or valve blinds may need to be installed.

The EPA standard test procedures require that the tank used in the evaluation be free of leaks and that no inflows or outflows occur during the evaluation. Unfortunately, the LRDP is the only system that could identify such small flows. The problem was identified and verified after a few tests during the checkout of the LRDP at San Pedro, but the problem could not be corrected in a timely manner. As a consequence, the evaluation was performed on a bulk UST at the Point Loma Fuel Terminal. New double block and bleed valve, which sealed tightly, had just been installed on the tanks in the fuel farm.

It was important to conduct the evaluation on a tight tank, because in the previous evaluation conducted at North Island, small inflows were present, but even though they were identified and quantified, the NWGLDE imposed unrealistic constraints on the use of the method in their listing [5]. These constraints included requiring a much longer waiting period (24 h vice 2 h) and the suggestion of a system bias (due to a non-zero mean) even though none existed. The former was due to a data quality index preventing the start of the test until in the inflow, which took about 24 h to become small enough to be negligible, ceased. The latter had the potential for increasing the threshold, which would have result in declaring a leak when none was present during the conduct of an annual precision test at 0.2 gal/h.

The magnitude of this valve problem is not known for bulk tanks, but it is the same problem encountered and successfully addressed for routine monitoring of underground storage tanks at service stations.

Unlike many other environmental technologies, the LRDP and the DEM/VAL procedure is not site specific or geology dependent. The EPA evaluation procedure is designed to accommodate a wide range of conditions that might be encountered during actual leak detection tests at or other bulk fuel farms. The procedure places a constraint on the use of the equipment based on the conditions used in the evaluation. These constraints involve temperature conditions and tank size. Fifteen years of experience indicates that once a leak detection method is evaluated following an EPA standard test procedure, it can be used to test any tank.

# 10.0 Summary

A reliable, flexible, easy-to-use, and cost-effective system for leak detection and inventory control has been demonstrated and validated for bulk USTs. The novel design of the LRDP allows off-the-shelf, commercially available process-control pressure sensors, which have a long-term demonstrated track record of performance, to be used. Delicate, expensive, one-of-a-kind, or special sensors are not required. The LRDP is a fully automatic, computer-controlled system that can easily integrated with FAS or other fuel management systems. The LRDP has been evaluated for performance for bulk USTs with vertical walls following the standard test procedures developed by the EPA and approved by the National Work Group on Leak Detection Evaluations. The performance of the LRDP exceeds regulatory requirements for leak detection and is currently on the listing of the National Work Group for Leak Detection Evaluations. The results obtained on this ESTCP project have been submitted as an update to these results. Precision leak detection tests at 0.2-gal/h can be completed in 10 h for tanks with diameters less than 90 ft and in 24 h for larger tanks. Monthly monitoring tests at 1 or 2 gal/h can be accomplished with 10-h tests.

The DEM/VAL conducted in a 50,000-gal UST indicates that the LRDP has the performance to meet the 0.2-gal/h monthly monitoring requirements in EPA's UST regulations. If the LRDP is used to test these USTs, then a third-party evaluation will have to be conducted.

With some simple modifications, the LRDP should be able to test aboveground storage tanks for leaks with a performance that is similar to that obtained for bulk USTs. These modifications must address the effect of the large diurnal swings in ambient air temperature that occurs during a test.

The LRDP is ready for commercial use as a permanently installed system for monitoring, or a portable system for use in a testing service. Vista Research, Inc., has commercialized the system.

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# Appendix A

## Points of Contact

| Point of Contact | Organization | Phone/Fax/Email | Role in Project |
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| | | | |
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| John Kneece<br>South Carolina DHEC | South Carolina Department of Health and Environmental Control<br>2600 Bull Street<br>Columbia, SC 29201 | voice: (803) 898-4364<br>fax: (803) 898-4330<br>e-mail:<br>kneeceje@colum26.dhec.state.sc.us | NWGLDE, South Carolina Regulator |
| Curt D. Johnson<br>Alabama DEM | Alabama Department of Environmental Management<br>P. O. Box 301463<br>Montgomery, AL 36130-1463 | voice: (334) 271-7986<br>fax: (334) 270-5631<br>e-mail: cdj@adem.state.al.us | NWGLDE, Chairman,<br>Alabama Regulator |

# Appendix B

## Listings for the LRDP-10 and the Update for the LRDP-24

## Submitted to the National Work Group on Leak Detection Evaluations (NWGLDE)

**Vista Research, Inc. and Naval Facilities Engineering Service Center**

LRDP-24 (V1.0a.1.65,V1.0a.2.40)

# BULK FIELD-CONSTRUCTED AUTOMATIC TANK GAUGE MONITORING AND TIGHTNESS TEST LEAK DETECTION METHOD

**Certification:** Leak rate is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft², leak rate is 1.65 or 2.40 gph with $P_D = 95\%$ and $P_{FA} = 0.0015\%$ or $P_{FA} < 0.001\%$, respectively. Choose one to determine the scaled leak rate and scaled leak threshold for the tank being monitored.
For other tank sizes, scaled leak rate equals [(PSA in ft² ÷ 11,786 ft²) x (leak rate in gph)].
Example: For a tank with PSA = 10,000 ft², leak rate = 1.65 gph; scaled leak rate = [(10,000 ft² ÷ 11,786 ft²) x 1.65 gph] = 1.40 gph.
Calculated minimum detectable leak rate is 0.690 gph with $P_D = 95\%$ and $P_{FA} = 5\%$.
**Leak rate may not be scaled below 0.2 gph.**

**Leak Threshold:** Leak threshold is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft² and leak rate of 1.65 or 2.40 gph, leak threshold is 1.31 or 2.06 gph respectively.
For other tank sizes, scaled leak threshold equals [(PSA in ft² ÷ 11,786 ft²) x (leak rate in gph - 0.345 gph)].
Example: For a tank with PSA = 10,000 ft², leak rate = 1.65 gph; scaled leak threshold = [(10,000 ft² ÷ 11,786 ft²) x (1.65 gph - 0.345 gph)] = 1.40 gph.
A tank system should not be declared tight if the test result indicates a loss or gain that equals or exceeds the calculated leak threshold.

**Applicability:** Gasoline, diesel, aviation fuel.
Other liquids may be tested after consultation with the manufacturer.

**Tank Capacity:** Use limited to single field-constructed vertical tanks larger than 50,000 gallons.
Maximum product surface area (PSA) is 29,465 ft² (approximately 193.7 ft. diameter).
Performance not sensitive to product level.

**Waiting Time:** Minimum of 2 hours after delivery or dispensing.
Valve leaks and pump drain-back may mask a leak. Allow sufficient waiting time to minimize these effects.
Waiting times during evaluation ranged from 0 to 3 hours.

**Test Period:** Minimum of 24 hours.
There must be no dispensing or delivery during test.

**Temperature:** Measurement not required by this system.

**Water Sensor:** None. Water leaks are measured as increase in mass inside tank.

**Calibration:** Differential pressure sensor must be checked regularly in accordance with manufacturer's instructions.

**Comments:** Tests only portion of tank containing product.
As product level is lowered, leak rate in a leaking tank decreases (due to lower head pressure). Consistent testing at low levels could allow a leak to remain undetected.
Evaluated in a nominal 2,100,000 gallon, vertical underground tank with product surface area (PSA) of 11,786 ft².
Evaluated as a stand-alone system.
Performance of the system can be improved by combining results of 2 or more tests. If this option is used, it is important to determine the number of tests, their timing and the number of passing results necessary to confirm a tank is tight. The LRDP-24-n (V1.0a, V1.1a, V1.2a) combines the results of n tests, where $n \leq 12$ and is one evaluated option to improve the performance of this system.

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**Vista Research, Inc. and Naval Facilities Engineering Service Center**

LRDP-10 (V1.0a.1.90,V1.0a.2.40)

# BULK FIELD-CONSTRUCTED AUTOMATIC TANK GAUGE MONITORING AND TIGHTNESS TEST LEAK DETECTION METHOD

**Certification:** Leak rate is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft², leak rate is 1.90 or 2.40 gph with $P_D = 95\%$ and $P_{FA} = 0.075\%$ or 0.006%, respectively. Choose one to determine the scaled leak rate and scaled leak threshold for the tank being monitored.
For other tank sizes, scaled leak rate equals [(PSA in ft² ÷ 11,786 ft²) x (leak rate in gph)].
Example: For a tank with PSA = 10,000 ft², leak rate = 1.90 gph; scaled leak rate = [(10,000 ft² ÷ 11,786 ft²) x 1.90 gph] = 1.61 gph.
Calculated minimum detectable leak rate is 1.14 gph with $P_D = 95\%$ and $P_{FA} = 5\%$.
**Leak rate may not be scaled below 0.2 gph.**

**Leak Threshold:** Leak threshold is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft² and leak rate of 1.90 or 2.40 gph, leak threshold is 1.33 or 1.83 gph respectively.
For other tank sizes, scaled leak threshold equals [(PSA in ft² ÷ 11,786 ft²) x (leak rate in gph - 0.569 gph)].
Example: For a tank with PSA = 10,000 ft², leak rate = 1.90 gph; scaled leak threshold = [(10,000 ft² ÷ 11,786 ft²) x (1.90 gph - 0.569 gph)] = 1.13 gph.
A tank system should not be declared tight if the test result indicates a loss or gain that equals or exceeds the calculated leak threshold.

**Applicability:** Gasoline, diesel, aviation fuel.
Other liquids may be tested after consultation with the manufacturer.

**Tank Capacity:** Use limited to single field-constructed vertical tanks larger than 50,000 gallons.
Maximum product surface area (PSA) is 29,465 ft² (approximately 193.7 ft. diameter).
Performance not sensitive to product level.

**Waiting Time:** Minimum of 2 hours after delivery or dispensing.
Valve leaks and pump drain-back may mask a leak. Allow sufficient waiting time to minimize these effects.
Waiting times during evaluation ranged from 0 to 3 hours, with one at 7 hours and another at 10 hours.

**Test Period:** Minimum of 10 hours.
There must be no dispensing or delivery during test.

**Temperature:** Measurement not required by this system.

**Water Sensor:** None. Water leaks are measured as increase in mass inside tank.

**Calibration:** Differential pressure sensor must be checked regularly in accordance with manufacturer's instructions.

**Comments:** Tests only portion of tank containing product.
As product level is lowered, leak rate in a leaking tank decreases (due to lower head pressure). Consistent testing at low levels could allow a leak to remain undetected.
Evaluated in a nominal 2,100,000 gallon, vertical underground tank with product surface area (PSA) of 11,786 ft².
Evaluated as a stand-alone system.
Performance of the system can be improved by combining results of 2 or more tests. If this option is used, it is important to determine the number of tests, their timing and the number of passing results necessary to confirm a tank is tight. The LRDP-10-n (V1.0a, V1.1a, V1.2a) combines the results of n tests, where n ≤ 12 and is one evaluated option to improve the performance of this system.

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**Vista Research, Inc. and Naval Facilities Engineering Service Center**

LRDP-24 (V1.1a)

# BULK FIELD-CONSTRUCTED AUTOMATIC TANK GAUGE MONITORING AND TIGHTNESS TEST LEAK DETECTION METHOD

**Certification:** Leak rate is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft², leak rate is 0.95 gph with $P_D$ = 95% and $P_{FA}$ =0.48%.
For other tank sizes, leak rate equals [(PSA in ft² ÷ 11,786 ft²) x 0.95 gph].
Example: For a tank with PSA = 10,000 ft²; leak rate = [(10,000 ft² ÷ 11,786 ft²) x 0.95 gph] = 0.81 gph.
Calculated minimum detectable leak rate is 0.690 gph with $P_D$ = 95% and $P_{FA}$ = 5%.
**Leak rate may not be scaled below 0.2 gph.**

**Leak Threshold:** Leak threshold is proportional to product surface area (PSA).
For tanks with PSA of 11,786 ft², leak threshold is 0.60 gph.
For other tank sizes, leak threshold equals [(PSA in ft² ÷ 11,786 ft²) x 0.60 gph].
Example: For a tank with PSA = 10,000 ft²; leak threshold = [(10,000 ft² ÷ 11,786 ft²) x 0.60 gph] = 0.51 gph.
A tank system should not be declared tight if the test result indicates a loss or gain that equals or exceeds the calculated leak threshold.

**Applicability:** Gasoline, diesel, aviation fuel.
Other liquids may be tested after consultation with the manufacturer.

**Tank Capacity:** Use limited to single field-constructed vertical tanks larger than 50,000 gallons.
Maximum product surface area (PSA) is 29,465 ft² (approximately 193.7 ft. diameter).
Performance not sensitive to product level.

**Waiting Time:** Minimum of 2 hours after delivery or dispensing.
Valve leaks and pump drain-back may mask a leak. Allow sufficient waiting time to minimize these effects.
Waiting times during evaluation ranged from 0 to 3 hours.

**Test Period:** Minimum of 24 hours.
There must be no dispensing or delivery during test.

**Temperature:** Measurement not required by this system.

**Water Sensor:** None. Water leaks are measured as increase in mass inside tank.

**Calibration:** Differential pressure sensor must be checked regularly in accordance with manufacturer's instructions.

**Comments:** Tests only portion of tank containing product.
As product level is lowered, leak rate in a leaking tank decreases (due to lower head pressure). Consistent testing at low levels could allow a leak to remain undetected.
Evaluated in a nominal 2,100,000 gallon, vertical underground tank with product surface area (PSA) of 11,786 ft².
Evaluated as a stand-alone system.
Performance of the system can be improved by combining results of 2 or more tests. If this option is used, it is important to determine the number of tests, their timing and the number of passing results necessary to confirm a tank is tight. The LRDP-24-n (V1.0a, V1.1a, V1.2a) combines the results of n tests, where n ≤ 12 and is one evaluated option to improve the performance of this system.

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**Vista Research, Inc. and Naval Facilities Engineering Service Center**

LRDP-10 (V1.1a)

# BULK FIELD-CONSTRUCTED AUTOMATIC TANK GAUGE MONITORING AND TIGHTNESS TEST LEAK DETECTION METHOD

| | |
|---|---|
| **Certification:** | Leak rate is proportional to product surface area (PSA).<br>For tanks with PSA of 11,786 ft², leak rate is 1.65 gph with $P_D$ = 95% and $P_{FA}$ =0.29%.<br>For other tank sizes, leak rate equals [(PSA in ft² ÷ 11,786 ft²) x 1.65 gph].<br>Example: For a tank with PSA = 10,000 ft²; leak rate = [(10,000 ft² ÷ 11,786 ft²) x 1.65 gph] = 1.40 gph.<br>Calculated minimum detectable leak rate is 0.690 gph with $P_D$ = 95% and $P_{FA}$ = 5%.<br>**Leak rate may not be scaled below 0.2 gph.** |
| **Leak Threshold:** | Leak threshold is proportional to product surface area (PSA).<br>For tanks with PSA of 11,786 ft², leak threshold is 1.08 gph.<br>For other tank sizes, leak threshold equals [(PSA in ft² ÷ 11,786 ft²) x 1.08 gph].<br>Example: For a tank with PSA = 10,000 ft²; leak threshold = [(10,000 ft² ÷ 11,786 ft²) x 1.08 gph] = 0.92 gph.<br>A tank system should not be declared tight if the test result indicates a loss or gain that equals or exceeds the calculated leak threshold. |
| **Applicability:** | Gasoline, diesel, aviation fuel.<br>Other liquids may be tested after consultation with the manufacturer. |
| **Tank Capacity:** | Use limited to single field-constructed vertical tanks larger than 50,000 gallons.<br>Maximum product surface area (PSA) is 29,465 ft² (approximately 193.7 ft. diameter).<br>Performance not sensitive to product level. |
| **Waiting Time:** | Minimum of 2 hours after delivery or dispensing.<br>Valve leaks and pump drain-back may mask a leak. Allow sufficient waiting time to minimize these effects.<br>Waiting times during evaluation ranged from 0 to 3 hours, with one at 7 hours and another at 10 hours. |
| **Test Period:** | Minimum of 10 hours.<br>There must be no dispensing or delivery during test. |
| **Temperature:** | Measurement not required by this system. |
| **Water Sensor:** | None. Water leaks are measured as increase in mass inside tank. |
| **Calibration:** | Differential pressure sensor must be checked regularly in accordance with manufacturer's instructions. |
| **Comments:** | Tests only portion of tank containing product.<br>As product level is lowered, leak rate in a leaking tank decreases (due to lower head pressure). Consistent testing at low levels could allow a leak to remain undetected.<br>Evaluated in a nominal 2,100,000 gallon, vertical underground tank with product surface area (PSA) of 11,786 ft².<br>Evaluated as a stand-alone system.<br>Performance of the system can be improved by combining results of 2 or more tests. If this option is used, it is important to determine the number of tests, their timing and the number of passing results necessary to confirm a tank is tight. The LRDP-10-n (V1.0a, V1.1a, V1.2a) combines the results of n tests, where n ≤ 12 and is one evaluated option to improve the performance of this system. |

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# Appendix C

# Product Description and Product Specification Sheets

Product Data Sheet and System Specification

# LRDP-10

## Low Range Differential Pressure System

### Dimensions

| | |
|---|---|
| *Diameter of Base Sensor Cylinder* | 7 13/16 in. (19.9 cm) |
| *Height of Base Sensor Cylinder* | 16.0 in. (45.7 cm) |
| *Diameter of reference tube* | 3 ½ in. (8.9 cm) |
| *Height of constant diameter reference tube* | 0 to 50 ft (15.2 m) |
| *Height of shaped reference tube* | 0-12 ft (3.7 m); 0-50 ft (15.2 m) |
| *Embedded controller (2 connected units)* | 12 in. x 12 in. x 8 in. (ea. unit)<br>(30.5 cm x 45.7 cm x 10.2 cm) |

### Weight

| | |
|---|---|
| *Base Sensor Cylinder (Empty)* | 35 lbs (16 kg) |
| *Constant diameter reference tube, including conduit* | 5 lbs/ft (2.3 kg) |
| *Shaped reference tube, including conduit* | 5 lbs/ft (2.3 kg) |
| *Embedded controller (2 units)* | 60 lbs (27.3 kg) |

### Detectable Leak Rate

| | | |
|---|---|---|
| (Probability of detection of 95% with a probability of false alarm of 5%) | *For tank diameters less than 51.3 ft* | 0.20 gal/h |
| | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11,786)*1.139$ gal/h |
| | *For tank diameters* $D = [2,635.0*(n)^{0.5}]^{0.5}$ *(LRDP-10-n)* | 0.20 gal/h (average of 1 < n $\leq$ 12 tests) |
| (Probability of detection of 95% with a probability of false alarm of 0.29%) | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11,786)*1.653$ gal/h |
| | *For tank diameters* $D = [1,817.3*(n)^{0.5}]^{0.5}$ *(LRDP-10-n)* | 0.20 gal/h (average of 1 < n $\leq$ 12 tests) |
| (Probability of detection of 95% with a probability of false alarm of <0.15%) | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11,786)*(2.0-0.569)$ gal/h |
| | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11,786)*(3.0-0.569)$ gal/h |

### Power

| | |
|---|---|
| *In-tank sensor unit, embedded controller, interface computer* | *Single-phase 120 VAC 60 Hz* |

### Temperature

| | |
|---|---|
| *Operating* | $-20^{\circ}$ to $100^{\circ}$ F ($-29^{\circ}$ to $38^{\circ}$ C) |

### User Interface

| | |
|---|---|
| *System monitor* | *Vista GUI software*<br>*Windows 95 or FAS software* |

## Product Data Sheet and System Specification

# LRDP-24

## Low Range Differential Pressure System

### Dimensions

| | |
|---|---|
| *Diameter of Base Sensor Cylinder* | 7 13/16 in. (19.9 cm) |
| *Height of Base Sensor Cylinder* | 16.0 in. (45.7 cm) |
| *Diameter of reference tube* | 3 ½ in. (8.9 cm) |
| *Height of constant diameter reference tube* | 0 to 50 ft (15.2 m) |
| *Height of shaped reference tube* | 0-12 ft (3.7 m); 0-50 ft (15.2 m) |
| *Embedded controller (2 connected units)* | 12 in. x 12 in. x 8 in. (ea. unit)<br>(30.5 cm x 45.7 cm x 10.2 cm) |

### Weight

| | |
|---|---|
| *Base Sensor Cylinder (Empty)* | 35 lbs (16 kg) |
| *Constant diameter reference tube, including conduit* | 5 lbs/ft (2.3 kg) |
| *Shaped reference tube, including conduit* | 5 lbs/ft (2.3 kg) |
| *Embedded controller (2 units)* | 60 lbs (27.3 kg) |

### Detectable Leak Rate

| | | |
|---|---|---|
| (Probability of detection of 95% with a probability of false alarm of 5%) | *For tank diameters less than 66.0 ft* | 0.20 gal/h |
| | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11{,}786)*0.69$ gal/h |
| | *For tank diameters* $D = [4{,}349.7*(n)^{0.5}]^{0.5}$ *(LRDP-24-n)* | 0.20 gal/h (average of $1 < n \leq 12$ tests) |
| (Probability of detection of 95% with a probability of false alarm of 0.48%) | *For tank diameters (D in ft) up to 193.7 ft* | $(3.14*(D*0.5)^2/11{,}786)*0.946$ gal/h |
| | *For tank diameters* $D = [3{,}172.4*(n)^{0.5}]^{0.5}$ *(LRDP-24-n)* | 0.20 gal/h (average of $1 < n \leq 12$ tests) |
| (Probability of detection of 95% with a probability of false alarm of <0.003%) | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11{,}786)*(2.0-0.345)$ gal/h |
| | *For tank diameters (D in ft) up to 193.4 ft* | $(3.14*(D*0.5)^2/11{,}786)*(3.0-0.345)$ gal/h |

### Power

| | |
|---|---|
| *In-tank sensor unit, embedded controller, interface computer* | *Single-phase 120 VAC 60 Hz* |

### Temperature

| | |
|---|---|
| *Operating* | $-20^{\circ}$ to $100^{\circ}$ F ($-29^{\circ}$ to $38^{\circ}$ C) |

### User Interface

| | |
|---|---|
| *System monitor* | *Vista GUI software*<br>*Windows 95 or FAS software* |

# Appendix D

# Software User Interface Screens

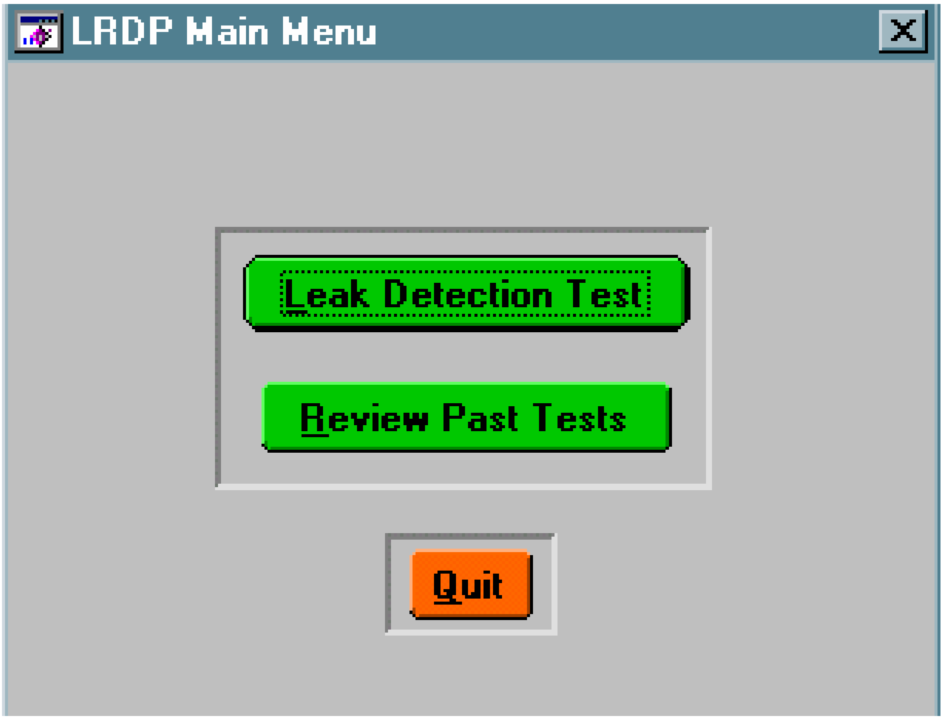


**Figure D-1.** *LRDP Main Menu:* display screen allowing the user to conduct a leak detection test or to review the results of previous leak detection tests

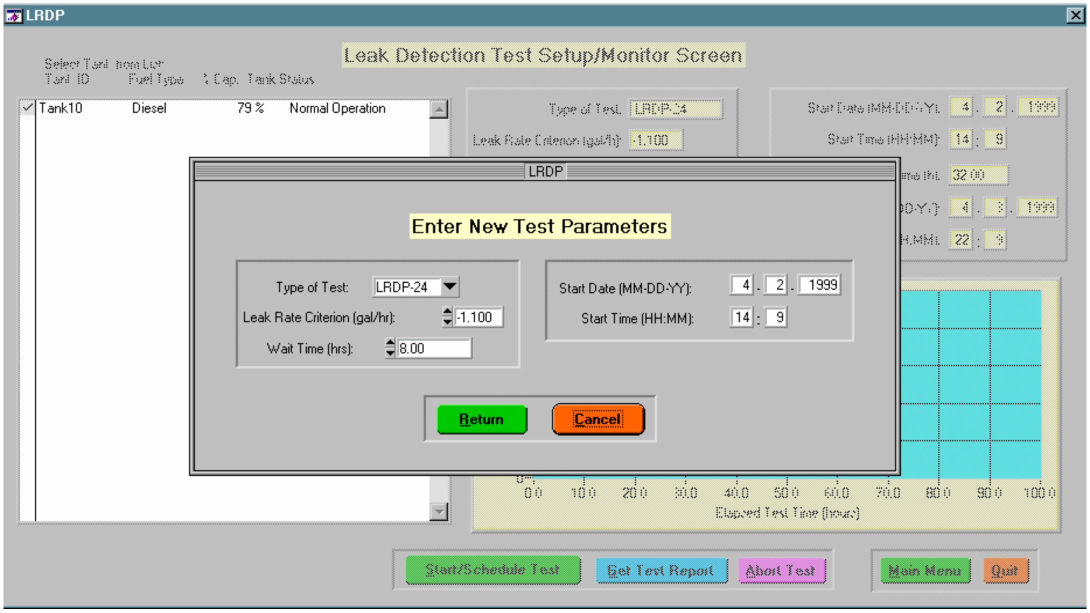


**Figure D-2.** *Enter New Test Parameters:* display screen allowing the user to use the default testing option and test parameters shown on the screen or to enter new test parameters.

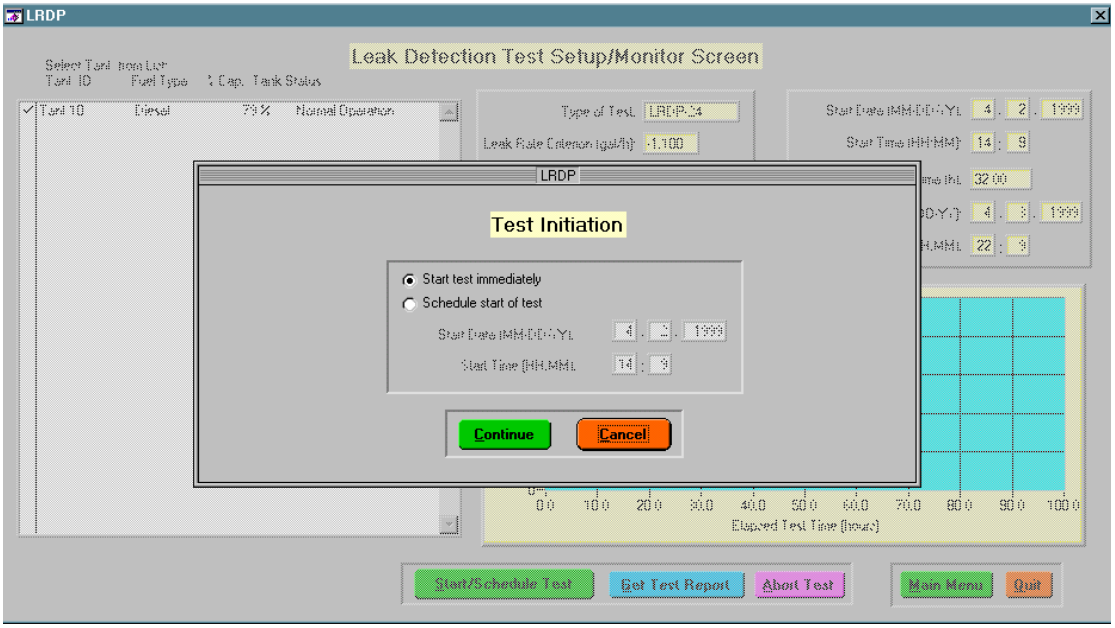


**Figure D-3.** *Test Initiation:* display screen allowing the user to start the test immediately or to schedule the start of the test for a later time.

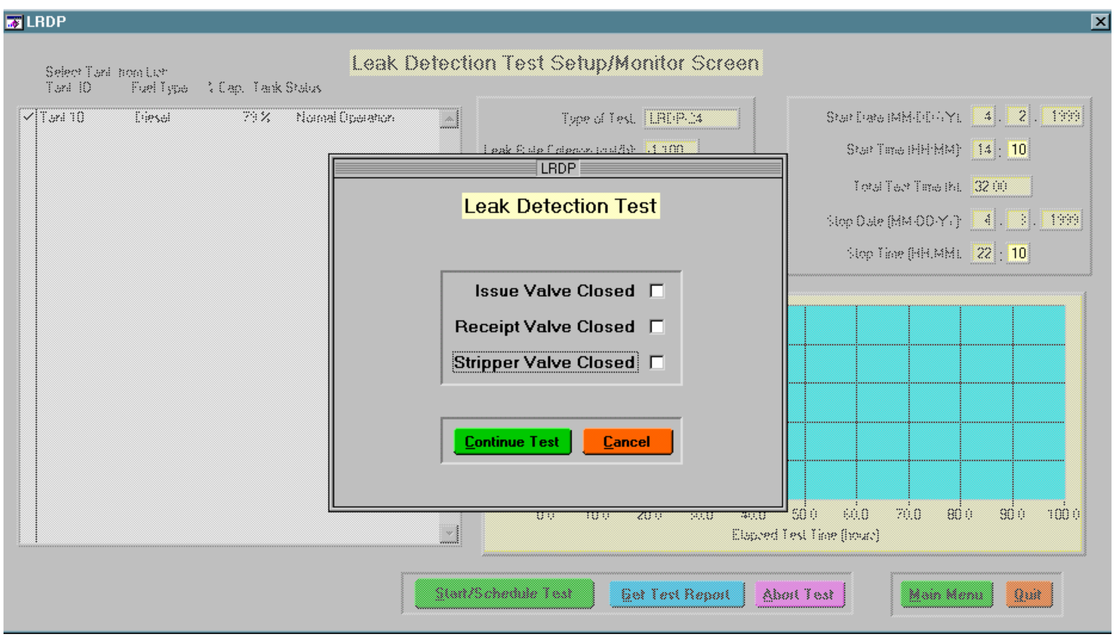


**Figure D-4.** *Leak Detection Test Preparation:* display screen reminding the user that valves need to be closed before a test can be conducted.

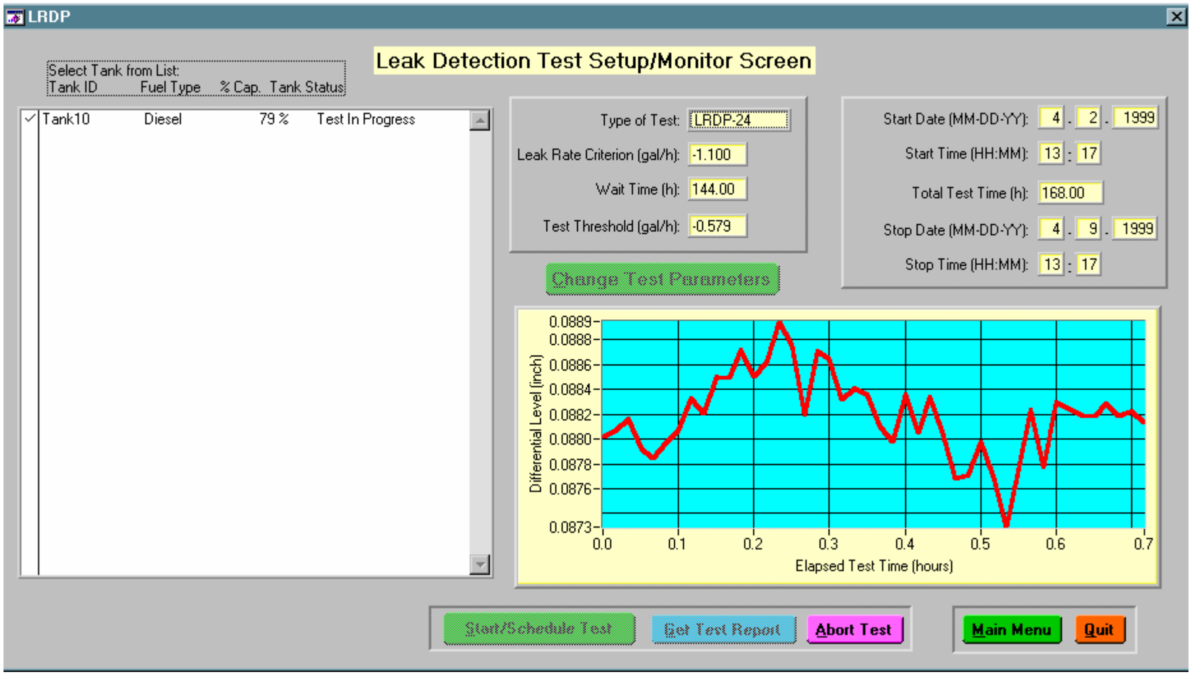


**Figure D-5.** *Leak Detection Test Setup/Monitor Screen:* display screen allowing the user to monitor the level in real time**.**

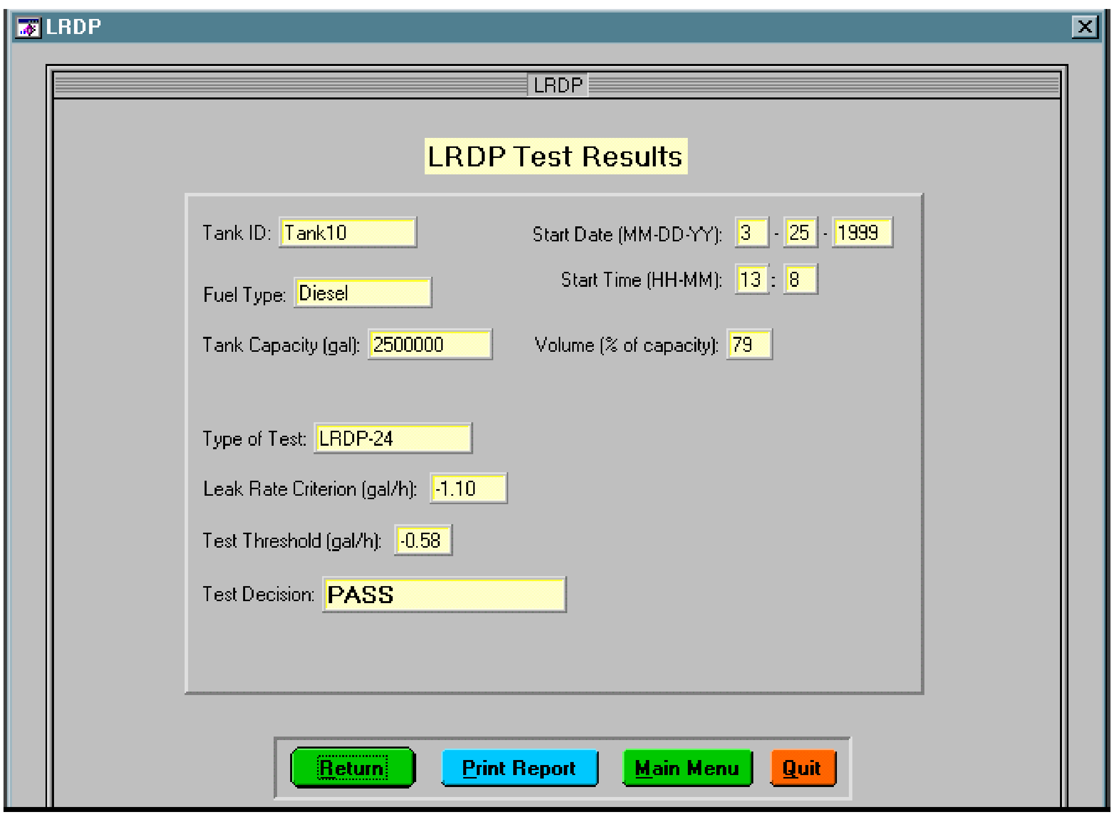


**Figure D-6.** *LRDP Test Results:* display screen presenting the results of the leak detection to the user.

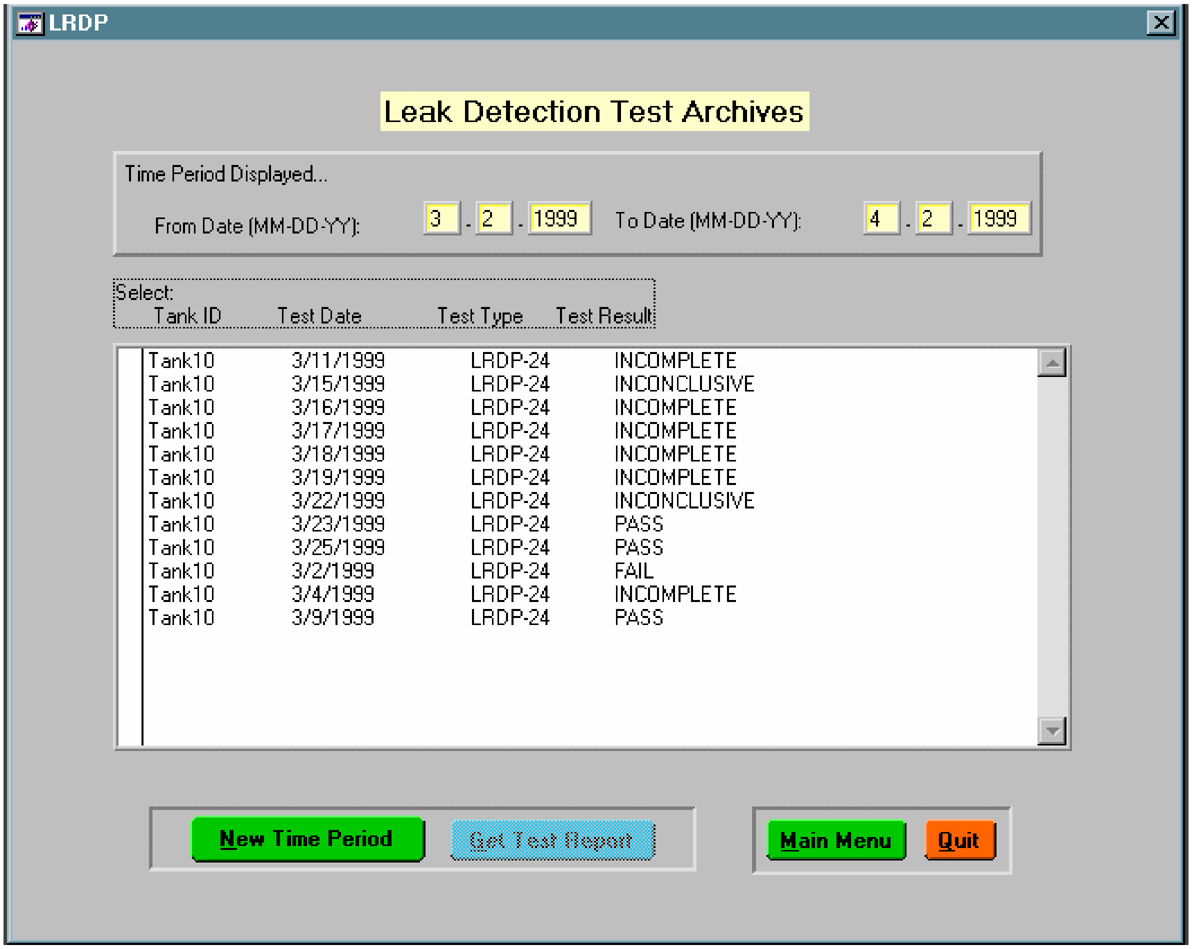


**Figure D-7.** *Leak Detection Test Archives:* display screen allowing the user to review previous test results and test data**.**

# Appendix E

## Performance Equations for Version a of the LRDP-10, LRDP-24, LRDP-10-n and LRDP-24-n

## Operation of the Evaluated System

| Version a<br>Mass Based Systems (with scaling included) | |
|---|---|
| | **Test Threshold *****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL<br>to insure PFA $\leq$ 5% |
| **Target Leak Rate,<br>TLR – gal/h** | TLR $\geq$ [MDL $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[(MDL $(A_2/A_1)$] < 0.2 |
| **Threshold,<br>C – gal/h** | [TLR - $C_{MDL}$ $(A_2/A_1)$] $\geq$ 0.1 or 0.1 for<br>[TLR - $C_{MDL}$ $(A_2/A_1)$] < 0.1 |
| **PD – %** | 95% |
| **PFA - %** | $\leq$ 5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate.<br>**Define MDL and $C_{MDL}$ = MDL/2 for $A_1$; S for $A_1$; and $A_1$ | |

## Operation of the Evaluated System

| Version a<br>Mass Based Systems (with scaling and averaging included) | |
|---|---|
| | **Test Threshold *****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL<br>To insure PFA $\leq$ 5% |
| **Target Leak Rate,<br>TLR – gal/h** | [$(MDL/n^{0.5})$ $(A_2/A_1)$] = 0.2<br>such that $1 \leq n \leq 12$<br>or 0.2 for<br>[(MDL $(A_2/A_1)$] < 0.2 |
| **Threshold,<br>C – gal/h** | [TLR-$(C_{MDL}/n^{0.5})$ $(A_2/A_1)$] $\geq$ 0.1<br>such that $1 \leq n \leq 12$<br>or 0.1 for<br>[TLR- $(C_{MDL}/n^{0.5})$ $(A_2/A_1)$] < 0.1 |
| **PD – %** | 95% |
| **PFA - %** | $\leq$ 5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate.<br>**Define MDL and $C_{MDL}$ = MDL/2 for $A_1$; S for $A_1$; and $A_1$; $1 \leq n < 12$ | |

| LRDP-24 Version a | |
|---|---|
| | **Test Threshold 1*,**** Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% |
| **Target Leak Rate, TLR – gal/h** | $[0.69\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[0.69\ (A_2/11{,}786)] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR - (0.345)\ (A_2/11{,}786)] \geq 0.1$ or 0.1 for $[TLR - (0.345)\ (A_2/A_1)] < 0.1$ |
| **PD – %** | 95% |
| **PFA - %** | $\leq$5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate. **MDL = 0.69 gal/h; S = 0.192 gal/h; and $A_1$ = 11,786 $ft^2$. | |

| LRDP-24-n Version a | |
|---|---|
| | **Test Threshold 1*,**** Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% |
| **Target Leak Rate, TLR – gal/h** | $[(0.69/n^{0.5})\ (A_2/11{,}786] = 0.2$ such that $1 \leq n \leq 12$ or 0.2 for $[(0.69/n^{0.5})\ (A_2/11{,}786)] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR-((0.345)/n^{0.5})\ (A_2/11{,}786] \geq 0.1$ such that $1 \leq n \leq 12$ and 0.1 for $[TLR-((0.345)/n^{0.5})\ (A_2/11{,}786] < 0.1$ |
| **PD – %** | 95% |
| **PFA - %** | $\leq$ 5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate. **MDL = 0.69 gal/h; S = 0.192 gal/h; and $A_1$ = 11,786 $ft^2$; $1 \leq n < 12$. | |

| LRDP-10 Version a | |
|---|---|
| | **Test Threshold 1*,*****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% |
| **Target Leak Rate, TLR – gal/h** | $[(1.139)\ (A_2/11{,}786)] \geq 0.2$<br>or 0.2 for<br>$[(1.139)\ (A_2/11{,}786)] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR - (0.569)\ (A_2/11{,}786)] \geq 0.1$<br>or 0.1 for<br>$[TLR - (0.569)\ (A_2/11{,}786)] < 0.1$ |
| **PD – %** | 95% |
| **PFA - %** | $\leq$ 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
**MDL = 1.14 gal/h; S = 0.317 gal/h; and $A_1$ = 11,786 $ft^2$.

| LRDP-10-n Version a | |
|---|---|
| | **Test Threshold 1*,*****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% |
| **Target Leak Rate, TLR – gal/h** | $[(1.139/n^{0.5})\ (A_2/11{,}786] = 0.2$<br>such that $1 \leq n \leq 12$ or<br>0.2 for $[(1.139/n^{0.5})\ (A_2/11{,}786)] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR-((0.569)/n^{0.5})\ (A_2/11{,}786] \geq 0.1$ such that $1 \leq n \leq 12$<br>or 0.1 for<br>$[TLR-((0.569)/n^{0.5})\ (A_2/11{,}786] < 0.1$ |
| **PD – %** | 95% |
| **PFA - %** | $\leq$ 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
** MDL = 1.14 gal/h; S = 0.317 gal/h; and $A_1$ = 11,786 $ft^2$; $1 \leq n < 12$ .

# Appendix F

## Performance Equations for Versions 1.0a, 1.1a, and 1.2a of the LRDP-10, LRDP-24, LRDP-10-n and LRDP-24-n

## Operation of the Evaluated System as Designed

| **LRDP-24<br>Mass Based Systems (with scaling included)** | | | |
|---|---|---|---|
| | **Version 1.0a**<br>**Test Threshold *,****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL<br>to insure PFA $\leq$ 5% | **Version 1.1a**<br>**Test Threshold 2****<br>Set PFA $\leq$ 5% and set PD $\geq$ 95% such that the Target Leak Rate $\leq$ 2 scaled-MDL | **Version 1.2a**<br>**Test Threshold 3****<br>Operate at the MDL (Set PD = 95% and set PFA = 5%) |
| **Target Leak Rate, TLR – gal/h** | TLR $\geq$ [MDL $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[(MDL $(A_2/A_1)$] < 0.2 | [$\alpha$ MDL $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[($\alpha$ MDL $(A_2/A_1)$] < 0.2<br>such that $\alpha \leq 2$ | [MDL $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[(MDL $(A_2/A_1)$] < 0.2 |
| **Threshold, C – gal/h** | [TLR - $C_{MDL}$ $(A_2/A_1)$] $\geq$ 0.1 or 0.1 for<br>[TLR – $C_{MDL}$ $(A_2/A_1)$] < 0.1 | [$\beta$ MDL $(A_2/A_1)$] $\geq$ 0.1<br>or 0.1 for<br>[($\beta$ MDL $(A_2/A_1)$] < 0.1<br>such that $\alpha \leq 2$ | [($C_{MDL}$ = MDL/2) $(A_2/A_1)$] $\geq$ 0.1<br>or 0.1 for<br>[(MDL/2) $(A_2/A_1)$] < 0.1 |
| **PD – %** | 95% | $\geq$ 95% | 95% |
| **PFA - %** | $\leq$ 5% | $\leq$ 5% | 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
**Define MDL and $C_{MDL}$ = MDL/2 for $A_1$; S for $A_1$; and $A_1$; $\alpha \leq 2$ and $\beta$ is a constant multiplier on MDL

## Operation of the Evaluated System as Designed

| **LRDP-24-n<br>Mass Based Systems (with scaling and averaging included)** | | | |
|---|---|---|---|
| | **Version 1.0a**<br>**Test Threshold 1*,****<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL<br>To insure PFA $\leq$ 5% | **Version 1.1a**<br>**Test Threshold 2****<br>Set PFA $\leq$ 5% and set PD $\geq$ 95% such that the Target Leak Rate $\leq$ 2 scaled-MDL | **Version 1.2a**<br>**Test Threshold 3****<br>Operate at the MDL (Set PD = 95% and set PFA = 5%) |
| **Target Leak Rate, TLR – gal/h** | [(MDL/$n^{0.5}$) $(A_2/A_1)$] = 0.2<br>such that $1 \leq n \leq 12$<br>or 0.2 for<br>[(MDL $(A_2/A_1)$] < 0.2 | [($\alpha$ MDL//$n^{0.5}$) $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[($\alpha$ MDL//$n^{0.5}$) $(A_2/A_1)$] < 0.2<br>such that $\alpha \leq 2$ | [(MDL/$n^{0.5}$) $(A_2/A_1)$] $\geq$ 0.2<br>or 0.2 for<br>[(MDL//$n^{0.5}$) $(A_2/A_1)$] < 0.2 |
| **Threshold, C – gal/h** | [TLR-($C_{MDL}$/$n^{0.5}$) $(A_2/A_1)$] $\geq$ 0.1<br>such that $1 \leq n \leq 12$<br>or 0.1 for<br>[TLR- ($C_{MDL}$/$n^{0.5}$) $(A_2/A_1)$] < 0.1 | [($\beta$ MDL/$n^{0.5}$) $(A_2/A_1)$] )] $\geq$ 0.1<br>or 0.1 for<br>[($\beta$ MDL//$n^{0.5}$) $(A_2/A_1)$] < 0.1<br>such that $\alpha \leq 2$ | [(0.5 MDL/$n^{0.5}$) $(A_2/A_1)$] )] $\geq$ 0.1<br>or 0.1 for<br>[(0.5 MDL//$n^{0.5}$) $(A_2/A_1)$] < 0.1 |
| **PD – %** | 95% | $\geq$ 95% | 95% |
| **PFA - %** | $\leq$ 5% | $\leq$ 5% | 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
**Define MDL and $C_{MDL}$ = MDL/2 for $A_1$; S for $A_1$; and $A_1$; $\alpha \leq 2$ and $\beta$ is a constant multiplier on MDL; $1 \leq n < 12$

## LRDP-24

| | **Version 1.0a**<br>**Test Threshold 1******<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% | **Version1.1a**<br>**Test Threshold 2****<br>Set PFA $\leq$ 5% and set PD = 95% such that the Target Leak Rate $\leq$ 2 scaled-MDL | **Version 1.2a**<br>**Test Threshold 3****<br>Operate at the MDL (Set PD = 95% and set PFA = 5%) |
|---|---|---|---|
| **Target Leak Rate, TLR – gal/h** | [0.69 ($A_2$/11,786)] $\geq$ 0.2<br>or 0.2 for<br>[0.69 ($A_2$/11,786)] < 0.2 | [1.3711 (0.69) ($A_2$/11,786)] $\geq$ 0.2 or 0.2 for<br>[(1.3711 (0.69) ($A_2$/11,786] < 0.2<br>such that $\alpha \leq 2$ | [0.69 ($A_2$/11,786)] $\geq$ 0.2<br>or 0.2 for<br>[(MDL ($A_2$/$A_1$)] < 0.2 |
| **Threshold, C – gal/h** | [TLR – (0.345) ($A_2$/11,786)] $\geq$ 0.1<br>or 0.1 for<br>[TLR – (0.345) ($A_2$/$A_1$)] < 0.1 | [0.8711) (0.69) ($A_2$/11,786)] $\geq$ 0.1<br>or 0.1 for<br>[(0.8711) (0.69) ($A_2$/11,786)] < 0.1<br>such that $\alpha \leq 2$ | [0.345 ($A_2$/11,786)] $\geq$ 0.1<br>or 0.1 for<br>[(0.345 ($A_2$/11,786)] < 0.1 |
| **PD – %** | 95% | 95% | 95% |
| **PFA - %** | ≤5% | 0.48% | 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
**MDL = 0.69 gal/h; S = 0.192 gal/h; and $A_1$ = 11,786 ft$^2$; $\alpha$ = 1.3711; $\beta$ = 0.8711.

## LRDP-24-n

| | **Version 1.0a**<br>**Test Threshold 1******<br>Set PD = 95% against a Target Leak Rate $\geq$ MDL to insure PFA $\leq$ 5% | **Version 1.1a**<br>**Test Threshold 2****<br>Set PFA $\leq$ 5% and set PD = 95% such that the Target Leak Rate $\leq$ 2 scaled-MDL | **Version 1.2a**<br>**Test Threshold 3****<br>Operate at the MDL (Set PD = 95% and set PFA = 5%) |
|---|---|---|---|
| **Target Leak Rate, TLR – gal/h** | [(0.69/$n^{0.5}$) ($A_2$/11,786] = 0.2<br>such that $1 \leq n \leq 12$<br>or<br>0.2 for<br>[(0.69/$n^{0.5}$) ($A_2$/11,786)] < 0.2 | [(1.3711 (0.69)//$n^{0.5}$) ($A_2$/11,786)] $\geq$ 0.2<br>or 0.2 for<br>[(1.3711 (0.69)//$n^{0.5}$) ($A_2$/11,786)] < 0.2<br>such that $\alpha \leq 2$ | [(0.69/$n^{0.5}$) ($A_2$/11,786)] $\geq$ 0.2<br>or 0.2 for<br>[(0.69//$n^{0.5}$) ($A_2$/11,786)] < 0.2 |
| **Threshold, C – gal/h** | [TLR-((0.345)/$n^{0.5}$) ($A_2$/11,786] $\geq$ 0.1<br>such that $1 \leq n \leq 12$<br>and 0.1 for<br>[TLR-((0.345)/$n^{0.5}$) ($A_2$/11,786] < 0.1 | [0.8711) (0.69)/$n^{0.5}$) ($A_2$/11,786)] $\geq$ 0.1<br>or 0.1 for<br>[(0.8711) (0.69)//$n^{0.5}$) ($A_2$/11,786)] < 0.1<br>such that $\alpha \leq 2$ | [(0.345/$n^{0.5}$)} ($A_2$/11,786)] )] $\geq$ 0.1<br>or 0.1 for<br>[(0.345/$n^{0.5}$) ($A_2$/11,786)] < 0.1 |
| **PD – %** | 95% | 95% | 95% |
| **PFA - %** | ≤ 5% | 0.48% | 5% |

*There may be more than one threshold specification for system operation; TLR = target leak rate.
**MDL = 0.69 gal/h; S = 0.192 gal/h; and $A_1$ = 11,786 ft$^2$; $\alpha$ = 1.3711; $\beta$ = 0.8711; $1 \leq n < 12$.

| LRDP-10 | | | |
|---|---|---|---|
| | **Version 1.0a** **Test Threshold 1*'**** Set PD = 95% against a Target Leak Rate ≥ MDL to insure PFA ≤ 5% | **Version 1.1a** **Test Threshold 2**** Set PFA ≤ 5% and set PD = 95% such that the Target Leak Rate ≤ 2 scaled-MDL | **Version 1.2a** **Test Threshold 3**** Operate at the MDL (Set PD = 95% and set PFA = 5%) |
| **Target Leak Rate, TLR – gal/h** | $[(1.139)\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[(1.139)\ (A_2/11{,}786)] < 0.2$ | $[(1.4514)\ (1.139)\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[(1.4514)\ (A_2/11{,}786)] < 0.2$ such that $\alpha \leq 2$ | $[1.139\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[(1.139)\ (A_2/11{,}786] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR – (0.569)\ (A_2/11{,}786)] \geq 0.1$ or 0.1 for $[TLR – (0.569)\ (A_2/11{,}786)] < 0.1$ | $[0.9514)\ (1.139)\ (A_2/11{,}786)] \geq 0.1$ or 0.1 for $[(0.9514)\ (1.139)\ (A_2/11{,}786)] < 0.1$ such that $\alpha \leq 2$ | $[(0.569)\ (A_2/11{,}786)] \geq 0.1$ or 0.1 for $[(0.569)\ (A_2/11{,}786)] < 0.1$ |
| **PD – %** | 95% | 95% | 95% |
| **PFA - %** | ≤ 5% | 0.29% | 5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate.<br>**MDL = 1.14 gal/h; S = 0.317 gal/h; and $A_1$ = 11,786 $ft^2$; $\alpha$ = 1.4514; $\beta$ = 0.9514. | | | |

| LRDP-10-n | | | |
|---|---|---|---|
| | **Version 1.0a** **Test Threshold 1*'**** Set PD = 95% against a Target Leak Rate ≥ MDL to insure PFA ≤ 5% | **Version 1.1a** **Test Threshold 2**** Set PFA ≤ 5% and set PD = 95% such that the Target Leak Rate ≤ 2 scaled-MDL | **Version 1.2a** **Test Threshold 3**** Operate at the MDL (Set PD = 95% and set PFA = 5%) |
| **Target Leak Rate, TLR – gal/h** | $[(1.139/n^{0.5})\ (A_2/11{,}786] = 0.2$ such that $1 \leq n \leq 12$ or 0.2 for $[(1.139/n^{0.5})\ (A_2/11{,}786)] < 0.2$ | $[(1.4514)\ (1.139)//n^{0.5})\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[(1.4514\ (1.139)//n^{0.5})\ (A_2/11{,}786)] < 0.2$ such that $\alpha \leq 2$ | $[(1.139/n^{0.5})\ (A_2/11{,}786)] \geq 0.2$ or 0.2 for $[(1.139//n^{0.5})\ (A_2/11{,}786)] < 0.2$ |
| **Threshold, C – gal/h** | $[TLR\text{-}((0.569)/n^{0.5})\ (A_2/11{,}786] \geq 0.1$ such that $1 \leq n \leq 12$ or 0.1 for $[TLR\text{-}((0.569)/n^{0.5})\ (A_2/11{,}786] < 0.1$ | $[0.9514)\ (1.139)/n^{0.5})\ (A_2/11{,}786)] \geq 0.1$ or 0.1 for $[(0.9514)\ (1.139)//n^{0.5})\ (A_2/11{,}786)] < 0.1$ such that $\alpha \leq 2$ | $[(0.569/n^{0.5})\}\ (A_2/11{,}786)]\ )] \geq 0.1$ or 0.1 for $[(0.569/n^{0.5})\ (A_2/11{,}786)] < 0.1$ |
| **PD – %** | 95% | 95% | 95% |
| **PFA - %** | ≤ 5% | 0.29% | 5% |
| *There may be more than one threshold specification for system operation; TLR = target leak rate.<br>** MDL = 1.14 gal/h; S = 0.317 gal/h; and $A_1$ = 11,786 $ft^2$; $\alpha$ = 1.4514; $\beta$ = 0.9514; $1 \leq n < 12$ . | | | |

# Appendix G

# Performance Estimates for the LRDP-10 for Versions 1.0a, 1.1a, and 1.2a as a Function of TLR and Tank Diameter

**Table G-1.** LRDP-10. The threshold is set to give the MDLR (i.e., a system with a $P_D$ = 95% and a $P_{FA}$ = 5%) by selecting a threshold that gives a $P_D$ = 95% and a $P_{FA}$ = 5%. (Version 1.2a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area ($ft^2$) | MDLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.14 | 0.317 | 0.569 | 5.0% | 95.0% | |
| 1 | 204,093 | 13.2 | 51.30 | 2,067 | 0.20 | 0.056 | 0.100 | 5.0% | 95.0% | 1.0 |
| 2 | 433,533 | 14.0 | 72.60 | 4,140 | 0.40 | 0.111 | 0.200 | 5.0% | 95.0% | 4.0 |
| 3 | 500,687 | 13.2 | 80.35 | 5,071 | 0.49 | 0.136 | 0.245 | 5.0% | 95.0% | 6.0 |
| 4 | 1,255,054 | 23.4 | 95.55 | 7,170 | 0.69 | 0.193 | 0.346 | 5.0% | 95.0% | 12.0 |
| 5 | 306,341 | 13.2 | 62.85 | 3,102 | 0.30 | 0.083 | 0.150 | 5.0% | 95.0% | 2.2 |
| 6 | 1,548,582 | 20.0 | 114.80 | 10,351 | 1.00 | 0.278 | 0.500 | 5.0% | 95.0% | |
| 7 | 3,097,099 | 20.0 | 162.35 | 20,701 | 2.00 | 0.557 | 1.000 | 5.0% | 95.0% | |
| 8 | 4,643,904 | 20.0 | 198.80 | 31,040 | 3.00 | 0.835 | 1.499 | 5.0% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.59 | 0.164 | 0.294 | 5.0% | 95.0% | 8.6 |
| 10 | 2,125,666 | 20 | 134.50 | 14,208 | 1.37 | 0.382 | 0.686 | 5.0% | 95.0% | |
| 11 | 2,274,866 | 20 | 134.50 | 15,205 | 1.47 | 0.409 | 0.734 | 5.0% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 2.85 | 0.793 | 1.423 | 5.0% | 95.0% | |

**Table G-2.** LRDP-10. The threshold is set to give a specific $P_{FA} \leq 5\%$ and a specific $P_D \geq 95\%$. The largest tank needs to be below the regulatory standard (e.g., 2 gal/h). This is accomplished by selecting a threshold that gives the $P_D$ and $P_{FA}$ of interest. The target leak rate is less or equal to twice the MDLR. (Version 1.1a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area ($ft^2$) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.65 | 0.317 | 1.083 | 0.288% | 95.0% | |
| 1 | 140,739 | 13.2 | 42.60 | 1,425 | 0.20 | 0.038 | 0.131 | 0.288% | 95.0% | 1.0 |
| 2 | 281,987 | 13.2 | 60.30 | 2,856 | 0.40 | 0.077 | 0.262 | 0.288% | 95.0% | 4.0 |
| 3 | 344,504 | 13.2 | 66.65 | 3,489 | 0.49 | 0.094 | 0.321 | 0.288% | 95.0% | 6.0 |
| 4 | 864,695 | 23.4 | 79.31 | 4,940 | 0.69 | 0.133 | 0.454 | 0.288% | 95.0% | 12.0 |
| 5 | 211,479 | 13.2 | 52.22 | 2,142 | 0.30 | 0.058 | 0.197 | 0.288% | 95.0% | 2.3 |
| 6 | 1,067,177 | 20.0 | 95.30 | 7,133 | 1.00 | 0.192 | 0.656 | 0.288% | 95.0% | |
| 7 | 2,133,576 | 20.0 | 134.75 | 14,261 | 2.00 | 0.384 | 1.311 | 0.288% | 95.0% | |
| 8 | 3,200,970 | 20.0 | 165.05 | 21,395 | 3.00 | 0.575 | 1.967 | 0.288% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.85 | 0.164 | 0.559 | 0.288% | 95.0% | |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 1.99 | 0.382 | 1.306 | 0.288% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 2.13 | 0.409 | 1.398 | 0.288% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 4.13 | 0.793 | 2.708 | 0.288% | 95.0% | |

**Table G-3.** LRDP-10. The threshold is set to give a specific $P_{FA} \leq 5\%$ and a specific $P_D \geq 95\%$. The largest tank needs to be below the regulatory standard (e.g., 2 gal/h). This is accomplished by selecting a threshold that gives the $P_D$ and $P_{FA}$ of interest. The TLR = 1.90 gal/h for the evaluation tank. (Version 1.0a TLR = 1.9 gal/h)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** **($ft^2$)** | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | **$P_{FA}$** (%) | **$P_D$** (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.90 | 0.317 | 1.330 | 0.075% | 95.0% | |
| 1 | 122,537 | 13.2 | 39.75 | 1,241 | 0.20 | 0.033 | 0.140 | 0.075% | 95.0% | 1.0 |
| 2 | 245,119 | 13.2 | 56.22 | 2,482 | 0.40 | 0.067 | 0.280 | 0.075% | 95.0% | 4.0 |
| 3 | 300,037 | 13.2 | 62.20 | 3,039 | 0.49 | 0.082 | 0.343 | 0.075% | 95.0% | 6.0 |
| 4 | 752,723 | 23.4 | 73.99 | 4,300 | 0.69 | 0.116 | 0.485 | 0.075% | 95.0% | 12.0 |
| 5 | 183,930 | 13.2 | 48.70 | 1,863 | 0.30 | 0.050 | 0.210 | 0.075% | 95.0% | 2.3 |
| 6 | 612,912 | 13.2 | 88.90 | 6,207 | 1.00 | 0.167 | 0.700 | 0.075% | 95.0% | |
| 7 | 1,856,612 | 20.0 | 125.70 | 12,410 | 2.00 | 0.334 | 1.400 | 0.075% | 95.0% | |
| 8 | 2,784,902 | 20.0 | 153.95 | 18,614 | 3.00 | 0.501 | 2.100 | 0.075% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.98 | 0.164 | 0.686 | 0.075% | 95.0% | |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 2.29 | 0.382 | 1.603 | 0.075% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 2.45 | 0.409 | 1.715 | 0.075% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 4.75 | 0.793 | 3.324 | 0.075% | 95.0% | |

**Table G-4.** LRDP-10. The threshold is set to give a specific $P_D \geq 95\%$ and the $P_{FA}$, which needs to be less than or equal to 5%, is computed for this $P_D$. The TLR = 2.40 gal/h for the evaluation tank. (Version 1.0a TLR = 2.4 gal/h)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** **($ft^2$)** | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | **$P_{FA}$** (%) | **$P_D$** (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 2.40 | 0.317 | 1.831 | 0.00619% | 95.0% | |
| 1 | 96,911 | 13.2 | 35.35 | 981 | 0.20 | 0.026 | 0.152 | 0.00619% | 95.0% | 1.0 |
| 2 | 193,881 | 13.2 | 50.00 | 1,963 | 0.40 | 0.053 | 0.305 | 0.00619% | 95.0% | 4.0 |
| 3 | 237,505 | 13.2 | 55.34 | 2,405 | 0.49 | 0.065 | 0.374 | 0.00619% | 95.0% | 6.0 |
| 4 | 595,429 | 23.4 | 65.81 | 3,402 | 0.69 | 0.091 | 0.528 | 0.00619% | 95.0% | 12.0 |
| 5 | 145,402 | 13.2 | 43.30 | 1,473 | 0.30 | 0.040 | 0.229 | 0.00619% | 95.0% | 2.2 |
| 6 | 734,453 | 20.0 | 79.06 | 4,909 | 1.00 | 0.132 | 0.763 | 0.00619% | 95.0% | |
| 7 | 1,469,492 | 20.0 | 111.83 | 9,822 | 2.00 | 0.264 | 1.526 | 0.00619% | 95.0% | |
| 8 | 2,203,812 | 20.0 | 136.95 | 14,730 | 3.00 | 0.396 | 2.288 | 0.00619% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 1.24 | 0.164 | 0.945 | 0.00619% | 95.0% | |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 2.89 | 0.382 | 2.207 | 0.00619% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 3.10 | 0.409 | 2.362 | 0.00619% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 6.00 | 0.793 | 4.577 | 0.00619% | 95.0% | |

# Appendix H

# Performance Estimates for the LRDP-24 for Versions 1.0a, 1.1a, and 1.2a as a Function of TLR and Tank Diameter

**Table H-1.** LRDP-24. The threshold is set to give the MDLR (i.e., a system with a $P_D$ = 95% and a $P_{FA}$ = 5%) by selecting a threshold that gives a $P_D$ = 95% and a $P_{FA}$ = 5%. (Version 1.2a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area (ft²) | MDLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 0.69 | 0.192 | 0.345 | 5.0% | 95.0% | 11.9 |
| 1 | 337,306 | 13.2 | 65.95 | 3,416 | 0.20 | 0.056 | 0.100 | 5.0% | 95.0% | 1.0 |
| 2 | 1,022,854 | 20.0 | 93.30 | 6,837 | 0.40 | 0.111 | 0.200 | 5.0% | 95.0% | 4.0 |
| 3 | 1,252,653 | 20.0 | 103.25 | 8,373 | 0.49 | 0.136 | 0.245 | 5.0% | 95.0% | 6.0 |
| 4 | 2,072,501 | 23.4 | 122.78 | 11,840 | 0.69 | 0.193 | 0.346 | 5.0% | 95.0% | 12.0 |
| 5 | 767,138 | 20.0 | 80.80 | 5,128 | 0.30 | 0.084 | 0.150 | 5.0% | 95.0% | 2.3 |
| 6 | 2,555,394 | 20.0 | 147.47 | 17,080 | 1.00 | 0.278 | 0.500 | 5.0% | 95.0% | |
| 7 | 5,113,039 | 20.0 | 208.60 | 34,176 | 2.00 | 0.557 | 1.000 | 5.0% | 95.0% | |
| 8 | 7,670,653 | 20.0 | 255.50 | 51,271 | 3.00 | 0.835 | 1.500 | 5.0% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.36 | 0.099 | 0.178 | 5.0% | 95.0% | 3.2 |
| 10 | 2,125,666 | 20 | 134.50 | 14,208 | 0.83 | 0.231 | 0.416 | 5.0% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 0.89 | 0.248 | 0.445 | 5.0% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 1.72 | 0.480 | 0.862 | 5.0% | 95.0% | |

**Table H-2.** LRDP-24. The threshold is set to give a specific $P_{FA} \leq 5\%$ and a specific $P_D \geq 95\%$. The largest tank needs to be below the regulatory standard (e.g., 2 gal/h). This is accomplished by selecting a threshold that gives the $P_D$ and $P_{FA}$ of interest. The target leak rate is less or equal to twice the MDLR. (Version 1.1a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area (ft²) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 0.95 | 0.192 | 0.601 | 0.480% | 95.0% | |
| 1 | 262,577 | 14.1 | 56.30 | 2,489 | 0.20 | 0.041 | 0.127 | 0.480% | 95.0% | 1.0 |
| 2 | 492,619 | 13.2 | 79.70 | 4,989 | 0.40 | 0.081 | 0.254 | 0.480% | 95.0% | 4.0 |
| 3 | 602,887 | 13.2 | 88.17 | 6,106 | 0.49 | 0.099 | 0.311 | 0.480% | 95.0% | 6.0 |
| 4 | 1,511,447 | 23.4 | 104.85 | 8,635 | 0.69 | 0.141 | 0.440 | 0.480% | 95.0% | 12.0 |
| 5 | 369,226 | 13.2 | 69.00 | 3,739 | 0.30 | 0.061 | 0.191 | 0.480% | 95.0% | 2.2 |
| 6 | 1,865,484 | 20.0 | 126.00 | 12,469 | 1.00 | 0.203 | 0.636 | 0.480% | 95.0% | |
| 7 | 3,729,256 | 20.0 | 178.15 | 24,927 | 2.00 | 0.406 | 1.270 | 0.480% | 95.0% | |
| 8 | 5,594,483 | 20.0 | 218.20 | 37,394 | 3.00 | 0.609 | 1.906 | 0.480% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.49 | 0.099 | 0.310 | 0.480% | 95.0% | 6.0 |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 1.14 | 0.231 | 0.724 | 0.480% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 1.22 | 0.248 | 0.775 | 0.480% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 2.36 | 0.480 | 1.502 | 0.480% | 95.0% | |

**Table H-3.** LRDP-24. The threshold is set to give a specific $P_D \geq 95\%$ and the $P_{FA}$, which needs to be less than or equal to 5%, is computed for this $P_D$. The TLR = 1.65 gal/h for the evaluation tank. (Version 1.0a TLR = 1.65 gal/h)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.65 | 0.192 | 1.305 | 0.00148% | 95.0% | |
| 1 | 141,069 | 13.2 | 42.65 | 1,429 | 0.20 | 0.023 | 0.158 | 0.00148% | 95.0% | 1.0 |
| 2 | 281,987 | 13.2 | 60.30 | 2,856 | 0.40 | 0.047 | 0.316 | 0.00148% | 95.0% | 4.0 |
| 3 | 345,539 | 13.2 | 66.75 | 3,499 | 0.49 | 0.057 | 0.388 | 0.00148% | 95.0% | 6.0 |
| 4 | 866,271 | 23.4 | 79.38 | 4,949 | 0.69 | 0.081 | 0.548 | 0.00148% | 95.0% | 12.0 |
| 5 | 211,317 | 13.2 | 52.20 | 2,140 | 0.30 | 0.035 | 0.237 | 0.00148% | 95.0% | 2.2 |
| 6 | 705,076 | 13.2 | 95.35 | 7,141 | 1.00 | 0.116 | 0.791 | 0.00148% | 95.0% | |
| 7 | 2,136,744 | 20.0 | 134.85 | 14,282 | 2.00 | 0.233 | 1.582 | 0.00148% | 95.0% | |
| 8 | 3,202,909 | 20.0 | 165.10 | 21,408 | 3.00 | 0.349 | 2.371 | 0.00148% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.85 | 0.099 | 0.674 | 0.00148% | 95.0% | |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 1.99 | 0.231 | 1.573 | 0.00148% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 2.13 | 0.248 | 1.684 | 0.00148% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 4.13 | 0.480 | 3.263 | 0.00148% | 326.3% 2 | 0.9 |

**Table H-4.** LRDP-24. The threshold is set to give a specific $P_D \geq 95\%$ and the $P_{FA}$, which needs to be less than or equal to 5%, is computed for this $P_D$. The TLR = 2.40 gal/h for the evaluation tank. (Version 1.0a TLR = 2.40 gal/h)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 2.40 | 0.192 | 2.055 | 0.000019% | 95.0% | |
| 1 | 96,911 | 13.2 | 35.35 | 981 | 0.20 | 0.016 | 0.171 | 0.000019% | 95.0% | 1.0 |
| 2 | 193,881 | 13.2 | 50.00 | 1,963 | 0.40 | 0.032 | 0.342 | 0.000019% | 95.0% | 4.0 |
| 3 | 253,699 | 14.1 | 55.34 | 2,405 | 0.49 | 0.039 | 0.419 | 0.000019% | 95.0% | 6.0 |
| 4 | 595,429 | 23.4 | 65.81 | 3,402 | 0.69 | 0.055 | 0.593 | 0.000019% | 95.0% | 12.0 |
| 5 | 145,402 | 13.2 | 43.30 | 1,473 | 0.30 | 0.024 | 0.257 | 0.000019% | 95.0% | 2.2 |
| 6 | 484,739 | 13.2 | 79.06 | 4,909 | 1.00 | 0.080 | 0.856 | 0.000019% | 95.0% | |
| 7 | 1,469,492 | 20.0 | 111.83 | 9,822 | 2.00 | 0.160 | 1.713 | 0.000019% | 95.0% | |
| 8 | 2,578,460 | 23.4 | 136.95 | 14,730 | 3.00 | 0.240 | 2.569 | 0.000019% | 95.0% | |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 1.24 | 0.099 | 1.061 | 0.000019% | 95.0% | |
| 10 | 2,125,666 | 20.0 | 134.50 | 14,208 | 2.89 | 0.231 | 2.478 | 0.000019% | 95.0% | |
| 11 | 2,274,866 | 20.0 | 139.14 | 15,205 | 3.10 | 0.248 | 2.651 | 0.000019% | 95.0% | |
| 12 | 5,157,611 | 23.4 | 193.69 | 29,465 | 6.00 | 0.480 | 5.138 | 0.000019% | 95.0% | |

# Appendix I

## Performance Estimates for the LRDP-10 as a Function of TLR and Tank Diameter (Product Surface Area) for a Threshold Set to Yield a $P_D$ = 95% for the Selected TLR

**Table I-1.** LRDP-10. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 0.20 gal/h. (Version a)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n tests averaged** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.5 | 11,786 | 0.200 | 0.055 | 0.101 | 2.295% | 95.0% | 33.0 |
| 1 | 48,470 | 13.2 | 25.0 | 491 | 0.200 | 0.013 | 0.176 | 0.000001% | 95.0% | 1.0 |
| 2 | 69,797 | 13.2 | 30.0 | 707 | 0.200 | 0.019 | 0.166 | 0.000069% | 95.0% | 1.0 |
| 3 | 124,084 | 13.2 | 40.0 | 1,257 | 0.200 | 0.034 | 0.139 | 0.041125% | 95.0% | 1.0 |
| 4 | 193,881 | 13.2 | 50.0 | 1,963 | 0.200 | 0.053 | 0.105 | 1.742% | 95.0% | 1.0 |
| 5 | 279,188 | 13.2 | 60.0 | 2,827 | 0.200 | 0.054 | 0.103 | 1.956% | 95.0% | 2.0 |
| 6 | 337,306 | 13.2 | 65.950 | 3,416 | 0.200 | 0.053 | 0.105 | 1.793% | 95.0% | 3.0 |
| 7 | 380,006 | 13.2 | 70.0 | 3,848 | 0.200 | 0.052 | 0.107 | 1.526% | 95.0% | 4.0 |
| 8 | 496,334 | 13.2 | 80.0 | 5,027 | 0.200 | 0.055 | 0.101 | 2.298% | 95.0% | 6.0 |
| 9 | 506,273 | 13.2 | 80.8 | 5,127 | 0.200 | 0.052 | 0.106 | 1.599% | 95.0% | 7.0 |
| 10 | 628,173 | 13.2 | 90.0 | 6,362 | 0.200 | 0.054 | 0.103 | 2.034% | 95.0% | 10.0 |
| 11 | 1,175,034 | 20 | 100.0 | 7,854 | 0.200 | 0.055 | 0.102 | 2.137% | 95.0% | 15.0 |
| 12 | 1,421,791 | 20 | 110.0 | 9,503 | 0.200 | 0.054 | 0.102 | 2.126% | 95.0% | 22.0 |
| 13 | 1,692,049 | 20 | 120.0 | 11,310 | 0.200 | 0.056 | 0.100 | 2.386% | 95.0% | 30.0 |
| 14 | 1,985,808 | 20 | 130.0 | 13,273 | 0.200 | 0.055 | 0.101 | 2.271% | 95.0% | 42.0 |
| 15 | 250,591 | 14.1 | 55.0 | 2,376 | 0.200 | 0.045 | 0.119 | 0.567% | 95.0% | 2.0 |
| 16 | 600,565 | 13.2 | 88.0 | 6,082 | 0.200 | 0.055 | 0.102 | 2.134% | 95.0% | 9.0 |
| 17 | 2,125,666 | 20 | 134.5 | 14,208 | 0.200 | 0.055 | 0.101 | 2.289% | 95.0% | 48.0 |
| 18 | 2,273,551 | 20 | 139.1 | 15,197 | 0.200 | 0.056 | 0.100 | 2.408% | 95.0% | 54.0 |

**Table I-2.** LRDP-10. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 0.30 gal/h. (Version a)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **MDLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 48,470 | 13.2 | 25.00 | 491 | 0.30 | 0.013 | 0.276 | 0.000000% | 95.0% | 2.3 |
| 1 | 69,797 | 13.2 | 30.00 | 707 | 0.30 | 0.019 | 0.266 | 0.000001% | 95.0% | 2.3 |
| 2 | 124,084 | 13.2 | 40.00 | 1,257 | 0.30 | 0.034 | 0.239 | 0.001023% | 95.0% | 2.3 |
| 3 | 193,881 | 13.2 | 50.00 | 1,963 | 0.30 | 0.053 | 0.205 | 0.127% | 95.0% | 2.3 |
| 4 | 204,093 | 13.2 | 51.30 | 2,067 | 0.30 | 0.056 | 0.200 | 0.208% | 95.0% | 2.3 |
| 5 | 279,188 | 13.2 | 60.00 | 2,827 | 0.30 | 0.076 | 0.163 | 2.7% | 95.0% | 2.3 |
| 6 | 306,633 | 13.2 | 62.88 | 3,105 | 0.30 | 0.084 | 0.150 | 5.0% | 95.0% | 2.3 |
| 7 | 250,591 | 14.1 | 55.00 | 2,376 | 0.30 | 0.064 | 0.185 | 0.7% | 95.0% | 2.3 |
| 8 | 600,565 | 13.2 | 88.00 | 6,082 | 0.30 | 0.164 | 0.006 | 48.5% | 95.0% | 2.3 |

**Table I-3.** LRDP-10. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 1.00 gal/h. (Version a)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.00 | 0.317 | 0.431 | 10.1% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 1.00 | 0.013 | 0.976 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 1.00 | 0.019 | 0.966 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 1.00 | 0.034 | 0.939 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 1.00 | 0.053 | 0.905 | 0.000000% | 95.0% | |
| 5 | 204,093 | 13.2 | 51.30 | 2,067 | 1.00 | 0.056 | 0.900 | 0.000000% | 95.0% | |
| 6 | 279,188 | 13.2 | 60.00 | 2,827 | 1.00 | 0.076 | 0.863 | 0.000010% | 95.0% | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 1.00 | 0.104 | 0.814 | 0.000384% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 1.00 | 0.135 | 0.757 | 0.008007% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 1.00 | 0.171 | 0.693 | 0.096% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 1.00 | 0.211 | 0.621 | 0.675% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 1.00 | 0.256 | 0.541 | 2.9% | 95.0% | |
| 12 | 1,548,659 | 20 | 114.80 | 10,351 | 1.00 | 0.278 | 0.500 | 5.0% | 95.0% | |
| 13 | 250,591 | 14.1 | 55.00 | 2,376 | 1.00 | 0.064 | 0.885 | 0.000001% | 95.0% | |
| 14 | 600,565 | 13.2 | 88.00 | 6,082 | 1.00 | 0.164 | 0.706 | 0.061037% | 95.0% | |
| 15 | 2,125,666 | 20 | 134.50 | 14,208 | 1.00 | 0.382 | 0.314 | 21.5% | 95.0% | |
| 16 | 2,273,551 | 20 | 139.10 | 15,197 | 1.00 | 0.409 | 0.266 | 26.4% | 95.0% | |

**Table I-4.** LRDP-10. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 2.00 gal/h. (Version a)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 2.00 | 0.317 | 1.431 | 0.044% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 2.00 | 0.013 | 1.976 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 2.00 | 0.019 | 1.966 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 2.00 | 0.034 | 1.939 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 2.00 | 0.053 | 1.905 | 0.000000% | 95.0% | |
| 5 | 204,093 | 13.2 | 51.30 | 2,067 | 2.00 | 0.056 | 1.900 | 0.000000% | 95.0% | |
| 6 | 279,188 | 13.2 | 60.00 | 2,827 | 2.00 | 0.076 | 1.863 | 0.000000% | 95.0% | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 2.00 | 0.104 | 1.814 | 0.000000% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 2.00 | 0.135 | 1.757 | 0.000003% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 2.00 | 0.171 | 1.693 | 0.000041% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 2.00 | 0.211 | 1.621 | 0.000485% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 2.00 | 0.256 | 1.541 | 0.004284% | 95.0% | |
| 12 | 1,692,049 | 20 | 120.00 | 11,310 | 2.00 | 0.304 | 1.454 | 0.029% | 95.0% | |
| 13 | 1,985,808 | 20 | 130.00 | 13,273 | 2.00 | 0.357 | 1.359 | 0.146% | 95.0% | |
| 14 | 250,591 | 14.1 | 55.00 | 2,376 | 2.00 | 0.064 | 1.885 | 0.000000% | 95.0% | |
| 15 | 600,565 | 13.2 | 88.00 | 6,082 | 2.00 | 0.164 | 1.706 | 0.000024% | 95.0% | |
| 16 | 2,125,666 | 20 | 134.50 | 14,208 | 2.00 | 0.382 | 1.314 | 0.146% | 95.0% | |
| 17 | 2,273,551 | 20 | 139.10 | 15,197 | 2.00 | 0.409 | 1.266 | 0.146% | 95.0% | |
| 18 | 2,044,211 | 13.2 | 162.36 | 20,702 | 2.00 | 0.557 | 1.000 | 5.0% | 95.0% | |

**Table I-5.** LRDP-10. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq$ 5%. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 3.00 gal/h. (Version a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area (ft²) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 3.00 | 0.317 | 2.431 | 0.000488% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 3.00 | 0.013 | 2.976 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 3.00 | 0.019 | 2.966 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 3.00 | 0.034 | 2.939 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 3.00 | 0.053 | 2.905 | 0.000000% | 95.0% | |
| 5 | 204,093 | 13.2 | 51.30 | 2,067 | 3.00 | 0.056 | 2.900 | 0.000000% | 95.0% | |
| 6 | 279,188 | 13.2 | 60.00 | 2,827 | 3.00 | 0.076 | 2.863 | 0.000000% | 95.0% | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 3.00 | 0.104 | 2.814 | 0.000000% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 3.00 | 0.135 | 2.757 | 0.000000% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 3.00 | 0.171 | 2.693 | 0.000000% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 3.00 | 0.211 | 2.621 | 0.000004% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 3.00 | 0.256 | 2.541 | 0.000039% | 95.0% | |
| 12 | 1,692,049 | 20 | 120.00 | 11,310 | 3.00 | 0.304 | 2.454 | 0.000302% | 95.0% | |
| 13 | 1,985,808 | 20 | 130.00 | 13,273 | 3.00 | 0.357 | 2.359 | 0.001913% | 95.0% | |
| 14 | 250,591 | 14.1 | 55.00 | 2,376 | 3.00 | 0.064 | 2.885 | 0.000000% | 95.0% | |
| 15 | 600,565 | 13.2 | 88.00 | 6,082 | 3.00 | 0.164 | 2.706 | 0.000000% | 95.0% | |
| 16 | 2,125,666 | 20 | 134.50 | 14,208 | 3.00 | 0.382 | 2.314 | 0.004128% | 95.0% | |
| 17 | 2,273,551 | 20 | 139.10 | 15,197 | 3.00 | 0.409 | 2.266 | 0.008718% | 95.0% | |
| 18 | 5,157,611 | 23.4 | 193.69 | 29,465 | 3.00 | 0.793 | 1.577 | 3.603773% | 95.0% | |
| 19 | 3,066,365 | 13.2 | 198.85 | 31,054 | 3.00 | 0.835 | 1.500 | 5.0% | 95.0% | |

# Appendix J

## Performance Estimates for the LRDP-24 as a Function of TLR and Tank Diameter (Product Surface Area) for a Threshold Set to Yield a $P_D$ = 95% for the Selected TLR

**Table J-1.** LRDP-24. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 0.20 gal/h. (Version a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area (ft²) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n tests averaged |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.5 | 11,786 | 0.200 | 0.055 | 0.100 | 4.863% | 95.0% | 12.0 |
| 1 | 48,470 | 13.2 | 25.0 | 491 | 0.200 | 0.008 | 0.186 | 0.000000% | 95.0% | 1.0 |
| 2 | 69,797 | 13.2 | 30.0 | 707 | 0.200 | 0.012 | 0.179 | 0.000000% | 95.0% | 1.0 |
| 3 | 124,084 | 13.2 | 40.0 | 1,257 | 0.200 | 0.020 | 0.163 | 0.000337% | 95.0% | 1.0 |
| 4 | 193,881 | 13.2 | 50.0 | 1,963 | 0.200 | 0.032 | 0.143 | 0.048% | 95.0% | 1.0 |
| 5 | 279,188 | 13.2 | 60.0 | 2,827 | 0.200 | 0.046 | 0.117 | 1.359% | 95.0% | 1.0 |
| 6 | 337,306 | 13.2 | 65.950 | 3,416 | 0.200 | 0.056 | 0.100 | 4.982% | 95.0% | 1.0 |
| 7 | 380,006 | 13.2 | 70.0 | 3,848 | 0.200 | 0.044 | 0.120 | 1.004% | 95.0% | 2.0 |
| 8 | 496,334 | 13.2 | 80.0 | 5,027 | 0.200 | 0.047 | 0.115 | 1.657% | 95.0% | 3.0 |
| 9 | 506,273 | 13.2 | 80.8 | 5,127 | 0.200 | 0.048 | 0.113 | 1.919% | 95.0% | 3.0 |
| 10 | 628,173 | 13.2 | 90.0 | 6,362 | 0.200 | 0.052 | 0.107 | 3.173% | 95.0% | 4.0 |
| 11 | 1,175,034 | 20 | 100.0 | 7,854 | 0.200 | 0.052 | 0.106 | 3.345% | 95.0% | 6.0 |
| 12 | 1,421,791 | 20 | 110.0 | 9,503 | 0.200 | 0.055 | 0.102 | 4.505% | 95.0% | 8.0 |
| 13 | 1,692,049 | 20 | 120.0 | 11,310 | 0.200 | 0.056 | 0.100 | 4.930% | 95.0% | 11.0 |
| 14 | 1,985,808 | 20 | 130.0 | 13,273 | 0.200 | 0.054 | 0.103 | 4.170% | 95.0% | 16.0 |
| 15 | 250,591 | 14.1 | 55.0 | 2,376 | 0.200 | 0.039 | 0.130 | 0.312% | 95.0% | 1.0 |
| 16 | 600,565 | 13.2 | 88.0 | 6,082 | 0.200 | 0.050 | 0.111 | 2.330% | 95.0% | 4.0 |
| 17 | 2,125,666 | 20 | 134.5 | 14,208 | 0.200 | 0.055 | 0.102 | 4.415% | 95.0% | 18.0 |
| 18 | 2,273,551 | 20 | 139.1 | 15,197 | 0.200 | 0.055 | 0.101 | 4.826% | 95.0% | 20.0 |

**Table J-2.** LRDP-24. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 0.30 gal/h. (Version a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area (ft²) | MDLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 48,470 | 13.2 | 25.00 | 491 | 0.30 | 0.008 | 0.286 | 0.000000% | 95.0% | 2.3 |
| 1 | 69,797 | 13.2 | 30.00 | 707 | 0.30 | 0.012 | 0.279 | 0.000000% | 95.0% | 2.3 |
| 2 | 124,084 | 13.2 | 40.00 | 1,257 | 0.30 | 0.020 | 0.263 | 0.000003% | 95.0% | 2.3 |
| 3 | 193,881 | 13.2 | 50.00 | 1,963 | 0.30 | 0.032 | 0.243 | 0.000541% | 95.0% | 2.3 |
| 4 | 279,188 | 13.2 | 60.00 | 2,827 | 0.30 | 0.046 | 0.217 | 0.031613% | 95.0% | 2.3 |
| 5 | 597,952 | 23.4 | 65.95 | 3,416 | 0.30 | 0.056 | 0.200 | 0.210% | 95.0% | 2.3 |
| 6 | 380,006 | 13.2 | 70.00 | 3,848 | 0.30 | 0.063 | 0.187 | 0.616% | 95.0% | 2.3 |
| 7 | 496,334 | 13.2 | 80.00 | 5,027 | 0.30 | 0.082 | 0.153 | 4.4% | 95.0% | 2.3 |
| 8 | 506,273 | 13.2 | 80.80 | 5,127 | 0.30 | 0.084 | 0.150 | 5.0% | 95.0% | 2.3 |
| 9 | 600,565 | 13.2 | 88.00 | 6,082 | 0.30 | 0.099 | 0.122 | 12.2% | 95.0% | 2.3 |

**Table J-3.** LRDP-24. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 1.00 gal/h. (Version a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area ($ft^2$) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 1.00 | 0.192 | 0.655 | 0.290% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 1.00 | 0.008 | 0.986 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 1.00 | 0.012 | 0.979 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 1.00 | 0.020 | 0.963 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 1.00 | 0.032 | 0.943 | 0.000000% | 95.0% | |
| 5 | 279,188 | 13.2 | 60.00 | 2,827 | 1.00 | 0.046 | 0.917 | 0.000000% | 95.0% | |
| 6 | 597,952 | 23.4 | 65.95 | 3,416 | 1.00 | 0.056 | 0.900 | 0.000000% | | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 1.00 | 0.063 | 0.887 | 0.000001% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 1.00 | 0.082 | 0.853 | 0.000025% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 1.00 | 0.104 | 0.814 | 0.000389% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 1.00 | 0.128 | 0.770 | 0.004338% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 1.00 | 0.155 | 0.722 | 0.034494% | 95.0% | |
| 12 | 1,692,049 | 20 | 120.00 | 11,310 | 1.00 | 0.184 | 0.669 | 0.197% | 95.0% | |
| 13 | 1,985,808 | 20 | 130.00 | 13,273 | 1.00 | 0.216 | 0.612 | 0.820% | 95.0% | |
| 14 | 250,591 | 14.1 | 55.00 | 2,376 | 1.00 | 0.039 | 0.930 | 0.000% | 95.0% | |
| 15 | 600,565 | 13.2 | 88.00 | 6,082 | 1.00 | 0.099 | 0.822 | 0.000% | 95.0% | |
| 16 | 2,125,666 | 20 | 134.50 | 14,208 | 1.00 | 0.231 | 0.584 | 1.4% | 95.0% | |
| 17 | 2,273,551 | 20 | 139.10 | 15,197 | 1.00 | 0.248 | 0.555 | 2.3% | 95.0% | |
| 18 | 1,687,589 | 13.2 | 147.52 | 17,091 | 1.00 | 0.278 | 0.500 | 5.0% | 95.0% | |

**Table J-4.** LRDP-24. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 2.00 gal/h. (Version a)

| Index | Volume (gal) | Ht (ft) | Dia (ft) | Area ($ft^2$) | TLR (gal/h) | Std Dev (gal/h) | Threshold (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | n for LR=0.2 gal/h |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 2.00 | 0.192 | 1.655 | 0.000159% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 2.00 | 0.008 | 1.986 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 2.00 | 0.012 | 1.979 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 2.00 | 0.020 | 1.963 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 2.00 | 0.032 | 1.943 | 0.000000% | 95.0% | |
| 5 | 279,188 | 13.2 | 60.00 | 2,827 | 2.00 | 0.046 | 1.917 | 0.000000% | 95.0% | |
| 6 | 597,952 | 23.4 | 65.95 | 3,416 | 2.00 | 0.056 | 1.900 | 0.000000% | | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 2.00 | 0.063 | 1.887 | 0.000000% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 2.00 | 0.082 | 1.853 | 0.000000% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 2.00 | 0.104 | 1.814 | 0.000000% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 2.00 | 0.128 | 1.770 | 0.000001% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 2.00 | 0.155 | 1.722 | 0.000013% | 95.0% | |
| 12 | 1,692,049 | 20 | 120.00 | 11,310 | 2.00 | 0.184 | 1.669 | 0.000098% | 95.0% | |
| 13 | 1,985,808 | 20 | 130.00 | 13,273 | 2.00 | 0.216 | 1.612 | 0.000636% | 95.0% | |
| 14 | 250,591 | 14.1 | 55.00 | 2,376 | 2.00 | 0.039 | 1.930 | 0.000000% | 95.0% | |
| 15 | 600,565 | 13.2 | 88.00 | 6,082 | 2.00 | 0.099 | 1.822 | 0.000000% | 95.0% | |
| 16 | 2,125,666 | 20 | 134.50 | 14,208 | 2.00 | 0.231 | 1.584 | 0.001391% | 95.0% | |
| 17 | 2,273,551 | 20 | 139.10 | 15,197 | 2.00 | 0.248 | 1.555 | 0.002989% | 95.0% | |
| 18 | 5,157,611 | 23.4 | 193.69 | 29,465 | 2.00 | 0.480 | 1.138 | 1.855026% | 113.8% | 0.9 |
| 19 | 3,375,098 | 13.2 | 208.62 | 34,181 | 2.00 | 0.557 | 1.000 | 5.0% | 95.0% | |

**Table J-5.** LRDP-24. The threshold is set to give a $P_D$ = 95% against a specific TLR given that the $P_{FA} \leq 5\%$. The $P_{FA}$ will change with tank size, because the TLR is the same for all tank sizes. The TLR = 3.00 gal/h. (Version a)

| **Index** | **Volume** (gal) | **Ht** (ft) | **Dia** (ft) | **Area** ($ft^2$) | **TLR** (gal/h) | **Std Dev** (gal/h) | **Threshold** (gal/h) | $P_{FA}$ (%) | $P_D$ (%) | **n for LR=0.2 gal/h** |
|---|---|---|---|---|---|---|---|---|---|---|
| Eval | 2,063,044 | 23.4 | 122.50 | 11,786 | 3.00 | 0.192 | 2.655 | 0.000001% | 95.0% | |
| 1 | 48,470 | 13.2 | 25.00 | 491 | 3.00 | 0.008 | 2.986 | 0.000000% | 95.0% | |
| 2 | 69,797 | 13.2 | 30.00 | 707 | 3.00 | 0.012 | 2.979 | 0.000000% | 95.0% | |
| 3 | 124,084 | 13.2 | 40.00 | 1,257 | 3.00 | 0.020 | 2.963 | 0.000000% | 95.0% | |
| 4 | 193,881 | 13.2 | 50.00 | 1,963 | 3.00 | 0.032 | 2.943 | 0.000000% | 95.0% | |
| 5 | 279,188 | 13.2 | 60.00 | 2,827 | 3.00 | 0.046 | 2.917 | 0.000000% | 95.0% | |
| 6 | 597,952 | 23.4 | 65.95 | 3,416 | 3.00 | 0.056 | 2.900 | 0.000000% | | |
| 7 | 380,006 | 13.2 | 70.00 | 3,848 | 3.00 | 0.063 | 2.887 | 0.000000% | 95.0% | |
| 8 | 496,334 | 13.2 | 80.00 | 5,027 | 3.00 | 0.082 | 2.853 | 0.000000% | 95.0% | |
| 9 | 628,173 | 13.2 | 90.00 | 6,362 | 3.00 | 0.104 | 2.814 | 0.000000% | 95.0% | |
| 10 | 1,175,034 | 20 | 100.00 | 7,854 | 3.00 | 0.128 | 2.770 | 0.000000% | 95.0% | |
| 11 | 1,421,791 | 20 | 110.00 | 9,503 | 3.00 | 0.155 | 2.722 | 0.000000% | 95.0% | |
| 12 | 1,692,049 | 20 | 120.00 | 11,310 | 3.00 | 0.184 | 2.669 | 0.000001% | 95.0% | |
| 13 | 1,985,808 | 20 | 130.00 | 13,273 | 3.00 | 0.216 | 2.612 | 0.000005% | 95.0% | |
| 14 | 250,591 | 14.1 | 55.00 | 2,376 | 3.00 | 0.039 | 2.930 | 0.000000% | 95.0% | |
| 15 | 600,565 | 13.2 | 88.00 | 6,082 | 3.00 | 0.099 | 2.822 | 0.000000% | 95.0% | |
| 16 | 2,125,666 | 20 | 134.50 | 14,208 | 3.00 | 0.231 | 2.584 | 0.000012% | 95.0% | |
| 17 | 2,273,551 | 20 | 139.10 | 15,197 | 3.00 | 0.248 | 2.555 | 0.000027% | 95.0% | |
| 18 | 5,157,611 | 23.4 | 193.69 | 29,465 | 3.00 | 0.480 | 2.138 | 0.048603% | 95.0% | |
| 19 | 5,062,631 | 13.2 | 255.50 | 51,271 | 3.00 | 0.835 | 1.500 | 5.0% | 95.0% | |