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**ENVIRONMENTAL
RESTORATION
PROGRAM**

**Selection of Liquid-Level Monitoring
Method for the Oak Ridge National
Laboratory Inactive Liquid Low-Level
Waste Tanks, Remedial
Investigation/Feasibility Study**

MANAGED BY
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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Energy Systems Environmental Restoration Program
ORNL Environmental Restoration Program

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National Laboratory Inactive Liquid Low-Level Waste Tanks,
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ACRONYMS

ALARA	as low as reasonably achievable
DOE	Department of Energy
EM	electromagnetic
EPA	Environmental Protection Agency
FFA	Federal Facility Agreement
LLW	liquid low-level waste
ORNL	Oak Ridge National Laboratory
SRS	Savannah River Site
TDEC	Tennessee Department of Environment and Conservation
UST	underground storage tank

EXECUTIVE SUMMARY

Several of the inactive liquid low-level waste (LLLW) tanks at Oak Ridge National Laboratory contain residual wastes in liquid or solid (sludge) form or both. A plan of action has been developed to ensure that potential environmental impacts from the waste remaining in the inactive LLLW tank systems are minimized.

This document describes the evaluation and selection of a methodology for monitoring the level of the liquid in inactive LLLW tanks. Criteria are established for comparison of existing level monitoring and leak testing methods; a preferred method is selected and a decision methodology for monitoring the level of the liquid in the tanks is presented for implementation. The methodology selected can be used to continuously monitor the tanks pending disposition of the wastes for treatment and disposal.

Tanks that are empty, are scheduled to be emptied in the near future, or have liquid contents that are very low risk to the environment were not considered to be candidates for installing level monitoring. Tanks requiring new monitoring equipment were provided with conductivity probes; tanks with existing level monitoring instrumentation were not modified. The resulting data will be analyzed to determine inactive LLLW tank liquid level trends as a function of time.

1. INTRODUCTION

1.1 PURPOSE

This document describes the process used to select the most appropriate method currently available for monitoring the inactive liquid low-level waste (LLLW) tanks at Oak Ridge National Laboratory (ORNL). The application of the selected testing methodology must take into consideration the unique characteristics of these tanks. The overall objective is to monitor the liquid level of these tanks to ensure that there is not outleakage to the environment prior to remediation. Available level monitoring methods are reviewed and evaluated in terms of their applicability to the unique requirements for testing and monitoring this group of tanks. Criteria are established for comparison of existing methods, a preferred method is selected, and a decision methodology for monitoring the liquid level trend in the tanks is presented for implementation.

1.2 BACKGROUND

ORNL is one of three principal facilities on the Oak Ridge Reservation, located 25 miles west of Knoxville, Tennessee (Fig. 1). The facility has been operating since 1943 and is currently managed by Martin Marietta Energy Systems, Inc., for the Department of Energy (DOE). Throughout the operational history of ORNL, facility operations have produced radioactive and/or hazardous chemical wastes (mixed wastes); LLLW storage tanks have been used to collect, neutralize, and store the liquid portion of these wastes pending final treatment and disposal.

Many of these tank systems are inactive (i.e., have been removed from service and are no longer receiving programmatic wastes), but residual liquids and sludge remain in some of the inactive tanks. A program for surveillance and maintenance of the inactive LLLW tanks has been implemented by ORNL as part of a comprehensive program to ensure that potential environmental impacts from the residual waste in these systems are minimized. Leak testing was determined not feasible for these tanks because of their age, suspect structural integrity, and known history of inleakage.

The Federal Facility Agreement (FFA) requirements for inactive tanks include characterizing the tank contents and the associated risk represented by the presence of the remaining hazardous constituents. A method to monitor the liquid level in the tanks as part of a continuous comprehensive tank surveillance program has been selected to help satisfy the requirement of characterizing the risk associated with the tanks.

The FFA identifies 54 inactive tanks at ORNL. Sufficient information exists regarding 38 of these tanks to evaluate the potential for application of level monitoring. These evaluations are presented in Appendix A.

Fig. 1. DOE Oak Ridge Reservation.

2. MONITORING METHOD SELECTION CRITERIA

The mixed wastes (low-level radioactivity and various hazardous chemical materials) in these tanks represent a significant health hazard to anyone coming in contact with them. In the interests of protecting human health and the environment, the selected method must minimize the potential for exposure of workers to the hazardous effects of the contents. The method must also minimize the possibility that the actual performance of tests or measurements could contribute to the potential for a release through damage to the tanks, uncontrolled contamination of testing equipment, or accidental release of hazardous materials to the environment. Because the physical setting, construction, and contents of the tanks are unique and cannot be compared with any known existing criteria or performance standards, ORNL developed a special set of criteria against which known tank monitoring methods were compared in order to select the most appropriate methodology.

No performance standards exist for tank tightness testing for mixed waste tanks. A set of standards was developed by the Environmental Protection Agency (EPA) for petroleum underground storage tanks (USTs) based upon the best available technology for that type of tank to meet certain goals, but those standards are not applicable to the inactive LLLW tanks for the reasons discussed below.

The millions of petroleum USTs in existence share certain similarities that made it possible to establish tightness testing measurement standards for those tanks. Historically, very little attention had been given to whether petroleum USTs were leaking or not leaking, and few or no records were maintained to monitor inventories. The EPA established criteria for regulatory standards for the petroleum industry which required a tightness test able to detect a specific minimum leak rate threshold with a 95% or better probability of detection and a 5% or less probability of false alarm. That numeric threshold was only adopted as a tool against which to measure the performance of a testing method and its ability to meet that probability.

As a result of those regulatory requirements, the petroleum industry developed very short-term high-precision tests for USTs. These tests minimize the "downtime" that results when testing is performed, and in recognition of the high cost of the tests to the tank owners, are only required to be performed annually. These tests also take advantage of the physical design, construction, and installation criteria for tanks that had been built and installed according to industry standards.

The precision tightness testing methods evaluated by the EPA and accepted as meeting the regulatory criteria are based upon measurement of the total contents of the tank during a period of time ranging from 1 to as many as 6 h in duration. Among other constraints, these methods rely upon being able to completely isolate the tank systems from inflow of water or petroleum while ensuring that any part of the system that might contain petroleum is subjected to the test. For the test to be valid, there must be a high degree of certainty that there is no inflow of liquid that might offset an outleak. For reasons described below, it is not possible to isolate the inactive LLLW tanks that continue to contain residual liquids; therefore, such precision tests, which are the basis for the petroleum UST regulatory numeric measurement criteria, cannot be applied to these tanks.

In the inactive LLLW tank circumstances, there is nothing to be gained by minimizing "downtime" and there is no need for minimizing the test duration; there is no need for a high-precision short-duration test with a high probability of detection such as that used for USTs. Conversely, because of the nature of the risks involved in the hazardous constituents in the mixed wastes, comprehensive surveillance and maintenance programs are necessary to continuously (daily) monitor the mixed waste (LLLW) tanks as opposed to the typical petroleum UST installation, where only minimal care and attention are given to the tanks.

Given that no tightness testing criteria exist for tanks that share the construction characteristics and contents characteristics inherent in the inactive LLLW tanks, a combination of criteria were selected to include not only some of the factors that are normally considered for evaluating a tank testing method, but also considerations that relate to the surrounding physical environment and the unique hazardous characteristics of the tanks and their contents.

Environmental factors unique to this site require certain restrictive criteria to be considered. Known contamination in the soils surrounding the tanks makes it undesirable to use a method that requires excavation or penetration of the surrounding soil or backfill or entry of operating personnel into the contaminated area. Subsurface features such as nearby active and abandoned tanks and piping systems make excavation and penetration undesirable; overfilling of the tanks such that old deteriorated piping would be flooded is also undesirable because it would likely result in a release of contaminated liquid. Nearby buildings occupied by the daily work force at ORNL make it preferable to use methods that do not require frequent access to the tanks or insertion and removal of equipment that can become contaminated from contact with the tank contents; any method that could possibly result in a release of liquid or airborne contamination from the tanks should be avoided.

Tank construction factors include age, service history, and materials of construction (several of the tanks were constructed from concrete sprayed over a steel cage, a type of construction called Gunitite). Video inspections using remotely operated cameras lowered into the tanks on robotic arms were performed on one steel tank and 10 Gunitite tanks that had sufficient headspace to permit camera operation above the liquid level. These inspections provided qualitative visual documentation of the physical condition of the insides of the tanks. Because it is impossible to perform definitive assessments of the physical integrity of the LLLW tanks because of their age, materials of construction, and the undetermined deterioration of those materials after more than 40 years of chemical and radiological exposure, it is preferable to avoid testing or monitoring methods that require operating personnel to work on the surface of the ground above these tanks and to avoid subjecting the tanks to any avoidable changes in hydrostatic pressure. Rather than risk exposure of personnel and spend a great deal of money to excavate or enter tanks for the purpose of examining their physical condition, and realizing that the tanks have been removed from service and are scheduled for the earliest possible complete remediation within existing budgetary constraints, it was decided to determine the best available monitoring method at the lowest possible cost so that the limited funds that are available can be directed toward final remediation of the tanks.

Each method or approach is evaluated against uniform criteria that include the above considerations to determine the most suitable method for monitoring the inactive LLLW tanks. To provide a sound basis for comparison of the methods, the criteria are based upon

some of the same physical factors that are considered when testing regulated USTs. To be acceptable, the method must meet each of the following criteria.

- Applicability
 - Can be readily demonstrated and evaluated in the LLLW tank environment.
 - Provides capability for continuous monitoring.
- Reliability
 - Produces consistent results with minimum maintenance.
 - Has proven performance.
 - Is resistant to degradation from exposure to mixed wastes.
- Radiological acceptability
 - Minimizes radiation exposure of operating personnel.
 - Minimizes generation of radiological waste.
 - Minimizes worker activity performed above and near tank systems.
- Economic acceptability
 - Is not cost prohibitive.
 - Is the optimum of cost vs performance.
- ORNL procedural acceptability
 - Does not increase tank internal hydrostatic pressure.
 - Does not increase existing leakage (if present).
 - Does not compromise tank integrity by overstressing the structure or attached piping.

Tank contents exhibit hazardous characteristics because of both chemical content and low-level radioactivity, and the latter requires imposition of precautions based on the principle of maintaining personnel exposure levels as low as reasonably achievable (ALARA).

The combined effect of these factors is to invoke a cautious and carefully planned approach toward investigation and monitoring that will not create an unavoidable risk to the personnel involved in the testing activities, the ORNL personnel who perform daily work in the immediate vicinity of the tanks, or the surrounding natural environment. While satisfying these criteria, the selected method must demonstrate the ability to provide a reasonable measure of tank integrity—both initially and on a continuous basis until the tank contents have been remediated.

Releases of liquid contents from storage tanks to the environment can occur in a number of ways, among them leaks in the tanks or in the interconnecting piping system. Releases can also occur because of spills and overfills, thermal expansion of liquid contents resulting in overflow from vent systems, and syphoning through connected piping or conduit that is not normally intended to contain the liquid being stored in the tank.

Each method for detecting leaks and for determining tightness of a tank system has its own set of unique characteristics, all of which were considered when selecting the most appropriate method for evaluating and monitoring these tanks. In meeting the previously mentioned selection criteria, the testing must also be performed in a manner consistent with typical Energy Systems procedures for leak testing of USTs containing mixed waste, which

specify that a nonhydrostatic test will be used and that the testing will not cause leak rates to increase if a leak is present.

The groundwater level in the immediate vicinity of the tanks may reduce the effectiveness of all the tank testing methods considered in this document. Should the groundwater rise above the liquid level in the tank, liquid inflow may result if there is an opening in the tank structure or connected piping that is at or below the elevation of the local water table, until the level in the tank reaches equilibrium with the surrounding water table. An opening in the tank or system that is constantly below the elevation of the local water table will result in the liquid level in the tank fluctuating both upward and downward, depending on changes in the water table. If the groundwater level fluctuates, causing intermittent inflow and outflow, testing results will be difficult to interpret; interpretation may be enhanced by monitoring the groundwater level adjacent to the tank. The effects of the water table can be minimized or eliminated by maintaining a localized depression in the water table adjacent to the tank through use of a sump pump system, as is currently being done around the Gunite tanks.

One of the most restrictive limitations involved in testing these tanks is the inability to totally isolate them and ensure that no inleakage can occur. Openings in the top of the tanks—whether in the tank shell or related to access ports that were installed for inspection, cleaning, or maintenance—are known sources of water inflow during normal storm events. It is therefore not possible to use a test method that would involve pressurization of the tanks with a gas or liquid because contaminated material would be forced out of the tanks through these openings. It is not practical to attempt sealing these openings because of the exposure that would result to personnel involved and because there is no assurance that after subjecting personnel to known radiation exposure and undetermined risk, the attempt at creating an absolute seal would be successful. Inflow of rainwater can also be the result of breaks in abandoned inlet piping that is still connected to the tanks. Therefore all ancillary piping would also have to be isolated from the tanks in order to achieve a pressure-tight seal. Such possibilities must be considered when evaluating the testing methods to be used.

When evaluating the data collected by a method that involves long-term level monitoring, the limitations imposed by the possibility of inleakage occurring simultaneously with outleakage must be considered. As long as the possibility of inleakage from any source exists (because of the difficulty of completely isolating the tanks as described above), it cannot be concluded with certainty that an apparent constant level reading is, in fact, indicative that a tank is not outleaking. Theoretically, an outleak could be occurring at the same rate as an inleak. By monitoring liquid levels over long periods of time (weeks and months) and taking into account the effects of precipitation or the lack thereof, it is possible to ameliorate the limitations imposed by not being able to totally and completely isolate the tanks, but a definitive result cannot be assured.

3. EVALUATION OF TRADITIONAL LEAK DETECTION METHODS

To select the most appropriate methods for investigating and monitoring the LLLW tanks at ORNL, it was necessary to review the technologies that have been used in the past to measure the tightness of regulated underground storage tank systems. Although the regulated tanks differ from the LLLW tanks in many of their characteristics, the physical and analytical principles that are applied in existing proven testing methods can be evaluated for their applicability to the given set of circumstances affecting the inactive LLLW tanks.

Four established methods of leak detection (statistical inventory analysis, external detection, precision tightness testing, and low-level alarms) were reviewed. Similar methods have been widely used for testing USTs, and these were selected as being potentially appropriate for assessing the inactive LLLW tanks. A set of criteria was developed to compare these technologies against each other and measure their relative appropriateness in regard to the unique limitations and requirements presented by the known characteristics of the inactive LLLW tanks and their contents. Various alternative approaches exist within each of these methods; additional information on each approach is contained in Appendix B.

3.1 STATISTICAL INVENTORY ANALYSIS

3.1.1 Description of the Method

Statistical inventory analysis is a method that applies statistical analytical methods to a set of data points collected over a period of time, the data points being the result of individual discrete measurements of the inventory (liquid contents) of a tank, usually by direct level measurement. Advantages of this method include the following:

- There is no need to add liquid to the tank to perform a test or continuously monitor the tank.
- There is no need to pressurize the tank in any way.
- Performance of a test does not create a significant increase in radiological waste.
- Installation of required equipment results in minimal potential for exposure of workers to hazardous chemicals or radiation.
- It is possible to use existing level monitoring equipment to collect the data for statistical analysis.

Although the precision of an individual measurement made by existing or newly installed inventory monitoring equipment may not be high, a sufficiently large set of data points collected with a consistent level of precision can be subjected to statistical analysis to satisfactorily identify trends over time. These statistical techniques can be used to overcome short-term, point-to-point variations that can occur because of measurement errors or other random variables (i.e., scatter) in the testing environment. A typical application of this

technique is to monitor the inventory level in underground petroleum storage tanks on a continuous basis, while carefully tracking and documenting additions and withdrawals from the inventory in the tank. A significant trend outside of the statistical limits applied to the tank system signals the need for a precision tightness test to be performed.

A variation of this technique is level trend analysis. Although still based upon collecting level measurement data points, there are no programmatic additions and withdrawals to account for as is done in inventory analysis. Level trend analysis consists of simply monitoring the liquid level in the tanks for an extended period, collecting a large number of data points, and performing a statistical evaluation to determine the liquid level trend. The same statistical principles apply.

Fluctuations in the level measurement data due to environmental effects such as temperature changes become part of the total random error of the system and are compensated for by the statistical evaluation. The evaluation yields a rate of change of the level in the tank having a margin of error that is a function of the standard deviation of the data; the margin of error is reduced by increasing the accuracy of the measurement method and the duration of the monitoring. This method is not as precise an indicator as short-term precision tightness testing used for petroleum USTs but has been used for many years as a reliable indication of an unaccounted for change in tank inventory that can be used to signal the need for additional investigation. It also meets the ORNL procedural requirements for personnel safety and risk minimization and is radiologically acceptable.

3.1.2 Limitations Inherent in the Method

The level measurement devices that can be used for data collection have unique features and limitations and are described in the following paragraphs. The relative precision and accuracy of a measurement device has an effect on the level of confidence that can be assigned to the level trend statistical data. To obtain higher confidence, it is necessary to have higher accuracy and precision.

Other limitations of the method should be recognized and acknowledged. While this method does not require isolation of the tanks, it is also subject to the possible effects of simultaneous inleaks that balance outleaks because isolation of the tank is not performed. Likewise, seasonal temperature fluctuations can also result in changes in level as a result of changes in the volume of the liquid due to thermal expansion and contraction; short-term day-to-day and diurnal (day-to-night) temperature changes can have an effect on certain types of measurement instrumentation resulting in apparent changes in level that do not really occur but are caused by equipment limitations (e.g., pneumatic devices). This method cannot be assumed to be a totally definitive test or indicator, and it is most effective when used within a program that involves continuous (i.e., daily) data collection and periodic (i.e., monthly) evaluation of the data.

When a change in a given tank's level trend profile occurs, a number of possible steps can be taken to determine why the observed change took place. For example, a given tank that is known to take on water from infiltration during rainy periods can be expected to regularly exhibit an increasing level trend. Should the level not increase during such a period, further investigation would be indicated to see if the cause is an instrument problem, a change in surface runoff or groundwater patterns due to construction or remediation activities

in the vicinity, or possibly an outleak that is partially offsetting the expected level increase that is part of the tank's "profile."

The need for a comprehensive monitoring and response methodology is a limitation and requirement for the successful application of this type of level monitoring approach. However, given the age and condition of the tanks being monitored, an intensive surveillance and maintenance program is strongly indicated as a preferred practice no matter what method is used, and given the advantages of this particular method (level trend analysis), it fits well with such a program.

Reliability and economic acceptability are dependent on the specific equipment used to measure and monitor the liquid level. Each approach below is evaluated against these remaining criteria to determine its acceptability.

3.1.3 Manual Gauging

Manual gauging could be used if no other level measuring device is available. A staff is lowered to the liquid/surface interface, and the reading is recorded. Accuracy is limited, and the method is not desirable because of tank access requirements, generation of waste, and potential for personnel exposure. Results may be unsatisfactory because of the limited accuracy of the measurement method, and collection of sufficient data points could result in excessive repeated potential personnel exposure to radiological hazards. Care is required to not impart damage to tanks when the gauge "stick" is lowered into the tank, especially steel tanks that have not been specifically reinforced at the point of impact from the stick. None of the LLLW tanks were built with such striker pads because manual gauging was not anticipated at the time they were constructed. Continuous repeated impacts of seemingly "normal" intensity are known to have resulted in leaks in steel petroleum USTs over long periods of time with repeated gauging.

3.1.4 Float Gauge

Float gauges have been used on some tanks at ORNL, and operators report that they are not very reliable and require frequent maintenance or replacement. Accuracy and precision are low because of the method of reading the gauges and the calibrations on the measurement indicator. The gauge apparatus remains in constant contact with the fluid and is therefore susceptible to deterioration and absorption of radioactive contaminants.

3.1.5 Ultrasonic Noncontact

Ultrasonic noncontact equipment investigated by ORNL and Savannah River Site (SRS) personnel has been found to be unsatisfactory and difficult to calibrate. In addition, a vendor reported a low probability of obtaining adequate results because of reflection of the signal within the tanks. A drop tube was suggested to reduce the reflection problem; however, the vendor pointed out that condensation within the tube would cause difficulties.

3.1.6 Ultrasonic Contact

Ultrasonic contact level equipment investigated by ORNL has been found to be inadequate. The equipment is dependent on the fluid density being uniform and constant, which is unlikely. For most of the tanks, it also presents some difficulty in installation and

calibration. Consistent performance is not assured because of the possible influences of sludges and other debris in the tanks.

3.1.7 Transducer

Transducers are not used on any of the tanks for level monitoring. All industry sources contacted indicated that durability and calibration difficulties would be encountered.

3.1.8 Pneumatic

Pneumatic systems are in operation on several of the tanks at ORNL, and the instrumentation is inexpensive and reliable. Although maintenance of the system requires opening the tanks, the need for maintenance is infrequent. The system is difficult to calibrate but yields good differential level measurements if accompanied by electronic instrumentation (mechanical instrumentation is less accurate and may vary by 3% of the pressure in the system). This system may be acceptable if the total random noise in the collected data set yields acceptable statistical reliability and accuracy. There is a potential for inconsistent results with this method if there is sufficient sludge in the tank to inhibit the bubbler or if debris interferes with the flow of the air through the tube. This system meets the criteria established for evaluation and is suitable for level monitoring provided that there is no interference from sludge or debris.

3.1.9 Conductivity Probe

Permanently installed conductivity probes are used on several tanks and are preferred at ORNL. The probe is suspended within the tank on a Mylar tape with an embedded metallic conductor that rolls on and off a finely calibrated tape reel. Measurements are recorded electronically and displayed on a digital meter. The devices are relatively expensive (\$6,000) but provide high reliability and accuracy. Parts requiring maintenance can be physically isolated from the tank during installation and removal to minimize the risk of personnel exposure. SRS personnel use these probes exclusively after having performed extensive tests on other systems, including sonar and microwave measurement devices. This method meets all the criteria established for evaluation and is suitable for monitoring the ORNL tanks.

3.2 LOW-LEVEL ALARMS

Low-level alarms have been used in some tanks and are mentioned here only to acknowledge their existence and establish their limitations. A conductivity switch is reported to be highly reliable. If placed near the surface of the liquid in an inactive tank, it can be an effective leak detection method, and it is inexpensive. However, because the switch is statically positioned, an unplanned addition of liquid to the tank could cause the contact to be immersed without providing an indication of a change in level; liquid could subsequently leak out without the change in level being detected. Being a single point alarm system, this method provides very limited information, has virtually no method for adapting to or compensating for temperature changes, deformation, evaporative losses, etc., and cannot be used to monitor trends. This approach is therefore not definitive and so is not acceptable.

3.3 EXTERNAL DETECTION

External detection consists of using various techniques to detect the presence of the tank contents in the environment. Tracer studies and electromagnetic (EM) conductivity surveys are two such approaches.

3.3.1 Tracer Studies

Tracer studies have been used at ORNL for various applications. A ^{82}Br tracer introduced into a tank is easily detectable and distinguishable from other constituents in the tank surroundings, and the tracer's short half-life makes it of no environmental consequence. However, the test is expensive and requires periodic repetition and potential personnel exposure to ensure that no changes have occurred. Continuous monitoring is not feasible. For these reasons, tracer studies are not considered an acceptable approach to monitoring the tanks. In certain circumstances tracers might be applied to assist in determining whether a suspect tank is, in fact, releasing its contents, and this method will be evaluated for such specific applications should the need arise.

3.3.2 EM Conductivity

EM conductivity surveys have been used at various sites to map plumes and detect underground discontinuities. The results are not likely to be definitive and therefore do not meet the for consistent results and ease of evaluation. Because of the presence of numerous below-ground piping systems and trenches, possible lingering subsurface influences of past releases, and the presence of nearby above-ground buildings and other structures with ongoing activities, it is unlikely that EM surveys could be used with an acceptable degree of certainty.

3.4 PRECISION TIGHTNESS TESTING

Several proprietary methods are reviewed in Appendix B for application on the inactive tanks. These methods are not considered all-inclusive but are representative of commercially available tightness testing methods. The tightness testing methods were developed primarily for the petroleum industry and are designed to meet the 40 CFR 280 standard for tightness tests. However, many of the tightness tests are "overfill" methods and require the introduction of liquids, thus increasing the pressure in the tank. Increasing tank pressure is prohibited by ORNL procedure, thereby eliminating test methods using this approach.

Precision tightness testing methods reviewed that do not use the "overfill" approach must still be used with a completely isolated tank system, which cannot be achieved with the LLLW tanks. Tightness testing alone must still be repeated on a periodic basis because it is a short-term test (measured in hours) that only indicates the apparent tightness of the tank at that specific period of time, and it provides no measure of tank tightness after the test is completed. Such repeated testing increases costs, generation of radiological waste, and the risk of personnel exposure. Without additional (supplemental) monitoring using methods described in Sect. 3.1 the criteria for continuous monitoring cannot be met.

Because of the limitations listed above and the lack of any advantages to be gained, precision testing was not selected as a monitoring method.

4. SELECTION OF MONITORING METHOD

Using the factors and criteria described above, level trend analysis based on statistical evaluation of level monitoring data was selected as the preferred monitoring method. This method is appropriate for application to those tanks for which level monitoring instrumentation must be installed and for tanks having existing level monitoring equipment.

Several of the tanks did not have level monitoring equipment, thus necessitating installation of level monitors. The cost of installing level monitoring equipment is high compared with the cost of the equipment because of the care that must be exercised to protect the personnel performing the installation, to minimize the risks to surrounding structures and the local working population at the site, and to ensure that no damage is inflicted upon the tank. This cost is also relatively uniform regardless of the type of instrument installed. Therefore, where level monitors were installed, a high level of accuracy was specified for the selected equipment because it provides a higher degree of confidence in the level trend results.

The conductivity probe used for level monitoring provides high resolution and is reported to be highly dependable; this is the instrument of choice when instrumentation must be added to the tanks. Pneumatic level monitors may also be used, and existing instrumentation will be included in the testing and monitoring program.

The limitations inherent in the capabilities of this method are described in Sect. 3.1. In summary, the limitations include the uncertainty imposed by the fact that the tanks cannot be isolated to prevent the addition of liquid from local precipitation, the limits of confidence in the statistical data that are derived from the precision and accuracy of the level measurement device that is used, the seasonal and short-term effects of temperature changes, and the requirement for constant surveillance and maintenance of the tanks to ensure the maximum effectiveness of this method.

These factors are outweighed by the low risk and exposure to workers, the low risk to the tanks themselves and the working population and surrounding structures and environment that would result from monitoring activities, and the relatively low costs involved, which helps to conserve available funds for complete remediation of these tanks.

5. LEVEL MONITORING PLAN

The plan for monitoring the inactive LLLW tanks includes three steps: determining the necessity for level trend analysis (i.e., monitoring criteria), selecting the proper level monitoring equipment configuration for each tank, and preparing detailed implementation plans.

Each tank identified as a candidate for level trend analysis will be evaluated in accordance with this procedure. The 38 tanks that have been evaluated are discussed in Appendix A. Additional tanks currently included in the FFA and tanks transferred from active to inactive status will be evaluated when sufficient information becomes available. The evaluation of these tanks will be performed under the Environmental Restoration Program. Figure 2 is a decision flow chart representing the evaluation applied to each tank. The three steps in the evaluation are discussed below.

5.1 LEVEL TREND ANALYSIS CRITERIA

Under three conditions, level trend analysis of the inactive LLLW tanks is not required. A tank identified as a candidate for level trend analysis will not be monitored if it is empty, if the contents are scheduled for prompt removal, or if the tank is determined to present no risk to the environment. If the tank is empty, no release to the environment can occur and level trend analysis is not necessary; if the tank contents are scheduled for prompt removal, then level trend analysis is not necessary; and if the tank can be externally inspected, leaks can be detected without level trend analysis. All tanks not eliminated by these criteria will be monitored.

5.2 LEVEL MONITORING EQUIPMENT CONFIGURATION

Tanks not excluded by the above criteria will be monitored with the most appropriate configuration. Level trend analysis will be performed using existing level monitoring equipment, if available. Tanks without existing level monitoring will be equipped with conductivity probe instrumentation.

5.3 LEVEL TREND ANALYSIS IMPLEMENTATION AND REPORTING

For each tank scheduled for level trend analysis, detailed procedures were prepared to describe the necessary steps. These procedures include requirements for installing level monitoring equipment and collecting and evaluating the data. The results will be presented in an initial Level Trend Analysis Summary Report; subsequent continuous monitoring of these tanks and additional tanks will be performed under the Surveillance and Maintenance Program.

Fig. 2. ORNL inactive LLLW tank leak testing decision flow chart.

Appendix A

Level Monitoring Equipment Configuration for 38 Inactive LLLW Storage Tanks

LEVEL MONITORING EQUIPMENT CONFIGURATION FOR 38 INACTIVE LLLW StORAGE TANKS

The plan for monitoring the inactive LLLW storage tanks is described in Sect. 5 of this document. The plan includes determining the necessity for level trend analysis and selecting the proper configuration for each tank.

Sufficient information exists to select a monitoring configuration for 38 of the tanks listed in the FFA. Physical data for these tanks are presented in Table A.1. The locations of these tanks are shown in Figs. A.1 and A.2. Each tank is evaluated below in accordance with the methodology established in Sect. 5. The resulting monitoring configurations and pertinent data are presented in Table A.2.

TANKS NOT REQUIRING LEVEL MONITORING

The following paragraphs identify the tanks eliminated from level monitoring by the criteria described in Sect. 5 of this report.

Empty tanks not receiving inflow of liquid

The most recent sampling effort indicates that these tanks are empty; therefore, level monitoring is unnecessary. The tanks have remained empty since they were removed from service and should, with proper administrative controls, remain empty until final closure.

W-13	W-14
W-15	WC-1
3001B	7503A
7560	

Empty tanks with termination of inflow not confirmed

These tanks have been removed from service and have had their contents removed but have not yet been confirmed as not receiving nonprogrammatic inflow. They are being monitored to determine that they will remain empty. Any recurring liquid that might be found will be removed, and the source will be found and eliminated if possible.

3013	3003A
3004B	H-209
T-30	TH-1
TH-2	TH-3
W-19	W-20

Tanks scheduled for contents removal

Tank TH4 is scheduled to have approximately 7000 gal of liquid removed in FY 1995.

Table A.1. Physical data of 38 inactive waste storage tanks at ORNL

Tank location ^a	Tank	Capacity (gal)	Volume (gal) ^b		Construction	Service	RCRA materials ^c
			Liquid	Sludge			
OHF	T-1	15,000	8,569	791	Mild steel	1963–1980	Yes
	T-2	15,000	10,687	1,205	Mild steel	1963–1980	Yes
	T-3	25,000	2,825	2,209	Mild steel/ rubber lined	1963–1980	Yes
	T-4	25,000	14,888	1,328	Mild steel/ rubber lined	1963–1987	Yes
	T-9	13,000	4,869	481	Mild steel	1963–1980	Yes
4507	T-30	824	0	0	Stainless steel	1945–?	No
3503	TH-1	2,500	0	0	Stainless steel	1948–1970	No
	TH-2	2,400	0	0	Stainless steel	1952–1970	No
	TH-3	3,300	0	0	Stainless steel	1952–1970	No
3500	TH-4	14,000	17,518	6,315	Concrete	1943–1970	Yes
NTF	W-1	4,800	519	0	Concrete	1943–1960s	No
	W-1a	4,000	Varies	0	Stainless steel	1955–1986	Yes
	W-2	4,800	1,330	0	Concrete	1943–1960s	No
	W-3	42,500	40,063	2,276	Concrete	1943–1960s	Yes
	W-4	42,500	24,854	3,982	Concrete	1943–1960s	Yes
STF	W-5	170,000	21,636	5,131	Concrete	1943–1980	Yes
	W-6	170,000	123,276	5,131	Concrete	1943–1980	Yes
	W-7	170,000	3,801	5,131	Concrete	1943–1980	Yes
	W-8	170,000	50,040	2,573	Concrete	1943–1980	Yes
	W-9	170,000	36,887	2,573	Concrete	1943–1980	Yes
	W-10	170,000	98,890	6,425	Concrete	1943–1986	Yes
	W-11	1,500	744	62	Concrete	1943–1984	Yes

Table A.1 (continued)

Tank location ^a	Tank	Capacity (gal)	Volume (gal) ^b		Construction	Service	RCRA materials ^c
			Liquid	Sludge			
NTF	W-13	2,000	0	0	Stainless steel	1940-1958	No
	W-14	2,000	0	0	Stainless steel	1940-1958	No
	W-15	2,000	0	0	Stainless steel	1940-1958	No
SSTF	W-19	2,250	0	0	Stainless steel	1955-1960s	No
	W-20	2,250	0	0	Stainless steel	1955-1960s	No
3803	WC-1	2,150	0	0	Stainless steel	1950-1968	No
SSTF	WC-15	1,000	<i>d</i>	0	Stainless steel	1951-1960s	No
	WC-17	1,000	<i>d</i>	Trace	Stainless steel	1951-1960s	No
HRE	7560	1,000	0	0	Stainless steel	1957-1961	No
	7562	12,000	Varies	Trace	Stainless steel	1957-1987	Yes
3517	H-209	2,500	0	0	Stainless steel		No
3001	3001B	375	0	0	Stainless steel		No
3003	3003A	16,000	0	0	Concrete		No
3008	3004B	30	0	0	Stainless steel		No
3013	3013	350	0	0	Stainless steel		No
7503	7503A	11,000	0	0	Stainless steel		No

^aAbbreviations: OHF—Old Hydrofracture Facility; NTF—North Tank Farm; STF—South Tank Farm; SSTF—South of South Tank Farm; HRE—Homogeneous Reactor Experiment Building.

^bResidual liquid volumes are approximate total volumes including sludge as of August 1, 1993.

^cSludge or liquid may exhibit RCRA characteristics. These are tentative indications from initial analyses.

^dThese tanks have been emptied but receive inleakage from groundwater; the liquid level approximately tracks the water table surrounding the tanks.

Fig. A.1. Waste storage tanks within the main plant area.

Fig. A.2. Waste storage tanks outside the main plant area.

Table A.2. Existing monitoring and proposed monitoring of inactive LLLW tanks

Tank	Residual volume (gal) ^a	Leak reported	Delta elevation ^b (ft)	Type of monitoring	Recorder type	Resolution	Recording interval (min)	Volume resolution (gal)	Proposed monitoring/testing	Liquid transfer information ^c
W-19	0			None					None	None
W-20	0			None					None	None
7560	0			None					None	None
T-30	0			None					None	None
W-11	744	GI ^d		Staff gauge	Gauge	0.5 in.			Evaluate data	Jet to W22
WC-1	0	GI		None					None	None
WC-15	<i>e</i>	Yes		Con. Probe					Evaluate data	None
WC-17	<i>e</i>	Yes		Pneumatic	Gauge	3%			Evaluate data	None
W-1A	Varies	GI		Pneumatic	WOCC	0.1 in.	Continuous	Varies	Evaluate data	Jet to W22
W-5	21,636	GI	-11	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
W-6	123,276	GI	-9	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
W-7	3,801	GI	-10	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
W-8	50,040	GI	-11	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
W-9	36,887	GI	-9.5	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
W-10	98,890	GI	-8	Con. probe	WOCC	0.012 in.	2	15	Evaluate data	None
T-1	8,569		+15	Pneumatic	Gauge	3%	Daily	400	Evaluate data	External pump
T-2	10,687		+15	Pneumatic	Gauge	3%	Daily	400	Evaluate data	External pump
T-3	2,825		+15	Pneumatic	Gauge	3%	Daily	120	Evaluate data	External pump
T-4	14,888		+17	Pneumatic	Gauge	3%	Daily	1,200	Evaluate data	External pump
T-9	4,869		+12	Pneumatic	Gauge	3%	Daily	50	Evaluate data	External pump
W-1	519		+5	Con. probe					Evaluate data	Gravity to W22
W-2	1,330		+4	Con. probe					Evaluate data	
W-3	40,063	GI	+4	Float	Staff	0.25 in.	Continuous	30	Evaluate data	Jet to W22
W-4	24,854	GI	+0.5	Float	Staff	0.25 in.	Continuous	30	Evaluate data	Jet to W3

Table A.2 (continued)

Tank	Residual volume (gal) ^a	Leak reported	Delta elevation ^b (ft)	Type of monitoring	Recorder type	Resolution	Recording interval (min)	Volume resolution (gal)	Proposed monitoring/ testing	Liquid transfer information ^c
W-13	0		+10	None					None	
W-14	0		+9	None					None	
W-15	0		+10	None					None	
TH-1	0		2.5	None					None	
TH-2	0		-5	None					None	
TH-3	0		-5	None					None	
TH-4	17,518		+2	Con. probe					Evaluate data	None
7562	Varies	GI		Pneumatic	Gauge	3%	Daily	360	Remove liquids	None
H209	0			None					None	None
3001B	0			None					None	None
3003A	0			None					None	None
3004B	0			None					None	None
3013	0			None					None	None
7503A	0			None					None	None

^aResidual volumes are approximate total volumes including liquid and sludge as of August 1, 1993.

^bDelta elevation = liquid elevation - groundwater elevation (September 1986).

^cSubject to field verification.

^dGI—groundwater infiltration reported.

^eThese tanks have been emptied but receive inleakage from groundwater; the liquid level approximately tracks the water table surrounding the tanks.

Appendix B

Leak Testing Systems

LEAK TESTING SYSTEMS

Tidal Systems, Inc. (214) 412-8222 (Mark Lavenick). This system is appropriate for application to partially filled tanks. The system uses an ultrasonic probe device, and nonuniform densities affect the performance. Mark Lavenick does not believe that it would work properly in waste tanks.

Gilbarco Tank Monitor (919) 292-3011 (Tim Harvey). The system is appropriate for partially filled tanks but works with dielectrics only.

Ames-Wheaton (800) 321-5233 (Ken Howard). Level monitoring and inventory control can be provided with the system. The probe is a magnetostrictive design utilizing floats. The American Petroleum Institute (API) gravity of the fluid must be known, eliminating its use for the ORNL tanks.

Sarasota Measurement and Control (813) 351-6900 (Mike Barber). Level monitoring is provided by a float and transponder that slides up and down on a shaft. It is accurate to 1 mm. This method is potentially acceptable for short-term tightness testing.

Petrovend (312) 485-4200 (Bob McKeown). This level monitoring system has a shaft with a magnetic float and is potentially acceptable for short-term tightness testing.

Veeder Root (203) 651-2700 (Joe Cote). This system measures liquid level using capacitance and is applicable to virgin fluids only.

Hunter Leak Locator (800) 523-4370. This system only works with overfilled tanks.

Health Consultants (525) 833-1579. Their tank testing methods are overfill methods. Sound-sensing equipment for leak detection is applicable to pressure piping only.

Robert Shaw (615) 546-0550 (Duane Speaks/Guy Fisher). The monitoring system consists of a sensor or probe on a reel. The sensor locates the liquid by conductivity contact, and the readout is electronic. The system is currently used on the South Tank Farm. According to Nat Langley (ORNL), it has a high reliability and is a preferred method of level monitoring. However, it is expensive (\$6,000).

Advanced Tank Certification (615) 482-6901 and (615) 675-6777 (Tom Conrad). The level detecting system consists of two tubes used as probes. After the tubes are inserted, one tube is closed at the bottom and the other is open. The level in each tube is monitored, and temperature effects are noted from the closed tube. The system design is not complete for large tanks; however, it is highly accurate (1 mm) if used on small tanks (less than 10,000 gal).

Omega (800) 872-9436. This system uses a remote ultrasonic sensor (noncontact). The vendor did not think the results would be adequate unless the sensor is placed inside a drop tube. Condensation in the tube may reduce reliability. Accuracy is ~0.5 in.

ORNL Pneumatic System (615) 576-8154 (Nat Langley). "Bubbler" tube systems consist of a drop tube with an adjustable air flow supply. The pressure required to form a bubble through the tube is translated into head. Temperature and density may affect accuracy, and fabrication is relatively inexpensive.

Leak Sensors (215) 269-2137 (Al Maas). This system detects leaks by determining differential conductivity across the barrier. The barrier must be nonconductive. Al Maas does not think it would work on concrete tanks. Holes in liners of steel tanks could be detected if no pipes are in contact with the contents, but holes in the tanks could not be detected. This method is not acceptable for the ORNL tanks.

Appendix C

Level Trend Analysis Approach

LEVEL TREND ANALYSIS APPROACH

INTRODUCTION

The following paragraphs describe the approach developed for level trend analysis of level monitoring data collected for the inactive LLLW tanks at ORNL. The analysis is designed to identify long-term trends that reflect general increase or decrease in level. A low level of precision (5% of the tank volume) is acceptable for collecting data as an input for this analysis. The inactive LLLW tanks are not in service and are being monitored as part of a continuing surveillance and maintenance program until they have been remediated. If changes in level trends occur, the tanks and monitoring equipment are investigated to determine the cause.

ANALYSIS APPROACH

This statistical approach uses existing equipment regardless of the type because of the low precision required. Tanks that do not have level monitors will have monitors installed if level trend analysis is to be performed.

The objective of the level trend analysis is to determine whether the liquid level in the tank is increasing or decreasing during the period evaluated and to provide an estimate of the rate of change (i.e., the liquid level trend in gallons per day). The trend analysis was performed using linear regression to generate a straight-line estimate of the collected data. The slope of the line represents the liquid level trend.

The statistical nature of the evaluation assumes that a mathematical variation in the estimated slope of the line exists termed "the standard error of the slope estimate." This error was calculated for each data set. From the standard error, the slope of the line was calculated at the 95% confidence boundaries using the "Student T" distribution. The objective was to produce results that indicated a 95% confidence that the slope of the line was positive (i.e., increasing in liquid level) or negative (i.e., decreasing in liquid level).

A period of 90 days was evaluated. The slope of the regression line and the 95% confidence boundaries for the slope were calculated. If the upper and lower 95% confidence boundaries were both positive or both negative, then the results of the level trend analysis reflect a 95% confidence that the direction of the trend has been determined. If the upper 95% confidence boundary was positive and the lower boundary was negative, the results were considered inconclusive. This result can occur when the level monitoring system (equipment and methods) causes scattered data points to be collected. An example calculation is included at the end of this appendix.

Data were selected from the period August 1 through October 31, 1993. These were the latest data available when the evaluation was performed.

LIMITATIONS

Level trend analysis provides an estimate of the trend for only the period evaluated. A period of 90 days was selected as a starting point to provide sufficient time and data points for the analysis. The longer the period evaluated, the more the results are influenced by environmentally induced error, instrument error, and other recurring interruptions. The shorter the time period, the less the results are influenced by the above factors. However, shorter durations of trend analysis reduce the sensitivity of the analysis, and the results may not reflect the direction of the trend at 95% confidence.

The trend analysis indicates a net increase or decrease in the liquid level. Absolute increase or decrease cannot be measured unless the tank is isolated from infiltration of rainwater into the connecting lines and/or through roof penetrations in the tank.

The data used for the analysis are from existing level monitoring equipment and were collected using existing procedures. The equipment and procedures were not designed nor approved for use as a leak detection system. The level monitoring instruments and their associated sensitivity (the smallest measurement that can be reliably made) vary greatly between instrument types and design. These factors may influence the quality of the data, resulting in analyses that generate inaccurate conclusions.

ASSUMPTIONS

In performing the level trend analyses, the following are assumed:

- The level measurement approach uses existing equipment regardless of type. Tanks that do not have level monitors will have monitoring equipment installed if level trend analysis is to be performed.
- The instruments are maintained in operable condition.
- The data have been collected with reasonable diligence.
- The evaluation is relatively insensitive to random error because of the statistical nature of the evaluation.
- The trend analysis indicates a net increase or decrease in the liquid level. Absolute increase or decrease cannot be measured unless the tank is isolated from infiltration of rainwater and/or groundwater into the connecting lines and/or through roof penetrations in the tank.

The approach for calculating the leak rate is to perform linear regression analysis on liquid level monitoring data for a minimum of 30 d. The line has the form of

$$y = a + bx ,$$

where x is the independent variable, time, in days; y is the dependent variable, tank volume, in gallons; a is the y -axis intercept at time $x = 0$; and b is the slope of the regression line. The slope of the line " b " represents the average rate of change in gallons per day.

$$b = SS_{xy}/SS_{xx} ,$$

where

$$SS_{xy} = \Sigma(X_{\text{mean}} - X)(Y_{\text{mean}} - Y),$$

$$SS_{xx} = \Sigma(X_{\text{mean}} - X)^2,$$

$$SS_{yy} = \Sigma(Y_{\text{mean}} - Y)^2,$$

$$X_{\text{mean}} = \Sigma X/n,$$

$$Y_{\text{mean}} = \Sigma Y/n,$$

n = number of observations.

The fit of the line to the data is a least squares fit and is subject to error. The measure of this error is the standard error, S_b . S_b is defined as follows:

where

$$S_b = S_{yx}/\sqrt{SS_{xx}},$$

S_{yx} = the standard deviation,

$$S_{yx} = \pm \sqrt{(SS_{yy} - SS_{xy}^2/SS_{xx}) / (n - 2)} .$$

Substituting S_{yx} in the equation for S_b results in

$$S_b = \frac{\sqrt{[SS_{yy} - (SS_{xy})(SS_{xy})/SS_{xx}]}}{\sqrt{(n - 2)(SS_{xx})}} .$$

EXAMPLE CALCULATION

X	Date (1990)	Y	Syy= Ymean - Y	Sxx= Xmean - X	Sxx x Syy	Square of Sxx	Square of Syy
1	01-Sep	38814	15.2	14.5	220.4	210.25	231.04
2	02-Sep	38826	3.2	13.5	43.2	182.25	10.24
3	03-Sep	38802	27.2	12.5	340.0	156.25	739.84
4	04-Sep	38846	-16.8	11.5	-193.2	132.25	282.24
5	05-Sep	38827	2.2	10.5	23.1	110.25	4.84
6	06-Sep	38812	17.2	9.5	163.4	90.25	295.84
7	07-Sep	38822	7.2	8.5	61.2	72.25	51.84
8	08-Sep	38787	42.2	7.5	316.5	56.25	1780.84
9	09-Sep	38807	22.2	6.5	144.3	42.25	492.84
10	10-Sep	38802	27.2	5.5	149.6	30.25	739.84
11	11-Sep	38836	-6.8	4.5	-30.6	20.25	46.24
12	12-Sep	38825	4.2	3.5	14.7	12.25	17.64
13	13-Sep	38817	12.2	2.5	30.5	6.25	148.84
14	14-Sep	38820	9.2	1.5	13.8	2.25	84.64
15	15-Sep	38800	29.2	0.5	14.6	0.25	852.64
16	16-Sep	38908	-78.8	-0.5	39.4	0.25	6209.44
17	17-Sep	38861	-31.8	-1.5	47.7	2.25	1011.24
18	18-Sep	38881	-51.8	-2.5	129.5	6.25	2683.24
19	19-Sep	38797	32.2	-3.5	-112.7	12.25	1036.84
20	20-Sep	38861	-31.8	-4.5	143.1	20.25	1011.24
21	21-Sep	38838	-8.8	-5.5	48.4	30.25	77.44
22	22-Sep	38861	-31.8	-6.5	206.7	42.25	1011.24
23	23-Sep	38836	-6.8	-7.5	51.0	56.25	46.24
24	24-Sep	38817	12.2	-8.5	-103.7	72.25	148.84
25	25-Sep	38841	-11.8	-9.5	112.1	90.25	139.24
26	26-Sep	38822	7.2	-10.5	-75.6	110.25	51.84
27	27-Sep	38831	-1.8	-11.5	20.7	132.25	3.24
28	28-Sep	38826	3.2	-12.5	-40.0	156.25	10.24
29	29-Sep	38812	17.2	-13.5	-232.2	182.25	295.84
30	30-Sep	38841	-11.8	-14.5	171.1	210.25	139.24
Sum of X = 465		Sum of Y = 1164876		Sums =	SSxy = 1717.0	Sxx = 2247.5	SSyy = 19654.8
Xmean = 15.5		Y mean = 38829.2					

$$X \text{ Coefficient} = \frac{SS_{xy}}{SS_{xx}}$$

$$X \text{ Coefficient} = 1717.0/2247.5$$

$$= 0.76396.$$

Example Calculation (continued)

Standard Error

$$\begin{aligned}
 \text{of Coefficient} &= \text{SQRT of } \frac{SS_{yy} - (SS_{xy})(SS_{xy})/SS_{xx}}{(n - 2)(SS_{xx})} \\
 &= \text{SQRT of } \frac{19654.8 - (1717)(1717)/2247.5}{(30 - 2)(2247.5)} \\
 &= 0.53989.
 \end{aligned}$$

95% Confidence

$$\begin{aligned}
 \text{Interval} &= X \text{ coefficient} \pm t(@0.025) (\text{Standard Error of Coefficient}) \\
 &= 0.76396 \quad -2.04 \times 0.53989 \text{ lower bound} \\
 &\quad \quad \quad +2.04 \times 0.53989 \text{ upper bound} \\
 &= -0.337 \text{ lower bound (gal/d)} \\
 &\quad \quad \quad +1.865 \text{ upper bound (gal/d)}
 \end{aligned}$$

Fig. C.1 Example of plotted data and calculated linear regression line.

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