Designation: D7048 – 04

Standard Guide for
Applying Statistical Methods for Assessment and Corrective Action Environmental Monitoring Programs[1]

This standard is issued under the fixed designation D7048; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The scope and purpose of this guidance is to present a variety of statistical approaches for assessment, compliance and corrective action environmental monitoring programs. Although the methods provided here are appropriate and often optimal for many environmental monitoring problems, they do not preclude use of other statistical approaches that may be equally or even more useful for certain site-specific applications.

1.2 In the following sections, complete details of select statistical procedures used in assessment and corrective action programs for environmental monitoring (soil, ground water, air, surface water, and waste streams) are presented.

1.3 The statistical methodology described in the following sections should be used as guidance. Other methods may also be appropriate based on site-specific conditions or for monitoring situations or media that are not presented in this document.

1.4 This practice offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education, experience and professional judgements. Not all aspects of this practice may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged without consideration of a project's many unique aspects. The word Standard in the title of this document only means that the document has been approved through the ASTM consensus process.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D5092 Practice for Design and Installation of Ground Water Monitoring Wells

D5792 Practice for Generation of Environmental Data Related to Waste Management Activities: Development of Data Quality Objectives

D6250 Practice for Derivation of Decision Point and Confidence Limit for Statistical Testing of Mean Concentration in Waste Management Decisions

D6312 Guide for Developing Appropriate Statistical Approaches for Ground-Water Detection Monitoring Programs

3. Terminology

3.1 *Definitions:*

3.1.1 *assessment monitoring*—investigative monitoring that is initiated after the presence of a contaminant has been detected in ground water above a relevant criterion at one or more locations. The objective of the program is to determine if there is a statistical exceedance of a standard or criteria at a Potential Area of Concern (PAOC) or at the ground water discharging to surface water interface, and/or to quantify the rate and extent of migration of constituents detected in ground water above applicable criteria.

3.1.2 *compliance monitoring*—as specified under 40 CFR 264.99, compliance monitoring is instituted when hazardous constituents have been detected above a relevant criterion at the compliance point during RCRA detection monitoring. Ground-water samples are collected at the compliance point, facility property boundary, and upgradient monitoring wells for analysis of hazardous constituents to determine if they are leaving the regulated unit at statistically significant concentrations above background.

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved May 1, 2004. Published June 2004. DOI: 10.1520/D7048-04.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.3 *corrective action monitoring*—under RCRA, corrective action monitoring is instituted when hazardous constituents from a RCRA regulated unit have been detected at statistically significant concentrations between the compliance point and the downgradient facility property boundary as specified under 40 CFR 264.100. Corrective action monitoring is conducted throughout a corrective action program that is implemented to address ground-water contamination. At non-RCRA sites, corrective action monitoring is conducted throughout the active period of corrective action to determine the progress of remediation and to identify statistically significant trends in ground-water contaminant concentrations.

3.1.4 *detection limit, DL*—the true concentration at which there is a specified level of confidence (for example, 99 % confidence) that the true concentration is greater than zero.

3.1.5 *detection monitoring*—a program of monitoring for the express purpose of determining whether or not there has been a release of a contaminant to ground water. Under RCRA, Detection Monitoring involves collection of ground-water samples from compliance point and upgradient monitoring wells on a semi-annual basis for analysis of hazardous constituents of concern, as specified under 40 CFR 264.98. Results are evaluated to determine if there is a statistically significant exceedance of the ground-water protection criterion and/or background. At non-RCRA sites, monitoring is conducted in a similar manner and results are compared to criteria to determine if there is a statistically significant exceedance.

3.1.6 *direct push sampling*—ground-water sampling conducted with a device that is temporarily pushed into the ground with a hydraulic system or with a hammer. After ground-water sample collection, the device is removed from the ground. Examples include Geoprobe®, Hydropunch® direct push, and environmental soil probe.

3.1.7 *false negative rate*—the rate at which the statistical procedure does not indicate contamination when contamination is present.

3.1.8 *false positive rate*—the rate at which the statistical procedure indates contamination when contamination is not present.

3.1.9 *lognormal distribution*—a frequency distribution whose logarithm follows a normal distribution.

3.1.10 *lower confidence limit, LCL*—a lower limit that has a specified probability (for example, 95 %) of including the true concentration (or other parameter). Taken together with the upper confidence limit, forms a confidence interval that will include the true concentration with confidence level that accounts for both tail areas (for example, 90 %).

3.1.11 *lower prediction limit, LPL*—a statistical estimate of the minimum concentration that will provide a lower bound for the next series of k measurements from that distribution, or the mean of m new measurements for each of k sampling locations, with specified level of confidence (for example, 95 %).

3.1.12 *nonparametric*—a term referring to a statistical technique in which the distribution of the constituent in the population is unknown and is not restricted to be of a specified form.

3.1.13 *nonparametric prediction limit*—the largest (or second largest) of n background samples. The confidence level associated with the nonparametric prediction limit is a function of n, m and k.

3.1.14 *normal distribution*—a frequency distribution whose plot is a continuous, infinite, bell-shaped curve that is symmetrical about its arithmetic mean, mode and median (which are numerically equivalent). The normal distribution has two parameters, the mean and variance.

3.1.15 *outlier*—a measurement that is statistically inconsistent with the distribution of other measurements from which it was drawn.

3.1.16 *parametric*—a term referring to a statistical technique in which the distribution of the constituent in the population is assumed to be known.

3.1.17 *quantification limit, QL*—a lower limit on the concentration at which quantitative determinations of an analyte's concentration in the sample can be reliably made during routine laboratory operating conditions. The QL is typically described quantitatively as the true concentration at which the signal to noise ratio of measured concentration or instrument response is 10:1. The signal to noise ratio is often determined by a percent relative standard deviation of 10 %.

3.1.18 *potential area of concern*—areas with a documented release or likely presence of a hazardous substance that could pose an unacceptable risk to human health or the environment.

3.1.19 *phase I environmental site assessment*—non-intrusive investigation that identifies PAOCs which may require further investigation in subsequent phases of work.

3.1.20 *phase II environmental site assessment, ESI*—intrusive survey to confirm or deny existence of a release into the environment at a PAOC at levels which may adversely impact public health or the environment.

3.1.21 *upper confidence limit, UCL*—an upper limit that has a specified probability (for example, 95 %) of including the true concentration (or other parameter). Taken together with the lower confidence limit, the UCL forms a confidence interval that will include the true concentration with confidence level that accounts for both tail areas.

3.1.22 *upper prediction limit, UPL*—a statistical estimate of the maximum concentration that will not be exceeded by the next series of k measurements from that distribution, or the mean of m new measurements for each of k sampling locations, with specified level of confidence (for example, 95 %) based on a sample of n background measurements.

3.2 *Symbols*:

μ = the true population mean of a constituent

$\bar{x}$ = the sample-based mean or average concentration of a constituent computed from n background measurements which differs from μ because of sampling variability, and other error

σ^2 = the true population variance of a constituent

s^2 = the sample-based variance of a constituent computed from n background measurements

s = the sample-based standard deviation of a constituent computed from n background measurements

$\bar{y}$ = the mean of the natural log transformed data (also the natural log of the geometric mean)

s_y = the standard deviation of the natural log transformed data

n = the number of background (offsite or upgradient) measurements

k = the number of future comparisons for a single monitoring event (for example, the number of downgradient monitoring wells multiplied by the number of constituents to be monitored) for which statistics are to be computed

α = the false positive rate for an individual comparison (that is, one sampling location and constituent)

m = the number of onsite or downgradient measurements used in computing the onsite mean concentration

α^* = the site-wide false positive rate covering all sampling locations and constituents

t = the $100(1 - \alpha)$ percentage point of Student's t-distribution on $n - 1$ degrees of freedom

H_L = the factor developed by Land (1971) (**1**)[3] to obtain the lower $100(\alpha)$ % confidence limit for the mean of a lognormal distribution

H_U = the factor developed by Land (1971) (**1**) to obtain the upper $100(\alpha)$ % confidence limit for the mean of a lognormal distribution

4. Summary of Guide

4.1 The guide is summarized as Figs. 1-7. These figures provides a flow-chart illustrating the steps used in computing the comparisons to regulatory or health based ground-water protection standard (GWPS) in assessment and corrective action environmental monitoring programs.

5. Significance and Use

5.1 The principal use of this standard is in assessment, compliance and corrective action environmental monitoring programs (for example, for any facility that could potentially contaminate ground water). The significance of the guidance is that it presents a statistical method that allows comparison of ground-water data to regulatory and/or health based limits.

5.2 Of course, there is considerable USEPA support for statistical methods applied to detection, assessment and corrective action monitoring programs that can be applied to environmental investigations. For example, the 90 % upper confidence limit (UCL) of the mean is used in SW846 (Chapter 9) for determining if a waste is hazardous. If the UCL is less than the criterion for a particular hazardous waste code, then the waste is not a hazardous waste even if certain individual measurements exceed the criterion. Similarly, in the USEPA Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities Addendum to the Interim Final Guidance (1992) (**2**), confidence intervals for the mean and various upper percentiles of the distribution are advocated for assessment and corrective action. Interestingly, both the 1989 and 1992 USEPA guidance documents (**2, 3**) suggest use of the lower 95 % confidence limit (LCL) as a tool for determining whether a criterion has been exceeded in assessment monitoring. The latest USEPA guidance in this area (that is, the draft USEPA Unified Statistical Guidance) calls for use of the LCL in assessment monitoring and the UCL in corrective action. In this way, corrective action is only triggered if there is a high degree of confidence that the true concentration has exceeded the criterion or standard, whereas corrective action continues until there is a high degree of confidence that the true concentration is below the criterion or standard. This is the general approach adopted in this guide, as well.

5.3 There are several reasons why statistical methods are essential in assessment and corrective action monitoring programs. First, a single measurement indicates very little about the true concentration in the sampling location of interest, and with only one sample there is no way of knowing if the measured concentration is a typical or an extreme value. The objective is to compare the true concentration (or some interval that contains it) to the relevant criterion or standard. Second, in many cases the constituents of interest are naturally occurring (for example, metals) and the naturally existing concentrations may exceed the relevant criteria. In this case, the relevant comparison is to background (for example, off-site soil or upgradient ground water) and not to a fixed criterion. As such, background data must be statistically characterized to obtain a statistical estimate of an upper bound for the naturally occurring concentrations so that it can be confidently determined if onsite concentrations are above background levels. Third, there is often a need to compare numerous potential constituents of concern to criteria or background, at numerous sampling locations. By chance alone there will be exceedances as the number of comparisons becomes large. The statistical approach to this problem can insure that false positive results are minimized.

5.4 Statistical methods for detection monitoring have been well studied in recent years (see Gibbons, 1994a, 1996, USEPA 1992 (**2, 4, 5**) and Practice D6312, formerly PS 64-96 authored by Gibbons, Brown and Cameron, 1996). Although equally important, statistical methods for assessment monitoring, Phase I and II investigations, on-going monitoring and corrective action monitoring have received less attention, (Gibbons and Coleman, 2001) (**6**).

5.5 The guide is summarized in Fig. 1, which provides a flow-chart illustrating the steps in developing a statistical evaluation method for assessment and corrective action programs. Fig. 1 illustrates the various decision points at which the general comparative strategy is selected, and how the statistical methods are to be selected based on site-specific considerations.

6. Procedure

6.1 In the following, the general conceptual and statistical foundations of the sampling program are described. Following this general discussion, media-specific details (that is, soil, ground-water, and waste streams) are provided.

6.1.1 Identify relevant constituents for the specific type of facility, media (for example, soil, ground water etc.) and area of interest. A facility is generally comprised of a series of subunits or "source areas" that may have a distinct set of sampling locations and relevant constituents of concern (referred to as a PAOC). The subunit may consist of a single sampling point or collection of sampling points. In some cases,

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

the entire site may comprise the area of interest and all sampling locations are considered jointly. The boundaries of the "source area" or "decision unit" should be defined. In all cases, the owner/operator should select the smallest possible list of constituents that adequately characterize the source area in terms of historical use.

6.1.2 For each constituent obtain the appropriate regulatory criterion or standard (for example, maximum contaminant level, MCL) if one is available. The appropriate criterion or standard should be selected based on relevant pathways (for example, direct contact, ingestion, inhalation) and appropriate land use criteria (for example, commercial, industrial, residential).

6.1.3 For each constituent which may have a background concentration higher than the relevant health based criterion, set "background" to the upper 95 % confidence prediction limit (UPL) as described in the Technical Details section. The prediction limits are computed from all available data collected from background, or outside source areas that are unlikely to be contaminated, upstream, upwind or upgradient locations only. Henceforth, background refers to any of these types of offsite sources. The background data are first screened for outliers and then tested for normality and lognormality (see Technical Details section).

6.1.3.1 If the test of normality cannot be rejected (for example, at the 95 % confidence level), background is equal to the 95 % confidence normal prediction limit.

6.1.3.2 If the test of normality is rejected but the test of lognormality cannot be rejected, background is equal to the 95 % confidence lognormal prediction limit.

6.1.3.3 If the data are neither normal nor lognormal, or the detection frequency is less than 50 %, background is the nonparametric prediction limit. When we are interested in a single potentially impacted measurement, normal, lognormal, and nonparametric prediction limits are identical with respect to the parameter being compared (that is, an individual measurement). However, when the comparison to background is for an onsite/downgradient mean concentration, they differ in that the nonparametric prediction limit is for the median whereas the parametric prediction limits are for the mean. This limitation is unavoidable, so whenever possible, parametric prediction limits should be used. Note that, if the detection frequency is zero, background is set equal to the appropriate Quantification Limit (QL) for that constituent which is the lowest concentration that can be reliably determined within specified limits of precision and accuracy by the indicated methods under routine laboratory operating conditions.

6.1.3.4 If the background is greater than the relevant criterion or standard or if there is no criterion or standard, then comparisons are made to the background prediction limit. If the criterion is greater than background, then compare the appropriate confidence limit to the criterion. Note that if nothing is detected in background, then the background is the QL. If the criterion is lower than the QL, then the criterion is the QL.

6.1.4 The number of samples taken depends on whether comparison is to background or a criterion and whether comparisons are made at individual locations or by pooling samples within a source area. If comparison is to background, collect a minimum of one sample from each source area or sampling location. If comparison is to a criterion (that is, the criterion is greater than background), and interest is in a single location, a minimum of four independent samples from each sampling location will be required. If the comparison is to a criterion for an entire source area, a minimum of one sample from each of four sampling locations within the source area are required. If there are fewer than four sampling locations within a given source area, then the total number of measurements from the source area must be four or more (for example, two sampling locations each with two independent samples). Note that these sample sizes represent absolute minimums necessary for the statistical computations. In general, a larger number of samples will be required to obtain a representative sample of the population of interest.

6.1.5 If comparison is to a criterion or standard there are two general approaches. In assessment, monitoring where interest is in determining if a criterion has been exceeded, compare the 95 % lower confidence limit (LCL) for the mean of at least four samples from a single location, source area or the entire site to the relevant criterion. In corrective action sampling and monitoring, where interest is in demonstrating that the onsite concentration is lower than the criterion, compare the 95 % upper confidence limit (UCL) for the mean of at least four samples from a single location, source area or the entire site to the relevant criterion.

6.1.6 If the background prediction limit is larger than the relevant criterion, then do one of the following: *(1)* for a single measurement obtained from an individual location, compare this individual measurement to the background prediction limit for the next single measurement from each of k locations, *(2)* for multiple measurements obtained from a given source area or the entire site, compare the mean of the measurements to the background prediction limit for the mean of m measurements based on the best fitting statistical distribution or nonparametric alternative.

6.1.7 Note that if the background UPL and the regulatory criterion are quite similar, it may be possible for the downgradient mean to exceed the background UPL but the LCL for the downgradient mean may still be less than the regulatory criterion. In this case, an exceedance is not determined. Fig. 1 presents a decision tree that can be used to step through the statistical analysis approach.

6.1.8 In the following sections, application to specific media and types of sampling and monitoring programs is described. The areas covered include soil, ground water and waste stream sampling; however, similar approaches can be taken for air and surface water monitoring.

6.2 *Soils—Evaluation of Individual Source Areas (PAOCs)*:

6.2.1 Collect soil samples from the surface to the groundwater table at appropriate intervals in the most likely contaminated location in the source area and screen soils to determine the interval with highest concentration(s).

6.2.2 At a minimum of three other nearby borings located in the same source area, collect one sample in the same vertical interval (geologic profile) as the previously identified highest concentration interval (that is, the first, boring in the interval of highest screening concentration).

6.2.3 Send the samples from the vertical interval in all four borings to the lab for analysis. As in 6.1.5 these intervals and sample sizes represent a minimum required for the statistical computations and larger numbers will typically be required in practice to insure adequate characterization of the area of interest.

6.2.4 Compute the 95 % LCL (assessment) or UCL (corrective action) for the mean of the *m* results to determine if the particular PAOC exceeds the regulatory criterion.

6.2.5 If an exceedance is found, assess whether it is naturally occurring (for example, metals) by obtaining a minimum of eight independent background samples (that is, offsite soil samples from the same interval) and compute the 95 % confidence upper prediction limit (UPL) for the mean of the *m* onsite/downgradient samples, and compare the UPL to the observed mean at each PAOC. An exceedance is determined only if the PAOC mean concentration exceeds both the regulatory criterion and the background UPL. Figs. 2 and 3 illustrate the sampling location approaches for this scenario. Eight samples are required because for any fewer, uncertainty in the background mean and variance will lead to unacceptably large UPLs.

6.3 *Soils—Area-Wide or Site-Wide Evaluations*:

6.3.1 Collect soil samples to be representative of the entire spatial distribution of constituents of concern (a minimum of four samples).

6.3.2 Compute the 95 % LCL (assessment) or UCL (corrective action) for the mean of all onsite samples and determine if the area or site as a whole exceeds the regulatory criterion.

6.3.3 If an exceedance is found, insure that it is not naturally occurring by obtaining a minimum of eight independent background samples (that is, offsite soil samples from the same stratigraphic unit) and compute the 95 % confidence UPL.

6.3.4 If the level of hazardous substance concentrations at the site is relatively homogeneous, compute the UPL for the mean of the *m* onsite measurements and compare the observed mean to the UPL.

6.3.5 If the level of hazardous substance concentrations at the site is heterogeneous, compute the UPL for the *m*, individual onsite measurements and compare each measurement to the UPL.

6.3.6 An exceedance is determined only if the area or site-wide mean concentration exceeds both the regulatory criterion and the background UPL.

6.3.7 If an exceedance is found, it is possible to exclude PAOCs one at a time until the Site minus the selected PAOCs does not exceed criterion. This method may be appropriate only when sufficient sampling of the PAOC has been conducted as part of the site or area-wide evaluation. Fig. 4 illustrates the sampling location approach for this scenario.

6.4 *Ground Water—Aquifer*:

6.4.1 As in the soil sampling above, if soil sampling and screening or prior ground-water monitoring indicates that ground water may be impacted, then one ground-water sample will be obtained in each of a minimum of four borings using a direct push methodology or from existing ground-water monitoring wells and results will be evaluated statistically to determine if the entire PAOC requires additional assessment. The general methodology previously described for Soil PAOCs can be used here as well, as illustrated in Figs. 2 and 3. To characterize background, a minimum of eight independent, samples must be collected. This can be four samples from each of two locations, two samples from four locations, or one sample from each of eight locations. A minimum of two locations are required. Statistical independence implies that the same ground water is not sampled repeatedly and that the background data are representative of the same temporal variation as are the onsite data. This precludes establishing background in the winter and comparing onsite measurements obtained in the summer. As in previous sections, these sampling requirements represents minimum requirements of the statistical procedures and the actual numbers of samples and time frames should be based on geologic criteria (for example, see "Guide for Developing Conceptual Models for Contaminated Sites").

6.4.2 Fig. 5 illustrates another approach for evaluating groundwater at a site. Sampling locations are set up as shown and four independent samples are collected from background locations GW-7 and GW-8 (that is, eight total background samples). If the background UPL exceeds the appropriate regulatory criterion, then the mean from downgradient samples GW-1 through GW-6 is compared to the background UPL to determine if an exceedance exists. If the background UPL is less than the appropriate regulatory criterion, then the downgradient LCL should be compared to the criterion. Another modification to this approach is if an exceedance exists, the *m* downgradient samples can be compared individually to background to determine if the impact is restricted to a subset of monitoring locations. As previously discussed, if the background UPL and the regulatory criterion are quite similar, it may be possible for the downgradient mean to exceed the background UPL but the LCL for the downgradient mean may still be less than the regulatory criterion. In this case, an exceedance is not determined. This applies equally to all media.

6.5 *Ground Water—Ground-water Surface Water Interface (GSI)*:

6.5.1 Characterize background. As previously indicated, background is established by obtaining at least eight independent, samples from a minimum of two locations (that is, to incorporate spatial variability). The background limit is established by computing the UPL from these data (that is, a minimum of eight background samples).

6.5.2 If the only comparison is to background, obtain a single sample from each GSI sampling location (that is, one sample from each compliance point) and compare to the appropriate upgradient UPL.

6.5.3 If comparison is to regulatory criteria, obtain a minimum of four independent samples from each GSI sampling location (that is, four samples from each compliance point) and compare the LCL (assessment) or the UCL (corrective action) to the regulatory criterion. If the upgradient UPL is greater than the regulatory criterion for a particular constituent, compare each GSI sampling location to background.

6.5.4 Depending on the application, each GSI sampling location can be compared to background or the appropriate regulatory criterion individually or as a group. Fig. 6 illustrates the sampling strategy for this scenario.

6.6 *Ground Water—Long-term Monitoring*:

6.6.1 When sampling for long-term monitoring of a plume, compute the 95 % normal UCL for the most recent four measurements in each sampling location and compare to the relevant regulatory criteria (see 7.2.1.4).

6.6.2 Compute Sen's test (**8**) to determine if there are increasing or decreasing trends (at a 95 % confidence level) at each sampling location (need a minimum of 8 measurements per well).

6.7 *Ground Water—Natural Attenuation Evaluation*:

6.7.1 Here temporal changes are considered in the mean of all wells within a plume or wells in the relatively higher concentration area of a plume.

6.7.2 Obtain a minimum of eight independent samples (for example, one from each of eight monitoring wells or two from each of four monitoring wells). This should be done either for all wells within the plume or the relatively higher concentration area of the plume. Note that if there is seasonal variability in analyte concentrations, four quarterly samples within a period of no less than one year should be obtained from each sampling location.

6.7.3 Compute the 95 % confidence lower prediction limit (LPL) and the UPL for the mean of all wells in the plume or all wells within the relatively higher concentration area. For example, if there are 8 wells, compute the LPL and UPL for the mean of the next 8 samples.

6.7.4 If the actual mean exceeds the UPL, there is evidence that the plume is getting significantly worse.

6.7.5 If the actual mean is less than the LPL, there is evidence that the plume is getting significantly better (that is, natural attenuation is occurring).

6.7.6 Compute Sen's test to determine if there are increasing or decreasing trends (at a 95 % confidence level) at each sampling location (need a minimum of 8 measurements per well).

6.8 *Waste Stream Sampling*:

6.8.1 To determine if a particular waste stream is hazardous, obtain a series of $n \geq 4$ representative samples from the waste stream for all relevant characteristically hazardous criteria.

6.8.2 Compute the appropriate 90 % UCL for the mean concentration.

6.8.3 Note that the 90 % confidence level is used based on guidance provided in SW846 Chapter 9 (US EPA).

6.8.4 If the 90 % UCL is less than the regulatory criterion or standard, the waste stream is not hazardous.

7. Technical Approach

7.1 The purpose of this section is to provide a description of the specific statistical methods to be used in assessment and corrective action sampling programs (see Gibbons and Coleman, 2001) (**6**).

7.2 *Comparison to a Regulatory Criterion or Standard*:

7.2.1 *Confidence Limits for the Mean or Median Concentration*:

7.2.1.1 The 95 % normal LCL (assessment sampling and monitoring) or 95 % normal UCL (corrective action) for the mean of at least four measurements is computed and compared to the Regulatory Criterion or Standard.

7.2.1.2 The 95 % normal LCL, for one-tailed (assessment sampling and monitoring) for the mean of m measurements is computed as:

$$\bar{x} - t_{[m-1, 0.95]} \frac{s}{\sqrt{m}} \quad (1)$$

7.2.1.3 The 95 % normal UCL (corrective action) for the mean of m measurements is computed as:

$$\bar{x} + t_{[m-1, 0.95]} \frac{s}{\sqrt{m}} \quad (2)$$

7.2.1.4 If $m < 8$, nondetects should be replaced either by the reported measured concentration (if available) or one-half of the QL since with fewer than eight measurements, more sophisticated statistical adjustments are not appropriate. Note that no direct comparison between measured concentrations below the QL and a regulatory standard should be made. Similarly, a normal UCL is used because seven or fewer samples are insufficient to confidently determine distributional form of the data. Use of a lognormal limit with small samples can result in extreme limit estimates, therefore default to normality for $m < 8$.

7.2.1.5 If $m \geq 8$, use Aitchison's (1955) (**9**) method to adjust for nondetects and test for normality and lognormality of the data using the single group or multiple group version of the Shapiro-Wilk test (see 7.3.2.2 for details). The multiple group version of the Shapiro-Wilk test is used when there are multiple measurements from multiple onsite locations (use 95 % confidence level). Note that alternatives such as Cohen's (1961) method can be used, however the reporting limit must be constant for each constituent, which is rarely the case.

7.2.1.6 If $m \geq 8$, and the data are neither normally nor lognormally distributed, compute the 95 % nonparametric LCL or UCL for the median of m, samples (see Hahn and Meeker (1991) section 5.2 (**10**), and Gibbons and Coleman (2001) (**6**)). Alternatively, if the data are lognormally distributed, compute a lognormal LCL or UCL for the mean (see Land, 1971) (**1**). The $(1 - \alpha)$ 100 % lognormal UCL for the mean is:

$$\exp\left(\bar{y} + 0.5 s_y + \frac{H_{1-\alpha} s_y}{\sqrt{m-1}}\right) \quad (3)$$

The $(1 - \alpha)$ 100 % lognormal LCL for the mean is:

$$\exp\left(\bar{y} + 0.5 s_y + \frac{H_{\alpha} s_y}{\sqrt{m-1}}\right) \quad (4)$$

In general, the LCL or UCL for the mean should be used except in the nonparametric case where it is not defined. In addition, caution should be taken using Land's method in that it is not robust to departures from lognormality.

7.2.1.7 The factors H are given by Land (1975) (**11**) and $\bar{y}$ and s_y are the mean and standard deviation of the natural log transformed data (that is, $y = \log_e(\bar{x})$). The lognormal LCL or UCL for the median is simply the exponentiated result of