ENGINEERING-PDH.com
ONLINE CONTINUING EDUCATION

ENVIRONMENTAL RADIOLOGICAL MONOTORING & SURVEILLANCE - VOL 3 OF 3

Main Category:	Nuclear Engineering
Sub Category:	-
Course #:	NUC-120
Course Content:	46 pgs
PDH/CE Hours:	4

OFFICIAL COURSE/EXAM

(SEE INSTRUCTIONS ON NEXT PAGE)

WWW.ENGINEERING-PDH.COM
TOLL FREE (US & CA): 1-833-ENGR-PDH (1-833-364-7734)
SUPPORT@ENGINEERING-PDH.COM

NUC-120 EXAM PREVIEW

- TAKE EXAM! -

Instructions:

- At your convenience and own pace, review the course material below. When ready, click "Take Exam!" above to complete the live graded exam. (Note it may take a few seconds for the link to pull up the exam.) You will be able to re-take the exam as many times as needed to pass.
- Upon a satisfactory completion of the course exam, which is a score of 70% or better, you will be provided with your course completion certificate. Be sure to download and print your certificates to keep for your records.

Exam Preview:

1. According to the reference material, there are three essential phases associated with the data life cycle; data verification, data validation, and data quality assessment.
    a. True
    b. False
2. Which of the following supporting documentation is responsible for guidance on determining whether the type, quantity and quality of data needed to support decisions have been achieved?
    a. EPA-505-F-03-001
    b. EPA/600/R-96/084
    c. EPA 530/R-09-007
    d. DTIC ADA 395303
3. As with any parametric test, Kruskal-Wallis test can be performed regardless of the group distribution or lack thereof although the test assumes the population distributions are identical.
    a. True
    b. False
4. Using TABLE 8-3: Examples of Statistical Tests for Multiple Hypothesis Goals, which of the following non-parametric model/test corresponds to a hypothesis whose goal is compare three or more paired groups?
    a. Wilcoxon rank sum (Mann-Whitney)
    b. Paired t test
    c. Friedman Test
    d. Regression

5. Which of the following models/tests matches the description: a nonparametric test for detecting trends, is based on a measure of the correlation of the sample values with time; may be used to test for a significant trend in any time series of four or more independent data points?
    a. Kruskal-Wallis Test
    b. Theil-Sen Slope Estimator
    c. Sign Test
    d. Man-Kendall Test
6. Exposure pathways are the routes of radiation exposure to human beings or biota. They generally include external exposure to penetrating radiation, inhalation, and ingestion.
    a. True
    b. False
7. The RESRAD modeling code was developed by DOE and the NRC to support the evaluation of radiation doses and risks from residual radioactive materials in soil at sites undergoing remediation. Which of the following Codes corresponds to designed to facilitate the implementation of operational guidelines and protective action guides for radiological or nuclear incidents?
    a. RESRAD Recycle
    b. RESRAD RDD
    c. RESRAD Offsite
    d. RESRAD Build
8. According to the reference material, as a general rule, the WRS test can be used with up to __ percent non-detect measurements present in either population sample.
    a. 40
    b. 50
    c. 60
    d. 70
9. Using TABLE 9-1: Potential Pathways to Be Considered in Environmental Pathway Analyses, which of the following exposure category corresponds to this environmental pathway: Grazing Animals.
    a. External
    b. Ingestion of drinking water
    c. Ingestion of soil
    d. Ingestion of terrestrial foods
10. According to the reference material, inappropriate prediction occurs when sophisticated models and detailed analyses are used too late in the assessment process.
    a. True
    b. False

TABLE OF CONTENTS

8 DATA ANALYSIS AND STATISTICAL TREATMENT

Good data analyses and statistical treatment practices are essential for the production of quality results from the environmental monitoring program required by DOE O 458.1. The goals for analyzing effluent monitoring and environmental surveillance data should include:

- Estimate radionuclide concentrations along with an estimated uncertainty for each sample or measurement;
- Compare the estimated radionuclide concentrations at each sampling and/or measurement point to previous concentration estimates at that point to identify changes or inconsistencies in radionuclide levels;
- Compare the radionuclide concentrations at each sampling and/or measurement point to the established limit(s), or concentrations related to the applicable dose limit, for those radionuclides; and
- Compare radionuclide concentrations at single sampling and/or measurement points or groups of points to those at control/background/baseline or other relevant points and evaluate the reliability of those comparisons.

The characteristics of effluent and environmental data should be considered when selecting the statistical techniques used to support the concentration estimates, to determine their corresponding measures of reliability, and to compare radionuclide data between sampling and/or measurement points, periods, and regulatory concentrations. For example, the statistical techniques selected may require establishing the underlying data distribution characteristic as being either symmetric or asymmetric. As further discussed in this chapter, conclusions reached from the data quality assessment (DQA) phase—including statistical evaluations and summaries as well the results of hypothesis tests when applicable—depend on the quality of the data themselves, as described in Chapter 7.

This chapter examines the design and implementation of data analysis and statistical treatment for the data obtained from the implementation of environmental monitoring programs. A “lines of inquiry” approach is provided in Appendix B to verify compliance with the appropriate requirements, evaluate the effectiveness of the data analysis and statistical treatments, and promote continuous improvements based on the aforementioned goals.

8.1 Key Requirements and Supporting Documents

The following directives and guidance documents apply to data analysis and statistical treatment of radiological effluent monitoring or environmental surveillance data:

DOE O 458.1, *Radiation Protection of the Public and the Environment*, requires demonstration of compliance with the public dose limit using a combination of documented surveys, measurements, and calculations to evaluate potential doses.

MARLAP is a multi-agency consensus document developed to provide guidance for project planners, managers, and laboratory personnel to ensure that radioanalytical laboratory data meet a project's or program's data requirements. MARLAP offers a framework for national consistency in the form of a performance-based, graded approach. Many of the data analyses and statistical techniques described in MARLAP for laboratory analyses are also applicable to the evaluation of effluent monitoring and environmental data.

Several multi-agency and EPA unified guidance and quality assurance documents provide accepted/recommended DQA processes for data analyses. These documents include:

Intergovernmental Data Quality Task Force, *Uniform Federal Policy for Implementing Environmental Quality Systems - Evaluating, Assessing, and Documenting Environmental Data Collection/Use and Technology Programs,* provides recommendations and guidelines for documentation and implementation of acceptable Quality Systems for Federal agencies. (Publication Numbers: EPA-505-F-03-001, DTIC ADA 395303, DOE/EH-0667).

Guidance for Data Quality Assessment, Practical Methods for Data Analysis, EPA QA/G-9, was developed to assist in the determining whether the type, quantity and quality of data needed to support decisions have been achieved. (EPA/600/R-96/084)

Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities, Unified Guidance, provides a suggested framework, recommendations for the statistical analysis of groundwater monitoring data at RCRA facility units to determine whether groundwater has been impacted by a hazardous constituent release, and provides examples and background information that will aid in successfully conducting the required statistical analyses. (EPA 530/R-09-007)

8.2 Data Verification and Validation

There are three essential phases associated with the data life cycle; data verification, data validation, and data quality assessment. Once data packages are received from the field,

laboratory, or other source, an initial assessment should be performed to ensure that the data quality meets the project objectives and as well as the quality assurance project plan requirements. For example, these parameters might include:

- Data verification: Conducted so as to provide an independent assessment of QC checks, calibrations, transcription reviews, etc. to identify mistakes that would invalidate or limit use of the data.
- Data validation: Confirms the sample collection and handling were performed in accordance with procedures with any deviations documented. Field observations which could invalidate or qualify the results include: (1) insufficient sample volume; (2) torn filters; and (3) mechanical malfunctions of sampling equipment. Validation confirms that the required number of samples and types of data were collected in accordance with the sampling/monitoring plan; confirms the usability of the data for the intended end use via validation of analyses performed and data reduction and reporting; and ensures requirements were met such as detection limits, QC measurements, impacts of qualifiers, etc.
- Preliminary data assessment: Performed to evaluate the structure of the data; identify patterns, relationships, and/or the presence of anomalies; assess the basic statistical quantities including the population mean, standard deviation, median, and range; and the initial comparisons with an action level. Data may also be graphed or plotted.

The initial data quality assessment is to evaluate the field collection and laboratory information. The field documentation review is conducted to identify sample collection issues encountered that would invalidate or limit use of the data. Field observations which could invalidate the sample result include: (1) insufficient sample volume; (2) torn filters; and (3) mechanical malfunctions of sampling equipment, deviations to procedural requirements, cross contamination, etc. The laboratory report case narrative is reviewed. The case narrative should provide a summary of the following information: the sample condition upon receipt—ensuring containers were intact, date/time of receipt, acceptable temperature (when required), sample screening results, condition of custody seals, chain-of-custody documentation, etc.—a narrative of the sampling handling, preparation, and analyses and any issues encountered; and acceptability of the quality control/quality assurance processes for sample preparation and analyses.

The initial laboratory analytical report review ensures all requested analytical results were reported for each sample together with the measurement uncertainty. The review also verifies

that the reported detection limits satisfied project requirements. Additionally, the quality control/quality assurance results are reviewed. Quality control samples may include field blanks, laboratory blanks, duplicates, matrix spikes, or other quality assurance project plan requirements. The laboratory report should include a qualification flag for any identified data quality issues.

Data that pass initial screening are further evaluated prior to reporting. Databases may be used to record analytical data and maintain the data in a readily available and retrievable format. Backup systems or protocols should also be implemented to minimize potential losses of data. Comments on the quality of the samples and/or abnormal conditions should be recorded appropriately and should accompany the reported results. In addition to the data collected during the regular sampling program, logs of events that could have affected analytical analyses should be documented.

8.3 Preliminary Data Assessment

Once data validation and verification are completed, a preliminary data assessment is performed. The goal of the initial assessment is to determine the structure of the data—i.e., normal distribution, skewness, etc.—identify relationships/associations, trends or patterns between sample points/variables or sampling events; identify anomalies; and lastly selecting the appropriate statistical tests for decision making.

8.3.1 Basic Statistical Quantities

The data quality assessment will include development of summary statistics. Descriptive statistical parameters associated with the data sets will generally include the number of observations, data range, mean, median, variance, standard deviation, and coefficient of variation. Other parameters beyond the basic summary statistics might include a measure of the relative standing of the data to the sampled population and/or the confidence interval or upper confidence level of the mean when applicable. Each data point should be compared to previously obtained data to help identify unusual measurements that may require investigation or further statistical evaluations. The reported results should be assessed in terms of statistical significance with respect to sample locations, reported releases, laboratory analytical uncertainties, meteorological data, and other events (e.g., local and infrequent worldwide events) that could potentially affect the environment at the DOE.

8.3.2 Graphical Reviews

Graphing and/or plotting the data allows the data user to visually identify patterns or trends that may not be apparent when reviewing numerical values alone. A further advantage is that the graphical presentation in many cases may be used to summarize and present the data when incorporating into monitoring reports or presenting the information to stakeholders. Common methods and uses for graphing and plotting data are:

- Histograms for assessing data symmetry and variability, and may be applied to spatial or temporal measurements. Additional information on the use of histograms is provided in Section 8.4.3.
- Ranked Data or Quantile Plots also provide a graphical data representation useful for assessing data density, symmetry, and skewness; however, unlike histograms each data point is plotted. Quantile-Quantile plots pair two data sets, for instance monitoring event data as compared to normal probability plot or a plot of background data.
- Posting Plots are useful for assessing spatial relationships where the measurement/sample location is replaced by the respective data value.
- Other plots that may be used for various applications are Stem and Leaf Plots (a simple form of a histogram/frequency chart), Box and Whisker Plots which show a schematic of the basic statistics, and Scatter Plots for paired observations or two or more variables measured together.

8.3.3 Data Variability

The observed variability of an analytical value, for example within repeated measurements of a sample, will be a function of the bias and precision of the sample acquisition procedures/methods and the analytical methods. In other words, uncertainty in the estimated value of the parameter of interest is introduced by bias (systematic errors in the sampling or analytical preparation processes) and precision (random errors) that will ultimately determine the overall accuracy of a result, or deviation from known/actual value. Ultimately, increased uncertainty in the individual data points that may be used to describe a population will be propagated as increased uncertainty in the population descriptors. Careful design and execution of the monitoring program can substantially improve the quality of the radiological effluent monitoring and environmental surveillance results by minimizing the potential for systematic errors during sample collection, handling, and processing steps.

Potential sources of variability in effluent monitoring data, in addition to natural variability of any background parameters, are listed in Table 8-1. These sources can be divided into three categories: environmental, sampling, and recording. The analyses performed to determine and reduce the sources of variability should consider the relative importance of these sources with respect to the actual conditions at the sampling and/or measurement point.

Based on previous site monitoring and surveillance experience, an estimate of an acceptable relative percent for the data uncertainty should be used to develop data analysis and handling strategies for radiological effluent monitoring and environmental surveillance programs. These strategies should then be re-evaluated periodically (and after significant modification to site conditions) to determine whether they are adequate for the present site conditions.

TABLE 8-1: Variability in Effluent Monitoring Data (adapted from DOE 1981)

Category	Source	Examples
Environmental	Space	Distance from emission source, elevation, heterogeneous dispersion of material or differences in background radiation at various locations.
	Time	Variation in rates of emissions, variation in rates of dispersion or variation in cosmic background radiation throughout the year.
	Space × Time	Non-stationary differences between sampling stations over time
Sampling	Sample Collection	Non-representative sampling, inconsistent sampling techniques, sampling equipment failure
	Sample Handling	Chemical reactions, non-uniform storage conditions, container effects
	Sample Processing	Volume or weight measurement errors, insufficient sample mixing, non-representative sub-sampling
	Measurement	Calibration errors, instrument errors, readout errors
	Cross-Contamination	Residual contamination of containers and work areas, imperfect sealing of containers for transport, surface contamination from transport, separation of high- and low-activity samples, decontamination practices
Recording	Data Recording and Transfer	Errors in data entry, errors in transfer of data from laboratory records to electronic formats

8.4 Data Distribution Evaluation

The planning phase of the data life cycle may include an assumption of the expected data distribution based on historical knowledge, relative to the population. This historical knowledge or estimation of the distribution is needed when determining the required number of samples, determining sample locations, and planning for data assessments when the sample data will be used to make a decision regarding the population. Required decisions may include an estimate of the population mean, a determination as to whether a trend exists or data demonstrate random variability, a conclusion that an action level threshold has been exceeded, and/or to provide an answer to other principle study question(s). Once data are available, this evaluation will determine whether data are consistent with the initial underlying assumption, and therefore validate the use of the proposed statistical test(s). Otherwise, different statistical procedures may be necessary.

The distribution evaluations include determining if the distribution is symmetric or asymmetric. Outliers may exist in either case and information on symmetry can be obtained based on whether the outliers exist on both tails of the distribution or result in a left- or right-skewed distribution. For environmental data, normal distributions—where the data tend towards a central value and positive and negative deviations from this value are equally likely—are common with background populations. Lognormal distributions will have outliers that cause a right-skewed distribution if there are elevated concentrations of contaminants or there have been impulses of the analytes of interest during the monitoring period. The number of samples collected will also impact the ability to assume an underlying distribution. As sample size increases, under certain conditions, the probability of the results approximating a normal distribution increases based on the central limit theorem.

8.4.1 Measures of Central Tendency

A measure of central tendency is a single value calculated from the sample data that attempts to describe the central position of the population. The appropriate measure of central tendency depends on the characteristics of the probability distribution of the data collected and the underlying assumptions of the population. For normally distributed data with only a small number of extreme values, the arithmetic mean is the appropriate estimator of central tendency. The median is less sensitive to extreme values and should be used as a measure of the central tendency when a dataset contains large numbers of extreme values and/or skewed data. Because extreme values may routinely be present in environmental data due to anthropogenic

sources, site releases, or contamination, the median many times will be the distribution descriptor evaluated via hypothesis tests discussed in this chapter. The mode may also be used as a measure of central tendency. The mode is defined as the value of the dataset that occurs most often.

The use of a “trimmed” mean (the average of the dataset after a specified percentage of the upper and lower data values has been removed) may reduce the influence of extreme values when they occur on both tails of the distribution. However, application of a trimmed mean is discouraged without sufficient technical justification to exclude data from the set (an attempt to reduce bias). The necessity of using the trimmed mean occurs most often when the data either include less than values, which represent results below the detection limit, or to guard against unexplainable extreme outlier data in symmetric distributions (Gilbert 1987). The inclusion of less than values can be avoided by reporting actual values or other means such as those methods discussed in this chapter.

The geometric mean may be a better measure of central tendency when: (1) the data are presented on a multiplicative scale (e.g., logarithmic); (2) the values in the dataset differ by orders of magnitude; and/or (3) the distribution is lognormal.

8.4.2 Measures of Dispersion

Measures of dispersion describe the spread or variability of the data. Measures of dispersion include the range, quantiles, standard deviation, and variance. The range is the difference between the maximum and minimum data values. Quantiles, which are similar to percentiles, divide the data into fractions (e.g., the 25^{th}, 50^{th}, and 75^{th} quantiles). The variance of a sample is determined by sum of the squared differences of each data point from the arithmetic mean (in the numerator) divided by the number of data points minus one. The standard deviation is calculated as the square root of the variance.

For data with substantial numbers of extreme values, other measures should be used to estimate the dispersion around the central value. For example, the inter-quartile range (the range of data between the 25^{th} and 75^{th} percentiles) and the median absolute deviation (the median of the differences between each data point and the indicator of central tendency) are also acceptable measures.

8.4.3 Distribution Analyses

Dependent upon the planned statistical assessments or tests that will be used for decision making, data or transformed data may need to be tested for normality before any statistical approaches are evaluated and implemented. The testing requirement will generally be determined based on the use of parametric vs. non-parametric statistics, where non-parametric tests do not require the assumption of a normal distribution. Acceptable methods to assess normality include:

a) Histogram

In a histogram, the frequency of data is determined and the dataset is subsequently arranged in bins containing a specified range. A plot of the bins and the number of occurrences is created to form a probability of distribution. The preparation of a histogram should include considerations for optimizing the number of bins. Guidance on optimizing histogram bins is provided in NUREG-1505. Once created, a visual inspection of the histogram should reveal whether the dataset is normal (or not) and belongs to a single group with a symmetrical distribution around a mean value, i.e., a "bell-shaped curve". However, histograms should be used carefully as the determination of the degree of symmetry is interpreted in a subjective manner.

b) Chi-Square (χ^2) Test

The chi-square test can be performed when parameters of the distribution are either known or unknown. The chi-square test is a hypothesis verification test; that is, the assumed hypothesis is that the dataset is normally distributed.

When the mean, $\bar{x}$, and variance, σ^2, are known, the χ^2 can be defined as:

$$\chi^2 = \sum_{i=1}^{n} \frac{(observed\ count - expected\ count)^2}{expected\ count}$$

The χ^2 is then compared to a critical value based on the statistical confidence level for assigned Type I error (α) and the *n-1* degrees of freedom of the dataset. If the calculated χ^2 exceeds the critical value, the hypothesis is rejected and the data distribution is assumed to deviate from normality.

NUREG-1475, Revision 1, *Applying Statistics* (NRC 2011), provides a modified chi-square test when the mean and variance are unknown.

c) Shapiro-Wilk (W-) Test

The most widely used test of normality is the Shapiro-Wilk W-Test (Shapiro and Wilk 1965). The Shapiro-Wilk W-Test is the preferred test of normality because of its statistical power properties as compared to a wide range of alternative tests (Shapiro et al. 1968). If the W statistic is significant, for example when the p-value is less than a typical alpha level of 0.05 ($p < 0.05$,) then the hypothesis that the distribution is normal should be rejected.

Graphical depictions of the data should be a component of any evaluation of normality. Figure 8-3 depicts a graphical histogram along with the results of the Shapiro-Wilk W-Test. The data used for the illustration are comprised of five years of weekly gross beta measurements taken from 1997 to 2001 at the Arco air monitoring location near the perimeter of the Idaho National Laboratory. In the depicted example, the W statistic is highly significant ($p < 0.0001$), indicating that the data are not normally distributed. The histogram shows that the data are asymmetrical with right skewness. This suggests that the data may be lognormally distributed. The Shapiro-Wilk W-Test can be used to test this distribution by taking the natural logarithms of each measurement and calculating the W statistic. Figure 8-4 presents this test of lognormality. The W statistic is not significant ($p = 0.80235$), indicating that the data appear to be lognormal.

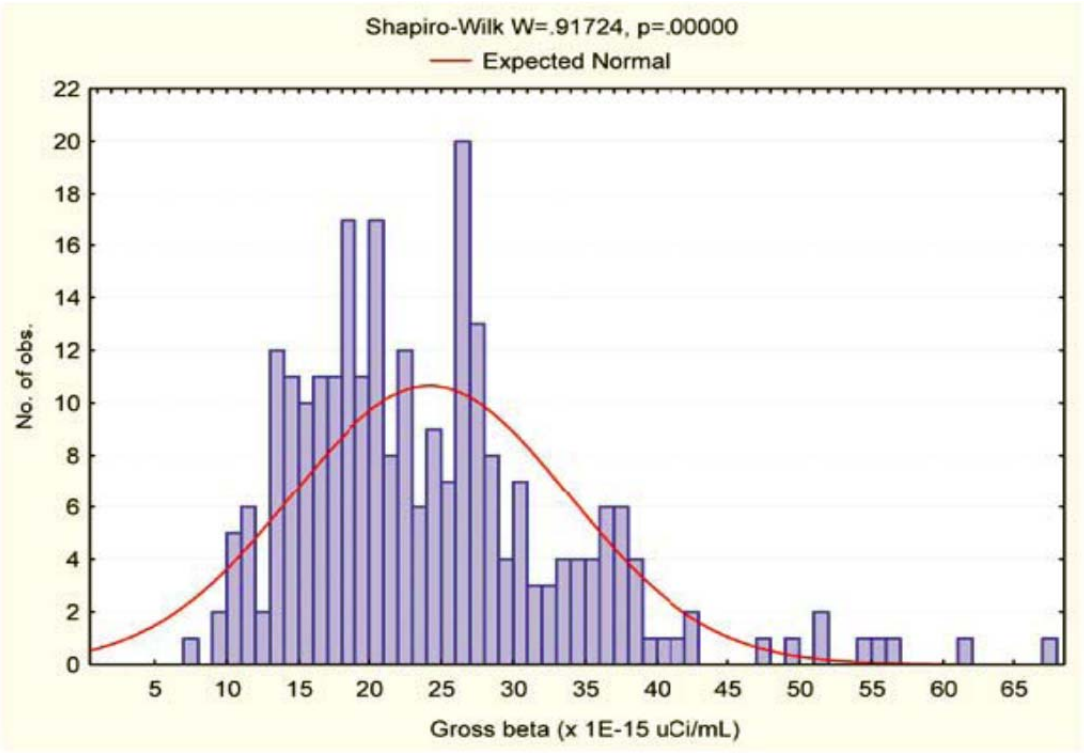

FIGURE 8-1: Example of Test of Normality for Arco Gross Beta Data (INL 2005)

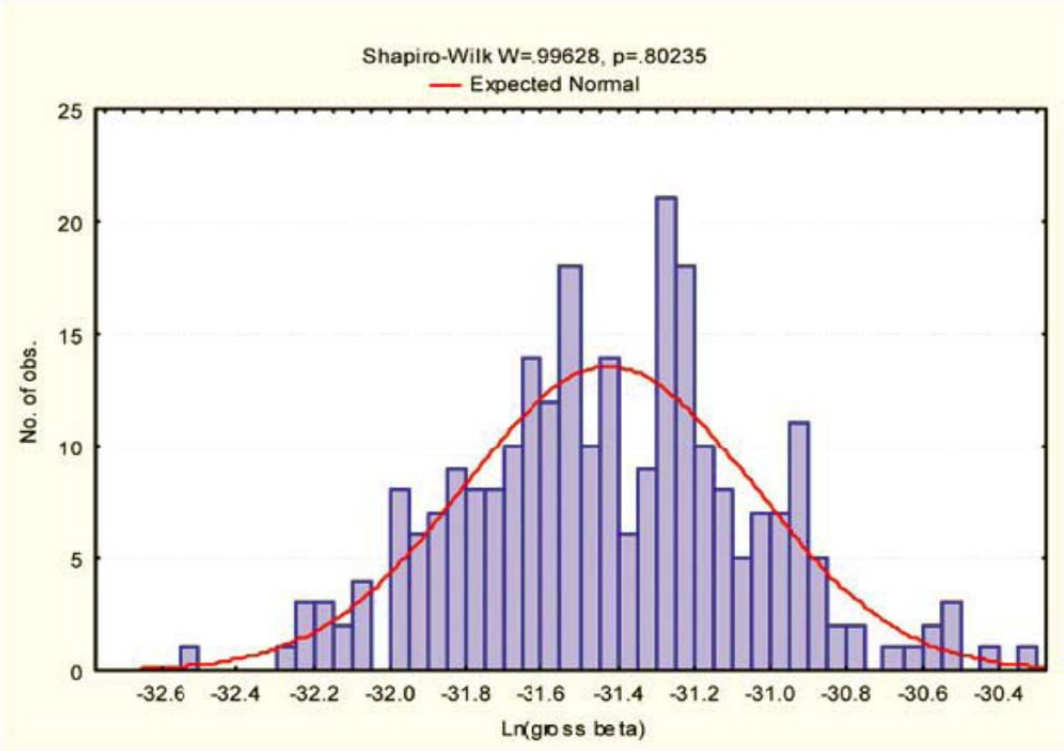

FIGURE 8-2: Example of Test of Lognormality for Arco Gross Beta (INL 2005)

Other normality tests, including the D'Agostino[7] and Ryan-Joiner[8], are available in the literature and the user should select the appropriate test based on specific features of the data set.

8.4.4 Testing for Outliers

Nonparametric statistical methods are usually less susceptible to the undue influence of outliers than parametric methods. If probable outliers are identified, nonparametric methods should be applied to the extent practicable.

Potential outliers can be identified using technical experience (e.g., values outside the range of measurement that are recognized as atypical) and visualization (e.g., boxplots, probability plots). Measures of dispersion can also be used to identify potential outliers. For example, a 2- or 3-standard-deviation probability ellipse can be constructed around a scatter-plot of all of the

---

[7] Additional information can be found in NUREG-1475.

[8] Additional information can be found at:
http://www.minitab.com/uploadedFiles/SharedResources/Documents/Articles/normal_probability_plots.pdf

data, with points falling outside of that ellipse considered outliers. Although these tests are statistically valid, they only determine whether a point is extreme with respect to the mean or median of the entire dataset. Therefore, these tests are not adequate to serve as the sole justification for the inclusion or exclusion of data from the set.

A better approach to assess the exclusion of potential outliers is to perform a statistical test to evaluate if the extreme value is statistically different than the remaining data group. Tests such as the Dixon's test, Chauvenet's criteria (Turner et al. 2012), and Grubbs test are examples of statistical tests used to evaluate potential outliers. However, these tests are not without limitations. A significant underlying assumption in all three tests is that the dataset is normally distributed. Additionally, Dixon's test and Chauvenet's criteria can only test one outlier at a time. Grubb's test provides greater flexibility by allowing two potential outliers to be tested simultaneously.

When outliers that are not attributable to errors are contained in the dataset, estimators and statistical tests might be computed with and without the outliers to see if the results of the two calculations are significantly different. If the results differ substantially because of outliers in the data, then both results should be reported. A preferred option may be the application of nonparametric tests followed by evaluation of each potential outlier with a pre-determined action level, such as maximum allowable concentration. This method is commonly referred to as an elevated measurement comparison.

8.5 Statistical Analyses

The final step of the DQA process is the performance of the statistical analyses from which decisions are made regarding the population from which the sample data were collected. As stated previously, the statistical analyses selected for environmental monitoring typically depend on the underlying population distribution assumption—symmetric or asymmetric. For example, one of the main assumptions for the application of parametric statistics to a data set is the assumption that the population follows a normal distribution where the data are clustered around a central value, the likelihood of outliers is low, and there is zero skewness—the data are symmetrical around a mean value. This type of distribution is called a normal or Gaussian distribution. On the other hand, non-parametric statistics are often more appropriate when the underlying distribution is unknown or is otherwise a continuous distribution, other than a normal distribution. Thus, they can be applied to any dataset (e.g., symmetric/normal or asymmetric/skewed).

8.5.1 Statistical Tests for the Presence of Radioactivity

It should be the goal of the DOE program to minimize the probability of making an incorrect decision. There are two types of decision errors that can occur in hypothesis testing. A Type I error is made by rejecting the null hypothesis when it is true. A Type II error is made by failing to reject the null hypothesis when it is, in fact, false. From an environmental or public health standpoint, the null hypothesis should be established such that the assumed base condition is the most protective and therefore limiting. Therefore, the evidence needs to be overwhelming in order to reject the null hypothesis and accept the alternative hypothesis. An example would be for a monitoring program established to determine if a specific contaminant is present in the environment. The null hypothesis would be established such that the assumed base condition is that the contaminant is present. A Type I error would occur if the conclusion was reached that the contaminant was not present when it actually was. Alternatively, a Type II error for this example would occur if the decision was that the contaminant was present when it was not. In general terms, these errors combined with estimates of mean and the uncertainty will drive the sample size and consequently the power of the statistical tests. Insufficient sample sizes are likely to increase the probability of Type II error but should not impact the probability of Type I error.

The user is encouraged to compare and understand the implications of the Type I and Type II error discussions that are presented in this section and the discussion in Chapter 7. Regardless of the case, the Type I error occurs when the assumed based condition is incorrectly rejected in favor of the alternative condition. The difference between the two examples is the assumed base condition. The base condition for sample analysis is that the sample does not contain radioactivity (clean base condition) vs. the assumed environmental monitoring base condition where the contaminant is present until environmental monitoring data prove otherwise (dirty base condition).

8.5.2 Less-Than-Detectable Values

Monitoring programs often include measurements of extremely low concentrations of radionuclides that are below the detection limit of the counting instruments. Datasets with

less-than-detectable values[9] require special consideration in statistical analyses (Gilbert 1987). Although several of the statistical tests discussed in this chapter can still be used when as much as 40 percent of the data are reported as “less than” values, the overall robustness of the test will suffer and the probability of Type 2 error may increase above an acceptable, or planned for, level based on what will ultimately correspond to a reduction in sample size when the detection limit is substituted as the sample value. Non-parametric methods will work well even when the sample population contains non-detect data—the methods will work with up to 40% of non-detect data—because the methods are based on the ranking of data, where the results are ranked from lowest concentration to highest. When non-detects present each non-detect will receive the average rank. For example, if there are 10 results with the same non-detect concentration, and those data represent the lowest concentrations of the sample population, these data would take on the first 10 rankings (ranks 1 through 10). However, assuming the detection limit is the same for each sample, then they are considered tied data will each receive the rank of 5 (the average of ranks 1-10).

It is possible to calculate net results that are less than zero, although “negative” radioactivity is not possible. A common misconception is that negative or near zero results should not be reported. This practice is not recommended. The assignment of a zero, detection limit, or some in-between value to the less than detectable data point, or discarding those data points, will bias the resulting parameter estimates and should be avoided. The best practice is to report all results, whether positive, negative, or zero, as obtained along with the combined standard or expanded uncertainty and also the detection limit (Gilbert 1987).

For radiological counting instrumentation, there will normally be some number of counts greater than zero obtained during the analysis consisting of either background or background plus source. Net instrument responses, together with other factors, are used to calculate activity present. As background is a random distribution of its own, a truly net background distribution would be centered around a mean value of zero with equal probability of positive of negative values around the distribution’s center. The net counts may therefore always be converted to activity units, positive or negative, and reported as such.

[9] Sometimes referred to as “non-detects.”

Data from censored distributions (for which the number of less-than-detectable values is known) are more amenable to standard statistical analyses than are those from truncated distributions (for which the number of values below the detection limit are not known and which require special statistical techniques) (Gilbert and Kinnison 1981).

Regression on Order Statistics (ROS) is a way to estimate the geometric mean and geometric standard deviation of a normal or lognormal distribution for data with non-detects (Helsel 2005). The ROS method is based on the least squares regression model. The method may be used to verify that the data follow a normal or lognormal distribution and provides estimates for the parameters of the distribution when there are values in the dataset below the detection limit of the sample analysis device. As discussed above, when possible, the use of “less than” values can be avoided by requesting the laboratory provide the actual result, even when below the detection/quantification limit. For situations where available data do contain “less than results”, then the general guidelines for managing datasets with such results are provided in the following table (EPA 2000d).

TABLE 8-2: Guidelines for Managing Non-detects (adapted from EPA 2000d)

Percentage of Non-detects	Statistical Analysis Method
< 15%	Replace non-detects with DL/2, DL, or a very small number.
15% - 50%	Trimmed mean, Cohen's adjustment, Winsorized mean and standard deviation.
> 50% - 90%	Use tests for proportions

8.6 Draw Conclusions from the Data: Hypothesis Testing

Hypothesis testing is a statistical tool for making decisions under conditions of uncertainty. Statistical hypothesis tests are used in many types of applications. Examples of these applications include determining the distribution of a dataset, comparing a dataset with a fixed upper or lower limit, comparing two or more datasets, or deciding if trends are appearing in the data.

The first step in developing a hypothesis test is to translate the decision into statistical terminology by formulating a null hypothesis (H_0) and an alternative hypothesis (H_A). The formulation of the hypotheses statement are important factors to consider, and should be completed early during the planning stages of a sampling campaign. The assumed base

condition is usually formulated as H_0. The acquired environmental monitoring sample data then need to provide overwhelming evidence to reject the H_0 and accept the H_A. This example can be further expanded into two scenarios, dependent upon base conditions and action levels. NUREG-1505 defines the two scenarios as Scenarios A and B (NRC 1998). For this example assume that environmental monitoring samples are collected to determine if a site-related contaminant, that is also naturally occurring at varying concentrations, is present at either concentrations above some predetermined action level or alternatively at concentrations that are distinguishable from background. The action level example can be used to illustrate Scenario A. As incorrectly concluding that the contaminant is less than the action level is the most severe consequence of a decision error, the assumed based condition would be that the contaminant is equal to or exceeds the action level (H_0). The alternative decision that would be made based on the principle study question is that the data demonstrate that the contaminant distribution is less than the action level (H_A). The Scenario B example might be applied if the principle study question was deciding if the site related contaminant environmental monitoring data distribution was indistinguishable from the background distribution. Application of this scenario is considered when the background distribution indicates significant variability, where the range on the variability is such that a sufficient minimum detectable difference between background and contamination cannot be established. For this case, the most severe consequence would be deciding that contamination is present when it is not and the results are due to random variation of background. Therefore, the assumed base condition (H_0) is that environmental monitoring data are indistinguishable from background.

Hypothesis testing can be performed using parametric statistics when the distribution of the data is known (e.g., normal, lognormal or fit some other distribution), and nonparametric statistics when the distribution is unknown. In parametric statistics, the observations need to be independent and obtained from a known group. Additionally, the sample variances are assumed to be identical. Alternatively, the general requirements for nonparametric statistics are that the observations are independent and that the variable of interest has continuity (e.g., can be ranked). The advantages of using nonparametric statistics are that there is no assumption about the sample distribution, the calculations are typically simpler, and the outliers do not influence the test. Table 8-3 presents examples of statistical tests that may be selected for multiple hypothesis goals.

TABLE 8-3: Examples of Statistical Tests for Multiple Hypothesis Goals (ORAU 2013)

Goal of Hypothesis	Continuous Data		Discrete Data
	Parametric	Nonparametric	
Compare one group to a hypothetical value	One-sample t test	Sign test or Wilcoxon	Chi-square or binomial
Compare two unpaired groups	Unpaired t test or Welch's test (unequal variances)	Wilcoxon rank sum (Mann-Whitney)	Chi-square (Fisher's for small samples)
Compare two paired groups	Paired t test	Wilcoxon signed-rank	McNemar's test
Compare three or more unpaired groups	One-way ANOVA	Kruskal-Wallis	Chi-square
Compare three or more paired groups	Repeated measures ANOVA	Friedman Test	Cochran's Q
Quantify association between two variables	Pearson correlation	Spearman correlation	Contingency coefficients
Predict value from another variable(s)	Regression	Nonparametric regression	Logistics/Poisson regression
Trend Detection	Regression	Mann-Kendall or Seasonal Kendall (when seasonal variation exists)	--

The objective for obtaining reliable estimates of radionuclide concentrations at environmental sampling locations is to compare those values to regulatory or administrative control standards or values at control stations to determine whether action needs to be taken to reduce the radionuclide levels to minimize potential exposures to members of the public and to protect the environment.

Environmental data often follows a lognormal probability distribution; and, as such, the geometric mean and geometric standard deviation are used to describe the data. Log-normally distributed environmental data appear approximately normal when the data are plotted on a logarithmic scale. In this particular case, parametric hypothesis testing can be carefully applied when the environmental data is converted to logarithmic scale. It is important to note that data conversion may introduce unwanted errors to the data due to round-offs. On the other hand, nonparametric tests would limit the introduction of unwanted errors because the data do not need to be converted and because no assumption for the data probability distribution is necessary to apply nonparametric statistics.

A determination is necessary regarding whether the hypothesis test be a two-tailed or one-tailed evaluation of the distribution(s). For example, in situations where the principle study question is to decide whether the sample data represents a population concentration that exceeds an established action level, a one-tailed test of the mean/median would be used—in this example the upper tail of the distribution is critical to the decision. More specifically, the hypothesis test is designed to determine if the mean/median concentration at a specified confidence level is above or below the action level threshold. When comparing two or more sample populations, either a one-tailed or two-tailed test could be used, dependent upon the specific study question. An example would be if the study was to answer whether two samples come from the same population distribution, perhaps a background distribution, then a two-tailed test would be considered. Alternatively, if the study question was to establish if a specific sample population mean was greater than or less than a second sample population, a one-tailed test would be applied.

The following are brief descriptions for the application of the parametric and nonparametric tests summarized in Table 8-3 that may be used for data comparison with regulatory or administrative control standards, or control data. Additional statistical tests not indicated here also may be used for data comparison and compliance verification as necessary.

8.6.1 Parametric Tests

8.6.1.1 One-Sample t Test

The One-Sample t test compares the sample data mean, $\bar{x}$, to a limiting/decision value such as a cleanup guideline, or the true, but unknown population mean (μ). The null hypothesis for the one sample t test is defined as:

$$H_o: \overline{x} = \mu$$

If the test statistic T value is greater than $t_{1-\alpha}(n-1)$, the null hypothesis is rejected.

Where the one-sample t test is used when the mean of the population is specified as part of the null hypothesis, the two-sample t test (Student's t test) assumes as the null hypothesis that the means of two populations being compared are equal but is only used when the variances of the populations can be assumed equal. The Welch's Test discussed below is applied when the variances of the data groups cannot be assumed to be equal. The unpaired t test is used to compare two independent populations such as those from an impacted areas (those that may be affected by DOE activities) and a non-impacted areas (background locations) while the

paired t test is for populations expected to have a logical pairing of observations with the same means and distribution (e.g., analysis of split sample).

8.6.1.2 Unpaired t Test (Welch's Test)

The unpaired t test is used to compare the mean values ($\bar{x}$) of two distinct groups. The null hypothesis of the unpaired t test is defined as: H_0, the means of the two groups are equal,

$$\bar{x}_A - \bar{x}_B = 0$$

where A and B represent the two groups of interest. Two important assumptions in the unpaired t test are that the group distributions and their means are normally distributed.

If the T value exceeds $t_q(v)$ for the Student's t-distribution (Figure 8-5), the null hypothesis is rejected.

8.6.1.3 One-Way Analysis of Variance (ANOVA)

Multiple samples (three or more) can be compared among themselves with a one-way ANOVA to determine if the means of the populations (μ_i) represented by the samples are the same or different. The null hypothesis is that the samples from the multiple groups are from populations with the same means. Like the previously described parametric tests, the one-way ANOVA test assumes that: (1) the observations are obtained under identical conditions; (2) the observations are independent; (3) the variance is the same for all groups; and (4) the groups are normally distributed. The one-way ANOVA test can be employed independently of the number of observations on each group. However, when the number of observations of each group is the same, the power of the one-way ANOVA test is higher. The null hypothesis in the one-way ANOVA test is defined as: H_0, the means of all groups are equal. That is:

$$H_0 = \mu_1 = \mu_2 = \cdots \mu_k$$

whereas H_A is that at least one of means are unequal; however, it may not be known which mean resulted in the rejection of H_0 and additional tests may be required to determine which of the means are statistically different. NUREG-1475, Chapter 16 provides procedural steps for performing the one-way ANOVA test.

8.6.2 Nonparametric Tests

8.6.2.1 Kruskal-Wallis

The Kruskal-Wallis test is the nonparametric analog to the ANOVA. The Kruskal-Wallis test may be applied when a decision is required to access background variability among several background reference populations that may then be used for the comparison with site environmental monitoring sample populations. The test may be a necessary component to determine indistinguishability from background. For this situation, the test evaluates whether significant variability exists between several (three or more) different sample background populations and if the medians of multiple groups are statistically different or not. Thus the null hypothesis, H_0, assumes that no significant variability exists between the groups and may be written as illustrated for the ANOVA H_0.

As with any nonparametric test, Kruskal-Wallis test can be performed regardless of the group distribution or lack thereof although the test assumes the population distributions are identical. NUREG-1475 and NUREG-1505, *A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys* (NRC 1998) provide procedural steps for performing the Kruskal Wallis test. NUREG-1505 provides the steps for assessment of the site data using additional statistical tests, the Wilcoxon Rank Sum and Quantile tests, to assess indistinquishability from background. NUREG-1475 provides procedural steps for performing the Kruskal-Wallis test.

8.6.2.2 Sign Test

The Sign test may be used to evaluate sample results to make a decision regarding the difference of the medians either relative to the sample population median as it relates to an action level (a one-sided Sign test) or a two-sided Sign test for paired sample evaluations. The null hypothesis for the one-sided Sign test may be stated as:

H_0: the median concentration ≥ the action level

The alternative hypothesis would then be:

H_A: the median concentration < the action level

MARSSIM recommends this approach for comparing sampling results with a guideline concentration value, and any background contribution to the sample is considered inconsequential. The test is relatively simple to perform and measures the number of positive or

negative differences between the paired data (where the paired data for this example consist of the action level value and the sample population). The magnitude of the difference between the pairs is not considered. To illustrate the basics of the test, if the differences between the action level and all sample results were negative, then strong evidence has been gathered to reject H_0 as clearly each result is less than the action level. However, when both positive and negative differences exist, a critical level is established for comparison with the Sign test statistic and deciding whether H_0 may be rejected. The critical level is a function of sample number (n). When the difference between data points equals zero, and therefore cannot be assigned either a positive or negative value, the n is reduced accordingly and the new associated critical level is used. To minimize zeroes, it is recommended to retain all significant figures provided with the analytical results when applying the test. This same strategy of retaining all significant figures should be considered for any of the tests discussed in this section that involve either the evaluation of differences or ranking of data.

The two-sided Sign test may be applied for two populations of independent paired measurements to determine if the medians are equal, or unequal (where one population is either > or < the second population). Similar to the one-sided Sign test, the paired sample results from one population are subtracted from the second population. For populations that are similar, one would expect, with a sufficient n, an equal number of positive and negative differences. Evidence that the two population medians are not equal is generated when the differences become increasingly more positive or negative. Dependent upon how the hypothesis statements are established will determine whether the number of positive or negative differences is compared with the critical value.

Additional information and examples concerning the application of the Sign test can be found in MARSSIM, MARSAME, and NUREG-1505.

8.6.2.3 Wilcoxon Rank Sum Test

In contrast to the Sign test, the Wilcoxon Rank Sum (WRS) or Mann-Whitney test is used to evaluate the results from independent data when the contaminant (e.g., a radionuclide) is present in background by comparing the results to measurements from an appropriately chosen background reference sample population. For comparison of these two groups, the WRS test (EPA 2010a) is a robust nonparametric alternative to the Student's two-sample t test.

Rather than a direct test of means, the WRS test is computed based on rank sums of the data from the two sample populations to detect differences between the means. Because of this,

outliers and non-detects do not present the serious problem encountered when using parametric tests. As a general rule, the WRS test can be used with up to 40 percent non-detect measurements present in either population sample. The test is applied by pooling the data from the two sample populations then ranking the sample concentrations from highest to lowest, tied data are assigned the average value of the ranks.

There are two forms of the test, Test Forms 1 and 2. With Test Form 1, the base condition is that the concentration difference between the site and background population is essentially zero. H_0 and H_A for Test Form 1 would be stated as follows:

> H_0: the mean/median contaminant concentration in environmental monitoring samples is ≤ the concentration in background samples
>
> H_A: the mean/median contaminant concentration in environmental monitoring samples is > the concentration in background samples

Test Form 2 also assumes the opposite base condition, where the contaminant concentration is assumed to exceed background. However, rather than assuming the difference in the means/medians as zero, Test Form 2 allows for a comparing the site data to the background data plus some investigation level (+S). S, also referred to as the “substantial difference” may be an action level, a release guideline, a percentile above the background mean concentration, or other variable. H_0 and H_A for Test Form 2 would be stated as follows:

> H_0: the mean/median contaminant concentration in environmental monitoring samples is > the background concentration +S (where S is the allowable substantial difference)
>
> H_A: the mean/median contaminant concentration in environmental monitoring samples is ≤ the concentration in background samples +S

Test Form 1 uses a more conservative investigation level but relaxes the burden of proof by requiring overwhelming evidence to reject H_0. With Test Form 2, the burden of proof is strict the investigation level is relaxed by allowing for the substantial difference between the means/medians.

Additional information and an example concerning the application of the WRS or Mann-Whitney tests can be found in MARSSIM, MARSAME, NUREG-1505, and EPA 540-R-01-003.

8.6.3 Regression and Trend Analysis

In addition to hypothesis testing, other statistical tests and approaches may be used to analyze environmental data and make decisions based on the statistical results. The detection and assessment of temporal or spatial trends are a critical objective of environmental monitoring and trend detection serves to identify the presence of new releases, when additional effluent release controls are required, to evaluate the effectiveness of controls or other contaminant release mitigation projects. The following approaches are suggested based on their application to effluent and environmental monitoring and are available to investigate trends. Detailed descriptions of tests for trends can be found in EPA QA/G-9S (EPA 2006).

8.6.3.1 Graphical Representations

Graphical representation of the effluent or environmental data over time can assist the user in identifying trends. Diurnal and nocturnal concentrations of radon, radiation exposure, or dose measured in a specific environmental location, and concentrations of airborne effluent releases are some practical examples of measurements that could represented as a time plot. A time plot can be used to identify temporal trends and potential outliers. It may also be used for comparing multiple data groups (e.g., background or baseline with operational measurements). When multiple measurements are obtained simultaneously, the results can be superimposed on a site or facility map to evaluate spatial trends during a sampling period or for multiple sampling periods.

NUREG-1475 and EPA QA/G-9S provide guidance for the application and construction of the variety of charts useful for analyses of both single and multi-variable data sets including the use of confidence intervals and/or action levels for trend analyses.

8.6.3.2 Linear Regression

Linear regression is a parametric method to test for the presence of trends and/or model (predict) trends over time using the slopes of the data regression line as an estimate of the strength of the trend (EPA QA/G-9S). The regression may be applied to two or more variables when data suggest a linear change with time and the data are normally distributed. The linear regression trend test relies on a variety of assumptions (e.g., normality and no non-detects or outliers) that require verification. A least squares method is used to develop a best-fit line of the data, e.g., concentration vs. time. A statistical test, such as the t test may then be applied to assess whether the slope of the line departs from zero, indicative of trend. Linear regression

includes simple regression for a single independent variable and multiple linear regression for more than one independent variable. Uses and applications for linear regression are provided in NUREG-1475, Gilbert 1987, and other referenced sources.

8.6.3.3 Mann-Kendall Test

The Mann-Kendall test, a nonparametric test for detecting trends, is based on a measure of the correlation of the sample values with time. The Mann-Kendall trend test may be used to test for a significant trend in any time series of four or more independent data points. Unlike linear regression, the time series may include non-detects, missing values, and/or outliers.

As with other non-parametric tests previously discussed, the Mann-Kendall test evaluates the relative magnitude of the data instead of the measurement result directly. The test is conducted by comparing each observation with all previous observations to determine if it is larger, smaller, or the same. If larger (or smaller), a score of +1 (or -1) is assigned; for ties the score is 0. The test statistic, S, is the sum of the scores for all comparisons. Positive (or negative) values of S indicate a positive (or negative) slope. The absolute value of S is compared with tabulated critical values of the test statistic determined if the slope is statistically significant. For large sample sizes ($n > 10$) a normal approximation for the Mann-Kendall test is available (EPA QA/G-9S). Corrections may be necessary during the evaluation period when periodic cycles in the dataset are identified (i.e., seasonality). A detailed description of the Mann-Kendall test can be found in EPA QA/G-9S. When seasonal cycles are evident in the data and need to be accounted for, the user is referred to the Seasonal Kendall Test (Gilbert 1987).

8.6.3.4 Thiel-Sen Slope Estimator

The Thiel-Sen slope estimator is a follow-on to the Mann-Kendall test that provides a nonparametric estimate of the value of the slope (an alternative to the parametric linear regression and least-square slopes) (Helsel 2005). As the Thiel-Sen Slope Estimator is non-parametric, the result shows how the median concentration changes with time.

An equal number of positives and negatives slopes may be interpreted as a lack of a trend in the dataset, while either a greater proportion of either positive or negative values are indicative of a respective positive or negative slope (increasing or decreasing concentrations over time). A detailed description of the Thiel-Sen's slope estimator can be found in Helsel 2005.

8.7 Computational Tools

In recent decades computer tools have been developed to assist in the implementation of statistical analyses. This chapter discusses several computer tools that have been widely used for developing environmental sampling plans, data analysis, graphical representations of data, and uncertainty propagation. Additional tools are available commercially and their versatilities vary between developers and intended uses. It is important to mention that computer tools used for verification of regulatory compliance should be verified and validated prior to use. A discussion regarding verification and validation is included in this chapter.

The following computational tools were selected based on their wide use, regulatory acceptance, and availability.

8.7.1 Visual Sample Plan

Visual Sample Plan (VSP)[10] was developed at Pacific Northwest National Laboratory. VSP is a software tool that supports the development of a defensible sampling plan based on statistical sampling theory and the statistical analysis of sample results. VSP helps ensure that the right type, quality, and quantity of data are gathered and provides statistical evaluations of the data with decision recommendations. VSP has many parametric and non-parametric statistical sampling design modules including random, systematic, sequential, adaptive cluster, collaborative, stratified, transect, multi-increment, combined judgment/probabilistic, and ranked set sampling. Sampling designs can be geo-referenced and may be applied to soils, sediments, surface water, streams, groundwater, and buildings. The software also includes statistical analysis/data quality assessment modules for performing the various hypothesis tests.

8.7.2 ProUCL Software

The ProUCL software package[11] was developed by EPA (EPA 2013a, EPA 2013b) and designed to do many of the statistical tests/analyses identified in this Handbook. A trend analysis module includes regression analysis, the Mann-Kendall trend test, and the Thiel-Sen estimate of the slope. Also included is a variety of other parametric and nonparametric

[10] http://vsp.pnnl.gov/

[11] http://www.epa.gov/osp/hstl/tsc/software.htm

statistical methods, including modules for plotting the data, identifying the type of probability distribution, parameter estimation and tolerance limits, and outlier tests.

8.8 Quality Assurance

As they apply to data analysis and statistical treatment activities, the general QA program provisions of Chapter 11 should be followed. Specific QA activity requirements for data analysis and statistical treatment activities at a site should be incorporated in the QA plan for the facility.

8.8.1 Software Validation and Verification

Multiple effluent and environmental guidance incorporate EPA's QA/G-4, *Guidance for the Data Quality Objectives Process* (EPA 2000c), and QA/G-9, *Guidance for Data Quality Assessment* (EPA 2000d), processes. As part of an adequate quality assurance program, it is customary to verify and validate computer tools used in the analysis and representation of data. Site- or project-specific computer tools may be developed as needed (e.g., spreadsheet programs) or commercially available software may be obtained to streamline the data analysis process. Requirements for validation of software will normally follow a graded approach. Custom designed software of extensively modified off-the-shelf software would generally necessitate a formal validation and verification plan prior to authorizing use of the application, whereas commercial software, government-funded software, and similar applications should have the verification and validation documentation available for the user and validation may be as simple verifying proper installation and running of test scripts that ensure functionality.

DOE-approved computational tools may be used without restrictions. User-developed computational tools should be verified and validated prior to use to ensure proper function, particularly when used to demonstrate compliance with regulatory requirements. Verification and validation may be performed by performing data analysis using known data that meet the characteristics for the statistical evaluation. The results from software or user-developed tools can be verified against independent verifications of the results (e.g., results from hand calculations or other approved software).

9 DOSE CALCULATIONS

For DOE sites, DOE O 458.1 and DOE O 231.1B describe the annual reporting requirements for releases of radioactive materials to the environment. In addition to the summary of airborne and liquid effluents released to the offsite environment, these Orders require the reporting of estimates of the effective doses to the population and to the MEI or representative person. The dose estimates require detailed knowledge (or estimates) of the concentrations of radionuclides in the facility effluents and emissions and in various environmental media resulting from site operations. Samples of air, soil, water and vegetation, and direct readings of external radiation can also be used to determine these concentrations. However, in most cases these concentrations are very low and challenge the sensitivity of the analytical techniques used. As a result, estimates of environmental concentration and human exposure and the resulting estimated radiation dose are frequently made using mathematical models that represent various environmental pathways. For situations where available environmental data are sufficiently accurate to determine radionuclide concentrations, their use in the dose assessment process is encouraged. For the purposes of this Handbook, the following basic definitions are used:

- Model – A mathematical formulation or description of a physical, ecological, or biological system, which includes specific numeric values or parameters.
- Computer program – The logical computer language statements in an executable form on a digital computer that represents the model (mathematical formulation) and appropriate data.

A lines of inquiry approach is provided in Appendix B that may be used to conduct self-assessments and to verify that the program is effective and in compliance with the appropriate requirements and to ensure continuous improvement of the program. For situations where available environmental data are sufficiently accurate to determine radionuclide concentrations, use them in the dose assessment process.

9.1 Key Requirements

The following regulations and directives apply to dose calculations:

- DOE O 458.1, *Radiation Protection of the Public and the Environment*, requires dose evaluations to demonstrate compliance with the public dose limit and to assess collective dose.

- DOE O 231.1B, *Environment, Safety and Health Reporting*, requires that information provided in the ASERs on individual, population, and biota radiation exposures, doses, and potential impacts should accurately portray the information required by DOE O 458.1, or other applicable regulations and requirements, such as 40 CFR Part 61, Subpart H, and State regulatory and administrative codes. To support consistent data collection and reporting under DOE O 231.1B, the DOE Office of Environment, Health, Safety and Security provides *Guidance for the Preparation of Department of Energy (DOE) Annual Site Environmental Reports (ASERs)*.

9.2 Required Performance Standards for Public Dose Calculations

Models and methods used for documenting compliance with radiation protection standards and regulations have evolved and matured, often driven by revised regulations and standardized reporting requirements. However, key to the preparation of the compliance documentation is having quality site-specific data collected for each DOE site, facility, or activity.

Except where mandated otherwise (e.g., compliance with 40 CFR Part 61), the assessment models selected for all environmental dose assessments should appropriately characterize the physical and environmental situation encountered. In some cases, the specific assessment model may be mandated (e.g., compliance with 40 CFR Part 61 Subpart H, or use of RESRAD for site restoration). The information used in dose assessments should be as accurate and realistic as possible. Complete documentation of models, input data, and computer programs should be provided in a manner that supports the ASER or other application.

9.3 Documentation and Conformance with Other Requirements

Default pathway analysis values used in model applications should be documented and evaluated to determine appropriateness to the specific modeling situation. Those values may be replaced with site-specific information when adequate data are available and appropriate.

When performing human food chain assessments, a complete set of human exposure pathways should be considered, consistent with current methods (IAEA 1982; NCRP 1984; NRC 1992b; Yu et al. 2001).

Documentation of pathway analysis models, input data, and computer programs should be provided in a manner that supports the ASER. Parameter sensitivities and uncertainties in modeling results should be documented whenever possible.

Surface- and ground- water modeling should be conducted, as necessary, to conform to the applicable requirements in DOE O 458.1 and to applicable requirements of the State government and the regional EPA office.

9.4 Pathway Analysis Modeling

Pathway analysis modeling is used to assess the immediate potential consequences of chronic routine releases or accidental releases, or potential future consequences for site remediation or waste management evaluations. Exposure pathways are the routes of radiation exposure to human beings or biota. They generally include external exposure to penetrating radiation, inhalation, and ingestion.

Within each type of exposure pathway, several separate mechanisms may be at play as shown in Table 9-1 and described in the following:

- External exposure may include exposure to contaminated ground surfaces or buried sources, submersion in an airborne plume of radioactive material, or submersion (swimming) in contaminated water. However, in most cases, air or water submersion will be secondary in magnitude compared with exposure to contaminated ground or buried sources.
- Inhalation can occur during submersion in a contaminated plume, or following resuspension of radioactive material in the soil.
- Ingestion pathways include ingestion of food products contaminated by radioactive material deposited from the air or through root uptake of radionuclides in soil, direct ingestion of radionuclides in soil, ingestion of radionuclides in water, or ingestion of radionuclides incorporated in aquatic foods.

Mathematical modeling for pathway analysis of radiation doses to members of the public caused by radioactive materials in the environment has become complex to meet the challenges encountered. However, the rule of thumb is that the simplest model that will adequately address the situation always should be applied first (NCRP 1984). Simple models often are highly conservative, but they rely on fewer data than complex models.

TABLE 9-1: Potential Pathways to Be Considered in Environmental Pathway Analyses

Exposure Category	***Environmental Pathway***
External	Direct Facility Radiation Submersion in an Airborne Plume Contaminated Land Aquatic Recreation (Swimming/Shoreline/Boating)
Inhalation	Submersion in an Airborne Plume Re-suspended Materials
Ingestion of Terrestrial Foods	Vegetables: Potatoes Other Root Vegetables Leafy Vegetables, Other Vegetables, Fruits Cereal Grains Animal Products: Liquid Milk Cheese Meat and Meat Products (Beef, Pork, Poultry, Game Animals) Eggs
Ingestion of Aquatic Foods	Fish Seafood (Shellfish) Waterfowl Reptiles Amphibians
Ingestion of Soil	Grazing Animals Humans (Children)
Ingestion of Drinking Water	Surface Water (Raw or Treated) Well Water (Raw or Treated) Rain Water

(Source: RESidual RADioactivity (RESRAD) Manual (Yu et al. 2001).

9.5 Misuse of Models

According to the National Council on Radiation Protection and Measurements (NCRP), the three most common misuses of these types of models are: 1) "overkill," 2) inappropriate prediction, and 3) misinterpretation (NCRP 1984).

"Overkill" occurs when the level of available data or the use of the results do not support the sophistication of the model selected. NCRP (1984) was responding to "overkill" in models used for radiological assessments in the following comment:

> *In recent years, the trend has been toward more complex models; however, the increased complexity has not necessarily improved the accuracy of estimates of dose and, in certain cases, has had the opposite effect.*

Inappropriate prediction occurs when sophisticated models and detailed analyses are used too early in the assessment process. Initial assessments should be conducted with very simple models; more detailed models and more detailed assessments should be made as data and knowledge of the system being modeled improve.

Misinterpretation of modeling results can occur when inappropriate boundary conditions or assumptions have been used. The results of any modeling application should be viewed as estimates of reality, and not reality itself. In many cases, seemingly minor changes in assumptions or input can cause drastic changes in the results obtained (NCRP 1984).

9.6 Transport Models

Models that are used to estimate the concentrations of radionuclides at locations that are distant from the point of release of a source are termed transport models. Transport models include transport by air, surface water, and ground water as discussed below.

The first level of model verification can be done by comparing the program results for sample problems against either documented sample problem results or against hand calculations.

> DOE encourages the use of realistic data (best estimate) that are not likely to underestimate doses or exposures. The goal is to minimize conservatism but provide reasonable assurance that doses or impacts are not underestimated.

Limited comparisons against field or laboratory data typically are conducted during development of a computer program because complete validation of all models usually is not feasible due to the size of some datasets and the inability to fully characterize most sites. Modifications then can be made to key parameter values to make the results compare more closely to measured conditions. This comparison process is called “model calibration” and often is used when site-specific model applications are desired.

In many situations, site-specific data are not available, so default parameters or datasets can be used in the transport calculations. These default values often are obtained from generic datasets and are designed to give conservative dose overestimates.

9.6.1 Atmospheric Transport and Dispersion Models

Atmospheric dispersion models typically are applied to model the transport of airborne releases of radioactive materials. These releases may be through active stacks or distributed area sources, such as those encountered during environmental remediation or waste management.

Atmospheric dispersion models and meteorological data will vary in sophistication and complexity from relatively simple spreadsheet computations, to extensive computations that require computers. Use of simple compliance assessment models such as the NCRP (1996)

screening model based on conservative assumptions and little or no meteorological data, could be sufficient for some DOE facilities. As the potential magnitude of the release increases, more detailed models used with site-specific data become necessary to assess the potential consequences.

Selection of an adequate atmospheric dispersion model first requires the determination of site-specific data for a variety of parameters. These data typically are collected through meteorological monitoring as described in Chapter 5. The types of parameters required include horizontal and vertical diffusion parameters, wind data, plume-rise parameters, and plume deposition and depletion factors (Randerson 1984).

For the purposes of routine dose assessment, it is assumed that: (1) the atmospheric releases occur over a long period of time (i.e., they are chronic releases from routine facility operation and not short-term accidental releases); (2) the purpose of estimating ground-level concentrations is to conduct annual public dose assessments; and (3) local terrain is not a complicating factor.

40 CFR Part 61 Subpart H establishes radiation dose limits for the maximally exposed member of the public from all airborne emissions and pathways, and requires that effective dose equivalent values to members of the public be calculated using EPA approved sampling procedures, computer models CAP88 or AIRDOS-PC, or other procedures for which EPA has granted prior approval. Other approved methods could include the use of environmental data in the evaluation.

9.6.2 Surface and Ground Water Transport Models

Information on DOE operations and activities reported annually on liquid releases needs to include: (1) statements concerning the quantity and type of radioactive materials discharged to receiving streams or aquifers, and (2) assessments of the potential radiation dose to the public that could have resulted from these discharges during the previous calendar year. Decisions about which transport model (or models) will be used in performing a specific assessment depend on the local site conditions, the receiving stream or aquifer characteristics, the duration of the release, the potential exposure pathways, the magnitude of the potential doses that result, and other factors.

There is much uncertainty in modeling surface- and ground- water systems, and many unanswered questions about radionuclide transport through surface- and ground- water

systems remain. Additional questions about surface- and ground- water dispersion models have arisen from the need to identify the parameters that can be measured in the field that correspond to the parameters used in the models. For ground water modeling, where the results are largely prospective, these uncertainties are magnified. Modeling should use site-specific data, taking into consideration the important characteristics of the site.

9.7 Environmental Restoration

The RESRAD (Yu et al. 2001) modeling code was developed by DOE and the NRC to support the evaluation of radiation doses and risks from residual radioactive materials in soil at sites undergoing remediation. RESRAD has undergone extensive review, benchmarking, verification, and validation and has been used widely by DOE, NRC, EPA, the U.S. Army Corps of Engineers, industrial firms, universities, and foreign government agencies and institutions. It is the preferred method for determining derived concentration guideline limits (DCGLs) for site cleanup using MARSSIM or MARSAME. An overview of the pathways and components evaluated in RESRAD is shown in Figure 9-1.

In addition to RESRAD[12], an entire family of codes[13] has been developed to respond to specific situations. Currently supported codes include:

- RESRAD Build – designed to estimate radiation doses to individuals in buildings following decontamination.
- RESRAD Recycle – designed to estimate radiation doses to industrial workers and other members of the public following release and recycle of metals.
- RESRAD Biota – designed to estimate radiation doses to biota consistent with DOE guidance.
- RESRAD Offsite – designed to estimate doses and risks to individuals down wind, down stream, or down plume from sources of radionuclide discharges to the environment.
- RESRAD RDD – designed to facilitate the implementation of operational guidelines and protective action guides for radiological or nuclear incidents.

[12] RESRAD may also be identified as RESRAD-Onsite to distinguish it from other members of the RESRAD family of codes.

[13] The RESRAD family of codes is available at: www.ead.anl.gov/RESRAD.

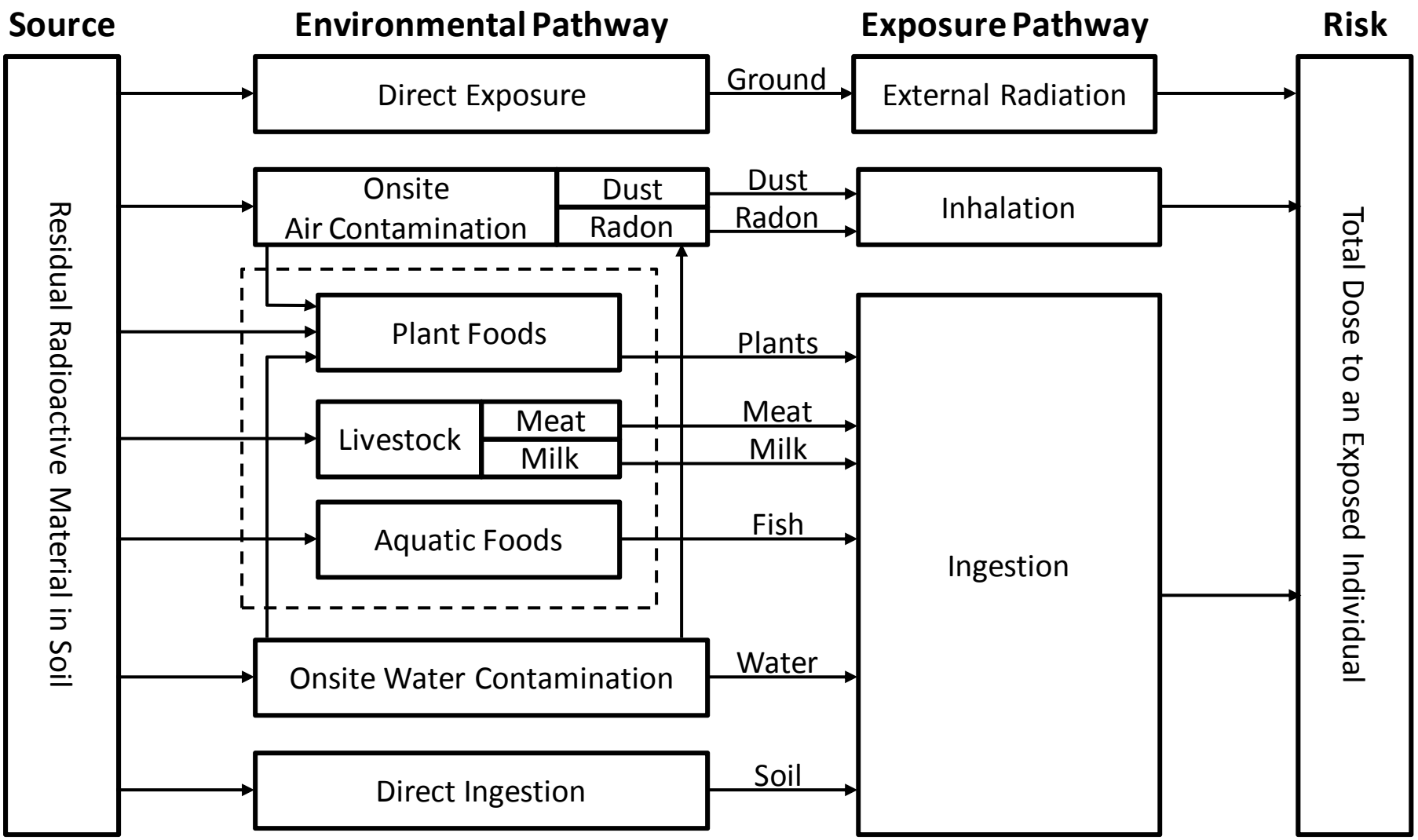

FIGURE 9-1: Pathways Considered in the RESRAD Family of Codes

9.8 Protection of Biota

DOE O 458.1 requires radiological activities that have the potential to impact the environment to be conducted in a manner that protects populations of aquatic animals, terrestrial plants, and terrestrial animals in local ecosystems from adverse effects due to radiation and radioactive material released from DOE operations.

When actions taken to protect humans from radiation and radioactive materials are not adequate to protect biota then evaluations are conducted to demonstrate compliance with paragraph 4.j.(1) of DOE O 458.1 in one or more of the following ways:

- Use DOE-STD-1153-2002, A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota.
- Use an alternative approach to demonstrate that the dose rates to representative biota populations do not exceed the dose rate criteria in DOE-STD-1153-2002, Table 2.2.
- Use an ecological risk assessment to demonstrate that radiation and radioactive material released from DOE operations will not adversely affect populations within the ecosystem.

Because of the diversity of biota and the variety of pathways and radionuclides that need to be considered, it is not possible to develop a single generalized model that can be assumed to cover all possible conditions. Instead, DOE developed DOE-STD-1153-2002 (DOE 2002a) that provides the methods, models, and guidance within a graded approach that DOE and its contractors may use to evaluate radiation doses to populations of aquatic animals, terrestrial plants, and terrestrial animals from DOE activities. The intent is to provide a means of meeting the DOE requirements for protection of biota.

> DOE O 458.1 requirements and tools are to help protect the health of the ecosystems around DOE sites, and are not intended to be applied to individual organisms.

The DOE graded approach includes a screening method and three detailed levels of analysis for demonstrating compliance. RESRAD-BIOTA is the preferred or recommended computer program to use to meet DOE-STD-1153-2002.

9.9 Dose Coefficients

DOE O 458.1 requires that DOE-approved dose coefficients be used to evaluate doses resulting from DOE radiological activities. Use of alternative dose coefficients need to be approved in accordance with DOE O 458.1.

Derived concentration guidelines (DCG) were issued in DOE 5400.5. Since then, the radiation protection framework on which Derived Concentration Standards (DCSs) are based has evolved with more sophisticated biokinetic and dosimetric information provided by the ICRP, thus enabling consideration of age and gender.

DOE-STD-1196-2011 establishes DCS values reflecting the current state of knowledge and practice in radiation protection. This Technical Standard also addresses radionuclides encountered at accelerator facilities. DCSs are radiological quantities used in the design and conduct of radiological environmental protection programs at DOE facilities and sites. These quantities provide reference values to control effluent releases from DOE facilities and may be used in implementing the ALARA process for environmental programs.

The DCSs are based on age-specific effective dose coefficients computed in the manner of ICRP (1996) and Federal Guidance Report 13 (EPA 1999), using revised gender-specific physiological parameters for members of the public set forth in ICRP Publication 89 (ICRP 2002), and the nuclear decay data of ICRP Publication 107 (ICRP 2008).

The DCSs represent the concentration of a given radionuclide in either water or air that results in a member of the public receiving 1 millisievert (mSv) (100 mrem) total effective dose (TED) following continuous exposure for one year for each of the following pathways: ingestion, submersion in air, and inhalation.

The tables of dose coefficients for an adult or Reference Person provided in Appendix A of DOE-STD-1196-2011 for ingestion, inhalation, and submersion can be used in estimating doses to the public for demonstrating compliance with DOE O 458.1. It should be noted that the adult dose factors are appropriate for worker related dose assessments and Reference Person factors should be used when assessing compliance of exposures to a representative person that is based on an age and gender average reference person and to the general population that may include members of the public of all ages.

9.10 Quality Assurance

The general QA provisions of Chapter 11 should be followed as they apply to performing calculations that assess dose impacts. Specific QA activity requirements for performing dose calculations for a facility/site are to be contained in the QA Plan associated with the facility.

12 REFERENCES

1. Title 42 U.S.C. 2011, et seq., *Atomic Energy Act of 1954*, as amended.

2. Title 42 U.S.C. 7401 et seq., *Clean Air Act*, as amended.

3. 40 CFR Part 60, Appendix A, *Test Methods.*

4. 40 CFR Part 61, *National Emission Standards for Hazardous Air Pollutants*.

5. 40 CFR Part 61, Subpart H. *National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities*.

6. 40 CFR Part 61, Subpart I, *National Emission Standards for Radionuclide Emissions from Federal Facilities Other Than Nuclear Regulatory Commission Licensees and Not Covered by Subpart H*.

7. 40 CFR Part 61, Appendix B, *Method 114, Test Methods for Measuring Radionuclide Emissions from Stationary Sources*.

8. 40 CFR Part 61, Appendix D, *Methods for Estimating Radionuclide Emissions*.

9. 40 CFR Part 61, Appendix E, *Compliance Procedures Methods for Determining Compliance with Subpart I.*

10. 40 CFR Part 192, *Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings*.

11. Allen, D.E., “Determination of MDA for a Two Count Method for Stripping Short-Lived Activity Out of an Air Sample,” *Health Physics,* 73:512-517, 1997.

12. American National Standards Institute (ANSI), *Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities,* ANSI N13.1-1969, American National Standards Institute, New York, NY, 1970 (Reaffirmed 1982).

13. American National Standards Institute (ANSI), *Performance Criteria for Instrumentation Used for Inplant Plutonium Monitoring,* ANSI N317-1980, American National Standards Institute, New York, NY, 1980.

14. American National Standards Institute (ANSI), *Sampling and Monitoring Releases of Airborne Radioactive Substances from the Stacks and Ducts of Nuclear Facilities,*

ANSI/HPS N13.1-1999, American National Standards Institute and Health Physics Society, New York, NY, 1999 (Reaffirmed in 2011).

15. American National Standards Institute (ANSI), *Specification and Performance of Onsite Instrumentation for Continuously Monitoring Radioactivity in Effluents*, ANSI N42.18-2004, American National Standards Institute, New York, NY, 2004.

16. American National Standards Institute/ American Society for Quality (ANSI/ASQ), *Quality Systems for Environmental Data and Technology Programs: Requirements with Guidance for Use*, ANSI/ASQ E4-2004, American National Standards Institute, New York, NY, 2004.

17. American National Standards Institute (ANSI), *Determining Meteorological Information at Nuclear Facilities*, ANSI/ANS-3.11-2005; R2010, American National Standards Institute and American Nuclear Society, Washington, DC, 2005 (Reaffirmed in 2010).

18. American Public Health Association (APHA), *Methods of Air Sampling and Analysis,* 3rd ed., American Public Health Association, New York, NY, 1988.

19. American Public Health Association (APHA), *Standard Methods for the Examination of Water and Wastewater* (22nd ed.), E.W. Rice, R.B. Baird, A.D. Eaton and L.S. Clesceri (Eds.), American Public Health Association; American Water Works Association; and Water Environment Federation, Washington, DC, 2012.

20. American Society for Testing and Materials (ASTM), *Standard Practice for Calibration of Type S Pitot Tubes,* ASTM Standard D3796-90(2004), ASTM International, West Conshohocken, PA, 2004, www.astm.org.

21. American Society for Testing and Materials (ASTM), *Standard Test Method for Average Velocity in a Duct (Pitot Tube Method),* ASTM Standard D3154-00(2006), ASTM International, West Conshohocken, PA, 2006, www.astm.org.

22. American Society for Testing and Materials (ASTM), *Standard Test Method for Average Velocity in a Duct Using a Thermal Anemometer,* ASTM Standard D3464-96(2007), ASTM International, West Conshohocken, PA, 2007, www.astm.org.

23. American Society for Testing and Materials (ASTM), *Standard Practice for Sampling Surface Soils for Radionuclides,* ASTM Standard C998-05(2010)e1, ASTM International, West Conshohocken, PA, 2010a, www.astm.org.

24. American Society for Testing and Materials (ASTM), *Standard Practice for Soil Sample Preparation for the Determination of Radionuclides*, ASTM Standard C999-05(2010)e1, ASTM International, West Conshohocken, PA, 2010b, www.astm.org.

25. American Society for Testing and Materials (ASTM), *Standard Practice for Rotameter Calibration,* ASTM Standard D3195/D3195M-10, ASTM International, West Conshohocken, PA, 2010, www.astm.org.

26. American Society for Testing and Materials (ASTM). *Standard Test Method for Radiochemical Determination of Plutonium in Soil by Alpha Spectroscopy*. ASTM Standard C1001. ASTM International, West Conshohocken, PA, 2011, www.astm.org.

27. Anspaugh, L.R., J.J. Koranda, W.L. Robison, and J.R. Martin, *The Dose to Man Via Food-Chain Transfer Resulting from Exposure to Tritiated Water Vapor in Tritium*, Messenger Graphics, Las Vegas, NV, 1973.

28. Arndt, M.F. and L. West, "A Study of the Factors Affecting the Gross Alpha Measurement, and a Radiochemical Analysis of some Groundwater Samples from the State of Wisconsin Exhibiting an Elevated Gross Alpha Activity," Michael F. Arndt, Ph.D., Assistant Researcher, Radiochemistry Unit and Inorganic Chemistry Unit, Wisconsin State Laboratory of Hygiene, Lynn West, Radiochemistry Unit, Wisconsin State Laboratory of Hygiene, http://digital.library.wisc.edu/1711.dl/EcoNatRes.ArndtStudy http://www.slh.wisc.edu/ehd/radiochem/dnr_reports/dnrfinal.pdf, 2004.

29. Barnett, J.M. and W.E. Davis, "Six Methods to Assess Potential Radioactive Air Emissions From a Stack," *Health Physics*, 71(5):773-778, 1996.

30. Barnett, J.M., V.I. Cullinan, D.S. Barnett, T.L.T. Trang-Le, M. Bliss, L.R. Greenwood, and M.Y. Ballinger, "Results of a Self-Absorption Study on the Versapor 3000 47-mm Filters for Radioactive Particulate Air Stack Sampling," *Health Physics,* 97(5): S161-S168, 2009.

31. Bellamy, R.R., "Elemental Iodine and Methyl Iodide Adsorption on Activated Charcoal at Low Concentrations," *Nuclear Safety*, Volume 1516, pages 711-723, U.S. Atomic Energy Commission Technical Information Center, Oak Ridge, TN, 1974.

32. Beres, D.A., *The Clean Air Act Assessment Package – 1988 (CAP-88): A Dose and Risk Assessment Methodology for Radionuclide Emissions to Air*, U.S. Environmental Protection Agency, Office of Radiation Programs, Washington DC, 1990.

33. Briggs, G.A., "Plume Rise and Buoyancy Effects," in: D. Randerson (Ed.), *Atmospheric Science and Power Production*, DOE/TIC-27601, Technical Information Center, U.S. Department of Energy, Oak Ridge, TN, 1984.

34. Denham, D.H., "Environmental Radiological Surveillance in Perspective: The Relative Importance of Environmental Media as a Function of Effluent Pathway and Radionuclides," *Health Physics,* 36: 273-281, 1979.

35. Denham, D.H., D.A. Waite, and J.P. Corley, *Summary of Selected AEC Contractor Environmental Surveillance Techniques and Capabilities,* BNWLB-384, Pacific Northwest Laboratory, Richland, WA, 1974.

36. Department of Defense (DoD) and Department of Energy (DOE), *Consolidated Quality Systems Manual (QSM) for Environmental Laboratories*, 2013.

37. Department of Energy (DOE), *A Guide for Environmental Radiological Surveillance at U.S. Department of Energy Installations*, DOE/EP-0023, Washington, DC, 1981.

38. Department of Energy (DOE), *Radiological and Environmental Sciences Laboratory, Analytical Chemistry Branch Procedures Manual,* DOE/IDO-12096, 1982.

39. Department of Energy (DOE), *Enewetak Radiological Support Project- Final Report,* NVO-213, Nevada Operations Office, Las Vegas, NV, 1982.

40. Department of Energy (DOE), *A Guide for Effluent Radiological Measurements at DOE Installations,* DOE/EP-0096, Washington, DC, 1983.

41. Department of Energy (DOE), *Procedures for Sampling Radium-Contaminated Soils,* Grand Junction Projects Office, Colorado, GJ/TMC-13 (UC-70A), 1985.

42. Department of Energy (DOE), *Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance*, DOE/EH-0173T, Washington, DC, 1991.

43. Department of Energy (DOE), Radiation Protection of the Public and the Environment, DOE 5400.5, Change 2, Washington, DC, 1993.

44. Department of Energy (DOE), U.S. Department of Energy and U.S. Environmental Protection Agency, *Memorandum of Understanding Between the U.S. Environmental Protection Agency and the U.S. Department of Energy Concerning the Clean Air Act Emission Standards for Radionuclides 40 CFR Part 61 Including Subparts H, I, Q and T,* joint DOE/EPA agreement, 1995.

45. Department of Energy (DOE), *Radioactive Waste Management*, DOE O 435.1 Chg 1, Washington, DC, 2001.

46. Department of Energy (DOE), *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota*, DOE STD-1153-2002, Washington, DC, 2002a.

47. Department of Energy (DOE), *Performance Analysis of the Environmental Monitoring, Surveillance, and Control Programs within the U.S. Department of Energy*, Office of Independent Oversight and Performance Assurance, Washington, DC, 2002b.

48. Department of Energy (DOE), *Comprehensive Emergency Management System*, DOE O 151.1C, Washington, DC, 2005.

49. Department of Energy (DOE), Radiological Control, DOE-STD-1098-2008, Washington DC, 2008.

50. Department of Energy (DOE), *Radiation Protection of the Public and the Environment*, DOE O 458.1, Washington, DC, February 11, 2011.

51. Department of Energy (DOE), *Derived Concentration Technical Standard*, DOE-STD-1196-2011, Washington, DC, April 2011.

52. Department of Energy (DOE), *Quality Assurance,* DOE O 414.1D, Washington, DC, April 25, 2011.

53. Department of Energy (DOE), *Environment, Safety and Health Reporting*, DOE O 231.1B, Washington, DC, June 27, 2011.

54. Department of Energy (DOE), *Quality Assurance Program Guide*, DOE G 414.1-2B, Washington, DC, August 16, 2011.

55. Department of Energy (DOE), *Occurrence Reporting and Processing of Operations Information*, DOE O 232.2, Washington, DC, August 30, 2011.

56. Department of Energy (DOE), *Records Management Program*, DOE O 243.1B, Washington, DC, 2013.

57. dePlanque, G., T.F. Gesell, and K. Becker, "Second International Inter-comparison of Environmental Dosimeters Under Field and Laboratory Conditions," In *Proceedings of the Tenth Midyear Topical Symposium of the Health Physics Society*, pages 555-574, Rensselaer Polytechnic Institute, Troy, NY, 1976.

58. Eastern Research Group, *Methods for Estimating Fugitive Air Emissions of Radionuclides from Diffuse Sources at DOE Facilities*, Report prepared for the U.S. Environmental Protection Agency, http://www.epa.gov/radiation/neshaps/pubs.html), 2004.

59. Eisenbud, M. and T. Gesell, *Environmental Radioactivity*, Academic Press, 1997.

60. Environmental Protection Agency (EPA), *Environmental Radioactivity Surveillance Guide,* EPA ORP/SID 72-2, Office of Radiation Programs, Washington, DC, 1972.

61. Environmental Protection Agency (EPA), *Prescribed Procedures for Measurement of Radioactivity in Drinking Water*, EPA 600/4-80-032, Environmental Monitoring and Support Laboratory, Cincinnati, OH, 1980a.

62. Environmental Protection Agency (EPA), Method 901.1 (modified), *Gamma Emitting Radionuclides in Drinking Water*, EPA 600/4/80.032, Environmental Monitoring and Support Laboratory, Cincinnati, OH, 1980b.

63. Environmental Protection Agency (EPA), *Methods for Chemical Analysis of Water and Wastes,* EPA-600/4-79/020, Environmental Monitoring and Support Laboratory, Cincinnati, OH, 1983.

64. Environmental Protection Agency (EPA), Turner, J., M. Branscome, R. Chessin, A. Damle, and R. Kameth, *Method for Estimating Fugitive Particulate Emissions from Hazardous Waste Sites*, EPA-600/2-87/066, Washington, DC, 1987.

65. Environmental Protection Agency (EPA), *User's Guide for CAP88-PC Version 1.0*, EPA 402-B-92-001, Las Vegas, NV, 1992.

66. Environmental Protection Agency (EPA), Federal Guidance Report No. 13, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, EPA 402-R-99-001, Washington DC, 1999.

67. Environmental Protection Agency (EPA), *Meteorological Monitoring Guidance for Regulatory Modeling Applications*, EPA 454/R-99-005, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 2000a.

68. Environmental Protection Agency (EPA), *Updated User's Guide for CAP88-PC, Version 2.0*, EPA 402-R-00-004, Environmental Protection Agency, Office of Radiation and Indoor Air, Washington DC, 2000b.

69. Environmental Protection Agency, *Guidance for the Data Quality Objectives Process*, QA/G-4. Washington, DC, 2000c.

70. Environmental Protection Agency, *Guidance for Data Quality Assessment*, QA/G-9. Washington, DC, 2000d.

71. Environmental Protection Agency (EPA), Radionuclide NESHAPs Subpart H Inspection Manual, available at: http://www.epa.gov/radiation/docs/neshaps/nshpinspman_092702.pdf, 2002a.

72. Environmental Protection Agency (EPA), *Guidance for Comparing Background and Chemical Concentrations in Soil for CERCLA Sites*. EPA 540-R-01-003/OSWER 9285.7-41, 2002b.

73. Environmental Protection Agency (EPA), *Data Quality Assessment: Statistical Methods for Practitioners, EPA QA/G-9S*. EPA/240/B-06/003, Office of Environmental Information, Washington, DC, 2006.

74. Environmental Protection Agency (EPA), *Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities: Unified Guidance*, EPA 530/R-09-007, 2009.

75. Environmental Protection Agency (EPA), *ProUCL Version 5.0.00 User Guide - Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations*. EPA/600/R-07/041, Office of Research and Development, Washington, DC, 2013a.

76. Environmental Protection Agency (EPA), *ProUCL Version 5.0.00 Technical Guide - Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations*. EPA/600/R-07/041, Office of Research and Development, Washington, DC, 2013b.

77. Gifford, F.A., "Turbulent Diffusion-Typing Schemes: A Review," *Nuclear Safety* 17(1):68-86, 1976.

78. Gilbert, R.O., *Statistical Methods for Environmental Pollution Monitoring,* Van Nostrand Reinhold Co., New York, NY, 1987.

79. Gilbert, R.O. and R.R. Kinnison, "Statistical Methods for Estimating the Mean and Variance from Radionuclide Data Sets Containing Negative, Unreported or Less-Than Values," *Health Physics,* 40: 377-390, 1981.

80. Gilbert, T.L., C. Yu, Y.C. Yuan, A.J. Zielen, M.J. Jusko, and A. Wallo III., *A Manual for Implementing Residual Radioactive Material Guidelines.* ANL/ES-160, DOE/CH/8901, Argonne National Laboratory, Argonne, IL, 1989.

81. Griffin, W.R., J.A. Cochran, and A.A. Bertuccio, *A Sampler for Nonaqueous Tritium Gases*, U.S. Environmental Protection Agency, Office of Radiation Programs, Winchester, MA, 1972.

82. Grossman, R.F. and R.W. Holloway, "Concentrations of Krypton-85 near the Nevada Test Site," *Environmental Science and Technology*. 19:1128-1131, 1985.

83. Guthrie, E.B., N.C. Shen, and B.B. Bandong, *Isotope Exchange and Fractionation Corrections for Extraction of Tritiated Water in Silica Gel by Freeze-Drying Techniques,* Lawrence Livermore National Laboratory Report UCRL-ID-148610, 2001.

84. Hanna, S.R., G.A. Briggs, J. Deardorff, B.A. Egan, F.A. Gifford, and F. Pasquill, "AMS Workshop on Stability Classification Schemes and Sigma Curves – Summary of Classification Recommendations," *Bulletin of the American Meteorological Society* 58:1305-1309, 1977.

85. HASL-195, *The Radiation Field in Air Due to Distributed Gamma-Ray Sources in the Ground,* New York Operations Office (Atomic Energy Commission) New York Health and Safety Laboratory, New York, NY, 1968.