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Standard Guide for Representative Sampling for Management of Waste and Contaminated Media[1]

1. Scope

1.1 This guide covers the definition of representativeness in environmental sampling, identifies sources that can affect representativeness (especially bias), and describes the attributes that a representative sample or a representative set of samples should possess. For convenience, the term" representative sample" is used in this guide to denote both a representative sample and a representative set of samples, unless otherwise qualified in the text.

1.2 This guide outlines a process by which a representative sample may be obtained from a population. The purpose of the representative sample is to provide information about a statistical parameter(s) (such as mean) of the population regarding some characteristic(s) (such as concentration) of its constituent(s) (such as lead). This process includes the following stages: (*1*) minimization of sampling bias and optimization of precision while taking the physical samples, (*2*) minimization of measurement bias and optimization of precision when analyzing the physical samples to obtain data, and (*3*) minimization of statistical bias when making inference from the sample data to the population. While both bias and precision are covered in this guide, major emphasis is given to bias reduction.

1.3 This guide describes the attributes of a representative sample and presents a general methodology for obtaining representative samples. It does not, however, provide specific or comprehensive sampling procedures. It is the user's responsibility to ensure that proper and adequate procedures are used.

1.4 The assessment of the representativeness of a sample is not covered in this guide since it is not possible to ever know the true value of the population.

1.5 Since the purpose of each sampling event is unique, this guide does not attempt to give a step by step account of how to develop a sampling design that results in the collection of representative samples.

1.6 Appendix X1 contains two case studies, which discuss the factors for obtaining representative samples.

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

2. Referenced Documents

2.1 *ASTM Standards:*

D 3370 Practices for Sampling Water from Closed Conduits[2]
D 4448 Guide for Sampling Groundwater Monitoring Wells[3]
D 4547 Practice for Sampling Waste and Soils for Volatile Organic Compounds[3]
D 4700 Guide for Soil Sampling from the Vadose Zone[4]
D 4823 Guide for Core Sampling Submerged, Unconsolidated Sediments[5]
D 5088 Practice for Decontamination of Field Equipment Used at Nonradioactive Waste Sites[4]
D 5792 Practice for Generation of Environmental Data Related to Waste Management Activities: Development of Data Quality Objectives[3]
D 5956 Guide for Sampling Strategies for Heterogeneous Wastes[3]
D 6051 Guide for Composite Sampling and Field Subsampling for Environmental Waste Management Activities[3]

3. Terminology

3.1 *analytical unit, n*—the actual amount of the sample material analyzed in the laboratory.

3.2 *bias*, *n*—a systematic positive or negative deviation of the sample or estimated value from the true population value.

3.2.1 *Discussion*—This guide discusses three sources of bias—sampling bias, measurement bias, and statistical bias.

There is a sampling bias when the value inherent in the physical samples is systematically different from what is inherent in the population.

There is a measurement bias when the measurement process produces a sample value systematically different from that

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[2] *Annual Book of ASTM Standards*, Vol 11.01.
[3] *Annual Book of ASTM Standards*, Vol 11.04.
[4] *Annual Book of ASTM Standards*, Vol 04.08.
[5] *Annual Book of ASTM Standards*, Vol 11.02.

inherent in the sample itself, although the physical sample is itself unbiased. Measurement bias can also include any systematic difference between the original sample and the sample analyzed, when the analyzed sample may have been altered due to improper procedures such as improper sample preservation or preparation, or both.

There is a statistical bias when, in the absence of sampling bias and measurement bias, the statistical procedure produces a biased estimate of the population value.

Sampling bias is considered the most important factor affecting inference from the samples to the population.

3.3 *biased sampling, n*—the taking of a sample(s) with prior knowledge that the sampling result will be biased relative to the true value of the population.

3.3.1 *Discussion*—This is the taking of a sample(s) based on available information or knowledge, especially in terms of visible signs or knowledge of contamination. This kind of sampling is used to detect the presence of localized contamination or to identify the source of a contamination. The sampling results are not intended for generalization to the entire population. This is one form of authoritative sampling (see *judgment sampling*.)

3.4 *characteristic, n*—a property of items in a sample or population that can be measured, counted, or otherwise observed, such as viscosity, flash point, or concentration.

3.5 *composite sample, n*—a combination of two or more samples.

3.6 *constituent, n*— an element, component, or ingredient of the population.

3.6.1 *Discussion*—If a population contains several contaminants (such as acetone, lead, and chromium), these contaminants are called the constituents of the population.

3.7 *Data Quality Objectives, DQOs, n*—qualitative and quantitative statements derived from a DQO process describing the decision rules and the uncertainties of the decision(s) within the context of the problem(s) (see Practice D 5792).

3.8 *Data Quality Objective Process*—a quality management tool based on the Scientific Method and developed by the U.S. Environmental Protection Agency to facilitate the planning of environmental data collection activities. The DQO process enables planners to focus their planning efforts by specifying the use of data (the decision), the decision criteria (action level), and the decision maker's acceptable decision error rates. The products of the DQO process are the DQOs (see Practice D 5792).

3.9 *error, n*—the random or systematic deviation of the observed sample value from its true value (see *bias* and *sampling error*).

3.10 *heterogeneity, n*—the condition or degree of the population under which all items of the population are not identical with respect to the characteristic(s) of interest.

3.10.1 *Discussion*—Although the ultimate interest is in the statistical parameter such as the mean concentration of a constituent of the population, heterogeneity relates to the presence of differences in the characteristics (for example, concentration) of the units in the population. It is due to the presence of fundamental heterogeneity (or fundamental error)[6] in the population that sampling variance arises. Degree of sampling variance defines the degree of precision in estimating the population parameter using the sample data. The smaller the sampling variance is, the more precise the estimate is. See also *sampling error*.

3.11 *homogeneity, n*— the condition of the population under which all items of the population are identical with respect to the characteristic(s) of interest.

3.12 *judgment sampling, n*—taking of a sample(s) based on judgment that it will more or less represent the average condition of the population.

3.12.1 *Discussion*—The sampling location(s) is selected because it is judged to be representative of the average condition of the population. It can be effective when the population is relatively homogeneous or when the professional judgment is good. It may or may not introduce bias. It is a useful sampling approach when precision is not a concern. This is one form of authoritative sampling (see *biased sampling*.)

3.13 *population, n*—the totality of items or units of materials under consideration.

3.14 *representative sample, n*—a sample collected in such a manner that it reflects one or more characteristics of interest (as defined by the project objectives) of a population from which it is collected.

3.14.1 *Discussion*—A representative sample can be a single sample, a collection of samples, or one or more composite samples. A single sample can be representative only when the population is highly homogeneous.

3.15 *representative sampling, n*—the process of obtaining a representative sample or a representative set of samples.

3.16 *representative set of samples, n*—a set of samples that collectively reflect one or more characteristics of interest of a population from which they were collected. See *representative sample*.

3.17 *sample, n*—a portion of material that is taken for testing or for record purposes.

3.17.1 *Discussion*—Sample is a term with numerous meanings. The scientist collecting physical samples (for example, from a landfill, drum, or monitoring well) or analyzing samples considers a sample to be that unit of the population that was collected and placed in a container. A statistician considers a sample to be a subset of the population, and this subset may consist of one or more physical samples. To minimize confusion, the term *sample*, as used in this guide, is a reference to either a physical sample held in a sample container, or that portion of the population that is subjected to in situ measurements, or a set of physical samples. See *representative sample*.

3.17.1.1 The term *sample size* also means different things to the scientist and the statistician. To avoid confusion, terms such as sample mass/sample volume and number of samples are used instead of sample size.

[6] Pitard, F. F., "*Pierre Gy's Sampling Theory and Sampling Practice: Heterogeneity, Sampling Correctness and Statistical Process Control*," 2nd ed., CRC Press Publishers, 1993.

3.18 *sampling error*—the systematic and random deviations of the sample value from that of the population. The systematic error is the *sampling bias*. The random error is the *sampling variance*.

3.18.1 *Discussion*—Before the physical samples are taken, potential sampling variance comes from the inherent population heterogeneity (sometimes called the "fundamental error," see *heterogeneity*). In the physical sampling stage, additional contributors to sampling variance include random errors in collecting the samples. After the samples are collected, another contributor is the random error in the measurement process. In each of these stages, systematic errors can occur as well, but they are the sources of bias, not sampling variance.

3.18.1.1 Sampling variance is often used to refer to the total variance from the various sources.

3.19 *stratum, n*—a subgroup of the population separated in space or time, or both, from the remainder of the population, being internally similar with respect to a target characteristic of interest, and different from adjacent strata of the population.

3.19.1 *Discussion*—A landfill may display spatially separated strata, such as old cells containing different wastes than new cells. A waste pipe may discharge into temporally separated strata of different constituents or concentrations, or both, if night-shift production varies from the day shift. In this guide, strata refer mostly to the stratification in the concentrations of the same constituent(s).

3.20 *subsample, n*—a portion of the original sample that is taken for testing or for record purposes.

4. Significance and Use

4.1 Representative samples are defined in the context of the study objectives.

4.2 This guide defines the meaning of a representative sample, as well as the attributes the sample(s) needs to have in order to provide a valid inference from the sample data to the population.

4.3 This guide also provides a process to identify the sources of error (both systematic and random) so that an effort can be made to control or minimize these errors. These sources include sampling error, measurement error, and statistical bias.

4.4 When the objective is limited to the taking of a representative (physical) sample or a representative set of (physical) samples, only potential sampling errors need to be considered. When the objective is to make an inference from the sample data to the population, additional measurement error and statistical bias need to be considered.

4.5 This guide does not apply to the cases where the taking of a nonrepresentative sample(s) is prescribed by the study objective. In that case, sampling approaches such as judgment sampling or biased sampling can be taken. These approaches are not within the scope of this guide.

4.6 Following this guide does not guarantee that representative samples will be obtained. But failure to follow this guide will likely result in obtaining sample data that are either biased or imprecise, or both. Following this guide should increase the level of confidence in making the inference from the sample data to the population.

4.7 This guide can be used in conjunction with the DQO process (see Practice D 5792).

4.8 This guide is intended for those who manage, design, and implement sampling and analytical plans for waste management and contaminated media.

5. Representative Samples

5.1 Samples are taken to infer about some statistical parameter(s) of the population regarding some characteristic(s) of its constituent(s) of interest. This is discussed in the following sections.

5.2 *Samples*—When a representative sample consists of a single physical sample, it is a sample that by itself reflects the characteristics of interest of the population. On the other hand, when a representative sample consists of a set of physical samples, the samples collectively reflect some characteristics of the population, though the samples individually may not be representative. In most cases, more than one physical sample is necessary to characterize the population, because the population in environmental sampling is usually heterogeneous.

5.3 *Constituents and Characteristics*—A population can possess many constituents, each with many characteristics. Usually it is only a subset of these constituents and characteristics that are of interest in the context of the stated problem. Therefore, samples need to be representative of the population only in terms of these constituent(s) and characteristic(s) of interest. A sampling plan needs to be designed accordingly.

5.4 *Parameters*—Similarly, samples need to be representative of the population only in the parameter(s) of interest. If the interest is only in estimating a parameter such as the population mean, then composite samples, when taken correctly, will not be biased and therefore constitute a representative sample (regarding bias) for that parameter. On the other hand, if the interest happens to be the estimation of the population variance (of individual sampling units), another parameter, then the variance of the composite samples is a biased estimate of the population variance and therefore is not representative. (It is to be noted that composite samples are often used to increase the precision in estimating the population mean and not to estimate the population variance of individual sampling units.)

5.5 *Population*—Since the samples are intended to be representative of a population, a population must be well defined, especially in its spatial or temporal boundaries, or both, according to the study objective.

5.6 *Representativeness*—The word "reflects" in this guide is used to mean a certain degree of low bias and high precision when comparing the sample value(s) to the population value(s). This is a broad definition of sample representativeness used in this guide. A narrower definition of representativeness is often used to mean simply the absence of bias.

5.6.1 *Bias*—Bias is sometimes mistakenly taken to be "a difference between the observed value of a physical sample and the true population value." The correct definition of bias is "a *systematic* (or consistent) difference between an observed (sample) value and the true population value." The word "systematic" here implies "on the average" over a set of physical samples, and not a single physical sample. Recall that sampling error consists of the random and systematic deviations of a sample (or estimated) value from that of the population. Although random deviations may occur on occasions due to imprecision in the sampling or measurement processes, or both, they balance out on the average and lead to no systematic difference between the sample (or estimated) value and the population value. The random deviation corresponds to the observation of "a random difference between a single physical sample value and the true population value," which can be randomly positive or negative, and is not a bias. On the other hand, a persistent positive or negative difference is a systematic error and is a bias.

5.6.1.1 In order to assess bias, the true population value must be known. Since the true population value is rarely known, bias cannot be quantitatively assessed. However, this guide provides an approach to identifying the potential sources of bias and general considerations for controlling or minimizing these potential biases.

5.6.2 *Precision*—Precision has to do with the level of confidence in estimating the population value using the sample data. If the population is totally homogeneous and the measurement process is flawless, a single sample will provide a completely precise estimate of the population value. When the population is heterogeneous or the measurement process is not totally precise, or both, a larger number of samples will provide a more precise estimate than a smaller number of samples.

5.6.2.1 In the case of bias, the goal in environmental sampling is its absence. In the case of precision, the goal in sampling will depend on factors such as:

(1) The precision level needed to achieve the desired levels of decision errors, both false positive and false negative errors,

(2) If the true value is known or suspected to be well below the regulatory limit, high precision in the samples may not be needed, and

(3) The study budget.

5.6.2.2 Note that the second item applies similarly to bias as well.

5.6.2.3 Since bias, especially during sampling, can be very large when proper procedures are not followed, it is considered to be the first necessary condition for sample representativeness. On the other hand, precision can be more or less controlled, for example, by increasing the number of samples taken or by decreasing the sampling or measurement variabilities, or both.

5.6.2.4 The optimal number of samples to take to achieve a desired level of precision is typically an issue in optimization of a sampling plan. Therefore, the precision issue will be covered only briefly in this guide.

6. A Systematic Approach to Representative Sampling

6.1 A systematic approach is one that first defines the desired end result and then designs a process by which such a result can be obtained. In representative sampling, the desired end result is a sample or a set of samples that achieves desired levels of low bias and high precision.

6.2 A representative sampling process is described in Fig. 1. The key components in the process are described in this section.

6.3 *Study Objective*— A sampling plan is designed according to a defined problem or a stated study objective. The samples are then collected according to the sampling plan. Generally, the study objective dictates that representative samples be taken for the purpose of inference about the

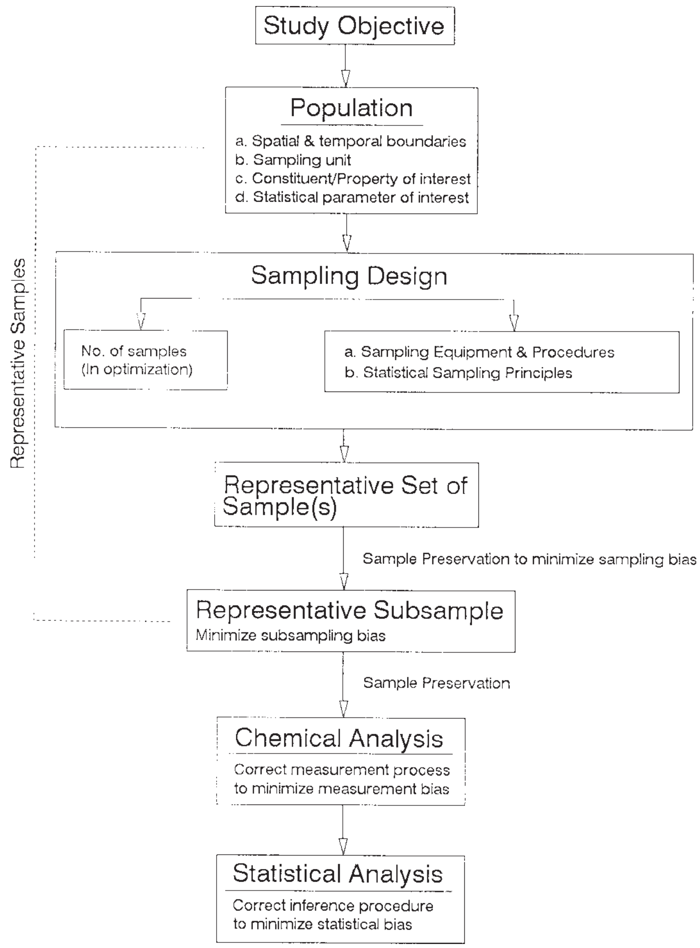

FIG. 1 A Systematic Approach to Representative Sampling

population. In that case, these samples will need to be collected according to this guide in order for the inference to be valid. Occasionally, the objective is merely to detect the presence of a contaminant or to obtain a "worst case" sample. In that case, an authoritative sampling approach (biased sampling or judgment sampling) may be taken and this guide does not apply.

6.4 *Population*—A population consists of the totality of items or units of materials under consideration (Compilation of ASTM Standard Definitions, 1990). Its boundaries (spatial or temporal, or both) are defined according to the problem statement. This population is usually called the *target population*. In order to solve the stated problem, samples must be taken from the target population.

6.4.1 *Sampled Population*—Sometimes some parts of the target population may not be amenable to sampling due to factors such as accessibility. The boundaries of the target population actually sampled due to factors such as incomplete accessibility define the sampled population.

6.4.1.1 Although the samples taken from the sampled population may be representative of the sampled population, they may not be representative of the target population. In this case, potential exists that the samples taken from the sampled population may systematically deviate from the true value of the target population, thereby introducing bias when making inference from the samples to the target population.

6.4.1.2 When the boundaries of the target and sampled populations are not identical, some possible solutions are:

(1) The parties to the decision-making may agree that the sampled population is a sufficient approximation to the target population. A sampling plan can then be designed to take representative samples from the" sampled population,"

(2) Qualifications on the sampling results are made based on the differences between the two populations. Some professional judgment may have to be exercised here, and

(3) Redefine the problem by considering what problem is solvable based on the observed differences between the two populations.

6.4.1.3 Occasionally, the sampled population is chosen on purpose to be different from the target population. For example, an investigator may be interested in the lead content in the sludge of a surface impoundment (the target population). He may decide to take samples from the sludge near the inlet (sampled population). Thus, the impoundment is the target population, while the inlet area is the sampled population. If the interest is in the target population, then this is an example of a biased sampling approach. On the other hand, the involved parties may decide to redefine the target population to include only the inlet area. Then the target population and the sampled population are identical. Again, the definition of a population depends on the problem statement.

6.4.1.4 In yet other circumstances, an investigator may take only a sample from the population. The following cases are possible:

(1) This one physical sample can be a sample from a biased sampling approach, for the purpose of detecting the presence of a contaminant or identifying the source of contamination. Therefore, it is not a representative sample due to its bias,

(2) This one physical sample can be a sample from judgment sampling, for the purpose of estimating the average condition of the population. Bias may or may not exist depending to some degree on the expertise of the sampler,

(3) This sample can be viewed as a population itself if the investigator is interested in the sample alone and a result from this sample is not to be used to infer to areas outside the sample. In this case, no bias exists, and

(4) If this sample is the composite of a few samples taken from the population, bias is likely to be minimal if the original samples are carefully taken.

6.4.2 *Decision Unit*—Often a population may be divided into several exposure units, cleanup units, or strata. If the environmental management decision is to be made for the entire population as a whole, representative samples can be obtained by designs such as a stratified random sampling design. Here the entire population is the decision unit. On the other hand, if the decision is to be made on each unit or stratum, then each unit or stratum is the decision unit. In this case, representative sample(s) need to be taken from each unit or stratum as if the unit or stratum is the population.

6.4.2.1 If the units or strata are relatively small in size or too numerous to take many samples per unit or stratum, composite sample(s) can be taken from each unit or stratum to increase precision without introducing bias. Alternatively, if precision is not a concern and there is sufficient professional expertise to avoid bias, a judgment sample(s) can be taken from each unit or stratum.

6.4.3 *Heterogeneity*— Heterogeneity is discussed in greater detail in Guide D 5956.

6.4.3.1 The degree and extent of population heterogeneity affect potential bias and precision in the samples. Population heterogeneity can be viewed at least in three different ways:

(1) When the population is heterogeneous in a random manner in only the distribution of the concentration, but not in the physical materials such as particle sizes, designs such as a simple random sampling design will generally produce samples with minimal bias. Its precision will then depend on the number of samples taken,

(2) When the population is randomly heterogeneous in concentrations due to large differences in the materials such as particle size, a simple random sampling design may still be effective if the sample volume/weight and sampling equipment are chosen to accommodate the largest particles and thereby prevent introduction of bias, and

(3) If the population is systematically heterogeneous, such as the presence of stratification in concentrations, then a simple random sampling design may not be biased, but will be less precise than an alternative design such as stratified random sampling.

6.4.3.2 Heterogeneity in the population affects the sampling variance. Sampling variance is a function of factors such as the population heterogeneity and the sample volume or weight. It is clear that the more heterogeneous the population is, the larger the inherent sampling variance is. It is also clear that samples of smaller volume or weight will have a higher sampling variance than those with greater volume or weight. However, the reduction in sampling variance due to increased volume or weight may eventually reach a limit. Determination of the optimal sample volume or weight is beyond the scope of this guide.[6]

6.4.3.3 The proper procedure is to first determine the right sample volume or weight, then to determine the number of samples needed for the chosen sample volume or weight.

6.4.3.4 Since stratification as a phenomenon of population heterogeneity is fairly common, it is discussed in greater details as follows.

6.4.4 *Stratification*—There are generally three types of stratification affecting sample representativeness. One is a stratification in the distribution of the contaminant concentration distribution alone. The second is a stratification in sampling materials or matrices alone. The third is a combination of both types. Stratification of any type is not a big problem regarding sample representativeness if each stratum is a decision unit. In that case, the units in a stratum are by definition relatively similar, apart from the random variations in concentrations. A simple random sampling design can be used to obtain representative samples (unbiased) for each stratum. The question of sample representativeness becomes more complicated when a decision is to be made over all the strata in the population.

6.4.4.1 *A Single Representative Sample in A Stratified Population*—When the objective is to obtain a single (physical) representative sample of all the strata, the sample must be a composite of individual samples from the strata (for example, at least one individual sample per stratum). Here the volumes or weights of the individual samples should be proportional to the relative stratum sizes. The composite sample so obtained would be unbiased. However, since there is only one composite sample, precision of the composite sample cannot be estimated. If there are existing data on the precision of the individual samples in the strata, then the precision of the composite sample can be inferred from the precision of the individual samples by theoretical or empirical relationship. See Guide D 6051.

6.4.4.2 *A Representative Set of Samples*—When the population is stratified, a set of samples obtained by statistical designs such as stratified random sampling, where the number of samples to be taken from the strata are proportional to the relative sizes of the strata, is unbiased and more precise than a set of samples taken without considering the stratification.

6.4.5 *Parameter(s) of Interest*—This refers to the statistical parameter such as mean or variance of the population. It is often used with a characteristic such as concentration of a constituent(s) of the population. An example is the mean (parameter) concentration (characteristic) of lead (constituent). Another example is a population of mixture of silt-size calcium carbonate particles and large cobble-size particles of calcium carbonate. The interest here could be in the mean (parameter) particle size or chemical composition (characteristic) of calcium carbonate (constituent), depending on the study objective.

6.5 *Develop A Sampling Design*—The objectives of a sampling design are to minimize bias and achieve a desired level of precision. Precision and bias are an issue at various stages of the process of inferring from the samples to the population. The first stage is the act of obtaining the physical samples. The second stage is the act of analyzing the physical samples and translating them into data. The third stage is the use of statistical method to infer from the sample data to the population. At the first stage, the main concerns are sampling precision and bias. At the second stage, the concerns are measurement of precision and bias. At the third stage, the concern is statistical bias.

6.5.1 At the first stage of obtaining physical samples, the issues of precision and bias are sometimes grouped together as sampling design issues.

6.5.2 Bias at this stage is often called the sampling bias. Sampling bias is the systematic difference between the value inherent in the physical samples and the true population value. The word "inherent" is used because at this point the physical samples have not been translated into data.

6.5.3 The phrase "systematic difference" implies a persistent difference in long-term average or expectation, not the occasional random difference. Representative samples, apart from the issue of precision, are obtained when this long-term expected difference is zero or nearly so.

6.5.4 Since the true population value is typically not known, sampling bias cannot be assessed. However, efforts to minimize sampling bias can be attempted in at least two areas:

6.5.4.1 *Proper Statistical Sampling Design*—Statistical sampling design has to do with where and how samples are to be taken, where equal probability of selecting any of the units or items in the population is often a primary requirement. If the probability of selection is not equal, it is highly likely that bias will have been introduced into the physical samples so obtained. Depending on the layout of the population, designs such as simple random sampling or stratified random sampling can be used.

6.5.4.2 *Proper Sampling Procedures and Sampling Equipment*—This includes proper procedures for compositing, subsampling, sample preparation and preservation, and proper use of the chosen sampling equipment. This is a major source affecting precision and bias, especially bias.

6.5.5 In the case of precision, it can be controlled by things such as the number of samples taken, the use of composite samples, or more precise sampling techniques. Often, the number of samples to take is considered the key design issue. Some considerations regarding precision are:

6.5.5.1 If a population is relatively small compared to the sample mass/volume and the distribution of the characteristic of interest is random, it may be appropriate to collect a smaller number of samples by a random or systematic sampling approach, and

6.5.5.2 If a population is relatively large compared to sample mass/volume and the characteristic of interest is not randomly distributed (for example, stratified), a greater number of samples and a stratified sampling approach may be needed.

6.5.6 *Compositing*— Compositing is the combination of two or more individual physical samples into a single sample. It is often used to reduce the analytical costs, while maintaining or increasing precision relative to the individual samples (see Guide D 6051). Bias may or may not be introduced in compositing, depending on the study objective and the physical means of compositing. For example:

6.5.6.1 If the study calls for the estimation of the population variance (or standard deviation) of individual samples, then composite samples will surely underestimate the population variance, and

6.5.6.2 If the physical means of compositing changes the characteristics of the samples, then bias may have been introduced (unless such changes are part of the study design).

6.6 *Subsampling*— Sampling bias can be introduced in subsampling unless the same proper sampling protocol is followed as in taking samples from the original population.

6.6.1 *Discussion*—After the physical samples have been obtained and before they are measured, bias can be prevented by following proper sample preservation and preparation procedures. It is not important whether these procedures are viewed as part of the sampling process or as part of the measurement process. It is only important in following the proper procedures to prevent bias.

6.7 *Measurement of Precision and Bias*:

6.7.1 The measurement process, like the sampling process, also consists of a random error and a systematic error. The random errors define the degree of measurement precision, and the systematic error defines the degree of measurement bias.

6.7.2 Like sampling precision, measurement precision is controlled by things such as the number of replicate analyses performed per sample and refinements of the analytical method.

6.7.3 Measurement bias is a systematic difference between the sample value produced by the measurement process and the true population value, assuming that the physical samples are unbiased before the analysis. The bias can come from contamination, loss or alteration of the sample materials, systematic errors in the measurement device, or from systematic human errors.

6.7.4 Often the measurement bias can be reasonably estimated in a laboratory testing setting when the true value is known. Laboratory samples spiked with known quantities of a chemical or certified reference standard can often be used to assess potential measurement bias. Minimization or adjustment for such estimable bias in the measurement process is essential in order to obtain data that are unbiased. When estimation of bias is not possible, care in measurement protocol and training is probably the only recourse.

6.7.4.1 *Discussion*—It is important to note that, when inferring from the sample data to the population, all the sources of imprecision, including sampling, subsampling, and measurement, need to be combined. The process of accumulating these sources of variation is sometimes called the "propagation of errors." The determination of the optimal numbers of samples, subsamples, and replicates are an issue of optimization and is not covered in this guide.

6.8 *Statistical Bias*—Statistical bias can result from an inappropriate sampling design or inappropriate estimation procedures, or both:

6.8.1 *Selection Bias from Sampling Design*—In the course of taking the sample, if the population units do not have the same probability of being selected, bias can be introduced. This bias can be prevented or minimized when a statistical sampling design is carefully selected, based on the study objective and the layout of the population. Some possible designs are the simple random sampling design and the stratified random sampling design.

6.8.2 *Estimation of Bias from Estimation Procedures*—This bias occurs when the expected value of the statistical estimator does not equal the true value.

6.8.2.1 Estimation bias can occur when the wrong statistical distribution of the data is used. For example, if the normal distribution assumption is used when the true data distribution is lognormal, the interval estimate of the mean concentration will be an biased estimate against the true interval. Thus, the expected value of the estimator will not be equal to the true value. To avoid this potential bias, it is wise to check the data distribution.

6.8.2.2 Estimation bias can also occur when a wrong statistical estimator is used. For example, if the sum of squares of deviations from the sample mean divided by the number of samples (that is, $\Sigma_{i = 1,n} (x_i - \bar{x})^2/n$) is used to estimate the population variance, then this estimator is biased (its mathematical expected value is not equal to the population variance). If its denominator is modified to be $(n - 1)$, then it is an unbiased estimator. For an unbiased statistical estimator, the reader is advised to check with a statistician.

7. Attributes of Representative Samples

7.1 The attributes of a representative (physical) sample or a representative set of (physical) samples can be described in the chronological order in which samples are taken. Note that these attributes apply only to how representative the physical samples are of the population. This corresponds to the upper half of Fig. 1.

7.2 *Design Considerations*:

7.2.1 A well-defined target population. The target population includes all the population units as determined from the stated problem.

7.2.2 The sampled population equals the target population in their spatial or temporal boundaries, or both. The sampled population consists of the population units directly available for measurement.[7]

7.2.2.1 When all the population units in the target population are accessible and directly available for measurement, then the sampled population is identical to the target population in its spatial or temporal boundaries, or both.

7.2.2.2 When not all the population units are directly available for measurement, then the inference from the sample is made to the sampled population, not the target population.

7.2.3 Size (weight or volume) of the sampling unit is well defined.

7.2.3.1 The population can be divided into various sizes (weight or volume) of population units. The size of the sampling unit is the size of the population unit most appropriate for the sampling purposes.

7.2.3.2 The appropriate size of the sample is determined by degree of heterogeneity of the materials to be sampled, such as particle size or shape.

7.3 *Sampling and Measurement Considerations*:

7.3.1 Correct sampling procedures are followed to minimize sampling bias.

7.3.1.1 Absence or minimization of bias is a key attribute of representative samples. Sampling bias can be minimized by following correct sampling procedures. Correct sampling procedures have two components.

(1) A sampling procedure that maximizes the potential of population units having equal probability of selection as sampled, and

(2) Correct sampling procedures. This includes the selection of appropriate equipment and proper use of that equipment.

7.3.2 Sample integrity is maintained during sampling and before chemical analysis.

7.3.3 If subsampling is performed, correct sampling procedures are followed to minimize sampling bias.

7.3.4 Sample preparation errors such as contamination and loss or alteration of constituents are prevented or minimized.

7.3.5 The samples, in the end, collectively reflect the target population within the context of the problem.

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[7] Gilbert, Richard O., *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinholt Co., New York, NY 1987.

7.3.6 These attributes can be summarized into three broad categories:

7.3.6.1 A well-defined population,

7.3.6.2 Correct sampling procedures, and

7.3.6.3 Samples collected in the context of the stated problem.

8. Practical Considerations

8.1 *Sampling Equipment*—The choice of appropriate sampling equipment can be crucial to the task of collecting a representative sample or a representative set of samples. Depending on the goals of the sampling activity, the sampling device used should minimize bias by having certain characteristics and capabilities, such as:

8.1.1 The ability to access and extract from every location in the target population,

8.1.2 The ability to collect a sample of proper shape,

8.1.3 The ability to collect a sufficient mass or volume of sample such that the distribution of particle sizes in the population are represented, and

8.1.4 The ability to collect a sample without the addition or loss of contaminants of interest.

8.2 *Equipment Design*—The improper design of sampling equipment may result in the collection of samples that are not representative of the population.

8.2.1 An example of equipment design influencing sampling results is samplers which exclude certain sized particles from a soil matrix or waste pile sample. The shape of some scoops may influence the distribution of particle sizes collected from a sample. Dredges used to collect river or estuarine sediments may also exclude certain sized particles, particularly the fines fraction which may contain a significant percentage of some contaminants such as polynuclear aromatic hydrocarbons (PAHs). Specific considerations in equipment design are outlined as follows.

8.2.1.1 *Sample Volume Capabilities*—Most sampling devices will provide adequate sample volume. However, the sampling equipment volumes should be compared to the volume necessary for all required analyses and the additional amount necessary for quality control (QC), split and repeat samples. Taking more than one aliquot to obtain an adequate sample volume can impact the representativeness of a sample.

8.2.1.2 *Compatibility*—It is important that sampling equipment, other equipment that may come in contact with samples (such as gloves, mixing pans, knives, spatulas, spoons, etc.) and sample containers be constructed of materials that are compatible with the matrices and analytes of interest. Incompatibility may result in the contamination of the sample and the degradation of the sampling equipment.

8.2.1.3 *Decontamination (see Practice D 5088) and Reuse*—Inadequate decontamination of sampling equipment can result in contamination of the sample and affects its representativeness. Due to design, some equipment is very difficult to adequately decontaminate. In some instances, it may even be desirable to either dispose of sampling equipment after use or to dedicate the equipment to a sampling point.

8.3 *Sampling Procedure*—Inappropriate use of sampling equipment is one of the largest sources of sampling bias. While it is beyond the scope of this guide to discuss it in depth, examples of how bias can be introduced during the sampling procedure are discussed in the following paragraphs. This guide does not provide comprehensive sampling procedures. It is the responsibility of the user to ensure that proper and adequate procedures are used.

8.3.1 *Ground Water*—For a more comprehensive discussion of sampling ground water refer to Guide D 4448.

8.3.1.1 Ground-water samples are usually collected through an in-place well, either temporarily or permanently installed. The following is a list of concerns that should be considered when collecting a ground-water sample.

(1) The well should be purged before collecting samples in order to clear the well of stagnant water which is not representative of aquifer conditions. Purging and sampling rates can cause chemical or physical changes in the water.

(2) Purging can be performed in such a way that the entire column of water is not removed. The best method for avoiding this situation is by lowering a pump or bailer into the top of the column of water.

(3) Bailing may stir up sediment in the well if conducted too vigorously. Increased turbidity can result in a higher metal content in the sample than in a non-turbid sample.

(4) Samples for volatile organic analysis should be collected in a fashion that minimizes agitation of the sample.

(5) Wells with in-place plumbing must also be purged. Samples should be collected immediately following purging. In order to collect a sample representative of ground water, samples should be collected before the water travels through any hoses or in-line treatment devices.

8.3.2 *Surface Water and Sediment*—For a more comprehensive discussion of sampling surface water and sediment, refer to Practice D 3370 and Guide D 4823. General and specific sampling concerns for collection of surface water and sediment samples are as follows:

8.3.2.1 *General Considerations*:

(1) Although bridges and piers may provide access for water and sediment sampling, these structures can also alter the nature of water flow and thus influence sediment deposition or scouring. Depending on the construction materials, these structures can contaminate samples collected in the immediate vicinity.

(2) Wading for water samples should be done with caution since bottom deposits are easily disturbed resulting in increased sediment in surface water samples and a removal of fines from the sediment sample.

8.3.2.2 *Rivers, Streams, and Creeks*:

(1) A good location to collect a vertically mixed surface water sample is immediately downstream of a riffle area. This location is also a likely area for deposition of sediment since the greatest deposition occurs where stream velocity slows down.

(2) Horizontal (cross-channel) mixing occurs in constrictions in the channel. However, this is a poor sediment sample collection area because of scouring.

(3) Surface water samples will be affected by point sources, such as tributaries and industrial and municipal effluents.

(4) Locations immediately upstream or downstream from the confluence of two streams or rivers may not immediately mix, and at times, due to possible back flow, can upset the normal flow patterns.

(5) Unless a stream is extremely turbulent, it is nearly impossible to measure the effect of a waste discharge or tributary immediately downstream of the source. Inflow frequently "hugs" the stream bank with very little cross-channel mixing for some distance. Samples from quarter points across a stream may miss the wastes altogether and reflect only the quality of water upstream from the waste source. Samples collected within the portion of the cross section containing the wastes would indicate excessive effects of the wastes with respect to the river as a whole.

(6) When sampling tributaries, care should be exercised to avoid collecting water from the main stream that may flow into the mouth of the tributary on either the surface or bottom.

8.3.2.3 *Lakes, Ponds, and Impoundments*:

(1) Stratification of surface water is of greater concern in standing water. For example: A turbidity difference may occur vertically where a highly turbid river enters a lake, and each layer of the stratified water column may need to be considered. In addition, stratification may be caused by water temperature difference; cooler, heavier river water is beneath the warmer lake water.

(2) Dredges used to collect sediment samples can displace and miss lighter materials if allowed to drop freely.

(3) Core samplers used to sample vertical columns of sediment are useful when there is a need to know the history of sediment deposition. Coring devices also minimize the disturbance of fines at the sediment-water interface. However, coring devices can only sample a relatively small surface area. Depending on the core diameter, larger particles may be excluded and a single aliquot may not be sufficient for analytical needs.

8.3.3 *Soils*—For more detailed information, refer to Practice D 4547 and Guide D 4700. General areas of concern for sampling soils are as follows:

8.3.3.1 Soil samples for purgeable organic analyses should be collected with a minimum disturbance of the sample.

8.3.3.2 Samples for VOA analysis should not be mixed.

8.3.3.3 Two potential problems are associated with compositing soil samples. Low concentrations of contaminants present in individual aliquots may be diluted to the extent that the total composite concentration is below the minimum quantification limit. In addition, depending on the soil type, it can be very difficult to produce a homogeneous mixture.

8.3.4 *Waste*—Wastes referred to in this section include any liquid, solid, or sludge from pits, ponds, lagoons, waste piles, landfills, and open or closed containers such as drums, tank trucks, and storage tanks.

8.3.4.1 Any of these units may have multiple phases (floating solids, different density liquid phases, and sludge) and one or all of them may need to be sampled.

8.3.4.2 If sampling from access valves or ports on an open or closed container, care should be taken to be sure that the desired layer is sampled. For example, bottom sampling ports would allow only the heavier contents to be sampled while surface or top sampling would allow only sampling of the lighter layers.

8.4 *Subsampling (Field)*:

8.4.1 Different analyses require different types of bottles and preservation. For multiple analyses of the same waste stream, this may require subsampling in the field. Subsampling in the laboratory may require many of the same procedures; however, laboratory subsampling is beyond the scope of this guide.

8.4.1.1 Samples for organic analyses should always be taken from the first material collected. This minimizes loss of volatile organics during handling of the material.

8.4.1.2 If necessary, place the appropriate volume of material in a tray or other suitable container to composite. The volume is dependent on the needed analyses, and should be specified by the analytical laboratory.

8.4.1.3 Transfer the material into the required containers for analyses. If subsampling takes place, then the analytical sample is the final portion of the material subsampled from the original sampling unit and analyzed in the laboratory.

8.4.2 In subsampling, the original sampling unit can be considered as the population and the correct sampling procedures must be followed to ensure a representative subsample.

9. Keywords

9.1 bias; contaminated media; precision; representative; sample; waste; waste management

APPENDIX

(Nonmandatory Information)

X1. TWO CASE STUDIES OF REPRESENTATIVE SAMPLING

X1.1 Case Study One—Waste Pile Investigation

X1.1.1 *Background*— An industrial facility has managed recovery furnace slag and baghouse dust in a waste pile located on the site. No active management was occurring with the waste pile. No buried containers or extremely heterogenous material (debris) was suspected of being present in the waste pile based on facility records and interviews of personnel.

X1.1.1.1 Lead and cadmium were the constituents of concern based on process knowledge, and the possibility for the waste being hazardous by means of the Toxicity Characteristic (TC) Rule was the regulatory consideration. No preliminary information on the variability of lead and cadmium within the piles was available. The potential for off-site migration of contaminants by means of a drainage ditch that leads to a stream adjacent to the facility was an immediate concern.

X1.1.2 *Phase 1: Objective*—The primary objective of the initial investigation was to determine if the slag and baghouse dust in the waste piles were characteristic for lead via the Toxicity Characteristic Rule. A secondary objective was to provide preliminary information on potential migration and transport of contaminants from the waste piles off site.

X1.1.2.1 The sampling design for this initial investigation utilized a judgmental sampling strategy to provide a preliminary estimate of the lead and cadmium concentrations in the waste pile, the variability of contaminant concentrations in the pile, and the potential for leaching using the TCLP. Four areal composite samples were collected from the surface (0 to 6 in.) at the four quadrants of the waste pile. Borings were completed at the center of each area that was sampled on the surface. Each four-foot interval was analyzed to assess vertical variability.

X1.1.2.2 The following environmental samples were also collected using a judgmental approach:

(1) Several soil samples in the vicinity of the waste pile,

(2) Sediment upstream and downstream in a stream that borders the facility,

(3) Sediment in a ditch which contained run-off from the pile, and

(4) Two background soil samples.

X1.1.2.3 *Results*—Zinc, copper, cadmium, and lead were all elevated (compared to background) in the samples collected from the waste piles. Since lead and cadmium are TC Rule constituents, the TCLP was completed, and the lead results exceeded the regulatory level of 5 mg/L. Cadmium was just under the regulatory level of 1.0 mg/L. Lead and cadmium concentrations in the soil near the waste piles were 2 to 3 times above background, and the drainage ditch and downstream sediment sample also had elevated lead and cadmium levels.

X1.1.2.4 *Conclusion*— The waste piles contain slag and baghouse dust that is hazardous for lead. The waste pile requires further characterization to determine the variability in the pile. The presence of lead and cadmium in soils and the stream sediment downstream of the facility was confirmed and should be further investigated to determine the extent of contaminant transport.

X1.1.3 *Phase 2: Objective*—The sampling design utilized a systematic grid approach. This design will delineate horizontal and vertical variability in lead and cadmium concentrations. The Phase 1 investigation also provided a good estimate of the anticipated variability in the waste pile.

X1.1.3.1 The number of samples required to adequately characterize the waste pile was calculated based on the anticipated variability, the regulatory level of concern, and the specified confidence interval. The grid sizes were then adjusted to accommodate the projection on the required number of samples. Composite samples were collected within each grid cell based on one center point and eight points on the compass (45 deg intervals) equidistant from the center point.

X1.1.3.2 Twenty percent of the grids were designated for vertical characterization (at the grid center) at four-foot intervals, as well as surface (0 to 6 in.) sample collection. Additionally, ten percent of the grids were randomly designated for duplicate sampling (using a different aliquot pattern within the cell) to check the preliminary estimate on the variability.

X1.1.3.3 Additional environmental sampling was conducted that included a systematic sampling design for the stream adjacent to the facility with sediment samples collected at 100-ft intervals. A systematic approach was also used for the drainage ditch (50-ft intervals), with judgmental samples being collected at any location where visible staining was observed.

X1.1.3.4 *Results*—The results supported the initial investigation with lead consistently exceeding the TC Rule regulatory level; cadium was consistently below the regulatory level. Vertical differences in the lead and cadmium concentrations were not significant. Lead and cadmium were detected at elevated concentrations (relative to background) in the adjacent stream at a point downstream of the confluence with the drainage ditch.

X1.1.3.5 *Conclusion*— The waste pile was characteristic for lead and subject to Subtitle C of RCRA. There was no significant variability with depth, although several gradients were noticed across the grid (horizontally) based on lead concentration (scan) results.

X1.2 Case Study Two—Drum Sampling

X1.2.1 *Background*— An industry has two areas where drums of waste have been stored. One area is a warehouse adjacent to an off-line plating process that contains less than 25 drums (55 gal). The drums have manufacturers' labels indicating they contain an acid solution, and all of the drums are similar in appearance. A second area is a covered shed that has an estimated 100 drums from a variety of processes, several of which are no longer in use at the facility. Information on the content of these drums is not available.

X1.2.2 *Objective*—The objective of the initial investigation was to survey both of the storage areas for safety purposes, assess and record information on the drums, and open drums that were candidates for screening. All drums that were opened were surveyed using an organic vapor analyzer (PID, FID), pH paper, halogen detector, cyanide detector, and radiation meter.

X1.2.2.1 A judgmental sampling design was utilized in the warehouse where the anticipated variability was low. Based on the site screening (pH measurement), six samples were collected for pH analysis from the warehouse.

X1.2.2.2 The drums in the shed were screened in a similar fashion. A variety of results were obtained which included elevated pH, high organic vapor readings, and so forth. A simple random sampling design was used which called for the collection of 15 samples, with five from each major group of drums based on the screening (five corrosives, five potential ignitables with no halogens, and five with elevated halogen readings).

X1.2.2.3 *Results*—The warehouse samples were all corrosive with pH values from 1 to 2 S.U. The shed samples resulted in the collection of five corrosive wastes, three that were both ignitable and characteristic for non-halogenated TC Rule constituents, and two that were ignitable and characteristic for halogenated constituents. In summary, of the 15 drums sampled, 10 contained hazardous waste.

X1.2.2.4 *Conclusions*—All of the drums in the warehouse are subject to Subtitle C of RCRA. The drums in the shed require further assessment due to the fact that several of those sampled did not contain hazardous waste.