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Standard Guide for Generation of Environmental Data Related to Waste Management Activities: Selection and Optimization of Sampling Design[1]

This standard is issued under the fixed designation D6311; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This document provides practical guidance on the selection and optimization of sample designs in waste management sampling activities, within the context of the requirements established by the data quality objectives or other planning process.

1.2 This document (*1*) provides guidance for selection of sampling designs; (*2*) outlines techniques to optimize candidate designs; and (*3*) describes the variables that need to be balanced in choosing the final optimized design.

1.3 The contents of this guide are arranged by section as follows:

1. Scope
2. Referenced Documents
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5. Summary of Guide
6. Factors Affecting Sampling Design Selection
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- A1.3 Combination Sample Designs

Appendix X1. Additional References

Appendix X2. Choosing Analytical Method Based on Variance and Cost

Appendix X3. Calculating the Number of Samples: A Statistical Treatment

1.4 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D5956 Guide for Sampling Strategies for Heterogeneous Wastes

D6044 Guide for Representative Sampling for Management of Waste and Contaminated Media

D6051 Guide for Composite Sampling and Field Subsampling for Environmental Waste Management Activities

D6232 Guide for Selection of Sampling Equipment for Waste and Contaminated Media Data Collection Activities

E135 Terminology Relating to Analytical Chemistry for Metals, Ores, and Related Materials

E943 Terminology Relating to Biological Effects and Environmental Fate

[1] This guide is under the jurisdiction of ASTM Committee D34 on Waste Management and is the direct responsibility of Subcommittee D34.01.01 on Planning for Sampling.

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

2.2 *USEPA Documents:*[3]

USEPA Guidance for the Data Quality Objectives Process, EPA QA/G-4, Quality Assurance Management Staff, Washington, DC, March 1995

USEPA Data Quality Objectives Process for Superfund—Workbook, EPA 540/R-93/078 (OSWER 9355.9-01A), Office of Emergency and Remedial Response, Washington, DC, September 1993

USEPA Environmental Investigations Branch Standard Operating Procedures and Quality Assurance Manual (EISOPQAM), Region 4—Science and Ecosystem Support Division, Athens, GA, May 1996

2.3 There are numerous useful references available from ASTM, USEPA, and private sector publishers. Appendix X1 contains a list, which is by no means comprehensive, of additional commonly used references.

3. Terminology

3.1 *accuracy, n*—closeness of a measured value to the true or an accepted reference or standard value. **(E135)**

3.2 *attribute, n*—a quality of samples or a population. **(D5956)**

3.3 *characteristic, n*—a property of items in a sample or population that can be measured, counted, or otherwise observed. **(D5956)**

3.3.1 *Discussion*—A characteristic of interest may be the cadmium concentration or ignitability of a population.

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

3.5 *confidence interval, n*—a numerical range used to bound the value of a population parameter with a specified degree of confidence (that the interval would include the true parameter value).

3.5.1 *Discussion*—When providing a confidence interval, the number of observations on which the interval is based should be identified.

3.6 *confidence level, n*—the probability, usually expressed as a percent, that a confidence interval will contain the parameter of interest.

3.7 *data quality objectives (DQOs), n*—qualitative and quantitative statements derived from the DQO process describing the decision rules and the uncertainties of the decision(s) within the context of the problem(s). **(D5956)**

3.8 *data quality objective process, n*—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. **(D5956)**

3.8.1 *Discussion*—The DQO process enables planners to focus their planning efforts by specifying the use of the 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.

3.9 *decision rule, n*—a set of directions in the form of conditional statements that specifies: (*1*) how the sample data will be compared to the decision point or action level, (*2*) which decision will be made as a result of that comparison, and (*3*) what subsequent action will be taken based on the decisions.

3.10 *false negative error, n*—an error which occurs when (environmental) data misleads the decision maker(s) into not taking action when action should be taken.

3.11 *false positive error, n*—an error which occurs when environmental data misleads the decision maker(s) into taking action when action should not be taken.

3.12 *heterogeneity, n*—the condition of the population under which items of the population are not identical with respect to the characteristic of interest. **(D5956)**

3.13 *homogeneity, n*—the condition of the population under which all items of the population are identical with respect to the characteristic of interest. **(D5956)**

3.14 *representative sample, n*—a sample collected such that it reflects one or more characteristics of interest (as defined by the project objectives) of a population from which it was collected. **(D5956)**

3.15 *risk, n*—the probability or likelihood that an adverse effect will occur. **(E943)**

3.16 *sample, n*—a portion of material which is collected for testing or for record purposes. **(D5956)**

3.16.1 *Discussion*—Sample is a term with numerous meanings. The project team member collecting physical samples (for example, from a landfill, drum, or waste pipe) or analyzing samples considers a sample to be that unit of the population collected and placed in a container. In statistics, a sample is considered to be a subset of the population and this subset may consist of one or more physical samples. To minimize confusion, the term "physical sample" is a reference to the sample held in a sample container or that portion of the population which is subjected to measurement.

3.17 *sampling design, n*—(*1*) the sampling schemes specifying the point(s) for sample collection; (*2*) the sampling schemes and associated components for implementation of a sampling event.

3.17.1 *Discussion*—Both of the above definitions are commonly used within the environmental community. Therefore, both are used within this document.

4. Significance and Use

4.1 The intended use of this guide is to provide practical assistance in the development of an optimized sampling design. This standard describes or discusses:

4.1.1 Sampling design selection criteria,

4.1.2 Factors impacting the choice of a sampling design,

4.1.3 Selection of a sampling design,

4.1.4 Techniques for optimizing candidate designs, and

4.1.5 The criteria for evaluating an optimized sampling design.

4.2 Within a formal USEPA data generation activity, the planning process or data quality objectives (DQOs) development is the first step. The second and third are the implementation of the sampling and analysis design and the data quality

[3] Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

assessment. Within the DQO planning process, the selection and optimization of the sampling design is the last step, and therefore, the culmination of the DQO process. The preceding steps in the DQO planning process address:

4.2.1 The problem that needs to be addressed,

4.2.2 The possible decisions,

4.2.3 The data input and associated activities,

4.2.4 The boundaries of the study,

4.2.5 The development of decision rules, and

4.2.6 The specified the limits on decision error.

4.3 This guide is not intended to address the aspects of the planning process for development of the project objectives. However, the project objectives must be outlined and communicated to the design team, prior to the selection and optimization of the sample design.

4.4 This guide references statistical aspects of the planning and implementation process and includes an appendix for the statistical calculation of the optimum number of samples for a given sampling design.

4.5 This guide is intended for those who are responsible for making decisions about environmental waste management activities.

5. Summary of Guide

5.1 The selection and optimization process is an iterative process of selecting and then evaluating the selected design

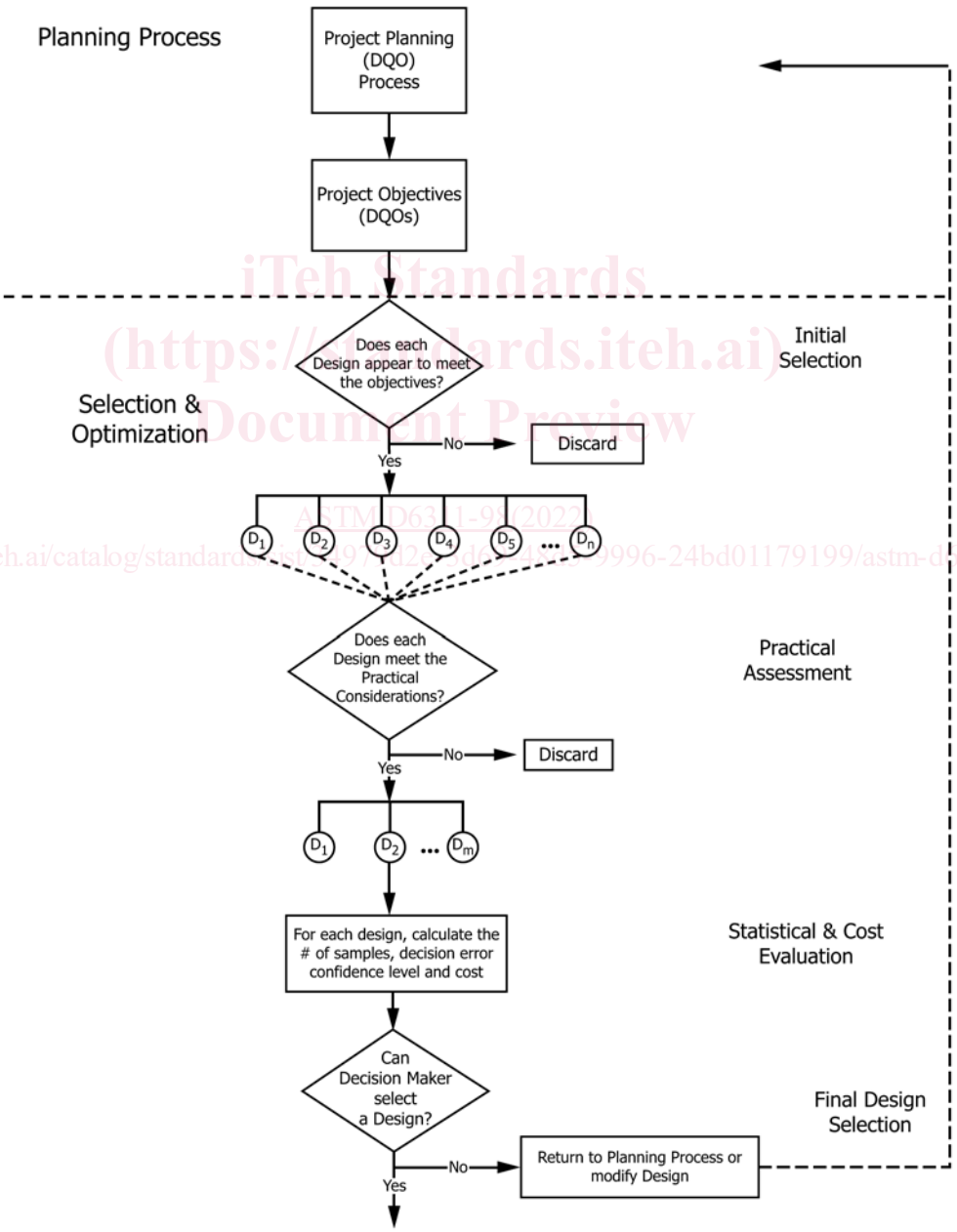

FIG. 1 Implement Sampling Design

alternatives and determining the most resource-effective design which satisfies the project objectives or DQOs. Fig. 1 illustrates this approach.

5.2 An appropriate sampling design may be implemented without a formal optimization, however, the following steps are recommended. Each evaluation step typically results in fewer design alternatives.

5.2.1 Evaluation of the designs against the project's practical considerations (for example, time, personnel, and material resources),

5.2.2 Calculation of the design cost and statistical uncertainty, and

5.2.3 Choice of the sample design decision by the decision makers.

5.3 The process steps for the evaluation can be followed in any order. And for a small project, the entire selection and optimization process may be conducted at the same time. If ultimately, a design meeting the project constraints, for example, schedule and budget, cannot be identified among the candidate sampling designs, it may be necessary to modify the closest candidate design or reevaluate and revise the project objectives.

6. Factors Affecting Sampling Design Selection

6.1 *Sampling Design Performance Characteristics:*

6.1.1 The sampling design provides the structure and detail for the sampling activity and should be chosen in light of the project objectives. Prior to this point, the planning process should have addressed and defined the project needs for each of the sampling design characteristics, including the characteristics of interest, population boundaries, decision rule, acceptable decision errors, and budgets. In considering all aspects of the project, the selected design should accommodate the spatial and temporal distribution of contaminants at the site, be practical, cost effective, and generate data that allow the project objectives to be met.

6.1.2 Whenever possible, technical guidelines for measurement of the sources of variability and levels of uncertainty should be established prior to developing sampling design alternatives, to ensure that it is possible to establish that the program objectives are met.

6.1.3 Annex A1 presents an overview of some of the more commonly used sampling designs and design tools and summarizes their advantages and disadvantages. Because numerous sampling strategies exist, this is limited to the more common. If the more common sampling strategies are not cost-effective or applicable to the population of interest, a statistician should be consulted to identify other strategies which may be more appropriate.

6.2 *Regulatory Considerations*—The selection of sampling design, the sampling techniques, and analytical methods may be dictated by current regulation, permits, or consent agreements, applicable to the site. These should be reviewed to determine their impact on the selection process.

6.3 *Project Objectives*—Project objectives are usually determined by the decision makers (for example, regulatory body, consent agreement group, company management) during the initial investigation and planning or DQO process. The decision makers should have identified the population boundaries, characteristics of interest, acceptability of an average analytical value, the need to locate areas of contamination or "hot spots," the statistical needs (for example, acceptable decision errors, levels of uncertainty), and the quality control acceptance criteria, as well as any other pertinent information.

6.4 *Knowledge of the Site*—The site knowledge (for example, geography/topography, utilities, past site use) used to determine project objectives will also provide for a more resource-efficient sampling design, for example, divide a site into separate design areas for sampling or exclude an area from sampling.

6.5 *Physical Sample Issues*—The physical material to be sampled and its location on or within the site will usually impact the sampling design and limit the choices of equipment and methods.

6.5.1 *Number of Samples:*

6.5.1.1 The project objectives should specify the confidence levels for decision making. Using this level of decision error, the proximity to a threshold or action limit and the anticipated population variance, the number of samples can be calculated. The statistical parameter of interest, for example, mean or 95 percentile, and type of frequency of distribution, for example, normal or log normal, will determine which equation is used to calculate the appropriate number of samples. Eq X3.5 from Appendix X3 can be used to calculate the number of samples when the objective is to measure the mean for a population that has a normal distribution for the characteristic of interest.

6.5.1.2 Appendix X3 contains statistical approaches to calculating the number of samples needed for estimating the mean concentration, for simple random, statistical random, multistage sampling, and search sampling (where the objective is to detect hot spots).

6.5.2 *Sample Mass or Volume:*

6.5.2.1 The sample mass or volume is determined by the size of the items that constitute the population, the heterogeneity of the population, the characteristics of available sampling equipment (for example, dimensions) and the mass or volume needed for analysis.

6.5.2.2 It is important that the sample mass be large enough to accommodate all item sizes or parts of all items. If items such as fine granular sand or large discarded automobile parts constitute the population, the sample may need to include those items or wipes of those items.

6.5.3 *Sample Access and Logistics*—Site access and logistics such as the following can alter the sampling design:

6.5.3.1 Whether equipment can maneuver on site to obtain the desired samples,

6.5.3.2 Availability of power and water,

6.5.3.3 Presence of buried, suspended, or surficial utilities, for example, power lines, water lines, etc.,

6.5.3.4 Terrain including slope, stability of site (subsidence considerations), presence of brush or trees, and soil condition (hard pack versus mud), and

6.5.3.5 Noise of equipment which could constitute a nuisance.

6.5.3.6 For further information, see Guides D6232 and D5956.

6.5.4 *Sample Matrix:*

6.5.4.1 The physical properties of the matrix to be sampled will determine the suitability of some sampling devices. Some devices work best with cohesive material, such as moist soils, while other work best with dry materials. Equipment used to dig, core, and sample abrasive materials needs to be strong enough to maintain its integrity during sampling. The sampling program should not be compromised by incompatibilities between the sampling device and the waste.

6.5.4.2 Heterogeneity will impact both the sampling design and the physical means of collecting the samples. Nonuniform distribution of the contaminant(s) of interest or varying particle size of the material, or both, for example, soil, concrete, building material, vegetation, will require different sampling equipment and sampling strategies. For further information, see Guides D6232 and D5956.

6.6 *Communication with the Laboratory*—Advanced planning with the laboratory should address the sampling schedule, sample preparation techniques, any subsampling instructions, analytical procedures, analytes of interest, matrices to be analyzed, data report format, data to be reported, and any specific requirements for accuracy, precision, quality control, calibration, and needed turnaround time.

6.7 *Analytical Turnaround Time*—Turnaround time is usually the time from sample receipt in the laboratory to analytical data delivery. This usually depends on the analytical considerations and the laboratory capabilities.

6.8 *Analytical Method Constraints*—The analytical methods need to be chosen prior to or in conjunction with the optimization of the sampling design. The selection of appropriate methods needs to take into account at least the following areas.

6.8.1 *Analytical Method Sensitivity*—The analytical method sensitivity, usually expressed as the method detection limit or detection limit, may dictate the mass or volume of sample needed, the selection of the analytical methods, and the accuracy and precision of the data. Analytical method sensitivity is influenced by a number of factors, including sample preparation, sample volume, percent moisture, dilutions, and analytical method used.

6.8.1.1 *Analytical Aliquot Mass or Volume*—In general, for a given method, the larger the analytical aliquot (up to the maximum accommodated by the analytical method), the lower the detection limit and the more representative the data. However, typical aliquots used by most methods range from a few millilitres to 1 L or 100 g. The laboratory instrumentation may not be physically capable of managing a much larger aliquot.

6.8.1.2 *Dilutions*—Any analytical dilution will decrease sensitivity and increase the detection limit, as a multiplier of the dilution factor. When the sample has parameters in high concentrations, the lab may dilute the sample to allow the parameter to fall within the analytical instruments' calibration range.

(1) Samples containing parameters of varied concentrations may need to be prepared and analyzed at different dilutions. The manner of reporting these multiple analyses need to be agreed upon with the laboratory prior to analysis.

6.8.1.3 *Action Levels*—Detection levels need to be lower than the decision points or regulatory levels. If the detection limit is at the action or regulatory level, the increased levels of imprecision will increase the uncertainty in the decision. Low detection limit requirements may require special method development. The validation and ruggedization of new methods can be costly and impact schedules.

6.8.2 *Moisture Content of Samples*—Reporting analytical results on a dry weight basis may increase the sample mass requirements. Dry weight reporting may be accomplished in one of two ways.

6.8.2.1 Dry the sample aliquot prior to analysis on the same sample aliquot. This approach usually yields the lower detection limit. However, drying may change the sample. For example, it may affect the results of an analytical extraction, such as oxidizing a constituent, for example, hexavalent chromium.

6.8.2.2 Employ two sample aliquots. One aliquot is used to determine the moisture content, which is then used to calculate a dry weight analytical result, based on an analysis of the second aliquot. This second approach can result is raised detection limits, but it is required for the analysis of volatile analytes, which would be lost during drying.

6.8.3 *Holding Times*—The holding time is usually the time from sample collection to sample extraction or analysis. Most regulatory agencies will not accept or will limit the use of data from a sample analyzed outside the specified holding time. Holding times differ depending on the media, analyte, and regulation.

6.8.3.1 Analyses such as pH, hexavalent chromium, semivolatile and volatile organics have short holding times and may necessitate special planning. Samples with very short holding times will need to be shipped as soon as possible to allow sufficient processing time or will need on-site analysis.

6.8.4 *Screening Measurements:*

6.8.4.1 *Screening*—Screening methods can be implemented in the field or the laboratory and can provide either qualitative or semi-quantitative analyses. Screening methods are faster and generally less costly than traditional laboratory methods, but may be less sensitive and employ less quality control than traditional methods. However, they allow field personnel to define problematic areas quickly and to guide the sampling and verification analyses, using traditional methods, for final compliance determination.

6.8.4.2 *Field and In-Situ Analyses*—When hold or turnaround times cannot be met by traditional laboratory analyses or to save time, reduce cost, or increase the number of samples, analytical testing may be performed at the sampling site. Field analytical methods include chemical-specific kits and portable instrumentation for various organic and inorganic compounds. Care should be taken that the needed detection limits, regulatory requirements, and quality control are achievable and that accuracy and precision criteria, trained staff, and data management practices are in place to produce data to meet the planning objectives or DQOs.

6.9 *Health and Safety*—Personnel safety must be considered. Of particular concern are any potential exposure of field personnel to hazardous materials and any possibility for explosion or fire which might be triggered by sampling equipment. Additionally, intrusive sampling, such as drilling, can result in the release of hazardous materials to the environment and potentially impact off-site personnel.

6.10 *Budget/Cost Considerations*—Budgets are almost always a significant factor. The challenge is to design a cost-effective sampling plan, while still achieving the specified project objectives. The sample design cost estimate comparisons need to include:

6.10.1 Personnel costs including travel and per diem,
6.10.2 Sampling equipment, including purchases/rentals,
6.10.3 Mobilization and demobilization costs,
6.10.4 Decontamination of equipment,
6.10.5 Waste collection and disposal,
6.10.6 Sample analyses or field screening, or both,
6.10.7 QA or QC samples, or both,
6.10.8 Consumables, and
6.10.9 Health and safety.

6.11 *Representativeness*—Representativeness is the degree to which samples collected reflect the characteristics of the population. The sampling design must be chosen such that bias is minimized and the other project objectives achieved. For further guidance, see Guide D6044.

7. Initial Design Selection

7.1 Sampling design options need to be selected consistent with the project objectives. Prior to selecting designs, the parameter(s) of interest (target compounds), population boundaries, decision rule, the spatial and temporal distribution of contaminants at the site (if known), the acceptable decision errors, and budgets should have been considered in the planning process. In addition, the final design should be practical and cost-effective. See Annex A1 for a listing of commonly used sampling designs.

7.2 *Meeting Project Objectives*—Prior to the selection of the initial set of sampling designs, those responsible for the project planning or DQO process need to establish and communicate the project objectives. Fig. 2 provides a guide to some common sampling designs as they could potentially satisfy some basic project objectives. Fig. 3 gives a guide to some of the attributes of the same designs.

7.2.1 *Estimating Population Parameters*—Waste classification, evaluation of waste treatability, or determining compatibility of wastes are types of projects where information of the population parameters, such as the mean and variance, may be required. Estimation of these parameters generally relies on a statistical sampling design and classical inferential statistics.

7.2.2 *Monitoring for Routine Purposes*—Monitoring, such as ground water or monitoring changes in waste streams over time may be useful in determining for example whether a characteristic of a waste stream has exceeded a prespecified quality control or permit limit.

7.2.3 *Describing Spatial or Temporal Distribution, or Both*—Information for corrective action purposes may be used to define spatially or temporally those portions of a waste stream that are to be managed in different ways (for example, disposal versus treatment, etc.). Information may also be used for locating additional sampling units for increased precision in defining boundaries separating wastes to be manage differently.

7.2.4 *Noncompliance Monitoring*—Identifying hot spots is a common noncompliance monitoring objective. Search sampling is used to locate or detect constituents of interest, objects, "hot spots" in the area to be sampled. Authoritative sampling based on site knowledge is frequently used to identify the possibility of the "worst case" scenario noncompliance.

7.3 *Sampling Designs for Complex Sites*—Many sites for environmental sampling are complex and require the selection of multiple sampling designs to address the various suspected problems. For these sites, optimization of several sample

	Sampling Designs							
	Authoritative		Statistical				Systematic	
Objectives \ Sampling Designs	Judgmental	Biased	Simple Random	Stratified	Search	Unequal Probability	Line	Grid
Estimate population parameters			✓	✓				✓
Routine Monitoring	✓		✓	✓			✓	
Describe spatial and/or temporal distribution				✓	✓	✓	✓	✓
Non-Compliance Monitoring	✓	✓			✓			

FIG. 2 Project Objectives and Sampling Designs Guidance

Sampling Designs / Attributes	Designs: Authoritative: Judgmental	Authoritative: Biased	Statistical: Simple Random	Statistical: Stratified Random	Statistical: Search	Statistical: Unequal Probability	Systematic: Line	Systematic: Grid
Some Knowledge of Contaminant Distribution	✓	✓		✓		✓		
Usually is less Costly	✓	✓						
Simple to Implement	✓	✓	✓				✓	✓
Estimates Average Conditions			✓	✓		✓	✓	✓
Estimates Variability			✓	✓				✓
Minimizes Personal Bias			✓	✓			✓	✓
Effectively Accommodates and Identifies Strata				✓			✓	✓
Identifies or Locates Hot Spots		✓			✓			✓
Considers Trends or Cycles in Contaminant Distribution						✓		✓
Identifies Trends and Cycles in Contaminant Distribution							✓	✓

FIG. 3 Relationships Between Sampling Designs and Some Attributes Guidance

designs is needed. Once the specific areas are defined, the process is similar to any other optimization. The following is an example.

7.3.1 *Example*—Fig. 4 illustrates a complex site, one where a multi-design program is appropriate. It represents a source of potential contamination such as a waste lagoon that is leaking contaminated liquids to the subsurface and the ground water. To determine the extent of the problem, it is necessary to collect samples from separate areas of the site and answer the following:

7.3.1.1 What are the potential contaminants present in the lagoon?

7.3.1.2 What are the background levels of contaminants?

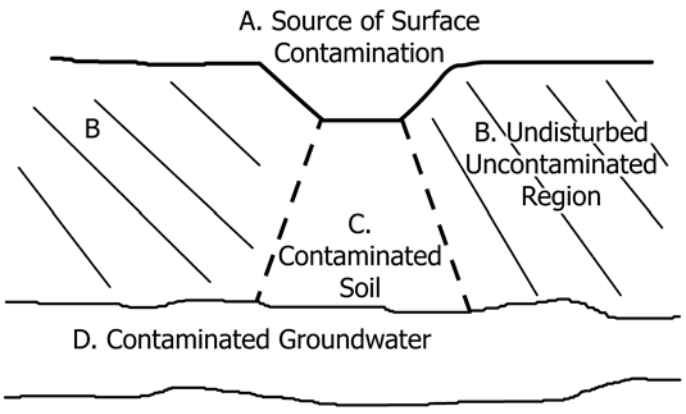

FIG. 4 Complex Site

7.3.1.3 What are the levels of the potential contaminants in the soil immediately adjacent to and beneath the lagoon?

7.3.1.4 Has the contamination reached the ground water and to what extent?

7.3.2 Assuming the planning team is familiar with the process waste and the spatial heterogeneity of the lagoon, the first question can be answered by an authoritative sampling. The second question can be answered by a systematic sampling of the areas adjacent to the site. The answer to the third question can be found by a systematic sampling design around and beneath the lagoon. The fourth question can be answered by a systematic sampling of the ground water along a line from the point of origin (the lagoon) in the direction of ground water flow.

7.3.3 The final integrated plan for the entire site should consider all the information needs, integrate multiple sampling designs (per area), and stage the field sampling to collect samples in such a manner that it will satisfy more than one area or question. For example, samples from the lagoon can be scheduled first and the results used to determine the analyte list for the soils and ground water. The soil borings used to determine the contamination around and beneath the lagoon and the ground water samples from the ground water beneath the site will provide information about the extent of any plume. This type of integrated planning occurs after the selection of the designs to answer the individual questions. Many times, considerable cost savings can be realized by this type of selection and optimization.

	Area of Site and Description	Candidate Design
A.	Lagoon (source of the contamination)	Authoritative Sampling
B.	Undisturbed soil area (presumed uncontaminated)	Systematic Sampling
C.	Soil directly under the spill (known to be contaminated, need to map extent of contamination)	Systematic Sampling
D.	Ground water (need to know the extent of contamination of ground water plume)	Grid Sampling

7.4 *Statistical versus Non-Statistical Designs:*

7.4.1 *Non-Statistical Designs*—Sampling designs can be classified as statistical or non-statistical sampling designs. Non-statistical sampling designs are sometimes referred to as non-probability or authoritative (biased or judgmental) sampling. These strategies rely upon a person's judgment or a pre-arranged decision rule to decide which portions of a population will be sampled. Non-statistical sampling designs can be the optimum strategy for certain populations or times in a sampling program. Non-statistical sampling may be appropriate under circumstances such as the following: (*1*) pilot studies (preliminary information is needed to facilitate planning); (*2*) spills: a spill of an unknown chemical has been encountered; (*3*) limited access to portions of the population; (*4*) field screening to select a limited number of samples for laboratory analysis; (*5*) historical site knowledge is available; and (*6*) noncompliance determinations.

7.4.1.1 While non-statistical sampling can generate useful data, because of its subjective nature, the logic used to choose the sampling location must be explained and defensible.

7.4.1.2 It is very important not to confuse non-statistical sampling with the use of historical information during sampling design. For example, if one area of a site is known to be heavily contaminated while another area is believed not to be contaminated, this information can be used to defensibly divide the site into strata or de-select an area from sampling. Use of historical information in conjunction with statistical sampling strategies should generate unbiased, representative, and defensible data.

7.4.2 *Statistical Designs*—Statistical sampling designs are also referred to as probability, non-biased, or non-judgmental designs and rely upon a random selection of sampling locations to minimize any bias in the sample selection process. Statistical sampling strategies allow for large populations to be characterized with a measured degree of confidence. In addition to considering all the other information, the following may apply:

7.4.2.1 Usually, the greater the number of samples, the narrower or tighter the confidence interval for the parameter of interest.

7.4.2.2 Composite samples are useful for locating the hot spot areas, although they may not identify a specific point source contaminant location.

7.4.2.3 For containerized waste, the sampling error for both the within (an individual) container and between multiple containers need to be considered.

7.4.2.4 Because sampling errors are usually larger and may be more difficult to quantify than analytical errors, field QC samples need to be included to help determine the potential errors.

7.4.2.5 Systematic grid sampling is preferred when spatial structure (correlation) is suspected or known. A random factor may be introduced by a random choice of origin. Systematic grid sampling usually provides a more accurate estimate of the mean.

8. Optimization Criteria

8.1 Optimization involves choosing between the initially selected sample designs which may or may not meet the project objectives. The optimum sample design will minimize project variables such as cost, time, and risk, the objective being to achieve a balance between the costs of acquiring environmental data and the costs or consequences of incorrect waste management decisions.

8.2 In general, the criteria for an optimized sampling design are that the design:

8.2.1 Be resource and cost effective,

8.2.2 Provide data of known quality,

8.2.3 Meet or not exceed the acceptable level of decision errors,

8.2.4 Be practical or at least possible to implement appropriately,

8.2.5 Comply with regulatory requirements,

8.2.6 Be implementable within the project schedule,

8.2.7 Have high reliability, and

8.2.8 Meet any other project specific objectives.

8.3 In the optimization process the above criteria will be used to choose the optimum design from the candidate sampling designs.

9. Optimization Process

9.1 The optimization process is an iterative process of evaluating the initially selected design alternatives and determining the most resource-effective design which satisfies the project objectives or DQOs. An appropriate sampling design may be implemented without a formal optimization; however, the following steps are recommended: (*1*) evaluation of the designs against the project's practical considerations (for example, time, personnel, and material resources); (*2*) calculation of the design cost and statistical uncertainty; and (*3*) choice of the sample design decision by the decision makers. Fig. 1 and Section 5 illustrate this approach.

9.1.1 The process steps for the evaluation can be followed in any order. For a small project, the entire selection and optimization process may be conducted simultaneously. Typically as the evaluation continues each evaluation step will result in fewer design alternatives. If ultimately, a design meeting the project constraints, for example, schedule and budget, cannot be identified among the candidate sampling designs, it may be necessary to modify the closest candidate design or return to the planning stage and reevaluate and revise the project objectives.

9.2 *Practical Evaluation of Design Alternatives*—Each design candidate should be evaluated with respect to the project's practical considerations. These aspects should have been taken into account initially and some may overlap. However, the purpose here is to go into more depth and then to compare the design candidates. After reviewing, eliminate any designs which do not meet the site's practical needs.

9.2.1 *Define the Population or Area(s) to be Sampled:*

9.2.1.1 Review the site history and assumptions that were used to define the population boundaries. This information may allow for stratification of the site, identification of specific areas of interest, and an estimate of heterogeneity. Determine which sampling design best accommodates the spatial and temporal boundaries of the population.

9.2.1.2 Subdivision of the site may involve spatial boundaries such as drums, tanks, an area within a grid, a boring location on a grid, a depth interval in a boring, distance along a conveyor belt, or any other appropriate defined physical unit from which material can be obtained. For example, a defined search area may be the answer to locate an 8-ft diameter area of PCB contamination from a 55-gal drum PCB spill.

9.2.2 *Determine Optimum Number of Samples:*

9.2.2.1 Budgets and the acceptable levels of uncertainty as defined by the DQO or project objective planning process are competing factors that affect the number of samples. Statistical techniques for balancing these competing factors are discussed in a number of places in the literature[4] and Appendix X1.

9.2.2.2 The following illustrates a calculation for the commonly used systematic grid sampling and the iterations which may be necessary, if the calculated number of samples should prove, for practical reasons, to be too large to implement.

9.2.2.3 *Example Calculation*—The number of samples to be collected can be calculated based on variance information derived from previous sampling data or estimated based on professional judgment. Usually the contaminants of concern (COCs) are parameters which are closest to or in excess of an action level. Their presence is normally the driving force behind the need to determine the extent and levels of contamination. The statistic of interest here is the mean and it assumes a normal distribution.

(1) Select a margin of error (p) acceptable for the subsequent use of the data. For soil studies, a margin of error of 0.20 is not unusual. The margin of error may be calculated by dividing the needed precision, in units of concentration, for example, = 10 ppm, by the known or anticipated mean concentration of the COCs. Note, that if the actual precision or mean concentration for the COC differs from those estimated during the planning process, a reevaluation of the assumed margin of error may be necessary.

(2) A coefficient of variation (CV), which is defined as the standard deviation of a COC divided by the mean of the COC, is either obtained using previous sampling data or estimated based on anticipated variability. If a CV above 0.65 is obtained, a large number of samples will usually be needed to make a decision with the selected margin of error.

(3) A confidence level 100 (1–α) % needs to be established. For work involving hazardous wastes, a confidence level of 95 % is frequently used. For a 95 % confidence level, using a standard Z statistical table, this corresponds to a one-sided statistical factor of $Z_\alpha = 1.645$.

(4) If a one-sided inference about the population is desired (for example, comparing a mean concentration to a regulatory threshold), the required number of samples is calculated using the following formula:

$$n = \{Z_\alpha\ (CV)/P\}^2 \tag{1}$$

where:

n = number of samples to collect,
Z_α = statistical factor for the desired confidence level,
CV = coefficient of variation, and
p = margin of error.

In a case where no previous sampling data is available, the values used in the above discussion can be used as a starting point.

$$n = \frac{(1.65)^2(0.65)^2}{(0.20)^2} \tag{2}$$

$$n = 29 \text{ samples} \tag{3}$$

If a two-sided inference is desired (for example the mean is equal to 10 ppm), the Z-value of 1.96 is used in the formula, instead of 1.65. The result is an $n = 40$.

(5) Upon completion of the calculation the number of samples and the margin of error is reviewed to determine that each is acceptable. If the value of n number of samples is too great, then an adjustment to the margin of error should be considered, or the sampling design may be modified. Alternately, if the population is stratified by concentration, the number of samples required may be reduced by selecting a sampling design for each of the strata. The inter-strata variability would then be removed from the calculation of the needed number of samples.

(6) Table 1 illustrates the number of samples required at a 95 % confidence level (Z-table factor of 1.65) with varying margins of error (p) and coefficients of variation (CV).

(7) Note that as the CV increases at a set margin of error, the number of samples required increases. When the variability is low (as measured by the standard deviation or the square root of the variance) relative to the mean of the data, then the CV is low. However, as the variability in the population begins to increase relative to the mean of the data, then the CV increases and the number of samples required increases if characterization of the site at a 95 % confidence level and a set margin of error is desired.

(8) A similar relationship is observed for the margin of error. When the precision required (say ±10 ppm lead) is high relative to the mean of the data (say 100 ppm lead), then the margin of error is low (in this case 0.1). In this case 115 samples would be required with a CV of 0.65. If the investigators could accept a higher margin of error (for example, ±20 %), and the mean concentration of the data is still 100

TABLE 1 Number of Samples (n) for given Coefficient of Variation and Margin of Error

	Coefficient of Variation (CV)				
	0.1	0.5	0.65	1.0	2.0
Margin of Error (p)					
0.1	3	68	115	272	1089
0.2	1	17	29	68	272
0.3	-	8	13	30	121
0.5	-	3	5	11	44
1.0	-	1	1	3	11
2.0	-	-	-	1	3

[4] Gilbert, R. O., *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold Co., New York, 1987.

ppm lead, then the resulting margin of error (0.2) would result in a lower number of required samples. Note that 29 samples would be required at the same CV of 0.65 and a one-sided inference.

(9) If the confidence level is decreased to 80 %, then the required number of samples reflected in this figure would be lower for each margin of error and CV combination. However, the confidence level may fixed. One alternative to analyzing the larger number of samples may be to use compositing.

9.2.2.4 *Site/Event Considerations*—The site and physical sampling event(s) constitute the majority of the practical aspects to be evaluated. Each design should be evaluated against all practical aspects to determine whether or not a given design will be practical to implement. This evaluation is subject to professional judgment as to whether or not a practical aspect, for example, the level of personnel training needed, is practical or acceptable, or both. If it is not, then the design needs to be modified or eliminated. These aspects include, but are not limited to the following:

(1) Site Access and Conditions—Site considerations: cross contamination potential; limits on access to sampling locations (for example, buildings, refusals).

(2) Equipment and Personnel—Equipment limitations; experience of the field sampling team; experience of the analysts; field and laboratory resources.

(3) Sampling Event—Special site concerns (for example, unexploded ordnance); special analytical needs (for example, low level analyses, dioxin); special analytical concerns (for example, interferences, multiple phases, incompatibility); health and safety considerations; resistant matrices (for example, solidified material); investigation derived waste (IDW) generation.

(4) Schedule—Transitory events (for example, start-up, shut-downs); potential impacts on project schedule.

(5) Safety Considerations.

9.3 *Statistical and Cost Evaluation*—Following the evaluation of each sampling design for the practical considerations, there should be a reduced set of design candidates. At this point, the statistical aspects (for example, uncertainty) and estimated costs should be calculated in preparation for the final review by the decision makers. The types of calculations and the degree to which statistics are needed will be dependent on the project objectives. The statistical evaluation routinely addresses issues of false positive or negative error, accuracy and precision, representativeness, and objectivity versus subjectivity.

9.3.1 *Statistical Considerations*—Statistical evaluation techniques are numerous and discussed in a number of places in the literature, including ASTM and USEPA guidance documents. The degree to which the statistical evaluation needs to be employed depends on the project objectives. Routinely, the statistical evaluation includes the acceptable limits of the potential sampling and analytical error and any mechanisms established for their controlling. The following are some general guidelines.

9.3.1.1 *Sensitivity Analysis*—A sensitivity analysis will determine how each design performs when the underlying assumptions about the sampling activity are modified. Typically, this involves changing specific parameters within some reasonable range and establishing how each of these changes influences the expected decision error rates. A statistical power curve is a useful statistical tool used to evaluate whether a sampling design has the ability to meet the project objectives.

9.3.1.2 *Hypothesis Test:*

(1) Each statistical sampling design should include a statistical hypothesis test. A statistical model should be developed which describes the relationship of the measured value to the "true" value. This mathematical formulation clarifies how data generated from a design is to be interpreted and processed in testing the hypothesis. A tentative analytic form for analyzing the resulting data (for example, a student's *t*-test or a tolerance interval) should be specified in the project objectives. This information can be used to determine the minimum sample size which satisfies the project objective's limits on decision error.

(2) The objectives of a statistical design are to limit the total error, which is a combination of sampling and measurement error, to acceptable levels. Traditional laboratory methods tend to minimize measurement error, but can be so expensive that only a limited number of samples can be analyzed within budget. The advantage to using less precise methods, which are relatively less expensive, is that it allows a significantly larger number of samples to be collected and analyzed. This may trade off an increase in measurement error for a decrease in sampling error. If so, given the natural variability in many environmental studies, this approach may reduce overall costs while limiting the total decision error rates to acceptable levels.

(3) Appendix X2 provides an example approach for a statistical treatment of the choice of an analytical method based on the analytical variance and the analytical cost per sample.

9.3.1.3 *Error Statements*—When authoritative or non-statistical designs are used, quantitative statements about data quality are limited to the measurement error component of the total study error. A statistical approach would allow a quantitative statement about the sampling error component of the total project error to be made and allow for determining the probability of making a decision error regarding the overall sampling event.

9.3.1.4 *Comparison of Sampling Designs Based on Statistical Considerations:*

(1) When Population Concentration Distribution is Random—When there are no trends, stratification, or spatial correlation in the distribution of the contaminant concentration over an area, systematic grid and simple random sampling are usually equally precise.

(2) When Population Concentration Distribution Has Trends—In general, systematic grid sampling is more precise than simple random sampling and is less precise than stratified random sampling (in the estimation of the population mean), assuming strata are appropriately identified.

(3) When Population Concentrations Are Spatially Correlated—Spatial correlation refers to the fact that the concentrations of two samples taken in close proximity tend to be similar or correlated and that this correlation decreases as the distance between the two samples increases. Often, the presence of spatial correlation or clustering can be minimized

by taking samples spatially far apart. A grid design and geostatistical data analysis may be used to eliminate the error associated with a random design. However, random sampling is useful in order to avoid human bias and is the design of choice when too little is known to stratify or grid. If the site has known differences due to the historical insult, fate, or transport, or combinations thereof, of the pollutants, then this knowledge can best be used by a stratified design. Stratified random sampling will generally be more precise than simple random sampling.

9.3.2 *Cost Estimates*—Development of an estimate of the total cost of sample collection and analysis for each design option enables the decision team to compare the financial aspects of the sampling designs which meet the project objectives. These should include all aspects of the sampling design and analytical event(s). The cost differential between the alternate designs will frequently, although not always, be closely related to the number of samples required. Detailed examples of cost estimates are included in USEPA's Guidance on DQOs (Appendix B).

10. Final Selection

10.1 The decision team should now have all the information needed to make a final selection of the most resource-effective design. The information is presented to the decision maker(s). The final comparison or evaluation may take the form of 10.2 or 10.3.

10.2 *Risk versus Cost*—Here, risk is an estimate of the probability of an incorrect decision and its associated degree of hazard. Because usually, the lower the risk, the more the implementation will cost, the acceptable level of risk is at the discretion of the decision maker. Assuming that each design option presented meets the project objectives, the dynamics of the final decision are usually a balance between risk and cost, as displayed in Fig. 5. The objective is to minimize the cost or risk, or both, relative to the project constraints (for example, false positives, false negatives).

10.3 *Confidence Level versus Cost versus Time*—The balancing of the confidence level, cost, and time constraints is shown in Fig. 6. Design modifications to achieve the needed balance can include: (*1*) an increase or decrease in the number of samples; (*2*) use of design tools such as compositing; (*3*) satisfying practical limitations; (*4*) a change in the study boundaries; (*5*) an increase in the tolerable design errors; (*6*) a relaxation of project constraints; or (*7*) modifications in the initial hypotheses.

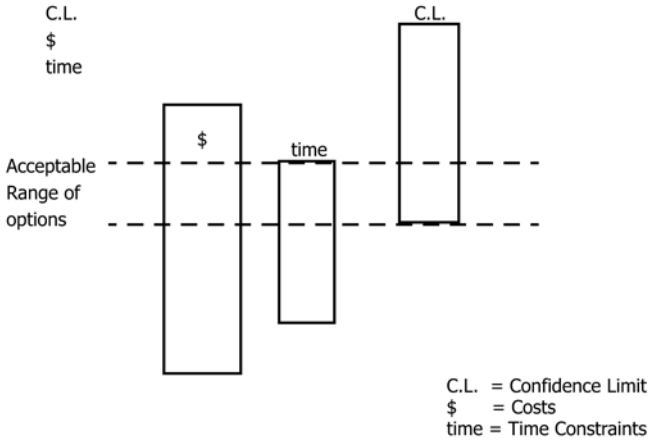

FIG. 6 Decision Variables

10.3.1 Significant changes to one or more of the alternate designs would require that the optimization process be repeated, with a review of the potential practical constraints, re-calculation of the number of samples, re-development of the statistical and cost estimates, and a final review by the decision maker.

10.4 *Final Selection Options:*

10.4.1 Using the information generated to compare cost, risk, confidence level, time constraints, and any other pertinent data, the decision maker can either (*1*) choose a sample design, or (*2*) reject the candidate designs.

10.4.2 If no design satisfactorily meets the requirements of the project objectives, including budgetary constraints and acceptable level of risk/error, then the sampling design or the project objectives will need to be modified. The design team should discuss with the decision maker whether modifications to the project objectives or the design option(s) are the most appropriate.

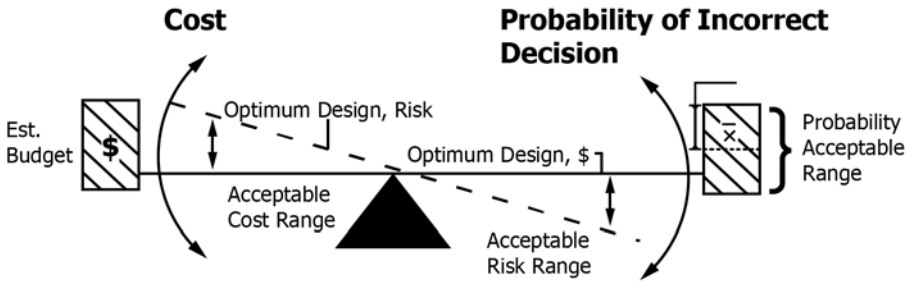

FIG. 5 Design Optimization