

**AIR FORCE REMEDIAL PROCESS OPTIMIZATION
FIELD PROCEDURES AND QUALITY ASSURANCE
HANDBOOK**

Version 2.0



**Prepared for the Air Force Center for Environmental
Excellence**

Brooks AFB, Texas

December 1999

AIR FORCE REMEDIAL PROCESS OPTIMIZATION FIELD PROCEDURES AND QUALITY ASSURANCE HANDBOOK

1. INTRODUCTION.....	E-1-1
2. QUALITY SYSTEMS AND DATA QUALITY OBJECTIVES	E-1-2
3. USEPA REQUIREMENTS FOR QUALITY MANAGEMENT AND DOCUMENTATION	E-1-4
3.1 Quality Management Plan	E-1-4
3.2 Quality Assurance Project Plans	E-1-6
4. THE DATA QUALITY OBJECTIVES PROCESS.....	E-1-6
5. STAKEHOLDER INVOLVEMENT.....	E-1-9
6. THE OPTIMIZATION PROCESS	E-1-9
6.1 Review Existing Documents and Goals	E-1-10
6.2 Develop Questions and Decision Rules to Address Remedial Optimization Goals	E-1-10
6.3 Review Existing Remedial Systems and Analytical and Field Data	E-1-11
6.4 Remedial Technology Decision Point.....	E-1-12
6.5 Evaluate the Field and Analytical Program for Optimization	E-1-12
6.6 Optimize the Field and Analytical Program.....	E-1-13
7. IMPLEMENTATION OF OPTIMIZATION RECOMMENDATIONS.....	E-1-19
8. AIR FORCE RECOMMENDED TECHNOLOGIES AND POINTS OF CONTACT.....	E-1-20
8.1. Points of Contact	E-1-20
ACRONYMS.....	E-1-21
KEY REFERENCES	E-1-22
ATTACHMENT 1 ADDITIONAL USEPA TOOLS.....	E-1-26
ATTACHMENT 2 ANALYTICAL PROTOCOL FOR 13 HIGH-PRIORITY TREATMENT TECHNOLOGIES.....	E-2

AIR FORCE REMEDIAL PROCESS OPTIMIZATION FIELD PROCEDURES AND QUALITY ASSURANCE HANDBOOK

1. INTRODUCTION

This document describes the field procedures and quality assurance (QA) aspects of remedial process optimization (RPO). It is designed to be used in conjunction with the Air Force Center for Environmental Excellence (AFCEE) *Remedial Process Optimization Handbook* (RPOH). As stated in the RPOH, RPO “is primarily intended for the optimization of existing remediation systems, but can also complement the remedial design process and promote more effective and efficient future systems.”

Two major sources of QA guidance apply to Air Force (AF) remediation systems. First are the QA requirements imbedded in the Federal, state, and local environmental regulations. Most of the state and local governments have adopted United States Environmental Protection Agency (USEPA) requirements. Consequently, this document summarizes key USEPA guidance and provides links to full text sources when available. Second are the AF-specific QA requirements. These documents are available on-line from various sites, and links are provided to them. Other groups such as the International Standards Organization (ISO) and American Society for Testing Materials (ASTM) have developed procedures and policies that are cited in this document and others. These groups do not have their documents on-line, and full-text sources must be obtained directly from each organization.

Various organizations have developed standardized field and laboratory procedures. The USEPA has published many of its procedures on-line, and links are provided to the index pages. Non-governmental organizations, such as ASTM, have not published their procedures and methods on-line, so these documents must be obtained elsewhere.

The overall optimization process is described in the RPOH. In general, all evaluations (including the optimization itself) are performed against explicit goals and data quality objectives (DQOs). The major steps in optimizing field procedures are:

- evaluating project DQOs
- assessing remedial system performance
- involving stakeholders
- evaluating the analytical and field program for optimization
- implementing the optimization decisions
- verifying optimization changes.

This document discusses the items to be considered during each of these steps.

This document describes optimization techniques for field procedures including analytical data collection during long term remediation system operation. As explained in the RPOH and as is shown in Figure 1, RPO may extend from the pre-Record of Decision (ROD) stages to Site Closeout. However, this document focuses more narrowly on the steps in Figure 1 labeled as Remedial Action Operation and Response Complete. During

the field procedures and analytical data optimization process, it may be determined that the remediation technology itself is ineffective or inappropriate. In such cases, this phase of the optimization process can lead the reviewers to reevaluate decisions made during earlier pre-ROD stages.

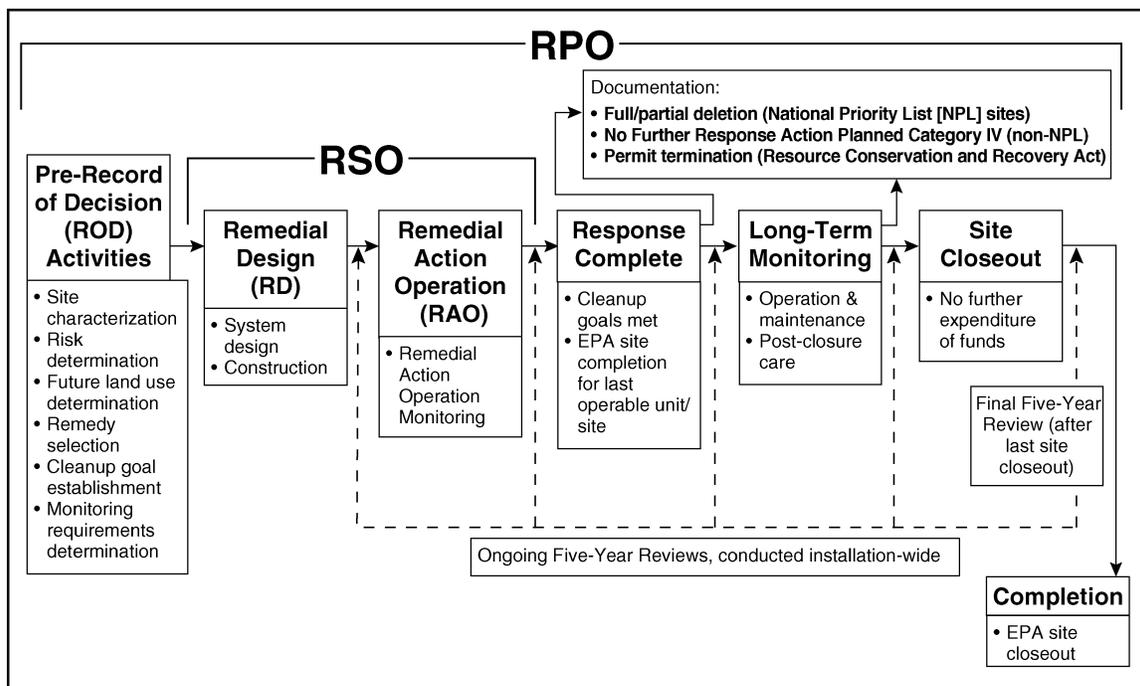


Figure 1 Overview of the RPO

2. QUALITY SYSTEMS AND DATA QUALITY OBJECTIVES

All optimization of the project-specific field and analytical procedures should be consistent with project goals and in compliance with all applicable quality systems.

For any project, the Quality Assurance Project Plan (QAPP) summarizes all quality requirements. Quality systems for all stakeholder organizations, e.g., AFCEE, regulators, and the laboratory, should have been considered when the QAPP was developed for the remediation. If a new QAPP is required as a result of the optimization process, the new QAPP should consider all stakeholder quality systems. Project quality requirements should be consistent with all applicable higher-level documents, and inconsistencies between higher-level guidance should be resolved before the project continues. Section 3 of this document describes USEPA requirements for quality systems and documents.

The QAPP is predicated on the project DQOs. As stated in the RPOH, “a clear definition of the type and quality of data that is [sic] required to track remediation progress should be established as the DQOs for individual remediation systems.” The DQO development process is described later in Section 4.

DQOs should be developed or confirmed for all aspects of the project, including field procedures such as sample locations, sample collection techniques, and reporting requirements. Project DQOs are oriented toward attaining regulatory compliance and site remediation. Broad project level DQOs require an understanding of the analytes and their concentration distributions, other measured system parameters, and the regulatory requirements for the remediation system operation and close out. More specific DQOs include analytical DQOs which commonly define the analytes to be monitored and the required detection limits, and may specify the analytical methods and the sampling frequency.

For field procedures, reevaluation of project DQOs may mean changes in some of the methods used to generate or evaluate data used to measure system effectiveness. For example, if an analytical method is changed, then selection of a method that is consistent with project DQOs will involve many factors. This selection should not be based simply on the use of “an approved method” or “an accepted method,” the least costly method, or the method with the lowest detection limit. Selecting the appropriate field and related analytical method and protocol requires a precise definition of the analytes, their action levels, the matrix, and the *question(s)* that the resulting data will be used to answer. These questions can be framed as project DQOs and should be the overriding criteria used in selecting an analytical method and protocol.

Analytical DQOs should be at least as stringent as project DQOs; otherwise, the analytical data quality will be insufficient for the project. Typically, this is not a problem because the uncertainty associated with the analysis is usually less than the uncertainty associated with sample collection and with the remediation system. In addition, the questions that are to be addressed by the analytical data collected during remediation are often of a general nature, so the project DQOs may not require highly precise and accurate data. One exception to this general rule is the measurement of effluent concentrations prior to release into the environment.

Commercial laboratories typically use analytical DQOs that are more stringent than the project DQOs require. Because laboratory (analytical) DQOs for reporting limits, precision, accuracy, representativeness, and comparability are defined in prescriptive laboratory methods, they are often incorporated into the project DQOs. This practice should be avoided for several reasons. First, when overly-stringent DQOs are not met, failure to achieve them will label project data as poor quality and unsuited for decision making. Although these data may fail to meet laboratory DQOs, they may still meet project DQOs, and therefore be suitable for making project decisions. Second, project DQOs should be reviewed simultaneously with the historical site or operational data and lead to development of the questions and decision points that will be used to judge whether the remedial system is achieving its goals. When the laboratory’s analytical DQOs are adopted as project DQOs, this critical examination of the data is often ignored and a chance to optimize the analytical methods and protocols is missed.

3. USEPA REQUIREMENTS FOR QUALITY MANAGEMENT AND DOCUMENTATION

The USEPA has published a series of documents describing quality management requirements for its remedial programs. These publications are listed in the reference section of this document. The USEPA documents are compliant with *American National Standard: Specifications and Guidelines for Quality Systems for Environmental Data Collection and Technology Programs*, ANSI/ASQC E4-1994 and also address criteria pertinent to the environmental perspective in ANSI/ASQC Q9000 series on quality management and quality system elements.

Project managers should assure that activities during the optimization process comply with USEPA quality systems requirements. During the historical review of project records, AFCEE managers may find that older data for projects currently being evaluated for optimization do not directly address the requirements for the DQO process. The usability of some of this older data to support the optimization process might be supported through statistical analysis.

The following sections summarize the USEPA requirements for quality system management and documentation as they apply to the optimization process. Specific requirements in the Quality Management Plan (QMP) and the QAPP critical to the optimization process are discussed in detail. Attachment 1 lists several additional tools developed by or available from the USEPA that are useful to project managers.

3.1 Quality Management Plan

The USEPA document *Policy and Program Requirements for the Mandatory Agency-wide Quality System*, (USEPA Order 5360.1 CGH 1) requires that USEPA organizations collecting environmental data must develop and operate management systems for assuring that the data collected are of the appropriate kind and expected quality for their intended use. *EPA Requirements for Quality Management Plans (QA/R-2)* defines the requirements for documentation of quality systems in a QMP. Since similar requirements will be issued by the USEPA for external organizations that collect environmental data, the following description of QMP requirements from QA/R-2 may apply to Air Force projects.

3.1.1 General Content

USEPA requires that the QMP address ten elements: management and organization; quality system and description; personnel qualifications and training; procurement of items and services; documentation and records; computer hardware and software; planning; implementation of work processes; assessment and response; and quality improvement.

For large organizations that conduct or manage many environmental projects, USEPA allows a core QMP that provides the system and procedural information relevant to all

projects. Individual groups within the organization that perform similar tasks may then provide more detailed system and procedural information relevant to their assigned functions as addenda or attachments to the core QMP. In any event, the system and procedural information in the QMP and its addenda must document the roles and responsibilities of all participants, and provide instructions to them. Systems and procedures unique to a specific project may be documented in a QAPP. Project managers should check with appropriate offices for the latest version of applicable QMPs.

3.1.2 Specific QMP Requirements Critical to the Optimization Process

The QMP specific requirements for systematic planning dictate use of the scientific method, common sense, and a level of detail in the planning that reflects the intended use of the work. USEPA QA/R-2 requires that the following minimum elements be included in the QMP:

- identification and involvement of the project manager, sponsoring organization and responsible official, project personnel, stakeholders, scientific experts, etc. (e.g., all customers and suppliers);
- description of the project goal, objectives, and questions and issues to be addressed;
- identification of project schedule, resources (including budget), milestones, and any applicable requirements (e.g., regulatory and contractual requirements);
- identification of the type of data needed and how the data will be used to support the project's objectives;
- determination of the quantity of data needed and specification of performance criteria for measuring quality;
- description of how, when, and where the data will be obtained (including existing data) and identification of any constraints on data collection;
- specification of needed QA and quality control (QC) activities to assess the quality performance criteria (e.g., QC samples for both the field and laboratory, audits, technical assessments, performance evaluations, etc.);
- description of how the acquired data will be analyzed (either in the field or the laboratory), evaluated (e.g., QA review, validation, verification), and assessed against its intended use and the quality performance criteria.

The QMP requires documentation of the assessments of environmental programs, including the responsibility and authority of the assessors, procedures for ensuring the competency of assessors, and the process by which management chooses an assessment

tool and the expected frequency of assessments. The QMP requires that senior management assess the adequacy of the quality system at least annually.

The QMP must also describe how assessment results are documented, reported, and reviewed by management. The procedures for responding to the findings and recommendations, for follow-up action to be taken, for confirmation of the implementation and effectiveness of the response action, and for dispute resolution must be included.

3.2 Quality Assurance Project Plans

USEPA requirements and guidance for development of the QAPP are documented in *EPA Requirements for Quality Assurance Project Plans (QA/R-5)* and *EPA Guidance for Quality Assurance Project Plans (QA/G-5)*. The AFCEE guidance on the preparation of a QAPP is available at the AFCEE web site at www.afcee.brooks.af.mil/er and is in compliance with the USEPA requirements described in this section.

The required elements for the QAPP are divided into four groups: Project Management; Measurement/Data Acquisition; Assessment and Oversight; and Data Validation and Usability. The documentation required in the QAPP mirror the QMP quality system on the project level.

The project management section documents the management, history, planning, objectives, and participant responsibility of the project. The measurement and data acquisition section describes measurement system design and implementation. The procedures to be used for sampling, analysis, data handling, QC, and for documenting these activities are addressed. The assessment and oversight section contains requirements to ensure that the project is implemented as prescribed and that documentation of the implementation is available. The data validation and usability concerns the requirements to ensure that the collected data are reconciled with the project's objectives.

In general, any QAPP prepared by organizations other than USEPA are reviewed and approved by USEPA prior to implementation. The QAPP must be periodically reviewed to keep it current. Any revisions to the QAPP must be formally approved and distributed to all participants in the project.

4. THE DATA QUALITY OBJECTIVES PROCESS

The DQO process developed by USEPA is a statistically-based, systematic, and iterative process. The DQO process results in a series of qualitative and quantitative statements that define the study objective, the appropriate type of data needed and the conditions for its collection, and specified tolerance limits for decision errors. The tolerance limits are used to identify the quantity and quality of data required to support decision making.

The full-text USEPA guidance on DQOs is provided in the following publications:
QA/G-4 Guidance for the Data Quality Objectives Process
QA/G-4D Data Quality Objectives Decision Errors Feasibility Trials (DEFT) Software
and may be accessed from http://es.epa.gov/ncercqa/qa/qa_docs.html.

The DQO process is composed of seven steps:

1. State the Problem
2. Identify the Decision
3. Identify the Inputs to the Decision
4. Define the Study Boundaries
5. Develop a Decision Rule
6. Specify Tolerable Limits on Decision Errors
7. Optimize the Design

Step One: State the Problem

The first step of the DQO process identifies the planning team; determines the procedures used for the planning; identifies the environmental project; and sets a schedule for the planning, implementation and assessment of the project. Because environmental problems present many complex technical, economic, social and political factors, members of the planning team should include representatives from all stakeholders in solving the problem.

Team members describe the conditions causing the problem and the reason for the project. The project may be divided into separate portions for management and decision making. The problem is defined in terms of project objectives or regulatory terms, interested parties in the project, any social or political issues, sources and amount of funding, previous study results, and existing sampling and analytical constraints. Team members then examine and review prior studies on the particular project, or similar studies, for use in the DQO process.

Team members identify the intermediate and final deadlines for the planning, implementation and assessment of the project. Team members should identify any interim stages available for previewing the correlation of the measurement data with the DQO requirements.

Step Two: Identify the Decision

Team members list the specific question(s) to be answered by the project and identify alternative actions that may be used to answer the question(s). The proposed alternative actions should always include the present condition.

Step Three: Identify the Inputs to the Decision

Team members list the information needed to solve the problem and identify the sources of the information. The sources may be previous studies, guidance, the literature or new data collection. Team members identify the information that is needed to identify the action level and identify the sources of this information. These may be regulatory thresholds or standards, or may be based on risk assessment. Team members develop a list of appropriate methods that may be used to measure the environmental conditions, noting the method detection limits and limits of quantitation. Information regarding cost and relative advantages and disadvantages of each of the methods is also gathered.

Step Four: Define the Boundaries of the Study

The team members identify the physical area to be studied, the location of any sampling, and the time frame for the project. The members identify any obstacles that may potentially interfere with the data collection design.

Step Five: Develop a Decision Rule

This step defines which statistic (the mean, median or proportion) of the sample population will be used to guide the decision-maker in selecting a course of action for solving the problem. Team members propose the methods for obtaining data from the specific sample population. The action levels for the project are then compared to the limitations of the proposed methods of data collection. The decision-maker postulates the rule for assessing compliance and noncompliance with the action level.

Step Six: Specify Tolerable Limits on Decision Errors

The team evaluates the potential total study error by considering both the sampling design error (due to the inability to sample all of the population) and measurement error (associated with sampling and analysis). The team enumerates various approaches to controlling these errors in the project. False negative and false positive decision errors are identified and evaluated separately, including the tolerance for each. The team should evaluate both the short and long-term impacts on the project resources, balanced against the risks of potential health and environmental effects, in considering the tolerable limits for the error. The evaluation of error should reflect the sampling, analytical, social, political and regulatory aspects of the project. The team should also consider the uncertainty or conservative nature of any risk-based level.

The final statement on the tolerable limit for the decision error is based on 'null and alternative hypotheses'. In some regulations, the 'null and alternative hypotheses' are predetermined. If not, the 'null' hypotheses is usually set for the condition of more severe consequences, and the 'alternative' hypotheses is set for the condition with less severe consequences. Then, the range of conditions under which the effect of error is considered to be relatively minor are identified. Probability limits are then assigned to the points above and below the relatively minor effects range.

When the tolerable limits are defined, the rationale should be documented in relationship to cost, human health and the status of site conditions. The values for the null and alternative hypotheses and the minor effects regions, accompanied by the probability limits, are usually charted for use in choosing the sampling design and in assessing the project data.

Step Seven: Optimize the Design for Obtaining the Data

In this final process step, the team reviews the DQO outputs for consistency and completeness, and then reviews any existing data that may be used to support the sampling design. Any historical patterns, estimates of variance, and the homogeneity and characteristics of the matrices should be considered in any new sampling design. Heterogeneity may dictate that more samples be collected, while proven homogeneity of the matrices may allow fewer samples to be collected. Historical levels of contamination greatly above the action level may allow composite sampling or use of less costly analytical methods at higher quantitation limits. Historical levels of contamination at levels near the action level may dictate use of analytical methods capable of lower quantitation limits. Historical data indicating contamination with only a few target analytes may allow modification of analytical methods to focus quality control on only the compounds of interest. Consistent confirmatory analyses in historical data may allow a reduction in the percentage of confirmations in the proposed sampling design.

The team proposes data collection design alternatives. The expense of collecting a larger number of samples and using more expensive analytical methods are balanced against the goal of obtaining adequate data quality. At this stage of the planning process, financial constraints may cause earlier decisions in the DQO process to be reassessed and redefined.

The optimal sample design is selected by the decision-maker using the DQOs and cost constraints. Upon satisfactory completion of the review, the designated procedures to be used in the sampling and analysis may be incorporated into the QAPP.

5. STAKEHOLDER INVOLVEMENT

The amount of stakeholder involvement will vary based on the phase of the RPO (see RPOH for definitions of Phases) and on the extent of the proposed modifications to the remedial process. At a minimum, all stakeholders should be notified after initial review has indicated areas of potential optimization, and should be involved during evaluation of the changes prior to implementation of any changes. The full extent of stakeholder involvement will vary depending on local conditions and requirements.

6. THE OPTIMIZATION PROCESS

Optimization of field protocols including analytical methods may take place at any time during the remedial design (RD) or remedial action operation (RAO) stages of the

Installation Restoration Program. The purpose of optimization is to evaluate and revise an existing remedial system based on long-term cost effectiveness while still meeting or exceeding all requirements. The RPOH should be consulted for a full discussion of the required schedule and steps in performing optimization. A summary of the process is provided below for the convenience of the reader.

6.1 Review Existing Documents and Goals

Optimization begins with a review of existing project documents, including the ROD, the Remedial Investigation/ Feasibility Study (RI/FS) data, the QAPP, and any applicable permits. The project goals and DQOs specified in these documents will be used as the basis for evaluation of the remedial technology and the existing suite of analytical protocols.

Existing remediation goals should be examined to ensure they are still appropriate and achievable. In addition, they should be reviewed to see if they adequately and appropriately define the analytical needs and field procedures. If the remediation goals need revision, stakeholder involvement should be high, since fundamental project documents may need to be reissued.

6.2 Develop Questions and Decision Rules to Address Remedial Optimization Goals

The success of a remediation system will be determined by how well it addresses the identified problem(s). Each operating system should have a set of written goals or objectives. Attainment of these goals is often determined by posing questions that are addressed by the collection and interpretation of data. Data should be collected to answer questions about system performance and attainment of remedial goals. Unless the questions are known prior to data collection, the quality and quantity of data needed may not be known, and the data collection effort may not properly answer the questions. Also, without definition of the data needed to make decisions, needless data might be collected.

In addition to establishing the efficacy of the remediation system through the proper formulation of questions and data collection, decision rules that determine when a remediation system stops, restarts, or is modified should exist. Decision rules are expressed in the form of an if/then statement that specifies the conditions under which a specific action will be taken. For example, a decision rule may state that if the contaminant has been below the applicable or relevant and appropriate regulation (ARARs) concentration for five years, then the remedial system should be stopped.

If an existing remedial system has been operating without a specific list of questions and decision rules, then these should be developed to help determine the degree of success and evaluate whether the right types of data with adequate data quality are being collected. This evaluation process will help optimize the system operation and focus attention on measuring the performance of the system and attainment of the remedial goals.

The goals of optimization process also should be formally defined. Questions should be developed that can be and are answered during the development of potential changes to the remedial process. The remediation optimization process can improve the effective use of resources while improving or maintaining remediation quality and effectiveness. All remediation process optimization efforts should have as a goal the protection of human health and meeting stakeholder expectations.

6.3 Review Existing Remedial Systems and Analytical and Field Data

After optimization goals are developed, the next step in the optimization process is a review of the remediation systems and the analytical and field data collected for the site to date. The historical data should be evaluated to see if they met the applicable analytical DQOs. All data that met applicable analytical DQOs should be used in the next phase of optimization.

The RPOH contains links to checklists that have been developed for evaluation of specific technologies. These checklists examine field criteria and system performance and should be used during the system review.

Earlier sample data from the RI/FS as well as current remediation data will provide information on analytes, concentrations, variability, sample points, and potential matrix problems. This information should be reviewed prior to evaluating the effectiveness of the remedial system. In addition, these data should form the basis for determining the analytes, analytical methods, sample collection frequencies, and sampling points to be considered during the optimization process. If different analytical methods are to be used or if there are questions about the adequacy of methods used earlier in the project, then it becomes important to assure comparability of the data and to verify the accuracy of the earlier data. This may involve additional sampling or analysis to fill data gaps and verify or refine the conceptual site model (CSM). RPO may result in additional initial expenditures, but improved system operation and focus will better meet the long term goals of the stakeholders. Thus, it is important that the previous analytical and sampling data be examined for quality and adequacy prior to optimization to ensure that:

- 1) the data sufficiently represent the site conditions,
- 2) all potential contaminants of concern have been addressed,
- 3) the data are of adequate quality for decision making,
- 4) samples are being collected from the most appropriate sampling points, and
- 5) proper sampling techniques are being used.

Any inconsistencies in the data should be carefully examined for the underlying cause(s) of the variation. At this point, the tolerance limits for changes in the analytical and sampling protocols should be established. If changes to the CSM are needed, they should be made at this time.

6.4 Remedial Technology Decision Point

After the project remediation goals, DQOs, CSM, data, and optimization goals have been established and reviewed, a decision should be made concerning the adequacy of the existing remediation technology. Is the existing technology capable of meeting the current project goals and DQOs? If not, the remediation technology itself is a candidate for optimization. The RPOH contains guidance for the modification and replacement of a technology, but the following paragraph briefly describes the process.

If the remediation technology is to be replaced, an evaluation of available remediation technologies should be performed. The Federal Remediation Technologies Roundtable (FRTR) *Remediation Technologies Screening Matrix and Reference Guide*, Version 3.0 can be found on the web (<http://www.frtr.gov>) and will aid the user in identifying appropriate technology. Information on widely used and presumptive remedies is provided in this document. The RPOH contains specific information to be developed and considered during evaluation of different technologies.

Site characterization data likely will be required for the new technology. Existing site data should be used when possible; however, additional sample collection and laboratory analyses may be needed. AFCEE provides several guidance documents for the collection and analysis of field samples including the *Model Quality Assurance Project Plan*, the *Model Field Sampling Plan*, and the *Environmental Analytical Protocols: A Program Manager's Survival Guide*. Full-text documents are available at www.afcee.brooks.af.mil/er.

If the existing technology is capable of meeting project goals, then the sampling and analytical program should be examined for the possibility of optimization.

6.5 Evaluate the Field and Analytical Program for Optimization

The next step is to evaluate the field and analytical program based on the project DQOs, permit requirements, ROD requirements, and historical data for the site. The evaluation may show that the sampling and analytical protocols used during remediation do not need to be the same as those used in either the design of the remedial system or in the early period of its operation. Less expensive, more targeted methods and protocols may be acceptable and meet DQO requirements. For example, samples may be taken less frequently for analysis. Also, analyses that are performed solely to monitor the remedial process and not for any regulatory purpose can often be performed by less definitive and rigorous methodology. If the analytical method used is changed, the types of samples and method used for sampling may also change to meet method requirements (such as container type or preservative).

A change in analytical methods, especially changes to less definitive methods, should be initially linked by comparative analyses with a definitive method in order to demonstrate that the method is acceptable and can meet project DQOs. Methods or laboratories should not be assumed to be comparable or capable of meeting project DQOs simply because the

published or stated method performance criteria are acceptable. Site specific demonstration and documentation are key elements, especially when deciding to use non-traditional or alternative methods. The key issues are quality, cost *effectiveness* and *performance* —not simply cost. While some methods are certainly less expensive, they may not meet the project DQOs and can ultimately result in higher costs if they lead to poor decisions. Demonstrating that a change in a protocol is within the tolerances of the project DQOs is essential to maintain adequate management and quality control of the project.

Many analyses are performed by prescribed protocols. In some cases, this approach is carried through to the end of the project and is acceptable by all measures; however, in other cases a better way may be found. Approaches should be optimized based on site-specific conditions. Prescribed methods may be inappropriate, unnecessarily expensive, or burdensome. However, before method changes are made, a complete understanding of the effect of sampling or method changes should be developed. In addition, failure to discuss or seek consensus prior to changing procedures can result in project delays and increased tension between stakeholders. The best and most reliable method for changing an approach is to *demonstrate* the effects and improvements of the change and to *document* those effects.

6.6 Optimize the Field and Analytical Program

Common assumptions regarding comparability or accuracy of analytical methods are sometimes found to be less than acceptable when actually tested. Differences among laboratories running the same methods are not uncommon, and can be more pronounced than differences between methods. Comparability and acceptance of one method over another should not be assumed to be valid without site-specific demonstration and documentation. This does not imply that information from other similar situations cannot be used, only that it is unwise to rely totally upon such information.

In general, confirmatory, high quality, and reliable methods should be utilized in the early phases of a remediation operation until the data trends and relationships are established. Once this has occurred, then a gradual transition to the less expensive and rigorous methods can be undertaken. This transition should include a period of overlap whereby the comparability of the “old” and “new” methods can be demonstrated.

Several on-line sources exist to aid program managers in the selection of analytical protocols. First, AFCEE has developed *The AFCEE Environmental Analytical Protocols: A Program Manager's Survival Guide* (on-line at www.afcee.brooks.af.mil/er.) Another source is the *FRTR Field Sampling and Analysis Technologies Matrix*, Version 1.0. This was developed by a consortium of federal agencies and is on the FRTR web site at <http://www.frtr.gov>. This site, along with the USEPA site at <http://www.epa.gov>, should be considered reference sources for sampling and analysis methods. An example summary from the FRTR tables is given in Table 1.

Generally, multiple methods are available for an analyte or group of analytes. The performance criteria for the methods vary. The decision of which method to employ, as well as the sample locations and frequency of sampling, can be determined only after applying the DQO process to particular key parameters and after consideration of site-specific data and the remedial technology.

The USEPA is developing a set of guidelines for performance based measurement systems (PBMS) where the precision, accuracy, and other criteria are used to evaluate the “correctness” of a method or sample measurement system. These guidelines have not been finalized as of the cover date of this document, but will be published soon. Prior to changing any analytical method from a prescriptive to a PBMS method, stakeholder agreement on the manner in which equivalence is shown must be obtained.

Different portions of a project may have different DQOs. For example, the analytical method selected for influent samples may not be appropriate for the effluent samples and the sampling frequency may not be the same. The sampling frequency and analytical methods for the effluent may be prescribed in permits or regulation, and may not be able to be optimized. In most cases, the influent analytes and their concentrations are very different from those present in the effluent. Consequently, different techniques may be necessary to meet regulatory requirements for detection limits. In addition, effluent sampling may be considerably more critical if fines, penalties, or bad publicity results from inaccurate or unacceptable data. In some cases, highly reliable and compound specific methods may need to be employed for effluent samples while influent samples may be analyzed with much less specificity and cost.

6.6.1 Optimization of Sample Types and Numbers

If optimization has shown that the number and types of samples to be collected should be reduced, decisions about changes in sampling techniques should be made after the analytical protocols and analyte lists have been optimized because different analytical methods have different sampling requirements. For example, on-site analysis of samples using test kits do not generally require the same volume of sample nor the preservatives necessary for samples that are shipped to fixed laboratories. In addition, the method and equipment used for sampling may vary depending on the requirements of the analytical method. For example, soil samples being collected for analysis of volatile organic compounds by an on-site laboratory do not need to be collected, stored, and shipped in the same manner as those samples being sent to an off-site laboratory. The number of quality control samples being collected may differ for on-site and off-site testing.

6.6.2 Optimization of Analyte Lists

Besides changing methods, it may be possible to eliminate or reduce target analytes based on historical data and other requirements. If a site has historically been free from a class of contaminants, then serious consideration should be given to eliminating that class of contaminants from future sampling events. If a limited number of analytes in a class of

contaminants has been found at the site, then shortening the analyte list of analytes for that class should be considered.

6.6.3 Considerations in the Analysis of Volatile Organic Compounds

Volatile organic compounds (VOCs) are commonly analyzed using either gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS) methods. GC methods are typically less expensive and are often chosen on this basis. Both GC and GC/MS have similar laboratory performance criteria and may meet project DQOs. However, GC methods commonly lack specificity when similar target analytes are present which could present significant problems depending upon the project DQOs.

Some permits and regulations require the use of GC/MS methods even though GC methods might be adequate. Stakeholders should consider all regulatory requirements when considering modifying these analytical procedures.

The following recommendations should be considered when evaluating possible changes to VOC analyses:

- Before changing the analytical methods from GC/MS to GC, a significant and representative portion of GC analyses should be confirmed by a GC/MS method to demonstrate that the GC analyses can be routinely used in long term monitoring or assessment of the remedial system.
- Occasional confirmation of GC results by split sample GC/MS analyses should be performed to assure continued reliability of GC results in a stable analytical program, and when there is a change in laboratory, sampling personnel, or other conditions that could impact the sample results.
- Sample contaminants should be evaluated by a review of past data. Sample results could be biased high if the sample contains multiple contaminants and there is insufficient selectivity in the analytical method.
- When demonstrating completion of remediation, a precise and highly reliable method should be used. Similarly, before installation of a remedial system, analyte identifications should be unquestionable and the concentrations adequately determined.
- Whenever a critical decision must be made about a remedial system and the decision will be largely based on analytical data, then a precise and highly reliable method should be used. GC/MS methods should be used periodically to confirm GC results and should be the basis for all critical decisions.
- If lower quality or less definitive methods are being used, there should be site specific data that demonstrate an acceptable correlation with a highly accurate and reliable method.

Table 1. Commonly Used Analytical and Field Methods, Continued

Analytes / Methodology	Method Characteristics							
	Detection Limits	Susceptibility to Interference	Selectivity	Turnaround Time per Sample	Quantitative Data Capability	EPA Approved Method	Relative Cost per Analysis	Technology Maturity
Volatile Organics								
Immunoassay Kits	Medium	High	Poor	Minutes	Limited	SA ¹	<\$50	Years
GC (SW8021)	Low	Low	Good	Hours	Yes	Yes	\$50-\$100	Decades
(GC/MS) (SW8260)	Low	Low	Excellent	Days	Yes	Yes	\$100+	Decades
Polynuclear Aromatic Hydrocarbons (PAHs)								
Immunoassay Kits	Medium	High	Poor	Minutes	Limited	SA	<\$50	Years
Gas Chromatography (GC) (SW8310)	Low	Low	Good	Hours	Yes	Yes	\$50-\$100	Decades
(GC/MS) (SW8270)	Low	Low	Excellent	Days	Yes	Yes	\$100+	Decades
Semivolatile Organics								
Immunoassay Kits	Medium	High	Poor	Minutes	Limited	SA	<\$50	Years
(GC) (SW8000 series)	Low	Low	Good	Hours	Yes	Yes	\$50-\$100	Decades
(GC/MS) (SW8270)	Low	Low	Excellent	Days	Yes	Yes	\$100+	Decades
Pesticides								
Immunoassay Kits	Medium	High	Poor	Minutes	Limited	SA	<\$50	Years
GC (SW8081)	Low	Low	Good	Hours	Yes	Yes	\$50-\$100	Decades
Metals								
Colorimetric Field Kits	Low-Med.	Low-Medium	Good	Minutes	Limited	SA	<\$50	Decades`
Immunoassay Kits	Low	Medium	Good	Minutes	Limited	SA	<\$50	Years
Atomic Absorption Spectrometry (SW7000 series)	Low	Low	Excellent	Hours	Yes	Yes	<\$50	Decades
Inductive Coupled Plasma Atomic Emission Spectroscopy (ICP) (SW6010)	Low	Medium	Excellent	Hours	Yes	Yes	<\$50	Decades
X-Ray Fluorescence	High	High	Good	Minutes	Limited	Yes	<\$50	Decade

SA¹ - Some analyte methods are approved by the USEPA.

- If conditions change during remedial operations such that there are unusually high or low spikes in concentrations, then confirmation analyses by a more accurate and reliable method should be employed.

6.6.4 Considerations in the Analysis of Metals

Metal concentrations in soil and water samples are determined by either atomic absorption (AA) or inductively coupled argon plasma (ICP). Both methods can be impacted by interferences, but ICP has historically suffered more significant problems than AA, especially for certain metals. For example, spectral interferences may cause ICP results for antimony, arsenic, cadmium, selenium, and thallium to be biased high when compared to AA. Each analytical method contains information on known interferents. Although properly calibrated ICP instruments automatically compensate for spectral interferences, data for the above stated metals should be closely reviewed when the interferences listed in the analytical method are present.

ICP is often chosen over AA for metals analysis because of its perceived advantages: lower total cost, large number of analytes, and adequate detection limits. The following recommendations should be considered when deciding between the use of ICP and AA for metals analyses:

- Identify the target analyte list needed for decision making and calculate the analytical cost by ICP and AA for these analytes. The cost of analysis by AA will often be similar or less when only a few elements are being analyzed. In addition, the need to store, report, and discuss non-essential elements is eliminated. If a wider range of analytes is required, then ICP can be used to report only selected analytes.
- Avoid analysis by ICP if antimony, arsenic, cadmium, selenium, or thallium are of interest. These five elements are sometimes less reliable by ICP and the detection limits are often higher than background and potential regulatory criteria.
- If ICP analysis was used, then a significant and representative portion of the ICP analyses should be confirmed by AA. Confirmation should be limited to critical elements. The values should be correlated and plotted on a scatter plot to demonstrate the usability of ICP analyses for decision making, long term monitoring, or assessment of the remedial system. Occasional confirmation analyses should be performed to assure continued reliability and should always be performed whenever there is a change in laboratory, sampling personnel, or other conditions that could impact the data usability.
- AA and ICP analyses should not be assumed to be comparable. In some cases, background concentrations (a potential remedial goal) have been determined using AA, while concentrations in site samples were measured using ICP. Attainment of cleanup to background may not be possible because of differences between the methods.

- For water samples, sample turbidity can greatly impact both ICP and AA analyses. Turbidity should always be measured and considered during data interpretation. Turbid water is generally *not* representative of an aquifer. Turbid water samples (i.e., >50 NTU) can yield high biased sample results and false positives. The issue of filtering to remove turbidity is debated and requires discussion with regulatory personnel.

6.6.5 Consideration of Field Test Kits

Field test kits are commonly employed during site investigations or removal actions when rapid turnaround is required. They are less commonly used for monitoring remedial system performance. Most of these test kits are designed for soils or sediments and are restricted to semi-volatile organic compounds (SVOCs) or generic categories such as total petroleum hydrocarbons (TPH), polynuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), or similar substances. Field test kits for water analysis such as those manufactured by the Hach Company[®] are usually designed for measuring general water quality parameters such as alkalinity, hardness, sulfate, or chloride. Although not commonly thought of as field tests, field instruments such as pH meters, dissolved oxygen sensors, and soil gas analyzers can also be employed to obtain real time analyses from many types of remedial systems. The USEPA lists approved test kits at <http://www.epa.gov>. The development of field tests is constantly and rapidly evolving. If project DQOs require rapid turnaround, the current status of field kits should be checked and their application considered.

6.6.6 Other Method Modifications

Other modifications to analytical methods may be possible with stakeholder approval. Some of these changes include an elevated reporting limit, a reduction in the percentage of samples used as matrix spikes or matrix spike duplicates (MS/MSD), or a limited list of analytes in the laboratory control sample. Potential changes to methods should be developed in collaboration with the laboratory, and approved by all stakeholders prior to implementation.

6.6.7 Coordination of Sampling Events

Sampling costs may be minimized by integrating remedial system sampling events with other events on the base. If the same contractor obtains samples for monitoring projects and for the remediation system, mobilization and sampling costs could be lowered if the samples are collected at the same time. The number of quality control samples, especially trip blanks for VOCs may be minimized if shipments to and from the laboratory can be combined.

7. IMPLEMENTATION OF OPTIMIZATION RECOMMENDATIONS

Once the potential changes to the field and analytical programs have been identified, new DQOs should be written for the project, and if necessary, quality documents should be edited to reflect the new requirements. Before any changes to the protocols are implemented, stakeholders and regulatory agencies should be consulted and approval obtained prior to making any changes. The RPOH gives further guidance on this subject.

If a new technology is to be implemented, the RPOH should be consulted for guidance on required and suggested steps.

If the sampling protocol is to be changed, the sampling teams must be notified of changes in procedures, equipment, frequency and types of samples to be collected. If necessary, teams should be trained in the new procedures.

All new analytical methods, especially those based on PBMS, should be documented. The number and frequency of samples should be modified to allow sufficient samples to be collected for demonstration and documentation of comparability of the new and old analytical methods. This transition period of dual data collection should be considered and addressed in the revised project documents. Guidelines must be established for evaluation of comparability, and the number of sampling events that involve both methods should be specified.

Another technique of demonstrating method comparability is the use of performance evaluation (PE) samples sent from the field to the laboratory. These samples are commercially available, and contain known amounts of the analytes of interest. The PE samples are placed in project sample containers and sent to the laboratory with routine field samples. The results can be evaluated by comparison to acceptance limits provided by the PE sample manufacturer.

Analytical method selection and changes must include a determination of allowable bias. Bias data is generally available from the laboratory or from the USEPA. Method bias must be considered when comparing method performance to DQOs.

As discussed in Section 6.6, critical data may have different DQOs from routine data. Critical data must be identified and methods selected that meet the required DQOs. Examples of critical data include effluent data, data used to determine when to close a site, and data used to modify remedial system operating conditions. Routine data may be confirmed on a regular basis by analytical methods with more stringent DQOs, especially if a modified method is used for routine data collection.

Data reporting should also be specified during analytical optimization. All data needed to characterize actual performance of the remediation technology should be identified and reported on a routine basis. During and immediately following the transition period, a report should be written that explicitly describes the effect of all sampling and method changes.

8. AIR FORCE RECOMMENDED TECHNOLOGIES AND POINTS OF CONTACT

Remedial technologies commonly used at Air Force sites include; (1) monitored natural attenuation, (2) pump and treat, (3) soil vapor extraction, (4) bioventing, (5) air sparging, and (6) free product recovery. Attachment 2 contains tables of potential field and analytical analyses for 13 remedial technologies. These tables should be used in conjunction with applicable guidance on environmental analytical protocols and with the *FRTR Field Sampling and Analysis Technologies Matrix* when developing revised sampling and analysis plan. Information about these technologies may be obtained from the AFCEE (<http://www.afcee.brooks.af.mil/er>) web site and from the CD-ROM Toolbox, available upon request from AFCEE Points of Contact noted below.

8.1 Points of Contact

Points of Contact for AFCEE publications include the following individuals.

Major Jeff Cornell
ERT Division Chief
210-536-4331
Jeff.Cornell@hqafcee.brooks.af.mil

Lt. Marcia Quigley,
Contracting Officer's Representative
210-536-4366
Marcia.Quigley@hqafcee.Brooks.af.mil

Dr. Javier Santillan
Geochemistry, Consultant
210-536-5207
Javier.Santillan@hqafcee.brooks.af.mil

Ms. Sylvia Ortega
ERT Division Secretary
210-536-4329
Sylvia.Ortega@hqafcee.brooks.af.mil

ACRONYMS

AA	Atomic Absorption Spectroscopy
AF	Air Force
AFCEE	Air Force Center for Environmental Excellence
ARAR	Applicable or Relevant and Appropriate Regulation
ASTM	American Society for Testing Materials
CSM	Conceptual Site Model
DEFT	<i>Decision Error Feasibility Trials</i>
DQO	Data Quality Objective
FRTR	Federal Remediation Technologies Roundtable
GC	Gas Chromatography
GC/MS	Gas Chromatography/ Mass Spectroscopy
GeoEAS	<i>Geostatistical Environmental Assessment Software</i>
ICP	Inductively Coupled Plasma Spectroscopy
ISO	International Standards Organization
MS/MSD	Matrix Spike/ Matrix Spike Duplicate
PAH	Polynuclear Aromatic Hydrocarbon
PBMS	Performance Based Measurement System
PCB	Polychlorinated Biphenyl
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
QMP	Quality Management Plan
RACER	<i>Remedial Actions Cost Engineering and Requirements System</i>
RAO	Remedial Action Operation
RD	Remedial Decision
RI/FS	Remedial Investigation/ Feasibility Study
ROD	Record of Decision
RPO	Remedial Process Optimization
RPOH	<i>Remedial Process Optimization Handbook</i>
SVOC	Semivolatile Organic Compound
TPH	Total Petroleum Hydrocarbons
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

KEY REFERENCES

- Air Force Center for Environmental Excellence (AFCEE), 1993, *Handbook to Support the Installation Restoration Program Remedial Investigations and Feasibility Studies*. San Antonio, Texas: Brooks AFB.
- AFCEE, 1997, *Long-term Monitoring Optimization Guide*. San Antonio, Texas: Brooks AFB.
- AFCEE, 1998a, *Model Field Sampling Plan*. San Antonio, Texas: Brooks AFB.
- AFCEE, 1998b, *Model Quality Assurance Project Plan*, Version 3.0. San Antonio, Texas: Brooks AFB.
- AFCEE, 1999, *Air Force Remedial Process Optimization Handbook*, Draft. San Antonio, Texas: Brooks AFB.
- Air Combat Command, 1998, *Site Closure Guidance Manual*. Washington D.C.: Government Printing Office.
- American Public Health Association, 1995, *Standard Methods for the Examination of Water and Wastewater*. Washington D.C.: American Public Health Association.
- American Society for Quality Control, 1994, *American National Standard: Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs*, ANSI/ASQC E4-1994. Milwaukee: Quality Press.
- Hach Company, 1999, *Products for Analysis*, Ames, IA.
- U.S. Department of Energy, 1993, *Remedial Investigation/Feasibility Study (RI/FS) Process, Elements And Techniques*. Washington D.C.: Government Printing Office.
- U.S. Environmental Protection Agency (USEPA), 1983, *Methods for Chemical Analysis of Water and Wastes*, 3rd edition. EPA 600/4-79/020. Environmental Monitoring and Support Laboratory. Washington D.C.: Government Printing Office.
- USEPA, 1987a, *A Compendium of Superfund Field Operations Methods, Part 2*, EPA/540/P-87/001 (OSWER Directive 9355.0-14). Washington D.C.: Government Printing Office.
- USEPA, 1987b, *Data Quality Objectives for Remedial Response Activities: Development Process*, EPA/540/G-87/003. Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1987c, *Data Quality Objectives for Remedial Response Activities: Example Scenario*, EPA/540/G-87/004. Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.

- USEPA, 1987d, *Selection Criteria for Mathematical Models Used in Exposure Assessments: Surface Water Models*, EPA/600/8-87/042. Office of Health and Environmental Assessment. Washington D.C.: Government Printing Office.
- USEPA, 1988a, *Field Screening Methods Catalog: User's Guide*, EPA/540/2-88/005. Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1988b, *Guidance for Performing Remedial Investigations and Feasibility Studies under CERCLA*, Interim Final, EPA/540/G-89/004, Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. Washington D.C.: Government Printing Office.
- USEPA, 1988c, *Selection Criteria for Mathematical Models Used in Exposure Assessments: Ground Water Models*, EPA/600/8-88/075. Office of Health and Environmental Assessment. Washington D.C.: Government Printing Office.
- USEPA, 1989a, *Risk Assessment Guidance for Superfund, Vol. I, Human Health Evaluation Manual (Part A)*, Interim Final, EPA/540/1-89/002, Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1989b, *Risk Assessment Guidance for Superfund, Vol. 2: Environmental Evaluation Manual*, Interim Final, EPA/540/1-89/001, Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1991a, *Description and Sampling of Contaminated Soils: A Field Pocket Guide*, EPA/625/12-91/002. Center for Environmental Research Information. Washington D.C.: Government Printing Office.
- USEPA, 1991b, *Preparation Aids for the Development of Category I Quality Assurance Project Plans*, EPA/600/8-91/003, Office of Research and Development. Washington DC: Government Printing Office.
- USEPA, 1991c, *Preparation Aids for the Development of Category II Quality Assurance Project Plans*, EPA/600/8-91/004, Office of Research and Development. Washington DC: Government Printing Office.
- USEPA, 1991d, *Preparation Aids for the Development of Category III Quality Assurance Project Plans*, EPA/600/8-91/005, Office of Research and Development. Washington DC: Government Printing Office.
- USEPA, 1991e, *Preparation Aids for the Development of Category IV Quality Assurance Project Plans*, EPA/600/8-91/006, Office of Research and Development. Washington DC: Government Printing Office.
- USEPA, 1991f, *Risk Assessment Guidance for Superfund, Vol. I, Human Health Evaluation Manual (Part B)*, EPA/540/R-92/003, Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.

- USEPA, 1991g, *Selection Criteria for Mathematical Models Used in Exposure Assessments: Air Dispersion Models*, EPA/600/8-91/038. Office of Health and Environmental Assessment. Washington D.C.: Government Printing Office.
- USEPA, 1991h, *Subsurface Characterization for Subsurface Remediation*, EPA/625/4-91/026. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA, 1992a, *Guidance for Data Usability in Risk Assessment (Part A)*, Final, Pub. 9285.7-09A, Office of Solid Waste and Emergency Response. Washington D.C.: Government Printing Office.
- USEPA, 1992b, *Technology Preselection Data Requirements*, EPA/540/S-92/009. Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1993a, *Data Quality Objectives Process for Superfund*, Interim Final Guidance, EPA/540/R-93/071. Office of Emergency and Remedial Response. Washington D.C.: Government Printing Office.
- USEPA, 1993b, *Preparation of Soil Sampling Protocol: Sampling Techniques and Strategies*, EPA/600/R-92/128. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA, 1993c, *Subsurface Characterization and Monitoring Techniques, A Desk Reference Guide*, EPA/625/R-93/003a & b. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA, 1994a, *Guidance for Planning Data Collection in Support of Environmental Decision Making Using the Data Quality Process*, EPA QA/G-4. EPA/600/R-96/055. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA, 1994b, *Methods for Monitoring Pump-and-Treat Performance*, EPA/600/R-94/123. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA. 1995a, *Environmental Monitoring Methods Index, Version 2.0*, PB97-502637INC. Office of Science and Technology, Washington, DC.: Government Printing Office.
- USEPA, 1995b, *Guidance for the Preparation of Standard Operating Procedures (SOPs) for Quality-Related Documents*, EPA QA/G-6, EPA/600/R-96/027. Office of Research and Development. Washington D.C.: Government Printing Office.
- USEPA, 1995c, *Land Use in the CERCLA Remedy Selection Process*, OSWER Directive 9355.7-04. Office of Solid Waste and Emergency Response. Washington D.C.: Government Printing Office.

USEPA, 1997, *Methods and Guidance for the Analysis of Water*, PB97-501308. Office of Water. Washington D.C.: Government Printing Office.

USEPA, 1998a, *EPA Guidance for Quality Assurance Project Plans*, EPA QA/G-5, EPA/600/R-98/018. Office of Research and Development. Washington D.C.: Government Printing Office.

USEPA, 1998b, *EPA Requirements for Quality Management Plans*, EPA QA/R-2, Draft Final. Office of Research and Development. Washington D.C.: Government Printing Office.

USEPA, 1998c, *EPA Requirements for Quality Assurance Project Plans for Environmental Data Operations*, EPA QA/R-5, Draft Final. Office of Research and Development. Washington D.C.: Government Printing Office.

USEPA, 1998d, *Guidance for Data Quality Assessment: Practical Methods for Data Analysis*, EPA QA/G-9, QA97 Version, EPA/600/R-96/084. Office of Research and Development. Washington D.C.: Government Printing Office.

USEPA, 1998e, *Title III Lists of Lists*. EPA/550/B-98/017. Office of Solid Waste and Emergency Response. Washington D.C.: Government Printing Office.

USEPA, 1998f, *Policy and Program Requirements for the Mandatory Agency-wide Quality System*, EPA Order 5360.1 CGH 1. Office for Research and Development. Washington D.C.: Government Printing Office.

USEPA, 1998g, *EPA Quality Manual for Environmental Programs*, EPA Manual 5360. Office for Research and Development. Washington, D.C.: Government Printing Office.

USEPA, 1999, *Test Methods for Evaluating Solid Waste*, SW-846, 3rd ed., rev. January 1995, and Draft Revision IVA, Office of Solid Waste and Emergency Response. Washington D.C.: Government Printing Office.

ATTACHMENT 1 ADDITIONAL USEPA TOOLS

The USEPA has identified three databases that may be used to identify analytical methods and regulatory thresholds:

- *Environmental Monitoring Methods Index* (EMMI), Version 2, provides a database of biological and analytical methods, as well as regulatory lists. The database does not include precision and bias information for the methods. This database is available from NTIS at www.ntis.gov.
- *Clean-Up Criteria for Contaminated Soil and Groundwater, 2nd Edition* provides summaries of clean-up criteria developed by USEPA, all 50 State regulatory agencies, and select countries outside the United States. This document with a searchable database is available through ASTM as Document DS64 at www.astm.org.

The USEPA has also identified a variety of software to assist in the creation of sampling designs:

- *Decision Error Feasibility Trials* (DEFT), EPA/600/R-96/056, is a software package designed to determine the feasibility of data quality objectives. This software and a User's Guide may be obtained from the USEPA Quality Assurance Division at http://es.epa.gov/ncercqa/qa/qa_docs.html.
- *Geostatistical Environmental Assessment Software* (GeoEAS) provides a two-dimensional geostatistical analyses of spatially distributed data. This software and a user's guide can be obtained from USEPA Office of Research and Development or downloaded from the World Wide Web site at www.epa.gov/ord.
- *ELIPGRID-PC* calculates the probabilities of hitting a hot spot for various sampling designs, and estimates the relative costs. This software was developed by Oak Ridge National Laboratory (TM-13103) and is available from NTIS as item number DE97006848INZ.

The USEPA provides software tools for performing data quality assessment. *DataQUEST* (EPA/600/R-96/085) provides verification of the DQO assumptions. This program can be obtained from http://es.epa.gov/ncercqa/qa/qa_docs.html. Additional statistical assistance can be obtained from the USEPA Quality Assurance Division.

Costs can be estimated using a software program designed for estimating the engineering and monitoring costs of remedial activities: *Remedial Actions Cost Engineering and Requirements System 99* (RACER 99). This product is available from Talisman Partners, Englewood, Colorado at www.talpart.com.

**ATTACHMENT 2: ANALYTICAL PROTOCOL FOR 13 HIGH-PRIORITY
TREATMENT TECHNOLOGIES**

**DRAFT ANALYTICAL PROTOCOL FOR 13 HIGH-PRIORITY
TREATMENT TECHNOLOGIES**

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final protocol. It is intended for the purpose of only peer review and comment only. **DO NOT CITE.**

**Prepared for
The Air Force Center for Environmental Excellence**

TABLE OF CONTENTS

INTRODUCTION.....	E-2-1
SECTION 1. PRIMARY REMEDIATION TECHNOLOGIES AND KEY INFLUENTIAL PARAMETERS.....	E-2-4
1.1 Biofiltration	E-2-4
1.2 Biopiles	E-2-7
1.3 Bioslurping	E-2-10
1.4 Bioventing.....	E-2-15
1.5 Cometabolic Treatment	E-2-17
1.6 Monitored Natural Attenuation	E-2-20
1.7 Chemical Oxidation/Reduction	E-2-31
1.8 Granulated Activated Carbon/Liquid-Phase Carbon Adsorption.....	E-2-33
1.9 Dual-Phase Extraction	E-2-35
1.10 Deep Well Injection	E-2-37
1.11 Ground-Water Pumping	E-2-40
1.11a Free Product Recovery	E-2-45
1.12 Air Stripping.....	E-2-49
1.13 Soil Vapor Extraction.....	E-2-53
SECTION 2. KEY INFLUENTIAL PARAMETER ANALYTICAL PROTOCOLS AND ASSOCIATED MEASUREMENT QUALITY OBJECTIVES... ..	E-2-54
2.1 Analytical Protocols and Measurement Quality Objectives.....	E-2-54
2.2 Chemicals Of Concern	E-2-113
SECTION 3. GENERAL DESCRIPTION OF ENVIRONMENTAL FATE AND TRANSPORT OF REPRESENTATIVE HAZARDOUS WASTE CLASSES.....	E-2-115
BIBLIOGRAPHY	E-2-117
ATTACHMENT 3: GENERAL DESCRIPTION OF THE ENVIRONMENTAL FATE AND TRANSPORT OF REPRESENTATIVE HAZARDOUS WASTE CLASSES.....	E-2-120

LIST OF TABLES

1.1 Biofiltration - Parameters and Associated Data Use.....	E-2-5
1.2 Biopiles - Parameters and Associated Data Use	E-2-8
1.3 Bioslurping - Parameters and Associated Data Use	E-2-11
1.4 Bioventing - Parameters and Associated Data Use.....	E-2-16
1.5 Cometabolic treatment - Parameters and Associated Data Use	E-2-18

1.6	Monitored Natural Attenuation - Parameters and Associated Data Use	E-2-22
1.7	Chemical Oxidation/Reduction- Parameters and Associated Data Use ...	E-2-32
1.8	Granulated Activated Carbon/Liquid-Phase Carbon Adsorption – Parameters and Associated Data Use	E-2-34
1.9	Dual-Phase Extraction - Parameters and Associated Data Use	E-2-36
1.10	Deep Well Injection - Parameters and Associated Data Use.....	E-2-38
1.11	Ground-Water Pumping - Parameters and Associated Data Use.....	E-2-42
1.11a	Free Product Recovery - Parameters and Associated Data Use	E-2-46
1.12	Air Stripping - Parameters and Associated Data Use	E-2-49
1.13	Soil Vapor Extraction - Parameters and Associated Data Use	E-2-52
2.1	Master Table Of Analytical Protocols and Measurement Quality Objectives.....	E-2-55
2.1.1	Chemicals Of Concern, Analytical Protocols, and Performance Criteria.....	E-2-113
3.1	General Description Of The Environmental Fate And Transport Of Representative Hazardous Waste Constituents.....	E-2-116

PROTOCOLS FOR 13 HIGH-PRIORITY TREATMENT TECHNOLOGIES

INTRODUCTION

Data collection and site characterization are prerequisites for all remedial designs and remedial system optimizations. The knowledge from these processes is extremely important for remedial systems that rely on removal from the subsurface via pumping, especially when water is the medium of concern. If the data used for decision making are incorrect or inadequate, then the resulting prediction of treatment performance will probably be erroneous. If the remedial investigation or feasibility study does not produce the required design data, additional effort will be required to obtain this information during the design phase. Alternatively, the design may not function as required to meet the remedial quality objectives (RQOs). Appropriate remedial project managers to determine the actual data to collect during field investigations may use these procedures.

The tables provide quality control parameters for each test procedure, where quality control parameters are specified. Another critical element is the number of samples necessary to obtain representative field data for the engineering design. The number of samples to obtain the engineering data should be based on the area or volume sampled, the type of parameter, the ease of obtaining the data, and the reliability required.

The objective of this document is to identify the likely key, influential design and characterization parameters for the 13 high-priority treatment technologies identified by the Air Force Center for Environmental Excellence (AFCEE). It will present the reader with optional analytical protocols that can be used for the determination of those key parameters. It is beyond the scope of this document to assist the reader in selecting the appropriate analytical method for each key parameter, as that process will require an evaluation of the site-and technology-specific data, as well as the application of the data quality objectives process. Information on how to select the appropriate analytical method from the tables presented in the enclosed document will be addressed in a separate guidance document.

This protocol is divided into three major sections. Section 1 consists of 13 high-priority treatment technologies, as identified by AFCEE, and their corresponding key, influential parameters. Section 2 is a master table of the key, influential parameters identified in Section 1, along with the analysis methods and associated precision, accuracy, and sensitivity performance data that can be used for their determination. Section 3 is a table of relevant characteristics, which may impact the decisions made during the remedial selection, design, and/or optimization process, for each of the primary classes of environmental analytes.

The remedial technologies presented in Section 1 are divided into three types of treatment processes as requested by the client: biological, chemical, and physical. The following table presents the technologies according to type, and the rows shaded gray are technologies that are included in this protocol.

Table 1.0. Technologies Segregated According to Treatment Process

Technology	Contaminants	Medium		Priority		
		Soil	Water	High	Med	Low
Biological						
Biofiltration	Os,Ov		X	X		
Biopiles	Os,Ov	X	X	X		
Bioreactors	Os,Ov		X		X	
Bioslurping	Os,Ov		X	X		
Bioventing	Os,Ov	X		X		
Cometabolic treatment	Os,Ov		X	X		
Composting	Os,Ov	X			X	
Constructed wetlands	Os,Ov		X		X	
Enhanced bioremediation/biodegradation	Os,Ov	X	X		X	
Fungal biodegradation	Os,Ov	X			X	
Landfarming	Os,Ov	X				X
Monitored natural attenuation	Os,Ov	X	X	X		
Phytoremediation	Os,Ov	X	X	X		
Slurry-phase biological treatment	Os,Ov	X				X
Chemical						
Ion exchange	M		X	X		
Precipitation/coagulation/flocculation	M		X	X		
Chemical reduction/oxidation	Os,Ov	X		X		
Open burn/open detonation	Os,Ov	X		X		
Oxidation	Os,Ov		X	X		
Pyrolysis	Os,Ov	X	X	X		
Solar detoxification	Os,Ov	X				X
UV oxidation	Os,Ov		X	X		
High-energy destruction	Os,Ov,Df		X		X	
Incineration	Os,Ov,Df	X		X		
Passive/reactive treatment walls	Os,Ov,M		X	X		
Physical						
Electrokinetic separation	M	X			X	
Membrane separation	M		X		X	
Solidification/stabilization	M	X				X
Aeration	Os,Ov		X	X		
Granulated activated carbon/liquid-phase carbon absorption	Os,Ov		X	X		
Dual-phase extraction	Os,Ov		X	X		
Fluid/vapor extraction	Os,Ov		X		X	

Table 1.0. Technologies Segregated According to Treatment Process

Technology	Contaminants	Medium		Priority		
		Soil	Water	High	Med	Low
Hot gas decontamination	Os,Ov	X				X
Hot water or stream flushing/stripping	Os,Ov		X		X	
Land treatment	Os,Ov	X			X	
Soil washing	Os,Ov	X		X		
Thermal desorption	Os,Ov	X		X		
Thermally enhanced soil vapor extraction	Os,Ov	X		X		
Adsorption/absorption	Os,Ov,M		X			X
Chemical Extraction	Os,Ov,M	X		X		
Deep well injection	Os,Ov,M		X	X		
Excavation, retrieval, and off-site disposal	Os,Ov,M	X		X		
Ground-water pumping	Os,Ov,M		X	X		
Landfill cap	Os,Ov,M	X		X		
Landfill cap enhancements	Os,Ov,M	X		X		
Separation	Os,Ov,M	X	X	X		
Slurry walls	Os,Ov,M		X	X		
Soil flushing	Os,Ov,M	X			X	
Air sparging	Ov		X		X	
Air stripping	Ov		X	X		
Directional wells	Ov		X	X		
Fracturing	Ov	X				X
Soil vapor extraction	Ov	X		X		
Sprinkler irrigation	Ov		X	X		
Vapor-phase carbon adsorption	Ov		X	X		
Ov – Organic volatiles Os – Organic semivolatiles M – Metals Df – Dioxins/furans						

SECTION 1 PRIMARY REMEDIATION TECHNOLOGIES AND KEY INFLUENTIAL PARAMETERS

This section of the protocol presents a list of the top candidate cleanup technologies to be considered for contaminated waste sites at installations, along with likely key parameters for each technology. A variety of analysis methods for key parameter determination to meet a range of data quality objectives (DQOs) are presented in Section 2. The key parameters have been selected primarily based on variables that are likely to influence the operation of a remedial system. This list of parameters for each cleanup technology may not be exhaustive. Each site and contaminant present may require modifications to the recommended analytical parameters, and in some cases, the engineer may elect to use professional judgment instead of actual data. However, in many cases, using standard values for some parameters may result in a design that does not meet the remedial action objectives (RAOs).

1.1 Biofiltration

Biofiltration is a proven technology to treat vapor-phase organics (such as from an air stripper, soil vapor extraction system, or wastewater treatment plant) by passing the off-gas through a soil filter. The organics sorb to the soil and are metabolized by microorganisms. The ability of the organics to sorb to the soil and the capability of the microorganisms to utilize the organics are essential for this process to properly remove the contaminants from the air.

The selection of biofiltration reduces the requirement to regenerate or handle activated carbon or to treat the off-gas by construction means. However, the size of the biofilter to achieve the sorption and degradation of the organics may require larger facilities than just for sorption of the organics.

The use of biofiltration requires other systems to obtain the off-gas and may require additional treatment if some of the chemicals of interest are not amenable to biological activity (polychlorinated biphenyl [PCBs], metals).

As air permits require greater removal of volatile organics, this process may receive increased analysis in comparing alternative systems (combustion processes) to meet the requirements for discharging air from treatment systems.

Table 1.1. Biofiltration-Parameters and Associated Data Use

This table presents site or design characterization parameters that may be necessary to implement biofiltration. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal biofiltration have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	PURPOSE	COMMENTS
Chemicals of concern (COCs)	Water, gas	To identify the COCs that may be amenable to sorption on soil from air and are amenable to utilization by microorganisms	Only chemicals that are readily sorbed to soil from air and are biodegradable.
Dissolved oxygen (DO)	Gas, soil	Depending on the biological process, the control of DO is required to facilitate the degradation of the organics	Normal benzene, toluene, ethylbenzene, and xylene (BTEX) compounds are degraded under aerobic conditions, while for chlorinated solvents, some anaerobic conditions may be required.
Henry's law constant	Gas	To determine the amount of the gas that will sorb to the soil under equilibrium conditions	Generally available in references; however, the effect of other chemicals may modify the value.
Intrinsic permeability	Soil	To evaluate the permeability of the soil treatment unit to air	The capability of the soil to transfer sufficient gas is required to reduce the size of the biofilter.
Metals	Gas	To prevent metals toxicity of the microbiological process	If the off-gas contains significant aerosols that may entrain metals dissolved in water, the process may be negatively affected.
Moisture	Soil, gas	To determine the moisture of the soil, which may reduce the air permeability Excessive moisture in the air may create water flooding of the soil biofilter	The testing of the soil for the degradation of the target organics should be performed at the approximate moisture range to be used during operation. Moisture on the soil also reduces porosity (to effective porosity).
Particle size	Soil	To determine the uniformity coefficient (UC)	Sieve analysis for sand particles should be employed. Hydrometer analysis for clays and silts should be employed.
pH	Soil, gas	The pH may affect the sorption capacity of the soil and the effectiveness of the microorganisms	The pH of the off-gas and the soil should be tested with the microorganisms during the treatability phase.
Porosity	Soil	To specify the void spaces in the treatment unit To identify the void spaces for air to flow	
Temperature	Gas, soil	The temperature of the gas and the soil are required	If the off-gas is hot, the ability of the soil to fully capture the contaminants will be reduced, and elevated temperatures may effect the types of organisms that are present. Soil that is cold will have reduced biological activity.

Table 1.1. Biofiltration—Parameters and Associated Data Use (Continued)

Parameter	<i>Matrix</i>	PURPOSE	COMMENTS
Density	Soil	To identify the size of the facility and the structural requirements	
Carbonates	Soil	To determine of carbonate precipitation will affect the treatment system.	
UC	Soil	To determine ratio of grain size of material that is smaller than 60% (D_{60}) of the total soil and the amount of material smaller than 10% (D_{10}) of the total soil	The biofilter soil should have a UC of less than or equal to 2.0. The UC is the ratio of D_{60} to D_{10} . A relative uniform grain (soil) size should reduce plugging and is similar to filters in water treatment plants.
Unit rate (k)	Soil	The rate microorganisms utilize the organics	Also defined as the maximum rate of substrate utilization or k in the Monod equation: $C = C_0 e^{-kt}$. This will govern with the sorption, the total biofilter size. For many organics in water systems, the ranges for k 's for the compounds are published. However, bench- or pilot-scale testing should be performed to obtain actual design data. This parameter is also referred to as a first order degradation rate constant, and is reported as units per day.

1.2 Biopiles

Biopiles are an ex situ engineered treatment process used to treat soil, sludges, or sediment that have been contaminated with petroleum products. This is a proven technology. Additional treatment of leachate and air from the biopiles may be required.

Biopiles have been used primarily to treat petroleum products. Biopiles have also been used to treat some nonhalogenated volatile organic compounds (VOCs), VOCs, semivolatile organic compounds (SVOCs), and pesticides; however, bench-scale testing is generally required for these compounds, and the effectiveness may vary with specific compounds and additives.

Biopiles require a treatment area that is lined to contain any leachate for additional treatment (or to recycle the leachate onto the biopile), and to prevent seepage of leachate into the soil below the biopile. In addition, biopiles may be covered with black plastic to control rainfall runoff, evaporation, and volatilization into the airstream. Biopiles generally include methods to increase the oxygen in the biopile.

Vendors have developed specific soil amendments to assist in the bioremediation of the chemicals of concern (COCs).

Table 1.2. Biopiles-Parameters and Associated Data Use

This table presents site and design characterization parameters that may be necessary to implement biopiles. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement biopiles have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Carbonates	Soil	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Chemicals of concern (COC)	Soil	To identify the COCs	This is necessary to ensure that the chemicals are amenable to biopile degradation.
Metals	Soil	To determine whether metals treatment will also be required or if the metals may decrease biological activity	
Moisture	Soil	To estimate the amount of water in the soil (possible leachate)	Biological processes require moisture; however, the moisture should be within the range determined from the pilot or bench testing. Moisture may be added if the moisture is not adequate.
Nitrogen (total)	Soil	To determine whether sufficient nutrients are present to sustain the required treatment rate	
pH	Soil	To determine whether the pH is in the optimum range to promote the biological process	pH may require adjustment.
Soil density	Soil	To estimate the amount of nutrients, and additives required to improve the biological process	
Sulfate	Soil	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Total iron	Soil	To determine whether sufficient nutrients are present to sustain the required treatment rate	

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Total manganese	Soil	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Unit rate (k)	Soil	To estimate the treatment period and amendments required	Also defined as the maximum rate of substrate utilization or k in the Monod equation: $C = C_0 e^{-kt}$. This will govern with the sorption, the total biofilter size. For many organics in water systems, the ranges for k 's for the compounds are published. However, bench or pilot scale testing should be performed to obtain actual design data. This parameter is also referred to as a first order degradation rate constant, and is reported as units per day.
For additional explanations for parameters, see the discussion on monitored natural attenuation (Section 1.6).			

1.3 Bioslurping

Bioslurping is a proven technology combining bioventing and vacuum-enhanced free product recovery. The bioventing encourages the biodegradation of hydrocarbon-contaminated soils, and the vacuum-enhanced free product recovery system extracts free product from the capillary fringe and the water table. The vacuum-enhanced free product recovery is designed to reduce the quantity of ground water recovered and the quantity of ground water requiring treatment by lifting the free product from the water table and the capillary fringe. Biological degradation is enhanced by the air is drawn into the subsurface to replace the soil gas that is removed by the vacuum.

The primary purpose of bioslurping is to remove free product and reduce the quantity of free product dissolving into the ground water.

This process requires knowledge of both the free product and bioventing. The depth to free product is important. The ability of the vacuum to lift the free product is limited to approximately 29 feet; however, the more volatile fractions may be extracted by the vacuum. Entrainment of free product on gas bubbles or aerosols will be the principal method for removing free product below 29 feet.

Table 1.3. Bioslurping-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to implement bioslurping. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal bioslurping have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	PURPOSE	COMMENT
Benzene, toluene, ethylbenzene, and xylenes (BTEX) and carbon chain	Free product	To determine the relative amounts of constituents of concern	The Gas Processors Association (GPA) method is the most accurate method to determine the percentage of BTEX compounds and carbon chains.
Chemicals of concern (COC)	Water, gas	To identify the COCs that may be amenable to vapor recovery and may be reduced by the removal of JP-4 Also, identify organics that may be biologically degraded by the increase in air flow	Only chemicals that are biodegradable, mobile, or volatile will be amenable to this technology.
Depth to free product	JP-4	The depth to free product is required For depths greater than 29 feet, the amount of free product recovered by vacuum will depend on entrainment of the JP-4	Efficiency of JP-4 recovery depends on grain size, pore size, interstitial tension, and viscosity of the JP-4, and the vacuum applied.
Dissolved oxygen (DO)	Gas, soil	Depending on the biological process, the control of DO is required to facilitate the degradation of the organics	Normal BTEX compounds are degraded under both aerobic and anerobic conditions, although aerobic conditions are preferred. Anaerobic conditions are required for most chlorinated organics, especially ones that are highly chlorinated.
Fraction of organic carbon (F _{OC})	Soil	To determine the fraction of organic carbon in the soil, which affects contaminant mobility	The fraction of organic carbon in the soil can be determined from laboratory tests.
Henry's law constant	Gas	To determine the amount of the contaminant in the gas phase, from the free product, that will be available for biodegradation under equilibrium conditions	This parameter is generally available in references; however, the effect of other chemicals may modify the value.

Table 1.3. Bioslurping-Parameters and Associated Data Use (Continued)

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Hydraulic conductivity (K)	Soil	To measure the capacity of the soil media to transmit flow of a specific fluid such as water To estimate the ground-water velocity and migration rate of the chemicals of concern (COCs) To determine effective location, number, and pumping rates of extraction wells	Numerous aquifer tests can be employed to determine hydraulic conductivity. The test used to acquire adequate data quality should be determined based on site-specific conditions.
Hydrocarbon pore saturation	Soil	To determine the percentage of pore spaces filled by the free product	Amount of free product in the pore spaces affects the recoverability of the free product.
In situ respiration test (oxygen utilization)	Soil gas	To determine oxygen utilization, carbon dioxide production	Measures effectiveness of bioventing and biological activity.
Interfacial tensions	Free product, ground water	To determine the interfacial tensions between free product and air, free product and ground water, and ground water and air	
Intrinsic permeability	Soil	To determine the permeability of the soil	This parameter allows the determination of the permeability of soil to water, free product, and air.

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Intrinsic permeability	Soil, JP-4	To determine the permeability of the soil to air, water, and JP-4	The capability of the soil to transfer sufficient soil gas is required, and the permeability of the soil to JP-4 to induce the JP-4 to move to the bioslurper is also important. Permeability to water is also required.
Less dense nonaqueous -phase liquids (LNAPL) density	Free product	TO DETERMINE THE DENSITY OF THE FREE PRODUCT	This information with other data on the free product will be used to determine the age and type of original free product. This will also be used to model the contribution of the free product to the groundwater plume affected by the free product.
Metals	Water	To determine whether metals treatment will be required for wastewater	

Table 1.3. Bioslurping-Parameters And Associated Data Use (Continued)

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Moisture	Soil, gas	To determine the level of moisture in the soil, which may reduce the air permeability Excessive moisture in the air may reduce the effectiveness of the bioslurping process	
Nitrates	Soil	To determine the levels of nitrogen, which is an essential nutrient	Nitrogen is generally not rate limiting for the bioventing portion of the technology.
Particle size	Soil	To determine grain size distribution and relation to free product movement	Sieve analysis for sand particles should be employed. Hydrometer analysis for clays and silts should be employed.
pH	Soil, gas	The pH may affect the soil and the effectiveness of the microorganisms	
Phosphorus	Soil	To determine the levels of phosphorus, which is an essential nutrient	Phosphorus is generally not rate limiting for the bioventing portion of the technology.
Porosity	Soil	To identify the void spaces for air to flow and for JP-4 to move	
Soil capillarity	Soil	To determine capillary pressure of the soil	The soil should be collected in the zone with free product.
Soil density	Soil	To determine soil density	This parameter can be used to calculate porosity. It is the density of the soil at the field moisture content.
Sorption coefficient (K _{OC}) in soil	Soil	To estimate the retardation influence on fate and transport of contamination	This parameter is typically either determined from the literature or calculated experimentally.
Sulfates	Soil	To determine the levels of sulfate, which is an essential nutrient	Sulfate is generally not rate limiting for the bioventing portion of the technology.
Temperature	Soil, gas	The temperature of the gas and the soil are required as this parameter will affect the efficiency of the system	If the off-gas is hot, the ability of the soil to fully capture the contaminants will be reduced and elevated temperatures may effect the types of organisms that are present. Soil that is cold will have reduced biological activity.
Vapor pressure at soil temperature	COC	To determine the likelihood that the contaminant will volatilize	
Viscosity	Free product	To determine the ability of the free product to move	The free product viscosity affects the ability of the free product to move.
For additional explanations for parameters, see the discussion on monitored natural attenuation (Section 1.6).			

1.4 Bioventing

Bioventing is a proven technology. Bioventing encourages the biodegradation of hydrocarbon-contaminated soils by supplying oxygen (air) to the soil. The biological degradation is enhanced by the air (oxygen) pumped into the subsurface. This technology encourages naturally occurring soil microorganisms to biologically degrade the degradable compounds. Bioventing uses low airflow rates to provide increased oxygen to sustain biological activity. Many sites are oxygen deficient (anaerobic) or oxygen restricted, and anaerobic bacteria are not as efficient as aerobic bacteria at degrading many organic compounds.

Bioventing is used primarily for petroleum hydrocarbon contaminated sites. Chlorinated solvents may require a cometabolite to be present and anaerobic conditions for degradation to occur.

The use of bioventing in built-up areas may require additional monitoring or vapor recovery to prevent off-site migration of gas or contaminants or to prevent gas buildup.

Water table fluctuations may recontaminate an area, previously remediated by bioventing, with floating free product. The design should consider fluctuations of free product, and the bottom of the bioventing well should be located above the highest elevation of free product to prevent fouling of the bioventing well.

Table 1.4. Bioventing Data-Parameters And Associated Data Use

This table presents site and design characterization parameters that may be necessary to implement bioventing. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal bioventing have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	PURPOSE	COMMENT
Chemicals of concern (COC)	Water, gas	To identify the COCs that may be amenable to biological degradation by the increase in air flow	Only chemicals that are biodegradable will be amenable to this technology.
Depth to free product/ water	Water, JP-4	To determine placement of the bioventing wells	The bioventing wells should terminate several feet above the high water level
Dissolved oxygen (DO)	Gas, soil	Depending on the biological process, the control of DO is required to facilitate the degradation of the organics	Normal benzene, toluene, ethylbenzene, and xylene (BTEX) compounds are degraded under aerobic conditions, while for some chlorinated solvents, anaerobic conditions are required. Increases in DO should result in greater respiration and degradation of BTEX.
In situ respiration test	Soil gas	To determine oxygen utilization and carbon dioxide production	This test measures effectiveness of bioventing and related biological activity.
Intrinsic permeability	Soil, JP-4	To determine the permeability of the soil to air	The capability of the soil to transfer sufficient air is required.
Moisture	Soil, gas	The moisture of the soil may reduce the air permeability and reduce the effectiveness of the bioventing	If the moisture is too low, biological activity may decrease; if the moisture is too high, the available pore space for air to travel is reduced.
Nitrates	Soil	To determine nitrogen levels, which is an essential nutrient	Nitrogen is generally not rate limiting for the bioventing portion of the technology.
pH	Soil, gas	The pH may affect the soil and the effectiveness of the microorganisms	
Phosphorus	Soil	To determine phosphorus levels, which is an essential nutrient	Phosphorus is generally not rate limiting for the bioventing portion of the technology.
Porosity	Soil	To identify the void spaces for air to flow	
Sulfates	Soil	To determine sulfate levels, which is an essential nutrient	Sulfate is generally not rate limiting for the bioventing portion of the technology.
Temperature	Gas, soil	The temperatures of the gas and the soil are required to determine the efficiency of the system	
Total iron	Soil	To determine the levels of Fe(III), which is an essential nutrient	Iron is not usually rate limiting for the bioventing portion of the technology.
For additional explanations for parameters, see the discussion on monitored natural attenuation (Section 1.6).			

1.5 Cometabolic Treatment

Cometabolic processes are in situ treatment processes used to treat ground water contaminated with chlorinated solvents. This is an emerging technology. This process uses the addition of a primary substrate to supply the energy for the biological transformation of the target COCs.

The addition of another chemical into the ground water is not a short-term operation and requires detailed analysis and significant regulatory reviews.

This technology is based on field experience at many sites contaminated with petroleum products and chlorinated solvents where the biological degradation of the petroleum compounds has also resulted in a reduction in the chlorinated compounds. Additional research has been used to determine appropriate cometabolites. Some of the compounds used as primary substrate addition have been methane, toluene, propane, and butane. The methane has been used to support methanotropic bacteria for the degradation of trichloroethylene (TCE).

This application is very site specific.

Table 1.5. Cometabolic Treatment -Parameters And Associated Data Use

This table presents site characterization parameters that may be necessary to implement the cometabolic treatment process. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement cometabolic treatment have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	PURPOSE	COMMENT
Alkalinity	Water	TO DETERMINE BUFFERING CAPACITY	
Carbonates	Water	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Chemicals of concern (COCs)	Water	To identify the COCs	
Dissolved oxygen (DO)	Water	To determine whether the process will be aerobic or anaerobic	The COC and the degradation process (aerobic or anaerobic) may affect the selection of the cometabolite. If the ground water is anaerobic, the addition of oxygen will be required in addition to the cometabolite.
Intrinsic permeability	Soil, water		It will be necessary to determine whether highly permeable areas are interspersed with low-permeability areas.
Metals	Water		High concentrations of metals may retard biological activity.
Nitrogen (total)	Water	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Oxidation/reduction	Water		
pH	Water		
Porosity	Soil		Only the pore spaces will transmit water.
Sulfate	Water	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Temperature	Water		
Total iron	Water	To determine whether sufficient nutrients are present to sustain the required treatment rate	
Total manganese	Water	To determine whether sufficient nutrients are present to sustain the required treatment rate	

Table 1.5. Cometabolic Treatment -Parameters and Associated Data Use (Continued)

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Unit rate (k)	Water	To estimate the treatment period and amendments required	Also defined as the maximum rate of substrate utilization or k in the Monod equation: $C = C_0 e^{-kt}$. This will govern with the sorption, the total biofilter size. For many organics in water systems, the ranges for k 's for the compounds are published. However, bench or pilot scale testing should be performed to obtain actual design data. This parameter is also referred to as a first order degradation rate constant, and is reported as units per day.
For additional explanations for parameters, see the discussion on monitored natural attenuation (Section 1.6).			

1.6 Monitor Natural Attenuation

The Environmental Protection Agency (EPA) published guidance on the use of monitored natural attenuation (MNA) at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites and underground storage tank (UST) sites. The phrase “natural attenuation” (NA) is used to describe the process, and the term “MNA” is used to describe the remedy. MNA differs from the many other remedial alternatives presented in this part of the appendix in that MNA is not an actively engineered system, but is actively modeled and monitored. Therefore, the usual adjusting and modification of engineering parameters do not apply to MNA. However, effective data collection and monitoring of MNA are crucial, just as with any other engineered remedial system, for ensuring that the models chosen to simulate MNA processes in the subsurface and the data used as input in the chosen model are of adequate quality. This section on MNA presents the likely primary key parameters necessary to simulate and predict the occurrence of NA in the subsurface and presents analytical methods that can be used for their measurement. For a more exhaustive description of how each parameter is related to MNA in the subsurface, as well as a more detailed look at MNA processes, see the *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water Draft Revision 1* (AFCEE 1996) and the *Technical Protocol for Implementing Intrinsic Remediation for Natural Attenuation of Fuel Contamination Dissolved in Ground Water* (AFCEE 1995).

MNA, which is not the same as biodegradation, describes a remedy for reducing the contaminant toxicity, mobility, or volume to levels that are protective of human health and the ecosystem. Many processes can be responsible for attenuating the risk associated with the hazardous COCs (in alphabetical order):

- biodegradation,
- chemical stabilization,
- dilution,
- dispersion,
- sorption, and
- volatilization.

NA requires extensive monitoring and data evaluation and often results in faster cleanup than other engineering approaches due to natural processes. However, the absence of overt engineering field activities creates the common perception that nothing is being done to treat the site. While all remediation technologies must have evidence of probable success before acceptance in a record of decision (ROD), the extreme demand placed on NA is a direct result of its do-nothing appearance. In EPA’s Directive 9200.4-17, *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites* (USEPA 1997), primary and secondary lines of evidence are presented as crucial components for demonstrating the occurrence of NA. The EPA attributes great significance to the primary line of evidence, which is the demonstration of historical (temporal) trends in contaminant concentrations. The EPA also relies on second lines of evidence, which consist of the calculation of rates of NA and the evaluation of subsurface geochemical data.

In addition to the historical data demonstrating the obvious trends in contaminant concentrations and associated attenuation rates, geochemical data provide additional qualitative evidence as an indication of historical and potential future contribution of biodegradation to the overall NA process. Ground-water parameters such as dissolved oxygen, redox potential, ferrous iron, sulfate, ethane, ethene, and, dissolved methane levels can be important in demonstrating the occurrence of biodegradation. In addition, a comprehensive understanding of site-specific ground-water flow and contaminant movement is critical for gaining approval for MNA as an acceptable remedial alternative. Models and calculations that rely on these parameters as input are key components in estimating the ultimate state and movement of the COCs. Table 1.6 presents the parameters that could be critical input data for the selected model of NA and their purpose. Table 2.1 of Section 2, the master table, presents the associated methods used to measure each parameter and each method's associated performance criteria and limitations.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use

Parameter	Matrix	Purpose	Comments
Alkalinity	Water	To measure the buffering capacity of ground water In combination with pH, alkalinity allows an estimate of the quantity of carbon dioxide (CO ₂) available for methanogenesis	It is important to conduct the measurement on a filtered sample to ensure that the alkalinity being measured is not from suspended sediments. It is important to document the initial pH and temperature of the sample at the time the titration is performed.
Aqueous solubility	Chemical of concern (COC)	To predict the effect of mobilization potential of contaminants in the water phase on fate and transport	This parameter is typically either determined from the literature or calculated experimentally.
Aquifer thickness	Soil	To identify confining layers which help to prevent impact to deeper aquifers and for the design of monitoring points	Regional hydrogeology should be considered in the evaluation of aquifer thickness.
COCs	Water, soil, soil gas	To understand the key biological processes that can affect the fate and transport of the COCs	The laboratory should be required to report all analytical runs. These include the primary analysis conducted at the lowest detection level and the results from the analysis of the dilutions. In addition, a tentatively identified compound (TIC) list may be helpful in delineating any fuel hydrocarbons, which may be the food source for subsurface microbes.
Chloride	Water	Released during reductive dehalogenation of chlorinated solvents To estimate dilution in calculation of rate constants	Samples with naturally high levels (100 mg/L) of chloride in ground water require dilution which raises the detection limit an order of magnitude (to 1 mg/L) or greater. This results in insufficient sensitivity to detect the low levels of chloride resulting from reductive dechlorination. Chloride is a ubiquitous anion, and being able to distinguish natural, background sources of chloride from organochlorine sources is unlikely. The EPA does use chloride measurements to indicate the rate of transport, however.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
CO ₂	Water, soil gas	To estimate aerobic biological oxidation of organics as CO ₂ is the final stage product To evaluate other microbiological processes To evaluate the presence of methanogenesis as CO ₂ can also act as an alternate electron acceptor	Elevated levels may indicate aerobic biodegradation. Depleted levels may indicate methanogenesis is occurring provided that the aerobic electron acceptor, oxygen, is not present. The simpler way to measure carbon dioxide available to microbes is by measuring alkalinity, pH, and temperature. In most subsurface systems, carbon dioxide is normally present in sufficient quantities for microbial use at concentrations well below the instrument's ability to detect it. Sampling of ground water for dissolved gas analysis should minimize contact with the atmosphere to prevent the loss of volatile constituents and the contamination of the sample with volatile constituents from the atmosphere. Apparatus exists that utilizes a flow-through cell and thereby eliminates the contact of the water sample with the atmosphere. The headspace of the flow-through cell can then be removed with a gas-tight syringe and injected into a vial that has been purged with an inert gas. Laboratory analysis can then be conducted on the headspace, which can be used to back calculate the original concentration of the gas in the ground-water sample.
Conductivity	Water	To verify that site samples are obtained from the same ground-water system	
Depth to ground water	Water	To evaluate the impact of unsaturated soil contamination on ground water and estimate the volatilization rates of contaminants from ground water	
Dissolved iron	Water	To determine whether Fe(III) is being used as an electron acceptor during an anaerobic degradation process due to depletion of oxygen, nitrate, and manganese	Ferrous iron is much more soluble than ferric iron. Because dissolved iron analyses do not distinguish between ferrous and ferric iron, direct results indicating favorable biodegradation conditions are not achieved. Ferrous iron alone (see below) is more useful.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Dissolved manganese	Water	To determine the degree of anaerobic activity using manganese(IV) as an electron acceptor	<p>Manganese(IV) is an alternative electron acceptor, and its presence in a dissolved state is an indication of biological activity.</p> <p>Mn(IV) is very insoluble. Mn(II) is very soluble. Dissolved manganese may be useful if the analysis is conducted on a 0.45-μm field-filtered sample. However, manganese is not likely to be found in many environments and adds an expense that may not be justified based on the usability of the result. This parameter should be analyzed for only after careful consideration.</p>
Dissolved oxygen (DO)	Water	To assess the potential for aerobic or anaerobic processes to occur	<p>Aerobic degradation relies on the presence of oxygen, while many of the biological processes that promote degradation of chlorinated species occur in anaerobic conditions.</p> <p>High oxygen concentrations are a strong positive indicator of NA potential of petroleum-related compounds, while concentrations less than 1 mg/L generally indicate an anaerobic pathway and favor degradation of the multisubstituted chlorinated compounds.</p> <p>DO in the field is a standard field screening method and, as such, can be used for well purging; however, a definitive method that employs better quality control than the field meter is preferable. EPA RSK-175, <i>Dissolved Oxygen and Methane in Water by a GC Headspace Equilibrium Technique</i>, may be a better choice for low concentrations of the dissolved gas.</p> <p>Sampling of ground water for dissolved gas analysis should minimize contact with the atmosphere to prevent the loss of volatile constituents and the contamination of the sample with volatile constituents from the atmosphere. Apparatus exists that utilizes a flow-through cell and thereby eliminates the contact of the water sample with the atmosphere. The headspace of the flow-through cell can then be removed with a gas-tight syringe and injected into a vial that has been purged with an inert gas. Laboratory analysis can then be conducted on the headspace, which can be used to back calculate the original concentration of the gas in the ground-water sample.</p>

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Ferrous iron (Fe[II])	Water	<p>Product of Fe(III) reduction through microbial use as an electron acceptor. To determine whether Fe(III) is being used as an electron acceptor for the anaerobic degradation of petroleum hydrocarbons</p> <p>To determine whether reducing conditions exist to support dechlorination</p> <p>To determine whether an anaerobic degradation process is occurring due to depletion of oxygen, nitrate, and manganese</p>	This analysis must be done in the field on a 0.45- μm filtered sample with adequate quality control (more than typical field methods) to ensure that the results are of definitive quality.
Fraction of organic carbon (F_{OC})	Soil	The fraction of organic carbon in the soil affects contaminant mobility.	The fraction of organic carbon in the soil can be determined from laboratory tests.
Hydraulic conductivity (K)	Soil	<p>To measure the capacity of the soil media to transmit flow of a specific fluid such as water</p> <p>To estimate the ground-water velocity and migration rate of the COCs</p> <p>To determine effective location, number, and pumping rates of extraction wells</p>	<p>Numerous aquifer tests can be employed to determine hydraulic conductivity.</p> <p>The test used to acquire adequate data quality should be determined based on site-specific conditions.</p>
Hydrogen (H_2)	Water	To determine the presence of methanogenic bacteria, which survive on the H_2 that is released as a waste product of other microbes that use carbon dioxide as the terminal electron acceptor	Sampling of ground water for dissolved gas analysis should minimize contact with the atmosphere to prevent the loss of volatile constituents and the contamination of the sample with volatile constituents from the atmosphere. Apparatus exists that utilizes a flow-through cell and thereby eliminates the contact of the water sample with the atmosphere. The headspace of the flow-through cell can then be removed with a gas-tight syringe and injected into a vial that has been purged with an inert gas. Laboratory analysis can then be conducted on the headspace, which can be used to back calculate the original concentration of the gas in the ground-water sample.
K_{OC} in soil/sediment	Soil	To estimate the retardation influence on fate and transport of contamination	This parameter is typically either determined from the literature or calculated experimentally.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Lithology and stratigraphy	Soil	<p>To assess preferential directions of ground-water flow and contaminant transport</p> <p>To guide proper location of monitoring points and determine appropriate screened intervals for monitoring points</p> <p>To identify hydrogeologic features which may prevent impact to potential receptors</p>	
Methane, ethane, ethene (MEE)	Water, soil gas	To estimate the occurrence of methanogenesis and the degree of dechlorination occurring	<p>MEE are important indicators of microbial activity. The presence of methane suggests biodegradation of organic carbon via methanogenesis. The more methane, the more likely there is sufficient organic matter and an insufficiency of electron acceptors. This indicates a potential for use of chlorinated species as electron acceptors.</p> <p>Ethane and ethene are close-to-end products produced during reductive dechlorination.</p> <p>Sampling of ground water for dissolved gas analysis should minimize contact with the atmosphere to prevent the loss of volatile constituents and the contamination of the sample with volatile constituents from the atmosphere. Apparatus exists that utilizes a flow-through cell and thereby eliminates the contact of the water sample with the atmosphere. The headspace of the flow-through cell can then be removed with a gas-tight syringe and injected into a vial that has been purged with an inert gas. Laboratory analysis can then be conducted on the headspace, which can be used to back calculate the original concentration of the gas in the ground-water sample.</p>
Nitrate	Water	To determine the capacity for anaerobic degradation of hydrocarbons	Nitrate ranks just below oxygen in oxidation potential for microbial use and represents a significant capacity to support anaerobic degradation of hydrocarbons.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Nitrogen	Water, soil gas	To indicate anaerobic biological activity	<p>Nitrogen gas is released during the denitrification process. However, the presence of nitrogen due to anaerobic activity is difficult if not impossible to distinguish from the far more significant contribution of atmospheric nitrogen. This parameter will typically not provide useful data for the determination of biodegradation activity.</p> <p>Sampling of ground water for dissolved gas analysis should minimize contact with the atmosphere to prevent the loss of volatile constituents and the contamination of the sample with volatile constituents from the atmosphere. Apparatus exists that utilizes a flow-through cell and thereby eliminates the contact of the water sample with the atmosphere. The headspace of the flow-through cell can then be removed with a gas-tight syringe and injected into a vial that has been purged with an inert gas. Laboratory analysis can then be conducted on the headspace, which can be used to back calculate the original concentration of the gas in the ground-water sample.</p>
Octanol-water partition coefficient (K_{ow})	COC	To predict the retardation influence of insoluble soil organic matter on fate and transport of organic contaminants in the ground water	This parameter is typically either determined from the literature or calculated experimentally.
Oxidation-reduction	Water	<p>To measure of the overall conditions promoting chemical reactions</p> <p>To help validate concentrations of DO measurements and other microbial electron acceptors</p>	<p>Negative values indicate an excess of electron donors; positive values indicate an excess of electron acceptors.</p> <p>Many of the assumptions (e.g., reversible chemical equilibrium, fast electrode kinetics, and lack of interfering reactions) are often not met in natural water (e.g., irreversible reactions, electrode poisoning, multiple redox couples, small exchange currents, and inert redox couples).</p> <p>Redox is generally taken in the field with a lower level of quality than should be accorded for biodegradation. If the procedure is followed closely, and if calibrations, blanks, calibration checks, and the temperatures of the standards are well documented, definitive results can be achieved. In addition, the results should be reported relative to the standard hydrogen electrode.</p>

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Particle size	Soil	To provide information on the types of materials encountered in the subsurface, as well as their degree of homogeneity To estimate porosity for the determination of retardation factors and seepage velocity	Sieve analysis for sand particles should be employed. Hydrometer analysis for clays and silts should be employed.
pH	Water	To determine the degradation potential of the ground water and associated microbes	Biological activity is strongly affected by the hydrogen ion concentration. pH differences between contaminated and uncontaminated ground water <i>may</i> sometimes indicate that biological activity is occurring. However, pH is very strongly buffered by the mineral matrix. Differences due to biological activity are rarely observed. An example of this rare observation would be in a high-organic, swamplike condition. pH is generally taken in the field with a lower level of quality than should be accorded for biodegradation.
Porosity	Soil	To calculate the relative amount of voids (Porosity is a percentage of the soil matrix that may contain water, free product, or air)	Typically either determined from the literature based on soil type(s) or calculated based on soil density measurements.
Soil classification	Soil	To measure the amenability of a particular treatment technology to site-specific conditions	
Sulfate	Water	To determine the potential use of sulfate as an electron acceptor for anaerobic degradation of compounds (the conversion of sulfate to sulfide indicates its use as an electron acceptor and the presence of sulfate indicates its lack of use as an electron acceptor)	Sulfate is a substrate for anaerobic microbial respiration.
Sulfide	Water	To provide primary information about sulfate reductive reactions, when used in conjunction with sulfate concentrations	If dissolved iron is present, sulfide will precipitate and little, if any, dissolved sulfide will be detectable. Analysis of sulfide should be carefully considered.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Temperature	Water	<p>To indicate well development and that the ground water being sampled is representative of the formation</p> <p>To gauge the effect of temperature on the thermodynamics and kinetics of reaction, especially with respect to biological activity</p> <p>To correct other measured data such as alkalinity and redox potential</p>	
Total iron	Water	To aid in the interpretation of iron concentration	<p>Prior to analysis, the samples must be solubilized/digested using acid.</p> <p>This parameter is virtually useless as an indicator of biologically available or biologically produced iron. It is more an indicator of turbidity from poor well-development or purging practices than a useful biodegradation parameter.</p>
Total manganese	Water	To determine the degree of anaerobic activity using manganese(IV) as an electron acceptor.	Total manganese suffers from the same limitation as total iron. It is controlled by turbidity rather than by biological processes. This analysis may not be justified as the presence of total manganese does not ensure biodegradation and its absence does not preclude NA.
Total organic carbon (TOC)	Water, soil	To assess the potential for the biodegradation component of NA to occur	<p>Since TOC represents only the carbon that is dissolved or suspended in the ground water, the dissolved TOC must be measured against the organic carbon in the aquifer sediments. Sorption is a significant control of organic contaminant mobility.</p> <p>Low levels do not preclude the potential for NA because total carbon available to microbes also includes insoluble forms such as buried plant debris.</p>
Turbidity	Water	<p>To indicate well development and that the ground water being sampled is representative of the formation</p> <p>To aid in the interpretation of metal concentrations</p>	Turbidity is generally taken in the field with a lower level of quality than should be accorded for biodegradation. Analysis should be conducted as soon as possible to prevent settling out of materials.

Table 1.6. Monitored Natural Attenuation-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Unit rate (k)	Water	To determine the utilization rate of the COCs To estimate the treatment period and amendments required	Also defined as the maximum rate of substrate utilization or k in the Monod equation: $C = C_o e^{-kt}$. This will govern with the sorption, the total biofilter size. For many organics in water systems, the ranges for k 's for the compounds are published. However, bench or pilot scale testing should be performed to obtain actual design data. This parameter is also referred to as a first order degradation rate constant, and is reported as units per day.

1.7 CHEMICAL OXIDATION/REDUCTION

Chemical oxidation/reduction is an ex situ process used to convert a hazardous contaminant to a less-hazardous or nonhazardous compound that is usually more stable, less mobile, or inert. This process is applicable to treat soil, sludges, and sediments. This is a proven industrial technology and is used primarily for inorganics. It has been used in the potable water industry and in the treatment of wastewaters.

The soil, sludge, or sediment may require pretreatment to physically separate or grade the soils into fractions: coarse and fine fractions. Most of the contaminants are usually in the fine fraction. The soil containing the contaminant will be mixed with the reducing/oxidizing agent to ensure contact with the treatment agent. The amount of mixing and contact time will determine the size of the reaction unit.

Chemical oxidation/reduction may also be used on some nonhalogenated organic compounds and pesticides.

Table 1.7. Chemical Oxidation/Reduction-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to implement chemical oxidation/reduction. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal chemical oxidation/reduction have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Chemicals of concern (COC)	Soil	To identify the COCs that may be amenable to reduction/oxidation	This technology is primarily applicable to heavy metals, but organics may also be treated by oxidation/ reduction. This is an ex situ process.
Grain size	Soil	In most situations the smaller grain size will require treatment	
Moisture	Soil		Moisture (and oil and grease) may affect the effectiveness of the process.
Total organic carbon	Soil	Excessive organic content may reduce the effectiveness of the treatment process	Oil and grease are a significant factor. Other organics that may react with the oxidizing/reducing agent in preference to the target COC will reduce the effectiveness of the treatment.
pH	Soil	The pH may affect the chemical addition	
Temperature	Soil	The temperature of the soil may affect the extraction process	Cold climates may require heating to improve the reaction rates.
Unit rate (k)	Soil	To estimate the reaction time required to treat the COC to the regulatory level	Also defined as the maximum rate of substrate utilization or k in the Monod equation: $C = C_0 e^{-kt}$. This will govern with the sorption, the total biofilter size. For many organics in water systems, the ranges for k 's for the compounds are published. However, bench or pilot scale testing should be performed to obtain actual design data. This parameter is also referred to as a first order degradation rate constant, and is reported as units per day. (Note: This may also represent a zero-order reaction.)

1.8 Granulated Activated Carbon/Liquid-Phase Carbon Adsorption

Granulated activated carbon (GAC)/liquid-phase carbon adsorption is a proven technology for removing dissolved organics from water. This treatment process removes the organics from the water by adsorbing the organics onto the activated carbon. The carbon must be regenerated (on site or off site) or disposed. Some halogenated organics, pesticides, water-soluble organics, and small molecules are not adsorbed as effectively as other organics.

This process has extensive use in treating municipal and industrial water supplies and wastewater. GAC has successfully been used to treat waters containing hazardous waste.

The GAC systems can be rapidly deployed, and the engineering requirements have been established. Many firms have GAC experience and have design guides to assist in the design of GAC systems based on the influent concentration and the detention time (empty bed contact time — EBCT). In addition, the usage rate for the carbon has been established. Vendors should be consulted in the selection of the type, pore size, and quality of the carbon.

The water may require pretreatment to remove suspended solids that can increase head loss through the GAC bed or to remove trace metals that will contaminate the GAC.

Table 1.8. Granulated Activated Carbon/Liquid-Phase Carbon Adsorption-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to implement granulated activated carbon (GAC)/liquid-phase carbon adsorption. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement GAC/liquid-phase carbon adsorption have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	<i>Matrix</i>	PURPOSE	COMMENT
Alkalinity	Water	To determine the buffering capacity of the water	
Carbon adsorption rates	Water		
Chemicals of concern (COCs)	Water	To identify the COCs	Whether carbon adsorption rates been established for the COCs should be determined.
Hardness	Water	To determine the potential for calcium carbonate precipitation onto the GAC, which will reduce the effectiveness	
Metals	Water	To determine the level of metals to evaluate the potential for the water to poison the carbon and prevent regeneration	
pH	Water		This parameter may require adjustment.
Total dissolved solids (TDS)	Water	To determine whether other material may coagulate in the GAC bed	Water passing through the GAC may change pH or other parameters and result in materials blocking the pore spaces of the carbon.
Total organic carbon (TOC)	Water		It should be determined whether naturally occurring organics will affect the GAC treatment.
Total suspended solids (TSS)	Water	To determine whether pretreatment is required	Increased head loss due to filter plugging requires frequent backwashing, which reduces effectiveness and may result in loss of GAC.

1.9 Dual-Phase Extraction

Dual-phase extraction (DPE) is used to extract various combinations of liquids (contaminated ground water and separate-phase hydrocarbons) and hydrocarbon vapors from the vadose zone. This is a proven technology. This process combines soil vapor extraction with vacuum extraction of the ground water and separate-phase hydrocarbon. This process is sometimes referred to as bioslurping.

This is a process to remove the contamination. The recovered vapors and contaminated liquids (ground water and/or separate-phase hydrocarbons) may require additional treatment depending on the discharge requirements.

Depth to the free product will affect the amount of separate-phase product that will directly recovered by the vacuum system. Pumping can be added to recover free-phase product if the product is at least 20 cm thick.

This process is applicable to treating soil and ground water.

Table 1.9. Dual-Phase Extraction—Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to implement dual-phase extraction. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement dual-phase extraction have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	Purpose	Comment
Chemicals of concern (COC)	Water, soil	To identify the COCs	
Depth to free product	Free product		
Intrinsic permeability-water/air/free product	Soil	To determine the permeability relative to the process If the well supports bioventing, the permeability should be to air, and if the well will be used for recovery of free product, permeability to free product should be obtained	
pH	Soil	To determine whether the pH of the water is compatible with the injection well equipment and receiving formation	
Porosity	Soil	To determine the pore space that water, free product, or air may flow through	
For additional parameters, see the tables for soil vapor extraction, bioslurping, and pump and treat.			

1.10 Deep Well Injection

Deep well injection is an ex situ disposal process. This process is applicable to disposal of ground water into deep geologic formations that have no potential to allow migration to useable aquifers. This is a proven industrial technology.

The use of deep well injection is limited to the existing deep injection wells and the chemicals authorized for disposal. The existing deep injection wells have been used to dispose of VOCs, SVOCs, explosives, and pesticides. The expansion of permit conditions for existing deep injection wells is not likely.

The ground water may require treatment to ensure that the water will not clog, corrode, foul, or grow bacteria, which may impact the receiving aquifer or formation, and the injection equipment.

Suspended solids and possible precipitates that will affect the injection well equipment or the receiving formation will require pretreatment.

Table 1.10. Deep Well Injection-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to implement deep well injection. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal deep well injection have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	Purpose	Comment
Bacteria (plate count)	Water	Excessive bacteria may result in fouling of the waste water prior to injection in the receiving formation	
Chemicals of concern (COC)	Water	To identify the COCs that will be injected into the formation To determine whether the COCs are within the permit limits for the deep well injection	
Hardness	Water	To determine the amount of precipitates that may be present	
Total iron	Water	To determine whether iron is likely to deposit in the formation	
Metals	Water	To identify other constituents that may impact the injection well	
pH	Water	The water must be compatible with the injection well equipment and receiving formation	
Total dissolved solids (TDSs)	Water	Excessive TDSs may result in plugging the injection ports or the receiving formation	
Total suspended solids (TSSs)	Water	Excessive TSSs may result in plugging the injection ports or the receiving formation	

1.11 Groundwater Pumping

The fundamental concepts of pump and treat (P&T) are simple and straightforward. In theory, one or more ground-water wells pump the contaminated ground water from the subsurface. The primary objective of the pumping is to disrupt COC movement to prevent exposure of down-gradient receptors and/or reduce the levels of COCs in the ground water to acceptable levels. The levels of COCs in the ground water are reduced by transferring the pumped water to an aboveground treatment unit (e.g., air stripping, catalytic oxidation, carbon adsorption, reverse osmosis, etc.), where the COCs are destroyed, removed, or converted to harmless form. The water is then discharged to a water body or publicly owned treatment works (POTW) or reinjected into the ground.

In 1994, P&T was the remedial treatment of choice for contaminated ground water at three-fourths of all CERCLA sites, as well as other non-Superfund sites including those governed by RCRA and state laws. However, because of the difficulty of achieving cleanup goals in a timely manner using P&T, the method has been extensively criticized. It is still popular for the removal of free product (that is, relatively pure quantities of a contaminant such as jet fuel) and to a lesser extent to prevent further COC migration down gradient. However, its use to extract and treat contaminated ground water is being replaced with other alternatives such as natural attenuation and air sparging.

P&T can be divided into two functions: (1) the pumping component and (2) the treatment component. The treatment aspect of the P&T is relatively straightforward and well understood. Much literature exists. However, the pumping component is more complex. Its success depends on how well the designers are able to predict the ultimate state and movement of the COCs and how the aquifer responds when the system is in operation. Without sufficient data to adequately characterize the subsurface environment, the efficient design of a P&T system is almost impossible. P&T is like other models that rely on subsurface characterization data as input. Subsurface characterization data are even more crucial for P&T than for other, less complex subsurface pumping systems such as soil vapor extraction (SVE) or air sparging. The key factors that must be thoroughly understood, at a minimum, to predict contaminant fate and transport include

- aquifer characteristics,
- geologic (matrix) characteristics,
- analyte characteristics, and
- extent of contamination.

Characterization data sufficient to understand and predict the behavior of the contaminant in the subsurface via models are essential in designing and operating a P&T system to its maximum potential. The following table presents key parameters for the pumping component of P&T, and various methods that can be employed for their determinations. The method necessary for the purposes of ensuring that the model input data are sufficient can be determined only after DQOs for each parameter have been defined by applying the DQO process to the site-specific conditions.

Table 1.11 presents the key parameters that provide input data for the selected model of P&T and their purpose. Table 2.1 of Section 2, the master table, presents the associated methods used to measure each parameter and each method's associated performance criteria and limitations.

Table 1.11. Ground-Water Pumping-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary for the design or optimization of the pumping component of P&T. Only those parameters that *may* produce a measurable and significant effect on the overall pumping processes have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	Purpose	Comments
Aqueous solubility	Chemicals of concern (COC)	To predict the retardation influence on fate and transport	This parameter is typically either determined from the literature or calculated experimentally.
Aquifer thickness	Soil	To identify confining layers, which help to prevent impact to deeper aquifers, and for the design of monitoring points	Regional hydrogeology should be considered in the evaluation of aquifer thickness.
COCs	Water, soil	To understand the key biological processes that can affect the fate and transport of the COCs	
Chloride	Water	To estimate dilution in calculation of rate constants	Samples with high levels (100 mg/L) of chloride in ground water require dilution, which raises the detection limit an order of magnitude (to 1 mg/L) or greater. This results in insufficient sensitivity to detect the low levels of chloride resulting from reductive dechlorination. The detection of minor changes in chloride concentrations in the presence of high background levels of chloride is difficult if not impossible.
Conductivity	Water	To verify that site samples are obtained from the same ground-water system	
Depth to ground water	Water	To evaluate the impact of unsaturated soil contamination on ground water and estimate the volatilization rates of contaminants from ground water	

Table 1.11. Ground-Water Pumping-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Hydraulic conductivity (K)	Soil	<p>To measure the capacity of the soil media to transmit flow of a specific fluid such as water</p> <p>To estimate the ground-water velocity and migration rate of the COCs</p> <p>To determine effective location, number, and pumping rates of extraction wells</p>	<p>Numerous aquifer tests can be employed to determine hydraulic conductivity.</p> <p>The test used to acquire adequate data quality should be determined based on site-specific conditions.</p>
Lithology and stratigraphy	Soil	<p>To assess preferential directions of ground-water flow and contaminant transport</p> <p>To guide proper location of monitoring points and determine appropriate screened intervals for monitoring points</p> <p>To identify hydrogeologic features that may prevent impact to potential receptors</p>	
Octanol-water partition coefficient (K_{ow})	COC	To predict the retardation influence on fate and transport	This parameter is typically either determined from the literature or calculated experimentally.
Particle size	Soil	<p>To provide information on the types of materials encountered in the subsurface, as well as their degree of homogeneity</p> <p>To estimate porosity for the determination of retardation factors and seepage velocity</p>	Sieve analysis for sand particles should be employed. Hydrometer analysis for clays and silts should be employed.

Table 1.11. Ground-Water Pumping-Parameters and Associated Data Use (Cont.)

Parameter	Matrix	Purpose	Comments
pH	Water	To determine the degradation potential of the ground water and associated microbes	Biological activity is strongly affected by the hydrogen ion concentration. Difference between contaminated and uncontaminated ground water may be an indicator that biological activity is occurring. PH is generally taken in the field with a lower level of quality than should be accorded for biodegradation.
Porosity	Soil	To calculate ground-water retardation factors and seepage velocities	Typically either determined from the literature based on soil type(s) or calculated based on soil density measurements. The procedure for calculating porosity is standardized.
Soil classification	Soil	To measure the amenability of a particular treatment technology to site-specific conditions	
Sorption coefficient (K _{oc})	Soil	To estimate the retardation influence on fate and transport of contamination	This parameter is typically either determined from the literature or calculated experimentally.
Total organic carbon (TOC)	Water, soil	To assess the potential for the biodegradation component of natural attenuation (NA) to occur	Since TOC represents only the carbon that is dissolved or suspended in the ground water, the dissolved TOC must be measured against the organic carbon in the aquifer sediments. Low levels do not preclude the potential for NA because total carbon available to microbes also includes insoluble forms such as buried plant debris.

1.11a Free Product Recovery

The presence of free product affects the selection of MNA and also P&T technology. The lack of adequate characterization of the free product has impacted several remedial alternatives. In most locations the inability to recover significant portions of the free product allows the free product to continue being the source of ground-water contamination. Most states and the EPA require some effort to remove the source of the contamination before MNA will be finalized as a remedy for the dissolved-phase contaminants.

Free product recovery is a challenging undertaking that is often ineffective. Typically, the maximum amount (e.g., mass) of free product that can be removed using this technique is only approximately 25% of the total amount. Other procedures such as flushing or washing with the aid of surfactants can increase the effectiveness; however, it is important to examine any available historical data and associated modeling results to estimate the overall impact of free product removal on the ability to achieve the remedial objectives. Prior to free product recovery, the team must be able to justify that the implementation of free product removal will have a positive effect on the overall ability to achieve site closure effectively and efficiently.

Several of the routine aquifer tests performed for both P&T and MNA are not adequate for the area with free product. For example, the normal determination of hydraulic conductivity will not adequately provide specific yield or storage capacity of the free product or provide reasonable flow per unit area.

Table 1.11a presents the key parameters and their intended purposes that are often necessary to conduct free product removal. Table 2.1 of Section 2, the master table, presents the associated methods used to measure each of the cited parameters and each method's associated performance criteria and limitations.

Table 1.11a. Free Product Recovery-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary for the recovery of free product. Only those parameters that *may* produce a measurable and significant effect on the overall ability to recover free product have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	Purpose	Comments
Benzene, toluene, ethylbenzene, and xylenes (BTEX) and carbon chain	Free product	To determine the relative amounts of constituents of concern	
Hydrocarbon pore saturation	Soil	To determine the percentage of pore spaces filled by the free product	The amount of free product in the pore spaces affects the recoverability of the free product.
Interfacial tension	Free product, ground water	To determine the interfacial tension between the free product and air, free product and ground water, and ground water and air	
Intrinsic permeability	Soil	To determine the permeability of the soil	This measurement allows the permeability of soil to water, free product, and air to be better understood.
Less-dense nonaqueous-phase liquid density	Free product	To determine the density of the free product	This information, with other data on the free product, will be used to determine the age and type of original free product. In addition, these data will be used to model the contribution of the free product to the ground-water plume affected by the free product.
Particle size	Soil	To determine the grain size distribution	This measurement allows a correlation between the grain size and free product movement to be established. Sand is determined by sieve analysis, and clay and silt are determined by hydrometer analysis.
Porosity	Soil	To determine the porosity with the free product	This method is different from the American Society of Testing and Materials (ASTM) method presented in the master table and determines the porosity with respect to the free product.
Soil capillarity	Soil	To determine the capillary pressure of the soil	The soil samples to be tested should be collected in the zone with the free product.

Parameter	Matrix	Purpose	Comments
Soil density	Soil	To determine soil density	The measurement of this parameter allows one to calculate the porosity.
Viscosity	Free product	To determine the ability of the free product to move	The free product viscosity affects the ability of the free product to move throughout the soil and therefore is important for predicting the rate of migration to ground water.

1.12. Air Stripping

Air stripping is a proven technology to remove volatile organics from ground water. Air stripping has been used to control taste and odor, to remove volatile organics from ground water, and to remove ammonia. The Air Force and other Department of Defense organizations to remove BTEX are using numerous air strippers and volatile chlorinated solvents. The systems have also removed TCE to less than 1 µg/L.

Air strippers are generally one of two types: waterfall towers or diffused aerators. The waterfall towers operate by having the water flow downward; the water droplets are exposed to air and the contaminant diffuses into the air. The waterfall towers include redwood slats and packed tower aerators. The redwood slats are used primarily for cooling towers. The packed tower aerators are either forced draft or induced draft. The ability of the treatment process to effectively treat the target organics will be dependent on the amount of the turbidity, pH, hardness (carbonates), airflow, the influent concentration, and the contact time. The design engineer should determine from the chemicals of concern the applicable physical properties (Henry's law and vapor pressure) that are generally available. However, some of the properties listed in various reference books are for pure constituents. The interference of other chemicals should be evaluated, and if laboratory data are required to properly evaluate the properties, the appropriate laboratory methods should be employed.

This treatment process requires other remedial technologies to recover the contaminated ground water and to transport the ground water to the treatment site. Depending on the water quality parameters, pretreatment may be required to remove metals or to prevent precipitation of carbonates. Additional treatment of the off-gas may be required. The proper sequencing of the process and equipment should be considered in the treatment plan.

Table 1.12. Air Stripping-Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to optimize the removal of contaminants from water using air stripping. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal air stripping have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Matrix	Purpose	Comments
Alkalinity	Water	To measure the amount of alkalinity present in the water	Water with little alkalinity may be changed during the air stripping process because the water does not have a significant buffering capacity.
Carbonates	Water	To measure the amount of carbonate material present that may precipitate and interfere with the stripping tower	The amount of carbonate present may indicate the amount of precipitation that may occur during or immediately after the air stripper. Material precipitating during the air stripping process may interfere with the efficiency of the stripper.
Chemicals of concern (COC)	Water, gas	To identify the COCs that may be amenable to removal from water by transferring the chemical of concern to air	Only chemicals that readily volatilized are amenable to air stripping.
Henry's law constant	Water, air	To measure the ability of the chemical to transfer from the water to air	Generally available in references; however, the effect of other chemicals may modify the value.
Metals	Water	To measure the concentration of metals in the water	The presence of metals (dissolved or in particulate form) may affect the ability of the air stripper to volatilize the target organics to the designed efficiency.
pH	Water	To determine water quality To monitor the water before air stripping and after to determine possible changes in geochemistry	The pH will indicate the acidity or alkalinity of the ground water. The change in pH during air stripping process may indicate changes in air stripper efficiency. pH is generally taken in the field with a lower level of quality than should be accorded for air stripping.
Temperature	Air, water	To evaluate vapor pressure and other parameters	

Table 1.12. Air Stripping-Parameters and Associated Data Use (Continued)

Parameter	Matrix	Purpose	Comments
Turbidity	Water	To measure the particles in the water To aid in the interpretation of metal concentrations	The presence of turbidity may increase the amount of buildup or precipitation in the tower. Turbidity may interfere with the air transfer or cause buildup on the packed tower material. Excessive turbidity may necessitate additional treatment of the water prior to air stripping. Turbidity is generally taken in the field with a lower level of quality than should be accorded for biodegradation or stripping. Analysis should be conducted as soon as possible to prevent settling out of materials.
Vapor pressure	Air	Measures the amount of chemical in air under equilibrium (no more of the gas will dissolve into the liquid)	The vapor pressure increases with temperature.

1.13. Soil Vapor Extraction

Soil vapor extraction (SVE) is a remedial technique that is widely used to remove VOCs and some SVOCs from the vadose zone with the objective of reducing contaminant soil concentrations to mandatory or risk-based regulatory limits or below. SVE systems are currently in operation at a number of Air Force bases. SVE may be either a stand-alone technology or be used in conjunction with other remedial technologies (i.e., MNA, air sparging, P&T, etc.)

SVE systems exploit the fact that in the vadose zone, contaminant mass is transferred to air within soil voids by volatilization from the nonaqueous liquid phase and the dissolved phase, and by desorption from soil particles. To implement SVE, a vacuum pump or blower is used to create a vacuum in the soil around one or more extraction wells. In response, the subsurface air moves toward and into the extraction wells, which conducts it to the surface, and the vapor-phase contaminants are carried along with the air by advection. As the extracted air is replaced by uncontaminated air infiltrating from the surface or entering the soil from passive injection wells, additional volatilization and desorption occurs, and a continuing process of mass transfer and advective removal is set up. Once on the surface, the contaminant-laden air may be treated to remove the contaminants or, if contaminant concentrations permit, simply discharged into the atmosphere.

Computer models are often used to assess the suitability of SVE for a particular site and to determine the most cost-effective system design that will achieve remedial objectives. The parameters presented in Table 1.13 are among those commonly required as input for the models. The parameters are related to (1) contaminant characteristics, (2) soil characteristics, and (3) site conditions.

Table 1.13 Soil Vapor Extraction—Parameters and Associated Data Use

This table presents site characterization parameters that may be necessary to optimize the removal of contaminants from water using SVE. Only those parameters that *may* produce a measurable and significant effect on the overall ability to implement optimal air stripping have been included. Their inclusion in this table does not imply that they will in fact be key parameters, but only that they *may* be key parameters.

Parameter	Type	Purpose	Comments
Depth to ground water	Water	To determines whether SVE can successfully be applied and may affect system design	The depth to ground water is often determined by measuring the depth to water in a borehole, monitoring well, or piezometer.
Fraction of organic carbon (f_{oc})	Soil	The f_{oc} in the soil affects chemical of concern (COC) mobility	The fraction of organic carbon in the soil can be determined from laboratory tests.
Henry's law constant	COC	To estimate contaminant partitioning between pore water and soil vapor	The Henry's law constant is functionally defined as the ratio of saturated vapor density to aqueous solubility for a given compound. Under moist soil conditions, SVE efficiency is Henry's law dependent. <u>To be considered as a candidate for SVE, a contaminant should have a Henry's law constant of greater than 100 atmospheres per mole fraction.</u>
Hydraulic conductivity (K)	Soil	Hydraulic conductivity is often extrapolated to the horizontal air permeability	This use of hydraulic conductivity is likely to result in errors due to a number of invalid assumptions.
Intrinsic permeability	Soil	Air permeability, also known as soil permeability or pneumatic permeability, is a measure of the ability of vapors to flow through porous media	Air permeability is the most important soil characteristic for determining whether SVE can feasibly be applied to a site. It is generally determined by means of a pilot test.
Lithology and stratigraphy	Soil	To assess preferential directions of airflow, as well as to guide proper location of and determine appropriate screened intervals for extraction or passive injection wells	Lithologic and stratigraphic characteristics of a site are generally determined through subsurface exploration.
Molecular weight	COC	To estimate how the contaminant will partition between pore water and soil vapor	Molecular weights can be obtained from the literature or calculated from the periodic table.

Table 1.13 Soil Vapor Extraction—Parameters and Associated Data Use (Continued)

Parameter	Type	Purpose	Comments
Octanol-water partition coefficient (K_{ow})	COC	To estimate contaminant partitioning between dissolved and adsorbed phases	This parameter is typically either determined from the literature or calculated experimentally.
Porosity	Soil	To provides information regarding the ability of gas or liquid to flow through the medium of concern	Porosity measurements are used to determine the relative amounts of voids through which flow (water or air) can occur. When water resides either in the pore space or attached to the soil particles, it reduces the available void space. This parameter is determined from laboratory tests.
Sorption coefficient (K_{oc})	COC	To estimate contaminant partitioning between dissolved and adsorbed phases	The distribution coefficient can be calculated experimentally or empirically.
Vapor pressure	COC	To determine whether a contaminant is volatile enough for successful removal by SVE	Vapor pressure is defined as the pressure exerted by a compound's vapor at equilibrium with its liquid phase at a given temperature. Some reported threshold values for vapor pressure include <ul style="list-style-type: none"> • 0.5 mm Hg, • 1 to 2 mm Hg at typical soil temperatures, and • greater than 1 mm Hg at 20°C.
Water solubility	COC	To estimate its partitioning between pore water and soil vapor	Solubility can be defined as the maximum amount of a contaminant that will dissolve in pure water at a specified temperature. It can be obtained from the literature. Under moist soil conditions (the most common scenario) contaminants are generally dissolved in soil pore water.

SECTION 2 KEY INFLUENTIAL PARAMETERS ANALYTICAL PROTOCOLS AND ASSOCIATED MEASUREMENT QUALITY OBJECTIVES

2.1 Analytical Protocols and Measurement Quality Objectives

This section presents the analytical methods and associated performance criteria for various parameters, which are listed in alphabetic order. Users should consider the performance criteria in deciding which method to use to achieve the DQOs and measurement quality objectives (MQOs) for a given set of site characteristics. For each parameter, the analytical methods have been segregated into method type (e.g., chromatography, titration, and colorimetric). In addition, each method type has an associated level of confidence and similar performance criteria. This segregation of methods should be kept in mind when selecting a method to meet a given set of remediation quality objectives (RQOs). When more than one type of method exists (e.g., there are several chromatography methods), the performance criteria for only one method (the first method listed) are presented. In general, the additional similar methods, which are provided in the table as “bullets,” will have comparable performance criteria. The differing methods are presented in random order. It is not possible to organize the methods in the order of performance characteristics, as each method has distinct advantages and disadvantages relative to its counterpart.

In the majority of instances, the limits/sensitivity, accuracy/bias, and precision performance information reported have been derived from the analysis of the analyte of interest present in the water matrix. Analytical methods that may also be used for the soil matrix will have performance criteria that will vary from those of the water matrix. The performance information for a given parameter in water has been chosen as the standard, so that when multiple methods exist for the analysis of a single parameter, they can be compared to one another to evaluate method performance. The majority of the methods listed are for the analysis of the water matrix. If soil is the matrix of interest, the reader should ensure that the method selected is applicable. In addition, for many of the methods, extensive performance criteria (i.e., accuracy and precision) are reported. In these cases, professional judgment was used to select the performance results that would be indicative of the overall performance of the method. The reader should keep in mind that the performance criteria reported for the analytical methods apply to a given concentration and that method-specific performance results will vary with certain factors, including concentration, matrix, instrument, and analyst.

NOTE: The methods themselves vary with respect to performance criteria. The decision of which methods are to be employed for the collection of the data, as well as the location and frequency of the samples, can be made only after applying the DQO process to particular key parameters and with the aid of site-specific data. The analytical methods are intended to serve as a starting point.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives

The majority of the popular methods for a given parameter have been included in this table. If a method exists that is well matched to a given set of DQOs and MQOs and the method is approved by the scientific and regulatory communities, then its use should be considered. It should also be noted that, while the performance criteria in the table provide a good indication as to the quality of data that can be expected to be achieved with a given method, the criteria achieved with a sample for a given set of conditions and by a given laboratory may be better or worse than those presented. The criteria presented should serve as a starting point for selecting the method that will achieve project DQOs and MQOs without consuming unnecessary resources.

In general, performance criteria (e.g., limits, accuracy, precision) for the various methods for a given organization (e.g., Standard Methods for the Examination of Water and Wastewater) can be directly compared. However, methods established by different organizations that may report the method information differently (e.g., Standard Methods versus SW-846) are not directly comparable. The performance criteria information (e.g., detection limits, quantitation limits, reporting limits) listed are presented in this table as they are presented in the respective methods. It is beyond the scope of this work to normalize the performance criteria for the methods presented. Not only is this approach infeasible; it is not technically appropriate to modify the method-specific performance criteria published by the respective organizations.

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Aqueous Solubility				
From literature	Not applicable (NA)	NA	NA	Literature values can often vary significantly depending on the method employed for their calculation. These values often provide a reasonable estimate of the parameters; however, the DQOs for a given project may require greater accuracy than literature values may provide.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
American Society for Testing and Materials (ASTM) E 1148 Standard Test Method for Measurements of Aqueous Solubility	Precision and bias will depend on the specific method chosen, the method used for detection and analysis, and the solubility of the material itself. No interlaboratory tests for precision and bias have been conducted at the time this guidance was written.			This parameter is typically either determined from the literature or calculated experimentally. This standard presents three methods to determine the solubility of organic compounds in water, over a variety of solubility ranges. The procedure chosen will depend on the estimated solubility of the compound. This may be obtained from literature values. The experimental test methods described are not applicable to compounds that react with water or air at ambient conditions.
Aquifer Thickness				
ASTM D 1452 Practice for Soil Investigation and Sampling by Auger Borings	NA	NA	NA	The augers must be capable of penetrating subsurface materials at site.
ASTM D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils	NA	Statements in the standard related to bias, precision, and limitations are directed toward the reproducibility of N-values (blow counts) rather than the determination of aquifer thickness.		
ASTM D 4700 Guide for Soil Sampling from the Vadose Zone	NA	NA	NA	Hand-operated sampling devices are limited in penetration depth and by subsurface rocks and gravel. They are generally not suitable for determination of aquifer thickness.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ALKALINITY				
Environmental Protection Agency (EPA) 310.1 (titration) <ul style="list-style-type: none"> • Standard Method 2320 (formerly Method 403) • ASTM D 1067 	This method is suitable to all concentration ranges of alkalinity.	Bias of -9.3 mg/L calcium carbonate at 113 mg/L calcium carbonate.	Standard deviation of 5.28 at 113 mg/L calcium carbonate.	The sample should be refrigerated at 4°C and run as soon as possible. See comments on the measurement of pH, as these methods employ a pH meter to detect the titration end point.
EPA 310.2 (colorimetric) <ul style="list-style-type: none"> • Standard Method 403 	The applicable range is 10–200 mg/L as calcium carbonate.	%Recovery (%R) of 100 at 31 mg/L calcium carbonate.	Standard deviation of 0.5 over a range of concentrations of calcium carbonate.	The sample should be refrigerated at 4°C and run as soon as possible. Sample turbidity and color may interfere with this method. Samples must be filtered prior to analysis.
HACH Method 8221 (field titration with phenolphthalein or bromcresol green)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented.	Minimum quantitation limit (MQL) of 50 mg/L.* Range of 5–100 mg/L.* *HACH model AL-AP		Standard deviation of 20 mg/L. *HACH model AL-AP	The sample should be refrigerated at 4°C and run as soon as possible.
Bacteria (plate count)				
Prior to selecting a method for enumerating bacteria, the reader is encouraged to review ASTM D 3870, <i>Standard Practice for Establishing Performance Characteristics for Colony Counting Methods in Microbiology</i> , which helps determine the suitability of an analytical method for a given purpose. The reader is also referred to ASTM D 1326, <i>Standard Guide for Evaluating Nonconventional Microbiological Test Used for Enumerating Bacteria</i> , which will aid the reader in selecting new, nonconventional test methods when necessary.				

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Standard Method 9215 B (pour plate)	Not addressed by method.	Analytical bias and precision in counting can be caused by carelessness, damaged or dirty optics that impairs vision, or failure to recognize colonies. As a rule, lab workers should be able to duplicate their own work on the same plate to within 5% and the counts of other workers to within 10%. If this amount of precision cannot be obtained, it is recommended that the worker discover the cause and correct the problem.		<p>The pour plate method is simple to perform and the colonies produced are small and compact, resulting in less of a tendency to encroach on each other than surface growth colonies.</p> <p>The submerged colonies are slow growing and often difficult to transfer. Heat shock to the bacteria may occur from the transient exposure of the sample to the temperature-controlled water bath used to temper the agar.</p>
Standard Method 9215 C (spread plate)	Not addressed by method.	Analytical bias and precision in counting can be caused by carelessness, damaged or dirty optics that impairs vision, or failure to recognize colonies. As a rule, lab workers should be able to duplicate their own work on the same plate to within 5% and the counts of other workers to within 10%. If this amount of precision cannot be obtained, it is recommended that the worker discover the cause and correct the problem.		<p>This method causes no heat shock, and all bacterial colonies are on the agar surface where they can be distinguished readily from particles and bubbles. Colonies can be transferred quickly.</p> <p>The method is limited by the small volume of sample that can be absorbed by the agar (0.1 to 0.5 mL).</p>

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Standard Method 9215 D (membrane filter)	Not addressed by method.	Analytical bias and precision in counting can be caused by carelessness, damaged or dirty optics that impairs vision, or failure to recognize colonies. As a rule, lab workers should be able to duplicate their own work on the same plate to within 5% and the counts of other workers to within 10%. If this amount of precision cannot be obtained, it is recommended that the worker discover the cause and correct the problem.		This method permits testing larger volumes of low-turbidity water and is the method of choice for low-count waters (<1 to 10 colony-forming units [CFU]/mL). The method produces no heat shock. Disadvantages include the smaller display area, the need to detect colonies by reflected light against a white background (unless colored filters are employed), possible damage to cells by excessive filtration pressures, and possible variations in membrane filter quality (see Standard Method 9020B.3g).
Standard Method 9216 B (epifluorescence microscopic method)	Not addressed by method.	Analytical bias and precision in counting can be caused by carelessness, damaged or dirty optics that impairs vision, or failure to recognize colonies. As a rule, lab workers should be able to duplicate their own work on the same plate to within 5% and the counts of other workers to within 10%. If this amount of precision can not be obtained, it is recommended that the worker discover the cause and correct the reason for the disagreement.		This method produces direct total cell counts with relative speed. It does not permit differentiation of bacterial cells on the basis of taxonomy, metabolic activity, or viability, and it can not be used to estimate the microbial biomass because of considerable variation in the volume of individual cells. The method requires an experienced technician who can distinguish microbial cells from debris on the basis of morphology.

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HACH Method 8241 (field test)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented.	Range of 0–1,000+ bacteria/mL	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements of bacteria in water and is useful for monitoring recreation waters, cooling towers, and similar systems.		

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Benzene, toluene, ethylbenzene, and xylenes (BTEX) and carbon chains				
<u>Gas Processors Association (GPA) Method 2186</u>				The GPA method is the most accurate method to determine the percentage of BTEX compounds and carbon chains.
<u>SW8260 (employs the positive identification mass spectrometric detector)</u> • <u>SW 524.2</u>	Method detection limit (MDL) of 0.03, 0.08, 0.03, 0.06, 0.03, and 0.06 µg/L for benzene, toluene, ethylbenzene, p-xylene, m-xylene, and o-xylene, respectively.* *Determined on a narrow-bore capillary column	%R of 97, 102, 99, 104, 97, and 103 for benzene, toluene, ethylbenzene, p-xylene, m-xylene, and o-xylene, respectively.* *Determined on a wide-bore capillary column	Relative standard deviation (RSD) of 5.7, 8.0, 8.6, 7.7, 6.5, and 7.2% for benzene, toluene, ethylbenzene, p-xylene, m-xylene, and o-xylene, respectively.* *Determined on a wide-bore capillary column	This method is used to detect a plethora of volatile organic compounds (VOCs) including BTEX. While this method does not specifically test for the gamut of other constituents that make up petroleum fuels (i.e., alkane hydrocarbons), a tentatively identified compound (TIC) list can be requested, which may allow a reasonable estimation of the desired parameter.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
SW8015/8021 (for total petroleum hydrocarbons and aromatics, respectively)	<p>Reporting limit (RL) of 0.1 mg/L for gasoline (SW8015).</p> <p>RL of 1.0 mg/L for diesel or jet fuel (SW8015).</p> <p>MDLs of 0.1 µg/L for the analytes spiked in reagent water (RW) (SW8021).</p>	<p>%R of 83.3.*</p> <p>%Rs of ≥99 for the analytes of interest.**</p> <p>*Method SW8015 for 105 parts per million of low-aromatic diesel spiked on sandy loam soil</p> <p>**Method SW8021 for 10 µg/L of each analyte spiked (7 replicates)</p>	<p>Standard deviation of 15 ppm.*</p> <p>Deviation of recovery of ≤1.4% for the analytes of interest.**</p> <p>*Method SW8015 for a 105 parts per million of low-aromatic diesel spiked on sandy loam soil</p> <p>**Method SW8021 for 10 µg/L of each analyte spiked (7 replicates)</p>	<p>Method SW8015 is applicable to the analysis of petroleum hydrocarbons, including gasoline-range organics (GRO [C₆–C₁₀]) and diesel-range organics (DRO [C₁₀–C₂₈]). The identification of specific fuel types is a very complicated and many times impossible task, due to the many environmental processes, including evaporation, biodegradation, multiple fuels, and varying rates of transport, that can cause the fingerprint of the fuel constituents to vary from its neat form.</p> <p>SW8021 is a gas chromatography (GC) technique, which employs a photoionization detector (PID) and an electrolytic conductivity detector (ELCD) to detect halogenated volatile organics, as well as benzene, toluene, ethylbenzene, and xylenes, collectively referred to as BTEX.</p>
Carbonates				
<p>EPA 310.1 (titration)</p> <ul style="list-style-type: none"> • Standard Method 2320 (formerly Method 403) • ASTM D 1067 	<p>This method is suitable to all concentration ranges of alkalinity.</p>	<p>Bias of –9.3 mg/L calcium carbonate at 113 mg/L calcium carbonate.</p>	<p>Standard deviation of 5.28 at 113 mg/L calcium carbonate.</p>	<p>The sample should be refrigerated at 4°C and run as soon as possible. See comments on the measurement of pH, as these methods employ a pH meter to detect the titration end point.</p> <p>The electrometric titration is the most precise and accurate of the titration methods. The other two types of titrations, one that is based on the change in color of an internal indicator and one that is based on an equivalent end point measured by a pH meter, are suitable for routine control measurements.</p>

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
EPA 310.2 (colorimetric) • Standard Method 403	The applicable range is 10–200 mg/L as calcium carbonate.	%R of 100 at 31 mg/L calcium carbonate.	Standard deviation of 0.5 over a range of concentrations of calcium carbonate.	The sample should be refrigerated at 4°C and run as soon as possible. Sample turbidity and color may interfere with this method. Samples must be filtered prior to analysis.
<u>Standard Method 4500-CO₂ (carbon dioxide) B (nomographic determination of free CO₂ and the three forms of alkalinity)</u>	This information is not provided in the method.	The overall bias depends on the bias of the analytical data applied to the nomographs and the validity of the theoretical equations and the numerical constants on which the nomographs are based.	The precision possible with the nomographs depends on the size and range of the scales. With practice, quality nomographs can be read with a precision of 1%.	pH, total alkalinity, temperature, and total mineral content are used to determine any or all of the alkalinity forms via nomographic equations. CO ₂ can also be determined. The nomographs and equations on which they are based are valid only when the salts of weak acids other than carbonic acid are absent or present in extremely small amounts.
HACH Method 8221 (field titration with phenolphthalein or bromocresol green)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented.	Minimum quantitation limit (MQL) of 50 mg/L.* Range of 5–100 mg/L.* *HACH model AL-AP		Standard deviation of 20 mg/L.* *HACH model AL-AP	The sample should be refrigerated at 4°C and run as soon as possible.
<u>Empirical calculation</u>	This information is not provided in the method.	This approach is subject to the same limitations as the nomographic procedure given above and the additional restriction of using a single temperature, 25°C.		This simple method can be used to calculate the alkalinity forms and free CO ₂ when the total alkalinity of water is due almost entirely to hydroxides, carbonates, or bicarbonates, and the total dissolved solids is not greater than 500 mg/L.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
CARBON ADSORPTION RATES				
<u>ASTM D 3860 (aqueous phase isotherm technique)</u>	The sensitivity is limited by the sensitivity of the test methods used in determining the concentrations of the constituents.	The bias is limited by the bias of the test methods used in determining the concentrations of the constituents.	The precision is limited by the precision of the test methods used in determining the concentration of the constituents.	This method can be used to determine the adsorptive capacity of activated carbon to remove constituents from water and wastewater. The water sample must not contain any immiscible oils.
CARBON DIOXIDE				
<u>Standard Method 4500-CO₂D (empirical calculation)</u>	This information is not provided in the method.	This approach is subject to the same limitations as the nomographic procedure given above and the additional restriction of using a single temperature, 25°C.	This simple method can be used to calculate the alkalinity forms and free CO ₂ when the total alkalinity of water is due almost entirely to hydroxides, carbonates, or bicarbonates, and the total dissolved solids is not greater than 500 mg/L.	pH, total alkalinity, temperature, and total mineral content are necessary to determine the amount of free CO ₂ present in natural or treated waters.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
<u>ASTM D 513 (coulometric titration method)</u>	Applicable range of 5–800 mg/L.	Bias of –0.64%.* *372.1 mg/L added to RW	The overall and single-operator precision of this method varies with the quantity tested as shown in Figure 5 of the method.	CO ₂ is easily lost from solution during transit and storage of samples. It is also possible for total CO ₂ to increase after sampling due to solution of finely divided calcium carbonate as a result of temperature or pressure changes. Any volatile acid or base not removed by the scrubbing solution will interfere with the test. See method for other method-specific interferences.
<u>ASTM D 513 (gas sensing electrode method)</u>	Applicable range of 2–800 mg/L.	Bias of –1.0%.* *101 mg/L added to RW	The overall and single-operator precision of this method varies with the quantity tested as shown in Figure 1 of the method.	CO ₂ is easily lost from solution during transit and storage of samples. It is also possible for total CO ₂ to increase after sampling due to solution of finely divided calcium carbonate as a result of temperature or pressure changes.
Field soil gas analyzer (common field instrument)	1% (volume/volume).		Coefficient of variation of 20% should be easily achieved.	The instrument must be calibrated properly.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HACH Model CA-23(field titration with phenolphthalein)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 5–100 mg/L	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements of bacteria in water and is useful for monitoring recreation waters, cooling towers, and similar systems.		
Chemicals Of Concern (Cocs)				
See Table 2.2	See Table 2.2	See Table 2.2	See Table 2.2	See Table 2.2
Chloride				
SW9056 (lab ion chromatography—Hall electrolytic conductivity detector [IC-HECD]) <ul style="list-style-type: none"> • EPA 300.0 • ASTM D 4327 • ASTM D 5542 • Standard Method 4110C 	MDL of 15 ug/L in RW, 0.1 mg/L nominally. RL of 1 mg/L.	%Rs of 97.7, 98.2, 105.0, and 82.7 for RW, drinking water (DW), surface water (SW), and waste water (WW), respectively.	Standard deviations of 0.0047, 0.289, 0.139, and 0.445 mg/L for RW, DW, SW, and WW, respectively.	The method indicates that the samples should be preserved at 4°C and analyzed as soon as possible after collection. In addition, samples need to be free of particulate matter. Turbid samples must be filtered through a 0.45-µm filter.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HACH Method 8224 (field colorimetric titration with silver nitrate)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 5–100 mg/L.* *HACH Model 8-P		Coefficient of variation of 20% should be easily achieved.	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter.
SW9252A (lab titration) <ul style="list-style-type: none"> • SW9253 • ASTM D 512 • EPA 325.3 • Standard Method 4500-Cl B/C/D 	RL of 1 mg/L.* *Estimated	Bias of +0.4 mg/L.* *EPA 325.3 results from a single lab, SW sample at 17 mg/L	Standard deviation of 1.0 mg/L.* *EPA 325.3 result from a single lab, SW sample at 17 mg/L	Anions and cations at high concentrations may cause problems; however, those concentrations normally found in SW will not.
SW9250 (lab colorimetric procedure) <ul style="list-style-type: none"> • EPA 325.1/325.2 • SW9251 • Standard Method 4500-Cl E (formerly Standard Method 602) 	MDL of 0.5 mg/L. RL of 1 mg/L. The applicable range is 1–250 mg Cl/L.	%R of 97 and 104% at 10 and 100 mg Cl/L, respectively.* *EPA 325 single laboratory results for SW samples	Standard deviation of 0.3 mg/L.* *EPA 325.1 single laboratory results for SW sample over a range of concentrations	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
CONDUCTIVITY				
SW9050A (field meter) <ul style="list-style-type: none"> • EPA 120.1 • Standard Method 2510 (formerly Standard Method 205) • ASTM D 1125 • ASTM D 512 • HACH Method 8160 	50 microsiemens (μS)/cm. ²	Not available.	RSD of 8%.	An improperly calibrated instrument affects data quality. Samples should be analyzed immediately.
Depth To Ground Water				
ASTM D 4750-87 Determining Subsurface Liquid Levels in a Borehole or Monitoring Well	NA	See the text of the standard for discussion of precision and bias.	Applies to boreholes or monitoring wells that are sufficiently vertical so a flexible-monitoring device can be lowered into the hole. Measured levels may not reflect aquifer levels unless sufficient time is allowed for equilibration.	

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
DISSOLVED IRON				
SW6010 (common lab analysis with inductively coupled plasma emission spectrometry [ICP-ES]) <ul style="list-style-type: none"> Standard Method 3120 EPA 200.7 	MDL of 10 µg/L. RL of 0.20 mg/L.	%R of 93 ± 6.* *Single lab evaluation of seven wastes for all elements	RSD of 9% ± 2%.* *Single lab evaluation of seven wastes for all elements	Precision and bias are very dependent on the method of sample collection and storage. Acid digestion is not necessary if analyzing for dissolved constituents only and if the samples are filtered and acid preserved prior to analysis.
SW7380/7381 (lab with atomic absorption [AA] spectrometry) <ul style="list-style-type: none"> Standard Method 3111 EPA 236.1/236.2 EPA 200.9 (graphite furnace) 	Sensitivity of 0.12 mg/L; MDL of 0.03 mg/L.* *These values are for direct aspiration; furnace technique is roughly 1 order of magnitude lower	Bias of 0.8%.* *At a fortified concentration of 840 µg/L using EPA 236.1	Standard deviation of 173 µg/L.* *at a fortified concentration of 840 µg/L using EPA 236.1	
SW6020 (ICP-MS) <ul style="list-style-type: none"> EPA 200.8 	MDLs are <1µg/L.	%R of 90–110 is typical.* *The %Rs presented in the method, resulting from an EPA multi-laboratory study, were determined based on a reference technique	RSD of less than 10%.	

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Standard Method 3500-Fe D (lab colorimetric procedure with phenanthroline)	MDL of 10 µg/L.	Not available.	RSD of 25.5%.* *44 laboratories analyzed a synthetic sample of numerous elements	Precision and bias are very dependent on the method of sample collection and storage. Sample variability and instability may affect precision and bias more than the errors inherent in the analysis. In addition, data quality may be affected by the presence of interfering color, turbidity, and foreign ions. Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter.
HACH Method 8008 (field colorimetric procedure with 1,10-phenanthroline)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 0–5 mg/L.* *Model IR-18	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.		HACH methods exist for the determination of low- and medium-range concentrations of iron in water.
Dissolved manganese				
See the methods listed under total manganese. Dissolved manganese analyses require filtering through a 0.45-µm filter prior to digestion or other pretreatment procedures to ensure that the analytical results are derived only from the manganese that resides in solution and not from suspended materials in the water matrix.				

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Dissolved oxygen (DO)				
EPA 360.1 (field meter) <ul style="list-style-type: none"> • Standard Method 4500O₂-G (formerly Standard Method 422F) • ASTM D 5462 • HACH Method 8157 	MQL of 0.2 mg/L.	±0.1 mg DO/L.* *Accuracy data taken from Standard Method 4500-0 G	±0.05 mg DO/L.* *Accuracy data taken from Standard Method 4500-0 G	Improperly calibrated electrodes, bubbles behind the membrane, a fouled membrane, or introduction of atmospheric oxygen (O ₂) during sampling can each cause problems with data quality. Frequent care should be given, especially when high levels of total organic carbon (TOC) or minute levels of nonaqueous-phase liquid (NAPL) are present. The presence of these types of constituents can result in a false negative measurement due to decreased diffusion of the molecular oxygen. Extra care must be taken to avoid aeration during well purging and sample collection, and samples should be analyzed immediately.
EPA RSK-175	RL of 1 µg/L.	Accuracies of 75–125% are easily achieved with actual samples.	Relative percent differences (RPDs) of <20% are easily achieved with actual samples.	The samples must be collected without headspace to minimize volatilization.
EPA 360.2 (Winkler titration) <ul style="list-style-type: none"> • ASTM D 888 • ASTM D 1589 • Standard Method 4500 O₂-B (formerly Standard Method 422B) • HACH Method 8229 	MDL data are not available.	Exact data are unavailable on the precision and accuracy of this technique. However, reproducibility is approximately 0.2 mg/L of DO at the 7.5-mg/L level.		This method is applicable for use with most wastewaters and streams that contain nitrate nitrogen and not more than 1 mg/L of ferrous iron [Fe(II)]. Oxidizing and reducing agents may cause interferences.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued.)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Ferrous Iron				
HACH Method 8146 (field colorimetric procedure)	MQL of 0.5 mg/L.		Coefficient of variation of 20% should be easily achieved.	The complexing reagents used in the colorimetric procedures are specific for ferrous iron. Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45- μ m filter. In addition, samples must be kept out of sunlight, and the analysis is time sensitive.
Standard Methods 3500-Fe D (lab colorimetric procedure with phenanthroline) <ul style="list-style-type: none"> Spectrometric methods which employ bathophenanthroline (see reference list for Standard Method 3500-Fe) 	MDL of 10 μ g/L.	Not available.	RSD of 25.5%.* *44 laboratories analyzed a synthetic sample of numerous elements	<p>The complexing reagents used in the colorimetric procedures are specific for ferrous iron. The atomic absorption procedures are not.</p> <p>The bathophenanthroline spectrometric method may yield the best quantitative distinction between ferrous and ferric iron but is not an EPA-approved method because EPA has not needed a method for this analysis.</p> <p>Precision and bias are very dependent on the method of sample collection and storage. Sample variability and instability may affect precision and bias more than the errors inherent in the analysis. In addition, data quality may be affected by the presence of interfering color, turbidity, and foreign ions. Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-μm filter.</p>

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Fraction Of Organic Carbon (F_{oc})				
Empirical calculation* *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater, 1995, Air Force Center for Environmental Excellence (AFCEEa), p. B-46	NA	The accuracy and precision of the calculation will be dependent on the accuracy and precision of measurement technique used to determine the parameters that are used to calculate f_{oc} (e.g., octanol/water partition coefficient [see methods for determining octanol/water partition coefficients below] and the surface area of the mineralogical component of the aquifer matrix).		The equation, along with a discussion of how the parameters are related and may impact one another, is presented in the <i>Technical Protocol for Implementing Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater</i> .
Hardness				
A 130.2 (lab titration with chelating agent)EP • Standard Method 2340 C • ASTM D 1126	Suitable to all concentration ranges of hardness. The method does not indicate an MDL.	Bias of -0.87% (-0.003 mg/L calcium carbonate) at 31 mg/L calcium carbonate.* *43 analysts in 19 labs analyzed 6 synthetic water samples containing calcium and magnesium salts	Standard deviation of 2.87 mg/L calcium carbonate at 31 mg/L calcium carbonate.* *43 analysts in 19 labs analyzed 6 synthetic water samples containing calcium and magnesium salts	Excessive amounts of heavy metals can interfere. This can be overcome by complexing the metals with cyanide, or by using a non-ethylenediaminetetraacetic acid (EDTA) method. For EPA 2430 C, suspended or colloidal matter may interfere with the end point of the titration.

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
EPA 130.1 (lab chelation with spectrophotometry)	Applicable range of 10–400 mg/L of calcium carbonate.	%Rs of 89 and 93.* *In a single lab, using surface water samples at concentrations of 39 and 296 mg/L as calcium carbonate	Standard deviations of 1.5, 1.5, 4.5, 5.0 mg/L.* *In a single lab, using surface water samples at 19, 120, 385, and 366 mg/L as calcium carbonate	

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
<u>Standard Method 2340 B (empirical calculation)</u>	This method determines hardness by computing it from the results of separate determinations of calcium and magnesium. The sensitivity is limited by the analytical technique employed to measure the metal concentrations.	This method determines hardness by computing it from the results of separate determinations of calcium and magnesium. The accuracy and precision of this method will be dependent on the analytical technique employed to measure the metal concentrations.		This method determines hardness by computing it from the results of separate determinations of calcium and magnesium. According to the Standard Method, this is the preferred method for determining the amount of hardness in a sample.
<u>HACH Method 8226 (field titration with EDTA)</u>	Range of 1–20 mg/L.* *HACH Model HA-71A	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.		

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HENRY'S LAW CONSTANT				
From literature	NA	NA	NA	Literature values can often vary significantly depending on the method employed for their calculation. These values often provide a reasonable estimate of the parameters; however, the DQOs for a given project may require greater accuracy than literature values may provide. In addition, the effect of other chemicals may modify the value significantly.

Table 2.1. Master Table Of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 2780	Not addressed by the method.	Because of the complex nature of this test method, there are not a sufficient number of volunteers to permit a cooperative laboratory program for determining the precision and bias.		This test method covers the determination of the solubility of fixed gases in liquids. It is suitable for gases and liquids that do not react with each other and are compatible with borosilicate glass, mercury, stainless steel, polytetrafluoroethylene (PTFE), and vinylidene fluoridehexafluoro propylene copolymer (FPM) under the conditions of the test. This method also covers the determination of the concentration of fixed gases in solutions, which are not saturated with the gas.
ASTM D 2779	Not addressed by the method.	Bias of <2% for each gas.	The precision has been shown to vary quite significantly depending on the gas being measured. See Table 2 in the method for precision data.	This test method covers the estimation of the equilibrium solubility of several common gases in hydrocarbon liquids, including oxygen, nitrogen, hydrogen sulfide, carbon dioxide, methane, and hydrogen.
Hydraulic Conductivity (K)				
ASTM D 5126 Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone	NA	NA	NA	
ASTM D 4043 Standard Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques	NA	NA	NA	The limitations are related primarily to simplifying assumptions implicit in each test method. Response of an aquifer system to stress is not unique; therefore, system must be known sufficiently to select proper analytical method.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 5270 Standard Test Method for Determining Transmissivity and Storage Coefficient of Bounded, Nonleaky, Confined Aquifers	NA	*	**	This method is limited to the determination of transmissivities and storage coefficients for aquifers in hydrogeologic settings with reasonable correspondence to assumptions of the Theis nonequilibrium method, except the aquifer is limited in areal extent by a fully penetrating linear boundary.
ASTM D 4105 Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky, Confined Aquifers by the Modified Theis Nonequilibrium Method	NA	*	**	This method's limitations are primarily related to correspondence between actual field conditions and simplifying assumptions of the test method.
ASTM D 5473 Standard Test method (Analytical Procedure) for Analyzing the Effects of Partial Penetration of Control Well and Determining the Horizontal and Vertical Hydraulic Conductivity in a Nonleaky, Confined Aquifer	NA	*	**	This method's limitations are primarily related to correspondence between actual field conditions and simplifying assumptions of the test method.
ASTM D 4104 Standard Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky, Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head	NA	*	**	Slug tests are considered to provide an estimate of transmissivity. This method assumes a fully penetrating well. Partially penetrating wells may be acceptable in stratified aquifers with horizontal hydraulic conductivity much greater than vertical hydraulic conductivity. In such a case, this test would be considered to represent the average hydraulic conductivity of the aquifer adjacent to the open interval of the well.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 4106 Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky, Confined Aquifers by the Theis Nonequilibrium Method	NA	*	**	This method's limitations are primarily related to correspondence between actual field conditions and simplifying assumptions of the test method.
ASTM D 5269 Standard Method for Determining Transmissivity of Nonleaky, Confined Aquifers by the Theis Recovery Method	NA	*	**	The valid use of this method is limited to the determination of transmissivities for aquifers in hydrogeologic settings with reasonable correspondence to assumptions of the Theis theory.
ASTM D 4044 Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug Tests) for Determining Hydraulic Properties of Aquifers	NA	*	**	This method should be used with an analytical procedure such as Test Method D 4104.
ASTM D 4050 Standard Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems	NA	*	**	Use with analytical procedure such as Test Method D 4105 or D 4106.
* No statement can be made about bias, because no true reference values exist.				
** Not practical to specify the precision of this test method, because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses.				
Hydrocarbon Pore Saturation				
American Petroleum Institute (API) RP40 (Dean Stark Method)				

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Hydrogen (H₂)				
There are currently no known regulatory approved methods for the analysis of H ₂ . However, numerous specialized laboratories are able to perform this analysis	Since no EPA-approved method exists, laboratories that perform the analysis generally consider their method proprietary and do not disclose the performance information.			
In Situ Respiration Test				
AFCEE (Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing, 1994)	NA	No accuracy or precision data on this test is available at this time		
Interfacial Tension				
ASTM D 2285	NA	The precision and bias have not been determined. This is a rapid procedure for use under field conditions. It gives a semiquantitative answer that is subject to significant error. For instances where a test value of known precision is required, use Test Method D 971 (see below).		<p>This method covers a comparatively rapid procedure particularly applicable for field use for measuring, under nonequilibrium conditions, the interfacial tensions of electrical insulating oils of petroleum against water. The method has been shown by experience to give a reliable indication of the presence of hydrophilic compounds.</p> <p>This test method may not be applicable for highly viscous insulating fluids.</p>

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 1331 <ul style="list-style-type: none"> • ASTM D 971 	NA	There being no criteria for measuring bias in these test-product combinations, no statement of bias can be made.	Repeatability exceeds 0.04 times the mean value in only 1 in 20 measurements.	These methods cover the determination of surface tension and interfacial tension of solutions. Method 971 is specifically for the measurement of, under nonequilibrium conditions, the interfacial tension of mineral oils against water.
Intrinsic Permeability				
ASTM D 2434 Test Method for Permeability of Granular Soils (constant head)	NA	There is no accepted reference value for this test method; therefore, bias cannot be determined	Not addressed by the method	This test method covers the determination of the coefficient of permeability by a constant-head method for the laminar flow of water through granular soils. This procedure is limited to disturbed granular soils containing not more than 10% soil passing the 75- μm (No. 200) sieve.
ASTM D 5084 Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter	NA	There is no accepted reference value for this test method; therefore, bias cannot be determined	Data are being evaluated to determine the precision of this test method	This test method covers laboratory measurement of the hydraulic conductivity (also referred to as the coefficient of permeability) of water-saturated porous materials with a flexible wall permeameter. The method may be used with undisturbed or compacted specimens that have a hydraulic conductivity of less than or equal to 1×10^{-5} m/s. If the conductivity is greater than this value, Test Method 2434 may be used.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Light Nonaqueous-Phase Liquid (Lnapl) Density				
ASTM D 4052 (digital density meter)	NA	The accuracy of results should not differ from the established value by more the 0.0005 g/mL when compared to pure reference material.	Repeatability (difference between two test results obtained by the same operator with the same test conditions) of 0.0001 for the range of 0.68–0.97 g/mL.	This method's application is restricted to liquids with vapor pressures below 600 mm mercury (Hg) and viscosities below about 15,000 mm ² /sec at the temperature of the test (i.e., 15–35°C). This method is not applicable to samples so dark in color that the absence of air bubbles cannot be established with certainty.
ASTM D 1298 (hydrometer method)	NA	A statement of bias for this method is being developed.	Repeatability for transparent product of 0.0005.	This method is most suitable for determining the density or relative density (specific gravity) of mobile transparent liquids. However, it can also be used for viscous oils by allowing sufficient time for the hydrometer to reach equilibrium, or for opaque oils by employing a suitable meniscus correction.
ASTM D 1217 (Bingham Pycnometer)	NA	The difference of results from the established values when compared to pure reference materials is not expected to be more than ±0.00003 g/mL.	Repeatability should not be >0.00002.	This method covers the measurement of the density of pure hydrocarbons or petroleum distillates boiling between 90 and 110°C that can be handled in a normal fashion as a liquid at the test method temperatures of 20 and 25°C.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Lithology And Stratigraphy				
ASTM D 5434 Field Logging of Subsurface Explorations of Soil and Rock	NA	NA	NA	NA
Metals				
SW6010 (ICP-ES) <ul style="list-style-type: none"> EPA 200.7 Standard Method 3120 	MDLs, sensitivity, optimum ranges, precision, and accuracy will vary with the matrices, instrumentation, and analyte. Typical MDLs of 1–50 µg/L should be achievable. In a single lab evaluation of 22 metals, the mean RSD for triplicate analysis was 9%. The mean %R for the spiked elements was 93.			
EPA 200.9 (graphite furnace atomic absorption [GFAA]) <ul style="list-style-type: none"> Standard Method 3111 	MDL of 0.02–7.8 µg/L.	%R of 90–110 for each element is typical.* *DW	RSD are typically less than 5%. *DW	
SW6020 (ICP-MS) <ul style="list-style-type: none"> EPA 200.8 	MDLs are typically <1 µg/L.	%R of 90–110 for each element is typical.* *The %Rs presented in the method, resulting from an EPA multi-laboratory study, were determined based on a reference technique	The precision may vary widely depending on the element of interest, as well as the matrix; most elements in an aqueous matrix yield %RSD of less than 10%.	

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Methane, Ethane, Ethene				
EPA RSK-175 (lab gas chromatography-flame ionization detector [GC-FID]) or SW3810 modified	RL of 1 µg/L.	Accuracies of 75–125% are easily achieved with actual samples.	Relative percent differences (RPDs) of <20% are easily achieved with actual samples.	The samples must be preserved against biodegradation and collected without headspace to minimize volatilization.
Moisture				
ASTM D 2216 (heating method) • ASTM D 4959	The sensitivity of the technique will depend on the limitations of the procedure used to determine the mass of the sample before and after drying.	The precision and bias of this test method has not been determined.		This method covers procedures for determining water content of soils by drying with direct heat. This is the standard by which other methods for the determination of moisture (e.g., ASTM D 3949, D 4643, and D 4944) are measured against. This method is applicable to most soil types. For some soils (e.g., halloysite, mica, montmorillonite, gypsum) or other hydrated materials, highly organic soils or soils that contain dissolved solids, this test method may not yield reliable water content values.
ASTM D 4944 (calcium carbide gas pressure tester method)	Not provided by the method.	There is no accepted reference value for this test method; therefore, bias cannot be determined.	The precision of this test method has not been determined.	This method determines water content in soil by chemical reaction using calcium carbide as a reagent to react with the available water in the soil, thereby producing a gas whose pressure is then measured. This method requires specimens consisting of soil having all particles smaller than the Number 4 sieve size. The method may not be as accurate as other accepted methods such as Test Method D 2216.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 425 (centrifuge method)	Not provided by the method.	Information on the accuracy of this test is not available. Information on the precision of this test is being gathered.		This test method is limited to disturbed specimens of coarse-grained soils having fines of low plasticity. This test is limited to soils passing the 2.00-mm sieve or that fraction of a soil passing a 2.00-mm sieve.
ASTM D 4643 (microwave method)	The sensitivity of the technique will depend on the limitations of the procedure used to determine the mass of the sample before and after drying.	This test method has no bias because the values determined can be defined only in terms of the test method, and there are no accepted reference materials suitable for determining the bias.	Studies on microwave drying have indicated single lab average precision (expressed as percentage moisture content) of 0.96% or less.	This method is applicable to most soil types. For some soils (e.g., halloysite, mica, montmorillonite, gypsum) or other hydrated materials, highly organic soils or soils that contain dissolved solids, this test method may not yield reliable water content values.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Molecular weight				
Empirical calculation based on literature values	NA	The accuracy of atomic weights on which molecular weights are calculated is adequate for the purposes of remedial design and optimization.	NA	
Nitrate				
SW9056 (lab IC-HECD) <ul style="list-style-type: none"> • EPA 300.0 • ASTM D 4327 • Standard Method 4110C 	MDL of 0.1 mg/L. RL of 1 mg/L.	%Rs of 102.1,104.3, 111.6, and 134.9 for RW, DW, SW, and WW, respectively.	Standard deviations of 0.0066, 1.475, 0.709, and 0.466 mg/L for RW, DW, SW, and WW, respectively.	The method indicates that the samples should be preserved at 4°C and analyzed as soon as possible after collection. In addition, samples need to be free of particulate matter. Turbid samples must be filtered through a 0.45-µm filter.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
SW9200 (lab colorimetric procedure) <ul style="list-style-type: none"> • EPA 353.2 • Standard Method 4500 NO₃⁻ E/F/H and G, which is potentiometric 	RL of ≤0.1 mg/L.	Relative error 6.79%.* *27 analysts analyzed water at 0.16 mg/L	Standard deviation of 0.092 mg/L.* *27 analysts analyzed water at 0.16 mg/L	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter. Temperature control is extremely critical. Strong oxidizing or reducing agents may cause interferences. Ferrous and ferric iron and quadrivalent manganese may produce slight positive interferences. Data quality is dependent on the proper preservation of samples. Analysis should be done as soon as possible. If analysis can be done within 24 hours, only a temperature preservation of 4°C is required. However, if samples will be stored for more than 24 hours, they should be preserved with sulfuric acid (2 mL/L concentrated sulfuric acid [H ₂ SO ₄]).
Standard Method 4500 NO ₃ ⁻ D (ion-selective electrode) <ul style="list-style-type: none"> • SW9210 	MDL of 0.14 mg/L.	Accuracy data are not available at this time.	Precision of ±0.4 mV over the range of the method is expected.	Chloride and bicarbonate ions may interfere. pH and ionic strength should be held constant for all standards and samples.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
<p><u>HACH Model NI-11 (field cadmium reduction)</u></p> <p>* Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented</p>	<p>Range of 1–50 mg/L.</p>	<p>Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.</p>		<p>HACH methods exist for low- and high- range nitrate concentrations in ground water.</p>

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Nitrogen (total)				
EPA 351.1 (colorimetric total Kjeldahl) <ul style="list-style-type: none"> • 4500-N_{org} B/C • ASTM E 147 • HACH Kjeldahl 	The applicable range is 0.05 to 2.0 mg N/L.	Bias is -1.21 mg N/L at 5.81 mg N/L.	Standard deviation of 1.85 mg N/L at 5.81 mg N/L.	Samples may be preserved by sulfuric acid addition and refrigeration at 4°C. Even when preserved, however, conversion of organic nitrogen to ammonia may occur. Samples should be analyzed as soon as possible.
EPA 351.4 (ion-selective electrode)	This method covers the range from 0.03 to 25 mg N/L.	Precision and accuracy data are not available at this time.		
Standard Method 4500-N _{org} D (persulfate method)	The method converts all nitrogenous compounds to nitrate; the detection limits depend on the method employed to measure the final nitrate concentration.	%R of 98.3.* *3 labs with 2 analysts at 2.0 mg N/L	Standard deviation of 0.015 mg/L.* *3 labs with 2 analysts at 2.0 mg N/L	
Octanol/water partition coefficient (K_{ow})				
From literature	NA	NA	NA	Literature values can often vary significantly depending on the method employed for their calculation. These values often provide a reasonable estimate of the parameters; however, the DQOs for a given project may require greater accuracy than literature values may provide.

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM E 1147 Standard Test Method for Partition Coefficient (N- Octanol/Water) Estimation by Liquid Chromatography	This test is useful for determining the log of the octanol/water partition coefficients over the range of 0-8.	The precision and bias have not been determined for this method.		

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
OXIDATION-REDUCTION				
Standard Method 2580B (field meter) <ul style="list-style-type: none"> ASTM D 1498 	MQL of ± 300 millivolts (mV).	Accuracy at stable temperatures and with a properly functioning electrode should be ± 10 mV.	Precision of ± 22 mV.* *Determined using 234 replicates on GW over a 2-year period in a closed flow cell	An improperly calibrated instrument or the introduction of O ₂ during sampling will lead to data quality problems. Oxidation-reduction (redox) is generally taken in the field with a lower level of quality than should be accorded for biodegradation. Results should be reported relative to the standard hydrogen electrode.
Particle size				
ASTM D 422 (sieve procedure) <ul style="list-style-type: none"> ASTM D 1556 ASTM D 421 ASTM D 2217 ASTM E 11 	NA	NA	NA	The distribution of particle sizes larger than 75 μm is determined by sieving, while the distribution of particle sizes smaller than 75 μm is determined by a sedimentation process. Mechanical stirring and air dispersion produce markedly different particle size distributions. Air dispersion is recommended.
ASTM D 2487	NA	NA	NA	When precise classification of soils for engineering purposes is required, the procedures described in this method should be used.
ASTM D 2488 Practice for Description and Identification of Soils Visual-Manual Procedure)	NA	NA	NA	The identification portion of this practice is limited to naturally occurring soils. This method uses visual examination and simple manual tests to describe and identify soils.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Ph				
SW9040B/SW9045C (field meter) <ul style="list-style-type: none"> • EPA 150.1 • ASTM D 1293 • Standard Method 4500-H⁺ B • HACH 8156 	MQL of 0.1 standard units.	Accuracy of ± 0.01 standard unit.	Standard deviation of 0.1–0.2 pH unit.* *For lab-analyzed synthetic water samples	An improperly calibrated instrument can result in poor data quality. This parameter is frequently used to monitor well purging to determine that the water is representative of the formation. For natural attenuation (NA), these parameters are essential for measuring biologic degradation potential. As with DO sensors, the electrode response can be impaired by coatings of oily material or particulate matter. Temperature affects pH readings and should be reported for each pH measurement taken.
HACH Method 17H (field titration with phenol red)* *Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 6.5–8.5.	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.		HACH test kits are available to encompass a range of pH measurements.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Phosphorus (Total)				
EPA 365.1 (colorimetric) <ul style="list-style-type: none"> • ASTM D 515 • Standard Method 4500 P-C/D/E/F (formerly Standard Method 606) • HACH Method 8190 	MDL of 3 µg /L.* The method is usable in the 0.01 to 1.0 mg P/L range. *For Standard Method 4500 P-D	%R of 99 and 100 at 0.07 and 0.76 mg P/L, respectively.* *Single laboratory results for SW	Standard deviations of less than 0.005 mg P/L were achieved over a range of concentrations.* *Single laboratory results for SW	If benthic deposits are present in the area being sampled, great care should be taken not to include these species. If the analysis cannot be performed the same day of collection, the sample should be preserved with sulfuric acid and refrigeration at 4°C.
Porosity				
ASTM D 4404 Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry	NA	See the text of the standard for discussion.		Use of this test method may alter the natural pore volume distribution that is being measured.
From literature based on soil type(s)	NA	NA	NA	
Soil capillarity				
ASTM D 425M (centrifuge method)				

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
SOIL CLASSIFICATION				
ASTM D 2487 Test Method for Classification of Soils for Engineering Purposes (United Soil Classification System [USCS])	NA	NA	NA	This standard describes a system for classifying mineral and organo-mineral soils for engineering purposes based on laboratory determination of particle-size characteristics, liquid limit, and plasticity index, and shall be used when precise classification is required.
ASTM D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)	NA	NA	NA	This identification process is limited to naturally occurring soils with particles less than 3 inches in diameter. It covers procedures for the description of soils for engineering purposes.
Soil Density—Ex Situ Tests				
<u>ASTM D 5550 Test Method for Soil Solids by Gas Pycnometer</u>	NA	The procedure in this test method has no bias because the value of specific gravity is defined only in terms of this test method	The precision for this test method is being determined	This test method covers the determination of the specific gravity of soil solids by means of a gas pycnometer. Test Method D 854 may be used instead of or in conjunction with this test method. Test Method D 854 does not require the specialized test apparatus needed by this test method; however, D 854 may not be used if the specimen contains matter that can readily dissolve in water.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
<u>ASTM D 854 Standard Test Method for Specific Gravity of Soils</u> <ul style="list-style-type: none"> <u>ASTM D 127</u> 	NA	Acceptable range (of 2 results) of 0.06% of the mean value* *Single operator precision for cohesive soils passing 4.75 mm (No. 4)	Standard deviation of 0.021* *Single operator precision for cohesive soils passing 4.75 mm (No. 4)	This test method covers the determination of the specific gravity of soils that pass the 4.75-mm (No.4) sieve, by means of a pycnometer. When the soil contains particles larger than the 4.75-mm sieve, Test Method C 127 should be used for the material retained on the sieve.
<u>ASTM D 4253 Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table</u> <ul style="list-style-type: none"> <u>ASTM D 4254</u> 	NA	Acceptable range (of 2 results) of 2.7% of the mean value* *Value reported for a single operator measuring the unit weight of fine to medium sands	Standard deviation of 0.8 lb/ft ³ * *Value reported for a single operator measuring the unit weight of fine to medium sands	This test method is applicable to soils that may contain up to 15% by dry mass, of soil particles passing a No. 200 (74-µm) sieve, provided they still have cohesionless, free-draining characteristics. This test method is applicable to soils in which 100%, by dry mass, of soil particles pass a 3-inch (75 mm) sieve.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued.)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 4718 PRESENTS THE PROCEDURE FOR CORRECTION OF UNIT WEIGHT AND WATER CONTENT FOR SOILS THAT CONTAIN OVERSIZE PARTICLES AND MAY BE HELPFUL FOR DENSITY DETERMINATION IN SUCH INSTANCES.				
Soil Density—In Situ Tests				
ASTM D 1556 (sand-cone method) <ul style="list-style-type: none"> • ASTM D 2167 (rubber balloon method) • ASTM D 2992 (nuclear method) • ASTM D 5195 (nuclear method) • ASTM D 2937 (drive-cylinder method) • ASTM D 4564 (sleeve method) • ASTM D 4914 (sand replacement method) • ASTM D 5030 (water replacement method) • ASTM D 3017 (nuclear method) • ASTM D 5220 (neutron depth probe method) 	NA	There are no absolute values of in-place density for soils against which these test methods can be compared. Therefore, this test method has no determinable bias since the values obtained can be defined only in terms of the test methods.	The precision of these test methods is operator dependent and a function of the care exercised in performing the steps of the procedures, giving particular attention to careful control and systematic repetition of the procedure used.	All of the methods presented are used for the determination of soil density in place via in situ procedures. Each method has corresponding advantages and disadvantages depending on site conditions and circumstances. The reader is urged to review the advantages and limitations of each method prior to selection of an in situ technique. While no standard soils exist, limited studies running repetitive adjacent test using ASTM Test Method D 2937 have indicated standard deviations of 1.98 for soils with an average wet density of 134 lb/ft ³ (ranging from 131.5 to 137.1 lb/ft ³) using a 5.125-inch-diameter cylinder, and standard deviations of 1.62 for soils with an average wet density of 119.9 lb/ft ³ (ranging from 117.1 to 122.2 lb/ft ³) using a 3.5-inch-diameter cylinder.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Sorption Coefficient (K_{oc})				
ASTM E 1195 Standard Test Method for Determining a K_{OC} for an Organic Chemical in Soil and Sediments	NA	See the text of the standard for discussion of precision and bias.	This method does not apply to all soils and sediments. See the text of the standard for discussion of laboratory procedures and chemical grades recommended for use.	
Sulfate				
SW9056 (common lab method using IC- HECD) <ul style="list-style-type: none"> ASTM D 4327 ASTM D 5542 Standard Method 4110C EPA 300.0 	MDL of 0.1 mg/L. RL of 1 mg/L.	%Rs of 102.1,104.3, 111.6, and 134.9 for RW, DW, SW, and WW, respectively.	Standard deviations of 0.0066, 1.475, 0.709, and 0.466 mg/L for RW, DW, SW, and WW, respectively.	The method indicates that the samples should be preserved at 4°C and analyzed as soon as possible after collection. Samples should be free of particulate matter. Turbid samples must be filtered through a 0.45- μ m filter.
SW9036 (lab colorimetric procedure) <ul style="list-style-type: none"> SW9035 EPA 375.1/375.2 Standard Method 4500 SO₄²⁻-F (automated) 	MDL of 10–20 mg/L. The applicable range is 10–400 mg sulfate/L.	%Rs of 99 and 102 were achieved at 82 and 295 mg sulfate/L, respectively.* *EPA 375.1 single laboratory results for SW	Standard deviation of 1.0 mg/L at 111 mg sulfate/L.* *EPA 375.1 single laboratory results for SW	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45- μ m filter. Samples should be refrigerated.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
EPA 375.3 (gravimetric) <ul style="list-style-type: none"> Standard Method 4500 SO₄²⁻-C/D (formerly Standard Method 427A) 	The method is most accurate for sulfate concentrations above 10 mg/L.	Relative error of 1.9%.	RSD of 4.7% at 259 mg sulfate/L.	Samples should be refrigerated at 4°C. High results may be obtained for samples that contain suspended matter.
SW9038 (lab turbidimetric procedure) <ul style="list-style-type: none"> Standard Method 4500-S²⁻ E (formerly Standard Method 427C) EPA 375.4 ASTM D 516 HACH Method 8051 	MDL of 1 mg/L. The applicable range is 1–40 mg sulfate/L.	Bias of –0.3 mg/L.* *34 analysts evaluated 6 synthetic water samples at 8.6 mg/L using EPA 375.4	Standard deviation of 2.30 mg/L.* *34 analysts evaluated 6 synthetic water samples at 8.6 mg/L using EPA 375.4	Color and turbidity due to the sample matrix can cause positive interferences that must be accounted for by use of blanks. Silica >500 mg/L will interfere.
HACH Method 8051 (field colorimetric test kit)	MDL of 5 mg/L.		Coefficient of variation of 20% should be easily achieved.	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter. Sample temperature should be preserved.
SULFIDE				
EPA 376.2 (colorimetric) <ul style="list-style-type: none"> Standard Method 4500-S²⁻ D/E (formerly Standard Method 428C) HACH Method 8131 	MDL of 1 mg/L. The method is suitable for sulfide concentrations up to 20 mg/L.	Average %Rs of 92 for 40 samples containing 0.5 to 1.5 mg/L.* *Accuracy data taken from the standard method	Standard deviation of 0.04 mg/L between 0.2 and 1.5 mg/L.* *Precision data taken from the standard method	Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter. Samples should be taken with a minimum of aeration; dissolved oxygen should not be present. The sample should be analyzed immediately.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
SW9030A (lab titration with phenyl arsine oxide [PAO] or sodium thiosulfate) <ul style="list-style-type: none"> SW9031 (extractable sulfides) 	MDL of 0.2–0.4 mg/L (in clean water). Practical quantitation limit (PQL) of 1.0 mg/L.	%Rs 84–100, 110–122, 94–106.* *Spike recovery results from 3 labs [acid solubles only]	Coefficient of variation of 0.86 to 45 (actual waste samples); 3.0 to 12 for RW.	Aqueous samples must be taken with minimum aeration to avoid volatilization of reaction with O ₂ , and the samples should be correctly preserved. Many other interferences may affect data quality (see method). The sample should be analyzed immediately.
EPA 376.1 (lab titration) <ul style="list-style-type: none"> ASTM D 4658-92 Standard Method 4500-S²-F 	This method is suitable for sulfide concentrations above 1 mg/L.	Precision and accuracy for this method have not been determined.		Samples should be taken with a minimum of aeration; dissolved oxygen should not be present. The sample should be analyzed immediately.
Standard Method 4500-S ² -G (ion-selective electrode) <ul style="list-style-type: none"> ASTM D 4658 	MDL of 0.032 mg/L.	Accuracy for this method is not reported in the method.	RSDs of 23% for 0.0081 mg/L and 5% for 0.182 mg/L have been reported.	Humic substances may interfere with the ion selective electrode. All samples and standards should be analyzed at the same temperature. Samples are time sensitive. Samples should be taken with a minimum of aeration; dissolved oxygen should not be present.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Temperature				
EPA 170.1 (field meter) <ul style="list-style-type: none"> Standard Method 2550 (formerly Standard Method 212) 	MQL of 0°C.	Accuracy and precision for this method have not been determined.		The field meter accuracy is dependent on proper calibration. The measurement is time sensitive and should be conducted immediately.
Total Dissolved Solids (Tds)				
EPA 160.2 <ul style="list-style-type: none"> Standard Method 2540C HACH Method 8163 	Applicable range of 4–20,000 mg/L.	Accuracy data on samples can not be obtained.	Standard deviation of differences of 21.20 mg/L.* *Single-laboratory analyses of 77 samples at 293 mg/L	Samples high in filterable residue (dissolved solids), such as saline waters, brines, and some wastes may be subject to positive interferences. In addition, waters highly mineralized with calcium, magnesium, chloride, and/or sulfate may be hygroscopic and may require an extended drying to drive of the retained water, proper desiccation, and rapid weighing, which helps prevent false positives. Samples high in bicarbonate require careful and possibly prolonged drying time to ensure conversion of bicarbonate to carbonate.
Total Iron				
SW6010 (ICP-ES) <ul style="list-style-type: none"> Standard Method 3120 EPA 200.7 	MDL of 10 µg/L. RL of 0.20 mg/L.	%R of 93 ± 6.* *Single lab evaluation of seven wastes for all elements	RSD of 9% ± 2%.* *Single lab evaluation of seven wastes for all elements	Precision and bias are very dependent on the method of sample collection and storage. Results include both dissolved ferrous and ferric iron, as well as iron from the turbidity component if not filtered before acid preservation.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
SW7380/7381 (lab AA) <ul style="list-style-type: none"> Standard Method 3111 EPA 236.1/236.2 EPA 200.9 (graphite furnace) 	MDL of 0.03 mg/L (direct aspiration), 1 µg/L (furnace).	%Bias of -0.5 (direct aspiration), accuracy data not available for graphite furnace.	Standard deviation of 131 µg/L (direct aspiration), precision data not available for graphite furnace.	
SW6020 (ICP-MS) <ul style="list-style-type: none"> EPA 200.8 	MDLs are <1 µg/L.	%R of 90-110 is typical.* *The %Rs presented in the method, resulting from an EPA multi-laboratory study, were determined based on a reference technique	RSD of less than 10%.	
Standard Method 3500-Fe D (lab colorimetric procedure)	MDL of 10 µg/L.	Not available.	RSD of 25.5%.* *44 laboratories analyzed a synthetic sample of numerous elements	Precision and bias are very dependent on the method of sample collection and storage. Sample variability and instability may affect precision and bias more than the errors inherent in the analysis. In addition, data quality may be impacted by the presence of interfering color, turbidity, and foreign ions. Colorimetric methods require an optically clear sample. Turbid samples must be filtered through a 0.45-µm filter.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HACH Method 8008 (field colorimetric procedure with 1,10-phenanthroline)* * Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 0–5 mg/L.* *Model IR-18	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.		HACH methods exist for the determination of low and medium range concentrations of iron in water.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Cont.inued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Total Manganese				
SW6010 (lab ICP-ES) <ul style="list-style-type: none"> • EPA 200.7 • Standard Method 3120 B 	MDL of 2 µg/L. RL of 3 µg/L.	%R of 93 ± 6.* *Single lab evaluation of seven wastes for all elements	RSD of 9% ± 2%.* *Single lab evaluation of seven wastes for all elements	Precision and bias are very dependent on the method of sample collection and storage. The sample preparation technique will be selected based on whether the analyst is interested in total manganese or dissolved manganese only. See the method for details.
SW7460/7461 (lab atomic absorption) <ul style="list-style-type: none"> • EPA 243.1/243.2 • Standard Method 3111 B • EPA 200.9 (graphite furnace) 	MDL of 0.01 mg/L (direct aspiration), 0.2 µg/L (furnace).	Bias of 1.5%.* *At a fortified concentration of 426 µg/L using EPA 43.1	Standard deviation of 70 µg/L.* *At a fortified concentration of 426 µg/L using EPA 243.1	
SW6020 (lab analysis with inductively coupled plasma [ICP]-mass spectrometry [MS]) <ul style="list-style-type: none"> • EPA 200.8 	RL of 2 µg/L.	Recoveries of 80–120% from water are easily achievable.	Precision of <15% relative percent deviation (RPD) for water should be easily achieved.	
Standard Method 3500 D (lab colorimetric technique)	MDQ of 42 µg Mn/L when a 5-cm cell is used.	Relative error of 0%. *A synthetic sample containing 120 µg Mn/L, along with various other metal constituents, was analyzed in 33 labs	RSD of 26.3% . *A synthetic sample containing 120 µg Mn/L, along with various other metal constituents, was analyzed in 33 labs	

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
HACH Method 8034 (colorimetric procedure with periodate oxidation) * Other HACH screening methods are available for this parameter. In general, performance criteria for the other methods are comparable to the one presented	Range of 0–10 mg/L.	Accuracy and precision data for this test procedure have not been obtained. However, this test is a screening test, which provides semiquantitative measurements.		
Total organic carbon (TOC)				
SW9060 (converted to CO ₂ then measured via FID or IR) <ul style="list-style-type: none"> • EPA 415.1/415.2 • ASTM D 4839 • ASTM D 2579 • Standard Method 5310 (formerly Standard Method 505) 	MDL of 50 µg/L. RL of 1 mg/L.	Bias of +1.08 mg/L was calculated for the analysis of distilled water.* *At 107 mg TOC/L by 28 analysts in 21 laboratories using 415.1	Standard deviation of 8.32 mg TOC/L for the analysis of distilled water.* *At 107 mg TOC/L by 28 analysts in 21 laboratories using 415.1	Carbonate/bicarbonate may represent an interference and must be removed or accounted for in the final calculation. Samples should be preserved with acid to prevent biodegradation and collected without headspace to minimize volatilization losses.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
ASTM D 4129 (lab via coulometric detector that measures electron flow through solution during a reaction with an oxidizing substance)	Applicable range of 2–20,000 mg/L.	Bias of –2.0 (% bias of –1.1%). *Determined for potassium hydrogen phthalate at 180 mg/L	Standard deviation of 7.3 mg/L. *Determined for potassium hydrogen phthalate at 180 mg/L	This method has the advantage of a wide range of concentrations, which may be determined without sample dilution and the provision for boat or capillary introduction of samples containing sediments and particulate matter where syringe injection is inappropriate. This procedure is applicable only to that carbonaceous matter in the sample that can be introduced into the reaction zone. Sludge and sediment samples must be homogenized prior to sampling.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Total Suspended Solids				
EPA 160.1 <ul style="list-style-type: none"> • Standard Method 2540D • HACH Method 8158 	Applicable range of 10–20,000 mg/L.	Accuracy data on samples can not be obtained.	Standard deviation of 5.2 mg/L (coefficient of variation of 33%) at 15 mg/L; 24 mg/L (10%) at 242 mg/L, and 13 mg/L (0.76%) at 1707 mg/L.* Single lab analyses of 50 samples resulted in standard deviation of differences of 2.8 mg/L. *2 analysts of four sets of 10 determinations each	Waters highly mineralized with calcium, magnesium, chloride, and/or sulfate may be hygroscopic and may require an extended drying to drive of the retained water, proper desiccation, and rapid weighing, which helps prevent false positives. Samples high in bicarbonate require careful and possibly prolonged drying time to ensure conversion of bicarbonate to carbonate.

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
TURBIDITY				
EPA 180.1 (field meter) <ul style="list-style-type: none"> • Standard Method 214A • ASTM D 1889 • HACH Method 8195 	The instrument can measure down to 0 units turbidity; the sensitivity should permit detection of a turbidity difference of 0.02 unit or less.* *In waters with turbidities less than 1 unit	Accuracy data are not available at this time.	Standard deviations of 0.60, 0.94, 1.2, and 4.7 at 26, 41, 75, and 180 nephelometric turbidity units (NTU).* *SW samples in a single laboratory	Turbidity is generally taken in the field as a screening measurement. Samples should be measured in the field without delay, which leads to settling out but not removal.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
Uniformity Coefficient (UC)				
Empirical calculation (Using results from ASTM D 422 Test Methods of Particle Size Analysis of Soils)* *Ernest W. Steel, Water Supply and Sewerage, 1960, McGraw-Hill Company, p. 267	NA	NA	NA	The uniformity coefficient is used to describe the overall uniformity in grain size. The uniformity coefficient is the ratio between the sieve size (in millimeters) that permits 60% of the matrix material to pass, to the sieve size (in millimeters) that permits 10% of the matrix material to pass. The later, which permits 10% of the matrix material to pass, is known as the material's effective size.
Unit (degradation) rate (k)				
Empirical calculation* *John T. Cookson, Jr., Bioremediation Engineering, 1995, McGraw-Hill Company, pp. 479-80	NA	The accuracy and precision of the calculation will be dependent on the accuracy and precision of measurement technique used to determine the parameters that are used to calculate the degradation rate constant, k (e.g., concentrations of the organic compounds).		The equation, along with a discussion of how to apply the equation, can be found in <i>Bioremediation Engineering, Design and Application</i> , by John T. Cookson, Jr. The degradation rates are frequently based on laboratory treatability studies. If these data are unavailable, published data can be used to estimate rates.
From literature	NA	NA		Literature values can often vary significantly depending on the method employed for their calculation. These values often provide a reasonable estimate of the parameters; however, the DQOs for a given project may require greater accuracy than literature values may provide.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
VAPOR PRESSURE				
ASTM E 1194	NA	Accuracy data are not available.	An interlaboratory evaluation was conducted at 8 labs using this procedure and 10 chemicals. The estimated standard deviations found by the separate lab ranged from 0.23 to 13.8 units.	This is a gas-saturation procedure for measuring vapor pressures from 1×10^{-11} to 1 kilopascal (kPa).
From literature	NA	NA	NA	Literature values can often vary significantly depending on the method employed for their calculation. These values often provide a reasonable estimate of the parameters; however, the DQOs for a given project may require greater accuracy than literature values may provide.
ASTM D 2879	NA	Because of the complex nature of this test method, there is not a sufficient number of volunteers to permit a comprehensive laboratory program for determining the precision and bias.		This is an isoteniscope (standard) procedure for measuring vapor pressures of liquids in the range of 1×10^{-1} to 100 kPa.

Table 2.1. Master Table of Analytical Protocols and Measurement Quality Objectives (Continued)

Method	Limits/Sensitivity	Accuracy/Bias	Precision	Comments/Limitations Specific To Method Of Interest
VISCOSITY				
ASTM D 445	NA	Not addressed by the method.	The method lists the expected precision for a range of numerous petroleum types. In general, the repeatability (i.e., the difference between successive results obtained by the same operator with the same experimental setup) is <1.5% of the average of the results being compared.	The time is measured for a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer under a reproducible driving head and at a closely controlled temperature.

2.2 CHEMICALS OF CONCERN

The type, quantity, and spatial and temporal distributions of the hazardous substance released must be known to understand the key processes that can affect the ultimate state and movement of the COCs in the subsurface, regardless of the remedial technique. The COCs are necessary components of any computer model of the subsurface. Many approved analytical protocols exist to make this determination. Table 2.1, the master table, presents a range of analytical methods that can be employed for the determination of several types of COCs. Only a few of the most common COCs found at hazardous waste sites have been included as examples. Project managers or decision makers should select a method for remedial system design or optimization only after comparing cost, usability, and ability to achieve the DQOs for the given design or optimization. Table 2.2 presents an example of the range of analytical methods that can be employed for the analysis of one common VOC, TCE.

Table 2.2. Chemicals of Concern, Analytical Protocols, and Performance Criteria

It is beyond the scope of this guidance to present all possible COCs, associated analytical protocols, and their performance criteria. The majority of the popular methods for a given parameter have been included in this table. If a method exists that is well matched to a given set of DQOs and MQOs and the method is approved by the scientific and regulatory communities, then its use should be considered. It should also be noted that, while the performance criteria in the table provide a good indication as to the quality of data that can be expected to be achieved with a given method, the criteria achieved with a sample for a particular set of conditions or by an individual laboratory may be better or worse than those presented. Because the data in the table were obtained using reagent water, which has minimal matrix effects. The criteria presented should serve as a starting point for selecting the method that will achieve project DQOs and MQOs without consuming unnecessary resources.

In selecting a particular method, users should evaluate parameters including but not limited to method detection limits (MDLs), reporting limits (RLs) or practical quantitation limits (PQLs), level of confidence, interferences, limitations, ease of use, analysis time, and cost.

Method	Matrix	Limits/Sensitivity	Accuracy/Bias	Precision	COST PER SAMPLE ¹
TRICHLOROETHYLENE (TCE)					
SW8260B (common lab gas chromatography-mass spectrometry [GC/MS] analysis)	Water	Method detection limit (MDL) of 0.03–0.35 µg/L for wide-bore capillary columns* *Narrow-bore columns are approximately one order of magnitude lower MDLs based on a 25-mL sample volume and spike amount between 0.5 and 10 µg/L	%Recovery (%R) of 90* *Results from single lab data using SW5030 and a wide-bore capillary column	Relative standard deviation (RSD) of 7.3%* *Results from single lab data using SW5030 and a wide-bore capillary column	\$150–250
EPA 624 (GC/MS)	Water	MDL of 1.9 µg/L	%R of 104		
EPA 1624 (Isotope dilution)	Water	MDL of 2.0 µg/L* *High solids content	This method has been shown to yield slightly better results than EPA 624		\$500
EPA 524.2 (GC/MS)	Water	MDL of 0.19 µg/L	%R of 90	RSD of 7.3%	\$150–250

Table 2.2. Chemicals of Concern, Analytical Protocols, and Performance Criteria

Method	Matrix	Limits/Sensitivity	Accuracy/Bias	Precision	COST PER SAMPLE ¹
SW8021B (GC/Hall electrolytic conductivity detector [HECD])	Water	MDL of 0.01 µg/L	%R of 96	Deviation of recovery of 3.5	\$100–150
SW8021B (GC/photoionization detector [PID])	Water	MDL of 0.02 µg/L	%R of 100	Deviation of recovery of 0.78	\$100–150
EPA 502.2 (GC/HECD)	Water	MDL of 0.01 µg/L	%R of 96	Deviation of recovery of 3.5	\$100–150
EPA 502.2 (GC/PID)	Water	MDL of 0.02 µg/L	%R of 100	Deviation of recovery of 0.78	\$100–150
Standard Method 6210 (GC-MS)	Water	MDL of 1.9 µg/L	%R of 90* *Packed column	RSD of 13.6%* *Packed column	
Standard Method 6230 (GC-ELCD)	Water	MDL of 0.12 µg/L	%R of 94* *Drinking water (DW)	RSD of 6.0%* *DW	
Immunoassay (IA) field test kits* *Not currently available for TCE, but available for a wide variety of classes of compounds	Water	MDLs for test kits typically range from mid-parts per billion (ppb) to mid-parts per million (ppm) depending on the analyte	Average recoveries from fortified matrices are typically 85 to 110%	The coefficients of variation are typically less than 20%* *Many kits exhibit coefficients of variation of less than 10%	\$20–60* *Cost includes estimation of capital costs and disposables, but excludes labor

¹The method costs relative to one another should not vary substantially. However, the method-specific ranges presented in the table will often vary because of lab geographic location, number and type of samples, contract-specific performance criteria (e.g., quality assurance/quality control and data reporting requirements), and/or other contract-specific modifications to the actual method.

SECTION 3. RELEVANT FATE AND TRANSPORT CHARACTERISTICS FOR THE PRIMARY CLASSES OF ENVIRONMENTAL ANALYTES

Table 3.1 summarizes the environmental fate and transport properties of hazardous environmental constituents in the most general terms. While the information in the table is useful for understanding the relative characteristics of these general classes of compounds, the exact properties of fate and transport are extremely dependent on the specific physical and chemical properties of the media (e.g., soil, ground water, sediment, and surface water) at a site.

Table 3.1. General description of the environmental fate and transport of representative hazardous waste constituents

Chemical of concern (COC)	Ground water	Surface water	Sediment	Soil
Benzene (nonchlorinated volatile organic compound [VOC])	Moderate mobility	High water solubility and volatility, biodegradable	Highly mobility, readily leached and biodegraded	High leachability, readily passes into soil vapor phase, rapidly biodegradable
Trimethylbenzene (nonchlorinated VOC)	Moderate mobility	Limited water solubility and volatility	Moderately sorbed, limited biodegradability	Moderately sorbed, limited biodegradation, poor leachability
Trichloroethylene – TCE (chlorinated VOC)	Moderate mobility	Limited water solubility, high volatility, biodegradable	Moderately sorbed, degradable under aerobic conditions, slowly under anaerobic	Moderately sorbed, degradable under aerobic conditions, slowly under anaerobic, volatilizes into soil vapor phase
Dioxins	Not mobile	Practically insoluble, degradable by sunlight	Very tightly sorbed, resistant to biodegradation	Very tightly sorbed, not leachable below surface, not biodegradable, degradable by sunlight
Polychlorinated biphenyls (PCBs)	Not mobile	Practically insoluble, degrade in sunlight	Very tightly sorbed, resistant to biodegradation with increased levels of chlorination	Very tightly sorbed, not leachable below surface
Polyaromatic hydrocarbons (PAHs)	Not mobile	Solubility decreases rapidly with number of rings, photoreactive	Tightly sorbed, biodegradable to a limited degree	Tightly sorbed to surface soils, not leachable, limited biodegradability, weathering decreases mobility
Metals	Limited to no mobility	Solubility dependent on water chemistry	Most are tightly sorbed, not biodegradable	Most are tightly sorbed, not biodegradable

BIBLIOGRAPHY

- AFCEE (Air Force Center for Environmental Excellence), 1993. Handbook to support the Installation Restoration Program (IRP) remedial investigations and feasibility studies. San Antonio, TX: Brooks Air Force Base.
- AFCEE, 1997. Long-term monitoring optimization guide.
- AFCEE, 1998a. Model field sampling plan.
- AFCEE, 1998b. Model quality assurance project plan, Ver. 3.0.
- Air Combat Command, 1998, Site closure guidance manual.
- Aller, L., et al., 1989. Handbook of suggested practices for the design and installation of ground-water monitoring wells. National Water Well Association.
- American Public Health Association, 1995. Standard methods for the examination of water and wastewater.
- ASTM (American Society for Testing and Materials), 1986. Standard test method for deep, quasi-static, cone and friction-cone penetration tests of soil, D3441-86, Vol. 4.08.
- ASTM, 1987. Standard Guide for Investigating Soil And Rock, D-420-97, Vol. 4.08.
- ASTM, 1990. Test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter, D-5084-90, Vol. 4.09.
- ASTM, 1991a. Guide for soil sampling from the vadose zone, D4700-91, Vol. 4.08.
- ASTM, 1991b. Test method (field procedure) for instantaneous change in head (slug test) for determining hydraulic properties of aquifer systems, D-4044-91.
- ASTM, 1991c. Test method (field procedure) for withdrawal and injection on well tests for determining hydraulic properties of aquifer systems, D-4050-91.
- ASTM, 1992. Method for penetration test and split-barrel sampling of soils, D-1586-84, Vol. 4.08.
- ASTM, 1993a. Draft standard guide for the use of hollow-stem augers for geoenvironmental exploration and installation of subsurface water-quality monitoring devices, D18.21.
- ASTM, 1993b. Practice for diamond core drilling for site investigation, D-2113-83.
- ASTM, 1993c. Site characterization—environmental purposes with emphasis on soil/rock/vadose zone/groundwater, D-5730.
- ASTM, 1993d. Standard practice for soil investigation and sampling by auger borings, D1452-80, Vol. 4.08.
- ASTM, 1994a. Practice for thin-walled tube sampling of soils, D1587-94, Vol. 4.08.
- ASTM, 1994b. Test method for infiltration rate of soils (in field) using double ring infiltrometer, D-3385-94, Vol. 4.08.
- ASTM, 1997. Standard guide for remediation of ground water by natural attenuation at petroleum release sites.
- Bouwer, H. 1989. The Bower and Rice slug test—An update, *Groundwater* 27(3).
- Bouwer, H., and R. C. Rice, 1976, A slug test for determining hydraulic conductivity of unconfined aquifer with completely or partially penetrating wells, *Water Resources Research* 12(3).
- Cookson, J. T., 1995. *Bioremediation Engineering*. McGraw-Hill, Incorporated. pp. 479-80.

- DOE (U.S. Department of Energy), 1993. Remedial investigation/feasibility study (RI/FS) process, elements and techniques.
- Freeze, R. A. and J. A. Cherry, 1979. Groundwater. Prentice-Hall.*
- Grasso, Domenic, 1993. Hazardous Waste Site Remediation Source Control. Chapter F: Soil Vapor Extraction. CRC Press, Inc.
- Hach Company, 1990. Hach Company catalog: Products for analysis. Ames, IA.
- Kruseman, G. P. and N. A. deRiddler, 1991. Analysis and evaluation of pumping test data, 2nd ed. The Netherlands.
- Luckner, L., and W. M. Schestakow, 1991. Migration processes in the soil and groundwater zone, Chelsea, MI: Lewis Publishers, Inc.
- National Research Council, 1993. In situ bioremediation: When does it work? Washington, D.C.: National Academy Press.
- Nyer, E. K., S. Fam., D. F. Kidd, F. J. Johns, P. L. Palmer, G. Boettcher, T. L. Crossman, and S. S. Suthersan, 1996. In Situ Treatment Technology. Chapter 4. Vapor extraction and Bioventing. Lewis Publishers.
- Steel, E. W., 1960. Water Supply and Sewerage. McGraw-Hill Book Company. p. 267.
- USEPA (U.S. Environmental Protection Agency), 1983. Methods of chemical analysis for water and waste, EPA 600/4-79-020, 1983 Rev.
- USEPA, 1986. Test methods for evaluating solid waste, SW-846, 3rd ed., rev. January 1995, Office of Solid Waste and Emergency Response.
- USEPA, 1987a. A compendium of Superfund field operations methods, Part 2, EPA/540/P-87/001 (OSWER Directive 9355.0-14).
- USEPA, 1987b. Data quality objectives for remedial response activities: Development process.
- USEPA, 1988a. Field screening methods catalog: User's guide, EPA/540/2-88/005.
- USEPA, 1988b. Guidance for performing remedial investigations and feasibility studies under CERCLA, Interim final, EPA/540/G-89/004, Office of Solid Waste and Emergency Response, Hazardous Site Evaluation Division.
- USEPA, 1988c. Selection criteria for mathematical models used in exposure assessments, EPA/600/8-91/038.
- USEPA, 1989a. Risk assessment guidance for Superfund, Vol. I, Human health evaluation manual (Part A), Interim final, EPA/540/1-89-002, Office of Solid Waste and Emergency Response.
- USEPA, 1989b. Risk assessment guidance for Superfund, Vol. II: Environmental evaluation, EPA/540/1-89-001, Office of Solid Waste and Emergency Response.
- USEPA, 1991a. Description and sampling of contaminated soils: A field pocket guide, EPA/625/12-91/002.
- USEPA, 1991b. Modeling of soil remediation goals based on migration to groundwater.
- USEPA, 1991c. Second International Symposium: Field screening method for hazardous waste and toxic chemicals, EPA/600/9-91/028.
- USEPA, 1991d. Subsurface characterization for subsurface remediation, EPA/625/4-91/026.
- USEPA, 1991e. USEPA lists of lists.
- USEPA, 1992a. Guidance for data usability in risk assessment (Part A), Final, Pub. 9285.7-09A, Office of Solid Waste and Emergency Response.
- USEPA, 1992b. Preparation of soil sampling protocol: Techniques and strategies, NTIS PB-9220532.
- USEPA, 1992c. Technology preselection data requirements, EPA/540/S-92/009.
- USEPA, 1993a. Data quality objectives process for Superfund, Interim final guidance, EPA540-R-93-071.

- USEPA, 1993b. EPA quality system requirements for environmental programs, Draft, EPA/QA/R-1.
- USEPA, 1993c. EPA requirements for quality assurance project plans for environmental data operations, Draft final, EPA/QA/R-5.
- USEPA, 1993d. Guidance for conducting environmental data assessments, Draft, EPA/QA/G-9.
- USEPA, 1993e. Guidance for planning data collection in support of environmental decision making using the data quality process, EPA/QA/G-4.
- USEPA, 1993f. Guide for conducting treatability studies under CERCLA, 540/R-93/519-A, Office of Research and Office of Emergency and Remedial Response.
- USEPA, 1993g. Standard guide for investigating and sampling soil and rock, D420-93, Vol. 4.08.
- USEPA, 1993h. Subsurface characterization and monitoring techniques, A desk reference guide, EPA/625/R-93/003a & b.
- USEPA, 1994. Guidance for the data quality objectives process, EPA QA/G-4.
- USEPA, 1995. Land use in the CERCLA remedy selection process, OSWER Directive 9355.7-04.
- USEPA, 1997. Analysis of Selected Enhancements for Soil Vapor Extraction. EPA-542-R-97-007.
- USEPA, 1997. Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank (OSWER Directive 9200.4-17)
- USEPA, 1998. Office of Water Analytical Methods.
- Weidemeir, T. H., et al., 1995. Technical protocol for implementing intrinsic remediation with long-term monitoring for natural attenuation of fuel contamination dissolved in groundwater. San Antonio, TX: Air Force Center for Environmental Excellence.
- Weidemeir, T. H., et al., 1996. Overview of the technical protocol for natural attenuation of chlorinated aliphatic hydrocarbons in ground water under development for the U.S. Air Force Center for Environmental Excellence. San Antonio, TX: Air Force Center for Environmental Excellence.
- Wong, J. H. C., Lim, C. H., Nolen, G. L., 1997. Design of Remediation Systems. Chapter 5: Design of soil vapor extraction systems. Boca Raton, FL: CRC Press, Inc.

ATTACHMENT 3 GENERAL DESCRIPTION OF THE ENVIRONMENTAL FATE AND TRANSPORT OF REPRESENTATIVE HAZARDOUS WASTE CLASSES

CHEMICAL CLASS	Groundwater	Surface Water	Sediment	Soil
Monoaromatic hydrocarbons (BTEX)	Moderate mobility	High water solubility, volatilizes, readily biodegraded	Highly mobile, readily leached and biodegraded	High leachability, readily passes into soil vapor phase, rapid biodegradation
Trimethylbenzenes	Limited mobility	Limited water solubility and volatility	Moderately sorbed, limited biodegradation	Moderately sorbed, limited biodegradation, poorly leached
Chlorinated VOCs (e.g., TCE, PCE)	Limited mobility	Limited water solubility, high volatility, biodegradable	Moderately sorbed, degradable under aerobic conditions, slowly degraded under anaerobic	Moderately sorbed, degradable under aerobic conditions, slowly degraded under anaerobic, volatilizes into soil vapor phase
Dioxins and Furans	Not mobile	Highly insoluble, degrade in sunlight	Very highly sorbed, resistant to biodegradation	Very tightly sorbed, not leached below surface, not biodegraded, degraded by sunlight
Polychlorinated Biphenyls (PCBs)	Not mobile	Highly insoluble, degrade in sunlight	Very highly sorbed, resistant to biodegradation with increased levels of chlorinating	Very tightly sorbed, not leached below surface
Polyaromatic Hydrocarbons (PAHs)	Not mobile	Solubility decreases rapidly with increasing number of rings, photoreactive	Highly sorbed, biodegradable to a limited degree	Highly sorbed to surface soils, not leached, biodegradable to a limited degree, weathering decreases mobility
Metals	Limited to no mobility	Solubility dependent on water chemistry	Most are highly sorbed, not biodegradable	Most are tightly sorbed, not biodegradable

* This table summarizes these characteristics only in the most general terms. The exact properties of fate and Transport are extremely dependent on the specific physical and chemical properties of the individual class members and of the media (e.g., soil, ground water, sediment, and surface water) at a site.