RCRA GROUND-WATER MONITORING:

DRAFT TECHNICAL GUIDANCE

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This document is distributed by the USEPA to update technical information contained in other sources of USEPA guidance, such as Chapter Eleven of SW-846 (Revision 0, September 1986) and the Technical Enforcement Guidance Document (TEGD).

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INTRODUCTION

The hazardous waste management regulations for permitted facilities (40 CFR Part 264) were promulgated in July 1982 under Subtitle C of the Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act of 1976 (RCRA), and the Hazardous and Solid Waste Amendments of 1984 (HSWA). Subpart F of these regulations, Releases From Solid Waste Management Units, sets forth performance standards for ground-water monitoring systems at permitted hazardous waste land disposal facilities. These standards require owners and operators of land-based hazardous waste management facilities to sample and analyze ground water at specific time intervals to determine whether or not hazardous wastes or constituents released from these facilities are contaminating ground water.

This Manual was prepared by the Office of Solid Waste of the United States Environmental Protection Agency ("USEPA" or "Agency") to provide guidance for implementing the ground-water monitoring regulations for regulated units contained in 40 CFR Part 264 Subpart F (hereafter referred to as "Subpart F"), and the permitting standards of 40 CFR Part 270. The Manual also provides guidance to owners and operators of treatment, storage, and disposal facilities (TSDFs) that are required to comply with the requirements of 40 CFR Part 264 Subparts J (Tank Systems), K (Surface Impoundments), L (Waste Piles), N (Landfills), and X (Miscellaneous Units). While sections of this Manual can be used as guidance for implementation of the ground-water monitoring regulations governing interim status facilities contained in 40 CFR Part 265, the methods and procedures presented in this Manual are designed for permitted facilities that are subject to the Part 264 regulations.

CHAPTER ONE

BACKGROUND AND SCOPE

The purpose of this Manual is to provide information that will assist facilities in conducting RCRA ground-water monitoring programs. Specifically, this Manual discusses techniques or procedures necessary to meet the requirements of the following sections of 40 CFR Parts 264 and 270:

- §264.97(a) - General performance standards for ground-water monitoring;
- §264.97(c) - Well casing and annular seal requirements;
- §264.97(d) - Sampling and analysis procedures;
- §264.97(e) - Appropriateness of sampling and analytical methods;
- §264.97(f) - Ground-water elevation measurements;
- §264.196(d)(3) - Geologic and hydrogeologic reports and the results of any monitoring or sampling, if applicable, that are submitted to the Regional Administrator in response to leaks or spills and disposition of leaking or unfit-for-use tank systems;
- §270.14(c) - Additional information requirements for Part B Permit Applications, and identification of the uppermost aquifer;
- §270.16(h)(1) - Hydrogeologic report for owners and operators of tank systems seeking a variance from design and operating requirements under §264.193(g);
- §270.17(b)(1) - Hydrogeologic report for owners and operators of surface impoundments seeking a variance from the design and operating requirements under §264.221(b);
- §270.18(c)(1) - Hydrogeologic report for owners and operators of waste piles seeking a variance from design and operating requirements under §264.251(b);

- §270.21(b)(1) - Hydrogeologic report for owners and operators of landfills seeking a variance from the design and operating requirements under §264.301(b); and
- §270.23(b) - Hydrogeologic and/or geologic assessments for owners and operators of miscellaneous units that are providing information to address and ensure compliance with the environmental performance standards of §264.601.

The Regional Administrator can, however, extend the Subpart F requirements to any corrective actions specified in the permit, including those initiated under §264.101(c).

1.1 Overview of Ground-Water Monitoring Programs Under Subpart F

Subpart F outlines a three-phase ground-water monitoring program for regulated units. "Detection monitoring," the first phase, involves at least semi-annual monitoring of parameters and/or constituents that provide a reliable indication of the presence of hazardous constituents in ground water. Detection monitoring is performed at permitted land based disposal units not believed to be releasing hazardous wastes or constituents into the ground water. If monitoring indicates a release, analysis of all Appendix IX constituents is required, and the facility enters "compliance monitoring."

Compliance monitoring, the second phase, requires at least semi-annual monitoring for those constituents detected in ground water during detection monitoring. A facility performing compliance monitoring also monitors ground water for all constituents on Appendix IX at least annually, and reports the concentration of any new compound detected to the Regional Administrator. Detected compounds are then added to the list of analytes monitored semi-annually. The concentrations of all compliance monitoring constituents are compared to their permitted concentration levels, one of the elements of the facility's ground-water protection standard, to determine whether or not corrective action is required.

If a unit in compliance monitoring contaminates the ground water above the allowable concentration set forth in the facility's permit, the unit enters "corrective action," the third phase of ground-water monitoring. In corrective action, a facility is required to "remove or treat in place" (§264.100(e)) all hazardous constituents that are detected in ground water at concentrations greater than their respective ground-water concentration limits specified in the facility's permit. The monitoring associated with corrective action tracks the progress of the clean-up and detects any other constituents entering the ground water at concentrations greater than the allowable concentration limits.

1.2 Relationship of this Manual to the Regulations and to Other Documents

The regulations in Subpart F and 40 CFR Part 270 will continue to be the primary location of the performance standards for ground-water monitoring, and the hazardous waste permit information requirements, respectively. This Manual serves to elaborate upon the applicable requirements and available options for meeting the performance standards. While directly applicable only to monitoring regulated units at permitted RCRA facilities, the contents of this Manual may provide useful guidance for other Agency ground-water monitoring programs as well, particularly municipal solid waste landfills regulated under 40 CFR Part 258, RCRA facilities that are in interim status (regulated under 40 CFR Part 265), RCRA facilities that are implementing the corrective action process for solid waste management units (40 CFR Part 264 §264.101), and hydrogeologic investigations at Superfund sites. The information contained in this Manual also could be useful for the design and operation of ground-water monitoring systems required by any regulatory program (e.g., Toxic Substances Control Act).

In September 1986 the Agency released two documents relating to RCRA ground-water monitoring: The RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (TEGD) and "Chapter Eleven - Ground-Water Monitoring" of EPA's manual titled Test Methods for Evaluating Solid Waste (USEPA 1986c, commonly known as "SW-846"). The TEGD was distributed by the Office of Waste Programs Enforcement (OWPE) and is the most recent USEPA guidance document that specifically addresses RCRA ground-water monitoring. The TEGD is presently available from the National Technical Information Service (703/487-4650) as document number PB87-107-751 and from the Government Printing Office (202/783-3238) as document number GPO:055-000-00-260-6. SW-846 is developed by the Office of Solid Waste and provides sampling and analysis methodology related to compliance with RCRA regulations. SW-846 is distributed through the Government Printing Office as document number GPO:955-001-00000-1 .

This Manual has been developed by the Agency to update and supplement information contained in the TEGD and Chapter Eleven of SW-846 to assist the regulated community in addressing the requirements Subpart F. The TEGD provides guidance for interim status facilities that have not received an operating permit and are thus subject to the requirements specified under 40 CFR Part 265. Whereas the TEGD was written primarily for the use of enforcement officials when implementing the interim status provisions, 40 CFR §265.90 et seq, this Manual was written to assist and direct owners and operators of permitted facilities in the design and implementation of ground-water monitoring programs. Although written for use by owners and operators of permitted facilities, Chapter Eleven of SW-846 was not intended to function as a comprehensive guide for ground-water monitoring; rather, it is a short listing of ground-water monitoring protocols.

The Agency recognizes that the science of ground-water monitoring is advancing and therefore, has issued this Manual to present viable new methodologies. Most of the hydrogeologic principles presented in the TEGD apply directly to permitted facilities as well as to those in interim status, and are the basis for much of the guidance presented in this Manual. Consequently, this Manual and the TEGD have a strong relationship and in certain cases may be used together to provide support for regulatory and facility owner/operator personnel. The contents of this Manual also are based on a review of the available open literature, and on other existing Agency and State enforcement and permitting guidance documents. In most cases, the procedures and methods presented in this Manual reflect technical findings presented in other Agency guidance documents. In a few cases, the weight of evidence in the open literature supports a deviation from the most recent Agency guidance. As a result, some of the procedures and recommendations included in the TEGD and in Chapter Eleven of SW-846 have been re-evaluated based on current scientific findings, and revised for inclusion in this Manual.

As stated previously, this Manual applies to permitted land disposal facilities operating under 40 CFR Part 264. The TEGD, Chapter Eleven of SW-846, and this Manual are, however, related thematically in terms of site characterization, monitoring well system design and installation, and sampling and analysis. To the extent that this Manual provides more current guidance on these ground-water monitoring activities, those individuals presiding over interim status facilities may wish to consult this Manual as a reference. In addition, the following documents are key references for this Manual and are readily available to the public:

- Aller, L., T.W. Bennett, G. Hackett, R.J. Petty, J.H. Lehr, H. Sedoris, D.M. Nielsen, and J.E. Denne. April 1989. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. EPA/EMSL-Las Vegas, USEPA Cooperative Agreement CR-812350-01, EPA/600/4-89/034, NTIS #PB90-159807.

- Barcelona, M.J., H.A. Wehrmann, M.R. Schock, M.E. Sievers, and J.R. Karny. September 1989. Sampling Frequency for Ground-Water Quality Monitoring. EPA Project Summary, EPA/600/S4-89/032, NTIS #PB-89-233-522/AS.

- Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske. September 1985. Practical Guide for Ground-Water Sampling. USEPA, Cooperative Agreement #CR-809966-01, EPA/600/2-85/104.

- USEPA. November 1991. Seminar Publication -- Site Characterization for Subsurface Remediation. EPA/625/4-91/026, 259 pp.

- USEPA. July 1991. Handbook -- Ground Water, Volume II: Methodology. EPA/625/6-90/016b.

- USEPA. September 1990. Handbook -- Ground Water, Volume I: Ground Water and Contamination. EPA/625/6-90/016a.

- USEPA. May 1989. RCRA Facility Investigation (RFI) Interim Final Guidance (4 vols). EPA/530/SW-89-031, OSWER Directive 9502.00-60, NTIS #PB89-200299.

- USEPA. December 1987a. A Compendium of Superfund Field Operations Methods. EPA/540/P-87/001.

Because the TEGD and the documents listed above are more comprehensive than this Manual, it may be necessary to refer to them when applying the procedures discussed herein.

CHAPTER TWO

DESCRIPTION OF APPROACH

This Manual describes procedures that the Agency believes are the most appropriate for designing, installing, and operating a detection monitoring system. This Manual also describes the basic approach that an owner/operator should take in designing a detection monitoring program. Figure 1 outlines this basic approach. Briefly, the steps are as follows:

STEP 1 Define the data that are required from a regulatory perspective, and develop technical objectives to meet those requirements (Chapter Three).

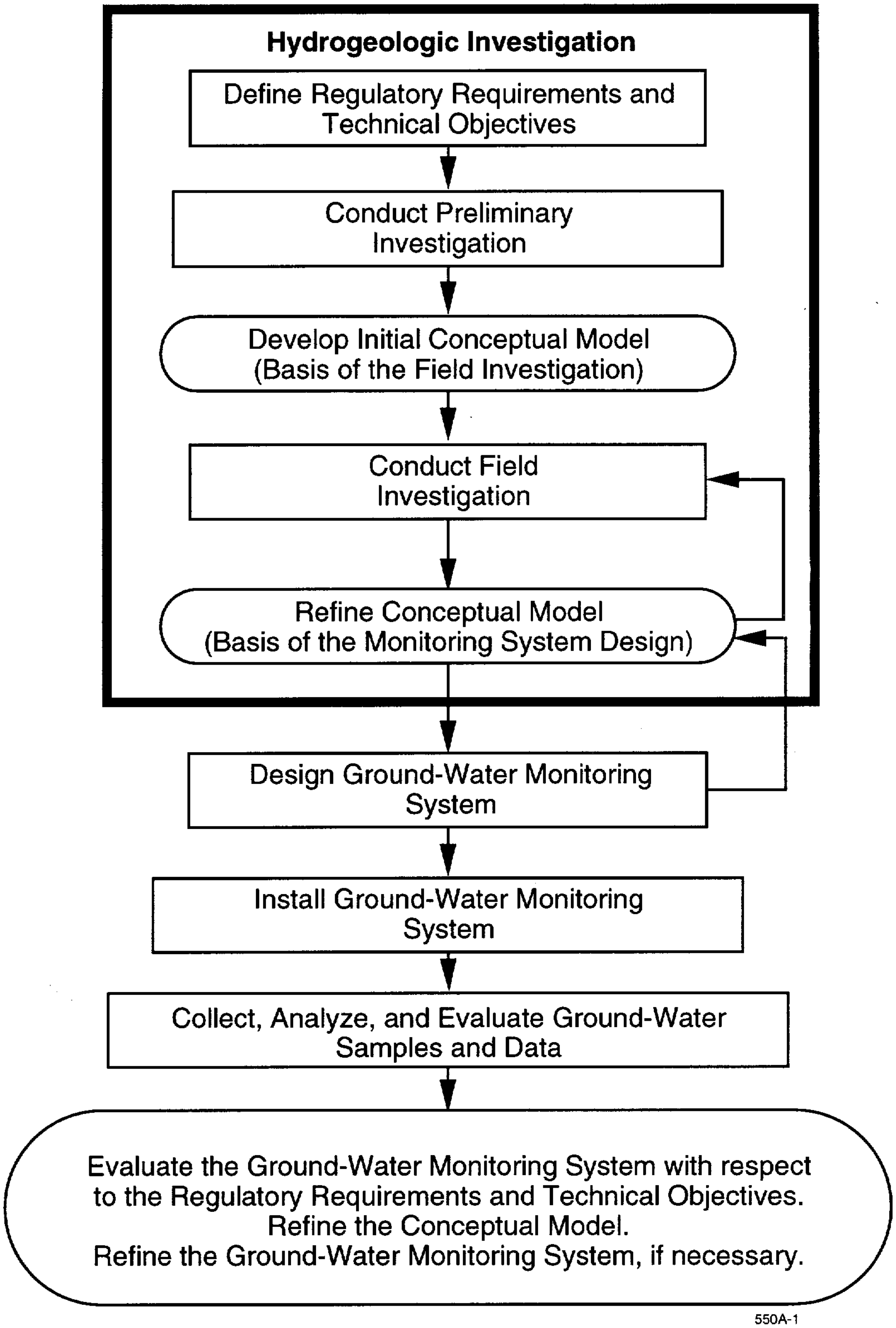
Steps 2, 3, 4, and 5 are considered the hydrogeologic investigation for the site (Chapter Four).

STEP 2 Perform a preliminary investigation. The preliminary investigation is a comprehensive review of existing information relating to the site. This includes a thorough review of available literature and, if available, existing field data. The purpose of the preliminary investigation is to characterize, to the extent possible, the hydrogeology of the region and the site, and to gather information that will be useful in planning field investigations. The preliminary investigation also includes characterizing the chemical and physical properties of the wastes or constituents of concern to the extent that this information is available.

STEP 3 Develop, using regional and site-specific data, a conceptual model of site hydrogeology. The conceptual model should be based on the regional hydrogeology and on the preliminary investigation, and should be used as the basis for designing field investigations at the site.

STEP 4 Perform field investigations at the site. The field investigations will include one or more of the following techniques:

- Subsurface boring programs;
- Laboratory analyses of soil, unconsolidated material, and rock samples;
- Geologic and hydrogeologic analyses;
- Mapping programs;
- Electric cone penetrometer surveys; and



STEPS IN DESIGNING A GROUND-WATER MONITORING SYSTEM

FIGURE 1

- Geophysical surveys.

STEP 5 Continue to develop and refine a conceptual model of the site based on the field investigations. The conceptual model will form the basis for the design of the ground-water monitoring system. The conceptual model should be based on information of sufficient amount and quality to ensure that the monitoring system will fulfill the established regulatory requirements and technical objectives. The quantity of data required will vary with the hydrogeologic complexity of the site. Facilities located in complex hydrogeologic settings require more hydrogeologic data than facilities located in less complex settings.

STEP 6 Design a detection monitoring system consisting of both downgradient monitoring wells that intercept and monitor the potential pathways of contaminant migration, and background (e.g., upgradient) monitoring wells that provide representative samples of background ground-water quality (Chapter Five).

STEP 7 Install downgradient monitoring wells and background (e.g., upgradient) monitoring wells (Chapter Six).

STEP 8 Collect and analyze ground-water samples from downgradient and background monitoring wells (and from springs or the vadose zone, when appropriate) at the frequency specified in the facility permit (Chapter Seven).

STEP 9 Evaluate the ground-water monitoring system with respect to the regulatory requirements, the technical objectives, and the accuracy of the conceptual model. Refine the ground-water monitoring system, if necessary (Chapter Six).

Each of the steps presented in Figure 1 is discussed in detail in the sections of the Manual noted. The Manual does not discuss the statistical evaluation of ground-water monitoring data. Guidance for the statistical evaluation of ground-water monitoring data is presented in EPA's April 1989 publication entitled "Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities - Interim Final Guidance" (USEPA, 1989a) and any subsequent addenda to this publication.

The approach described above relies heavily on the development and refinement of conceptual models. A conceptual model is an understanding of the hydrogeologic characteristics of a site, and of how the hydrogeologic characteristics are integrated into a hydrogeologic system that contains interacting and dynamic components. The Agency strongly emphasizes that the process of developing a conceptual model of a site is ongoing. After a ground-water monitoring system has been installed and numerous ground-water samples have been collected, the conceptual model for a site may be further refined.

CHAPTER THREE

DEFINING REQUIREMENTS AND TECHNICAL OBJECTIVES

One of the most important steps in the design and implementation of a ground-water monitoring program is defining the data, analyses, and information that are required from a regulatory standpoint. The next step is to develop technical objectives to meet those requirements. Once requirements are identified and objectives are developed, the owner/operator should thoughtfully consider the activities necessary to achieve the requirements and objectives. One of the keys to implementing a successful monitoring program is planning activities that logically progress to obtain the desired information.

3.1 Defining Requirements

As stated previously, owners and operators of TSDFs are required to comply with both the ground-water monitoring regulations contained in Subpart F and with the permitting standards of 40 CFR Part 270 Subpart B. This Manual is also applicable to owners and operators of TSDFs who are required to comply with 40 CFR Part 264 Subparts J (Tank Systems), K (Surface Impoundments), L (Waste Piles), N (Landfills), and X (Miscellaneous Units) when preparing hydrogeologic reports for various regulatory purposes. For owners and operators of TSDFs, the initial step in conducting a ground-water monitoring program should be to define the regulatory requirements with which they are required to comply.

The sources of applicable requirements will depend on whether a facility is designing a proposed ground-water monitoring program to submit with its permit application, or is already permitted and is designing a program or a portion of a program in response to a permit requirement. In the latter case, under the permit-as-a-shield provision of 40 CFR §270.4, the permit will contain, either expressly or by reference, all of the applicable requirements. In the former case, the program should comply with all applicable regulatory requirements of Parts 264 and 270 (or with applicable State regulations in an authorized State, along with any applicable EPA regulations promulgated under the authority of the Hazardous and Solid Waste Amendments of 1984 (HSWA) which the State is not authorized to administer). The requirements and objectives of a facility’s hydrogeological investigations and/or ground-water monitoring programs should always be discussed with the appropriate EPA representative prior to initiating any activities.

3.2 Defining Technical Objectives

In a broad sense, technical objectives are the data or information that the owner/operator wants to obtain. Technical objectives are typically developed to satisfy regulatory requirements. This Manual discusses the basic data necessary for meeting the performance standards for the design and implementation of a RCRA ground-water monitoring program. Performance standards, rather than specifications, are set forth in Subpart F because of the diversity of the environmental settings in which regulated units exist, and because of the need to tailor monitoring systems to fit each setting. While this is still the philosophy behind the regulations, the Agency has found through experience that it is necessary to provide specific protocols to guide the implementation of some portions of the ground-water monitoring regulations. This Manual presents protocols that correspond to the following areas: 1) a comprehensive review of existing information (Chapter Four); 2) the characterization of site hydrogeology, particularly the hydrogeology of the uppermost aquifer (Chapter Four); 3) choosing ground-water monitoring locations (Chapter Five); 4) well design and construction (Chapter Six); and 5) sample collection and analysis (Chapter Seven).

3.3 Data Quality Objectives for RCRA Ground-Water Monitoring

Inherent in the development of technical objectives is the determination of what quality of data is required or desired. Chapter One of SW-846 addresses Quality Assurance (QA) programs and Quality Control (QC) procedures that should be implemented by owners and operators who are conducting ground-water monitoring programs pursuant to RCRA. Chapter One of SW-846 states that it is the goal of EPA's QA program to ensure that all data be scientifically valid, defensible, and of known precision and accuracy. Data should be of sufficient known quality to withstand scientific and legal challenges relative to the use for which the data are obtained. The QA program is management's tool for achieving this goal.

All activities implemented pursuant to Subpart F (i.e., hydrogeologic site investigations, design and installation of ground-water monitoring wells, sampling, and sample analysis) should include a QA and QC program as required by §264.97(e). The QA/QC programs should be part of the facility permit application (§§270.14(c)(5), 270.14(c)(6)(iv) and 270.14(c)(7)(vi)) and operating record (§264.97(e)). QA/QC programs should meet the specifications of Chapter One of SW-846.

Chapter One of SW-846 defines fundamental elements of a data collection program:

1. Design of a project plan to achieve the data quality objectives (DQOs);

2. Implementation of the project plan; and

3. Assessment of the data to determine if the DQOs are met.

DQOs for the data collection activity describe the overall level of uncertainty that a decision-maker is willing to accept in results derived from environmental data. This uncertainty is used to specify the quality of the measurement data required, usually in terms of objectives for precision, bias, representativeness, comparability, and completeness. As described in Chapter One of SW-846, the owner/operator should define the DQOs prior to the initiation of the field and laboratory work. Also, the owner/operator should inform the field and laboratory organizations performing the work of the DQOs so that their personnel may make informed decisions during the course of the project to attain those DQOs. The procedures that an owner/operator uses to characterize the hydrogeology of a site, to design and construct a monitoring network, to collect and analyze environmental samples, and to evaluate analytical results should ensure that the data are of the type and quality necessary to allow for the detection of contamination when hazardous waste or hazardous constituents have migrated from the waste management area to the uppermost aquifer (§264.97(a)(3)).

EPA is using DQOs to define the type and quality of data required to support specific regulatory decisions. DQOs include both qualitative and quantitative data performance specifications. The type of data required is defined by a set of qualitative specifications that indicate the characteristics of the environment to be measured and the circumstances such measurements are intended to represent. The quality of data required may be specified in two ways: 1) qualitatively, as a set of procedures to follow for collecting data, or 2) quantitatively, as the amount of error (imprecision and bias) that may be tolerated in data without incurring an unacceptable probability of making incorrect or inappropriate decisions. This Manual represents a qualitative specification of data quality, requiring that certain procedures be followed when collecting hydrogeologic data. All projects that generate environmental data in support of RCRA should have a QA Project Plan (QAPjP). The recommended components of a QAPjP are provided in Chapter One of SW-846.

Field and laboratory operations should be conducted in such a way as to provide reliable information that meets the DQOs. To achieve this, certain minimal practices and procedures should be implemented, as outlined in Chapter One of SW-846. The applicable ground-water monitoring regulations contained in 40 CFR Parts 264 and 270 outline additional required practices and procedures. In addition, Chapter One of SW-846 specifies the information that should be contained in project documentation. Moreover, both this Manual and the TEGD provide supplemental information and guidance for conducting field operations.

CHAPTER FOUR

CHARACTERIZING SITE HYDROGEOLOGY

The adequacy of a ground-water monitoring program largely depends upon the quantity and quality of the hydrogeologic data used in designing the program. Clearly, if the design of the monitoring well system is based on incomplete or inaccurate data, the system will not fulfill its intended purpose. Because of the complexity of site characterization and ground-water monitoring system design, owner/operators should discuss the intended approach with the appropriate State or EPA Regional office prior to finalizing site characterization plans.

When characterizing the hydrogeology of a site prior to designing a monitoring well network, owner/operators should be concerned with questions relating to data quantity and quality:

(1) Has enough information been collected to identify and adequately characterize the uppermost aquifer and potential contaminant migration pathways? Does the information allow for the placement of monitoring wells that are capable of immediately detecting releases from the regulated unit(s) to the uppermost aquifer?

(2) Have appropriate techniques been used to collect and interpret the information that will be used to support the placement of monitoring wells, and is the quality and the interpretation of the information satisfactory when measured against the program's DQOs?

The answers to these questions will establish whether or not the site characterization is adequate. The Agency recognizes that the quantity of site characterization information and the appropriateness of investigation techniques vary according to site-specific conditions. Sites in complex geologic settings require more hydrogeologic data for ground-water monitoring system design than do sites in less complex settings. Likewise, investigatory techniques that may be appropriate in one geologic setting or for one waste type, may be inappropriate in another setting or for a different waste type.

This section identifies techniques that can be used to characterize a site prior to installing a monitoring well network, and describes the factors that should be considered when evaluating whether a particular method is appropriate in a specific case.

Table 1 lists a number of investigatory techniques commonly used to conduct hydrogeologic investigations. Also listed are preferred methods for presenting the data generated from a hydrogeologic investigation. Many States and Regions also may request or

TABLE 1
TECHNIQUES FOR HYDROGEOLOGIC INVESTIGATIONS

Investigatory Tasks	Investigatory Techniques	Data Presentation and Data Reduction
Characterization of Subsurface Materials (Geology)	• Review of existing geologic information • Subsurface boring (rock, unconsolidated materials, soils): lithologic and pedologic classification of samples of subsurface materials, standard penetration or soil density tests • Laboratory analyses of subsurface samples (e.g., grain size (sieve) analyses, permeability, cation exchange capacity, organic content, atomic absorption spectroscopy, x-ray diffraction, Atterberg limits) • Geophysical techniques (surface and borehole) • Mapping -- topography, geology, soil • Cone penetrometer surveys • Aerial photography • Ground-water modelling	• Narrative summary of site geology • Narrative summary of site geochemistry • Stratigraphic column • Geologic cross sections • Topographic maps (1":200' scale) that show all features required by §270.14(b)(19) • Geologic maps (1":200' scale) • Soil maps (1":200' scale) • Boring and/or coring logs • Structure contour maps • Isopach maps • Raw data and interpretive analysis of surface and borehole geophysical studies • Raw data and interpretive analysis of materials tests • Aerial photographs • Results of modelling efforts

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1. Topographic maps are required to fulfill the permiting requirements of §270.13(l) and §270.14(b)(19), however, they may be available from other sources.
2. Aerial photography may be required to satisfy the permiting requirements of §270.13(h) and §270.14(b)(11).

TABLE 1

TABLE 1
TECHNIQUES FOR HYDROGEOLOGIC INVESTIGATIONS (continued)

Investigatory Tasks	Investigatory Techniques	Data Presentation and Data Reduction
Characterization of Ground-Water Flow (Hydrogeology) and Ground-Water Chemistry	• Review of available hydrologic information • Water levels measured in piezometers and wells • Aquifer tests (slug tests, pump tests, packer tests, flowmeters) • Vadose zone monitoring • Tracer studies • Ground-water quality analyses (see §265.92(b)) • Meteorological and climatological data gathering • Surface water chemistry and flow data	• Narrative summary of hydrology and hydrogeochemistry • Piper, Stiff and other geochemical diagrams • Hydrogeochemical maps • Water table and potentiometric surface maps (1":200' scale) • Maps of recharge and discharge areas • Horizontal and vertical flow nets • Fracture trace maps • Maps of flow routes in karst terranes • Hydrographs • Estimates of hydraulic conductivity, hydraulic gradient, rate of ground-water flow • Raw data and interpretive analysis of aquifer tests

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TABLE 1 (CONTINUED)

require that all data be submitted in a computer-readable form. If the level of site characterization necessary to design a RCRA ground-water monitoring program is sufficient, it will be possible to obtain the information listed in the last column of the table. This information ultimately will be used to develop a conceptual model of the site prior to designing the ground-water monitoring system.

At a minimum, the site investigation should always include direct methods of determining site hydrogeology (e.g., subsurface borings, water level elevation measurements, textural analysis of soil samples). Indirect methods (e.g., aerial photography), especially geophysical methods (e.g., resistivity and seismic surveys), may provide valuable information for planning direct field measurements. Information obtained by indirect methods also can be used in conjunction with information obtained by direct techniques to interpolate geologic data between points where direct measurements are made. Information gathered by indirect methods alone will not provide the detailed information necessary for complete characterization of a site, however. Conclusions drawn from indirect site investigation methods (e.g., geophysical surveys, aerial photography) should be confirmed by, and correlated with, direct measurements. Lithologic data obtained from cone penetrometer (CPT) surveys should be compared with lithologic information obtained from adjacent conventionally-drilled and sampled boreholes to verify the CPT results. When geophysical surveys are used to characterize a site, information from geophysical surveys should be used in conjunction with other physical data both to verify the initial interpretations of the geophysical methods and to provide constraints to remove some of the non-uniqueness of the geophysical data.

A site investigation should include characterization of:

- The subsurface materials below the owner/operator’s hazardous waste facility, including:
  - The lateral and vertical extent of the uppermost aquifer;
  - The lateral and vertical extents of upper and lower confining units/layers;
  - The geology at the owner/operator’s facility (e.g., stratigraphy, lithology, structural setting); and
  - The chemical properties of the uppermost aquifer and its confining layers relative to local ground-water chemistry and hazardous wastes managed at the facility, as it relates to the parameters specified in 40 CFR Part 265.

- Ground-water flow below the owner/operator’s hazardous waste facility, including:
    - The vertical and horizontal directions of ground-water flow in the uppermost aquifer;
    - The vertical and horizontal components of hydraulic gradient in the uppermost aquifer;
    - The hydraulic conductivities of the materials that comprise the uppermost aquifer and its confining units/layers; and
    - The average linear horizontal velocity of ground-water flow in the uppermost aquifer.

The following sections outline the basic steps of a site hydrogeologic characterization, and detail methods for collecting and presenting data.

4.1 Preliminary Investigation

The preliminary investigation is a comprehensive review of the available information relating to the site. The preliminary investigation has two purposes: (1) to allow the owner/operator to formulate conceptual models of regional and site-specific hydrogeology, and (2) to provide a basis for designing field investigations that will be used to obtain data to refine the conceptual model of the site. This investigation should be performed prior to conducting a field investigation and designing and installing a ground-water monitoring system.

The owner/operator should review the available information about the hydrogeology of the site and the surrounding region to gain an understanding of the stratigraphic distribution of soil, unconsolidated materials, and rock, and of the surface and ground-water systems. The preliminary investigation should include the review of the following information, as available:

- The waste management history of the site, including:
    - A chronological history of the site that includes a description of the wastes and raw materials managed (treated, stored, or disposed) on-site;
    - A summary of documented releases from waste, product, or materials management/storage areas;

  - Information concerning the structural integrity of waste management units and physical (e.g., structural) controls on waste migration from the units; and

  - The chemical composition and character of wastes contained in waste management units throughout their history, and those wastes expected to be contained in the units in the future (e.g., waste analyses, leachate analyses, leachate generation rates, percent solids, and the past, present, and expected future chemical interaction of the waste and the geologic and soil units underlying the waste).

- Information obtained from a literature review, including:

  - Reports of academic research (e.g., dissertations and theses) performed in the area of the site or for the same aquifer(s) at the site;

  - Journal articles;

  - Studies, reports, or literature from local or regional offices, such as local water offices, planning commissions, and health departments;

  - Studies and reports provided by state geologic surveys or state water or environmental offices; and

  - Studies and reports obtained from Federal offices, such as the U.S. Geological Survey (USGS).

- Reports of previous investigations performed at the facility, or nearby facilities (e.g., the results of any previous sampling and analysis efforts).

- Climatic data, including precipitation, wind (direction and velocity), and evapotranspiration data.

- Topographic, geologic, soil, hydrogeologic, geohydrochemical, fracture trace, and conduit maps and aerial photographs.

- Other readily available information, for example:

  - Records documenting local influences on ground-water flow (e.g., on- or off-site pumping wells, irrigation or agricultural use, tidal variations, river stage variations, land use patterns, local waste disposal practices);

- Geologic and environmental assessment data available in state and Federal project reports for local dams, highways, subway systems, and other major construction projects;

- Logs from local private or public water supply wells; and

- Logs from building construction and quarry activities.

Appendix 4 provides a comprehensive list of sources of information that may be consulted during the preliminary investigation stage of the hydrogeological investigation. Information collection activities should be supplemented by a site reconnaissance to substantiate concepts developed from the preliminary investigation and to help identify problems that require resolutions during subsequent site investigation activities.

A properly conducted preliminary investigation is necessary for planning the direction and scope of subsequent field investigations. For example, information on stratigraphy, depositional environment, and tectonic history can be used to estimate the distribution and types of geologic materials likely to be encountered at the site. Topographic maps can assist in defining the locations of recharge or discharge areas, such as lakes, swamps, springs, and streams, and the locations of faults or fractures as indicated by surface drainage patterns. Geologic maps depict the locations of geologic contacts and provide the lithology of geologic units, as well as depicting the locations of faults, fractures, and folds. Information on regional ground-water flow rates and directions, depth to ground water, potentiometric surface elevations, water quality and chemistry, local ground-water pumping, evapotranspiration rates, transmissivities, storativities, and surface water hydrology allows for an effective first approximation of the site-specific hydrogeologic setting.

The owner/operator should develop a preliminary conceptual model of the site based on the information collected during the preliminary investigation. The conceptual model should incorporate all essential features of the system under study, and should be tailored to the amount, quality, and type of information available at each stage of the investigation. This model is an essential element for planning the subsequent field investigation (e.g., the initial placement of boreholes) and should be revised and updated as additional information becomes available and as new interpretations are made. A final conceptual model, incorporating the information collected during the site characterization activities described in the following section, is essential for designing an adequate detection monitoring system.

4.2 Characterizing the Geology of the Site

After completion of the preliminary investigation, subsurface samples (e.g., soil samples, unconsolidated material samples, rock borings) should be collected and lithologically or pedologically classified so that the lithology, stratigraphy, and structural characteristics of the subsurface are identified. As stated previously, indirect methods of geologic investigation such as geophysical studies may be used to plan and augment direct field methods, but should not be used as a substitute for them.

4.2.1 Subsurface Boring Program

All hydrogeological site investigations should include a subsurface boring program to identify the lithology, stratigraphy, and structural characteristics of the subsurface. Information obtained from boreholes is necessary to characterize the subsurface at a site and to identify potential contaminant migration pathways.

A subsurface boring program should be designed as follows:

- The initial number of boreholes and their spacing should be based on information obtained during the preliminary investigation and on the spatial orientation of the waste management units. Initial boreholes should be drilled to provide sufficient information to determine the scope of a more detailed evaluation of geology and to identify potential contaminant migration pathways. Boreholes should be spaced closely enough so that accurate cross-section(s) can be constructed. Factors that influence the initial number of borings are listed in Table 2.

- Additional boreholes should be drilled as needed to provide more information about the site and to refine the conceptual model. The number and placement of additional boreholes should be based on a preliminary conceptual model that has been refined with data obtained from initial boreholes and other site investigatory techniques (e.g., geophysical investigations).

- Samples should be collected from boreholes at all suspected changes in lithology. The deepest borehole drilled at the site should be continuously sampled. For boreholes that will be completed as monitoring wells, at least one sample should be collected from the interval that will be the monitoring well intake interval (i.e., screened interval or open (uncased) interval). EPA recommends that all borings be continuously sampled to obtain good stratigraphic control.

- All borehole samples should be collected with a Shelby tube, split barrel sampler, rock corer, or other appropriate device.

- Borehole samples should be classified according to their lithology or pedology by an experienced geologist. Owner/operators should ensure that samples of every geologic formation, especially all confining layers, are collected and described, and that the nature of stratigraphic contacts is determined. EPA recommends that owners/operators take color photographs (with scale) of

TABLE 2
FACTORS INFLUENCING THE DENSITY OF BOREHOLES

Factors That May Substantiate Reduced Density of Boreholes	Factors That May Substantiate Increased Density of Boreholes
• "Simple" geology (e.g., horizontal, thick, homogeneous geologic strata that are continuous across site and are unfractured) substantiated by site-specific geologic information • Use of electric cone penetrometer surveys with additional tools, i.e., d.c. resistivity, sampling • Use of surface geophysical methods to correlate hydrogeologic data between bore- holes. Suggested methods: d.c. resistivity, seismic refraction and reflection, electro- magnetic induction, and ground penetrating radar • Use of surface to borehole and cross borehole geophysical methods to interpret complex subsurface geological structure. Suggested methods: d.c. resistivity, seismic refraction and reflection, electromagnetic induction, and ground penetrating radar	• Fracture zones, conduits in karst terranes • Suspected pinchout zones (i.e., discontinuous strata across the site) • Tilted or folded geologic formations • Suspected zones of high hydraulic conductivity that would not be defined by drilling at large horizontal intervals • Laterally transitional geologic units with irregular hydraulic conductivity (e.g., sedimentary facies changes)

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representative samples from the boring. Where boreholes are drilled or cored through fractured rock, the boreholes, cores, or samples should be used to determine the orientation of the fractures. Keys and MacCary (1971) and Keys (1988) discuss the application of borehole geophysics to fracture characterization.

- Geophysical techniques can be used to plan and supplement the subsurface boring program. For example, surface geophysical surveys may be used to verify and modify the initial conceptual model prior to drilling boreholes. Based upon the results of the geophysical surveys, boreholes can be effectively located to obtain necessary hydrogeologic information. Information obtained from initial boreholes can be used to evaluate the geophysical data and resolve any ambiguities associated with the preliminary interpretation of the geophysical survey results. When continuous sampling is not performed, borehole geophysical methods should be used to correlate unsampled with sampled core sections. The use of surface to borehole geophysical methods may allow better resolution of geophysical and borehole data, and may help delineate the subsurface geology between boreholes.

- Any borehole that will not be completed as a monitoring well should be properly decommissioned. When considering the installation of ground-water monitoring wells in the vicinity of decommissioned boreholes, owners and operators should ensure that borehole sealant materials (e.g., cement) will not alter the chemistry of the ground water to be monitored.

The objective of a subsurface boring program is to begin to refine the broad, conceptual model derived during the preliminary investigation to better reflect the true site-specific hydrogeologic conditions. In other words, the boring program is necessary to directly investigate and to describe the geology of the area beneath the facility, and place it in the context of the regional geologic setting.

In some situations, it may be necessary to drill through actual or possible confining layers at a site. Special precautions should be taken when investigators believe they may encounter a confining layer during drilling. Moreover, if field personnel suspect they may have encountered a possible confining layer while drilling a borehole, drilling should be stopped immediately and the borehole should be decommissioned. Investigators, in conjunction with the appropriate regulatory authority, may then develop an appropriate method for drilling through the confining layer. Extreme care should be taken when drilling into confining units so that the borehole does not create a pathway for the migration of contaminants, particularly dense non-aqueous phase liquids (DNAPLs), between upper and lower hydraulically separated saturated zones. In all cases, owners and operators should prevent DNAPL mobilization (e.g., through gravity-driven transport) when drilling boreholes.

Owners and operators should obtain approval from the Regional Administrator prior to implementing a plan to drill through a possible confining layer.

There are at least two approaches for drilling through confining layers. Based on site-specific conditions, one or both of these approaches may be appropriate:

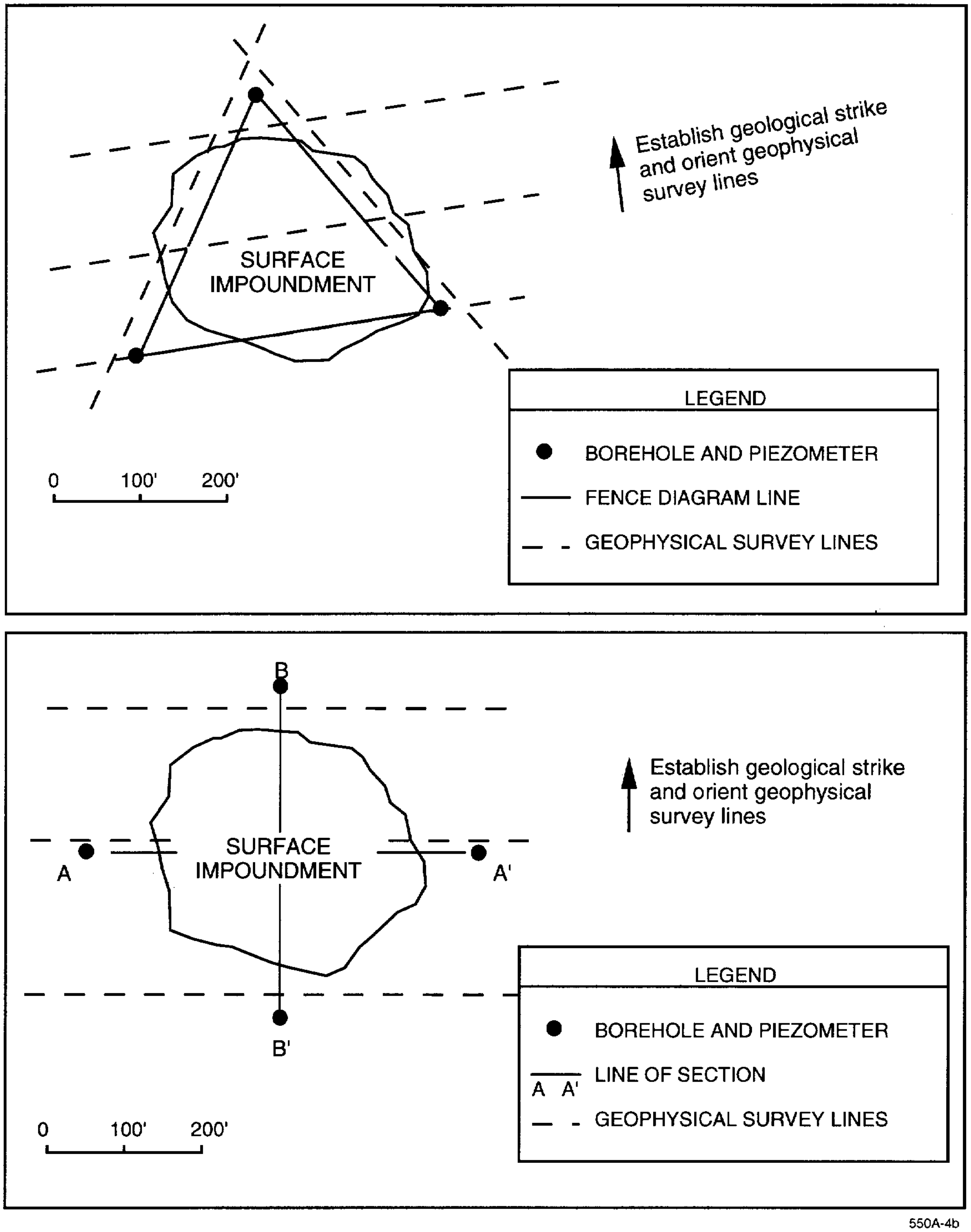
- Install the first boreholes on the perimeter of the site (in less contaminated areas or uncontaminated areas). The initial boreholes could penetrate the confining zone to allow characterization of the lower units. This approach is essentially to monitor from the "outside in." At a minimum, boreholes upgradient of the source (and upgradient of a DNAPL and/or dissolved-phase plume) could be drilled through the possible confining layer to characterize the geology of the site. The appropriateness of this approach should be evaluated on a site-specific basis (e.g., DNAPLs may migrate in directions different from ground-water flow).

- Drill the boreholes using techniques that minimize the danger of cross-contamination between water-bearing zones. Such techniques typically involve drilling an initial borehole partially into the possible confining layer, installing (grouting in) an exterior casing, emplacing grout in the cased portion of the borehole, and drilling a smaller diameter hole through the cased off/grouted portion of the borehole (i.e., telescoping casing) through the confining layer. Millison et al. (1989) provide an example of the use of telescoping casing to prevent cross-contamination of aquifers. The appropriateness and actual design of telescoping borings and casings should be determined on a site-specific basis. Telescoping boreholes may be completed as wells or piezometers.

A subsurface boring program usually requires more than one round of borehole installation. The number, placement, and depth of initial borings should be planned to provide sufficient information upon which to plan a more detailed site characterization. An example of a simple boring program is illustrated in Figure 2. If characterization is largely achieved with the initial placement, fewer additional boreholes and fewer additional indirect investigations will be necessary. In most cases, however, the Agency believes that additional boreholes will be necessary to complete the characterization because most hydrogeologic settings are relatively complex, even to experienced ground-water scientists. Figure 3 illustrates how subsequent borings and supplementary indirect techniques can be added to an initial boring configuration to characterize the site-specific geology.

Drilling logs and field records should be prepared detailing the following information:

- The lithology or pedology (i.e., geologic or soil classification) of each geologic and soil unit in the unsaturated and saturated zones, including the confining layer. The classification system used for lithologic and pedologic descriptions



POSSIBLE BOREHOLE CONFIGURATIONS FOR A SMALL SURFACE IMPOUNDMENT

FIGURE 2

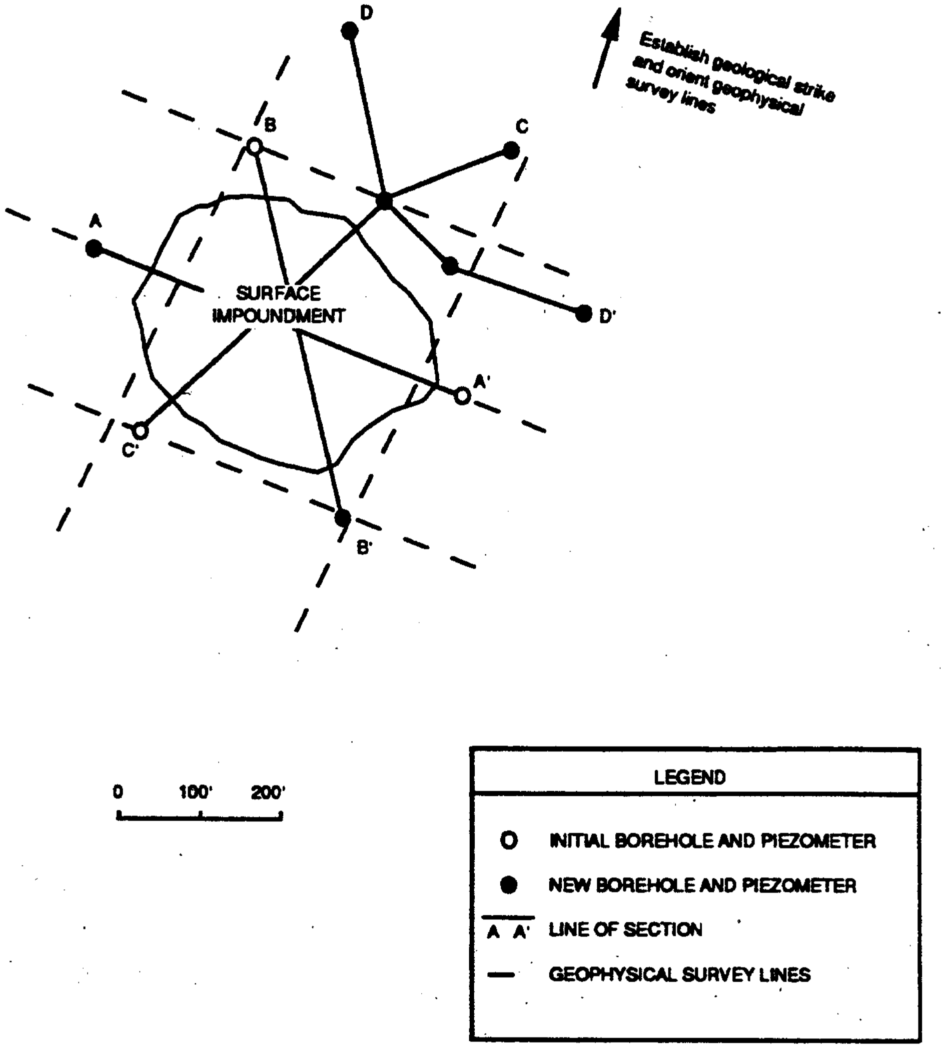

D
Establish geological strike and orient geophysical survey lines
B
C
A
SURFACE IMPOUNDMENT
D'
A'
C'
B'
0
100'
200'
LEGEND
○ INITIAL BOREHOLE AND PIEZOMETER
● NEW BOREHOLE AND PIEZOMETER
A A' LINE OF SECTION
— GEOPHYSICAL SURVEY LINES

FIGURE 3

should be a system described in the literature, and should be summarized or referenced in the permit application. For example, soils may be described using the Unified Soil Classification System, and rock may be described using the classification schemes of Dunham (1962) for carbonates, Pettijohn et al. (1972) for sandstones, Potter et al. (1980) for shales, and the common textural and compositional classification schemes for igneous and metamorphic rock (e.g., rhyolite, granite, basalt, schist, slate, marble, gneiss, etc.). Examples of these classifications schemes are presented in Appendix 2;

- Descriptions of the structural features encountered. As applicable, this should include a description of planar features (e.g., bedding planes, graded bedding), lineations, and other features related to vegetation, and discontinuities. The orientation of these features should be measured and described when possible;
- Moisture content (saturated, moist, dry), degree of weathering, color (referenced to standardized colors when possible (e.g., Munsell color for moist soil and unconsolidated materials)), and stain (e.g., presence of mottles, Fe_20_3), as applicable;
- If a field monitoring device (e.g., FID, PID) is used, the data from these measurements, including sampling method, background and sample concentrations, probe type, span setting, and calibration gas type and concentration, should be provided to EPA as part of the boring log or field record;
- Depth to the water table;
- Depth to water-bearing unit(s) and vertical extent of each water-bearing unit;
- Depth of borehole and reason for termination of borehole;
- Depth, location, and identification of any evidence of contamination (e.g., odor, staining) encountered in borehole;
- Observations made during drilling (e.g., advance rate, water loss); and
- Observations made during soil, unconsolidated material, or rock sampling (e.g., blow counts, sample recovery).

The subsurface boring log should contain at least the information identified with an "X" in Table 3. Aller et al. (1989) provide an example format for a field boring log.

TABLE 3
FIELD BORING LOG INFORMATION

General

x *Project (facility) name*
x *Hole name/number*
x *Date started and finished*
x *Geologist's name*
x *Driller's name*
- Sheet number

x *Hole location; map and elevation (surveyed)*
x *Rig type, bit size/auger size, hammer type*
x *Sampling equipment used*
x *Classification scheme used for soils (e.g., USDA textural classification system, or unified soil classification system)*
x *Classification scheme used for rocks (see Appendix 2 for examples)*

Information Columns

x *Depth of borehole*
x *Sample depth/number/type*
x *Blow counts and advance rate*
x *Percent sample recovery*
x *Narrative description*
x *Depth to saturation (nearest 0.01 foot)*

Narrative Description

- Geologic Observations (include depth, description):

x *soil/unconsolidated material/rock type*
x *color and stain*
x *texture*
x *gross petrology*
- friability

x *moisture content*
x *degree of weathering*
x *presence of carbonate minerals*
x *fractures*
x *solution cavities*
x *bedding, formation boundaries*
x *discontinuities: e.g., foliation*
x *water-bearing zones*
x *dip of bedding, foliations, etc.*
- fossils, with a taxonomic identification (i.e., brachiopod, trilobite, etc.)

x *sedimentary structures*
x *presence of organic matter*
x *odor*
x *suspected contaminants*

- Drilling Observations:

x *loss of circulation*
x *advance rates*
- rig chatter

x *depth to water table or saturation*
x *drilling difficulties*
x *changes in drilling method or equipment*
x *readings from detective equipment, if any*
x *amount of water yield or loss with depth*
x *amounts and types of any drilling fluids used*
x *presence of running sands*
x *caving/hole stability*
x *reason for termination of borehole*

- Other Remarks:

- equipment failures

x *possible contamination of soil/groundwater*
x *deviations from drilling plan*
x *weather*

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x Indicates items that the owner/operator should record, at a minimum.

4.2.2 Laboratory Analyses of Soil, Unconsolidated Material, and Rock Samples

In addition to the field descriptions outlined above, the owner/operator should conduct, where necessary, laboratory analyses of each significant geologic unit and each soil zone in the unsaturated and saturated zones. These analyses can provide the following information:

- Mineralogy and chemistry of the aquifer and confining units or layers, as determined by optical and analytical techniques (e.g., microscopic analysis and other analyses such as cation exchange capacity, atomic absorption spectroscopy, inductively coupled plasma atomic emission spectroscopy, and X-ray diffraction). In some circumstances, such as where high concentrations of solvents may come into contact with a clay confining layer, it is important to characterize the clay mineralogy accurately;

- Petrographic analysis of the confining layer and each unit above the confining unit/layer to determine petrology and petrologic variation including:

    - composition and degree of cementation of the matrix,

    - composition, degree of sorting, size fraction, and textural variation in the framework grains, and

    - existence of small-scale structures that may affect fluid flow;

- Moisture content and moisture variation of each significant soil zone and geologic unit;

- An estimate of hydraulic conductivity of each significant soil, unconsolidated material or rock unit in the unsaturated zone as determined by constant head and falling head laboratory permeability tests on core samples that have been collected in a manner that minimizes sample disturbance. The results of laboratory hydraulic conductivity tests should be evaluated and used carefully because these tests may not quantify secondary permeability factors that are important in contaminant migration;

- General composition of the sample as determined by examination of unconsolidated materials with a binocular microscope;

- Particle size analyses of unconsolidated or poorly consolidated samples using sieves and/or pipettes to determine gravel-sand-silt-clay content and the size range of sand and silt particles.

Table 4 lists these and other suggested methods for laboratory analysis of soil, unconsolidated materials, and rock samples. Laboratory methods for determining the properties of subsurface samples are provided by ASTM, and by both the American Society of Agronomy and the Soil Science Society of America.

4.2.3 Mapping Programs

Subsequent to the generation and interpretation of site-specific geologic data, the data should be presented in geologic cross-sections, topographic maps, geologic maps, and soil maps. The Agency suggests that owners/operators obtain or prepare and review topographic, geologic, and soil maps of the facility, in addition to site maps of the facility and waste management units. In cases where suitable maps are not available, or where the information contained on available maps is not complete or accurate, detailed mapping of the site should be performed by qualified and experienced individuals.

Although topographic coverage of the entire United States is available through the U.S. Geological Survey (USGS), owners and operators may find that detailed or smaller-scale topographic information is not directly available for their facility. Many facilities have been successful in preparing topographic maps, or altering or updating existing topographic maps (such as those obtained from local government offices), to include the level of detail appropriate for a site-specific hydrogeologic investigation. Often this includes adding information such as the locations of small or intermittent streams, wetlands, topographic depressions, and springs, or adding additional contours (i.e., decreasing the contour interval of the map to 2 or 5 feet) to existing maps. Developing a topographic map for the facility will generally require employing a conventional or photogrammetric survey company that develops topographic maps by obtaining data aerially. This information may be supplemented with information obtained from stereoscopic aerial photographs (Waste Management, Inc., 1989). Wetlands information may be obtained from National Wetlands Inventory Maps which was developed by the National Fish and Wildlife Service. This information is available through the USGS.

The USGS has prepared geologic maps at the 1:24,000 scale (7.5 minute quadrangle) for less than 10% of the United States. Consequently, it is likely that geology will not have been mapped at most facilities. Moreover, geologic mapping is generally not as easy to perform as topographic mapping, and the information provided on a geologic map obtained from the USGS may not be as detailed as topographic information. While mapping of outcrops is impossible in areas where geologic strata are not exposed at the surface, detailed mapping of exposed strata at and in the vicinity of the facility may provide necessary information on the local stratigraphic and structural setting. Field (1987) provides a detailed discussion of a RCRA site that required extensive geologic analysis by EPA Region II for a ground-water monitoring waiver determination. Table 5 lists the information that should be recorded during a mapping program. In general, for mapping of outcrops, the following information should be provided:

SUGGESTED LABORATORY METHODS FOR SEDIMENT AND ROCK SAMPLES

Sample Type	Parameter	Laboratory Method	Used to Determine
Geologic formation, unconsolidated sediments, consolidated sediments	Hydraulic conductivity	Falling head, constant head test	Hydraulic conductivity
	Grain-size distribution	ASTM D422	Well screen slot size
	Soil moisture content	ASTM D2216	Estimate of porosity
	Soil particle specific gravity	ASTM D854	Estimate of porosity
	Petrology/pedology	Petrographic analysis	Rock type, soil type
	Mineralogy/confining clay mineralogy/chemistry	Atomic absorption spectrophotometry, Cation exchange capacity (see SW-846), X-ray diffraction	Geochemistry, potential flow paths, chemical compatibility
	Atterberg limits	ASTM D427	Soil cohesiveness
	Soil pH	(see SW-846)	pH effect on sorption
Contaminated samples (e.g., soils producing higher than background organic vapor readings)	Appropriate subset of Appendix IX parameters	(see SW-846)	Identity and concentration of contaminants
	Total organic carbon	(see SW-846)	Contaminant mobility and time required for ground-water clean-up

TABLE 4

OUTCROP DESCRIPTION INFORMATION FOR MEASURED SECTIONS

General

x *Project (facility) name*
- Outcrop location with reference to an easily identified landmark
- Names of nearby landmarks

x *Location of outcrop plotted on the appropriate USGS topographic map (7.5 minute quadrangle)*
x *Geologist's name*
x *Citation of reference(s) in which earlier descriptions of the outcrop were published*
x *Narrative of regional stratigraphy and structural history*
- Narrative of regional land/water use

Information Columns

x *Thickness of measured section (nearest inch)*
x *Sample location/number*
x *Major minerals or grain types present*
x *Rock name or soil name*
x *Narrative description*

Narrative Description

x *Rock types and stratigraphic names*
x *Bed thicknesses (nearest inch)*
x *Colors and stains*
x *Gross petrology and mineralogy*
- Grain sizes (range)
- Friability and parting
- Degree of weathering
- Age of strata, if known (both relative and absolute)

x *Presence of carbonate minerals*
x *Evidence of karstification (e.g., solution cavities)*
x *Strike and dip of bedding, foliation, etc.*
x *Joints/fractures and their orientation*
x *Unconformities and their orientation*
x *Faults and folds and their orientation*
- Fossils, with a taxonomic identification

x Indicates items that the owner/operator should record, at a minimum, if an outcrop mapping program is necessary.

TABLE 5

- Location of rock exposure(s) on a topographic map, particularly with respect to the site being investigated, including strike and dip measurements for sedimentary rock strata, and orientation, bearing and plunge measurements for predominant metamorphic/igneous linear features (large and small scale).

- Photograph(s) of exposure(s).

- Measured section, with name(s) of stratigraphic units present. A measured section includes a bed-by-bed description of the exposure using appropriate lithologic terminology. A scale drawing or photograph of the section, including sample locations, should be part of the outcrop description.

- Structural features such as folds, faults, joints, fractures, cleavage, schistosity, and lineation. Other features that can control the hydraulic properties of the units such as solution cavities also should be noted. It is important to determine the orientation of these features, as they may exert significant influence on the local or regional movement of ground water. When sedimentary strata are nearly horizontal and structurally uncomplicated, the orientation of any joints not parallel to bedding should be determined, as movement of ground water along joints and bedding planes can be a significant part of the ground-water flow regime.

Where fractures, faults, or subsurface conduits exist, maps of fracture traces, fault traces, and subsurface conduits should be included as part of, or in addition to, the geologic map prepared for the site. Mapping of subsurface conduits is successfully accomplished by performing tracer studies. Fracture trace mapping is performed by analyzing aerial photographs, and is often supplemented with information from field reconnaissance, tracer tests, and/or geophysical investigations.

Soil maps are typically available from the U.S. Department of Agriculture's Soil Conservation Service. A soil map should be prepared for facilities that do not have one available, or for facilities where existing soil maps are incomplete or out-of-date (e.g., soils have been disturbed). A soil survey will involve mapping soils with respect to their unit and type, based primarily on grain size distribution.

4.2.4 Cone Penetrometer Survey

Cone penetrometer testing (CPT) consists of advancing an electric, telescoping penetrometer tip into a subsurface formation to determine the end bearing and side friction components of penetration resistance (ASTM D3441-86). Application of the CPT method is limited by the availability of equipment and by the relatively few contractors that offer conventional or specialized CPT services. In all cases, lithologic data obtained from CPT surveys should be compared with lithologic information obtained from conventionally-drilled and sampled boreholes at the site to verify the CPT results.

Conventional CPT tools record bearing pressure on the conical penetrometer tip as a function of depth. Penetrometer tools equipped with a calibrated friction sleeve attachment allow for the interpretation of subsurface lithologic changes on a continuous vertical scale based on cone and friction resistance criteria (Sangerlat, 1972; Schmertmann, 1978). Measured CPT values also are used to estimate relative formation density and bearing capacity variations as a function of depth. CPT surveys are applicable to many sites where the subsurface formations are uncemented and unlithified, free from impenetrable obstructions such as rock ledges, hardpans, caliche layers, or boulders, and where cone advancement can be achieved through the formation with minimal stress to the testing equipment. Dependent upon the site geology, a standard CPT survey can be used as a reconnaissance tool to provide preliminary site data for planning, or the surveys can be integrated into a broader investigation program to provide supplemental data between widely spaced drill holes or other data measurements. At sites where the technique is applicable, CPT surveys can provide a continuous vertical profile of subsurface stratigraphy and indicate formation permeability.

Cone penetrometer devices are used in off-shore and land-based applications. The equipment is highly portable and can be adapted to a variety of specialized applications. Instruments are commonly truck-mounted with equipment to manipulate the probes and rods and to record and interpret the survey results. Other versions of the tools can be adapted to drill rods for use with a drilling rig. In addition to conventional surveys that measure the mechanical response of the formation to the CPT probe, specialized probes have been developed that can provide measurements of in situ pore pressure, formation resistivity, formation thermal response to penetration, and seismic source detection. Further probe specialization can provide measurement of soil moisture by nuclear methods, in situ pressuremeter measurements, formation fluid and gas sampling, and soil sampling.

Application of CPT is limited to sites where mechanical penetration of the subsurface formation can be achieved through the zone of interest. In some cases, the penetrometer used in combination with a drilling rig can allow the CPT survey to progress through difficult subsurface zones by penetrating these zones ahead of the survey. The continuous survey is interrupted at these points and no data are collected.

4.2.5 Geophysical Techniques

Geophysical surveys, including surface and borehole methods, are conventionally applied to site investigations as a means to obtain subsurface information over broad lateral and vertical extents of the investigated area. The applicability of a particular method or tool to a site is contingent on the purpose of the survey and the scope of the site investigation. Integration of one or more geophysical techniques into an overall site investigation plan can maximize the amount of information obtained for the site and can potentially allow extension of geological interpretations beyond the limits of physical data locations (drillholes, outcrops, soil gas survey points, aerial photography, satellite imagery), provided that sufficient confidence is established between the interpreted geologic and geophysical models. Applied in this complementary manner, the geophysical and physical sampling data provide the means to optimize and direct the site investigation. The U.S. EPA's "Geophysical Expert Advisor System, Version 1.0" (1989) software is a tool for assisting in the selection of appropriate site-specific geophysical techniques.

Surface geophysical techniques include resistivity, electromagnetic induction, ground penetrating radar, seismic refraction and reflection, and gravimetry. The precise physical location and elevation (land survey) of the geophysical measurement points, transects, or grids in site or other coordinate systems are integral to conducting successful geophysical surveys in the field that can be readily interpreted with other site data. Information regarding surface and borehole geophysical surveys and their applications to hydrogeologic investigations is abundant in the literature. Several general references include Driscoll (1986); Schlumberger (1989); Ellis (1987); Benson et al. (1982); Telford et al. (1976); and Zhody et al. (1974).

Borehole geophysical techniques are conventionally applied as a suite of tool measurements that, when used in combination, allow the interpreter to determine physical properties of the formation. Borehole surveying is advantageous in that it provides a means for continuous measurement of in situ parameters and provides elements for the development of a three dimensional site model when combined with other site data. A wide array of tools are available that measure formation neutron and gamma ray attenuation, natural gamma ray radiation, sonic wave propagation and formation imaging, formation resistivity and conductivity, spontaneous potential, downhole/crosshole detection of seismic sources, and borehole size and direction. Formation properties that can be interpreted from the measured log data include: formation porosity, density, resistivity, conductivity, and spontaneous potential; clay content estimation; water saturation and water quality estimation; permeability estimation; formation dynamic elastic moduli; and fracture detection (Schlumberger, 1989).

General limitations in the application of surface geophysical techniques are related to the resolution of the surveys and to the non-unique interpretation of the measured data. The capacity of a surface geophysical method to resolve (detect) small scale, isolated sources is not typically a goal of a large scale geologic or hydrogeologic investigation. However, location of buried containers, voids, trenches or other smaller scale objects is a primary goal of investigations at many hazardous waste sites. Because surface geophysical techniques are commonly conducted along transect lines that intersect to form a grid over the area of interest, the resolution for a particular survey target can be enhanced by careful planning and adjustment of the survey transects. More closely spaced transect lines will provide more data points over the same area of interest. Attendant with the collection of more data, however, is the increased level of effort required for data collection and processing. The ability of a specific geophysical instrument to adequately measure details of the geology at a specific site is also contingent on the selection of the proper technique for the application. Techniques that are dependent on subsurface contrasts in density, velocity, or salinity, for example, will not adequately resolve details of the geology in formations where these physical contrasts are minimal.

Limitations associated with borehole geophysical surveys are generally related to individual tool response in different environments. As with surface geophysical techniques, the proper tools should be selected for the individual application formation or borehole conditions. Typical borehole geophysical surveying requires specialists trained in tool operation and handling and data collection. Collected data will routinely require corrections for borehole conditions prior to interpretation.

The potential for multiple interpretations of geophysical data results from the large number of potential combinations of subsurface conditions that can occur to produce the measured response. The limits in resolution and non-uniqueness in interpretations of geophysical methods should be recognized. Isolated surveys with no supporting information should be carefully interpreted. Information from geophysical surveys should be utilized in conjunction with other physical data to verify the initial interpretations of the geophysical methods and provide constraints to remove some of the non-uniqueness. In more complex areas, surface to borehole and cross borehole geophysical methods may be considered to delineate subsurface structure (Dobecki and Romig, 1985). However, application of multiple geophysical methods at a site is not a guarantee that one survey will resolve the ambiguities of another survey.

Equipment for performing many surface geophysical surveys is available from a variety of sources, and include modern, computerized microprocessors and electronics. Although the equipment can generally be operated by trained technicians, all aspects of data collection, processing, and interpretation will require the oversight of a qualified geophysicist, geologist, or ground-water scientist having extensive experience with the equipment operation and data interpretation. Borehole geophysical equipment is highly specialized and will require a qualified contractor to obtain the logs.

Johnson and Johnson (1986) discuss some of the problems that are commonly encountered when using geophysical techniques to investigate the shallow subsurface. These problems include:

- Incorrect Method Applied - Possible causes include lack of understanding of geophysical technology, site conditions or survey objectives;

- Poor Data Quality - Possible causes include high ambient noise, poor field procedures, improper use of equipment, faulty equipment, adverse geologic conditions, or inexperienced operators;

- Poor Interpretation - Possible causes include an inadequate interpretation method, insufficient background information, or insufficient or noisy data;

- Insufficient Data - Possible causes include a lack of understanding of methods and/or site conditions and objectives, operator inexperience, or lack of up-to-date plotted data in the field (some contractors gather data but do not plot it or look at it until they are back in the office).

4.2.5.1 Geophysical Surveys - Surface Techniques

Surface geophysical methods, as previously noted, are useful in mapping subsurface conditions over a broad area of interest. The measurements are particularly useful when they are integrated into an overall site investigation program where they can be interpreted along with other available information for the site. The techniques are useful both as a means of rapid site reconnaissance that can provide information for planning subsequent field activities, and also in extrapolation of existing data to previously uninvestigated areas -- provided that sufficient site-specific correlations have been established between the physical feature being extrapolated and the geophysical survey. Survey data should be collected, processed, and interpreted by a qualified geophysicist, geologist, or ground-water scientist familiar with the theory, application, interpretation, and limitations of the applied geophysical techniques.

Direct Current (DC) Electrical Resistivity Methods

The direct current (DC) resistivity method is used to measure the bulk resistivity of soil or rock volumes occurring between the measuring electrodes. This technique utilizes electric currents that are introduced into the ground through electrodes or long line contacts. The apparent resistivity of the subsurface volume is determined by measuring the potentials at other electrodes in the vicinity of the current flow (Telford et al., 1976). The objective, through the use of inverse modeling and curve matching, is to obtain the true resistivities and layer thicknesses of the subsurface geologic strata from the apparent resistivities measured at the ground surface. In ground-water studies, DC resistivity techniques can be used to model the geoelectric response of the bulk formation and to estimate ground-water quality (Zhody, 1974; Stollar and Roux, 1975; Van Dam, 1976; Rogers and Kean, 1980; Urish, 1983).

The electrical resistivity technique is used for lateral profiling or vertical electric sounding. Through application of both techniques, a vertical geoelectric cross-section of the subsurface along the survey transect can be obtained. Lateral profiling techniques enable the scientist to map lateral changes in subsurface electrical properties along a transect line to a finite investigation depth related to the spacing of the measurement electrodes and the applied current. Vertical electrical sounding measures vertical changes in subsurface resistivity as the measuring electrode is moved various finite distances away from a stationary electrode at the center of the measurement array. Qualified interpretation of sounding data can provide an estimate of the depth and thickness of subsurface layers having contrasting apparent resistivities. Information generated from multiple resistivity profiling and sounding arrays can be used to produce two- and three-dimensional geoelectric models.

Resistivity techniques are dependent on resistivity contrasts in subsurface materials and predictably will not be useful at sites where measurable contrasts do not exist. The accuracy of resistivity methods is limited by several factors including: heterogeneity in surface and subsurface conditions, proximity of human-made sources of electrical interference, departure of the subsurface structure from a horizontally-layered model, and the inherent lack of a unique data interpretation (Mooney, 1980; Mooney and Wetzel, 1956; Urish, 1983; and Telford et al., 1976). Field procedures for conducting electrical resistivity surveys are relatively more tedious than other applicable techniques such as electromagnetics.

Seismic Methods

Seismic survey methods of subsurface exploration are based on the principle that seismic waves, consisting of compressional and shear pulses, emanate from a seismic source (e.g., hammer blow, large weight drop, explosion, pipe gun, vibratory source) and travel through subsurface soil and rock at velocities that vary with the elastic properties of the materials. Two surface geophysical methods commonly applied to hydrogeologic investigations include seismic refraction and seismic reflection. Seismic surveys are typically conducted along intersecting traverses to provide a grid of measurements over the survey area and to allow for two-dimensional contouring of velocity, depth, or thickness at each geophone location. The geometry of the established grid is related to the goals of the survey, known data, cultural features, and surface obstructions.

Seismic refraction is used to determine the thickness and depth of subsurface geologic layers having contrasting seismic velocities. In the presence of sufficient subsurface contrasts, refraction techniques can be used to map depths to specific horizons, including bedrock surfaces, clay layers, and the water table.

Equipment necessary for conducting seismic refraction surveys includes a seismic source, geophones, a seismograph, and a qualified operator. Equipment for conducting seismic surveys has become sophisticated in recent years so that high quality data are accessible for most applications. The following technological developments have greatly improved the quality of collected refraction data: relatively low-cost, multi-channel seismographs; increased geophone sensitivity and improvements in multi-shot pattern surveying; signal enhancement; and digital signal processing.

The seismic source typically consists of a sledgehammer blow or explosive detonation at or slightly below the ground surface. The use of explosives is warranted in many applications where extensive loose material is present at the surface or when a higher energy source pulse is needed. The seismic source transmits elastic waves traveling at different velocities into the subsurface where they are refracted at the interfaces between layers having contrasting impedances. A geophone array at the ground surface detects the refracted wave arrival at each geophone and allows for measurement of the travel time from source to detector. Geophone arrays for engineering studies can range from 12 to 48 channels depending on the survey goals. The measured travel time data at each geophone is interpreted from multiple shot points to determine the velocity, thickness and depth of the subsurface layers that exhibit sufficient contrast to be distinguished as seismic layers.

Seismic refraction profiling has several limitations, the most severe of which include the presence of blind zones (hidden layers with insufficient velocity contrast) and velocity reversals. The interpretation of refraction data requires the assumption that velocity increases progressively as a function of depth. A velocity reversal consisting of a lower velocity layer underlying a higher velocity layer is undetectable at the surface. Field procedures are relatively slow in the absence of sufficient crews for running seismic lines and setting geophones. Extraneous noise resulting from cultural features, wind, traffic, trains, or other sources of seismic waves can be controlled to a certain degree through filtering, signal stacking, geophone selection, geophone burial, logistics, and noise source control. The use of explosives as a source requires that extra safety precautions be exercised by field personnel and that a licensed explosives expert be responsible for explosives control, handling, and detonation.

Seismic reflection surveying methods are capable of obtaining continuous vertical and lateral profiles of the subsurface geology using generally the same equipment requirements as the refraction method. Shallow seismic reflection applications have, until recently, been hindered by the lack of high frequency, short pulse seismic sources and by the inability to overcome severe noise constraints generated by near surface ground "roll" phenomena.

The "optimum window" and "optimum offset" shallow seismic reflection profiling techniques described by Hunter et al. (1984) have been used to map overburden and bedrock reflections occurring at depths greater than approximately 60 to 100 feet in areas where large velocity contrasts are observed. The optimum window shallow reflection technique is based on the location of a shot-geophone spacing that allows non-normal incident reflections to be observed with minimum interference from ground roll or from direct and refracted waves.

The resolution of the reflection method depends on the frequency of the seismic energy that can be returned from the target reflector to the surface (Pullan et al., 1987), and on the control of ground roll phenomena through filtering and the use of higher frequency geophones. Optimum conditions for the technique occur when near-surface sediments are fine-grained and water saturated (Pullan et al., 1987).

The shallow seismic reflection technique requires a geophysicist or geologist experienced in the application and interpretation of the obtained seismic records. In contrast to seismic refraction data, seismic reflection records can require sophisticated computer processing and corrections to enhance the coherent features observable in the traces.

Refraction surveying is frequently necessary along the same transect line to resolve shallow velocity relationships.

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) technology uses repetitive, high-frequency (80-1000 MHz), short time duration (nanoseconds) electromagnetic energy radiated into the ground to acquire continuous subsurface profile data along a transect. The electromagnetic pulses are emanated using a broad bandwidth radar antenna that is placed in close proximity to the surface and is electromagnetically coupled to the ground (Morey, 1974). The antenna is moved across the measurement surface along the line of the survey. The transmitted radar signals are reflected from various subsurface interfaces in response to contrasts in the dielectric properties of the subsurface materials and are received back at the transmitting antenna where the signal is processed. The method is capable of producing a high quality graphic profile at speeds of up to several kilometers per hour. GPR can resolve subsurface conditions on the order of centimeters. Commonly, a printed record of the survey run is produced in the field so that the applicability of the method to a particular site is quickly determined. Interpretation skills of the operator are critical in obtaining reliable data.

GPR has been used to profile both the water table and the overburden/bedrock interface, to locate buried objects including storage tanks and utilities, and to identify voids and areas of soil subsidence; GPR also has had considerable utility in mine applications. Beres and Haeni (1991) provide results of the application of GPR to stratified drift deposits in Connecticut.

The depth of radar signal penetration is highly site-specific and dependent on the electrical conductivity properties of subsurface soil and rock. Morey (1974) reported penetration depth of greater than 75 feet in water-saturated sand and 230 feet in an Antarctic ice shelf. Fountain (1976) states that this method has shown detection capacity only to depths of approximately 2.4 meters in moist, clay-rich soils. If the specific conductance of the pore fluid is sufficiently low, however, data can commonly be obtained to a depth of 3 to 10 meters in saturated materials (Dobecki and Romig, 1985). Electrically conductive subsurface materials such as wet clay, sea water, or extensively micaceous materials with high dielectric permittivity properties can significantly attenuate radar signals. Signal attenuation for a particular material is also dependent on the frequency of the radar pulse. In general, good results can be obtained in dry, sandy, rocky areas.

The continuous nature of GPR offers a number of advantages over many other geophysical methods and allows for a substantial increase in the detail obtained along a traverse line. Additionally, the high speed of data acquisition permits many lines to be run across a site, and in some cases, total site coverage is economically feasible (Benson et al., 1982). The method is limited by the attenuative properties of many subsurface materials, by the radar signal, and by the highly site-specific application of the technique. Multiple reflections can complicate data interpretation.

Electromagnetic (EM) Induction-Conductivity

The electromagnetic (EM) induction method uses alternating electric currents flowing between a transmitter and a receiver coil to induce secondary magnetic fields in the subsurface that are linearly proportional to ground conductivity up to approximately 100 mmhos/m (McNeill, 1980). The instrument reading is a bulk measurement of the apparent formation conductivity calculated as the cumulative response to subsurface conditions ranging from the ground surface to the effective depth of the instrument. The effective exploration depths for commercially available equipment range from 3 to 60 meters depending on the instrument orientation and the intercoil spacing. The EM technique has been applied to mapping geologic deposits, locating subsurface cavities in karst environments, locating subsurface trenches, mapping contaminant plumes, locating metallic conductors, mapping saltwater intrusion, and locating buried drums, tanks, and subsurface utilities. By changing the orientation and spacing of EM coils, it is possible to profile vertical changes in subsurface conductivity, potentially allowing for vertical tracking of contaminant plumes. Like other geophysical techniques, delineation of a particular subsurface feature from the bulk apparent conductivity measurement requires a sufficient conductivity contrast in the subsurface.

When dry, soil and rock typically have low conductivities. In some areas, conductive minerals like magnetite, graphite, and pyrite occur in sufficient concentrations to greatly increase natural subsurface conductivity. Most often, conductivity is overwhelmingly influenced by water content and by the following soil and rock parameters:

- The porosity and permeability of the materials;
- The extent to which the pore space is saturated;
- The concentration of dissolved electrolytes and colloids in the pore fluids; and,
- The temperature and phase state (i.e., liquid or ice) of the pore water.

In some cases, contaminants increase the electrolyte and colloid content of the unsaturated and saturated zones. Examples of common ionic contaminants include chloride, sulfates, the nitrogen series, and metals such as sodium, iron, and manganese. With the addition of electrolytes and/or colloids, the ground conductivity can be affected, sometimes increasing by one to three orders of magnitude above background values. However, if the natural variations in subsurface conductivity are low, conductivity variations of only 10 to 20 percent above background may be observed.

Interferences due to overhead power lines, known subsurface utilities, and metal objects such as fences, above-ground oil tanks, and cars are noted when conducting an EM survey. Readings obtained in the vicinity of such instrument interferences are either discarded or regarded as suspect during the interpretation of the data. In areas of large power lines, instrument overloading can occur. To ensure that measurements are consistent and that instrumental overloading is not present, readings are typically obtained at two different sensitivity scales in areas of such interferences. The survey also may be operated perpendicular rather than parallel to linear sources.

Gravity Methods

Gravity measurements are useful for estimating depth to bedrock, for locating voids and fault zones, for estimating the ground-water volume in alluvial basins (Hinze, 1988). The observed density contrasts between rock, air, water, and soil make gravity measurements a useful mapping tool. A low value of gravity indicates an anomalously low density subsurface mass, which might be due to a subsurface void, a cavity in rock filled with lighter density material, a thickening of the soil layer overlying bedrock, a decrease in soil density, or a variation of ground-water volume (Hinze, 1988). Gravity measurements alone are not sufficient to uniquely determine the cause of a gravity anomaly; however, an experienced interpreter can often define the source of the anomaly when gravity methods are used in conjunction with knowledge of the local geologic setting and a soil/rock boring program.

4.2.5.2 Borehole Geophysical Techniques

Borehole geophysical logging is used to obtain continuous vertical profiles of subsurface conditions at resolutions that cannot be obtained economically from the physical drilling, sampling, and testing of subsurface formations. Borehole geophysical methods measure the responses of subsurface rock, soils, and fluids to various logging tools and utilize the measurements to ascertain physical characteristics of the subsurface formations and their contained fluids. Available logging tools include electrical, visual, thermal, acoustic (sonic), magnetic, nuclear (radioactive), fiber optic, and mechanical sensors. Some tools that are available to measure the physical properties of the borehole include borehole calipers, borehole deviation surveying tools, temperature measurement tools, and downhole video surveying cameras. Borehole geophysical measurements can be obtained in open boreholes or cased wells, however all tools are not functional in both environments. Generally only nuclear and sonic tools are applied to cased hole logging. In either instance, the application of a specific tool to a borehole or cased well may require that the borehole or well be fluid-filled and that the composition or clarity of the fluid be constrained within the tool's limits for optimum performance.

Borehole geophysical logs can be utilized to correlate formation properties between boreholes and to refine surface geophysical interpretations. Geophysical logs obtained with equipment that is properly calibrated and standardized can provide objective and consistent data that can be used in: the interpretation of stratigraphy, thickness, and extent of aquifers and confining units; relative permeability, porosity, bulk density, resistivity, moisture content, and specific yield of aquifers and confining layers; borehole deviation; casing integrity; subsurface temperature; formation-resistivity factors; and the source, movement, and chemical/physical nature of ground water (Keys, 1988). Sources of information on the use and interpretation of geophysical logs include Keys (1988); Keys and MacCary (1971); Labo (1986); Telford et al. (1976); Ellis (1987); Schlumberger (1989); and Taylor et al. (1990).

In many instances, different tools (such as radioactive or sonic tools) are used to determine the same formation property (such as porosity) by measuring the response of the formation to the specific tool. The electrode, coil, transmitter/receiver, or source/detector spacings of the method used reflect the properties of the formation by integrating the data gathered over a fixed distance as a function of the source/detector spacings. These spacings vary the depth of investigation of a particular tool into an unaltered formation. Factors such as these emphasize the importance of having knowledgeable and experienced operators obtain borehole geophysical logs and having qualified log analysts interpret the data.

Downhole measurements are recorded in the field using portable field equipment or (more routinely) a service company logging truck. The service company logging truck generally provides all downhole measurement tools, electrical cables, a winch, and extensive truck-mounted surface instrumentation for controlling tool operations and acquiring response data. Office processing of the log data may include making corrections for borehole conditions, mud cake, and tool standoff, and calculating formation mechanical properties, permeability, or mineralogy. Variations in the physical environment where the geophysical sondes operate make it necessary to correct the measured values for the borehole effects. Corrections commonly applied to the measured data include compensation for borehole diameter, sonde eccentricity, drilling fluid invasion, bed thickness, and mudcake formation. By the nature of the tool design, many modern logging tools are dual-detector, compensating devices that provide a large degree of correction for the borehole environment.

Electrical Methods

Electrical logging methods that are applicable to the borehole environment include resistivity/conductivity and spontaneous potential measurements. Borehole resistivity and conductivity methods are analogous to surface resistivity/conductivity techniques in that the measurements are obtained using fixed-spaced electrodes or coils, and electrical currents are passed through the formation across the fixed-spaced electrodes or transmitter/receiver arrays. The voltage is measured between the electrodes and is proportional to the formation resistivity. Because of the need for electrical coupling among the tool electrodes, borehole fluid, and formation, electrical resistivity curves are obtained from uncased boreholes. The induction log, used to measure formation conductivity, is generally applicable to boreholes drilled with moderate to non-conductive drilling fluids and to empty or air-drilled boreholes.

Downhole electrical resistivity/induction surveys are run to provide data for the evaluation of drilling mud invasion, to determine true formation resistivity/conductivity and flushed zone resistivity, to determine pore water resistivity/conductivity, and to potentially provide a means for correlation across wells. Resistivity data also are used in conjunction with other log measurements to estimate permeability and in situ mineralogy. Applicability of a particular resistivity or induction tool to a specific borehole environment is a function of the formation electrical properties, the properties of the borehole fluid, and the desired resolution of the survey. In general, a wide array of electrode and coil configurations are available for borehole applications. The development of focused, multiple-electrode resistivity and multi-coil induction sondes have improved the vertical resolution and depth of penetration of electrical tools.

The spontaneous potential (SP) tool records the electrical potential produced by the interaction between formation pore water, conductive drilling fluid, and ion-selective formation components. The SP curve can potentially differentiate between porous and permeable zones and non-porous, impermeable zones, and can define layer boundaries and estimate ground-water resistivity. However, the SP curve cannot be recorded in boreholes filled with non-conductive drilling fluids or cased boreholes because the fluid does not provide electrical continuity between the SP electrode and the formation. Similarly, if the borehole fluid filtrate in the formation and the natural formation water have approximately equal resistivities, the SP curve deflections will be small and the curve will appear featureless. Electrical noise and anomalous potentials are common problems on SP logs, a result of insufficient electrical insulation of the steel cables used to lower the SP electrodes into a borehole. Surface or subsurface electrical sources, and weather effects also are possible sources of anomalous potentials.

Nuclear Methods

Nuclear radiation tools are used to measure passive or induced radiations from the nuclei of the atoms comprising a formation. Commonly applied nuclear tools are the natural gamma ray, gamma-gamma, and neutron devices that can be applied in either cased or open boreholes filled with any type of fluid.

Conventional gamma ray logging is a passive process that uses a sonde containing a scintillation counter to measure the total natural radioactivity emitted by the formation. The measured total radioactivity is a linear combination of source radiation from potassium, thorium, and uranium-bearing formation elements. Natural Gamma Ray Spectrometry (NGS) logging is a refinement of conventional gamma ray logging that uses five window (energy levels) spectroscopy to resolve the total natural gamma ray spectra into the potassium, thorium, and uranium components. The tool has a sodium iodide scintillation detector to measure the number and energy level of detected gamma rays and uses the data to calculate the concentrations of each component.

Gamma-gamma logs record the intensity of gamma radiation at the tool detectors resulting from the backscattering and attenuation of gamma radiation emitted by the tool source. The primary use of the gamma-gamma tool is for the identification of lithology and for the measurement of the bulk density of the formation. The modern gamma-gamma log records the bulk density of the measured formation using a compensating, skid-mounted, borehole sidewall device that contains a gamma ray source and two detectors. The instrument skid is pressed against the borehole sidewall by a spring activated arm with sufficient force to cut through soft mudcakes. The density sonde measures the formation's ability to attenuate gamma rays emitted from the tool's radioactive source by measuring the number of scattered gamma rays reaching the detectors. The number of scatterings is related to the number of electrons in the formation, therefore, the response of the tool is determined by the electron density of the formation. The electron density is related to the true bulk density of the formation. The bulk density information is used to provide a measure of the formation density and to calculate the formation porosity. More advanced density tools, in addition to providing measurement of formation density, record low energy gamma rays in the domain of photoelectric absorption. By comparing the number of gamma rays detected in each domain, these density tools can determine a photoelectric absorption cross section index, Pe. The Pe value is primarily a function of the formation mineralogy and is used to estimate the in situ mineralogic composition of the formation. The depth of penetration of the density tool is approximately 4 feet with vertical resolution ranging from 1.5 to 3 feet, depending on the logging speed. Instruments of lesser quality may obtain penetration depths of only 6 inches.

Neutron logging is one of several methods used to derive porosity values for subsurface formations. The neutron log response is a function of the hydrogen content of the borehole environment and is used for the measurement of moisture content above the water table and of total porosity below the water table. A modern, compensated neutron tool uses an americium-beryllium radioactive source (3-16 curies) to generate high energy neutrons that interact with the formation. The sonde is a dual-spaced device with two sets of thermal neutron detectors, near and far. The tool compensation resulting from the dual-detector arrangement reduces the effects of borehole conditions by using the ratio of two counting rates similarly affected by the environment. As the neutrons are attenuated or rebounded from the formation, the tool detects and counts neutrons in the thermal energy regime. The ratio of the counting rates from the two detectors is processed by the surface equipment to produce a linearly scaled measure of the neutron porosity index.

The response of the neutron tool is affected by formation elements having high thermal neutron capture cross sections (elements having higher probabilities of capturing thermal neutrons) that act to moderate (attenuate) neutrons in the formation. Hydrogen, boron, and chlorine are particularly effective. Reduced counting rates as a result of neutron attenuation by an element result in poorer counting statistics and unrealistically higher measured porosity values. Thermal neutron measurements also may be influenced by the presence of hydrogen or chlorine bound in the lattice structures of clay minerals, micas, and other hydrogen/chlorine bearing minerals. A thermal-epithermal neutron tool is a dual compensated, dual porosity tool that detects interacted neutrons in the thermal and (higher energy) epithermal ranges. Because of the higher (epithermal) neutron energy levels, the impacts of this tool include significantly improved neutron counting statistics in the epithermal range, and less affected porosity values by neutron attenuators. The vertical resolution of the neutron tool is approximately 2 feet with processing enhancement possible to 1 foot. The depth of investigation of the tool is a function of porosity and typically is in the range of 10 to 12 inches.

Limitations associated with nuclear logging methods are related to the correction of the logs for borehole parameters in the absence of tool compensation, the need to handle and operate devices containing radioactive source material in an underground environment, and the effects of radiation moderators in the borehole environment. Additionally, formation porosities derived from gamma-gamma and neutron measurements are dependent on knowledge of the formation matrix density (not bulk density) which in many cases is estimated in the absence of physical measurements. In formations where the matrix density is significantly different from the response density utilized by the tool operator, the calculated porosity may be in error. This is known as the matrix effect.

Sonic Methods

The sonic log is a recording of the transit time of an acoustic pulse through a formation between a series of acoustic transmitters and receivers in a sonic probe as a function of depth in a borehole. Application of the sonic tool in a borehole is analogous to the surface seismic geophysical technique. Many of the tools commonly used for engineering or ground-water investigations are simple devices capable of providing detailed compressional and shear wave velocity measurements. Multiple transmitter-receiver sonic tools are available for larger-scale applications and provide greater vertical resolution of the formation and enhanced delineation of the sonic waveform at later arrival times along the wavetrain. Full wavetrain recording allows for extraction of information from the deeper sections of the waveform such as the delineation of stonely wave arrivals. The measured interval travel times (µsec/ft) are functions of the transmitter to receiver distances and the competence of the measured formation. Computations using sonic interval transit times (compressional and shear) are used to calculate porosity, formation dynamic elastic moduli, compressibilities (bulk, rock), poisson’s ratio, tensile strength, fracture pressure, and minimum horizontal stress.

Sonic log measurements are commonly obtained in open, fluid-filled boreholes, although cased hole measurements are used to evaluate cement bond integrity. In instances where the cement bond between the formation and casing is adequately high, the sonic log may be used to evaluate formation properties through the casing (Keys and MacCary, 1971).

Advanced sonic log tools are capable of providing high resolution borehole caliper measurements and full borehole imagery. Borehole televiewer surveys are capable of taking high resolution acoustic pictures of the walls of fluid-filled boreholes. The televiewer allows identification of fractures and fracture orientation, deformation, pitting, vugs, bedding planes, lithology changes, and well casing and screen integrity. Limitations of sonic logging are related both to signal attenuation as a result of borehole environmental or tool factors, and to variability in formation properties affecting the elastic wave transmission and attenuation. The previously discussed "matrix effect" is applicable to the interpretation of sonic data.

Physical Methods

Physical methods of subsurface investigation include caliper, temperature, borehole deviation, and downhole video surveying. Caliper surveys are commonly run in combination with the other tools and are used to apply borehole corrections to the measured log data. Caliper surveys also are valuable in delineating enlarged borehole zones that may be indicative of subsurface fracturing, karstification/solution channels, or water-bearing zones. High resolution, multi-arm caliper devices can provide valuable information regarding the borehole geometry and directional aspects of borehole enlargement. Caliper devices range in resolution from single-arm tools measuring the borehole diameter in a single direction, to multi-arm tools measuring the hole diameter in several simultaneous directions.

A temperature log is obtained by lowering a temperature sonde into a fluid filled borehole at a constant rate. The probe is constructed so that borehole fluid flows by a temperature sensor on the probe. Temperature is recorded as a function of depth. A temperature log can provide information on the temperature variation with depth and can provide a measure of the thermal gradient. The log is commonly run in open hole environments although cased hole applications are common, particularly for locating cement grout behind a casing or for confirming fluid flow in perforated intervals. Temperature anomalies in open boreholes may be indicators of permeable zones reflecting the movement of cooler, unequilibrated water into a warmer, equilibrated borehole environment.

Borehole geometry and deviation are determined from high resolution microresistivity measurements obtained using dipmeter or gyroscopic tools. The dipmeter tool uses four dual electrodes to record eight microconductivity curves and a triaxial accelerometer and three magnetometers to provide detailed information on borehole microresistivity, tool deviation, and azimuth. Caliper measurements are obtained at 90 degree intervals for input to borehole geometry and volume calculations. Borehole video surveys are a valuable means of visually assessing downhole conditions in stable, open holes and in cased wells. Completion of a successful video survey is contingent on the clarity of the fluid filling the borehole or well.

4.2.5.3 Surface to Borehole, Cross Borehole Geophysical Methods

Surface to borehole and cross borehole geophysical methods combine the use of electrodes or geophones in boreholes with surface electrodes or sources to affect surface to borehole and cross borehole measurements (Dobecki and Romig, 1985). Application of both surface and borehole geophysical techniques increases the resolution of targets because borehole probes can be positioned close to the target of interest (Van Nostrand and Cook, 1966). Geophysical techniques applied within and between boreholes include vertical seismic profiling, geotomography (utilizing both seismic and EM waves) and DC resistivity. Cross borehole EM techniques have been used by Lytle et al. (1979, 1981) to locate high-contrast electrical anomalies (e.g., tunnels) and to monitor the direction and flow rate of injected fluids. Butler and Curro (1981) have described cross borehole procedures for obtaining accurate seismic velocity profiles.

Cross borehole and surface to borehole methods provide a greater lateral radius of investigation than can be achieved through single borehole logging, thereby providing measurement over a larger formation volume. The region surveyed is a path between the energy source and the detector, but it is not necessarily the straight line path between the two points. The probability that the sampled region is along a straight line path between the source and detector increases as the distance between the source and detector decreases. The surface to borehole and cross borehole techniques are limited by many of the factors affecting most geophysical surveys such as non-uniqueness of results, and therefore, require other integrated data for verification of results.

4.3 Characterizing Ground-Water Flow Beneath the Site

In addition to characterizing site geology, the owner/operator should characterize the hydrology of the uppermost aquifer and its confining layer(s) at the site. The owner or operator should install wells and/or piezometers to assist in characterizing site hydrology. The owner/operator should determine and assess:

- The direction(s) and rate(s) of ground-water flow (including both horizontal and vertical components of flow);
- Seasonal/temporal, natural, and artificially induced (e.g., off-site production well pumping, agricultural use) short-term and long-term variations in ground-water elevations and flow patterns; and
- The hydraulic conductivities of the stratigraphic units at the site, including vertical hydraulic conductivity of the confining layer(s).

Section 4.3.1 provides a brief introduction to ground-water flow in porous media and conduits; Section 4.3.2 provides a discussion of the Agency’s definition of "uppermost aquifer"; Section 4.3.3 discusses methods for determining ground-water flow direction and hydraulic gradient; Section 4.3.4 discusses methods for determining hydraulic conductivity; and Section 4.3.5 discusses determining ground-water flow rate. The special case of ground-water flow in aquifers dominated by conduit flow is discussed in Sections 4.3.1 and 5.2. Most of the discussions provided in Sections 4.3.3, 4.3.4, and 4.3.5 do not apply to this special case.

4.3.1 Introduction

Conventional ground-water hydrology considers aquifers to be porous granular media (either unconsolidated granular deposits or rock) having a well-defined water table or potentiometric surface. The flow of ground water in these types of aquifers is described by Darcy's law:

$$Q = -KiA$$

where:

Q = quantity of flow per unit of time, in (volume/time)
K = hydraulic conductivity, in (length/time)
i = hydraulic gradient, in (length/length)
A = cross-sectional area through which the flow occurs, in (length^2)

Darcy's law assumes laminar flow of individual particles of water moving parallel to the direction of flow, with no mixing or transverse component in their motion. The right-hand side of the Darcy equation is preceded by a negative sign because ground water flows from high head to low head.

There are two types of ground-water systems where the relationship expressed by Darcy's law does not apply. These are systems where ground water flows through materials with low hydraulic conductivities under extremely low gradients, and systems in which a large amount of flow passes through materials with very high hydraulic conductivities (turbulent flow). These two situations can be considered, respectively, as the lower and upper limits of the validity of Darcy's law (Freeze and Cherry, 1979).

The Reynolds number (the ratio of inertial to viscous fluid forces) is a dimensionless number used to define the limits of the validity of Darcy's law. The Reynolds number (R_e) is defined as:

$$R_e = \frac{\rho \ v \ d}{\mu}$$

where:

ρ = fluid density, in (mass/length^3)
μ = fluid viscosity, in (mass/length·time)
v = specific discharge, in (length/time)
d = some characteristic dimension of the system, often represented by the average grain size diameter.

The range of the Reynolds numbers over which Darcy’s law is valid depends on the definition of "d," or diameter of the passageway through which the ground water moves. When "d" is approximated as average grain size diameter, Darcy’s law is only valid for Reynolds numbers in the range of 1 to 10.

The basic hydraulic principles governing flow through porous media are not applicable to aquifers where ground-water flow is primarily through conduits. Flow through caves (conduits that can be entered at the earth’s surface) and conduits is referred to as conduit flow. Most conduit flow is turbulent, is analogous to the flow of surface streams, and resurfaces at a spring or group of springs. Water quality in these springs is usually representative of the mean water quality of the ground-water basin. Aquifers in which subsurface conduits dominate the flow regime are described in terms of their drainage pattern rather than by the concept of a water table; these drainage patterns are usually a network of smaller conduits that contribute their flow to the larger "trunk" conduits. The prediction of flow paths in such aquifers is not usually possible from wells alone, unlike other aquifers.

Ground-water flow in conduits of karst aquifers differs radically from flow in porous media. Velocities on the order of hundreds of feet per hour may occur in conduits (Quinlan, 1990). Thus, the effects of a release of hazardous material on water quality in an aquifer dominated by conduit flow can commonly be detected at great distances in less than a day. In addition, water levels in these aquifers can commonly change rapidly and substantially in response to heavy rains. Observation wells that intercept conduits in the Mammoth Cave area of Kentucky typically have water-level fluctuations of 60 to 80 feet and at times exceed 100 feet or more.

"Diffuse flow" is a term applied to aquifers in which ground-water flow is predominantly through poorly integrated pores, joints, and tubes. Diffuse flow is intermediate between flow through fractures and conduits, and flow through porous media. Ground-water flow in aquifers in which diffuse flow predominates is generally laminar and can be described by Darcy’s law (Quinlan, 1989). Many springs in karst terranes are fed by a mixture of both diffuse and conduit flow, and, in a given region, some springs can be fed by primarily conduit-flow systems, while other nearby springs can be fed by primarily diffuse-flow systems. Although conduit flow is turbulent by definition (and as such, is not described by Darcy’s law), a spring fed by a diffuse-flow system may discharge from a conduit and may have turbulent flow. This is particularly true in structurally and stratigraphically complex areas, such as the karst terrane described in a study by Shuster and White (1971). Quinlan (1990) discusses the differences between conduit and diffuse flow and provides a relatively simple method for distinguishing between a conduit flow spring and a diffuse flow spring.

Karst ground-water systems developed in both younger limestones, such as those in Puerto Rico and Florida, and in older limestones, such as those in the Appalachians, the Ozarks, and the Kentucky-Indiana karst region, may be either conduit-flow or diffuse flow. Younger limestones, however, may have significant primary porosity, so that they can be likened to a gigantic sponge in which flow occurs throughout the entire aquifer through huge pores rather than being constrained in conduits. Consequently, the type of flow found in some younger, highly porous limestones may be rapid and turbulent -- not the slow, linear flow described by Darcy's law.

In the United States, lava tubes and caves occur in areas of great thicknesses of basaltic lava flows (Hawaii and the Columbia Plateau and Snake River Plain of the Pacific Northwest), but conduit flow rarely is present.

4.3.2 Definition of the "Uppermost Aquifer"

The owner/operator is required under 40 CFR §264.97 to install a ground-water monitoring system that yields representative samples from the uppermost aquifer beneath the facility. The ground-water monitoring system should allow for the detection of contamination when hazardous waste or hazardous constituents have migrated from the waste management area to the uppermost aquifer. Owners and operators should properly identify the uppermost aquifer when establishing a ground-water monitoring system that meets the requirements of §264.97. EPA has defined the uppermost aquifer as the geologic formation nearest the ground surface that is an aquifer, as well as lower aquifers that are hydraulically connected within the facility's property boundary. "Aquifer" is defined as the geologic formation, group of formations, or part of a formation that is capable of yielding a significant amount of ground water to wells or springs (40 CFR §260.10). The identification of the confining layer or lower boundary is an essential facet of the definition of uppermost aquifer. Interconnected zones of saturation below an aquifer that are capable of yielding significant amounts of water also comprise the uppermost aquifer. Quality and use of ground water are not factors in the definition. Even though a saturated zone may not be presently in use, or may contain water not suitable for human consumption, it should be monitored if it is part of the uppermost aquifer to ensure that the performance standard of §264.97(a)(3) is met. Identification of formations capable of "significant yield" is made on a case-by-case basis.

There are saturated zones, such as low permeability clays, that do not yield a significant amount of water, yet act as pathways for contamination that can migrate horizontally for some distance before reaching a zone that yields a significant amount of water. If there are hydrogeologic data supporting the belief that potential exists for contamination to migrate along such pathways, the Regional Administrator may invoke the authorities of §264.97 to require such zones to be monitored. In addition, the Regional Administrator may require the use of supplemental monitoring wells in conjunction with point of compliance wells to monitor sites where hydrogeologic conditions or contaminant characteristics allow contaminants to move past or away from the point of compliance without being detected (§264.97(a)(3)). The Agency recommends the use of unsaturated zone monitoring where it would aid in detecting early migration of contaminants into ground water. In determining the necessity for and scope of unsaturated zone monitoring, the Regional Administrator will consider site specific factors that include geologic and hydrogeologic characteristics.

Other authorities that can be used to require monitoring include §3004(u) for corrective action for permitting; the "omnibus" permitting authority under §3005(c)(3) of RCRA and 40 CFR §270.32(b) that mandates permit conditions to protect human health and the environment; and §3013 authority that authorizes the Agency to require monitoring, testing, analyses, and reporting in certain circumstances upon a finding of a substantial hazard. If a release to ground water is detected, the release should be characterized in all saturated zones regardless of yield.

The owner/operator should assess hydraulic connection between zones of saturation yielding significant amounts of water, and properly define potential zones of contaminant migration. The owner/operator also should be able to demonstrate to the satisfaction of the EPA Regional Administrator (e.g., through the use of aquifer testing and/or modeling) that the units identified as the confining units below the uppermost aquifer are of sufficiently low permeability to minimize the passage of contaminants to saturated, stratigraphically lower units. Owners and operators should be aware that true confining layers rarely exist. Facies changes are the rule, and not the exception at most sites, and may preclude the existence of a confining layer. Furthermore, particularly with regard to DNAPLs, a confining layer may not inhibit flow laterally downdip of the layer. Solvents also have been shown to interact with clays, causing dessication and the formation of fractures. Consequently, even if the confining layer is continuous (it usually is not), the confining layer may not prevent contaminant migration.

4.3.3 Determining Ground-Water Flow Direction and Hydraulic Gradient

Installing monitoring wells that will provide representative background and downgradient water samples requires a thorough understanding of how ground water flows beneath a site. Developing such an understanding requires obtaining information regarding both ground-water flow direction(s) and hydraulic gradient. Ground-water flow direction can be thought of as the idealized path that particles of ground water follow as they pass through the subsurface. Hydraulic gradient (i) is the change in static head per unit of distance in a given direction. The static head is defined as the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point (i.e., the sum of the elevation head and pressure head).

To determine ground-water flow directions and hydraulic gradient, owners and operators should develop and implement a water level monitoring program. The water level monitoring program should be structured to provide precise water level measurements in a sufficient number of piezometers or wells at a sufficient frequency to gauge both seasonal average flow directions and temporal fluctuations in ground-water flow directions (§264.97(f)). Ground-water flow direction(s) should be determined from water levels measured in wells screened in the same hydrostratigraphic position. In heterogeneous geologic settings (i.e., settings in which the hydraulic conductivities of the subsurface materials vary with location in the subsurface), long well screens can intercept stratigraphic horizons with different (e.g., contrasting) ground-water flow directions and different heads. In this situation, the resulting water levels will not provide the depth-discrete head measurements required for accurate determination of the ground-water flow direction.

In addition to evaluating the component of ground-water flow in the horizontal direction, a program should be undertaken to accurately and directly assess the vertical component of ground-water flow. Vertical ground-water flow information should be based at least in part on field data from wells and piezometers such as multi-level wells, piezometer clusters, or multi-level sampling devices, where appropriate. The following sections provide acceptable methods for assessing the vertical and horizontal components of flow at a site.

4.3.3.1 Ground-Water Level Measurements

To determine ground-water flow directions and ground-water flow rates, accurate water level measurements (measured to the nearest 0.01 foot) should be obtained. Procedures for obtaining water level measurements are presented in Section 7.2.2. At facilities where it is known or plausible that immiscible contaminants (i.e., light non-aqueous phase liquids (LNAPLs) or DNAPLs) occur (or are determined to potentially occur after considering the waste types managed at the facility) in the subsurface at the facility, both the depth(s) to the immiscible layer(s) and the thickness(es) of the immiscible layer(s) in the well should be recorded. Section 7.2.3 provides procedures for measuring the thickness of immiscible layers in wells.

If accurate documentation cannot be produced to show that the procedures for well surveying contained in Section 6.6, water level elevation measurements contained in Section 7.2.2, and detection of immiscible layers contained in Section 7.2.3 were met during the collection of water level measurements, the information generated may be judged inadequate.

For the purpose of measuring total head, piezometers and wells should have as short a screened interval as possible. Specifically, EPA recommends that the screens in piezometers or wells that are used to measure head be less than 10 feet long. In circumstances including, but not limited to the following, well screens longer than 10 feet may be warranted:

- Natural water level fluctuations necessitate a longer screen length;
- The interval monitored is slightly greater than the appropriate screen length (e.g., the interval monitored is 12 feet thick); or
- The aquifer monitored is homogeneous and extremely thick (e.g., greater than 300 feet), thus a longer screen (e.g., a 20-foot screen) represents a fairly discrete interval.

The head measured in a well with a long screened interval is a function of all of the different heads over the entire length of the screened interval. Care should be taken when interpreting water levels collected from wells that have long screened intervals (e.g., greater than 10 feet).

Hydrostratigraphic relationships should be determined by a qualified ground-water scientist when obtaining and evaluating water level data. Unqualified individuals may confuse a potentiometric surface with the water table in areas where both confined and unconfined aquifers exist. In all cases, well or piezometer screen placement should be based on the detailed boring log, and the well or piezometer screen should not intercept hydraulically separated zones of saturation.

At sites where the hydraulic gradient is so small that the error introduced by measuring water levels in crooked or out-of-plumb wells will produce an inaccurate determination of hydraulic gradient or flow direction, a deviation survey should be performed on all wells. If a well is out-of-plumb and/or not straight (crooked), the information gathered from the deviation survey should be used to correct water level elevations measured in the well. A deviation survey will determine whether the wells are in vertical alignment (i.e., straight) and are plumb. Several instruments and methods have been designed for this purpose; a good description of these instruments and methods is provided by Driscoll (1986). A proper deviation survey will consider both magnitude of well deviation and direction of deviation. If a well is out-of-plumb and/or not straight (crooked), the information gathered from the deviation survey should be used to correct water level elevations measured in the well, because the depth to ground water measured in an out-of-plumb or crooked well will be greater than the depth to ground water measured in a straight well. A correction can be accomplished easily by first graphing the actual vertical configuration of the well, and then by establishing a relationship between a measured water level elevation in the crooked and/or out-of-plumb well and the water level elevation in an imaginary straight and plumb well at the same location. A method for graphing the actual vertical configuration of an out-of-plumb and/or crooked well is provided by Driscoll (1986).

4.3.3.2 Establishing Horizontal Flow Direction and the Horizontal Component of Hydraulic Gradient

After the water level data and measurement procedures are reviewed to determine that they are accurate, the data should be used to:

- Construct potentiometric surface maps and water table maps that are based on the distribution of total head, such as the example in Figure 4. The data used to develop water table maps should be from piezometers or wells screened across the water table. The data used to develop potentiometric surface maps should be from piezometers or wells screened at approximately the same elevation in the same hydrostratigraphic unit;

- Determine the horizontal direction(s) of ground-water flow by drawing flow lines on the potentiometric surface map or water table map (i.e., construct a flow net); and

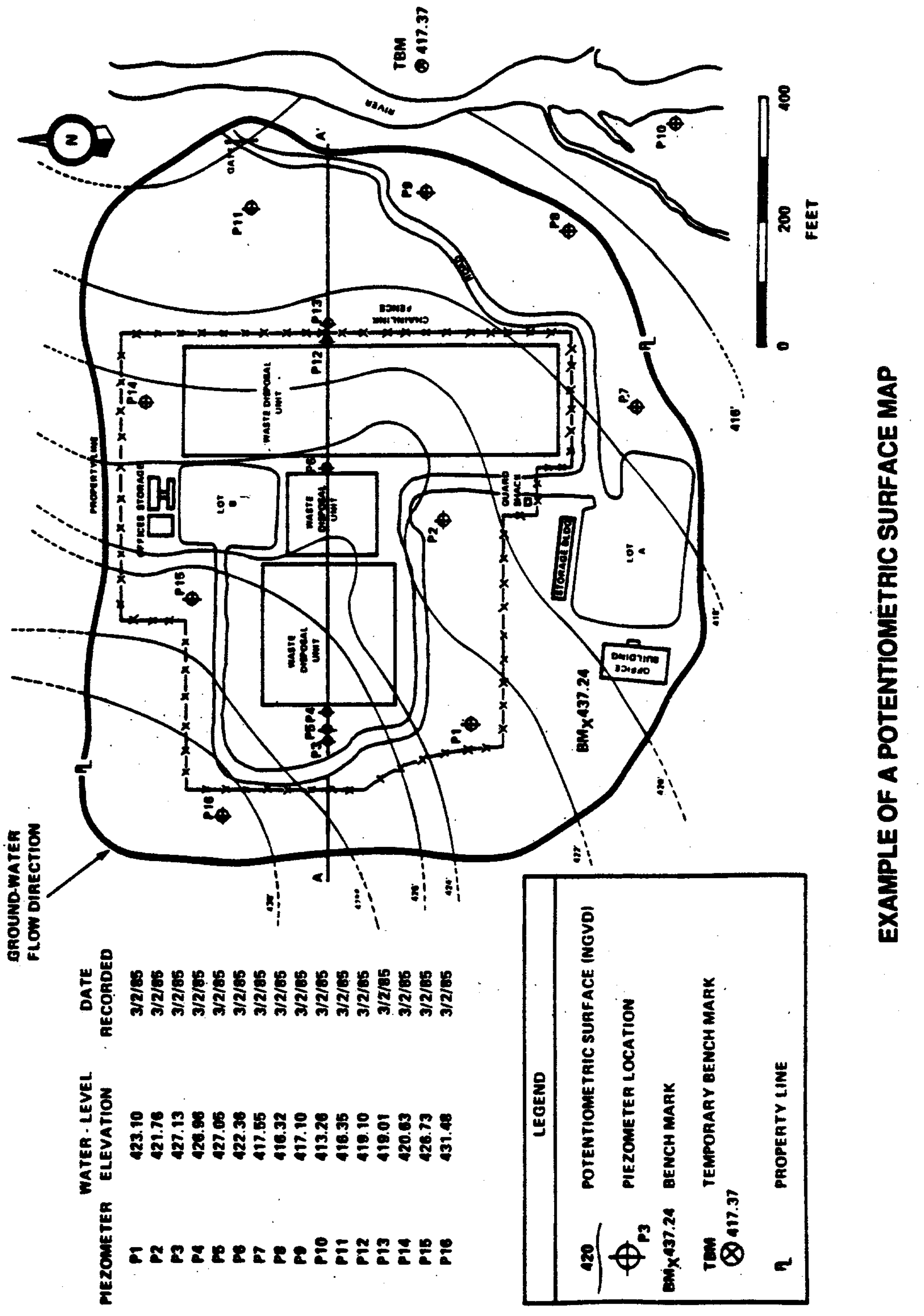
- Calculate value(s) for the horizontal and vertical components of hydraulic gradient.

Methods for constructing potentiometric surface and water table maps, constructing flow nets, and determining the direction(s) of ground-water flow, are given by USEPA (1989c) and Freeze and Cherry (1979). Methods for calculating hydraulic gradient are provided by Heath (1982) and USEPA (1989c).

A potentiometric surface or water table map will give an approximate idea of general ground-water flow directions; however, to locate monitoring wells properly, ground-water flow direction(s) and hydraulic gradient(s) should be established in both the horizontal and vertical directions and over time at regular intervals (e.g., over a one-year period at three-month intervals).

4.3.3.3 Establishing Vertical Flow Direction and the Vertical Component of Hydraulic Gradient

To adequately determine the ground-water flow directions, the vertical component of ground-water flow should be evaluated directly. This generally requires the installation of multiple piezometers or wells in clusters or nests, or the installation of multi-level wells or sampling devices. A piezometer or well nest is a closely spaced group of piezometers or wells screened at different depths, whereas a multi-level well is a single device. Both piezometer/well nests and multi-level wells allow for the measurement of vertical variations in hydraulic head. To obtain reliable measurements, the following criteria should be considered in the evaluation of data from piezometer/well nests and multi-level wells:



PIEZOMETER	WATER - LEVEL ELEVATION	DATE RECORDED
P1	423.10	3/2/85
P2	421.76	3/2/85
P3	427.13	3/2/85
P4	426.96	3/2/85
P5	427.05	3/2/85
P6	422.36	3/2/85
P7	417.55	3/2/85
P8	416.32	3/2/85
P9	417.10	3/2/85
P10	413.26	3/2/85
P11	416.35	3/2/85
P12	419.10	3/2/85
P13	419.01	3/2/85
P14	420.63	3/2/85
P15	426.73	3/2/85
P16	431.48	3/2/85

LEGEND

420	POTENTIOMETRIC SURFACE (NGVD)
⊕ P3	PIEZOMETER LOCATION
BM x 437.24	BENCH MARK
TBM ⊗ 417.37	TEMPORARY BENCH MARK
℄	PROPERTY LINE

EXAMPLE OF A POTENTIOMETRIC SURFACE MAP

FIGURE 4

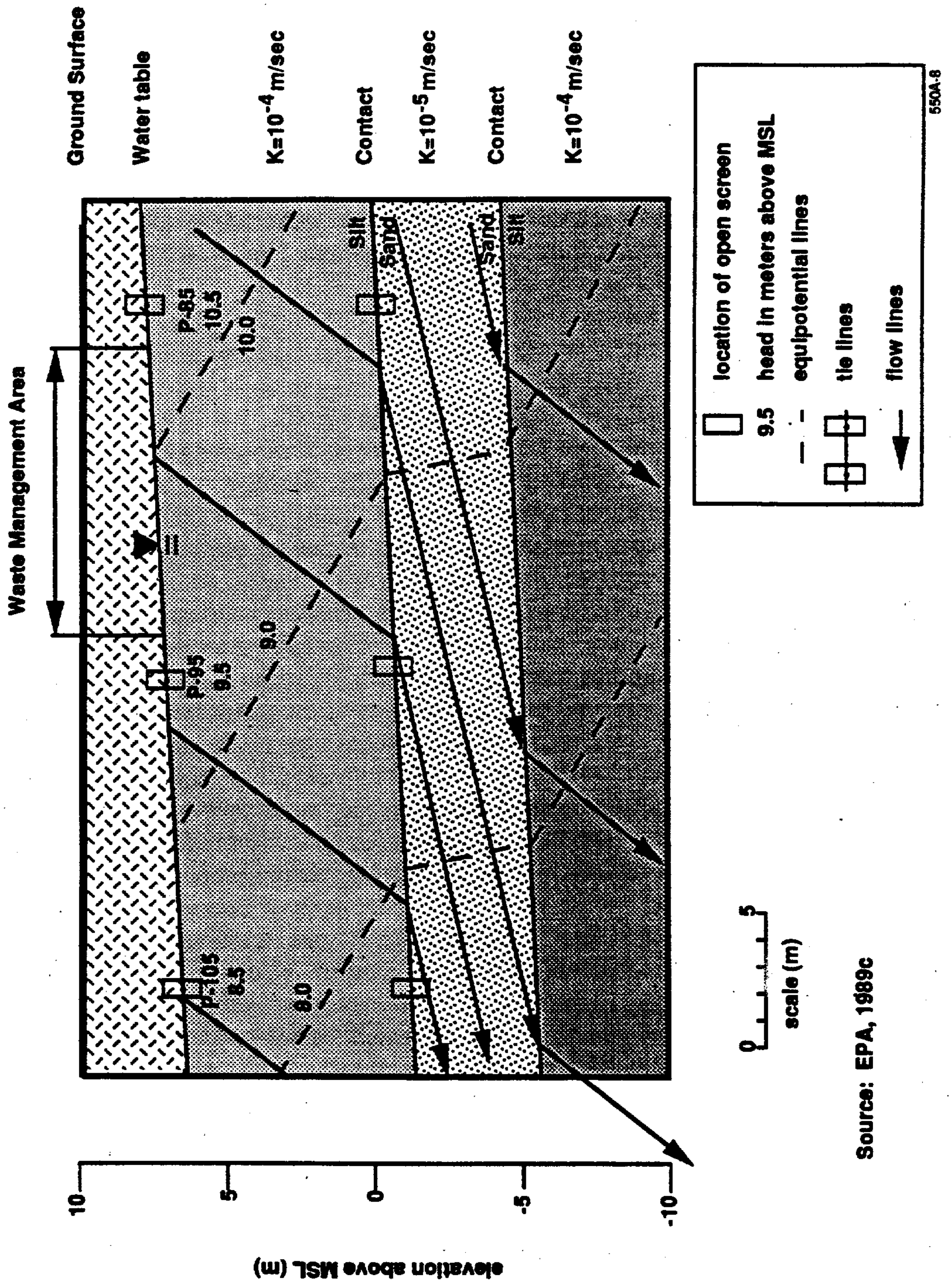
- Data obtained from multiple piezometers or wells placed in a single borehole may be erroneous. Placement of vertically nested piezometers or wells in closely-spaced, separate, boreholes, or single multi-level devices in single boreholes, is preferred.

- The vertical component of hydraulic gradient should be calculated, and the vertical direction of ground-water flow should be determined, for a minimum of two vertical profiles at the site. These profiles should be aligned roughly parallel to the horizontal direction of ground-water flow as indicated by the potentiometric surface or water table map.

- All other procedures for water level measurement described in this Manual should be met.

When reviewing data obtained from multiple placement of piezometers or wells in single boreholes, the construction details of the well should be carefully evaluated. Not only is it extremely difficult to adequately seal several piezometers/wells at discrete depths within a single borehole, but sealant materials may migrate from the seal of one piezometer/well to the screened interval of another piezometer/well. Therefore, the design of a piezometer/well nest should be carefully considered. Placement of piezometers/wells in closely-spaced boreholes, where piezometers/wells have been screened at different, discrete depth intervals, is likely to produce more accurate information. The primary concerns with the installation of piezometers/wells in closely-spaced, separate boreholes are: 1) the disturbance of geologic and soil materials that occurs when one piezometer is installed may be reflected in the data obtained from another piezometer located nearby, and 2) the analysis of water levels measured in piezometers that are closely-spaced, but separated horizontally, may produce imprecise information regarding the vertical component of ground-water flow. The limitations of installing multiple piezometers either in single or separate boreholes may be overcome by the installation of single multi-level monitoring wells or sampling devices in single boreholes. The advantages and disadvantages of these types of devices are discussed by Aller et al. (1989).

The owner or operator should determine the vertical direction(s) of ground-water flow using the water levels measured in multi-level wells or piezometer/well nests to construct flow nets. Flow nets should depict piezometer/well depth and length of the screened interval. It is important to accurately portray the screened interval on the flow net to ensure that the piezometer/well is actually monitoring the desired water-bearing unit. A flow net such as that presented in Figure 5 should be developed from information obtained from piezometer/well clusters or nests screened at different, discrete depths. Detailed guidance for the construction and evaluation of flow nets in cross section (vertical flow nets) is provided by USEPA (1989c). Further information can be obtained from Freeze and Cherry (1979).



Source: EPA, 1989c

EXAMPLE OF FLOW NET DERIVED FROM PIEZOMETER DATA

FIGURE 5

4.3.3.4 Seasonal and Temporal Factors

The water level monitoring program should be structured to provide precise water level measurements in a sufficient number of piezometers or wells at a sufficient frequency to gauge both seasonal average flow directions and temporal fluctuations in ground-water flow directions (§264.97(f)). The owner/operator should determine and assess seasonal/temporal, natural, and artificially-induced (e.g., off-site production well pumping, agricultural use) short-term and long-term variations in ground-water elevations, ground-water flow patterns, and ground-water quality. Such factors that may influence ground-water elevations and flow include:

- Barometric effects;
- Variations in precipitation and runoff/recharge rates;
- On-site or off-site well pumping, recharge, and discharge;
- Tidal processes or other intermittent natural variations (e.g., river stage);
- Off-site or on-site construction, or changing land use patterns;
- Off-site or on-site lagoons, ponds, or streams;
- Deep well injection;
- On-site waste disposal practices; and
- Other anthropogenic effects, such as a nearby passing train;

Ground-water flow may exhibit significant seasonal variations. For example, in the humid eastern regions of the United States, heads are generally highest in late winter or spring and lowest in late summer or early autumn. However, short-term processes may create ground-water flow patterns that are markedly different from ground-water flow patterns determined by seasonal averages. Such processes include changes in river stage, tides, and storm events.

Changes in land use may affect ground-water flow by altering recharge or discharge patterns. Examples of such changes in land use patterns include the paving of recharge areas or damming of waterways. Municipal, industrial, or agricultural off-site or on-site well pumping may affect both the rate and direction of ground-water flow. On-site and off-site well pumping may be seasonal, or dependent on more complex water use patterns.

Characterizing seasonal and temporal variations in ground-water flow is important for site investigations involving aquifer tests. Methods are available for correcting most seasonal and temporal effects, and they should be considered when designing aquifer tests and interpreting the results. When determining hydraulic conductivities and other aquifer parameters using aquifer tests, piezometers/wells should be installed and continuously monitored during the test outside of the stressed aquifer zone to document and allow correction for any changes in the potentiometric surface or water table that are not related to the aquifer test.

4.3.4 Determining Hydraulic Conductivity

Hydraulic conductivity is a measure of a material's ability to transmit water. Generally, poorly sorted silty or clayey materials have low hydraulic conductivities, whereas well-sorted sands and gravels have high hydraulic conductivities. An aquifer may be classified as either homogeneous or heterogeneous and either isotropic or anisotropic according to the way its hydraulic conductivity varies in space. An aquifer is homogeneous if the hydraulic conductivity is independent of location within the aquifer; it is heterogeneous if hydraulic conductivities are dependent on location within the aquifer. If the hydraulic conductivity is independent of the direction of measurement at a point in a geologic formation, the formation is isotropic at that point. If the hydraulic conductivity varies with the direction of measurement at a point, the formation is anisotropic at that point.

In heterogeneous aquifers, owners and operators should determine horizontal hydraulic conductivity as a function of vertical position in the aquifer. Knowledge of the variation in hydraulic conductivity as a function of vertical position in the subsurface is essential to understanding the potential migration of contaminants. Molz et al. (1989) explain that the common practice of averaging hydraulic conductivity over a vertical interval can mislead investigators about the dispersive properties of an aquifer. Impeller flowmeters, multilevel slug tests, or tracer tests may be used to determine hydraulic conductivity with vertical position in an aquifer (Molz et al., 1990; Molz et al., 1989).

Determining values for hydraulic conductivity as a function of direction of measurement within an anisotropic saturated zone also is important in evaluating ground-water flow and contaminant migration. Anisotropy within an aquifer is typically the result of small-scale stratification (bedding) of sedimentary deposits and/or fractures (Hsieh and Neuman, 1985; McWhorter and Sunada, 1977). In bedded deposits, hydraulic conductivity in the direction parallel to bedding is typically (1) the maximum hydraulic conductivity, and (2) the same magnitude in all directions within planes parallel to the bedding. The magnitude of hydraulic conductivity is typically smallest in the direction perpendicular to bedding (McWhorter and Sunada, 1977). Therefore, for the purpose of understanding ground-water flow and contaminant migration in stratified aquifers, investigators are typically concerned with determining the ratio of the horizontal component of hydraulic conductivity (Kh) and the vertical component of hydraulic conductivity (Kv), or Kh:Kv ratio. Way and McKee (1982) present one method for determining the horizontal and vertical components of hydraulic conductivity. In fractured media, the principal components of hydraulic conductivity may be in directions other than horizontal and vertical. Hsieh and Neuman (1985) provide a method for determining the primary components of hydraulic conductivity in these settings.

4.3.4.1 Determining Hydraulic Conductivity Using Field Methods

Sufficient aquifer testing (i.e., field methods) should be performed to provide representative estimates of hydraulic conductivity. Acceptable field methods include conducting aquifer tests with single wells, conducting aquifer tests with multiple wells, and using flowmeters. This section provides brief overviews of these methods, including two methods for obtaining vertically-discrete measurements of hydraulic conductivity. Complete descriptions of the methods summarized in this section are presented in greater detail in the references provided.

A commonly used test for determining horizontal hydraulic conductivity with a single well is the slug test. A slug test is performed by suddenly adding, removing, or displacing a known volume of water from a well and observing the time that it takes for the water level to recover to its original level (Freeze and Cherry, 1979). Similar results can be achieved by pressurizing the well casing, depressing the water level, and suddenly releasing the pressure to simulate removal of water from the well. In most cases, EPA recommends that water not be introduced into wells during aquifer tests to avoid altering ground-water chemistry. Single well tests are limited in scope to the area directly adjacent to the well screen. The vertical extent of the well screen generally defines the part of the geologic formation that is being tested.

The following should be accurately recorded when conducting slug tests: the volume of the slug added (e.g., plugged stainless steel pipe) or the volume of water removed from the well; the changing static water elevation (±0.01 inch) prior to, during, and following completion of the test; and the time elapsed between water level measurements. Tests in highly permeable materials often require the use of pressure transducers and high speed recording equipment. The well screen and filter pack adjacent to the interval under examination should be properly developed either to ensure the removal of fines or to correct for drilling effects. The interpretation of the single well test data should be consistent with existing geologic information (e.g., boring log data).

A modified version of the slug test, known as the multilevel slug test, is capable of providing depth-discrete measurements of hydraulic conductivity. The drawback of the multilevel slug test is that the test relies on the ability of the investigator to isolate a portion of the aquifer using a packer. Nevertheless, multilevel slug tests, when performed properly, can produce reliable measurements of hydraulic conductivity. All equipment necessary for performing multilevel slug tests is available commercially. The procedure for conducting a multilevel slug test involves inflating two packers separated by a length of perforated pipe within the well’s screened interval to isolate the desired test region of the aquifer. A slug test is then performed for the test region of the aquifer by inducing water flow through the isolated section of the well screen. The slug test data collected can be analyzed by a number of methods. A multilevel slug test method is described by Molz et al. (1990).

Multiple well tests involve withdrawing water from, or injecting water into, one well, and obtaining water level measurements over time in observation wells. Multiple well tests are often performed as pumping tests in which water is pumped from one well and drawdown is observed in nearby wells. A step-drawdown test should precede most pumping tests to determine an appropriate discharge rate. Aquifer tests conducted with wells screened in the same water-bearing zone can be used to provide hydraulic conductivity data for that zone. Multiple well tests for hydraulic conductivity characterize a greater proportion of the subsurface than single well tests and thus provide average values of hydraulic conductivity. Multiple well tests require measurement of parameters similar to those required for single well tests (e.g., time, drawdown). When using aquifer test data to determine aquifer parameters, it is important that the solution assumptions can be applied to site conditions. Aquifer test solutions are available for a wide variety of hydrogeologic settings, but are often applied incorrectly by inexperienced persons. Incorrect assumptions regarding hydrogeology (e.g., aquifer boundaries, aquifer lithology, and aquifer thickness) may translate into incorrect estimations of hydraulic conductivity. A qualified ground-water scientist with experience in designing and interpreting aquifer tests should be consulted to ensure that aquifer test solution methods fit the hydrogeologic setting. Kruseman and deRidder (1989) provide a comprehensive discussion of aquifer tests.

Multiple well tests conducted with wells screened in different water-bearing zones furnish information concerning hydraulic communication between the zones. For these aquifer tests, piezometers should be located and screened in permeable, semi-permeable, and "impermeable" zones. Water levels in these zones should be monitored during the aquifer test to determine the type of aquifer system (e.g., confined, unconfined, semi-confined, or semi-unconfined) beneath the site, and their leakance (coefficient of leakage) and drainage factors (Kruseman and deRidder, 1989). A multiple well aquifer test should be considered at every site as a method to establish the vertical extent of the uppermost aquifer and to evaluate hydraulic connection between aquifers.

Certain aquifer tests are inappropriate for use in karst terranes characterized by a well-developed conduit flow system, and they also may be inappropriate in fractured bedrock. When a well that is located in a karst conduit or a large fracture is pumped, the water level in the conduits is lowered. This lowering produces a drawdown that is not radial (as in a granular aquifer), but is instead a trough-like depression that is parallel to the pumped conduit or fracture. Radial flow equations do not apply to drawdown data collected during such a pump test. This means that a conventional semi-log plot of drawdown versus time is inappropriate for the purpose of determining the aquifer’s transmissivity and storativity. Aquifer tests in karst aquifers can be useful, but valid determinations of hydraulic conductivity, storativity, and transmissivity may be impossible. However, an aquifer test can provide information on the presence of conduits, on storage characteristics, and on the percentage of Darcian flow. McGlew and Thomas (1984) provide a more detailed discussion of the appropriate use of aquifer tests in fractured bedrock, and the suitable interpretation of test data. Dye tracing also is used to determine the rate and direction of ground-water flow in karst settings (Section 5.2.4).

Several additional factors should be considered when planning an aquifer test:

- Owners and operators should provide for the proper storage and disposal of potentially contaminated ground water pumped from the well system;

- Owners and operators should consider the potential effects of pumping on existing plumes of contaminated ground water;

- In designing aquifer tests and interpreting aquifer test data, owners/operators should account and correct for seasonal, temporal, and anthropogenic effects on the potentiometric surface or water table. This is usually done by installing piezometers outside the influence of the stressed aquifer. These piezometers should be continuously monitored during the aquifer test. It may be necessary to correct for anomalies when evaluating the aquifer test data. A qualified ground-water scientist could recommend several methods for this, many of which are presented by Kruseman and deRidder (1989); and

- EPA recommends the use of a step-drawdown test to provide a basis for selecting discharge rates prior to conducting a full-scale pumping test. This will ensure that the pumping rate chosen for the subsequent pump test(s) can be sustained without exceeding the available drawdown of the pumped wells, and will produce a measurable drawdown in the observation wells.

Certain flowmeters have recently been recognized for their ability to provide accurate and vertically discrete measurements of hydraulic conductivity. One of these, the impeller flowmeter, is currently available commercially; more sensitive types of flowmeters (i.e., the heat-pulse flowmeter and electromagnetic flowmeters) should be available in the near future. Use of the impeller flowmeter requires running a caliper log to measure the uniformity of the diameter of the well screen. The well is then pumped with a small pump operated at a constant flow rate. The flowmeter is lowered into the well and the discharge rate is measured every few feet by raising the flowmeter in the well. Hydraulic conductivity values can be calculated from the recorded data using the Cooper-Jacob (1946) formula for horizontal flow to a well. Use of the impeller flowmeter is limited at sites where the presence of low permeability materials does not allow pumping of the wells at rates sufficient to operate the flowmeter. The applications of flowmeters in the measure of hydraulic conductivity is described by Molz et al. (1990) and Molz et al. (1989).

4.3.4.2 Determining Hydraulic Conductivity Using Laboratory Methods

It may be beneficial to use laboratory measurements of hydraulic conductivity to augment results of field tests; however, field methods provide the best estimate of hydraulic conductivity in most cases. Because of the limited sample size, laboratory tests can miss secondary porosity features such as fractures and joints, and hence, can greatly underestimate overall aquifer hydraulic conductivities. Laboratory tests may provide valuable information about the vertical component of hydraulic conductivity of aquifer materials. However, laboratory test results always should be confirmed by field measurements, which sample a much larger portion of the aquifer. In addition, laboratory test results can be profoundly affected by the test method selected and by the manner in which the tests are carried out (e.g., the extent to which sample collection and preparation have changed the in situ hydraulic properties of the tested material). Special attention should be given to the selection of the appropriate test method and test conditions, and to quality control of laboratory results. McWhorter and Sunada (1977), Freeze and Cherry (1979), and Sevee (1991) discuss determining hydraulic conductivity in the laboratory. Laboratory tests may provide the best estimates of hydraulic conductivity for materials in the unsaturated zone, but are likely to be less accurate than field methods for materials in the saturated zone (Cantor et al., 1987).

4.3.4.3 Data Evaluation

For comparisons of hydraulic conductivity measurements, the following criteria should be used to determine the accuracy or completeness of information:

- Use of a single well test will necessitate that more individual tests be conducted at different locations to define sufficiently the variation in hydraulic conductivity across the site.

- Field hydraulic conductivity measurements generally provide average values for the entire area across a well screen. Short well screens are necessary to measure the hydraulic conductivity of discrete stratigraphic intervals. On the other hand, in situations where well screens only partially penetrate an aquifer, it is difficult, if not impossible, to correct mathematical equations for the resultant distortion in flow patterns created during the pump test (Driscoll, 1986; Fetter, 1980). If the average hydraulic conductivity for a formation is required, entire formations may be screened, or data may be combined from overlapping clusters.

It is important that measurements define both the vertical and horizontal components of hydraulic conductivity across a site. Laboratory tests on cores collected during the boring program may be helpful in ascertaining vertical hydraulic conductivity in saturated strata. In assessing the accuracy of hydraulic conductivity measurements at a site, results from the boring program used to characterize the site geology should be considered. Zones of high permeability or fracture identified from drilling logs should be considered when evaluating hydraulic conductivity. Information from boring logs can be used to refine the data generated by single or multiple well tests, and a comparison with existing data from nearby localities that are in a similar geologic setting also can be useful.

4.3.5 Determining Ground-Water Flow Rate

The calculation of average ground-water flow rate (average linear velocity of ground-water flow), or seepage velocity, is discussed in detail in USEPA (1989c), in Freeze and Cherry (1979), and in Kruseman and deRidder (1989). The average linear velocity of ground-water flow ($\bar{v}$) is a function of hydraulic conductivity (K), hydraulic gradient (i), and effective porosity (n_e):

$$\bar{v} = -\frac{Ki}{n_e}$$

Methods for determining hydraulic gradient and hydraulic conductivity are presented in Sections 4.3.3 and 4.3.4 of this Manual. Effective porosity, the percentage of the total volume of a given mass of soil, unconsolidated material, or rock that consists of interconnected pores through which water can flow, should be estimated from laboratory tests or estimated from values cited in the literature. (Fetter (1980) provides a good discussion of effective porosity. Barari and Hedges (1985) provide default values for effective porosity.) USEPA (1989c) provides methods for determining flow rates in heterogeneous and/or anisotropic systems and should be consulted prior to calculating flow rates.

4.4 Interpreting and Presenting Data

The following sections offer guidance on interpreting and presenting hydrogeologic data collected during the site characterization process. Graphical representations of data, such as cross sections and maps, are typically extremely helpful both when evaluating data and when presenting data to interested individuals.

4.4.1 Interpreting Hydrogeologic Data

Once the site characterization data have been collected, the following tasks should be undertaken to support and develop the interpretation of site hydrogeologic data:

- Review borehole and well logs to identify major rock, unconsolidated material, and soil types and establish their horizontal and vertical extent and distribution;

- From borehole and well log (and outcrop, where available) data, construct a minimum of two representative cross-sections for each hazardous waste management unit, one in the direction of ground-water flow and one orthogonal to ground-water flow;

- Identify zones of suspected high hydraulic conductivity, or structures likely to influence contaminant migration through the unsaturated and saturated zones;

- Compare findings with other studies and information collected during the preliminary investigation to verify the collected information; and

- Determine whether laboratory and field data corroborate and are sufficient to define petrology, effective porosity, hydraulic conductivity, lateral and vertical stratigraphic relationships, and ground-water flow directions and rates.

After the hydrogeologic data are interpreted, the findings should be reviewed to:

- Identify information gaps;

- Determine whether collection of additional data or reassessment of existing data is required to fill in the gaps; and

- Identify how information gaps are likely to affect the ability to design a RCRA monitoring system.

Generally, lithologic data should correlate with hydraulic properties (e.g., clean, well sorted, unconsolidated sands should exhibit high hydraulic conductivity). If the investigator is unable to: 1) correlate stratigraphic units between borings; 2) identify zones of potentially high hydraulic conductivity, their thickness and lateral extent; or 3) identify confining formations/layers, their thickness and lateral extent, then additional boreholes should be drilled and additional samples should be collected to adequately describe the hydrogeology of the site.

Owners and operators should evaluate the potential for confining units to degrade in the presence of site-specific waste types. In pristine areas, the possible future chemical degradation of a confining layer should be of concern during any assessment monitoring or corrective action at the facility. Marls, limestones, and dolomites, for instance, are chemically attacked by low pH wastes because of their carbonate content. Studies have shown that certain concentrated organic liquids can cause desiccation of clay minerals, which can lead to cracking and to a significant increase in permeability (Daniel et al., 1988). Smectitic, and to a lesser extent illitic, clays are ineffective barriers to the migration of many highly-concentrated organic chemicals. In contaminated areas, a clay-rich, but chemically- degraded confining layer may lead to unanticipated contaminant migration. An example of how a contaminant may affect the integrity of a confining layer is shown in Figure 6.

When establishing the locations of wells that will be used to monitor ground water in hydrogeologic settings characterized by ground-water flow in porous media, the following should be documented:

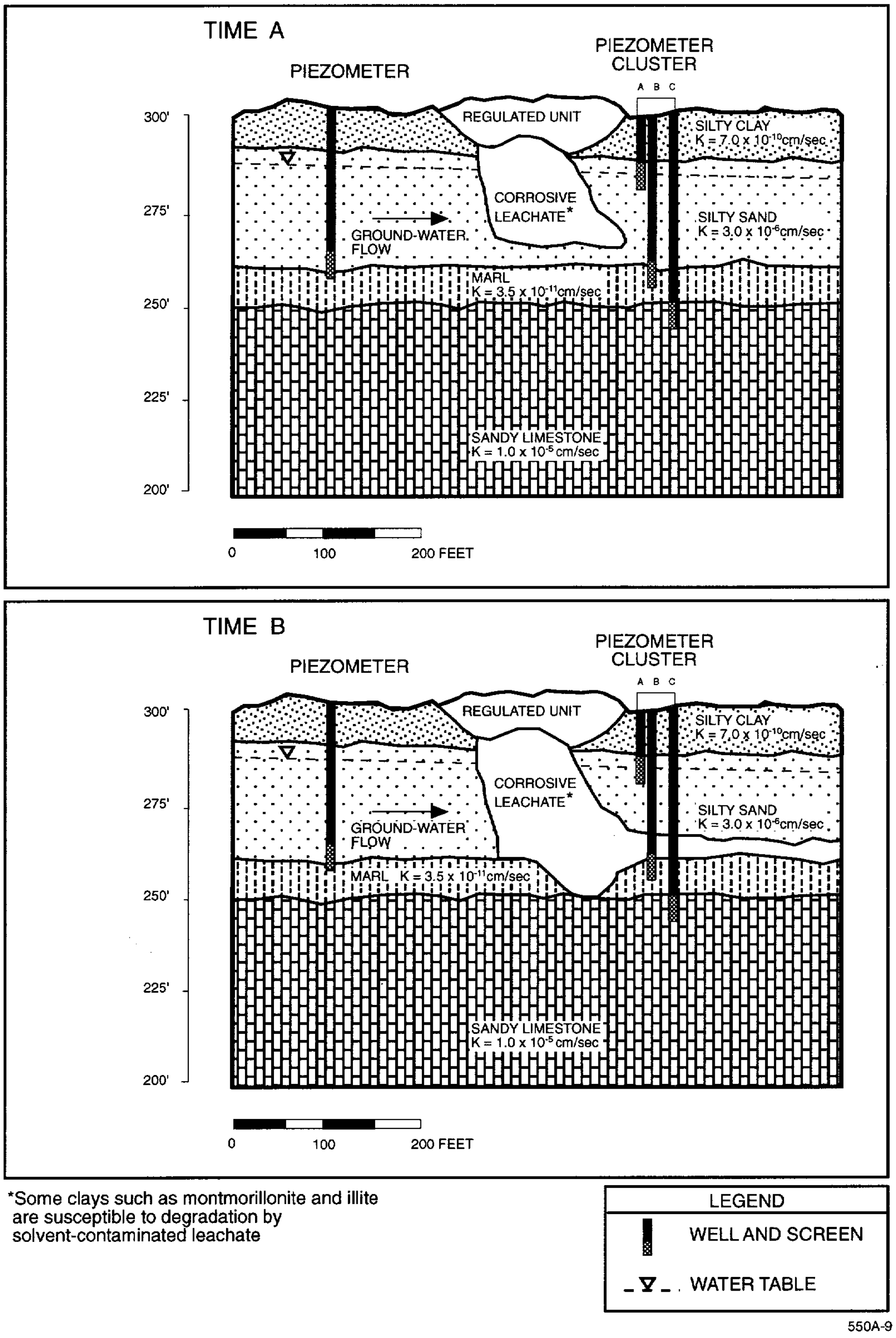
- Ground-water flow rate should be based on accurate measurements of hydraulic conductivity and hydraulic gradient, and accurate measurements or estimates of effective porosity;
- The horizontal and vertical components of flow should be accurately depicted in flow nets and based on valid data; and
- Any seasonal or temporal variations in the water table or potentiometric surface, and in vertical flow components, should be determined.

Once an understanding of horizontal and vertical ground-water flow has been established, it is possible to estimate where monitoring wells will most likely intercept contaminant flow.

4.4.2 Presenting Hydrogeologic Data

Subsequent to the generation and interpretation of site-specific geologic data, the data should be presented in geologic cross-sections, topographic maps, geologic maps, and soil maps. The Agency suggests that owners/operators obtain or prepare and review topographic, geologic, and soil maps of the facility, in addition to site maps of the facility and waste management units. In cases where suitable maps are not available, or where the information contained on available maps is not complete or accurate, detailed mapping of the site should be performed by qualified and experienced individuals. An aerial photograph and a topographic map of the site should be included as part of the presentation of hydrogeologic data and should meet the requirements of §§270.13(h) and 270.14(b)(19), respectively. The topographic map should be constructed under the supervision of a qualified surveyor and should provide contours at a maximum of two-foot intervals, as shown in Figure 7. Aerial photographs with acetate overlays, the use of geologic data bases, or Geographic Information Systems (GIS) may be suitable methods for presenting some data.

Geologic and soil maps should be based on rock, unconsolidated material, and soil identifications gathered from borings and outcrops. The maps should use colors or symbols to represent each soil, unconsolidated material, and rock type that outcrops on the surface. The maps also should show locations of all borings and outcrops placed during the site characterization. Geologic and soil maps are important because they can provide interpretive information describing how site geology fits into the local and regional geologic setting.



*Some clays such as montmorillonite and illite are susceptible to degradation by solvent-contaminated leachate

EXAMPLE OF A CONTAMINANT AFFECTING THE INTEGRITY OF A CONFINING LAYER

FIGURE 6

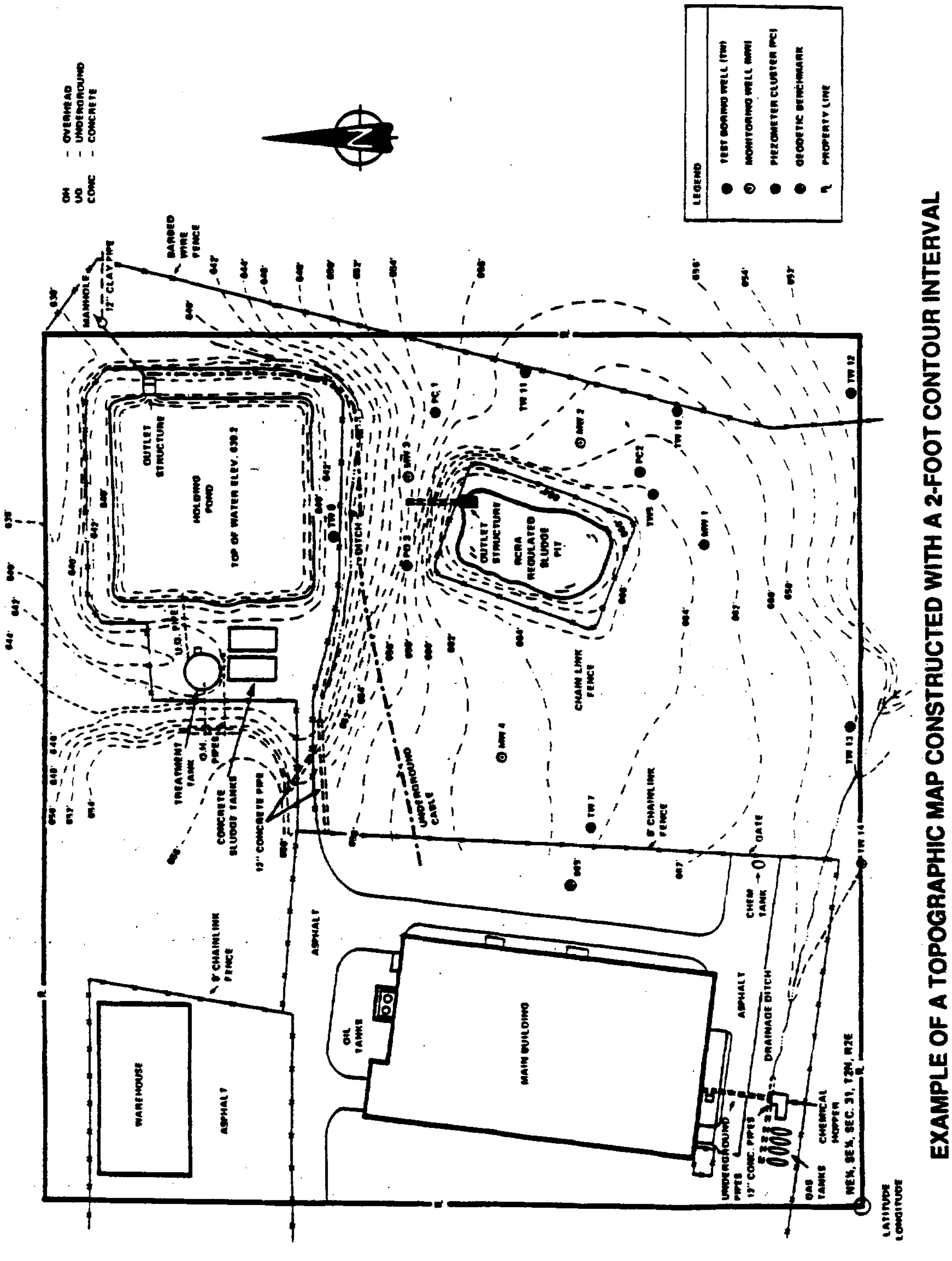


FIGURE 7

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Structure contour maps and isopach maps should be prepared for each water-bearing zone that comprises the uppermost aquifer and for each significant confining layer, especially the one underlying the uppermost aquifer. A structure contour map depicts the configuration (i.e., elevations) of the upper or lower surface or boundary of a particular geologic or soil formation, unit, or zone. Structure contour maps are especially important in understanding DNAPL movement because DNAPLs may migrate in the direction of the dip of lower permeability units. Separate structure contour maps should be constructed for the upper and lower surfaces (or contacts) of each of the zones of interest. Isopach maps should depict contours that indicate the thickness of each of these zones. These maps are generated from borings and geologic logs, and from geophysical measurements. In conjunction with the cross-sections, these maps are used to help determine monitoring well locations, depths, and screen lengths during the design of the detection monitoring system.

A potentiometric surface map or water table map should be prepared for each water-bearing zone that comprises the uppermost aquifer. Potentiometric surface and water table maps should show both the direction and rate of ground-water flow and the locations of all piezometers and wells on which they are based. The water level measurements for all piezometers and wells on which the potentiometric surface map or water table map is based should be shown on the potentiometric surface or water table map. If seasonal or temporal variations in ground-water flow occur at the site, a sufficient number of potentiometric surface or water table maps should be prepared to show these variations. Potentiometric surface and water table maps can be combined with structure contour maps for a particular formation or unit.

An adequate number of cross sections (at least two for each hazardous waste management unit at the facility) should be prepared to depict significant stratigraphic and structural trends and to reflect stratigraphic and structural features in relation to local and regional ground-water flow. On each cross section, the following should be depicted or reported:

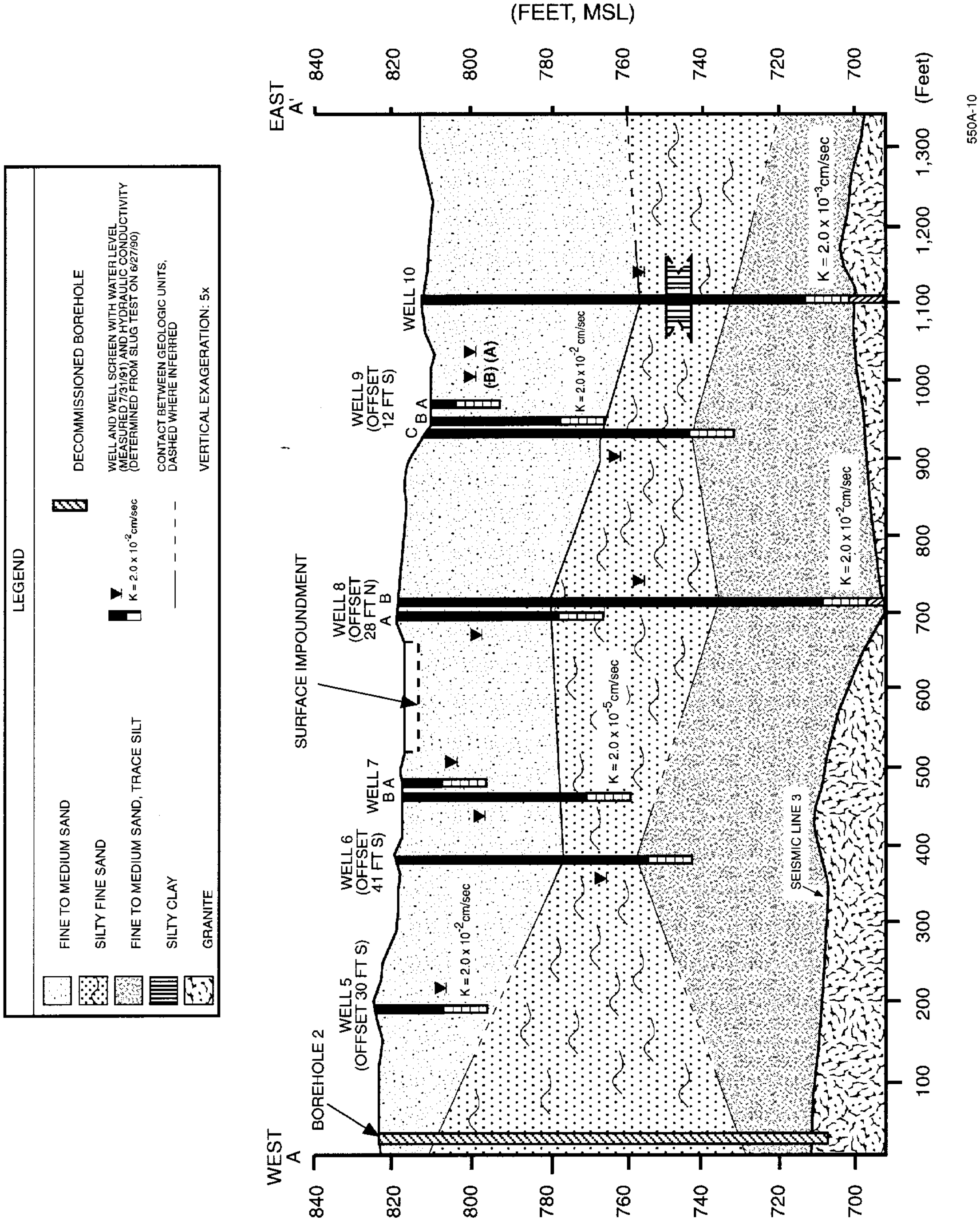
- Orientation (aspect);
- Horizontal and vertical scale;
- Location of match points or intersections with other cross sections or with geophysical survey lines;
- Topography;
- Lithology of all stratigraphic units;
- Structural features;

- Measured hydraulic conductivity values;
- Each well used to construct the cross section, including:
    - Well identifier (well number),
    - Distance and direction the well is offset from the line of section,
    - Total depth of borehole,
    - Well depth,
    - Screened interval, and
    - Water level and date measured;
- Each borehole used to construct the cross section, including:
    - Borehole identifier (borehole number),
    - Distance and direction the borehole is offset from the line of section, and
    - Borehole depth;
- Information obtained from surface and borehole geophysical surveys, as available; and
- Total depths and liquid depths of natural and human-made surface water bodies and waste management units (e.g., streams, ditches, impoundments, ponds), as available.

If these details are not available, the site characterization is inadequate. Figure 8 is an example of an acceptable geologic cross-section.

4.4.3 The Conceptual Model

Conceptualization is the process of integrating the individual components or characteristics of the hydrogeologic system, including the characteristics of the managed wastes. The conceptual model is the integrated picture of the hydrogeologic system and the waste management setting. Conceptual models are expressed both narratively and graphically. The two objectives of a conceptual model in a detection monitoring program are:



EXAMPLE OF A GEOLOGICAL CROSS-SECTION

FIGURE 8

- To develop a sound and informed understanding of both the waste type and waste management scenario, and of the geology, hydrogeology, andgeochemistry of the vadose zone, the uppermost aquifer, and its confining layer(s); and

- To predict the movement of contaminants into and through the uppermost aquifer.

The conceptual model is the product of the review and interpretation of the data presentation/reduction outputs (e.g., maps, cross-sections) described in the previous sections.

An accurate conceptual model of the site should be the final output of the site characterization program. The conceptual model should incorporate all essential features of the hydrogeologic system and waste type under study. The final conceptual model should be a site-specific description of the hydrogeology of the vadose zone, the uppermost aquifer, and its confining units; it should consider the characteristics of the wastes managed at the facility; and it should contain all of the information necessary to design an adequate monitoring system. The degree of detail and accuracy that is necessary to develop a conceptual model varies according to hydrogeologic setting and waste type. For example, a homogeneous unconfined aquifer may demand only simple cross-sections and water table maps to illustrate the conceptual model. In contrast, more complicated settings with multiple aquifers, multiple confining layers, and complex waste types will demand more complex hydrogeologic models such as flow-nets, potentiometric surface or water table maps for each aquifer, geochemical diagrams, and a series of structure contour and isopach maps. In formulating the conceptual model, the hydrogeologist should only consider those geologic features that affect ground-water flow, quality, and contaminant transport.

A preliminary conceptual model is formulated early in the site investigation process using data obtained during the preliminary investigation to establish the hydrogeologic and waste management setting. The model is gradually refined by building an understanding of the site-specific information obtained during the boring program and other field investigations. Interpretation of data through cross-sections and maps improves the model until a final integrated picture of the site's hydrogeologic and waste management setting is established. The development of the conceptual model is an ongoing process that should continue throughout the entire site characterization program. Interim conceptual models developed at the various stages of the site characterization are invaluable for planning subsequent field investigation activities so that they are properly directed towards supplying missing information.

After the detection monitoring system has been installed, the conceptual model of a site should be further refined as additional information regarding the site is obtained. For instance, various natural and artificial factors (e.g., the installation of a water supply well in the vicinity of the site, salt-water intrusion, the construction of a dam) may affect environmental conditions at the site years after the monitoring system is installed. Similarly, environmental characteristics or conditions that were not discerned during field investigations (e.g., reversal in the direction of ground-water flow during flood conditions) may become evident in the future, thus requiring reevaluation of the conceptual model. A refinement of the conceptual model may require that the owner/operator modify the ground-water monitoring system.

CHAPTER FIVE

DETECTION MONITORING SYSTEM DESIGN

This chapter discusses the design of detection monitoring systems. Section 5.1 addresses the design of detection monitoring systems in environments where ground-water flow occurs through porous media. As discussed in Section 4.3.1, the term "porous media" generally encompasses both unconsolidated granular deposits and rock (Freeze and Cherry, 1979). In some areas underlain by fractured rock or karst terrane, ground-water flow does not conform to the principles that describe ground-water flow through porous media. In these settings, ground-water flow may occur predominantly through conduits and fractures. Appropriate supplemental monitoring strategies for these settings are discussed in detail in Section 5.2.

5.1 Ground-Water Monitoring in Aquifers Dominated by Ground-Water Flow Through Porous Media

This section provides guidance for determining the number and location of detection monitoring wells in aquifers dominated by ground-water flow through porous media. The correct placement of monitoring wells relative to hazardous waste management units is an obvious goal of a detection monitoring program.

5.1.1 Introduction

The location of both background and point of compliance (i.e., downgradient) monitoring wells at permitted facilities must comply with the requirements of §264.97. Point of compliance monitoring wells should be located so that they intercept potential pathways of contaminant migration. Background wells should be located so that they provide ground-water samples that are representative of the quality of ground water that has not been affected by leakage from the waste management unit. The number and location of monitoring wells must allow for the detection of contamination when hazardous waste or hazardous constituents have migrated from the waste management area to the uppermost aquifer (§264.97(a)(3)).

There is no required minimum number of wells at permitted facilities; the owner/operator is simply required to install a "sufficient" number of wells to allow for determination of background water quality and the water quality at the point of compliance. Typically, the minimum number of wells specified for interim status facilities in 40 CFR §265.91(a) will not be sufficient for achieving the performance objectives of a detection monitoring system because site hydrogeology is too complex or the hazardous waste unit is too large. Supplemental monitoring wells may be required in conjunction with point of compliance wells to ensure early detection of contamination. In addition, unsaturated zone monitoring may be necessary where it would aid in detecting early migration of contaminants into ground water.

The basic goals of the site characterization process described in the previous chapter are the description of the hydrogeological setting and the identification of the potential pathways for contaminant migration. This information is the foundation for the entire ground-water monitoring program and is crucial to the proper placement of monitoring wells. Although a monitoring system should be designed based on site-specific conditions, there are a number of practices that can be applied to ensure that detection monitoring systems satisfy RCRA regulatory requirements. These are discussed in the following sections.

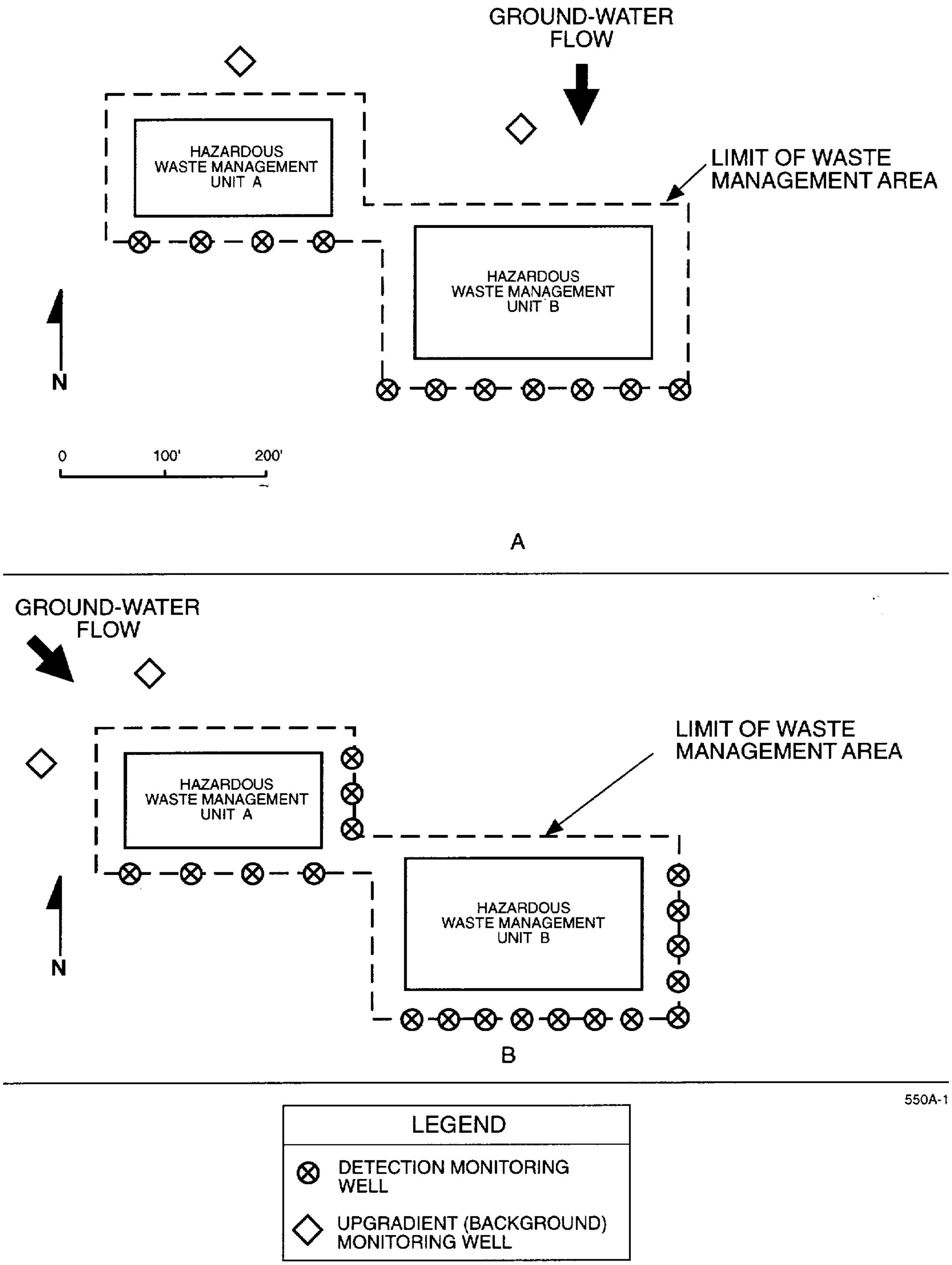
5.1.2 Placement of Point of Compliance Monitoring Wells

This section separately addresses the lateral placement and the vertical sampling intervals of point of compliance wells. However, these two aspects of well placement should be evaluated together in the design of the detection monitoring system. Site-specific hydrogeologic data obtained during the site characterization should be used to determine the lateral placement of detection monitoring wells, and to select the length and vertical position of monitoring well intakes. Potential pathways for contaminant migration are three dimensional. Consequently, the design of a detection monitoring network that intercepts these potential pathways requires a three-dimensional approach.

The criteria for evaluating the location of point of compliance wells relative to waste management areas are described in Section 5.1.2.1. Section 5.1.2.2 contains the hydrogeologic criteria for evaluating lateral placement of point of compliance wells. Section 5.1.2.3 details the rationale for selection of the vertical placement and sampling intervals of detection monitoring wells. Section 5.1.2.4 discusses the need for vadose zone monitoring.

5.1.2.1 Location of Wells Relative to Waste Management Areas

RCRA regulations for permitted facilities require point of compliance wells to be designed and installed to detect releases of hazardous waste or hazardous waste constituents to ground water. To meet regulatory requirements (§264.95(a) and §264.97(a)(3)), point of compliance monitoring wells should be installed adjacent to a hazardous waste management unit along its downgradient limit unless the Regional Administrator has specified an alternate point of compliance pursuant to §264.95(a)(1). In a practical sense, this means that point of compliance monitoring wells should be as close as physically possible to the edge of hazardous waste management unit(s), as shown in Figure 9, and screened in all transmissive zones that may act as contaminant transport pathways. The lateral placement of monitoring wells should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways.



DOWNGRADIENT WELLS IMMEDIATELY ADJACENT TO THE HAZARDOUS WASTE MANAGEMENT AREA LIMITS

FIGURE 9

At certain existing units, physical obstacles may prevent the installation of monitoring wells at the point (or points) of compliance. In these cases, the Regional Administrator may specify an alternate point (or points) of compliance that is as close to the waste management area as practical, provided the performance standard of early detection of contamination is met.

5.1.2.2 Lateral Placement of Point of Compliance Monitoring Wells

Point of compliance monitoring wells should be placed laterally along the downgradient edge of hazardous waste management units to intercept potential pathways for contaminant migration. The local ground-water flow direction and gradient are the major factors in determining the lateral placement of point of compliance wells. In a homogenous, isotropic hydrogeologic setting, well placement can be based on general aquifer characteristics (e.g., direction and rate of ground-water flow), and potential contaminant fate and transport characteristics (e.g., advection, dispersion). More commonly, however, geology is variable and preferential pathways exist that control the migration of contaminants. These types of heterogeneous, anisotropic geologic settings can have numerous, discrete zones within which contaminants may migrate.

Potential migration pathways include zones of relatively high intrinsic (matrix) hydraulic conductivities, fractured/faulted zones, and subsurface material that may increase in hydraulic conductivity if the material is exposed to waste(s) managed at the site (e.g., a limestone layer that underlies an acidic waste). In addition to natural hydrogeologic features, human-made features may influence the ground-water flow direction and thus, the lateral placement of point of compliance wells. Such human-made features include ditches, areas where fill material has been placed, buried piping, buildings, leachate collection systems, or adjacent disposal units. These considerations are discussed further in Section 4.3.3.4. The lateral placement of monitoring wells should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways.

In some settings, the ground-water flow direction may reverse seasonally (depending on precipitation), change as a result of tidal influences or river and lake stage fluctuations, or change temporally as a result of well pumping or changing land use patterns. In other settings, ground water may flow away from the waste management area in all directions. In such cases, EPA recommends that to comply with the requirements of §264.97(a)(3), monitoring wells should be installed on all sides (or in a circular pattern) around the waste management area to allow for the detection of contamination. In these cases, certain wells may be downgradient only part of the time, but such a configuration should ensure that releases from the unit will be detected. In these hydrogeologic settings, ground-water sampling and water level elevation measurements must be performed more frequently than semi-annually, which is the required minimum frequency specified in 40 CFR Part 264, Subpart F.

The lateral placement of monitoring wells also should be based on the physical/chemical characteristics of the hazardous waste or hazardous waste constituents that control the movement and distribution of the hazardous waste or hazardous waste constituents in the subsurface. These characteristics include, but are not limited to: solubility, Henry's Law constant, partition coefficients, specific gravity, contaminant reaction or degradation products, and the potential for contaminants to degrade confining layers. For example, contaminants with low solubilities and high specific gravities that occur as DNAPLs may migrate in the subsurface in directions different from the direction of ground-water flow. Therefore, in situations where the release of DNAPLs is a concern, the lateral placement of compliance point ground-water monitoring wells should not necessarily only be along the downgradient edge of the hazardous waste management unit. Considering both contaminant characteristics and hydrogeologic properties is important when determining the lateral placement of monitoring wells.

5.1.2.3 Vertical Placement and Screen Lengths

Proper selection of the vertical sampling interval is necessary to ensure that the monitoring system is capable of detecting a release from the hazardous waste management area. The vertical position and lengths of well intakes are functions of: (1) hydrogeologic factors that determine the distribution of, and fluid/vapor phase transport within, potential pathways of contaminant migration to and within the uppermost aquifer, and (2) the chemical and physical characteristics of contaminants that control their transport and distribution in the subsurface. Well intake length also is determined by the need to obtain vertically-discrete ground-water samples. Owners and operators should determine the probable location, size, and geometry of potential contaminant plumes when selecting well intake positions and lengths.

Site-specific hydrogeologic data obtained during the site characterization should be used to select the length and vertical position of monitoring well intakes. The vertical positions and lengths of monitoring well intakes should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways.

The depth to, and thickness of a potential contaminant migration pathway can be determined from soil, unconsolidated material, and rock samples collected during the boring program, and from samples collected while drilling the monitoring well. Direct physical data can be supplemented by geophysical data, available regional/local hydrogeological data, and other data that provide the vertical distribution of hydraulic conductivity. The vertical sampling interval is not necessarily synonymous with aquifer thickness. Monitoring wells are often screened at intervals that represent a portion of the thickness of the aquifer. When monitoring an unconfined aquifer, the well screen typically should be positioned so that a portion of the well screen is in the saturated zone and a portion of the well screen is in the unsaturated zone (i.e., the well screen straddles the water table).

The vertical positions and lengths of monitoring well intakes should be based on the physical/chemical characteristics of the hazardous waste or hazardous waste constituents that control the movement and distribution of the hazardous waste or hazardous waste constituents in the subsurface. These characteristics include, but are not limited to: solubility, Henry's Law constant, partition coefficients, specific gravity, contaminant reaction or degradation products, and the potential for contaminants to degrade confining layers. Considering both contaminant characteristics and hydrogeologic properties is important when choosing the vertical position and length of the well intake. Some contaminants may migrate within very narrow zones.

Different transport processes control contaminant migration depending on whether the contaminant dissolves or is immiscible in water. Immiscible contaminants may occur as LNAPLs, which are lighter than water, and DNAPLs, which are denser than water. Most LNAPLs are hydrocarbon oils and fuels. Most DNAPLs are highly chlorinated hydrocarbons (e.g., carbon tetrachloride, tetrachloroethylene, and PCBs). Identifying whether or not a compound may exist as an DNAPL or an LNAPL is complicated by the substance in which it is dissolved. For example, free phase PCBs may be denser than water (DNAPL), but PCBs in oil can be transported as an LNAPL. Additional information on NAPL migration is provided by USEPA (1989) and USEPA (1991).

LNAPLs migrate in the capillary zone just above the water table. Wells installed to monitor LNAPLs should be screened at the water table/capillary zone interface, and the screened interval should intercept the water table at its minimum and maximum elevation. LNAPLs may become trapped in residual form in the vadose zone and become periodically remobilized and contribute further to aquifer contamination, either as free phase or dissolved phase contaminants, as the water table fluctuates and precipitation infiltrates the subsurface.

The migration of free-phase DNAPLs may be primarily influenced by the geology, rather than the hydrogeology, of the site. That is, DNAPLs migrate downward through the saturated zone due to density, and then migrate by gravity along less permeable geologic units (e.g., the slope of confining units, the slope of clay lenses in more permeable strata, bedrock troughs), even in aquifers with primarily horizontal groundwater flow. Consequently, if wastes disposed at the site are anticipated to exist in the subsurface as a DNAPL, the potential DNAPL should be monitored:

- At the base of the aquifer (immediately above the confining layer);

- In structural depressions (e.g., bedrock troughs) in lower hydraulic conductivity geologic units that act as confining layers;

- Along lower hydraulic conductivity lenses and units within units of higher hydraulic conductivity; and/or

- "Down-the-dip" of lower hydraulic conductivity units that act as confining layers, both upgradient and downgradient of the waste management area.

Because of the nature of DNAPL migration (i.e., along structural, rather than hydraulic, gradients), wells installed to monitor DNAPLs may need to be installed both upgradient and downgradient of the waste management area. It may be useful to construct a structure contour map of lower permeability strata and identify lower permeability lenses upgradient and downgradient of the unit along which DNAPLs may migrate; then locate the wells accordingly.

The lengths of well screens used in ground-water monitoring wells can significantly affect their ability to intercept releases of contaminants. The complexity of the hydrogeology of a site is an important consideration when selecting the lengths of well screens. Most hydrogeologic settings are complex (heterogeneous and anisotropic) to a certain degree. Highly heterogeneous formations require shorter well screens to allow sampling of discrete portions of the formation that can serve as contaminant migration pathways. Well screens that span more than a single saturated zone or a single contaminant migration pathway may cause cross-contamination of transmissive units, thereby increasing the extent of contamination. Well intakes should be installed in a single saturated zone. Well intakes (e.g., screens) and filter pack materials should not interconnect, or promote the interconnecting of, zones that are separated by a confining layer.

Even in hydrologically simple formations, or within a single potential pathway for contaminant migration, the use of shorter well screens may be necessary to detect contaminants concentrated at particular depths. A contaminant may be concentrated at a particular depth because of its physical/chemical properties and/or because of hydrogeologic properties. In homogeneous formations, a long well screen can permit excessive amounts of uncontaminated formation water to dilute the contaminated ground water entering the well. At best, dilution can make contaminant detection difficult; at worst, contaminant detection is impossible if the concentrations of contaminants are diluted to levels below the detection limits for the prescribed analytical methods. The use of shorter well screens allows for contaminant detection by reducing excessive dilution and, when placed at depths of predicted preferential flow, shorter well screens are effective in monitoring the aquifer or the portion of the aquifer of concern.

Generally, screen lengths should not exceed 10 feet. However, certain hydrogeologic settings may warrant or necessitate the use of longer well screens for adequate detection monitoring. Unconfined aquifers with widely fluctuating water tables may require longer screens to intercept the water table surface at both its maximum and minimum elevations and to provide monitoring for the presence of contaminants that are less dense than water. Saturated zones that are slightly greater in thickness than the appropriate screen length (e.g., 12 feet thick) may warrant monitoring with longer screen lengths. Extremely thick homogeneous aquifers (e.g., greater than 300 feet) may be monitored with a longer screen (e.g., a 20-foot screen) because a slightly longer screen would represent a fairly discrete interval in a very thick formation. Formations with very low hydraulic conductivities also may require the use of longer well screens to allow sufficient amounts of formation water to enter the well for sampling. The importance of accurately identifying such conditions highlights the need for a complete hydrogeologic site investigation prior to the design and placement of detection wells.

Multiple monitoring wells (well clusters or multilevel sampling devices) should be installed at a single location when: (1) a single well cannot adequately intercept and monitor the vertical extent of a potential pathway of contaminant migration, or (2) there is more than one potential pathway of contaminant migration in the subsurface at a single location, or (3) there is a thick saturated zone and immiscible contaminants are present, or are determined to potentially occur after considering waste types managed at the facility. Conversely, at sites where ground water is contaminated by a single contaminant, where there is a thin saturated zone, and where the site is hydrogeologically homogeneous, the need for multiple wells at each sampling location is reduced. Table 6 summarizes factors affecting the decision to install multiple or single wells at a single location. The number of wells that should be installed at each sampling location increases with site complexity.

5.1.2.4 Vadose Zone Monitoring

At some sites where the potentiometric surface or water table is considerably below the ground surface, contaminants may migrate in the vadose zone for long distances or for long periods of time before they reach ground water. At other sites, the potential may exist for contaminants to migrate laterally beyond the downgradient extent the monitoring well network along low hydraulic conductivity layers within the vadose zone. A vadose zone monitoring system may be necessary in these and other cases to detect any release(s) from the hazardous waste management area before significant environmental contamination has occurred. Leachate released to the vadose zone, for example, may be detected and sampled using tensiometers. The use of vadose zone monitoring equipment can potentially save the owner/operator considerable expense by alerting him or her to the need for corrective action before large volumes of the subsurface have been contaminated.

The Agency recommends unsaturated zone monitoring where it would aid in detecting early migration of contaminants into ground water. The Regional Administrator also can require this monitoring on a case-by-case basis as necessary to protect human health and the environment under §§3004(u) and 3005(c). The elements, applications, and limitations of a vadose zone monitoring program are provided by Wilson (1980) and USEPA (1986b). Moreover, the Agency is currently updating its existing guidance on vadose zone monitoring.

TABLE 6
FACTORS AFFECTING THE NUMBER OF WELLS PER LOCATION (CLUSTERS)

One Well Per Sampling Location[1]	More Than One Well Per Sampling Location
• No LNAPLs or DNAPLs (immiscible liquid phases)	• Presence of LNAPLs or DNAPLs
• Thin flow zone (relative to screen length) • Horizontal flow predominates	• Thick flow zones • High vertical gradient present • Heterogeneous anisotropic uppermost aquifer; complicated geology - multiple, interconnected aquifers - variable lithology - perched water zones - discontinuous structures
• Homogeneous isotropic uppermost aquifer; simple geology	• Discrete fracture zones in bedrock • Solution conduits (i.e., caves) in karst terranes • Cavernous basalts

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1. At the majority of sites, well clusters will be necessary to establish vertical hydraulic gradient and the vertical distribution of contaminants.

5.1.3 Placement of Background (Upgradient) Monitoring Wells

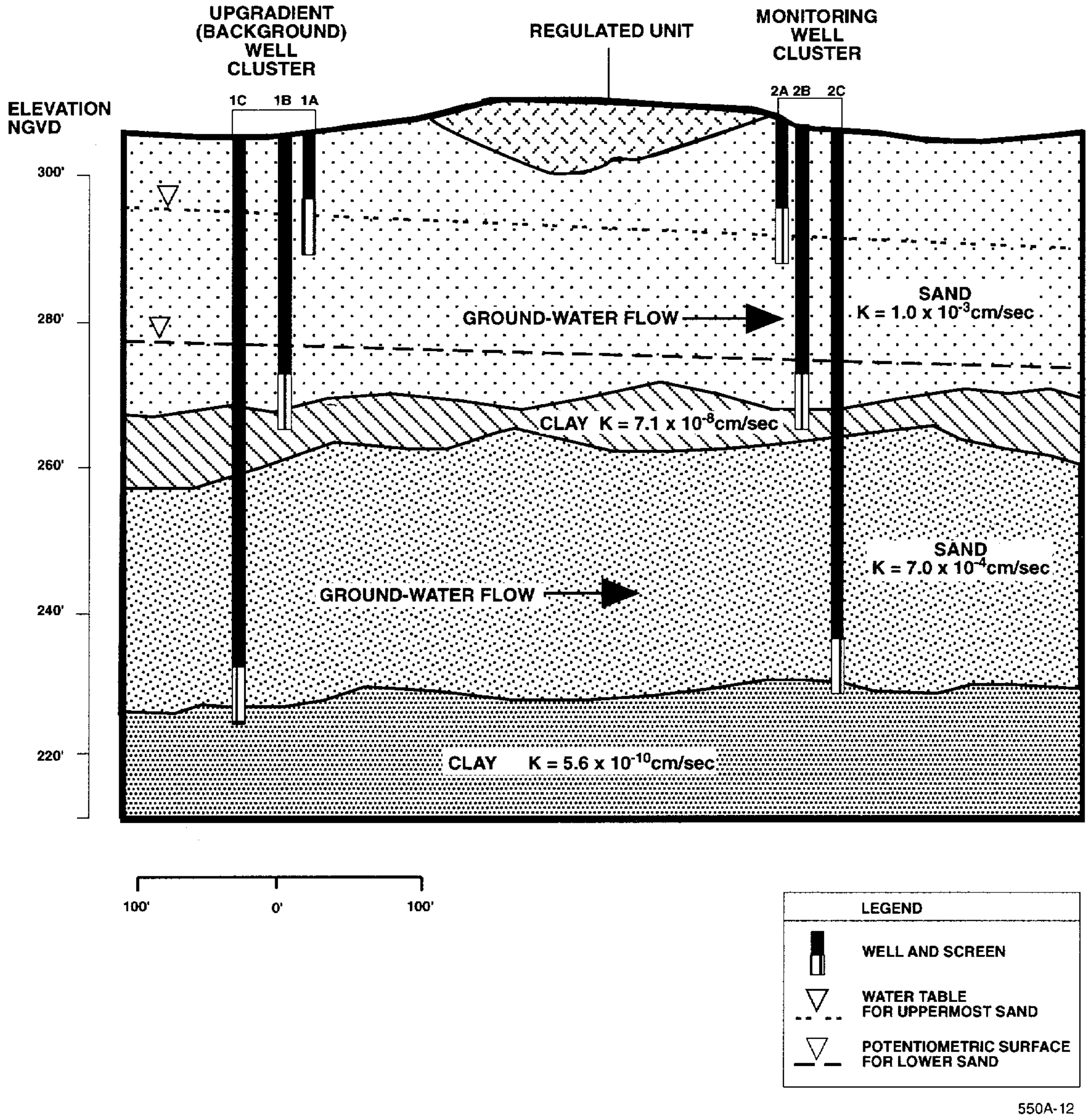
The ground-water monitoring well system must allow for the detection of contamination when hazardous waste or hazardous constituents have migrated from the waste management area to the uppermost aquifer. A sufficient number of background wells must be installed at appropriate locations and depths to yield ground-water samples from the uppermost aquifer that represent the quality of background water that has not been affected by leakage from a regulated unit (§264.97(a)). In most cases, background wells should be located hydraulically upgradient of the waste management unit(s); however, in certain circumstances a determination of background ground-water quality may include sampling of wells that are not hydraulically upgradient of the waste management area. Specifically, §264.97(a)(1)(i) provides that the determination of background ground-water quality may include sampling wells that are not hydraulically upgradient of the waste management area where:

- Hydrogeologic conditions do not allow the owner or operator to determine what wells are hydraulically upgradient; or
- Sampling at other wells will provide an indication of background ground-water quality that is representative or more representative than that provided by the upgradient wells.

A sufficient number of background monitoring wells should be installed to allow for stratified (depth-discrete) comparisons of water quality and to account for spatial variability in ground-water quality. Background monitoring wells should not be screened over the entire thickness of any saturated zone that can act as a contaminant transport pathway. Screening the entire thickness of such zones will not allow depth-discrete water quality data to be obtained. Instead, shorter well screens should be placed at depths comparable to those used for detection monitoring wells as shown in Figure 10. Background and point of compliance wells must be screened in the same hydrostratigraphic position to allow collection of comparable ground-water quality data. Stiff and Piper diagrams can aid in this determination. Hem (1989) is a good reference on ground-water chemistry.

To establish background ground-water quality, it is necessary to establish ground-water flow direction(s) and to place wells hydraulically upgradient of the waste management area. Certain geologic and hydrologic situations make the determination of hydraulically upgradient locations difficult. These cases require careful site characterization to position or place background wells properly. Examples of such cases include the following:

- Waste management areas above naturally occurring or human-made ground-water mounds;



EXAMPLE OF THE PLACEMENT OF BACKGROUND MONITORING WELLS

FIGURE 10

- Waste management areas located above aquifers in which ground-water flow directions change seasonally;

- Waste management areas located close to a property boundary in the upgradient direction;

- Waste management areas containing immiscible contaminants with densities greater than or less than water;

- Waste management areas located in areas where nearby surface water can influence ground-water elevations (e.g., river floodplains);

- Waste management areas located near intermittently or continuously used production wells; and

- Waste management areas located in structurally complex areas where folded strata or fault zones may modify flow.

In these situations, a monitoring well network in which the wells are located in a circular pattern or on all sides of the waste management unit may be necessary.

Background wells should be located far enough from waste management units to avoid contamination by the units. In the event that background wells become contaminated by a release from the waste management unit(s), new background wells that will not be affected by the release should be installed.

5.2 Ground-Water Monitoring in Aquifers Dominated by Conduit Flow

As described in Section 4.3.1, conventional ground-water hydrology considers aquifers to be porous media having a well-defined water table or potentiometric surface. The following sections provide a strategy for conducting ground-water monitoring in hydrogeologic settings where conduit flow predominates.

5.2.1 Introduction

Ground-water monitoring regulations of Subpart F require a ground-water monitoring system consisting in part of monitoring wells installed at the hydraulically downgradient limit of the waste management area(s) that are capable of detecting contamination that has migrated to the uppermost aquifer. For a facility to receive an operating permit, the ground-water monitoring system at the facility must meet the requirements of §264.97 (unless the owner or operator is exempted from the requirements under §264.90). While meeting these criteria is typically not problematic in aquifers dominated by flow through porous media, it can be difficult in aquifers dominated by conduit flow. In aquifers dominated by conduit flow, subsurface conduits are the primary pathways that contaminant releases follow. Identifying and intercepting these conduits with wells is an extremely formidable task. Identifying contaminant transport pathways requires detailed site characterization beyond what is currently performed at most RCRA facilities. In addition, the wide fluctuations in the water table that are characteristic of aquifers dominated by conduit flow make identification and satisfactory monitoring of the uppermost aquifer particularly difficult.

It may be possible for some facilities that are sited above conduit flow aquifers to have ground-water monitoring systems that meet the performance standards of 40 CFR §264.97. The Regional Administrator may require the facility owner or operator to monitor seeps, springs, and caves that are hydraulically connected to the uppermost aquifer and that are within the facility boundary to supplement the monitoring well network. These supplemental monitoring sites can be used in conjunction with point of compliance wells to detect releases from the facility (§264.97(a)(3)). However, the Agency expects that these cases will be rare, and that most facilities sited in karst settings will be unable both to meet the performance standards of §264.97 and to receive an operating permit. Therefore, prior to locating a waste management facility in an area where any conduit flow exists, an owner or operator should consider the inherent difficulties in meeting the ground-water monitoring requirements of Subpart F. The owner/operator should select a different location if it appears as though a release to a conduit flow aquifer could not be detected or controlled during a high precipitation event. The following sections of requirements and guidance are for owners and operators of facilities located above aquifers dominated by conduit flow that meet the performance standards of §264.97. These sections provide additional information on designing a supplemental monitoring well network for the seeps, springs, and conduits that are hydraulically connected to the uppermost aquifer and that are located on the facility property.

5.2.2 Using Springs as Monitoring Sites in Aquifers Dominated by Conduit Flow

In certain circumstances, the Regional Administrator may request that a strategy of monitoring seeps, springs, and cave streams be applied to supplement monitoring well systems in all aquifers dominated by conduits that drain to springs and that discharge on land or along the shores of streams, rivers, lakes, or seas. In terranes where conduit flow predominates, springs and cave streams (if they have been shown by tracer studies to drain from the facility being evaluated) are the easiest and most reliable sites at which to monitor ground-water quality (Field, 1988; Quinlan, 1989; Quinlan, 1990).

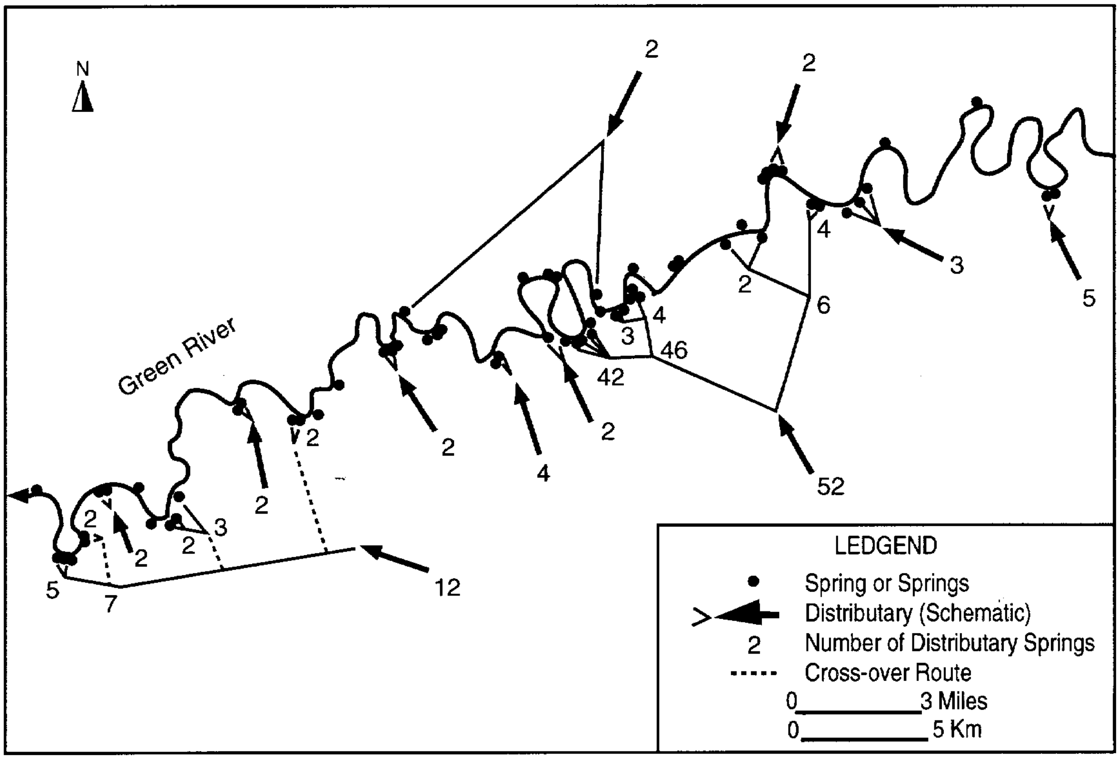
Most springs that should be sampled regularly during tracer tests and ground-water monitoring are not shown on USGS topographic quadrangle maps. Furthermore, the inclusion of a spring on a topographic map is not necessarily an indicator of the significance of its discharge, as many minor springs are included on maps because of their cultural associations. In certain cases, the owner/operator will need to conduct detailed field work to locate all springs in the area of a TSDF sited in a karst terrane. This is a necessary step in the process of determining whether conduit or diffuse-flow predominates.

Springs, seeps, and directly accessible cave springs may need to be tested by tracing not only during moderate flow, but also during flood flow and base flow, to prove their usefulness for monitoring. Testing must be conducted during the extremes of expected flow conditions because flow routing in conduit-flow systems commonly varies as stage changes. During flood conditions, water levels in streams, rivers, and lakes may rise, and some of this water may move temporarily through conduits that are dry during low-flow conditions and discharge into adjacent ground-water basins.

There are certain characteristics of water movement in a karst aquifer dominated by conduit flow that should be recognized if a monitoring strategy is to be effective. One characteristic is distributary flow. During periods of high stage, water (and contaminants if they are present) from the headwaters or mid-reaches of a ground-water basin may flow to all springs in its distributary system. Distributary flow is most pronounced in areas of aggradation of river valleys (e.g., Mammoth Cave, Kentucky) where many alternate conduits at and below base level are available (deep sediment fill covering the bedrock floor of the valley). Such a system is shown in Figure 11. Radial flow also may be identified during dye-tracing and monitoring of springs (Aley, 1988). Radial flow is most common in highly fractured mountain areas. Another unusual characteristic encountered is subsurface drainage paths that cut across surface drainage divides without any surface indication. Ground-water flow can parallel surface drainages, but usually not over long distances. This subterranean piracy of water from one surface watershed to another is not uncommon in many karst terranes. An example of watershed piracy that was discovered by tracer studies is described by Jones (1973). Given the possibility of variable ground-water movement in aquifers dominated by conduit flow, owners and operators may need to perform tracer studies to delineate flow paths for ground-water monitoring accurately.

5.2.3 Using Wells as Monitoring Sites in Aquifers Dominated by Conduit Flow

The placement of wells in karst terranes with subsurface conduits is rarely effective. Installing a suite of wells to intercept cave streams that have been shown by tracing to flow from the facility is a good strategy, but cave streams can be practically impossible to locate. A second alternative for selecting monitoring well locations in aquifers with conduit flow is to place wells along fractures or fracture trace intersections. Tracer studies should be used to verify a hydraulic connection with the ground water beneath a facility under base-flow and flood-flow conditions. Although some cave passages coincide with various types of fracture traces and lineaments, not all fractures and fracture-related features are directly connected with cave passages. Many cave streams are developed along bedding planes, and are thus unaffected by vertical fractures. This fact lessens the probability that a well drilled on a



DISTRIBUTARY SPRINGS ALONG THE GREEN RIVER NEAR MAMMOTH CAVE, KENTUCKY AS DETERMINED BY TRACER STUDIES. THE NUMBERS GIVE THE TOTAL NUMBER OF SPRINGS IN A GIVEN DISTRIBUTARY SYSTEM OR SUBSYSTEM (AFTER QUINLAN AND EWERS, 1985)

FIGURE 11

fracture trace or lineament, or at the intersection of such linear features, will intercept a cave stream.

Wells that were originally sited without consideration of conduit flow should be used for monitoring only if tracing has first proven a connection from the waste management facility to each of the monitoring wells under varying flow conditions. Domestic, agricultural, and industrial wells are sited and installed for purposes other than ground-water monitoring. Even previously installed monitoring wells designed to detect contaminants, to intercept contaminant plumes, or to function as upgradient monitoring wells should be considered randomly located unless they were deliberately sited along fracture traces or fracture-trace intersections. Piezometer clusters are excellent in porous media, but will provide relatively little information in most karst terranes. Piezometer clusters do have value in defining the diffuse-flow component of a karst aquifer, but this could lead to (1) incorrect interpretation of subsurface flow characteristics, and (2) greatly added site characterization expenses. Randomly located and non-randomly located wells not intended for aquifer testing or ground-water tracing should be used as monitoring wells only if tracing shows a direct link to the conduit system to be monitored. Such wells should not, however, be used as monitoring wells for a facility above an aquifer dominated by conduit flow or diffuse flow, unless tracer studies show that the well is downgradient from the facility to be monitored.

5.2.4 Tracing to Identify Monitoring Sites in Aquifers Dominated by Conduit Flow

Ground-water tracing is a well-developed tool that enables catchment boundaries to be delineated, ground-water flow velocities to be estimated, areas of recharge and discharge to be determined, and sources of pollution to be identified. Ground Water Tracers, by Davis et al. (1985) is an EPA-sponsored compendium that discusses many facets of ground-water tracing. Another good reference concerning ground-water tracing is Quinlan (1990). It is important to consult an individual who is experienced in ground-water tracing, and to get approval from the appropriate regulatory authorities before any tracer study is initiated.

A tracer should have a number of properties to be considered useful, including the following:

- Its potential chemical and physical behavior in ground water should be understood;
- It should travel with the same velocity as the water and not interact with solid material;
- It should be nontoxic for most uses;
- It should be inexpensive;

- It should be easily detected with widely available and simple technology;

- It should be present in concentrations well above background concentrations of the same constituent in the natural system that is being studied; and

- It should not modify the hydraulic conductivity or other properties of the medium being studied.

Three classes of water tracing agents are available:

- Natural labels
  - flora and fauna, principally micro-organisms
  - ions in solution
  - environmental isotopes

- Pulses
  - natural pulses of discharge, solutes and sediment
  - artificially generated pulses

- Artificial labels
  - radiometrically detectable substances
  - dyes
  - salts
  - spores.

Artificial fluorescent dyes are the principal and most successful water tracers for conduit-flow aquifers at the present time. Dyes are injected intentionally into ground water for the purpose of tracing the movement of fluids in active ground-water systems. Under ideal circumstances, dyes can be injected into a perennial sinking stream on the facility site. If a stream is not available, tank-trucks of water and dye can be injected at the following sites in a karst terrane, listed in decreasing order of desirability:

1. Sinkhole with a hole at its bottom.

2. Sinkhole without a hole at its bottom; excavation may reveal a hole that can be used.

3. Losing-stream reach with intermittent flow.

4. Class V stormwater drainage well.

5. Well drilled on a fracture trace or a fracture-trace intersection.

6. Abandoned domestic, agricultural, or industrial well.

7. Well randomly drilled for dye injection.

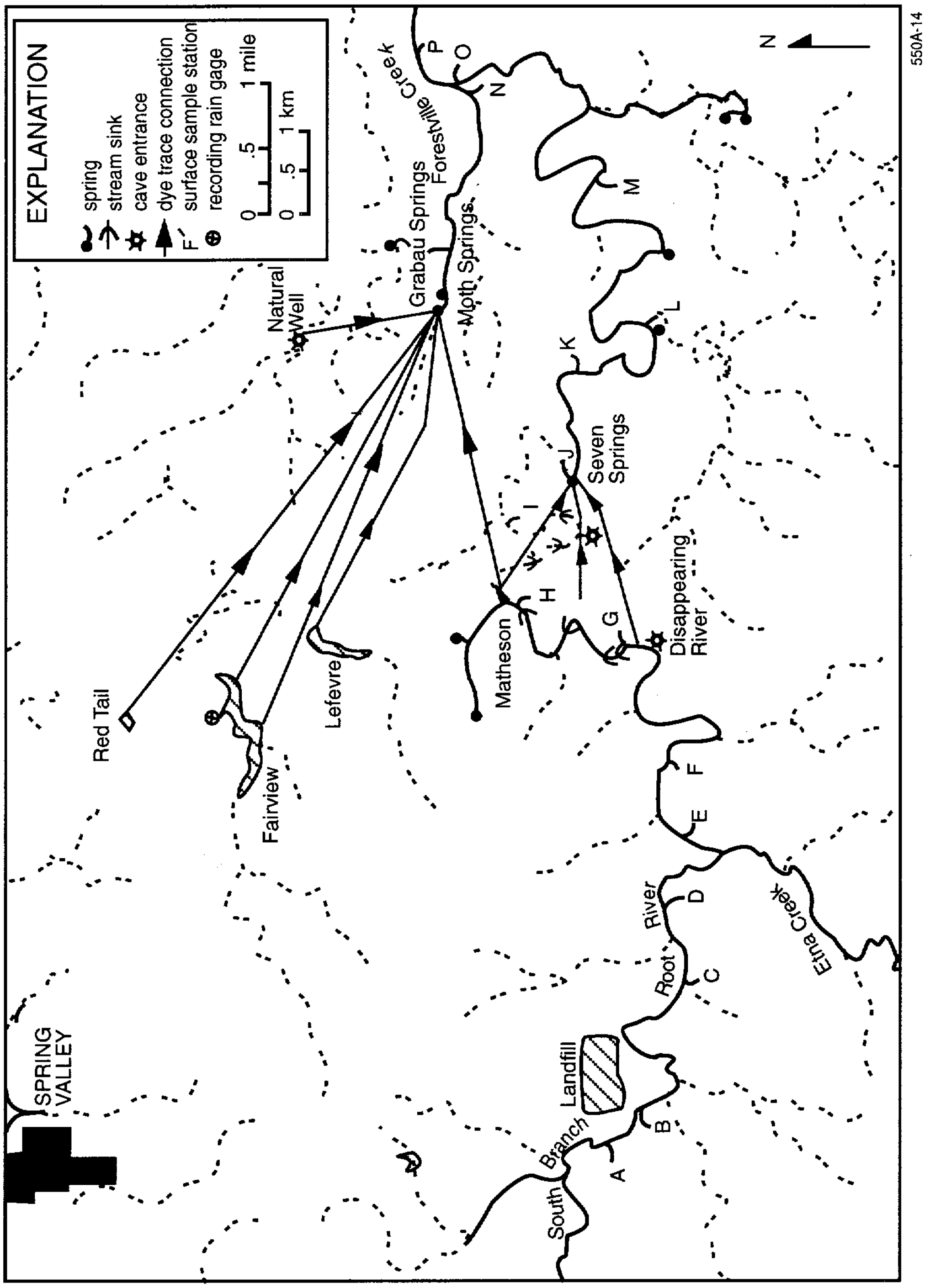
To save the trouble and expense of a wasted dye test, percolation or slug tests should be conducted at the injection point to determine if the injection point is open to the aquifer and to see how rapidly it drains. The tracer injection point should be on, or as near as is practicably possible to, the facility property. The use of injection sites that are not near the facility property will most certainly be questioned by the regulatory authority because of the possibility that the monitoring locations identified by the tracer test are not hydraulically connected to the facility.

The detection limit for fluorescent dyes is lower than nonfluorescent dyes, therefore, in general, less fluorescent dye is required for tracer tests (Quinlan, 1987). Although fluorescent dyes exhibit many of the properties of an ideal tracer, a number of factors interfere with concentration measurement. These factors include suspended sediment load, temperature, pH, $CaCO_3$ concentration, salinity, etc. (Quinlan, 1987). At the sampling point, preferably a spring, grab samples can be taken or small pockets of nylon can be filled with activated charcoal and suspended in the water. The dye adsorbs very strongly on to the charcoal and is later desorbed in a lab and analyzed. To detect dyes, a filter fluorometer can be used in the field or a spectrofluorometer can be used in the lab. For additional discussions of ground-water tracing, the reader is referred to Davis et al. (1985), and the EPA documents Application of Dye Tracing Techniques for Determining Solute Transport Characteristics of Ground Water in Karst Terranes (1988), and Ground-Water Monitoring in Karst Terranes (1989). In addition, Quinlan (1990) discusses the special problems of ground-water monitoring in karst terranes.

Figure 12 is a map that shows how the results of a dye-tracing study can be displayed graphically. The most important information to depict is the location of: all points where dye was introduced (sinkholes, sinking streams, wells, etc.); all springs and wells in the area; and those springs and wells where dye was recovered. The routes travelled by the dye are usually shown as straight or curvilinear lines that connect the tracer injection points and the springs. In most cases, straight lines should be used to schematically depict the routes travelled by the dye, unless extensive data have been collected to justify the depiction of the ground-water flow paths as curvilinear lines. Line drawings of known cave systems with hydraulically connected streams that occur between the surface introduction points and the springs or wells where dye was recovered also are useful for such a map.

5.2.5 Sampling Frequency in Aquifers Dominated by Conduit Flow

Under 40 CFR Part 264 Subpart F, ground-water monitoring frequency is specified by the Regional Administrator in the facility's permit and either must at a minimum include four samples collected semi-annually during detection and compliance monitoring periods pursuant



SUMMARY OF TRACER STUDIES IN THE KARST OF FILLMORE COUNTY, MINNESOTA, IN THE VICINITY OF IRONWOOD LANDFILL (AFTER ALEXANDER, 1987)

FIGURE 12

to §§264.98(d) and 264.99(f), or must be an alternate sampling procedure specified under §264.97(g)(2). This minimum monitoring frequency is inadequate for karst terranes dominated by conduit flow, because the storage time of the water is low and the concentrations of contaminants in conduit systems can vary over a short period of time. Therefore, hourly sampling of aquifers dominated by conduit flow is recommended before, during, and after storm or other runoff (e.g., snowmelt) events, although this is a site-specific determination. As described by Quinlan (1990), in aquifers dominated by conduit flow, "sampling should start at base flow, before the beginning of a storm or meltwater event, and continue until 4 to 30 times the time to the hydrograph peak has elapsed, depending upon the extent to which an aquifer is characterized by conduit flow as opposed to diffuse flow. Sampling may have to be done as often as at 1 to 6-hour intervals in the early part of a precipitation event and at 4 to 24-hour intervals in the waning part of its hydrograph."

Data from the samples collected during the peak runoff should be compared with samples collected during base flow under fair-weather conditions at other times of the year. This should enable a reliable assessment of the ground-water quality to be made. Quinlan and Alexander (1987) discuss the rationale for sampling frequencies of ground water in karst aquifers dominated by conduit flow in much greater detail. The work performed by Quinlan and Alexander (1987) is site-specific, and while it illustrates the considerable extent to which spring discharge should be evaluated, the results obtained by Quinlan and Alexander should not be taken as representative of all sites located above karst aquifers dominated by conduit flow.

The previous discussion highlights the various difficulties associated with ground-water monitoring in karst aquifers. Site characterization of these hydrogeologic settings is complex, time consuming, and potentially costly. The Agency again emphasizes its belief that most facilities sited in karst settings will not be able to meet the ground-water monitoring requirements of Subpart F; therefore, alternative locations for land disposal of hazardous wastes are preferred.

5.2.6 Fracture Trace Analysis

The detection of ground-water contamination in fracture-controlled aquifers can be problematic due to the difficulties in locating the fracture systems that often dominate the ground-water flow system. Fracture traces have been mapped for the purpose of locating zones of increased weathering, porosity, and permeability that act as preferential pathways of contaminant migration. Strong correlations between well yields and fracture traces in carbonates, igneous rock, metamorphic rock, fractured siltstones, and fractured sandstones have been documented by numerous authors (Jansen and Taylor, 1988). Fracture trace analysis should be performed at sites where hydrogeologic data indicate that contaminant migration may occur along fractures.

Fracture traces are believed to be the surface expressions of localized bedrock jointing and small faults (Casper, 1980). Recent studies have indicated that fracture orientations measured on the surface have similar orientations to those in the subsurface (McGlew and Thomas, 1984). Fractures may result from local adjustment to regional stress conditions, and may be the surface expression of minor faults, solution zones, concentrated jointing, or separation of strata during folding (Casper, 1980).

A fracture trace analysis is performed by examining remote sensing imagery such as aerial photography for linear and curvilinear features at various scales, which are related to bedrock fractures. There are many types of imagery available in different scales. The selection of the proper imagery for a given study area depends on the topography, type of vegetation, soil moisture content, expected size of surface expression of geologic features, size of the study area, and numerous other features (Jansen and Taylor, 1988).

Fracture traces are viewed in stereoscopic analysis of aerial photographs. By systematically viewing small portions of the area, it is possible to locate fracture traces expressed by continuous or discontinuous tonal variations of surface features (Casper, 1980).

CHAPTER SIX

MONITORING WELL DESIGN AND CONSTRUCTION

The following sections provide a basic summary of monitoring well design and construction techniques. Pursuant to §264.97(c)(1), owners and operators must document in the operating record the design, installation, development, and decommission of any monitoring wells, piezometers, and other measurement, sampling, and analytical devices. A comprehensive guide to choosing appropriate drilling techniques is presented by Aller et al. (1989). Although much of the guidance presented in this Chapter may be applied to the design and installation of piezometers, this section is geared to the design and construction of monitoring wells that will be used to meet the requirements of 40 CFR §264.97. Furthermore, many of the techniques presented in the following sections are described more completely in other references and generally will not be discussed in detail in this Chapter.

6.1 Monitoring Well Drilling Methods

The method chosen for drilling a monitoring well depends largely on the following factors described by Aller et al. (1989):

- Versatility of the drilling method;
- Relative drilling cost;
- Sample reliability (ground-water, soil, unconsolidated material, or rock samples);
- Availability of drilling equipment;
- Accessibility of drilling site;
- Relative time required for well installation and development;
- Ability of the drilling technology to preserve natural conditions;
- Ability to install well of desired diameter and depth; and
- Relative ease of well completion and development, including ability to install well in the given hydrogeologic setting.

In addition to these factors, Aller et al. (1989) have developed matrices to assist in selecting an appropriate drilling method. These matrices list the most commonly used drilling techniques for monitoring well installation taking into consideration hydrogeologic settings and the objectives of the monitoring program.

The Agency has developed basic guidance to assist in the selection of drilling procedures for installing monitoring wells pursuant to 40 CFR Part 264, Subpart F, as follows:

- Drilling should be performed in a manner that preserves the natural properties of the subsurface materials;
- Contamination and/or cross-contamination of ground water and aquifer materials during drilling should be avoided;
- The drilling method should allow for the collection of representative samples of rock, unconsolidated materials, and soil;
- The drilling method should allow the owner/operator to determine when the appropriate location for the screened interval has been encountered;
- The drilling method should allow for proper placement of the filter pack and annular sealants. The borehole should be at least 4 inches larger in diameter than the nominal diameter of the well casing and screen to allow adequate space for placement of the filter pack and annular sealants;
- The drilling method should allow for the collection of representative ground-water samples. Drilling fluids (including air) should be used only when minimal impact to the surrounding formation and ground water can be ensured.

The following guidance applies to the use of drilling fluids, drilling fluid additives, and lubricants when drilling ground-water monitoring wells:

- Drilling fluids, drilling fluid additives, or lubricants that impact the analysis of hazardous constituents in ground-water samples should not be used;
- The owner/operator should demonstrate the inertness of drilling fluids, drilling fluid additives, and lubricants by performing analytical testing of drilling fluids, drilling fluid additives, and lubricants and/or by providing information regarding the composition of drilling fluids, drilling fluid additives, or lubricants obtained from the manufacturer;
- The owner/operator should provide the Regional Administrator with a discussion of the potential impact of drilling fluids, drilling fluid additives, and

lubricants on the physical and chemical characteristics of the subsurface and on ground-water quality; and

- The volume of drilling fluids, drilling fluid additives, and lubricants used during the drilling of a monitoring well should be recorded.

The following sections summarize the most commonly used methods for drilling ground-water monitoring wells. These methods also are summarized briefly in Table 7. Table 8 summarizes the limitations and applications of each drilling method. Aller et al. (1989) should be consulted for additional information on the selection of drilling methods.

6.1.1 Hollow-Stem Augers

The hollow-stem, continuous-flight auger is the most frequently employed tool for drilling monitoring wells in unconsolidated materials. Augers are likened to giant screws, and continuous flighting refers to a design in which the flights ("threads") of the auger extend the entire length of the auger core or stem. Individual auger sections, typically 5-feet in length, are also called flights.

When drilling, a cutting head is attached to the first auger flight, and as the auger is rotated downward, additional auger flights are attached, one at a time, to the upper end of the previous auger flight. As the augers are advanced downward, the cuttings move upward along the continuous flighting. The hollow-stem or core of the auger allows drill rods and samplers to be inserted through the center of the augers. The hollow-stem of the augers also acts to temporarily case the borehole, so that the well screen and casing may be inserted down through the center of the augers once the desired depth is reached, minimizing the risk of possible collapse of the borehole that might occur if it is necessary to withdraw the augers completely before installing the well casing and screen.

The hollow-stem auger drilling technique is not without problems. These are more completely described in Aller et al. (1989) but generally include:

- Cross-contamination of subsurface materials -- Because drill cuttings are in contact with the entire length of the borehole as they are transported up the auger flights, hollow-stem augers may cause cross-contamination of subsurface materials;

- Heaving -- Sand and gravel heaving into the hollow-stem may be difficult to control and may necessitate adding water to the borehole;
- Smearing of silts and clays along the borehole wall -- In geologic settings characterized by alternating sequences of sands, silts, and clays, the action of the augers during drilling may cause smearing of clays and silts into the sand

DRILLING METHODS FOR VARIOUS GEOLOGIC SETTINGS

Geologic Setting	Drilling Methods							
	Air Rotary[1,2]	Water/Mud Rotary[1]	Cable Tool	Hollow-Stem Continuous Auger[2]	Solid-Stem Continuous Auger[3]	Jet Percussion[2]	Dual-Wall Reverse-Circulation	Driven Wells[2]
Unconsolidated or poorly consolidated materials less than 125 feet deep	●	●	●	●	●	●	●	●
Unconsolidated or poorly consolidated materials more than 125 feet deep	●	●	●				●	
Consolidated rock formations less than 500 feet deep	●	●	●				●	
Consolidated rock formations more than 500 feet deep	●	●	●				●	

550A-18

1. Includes conventional and wireline core drilling.
2. Not recommended for the installation of ground-water monitoring wells.
3. Above any saturated zones.

NOTE:
Although several methods are suggested as appropriate for similar conditions, one method may be more suitable than the others. This determination is based on site-specific conditions and the judgment of the geologist and the driller.

TABLE 7

APPLICATIONS AND LIMITATIONS OF WELL DRILLING METHODS (ALLER, ET AL. (1989))

HOLLOW-STEM AUGERS

Applications	Limitations
• All types of soil investigations • Permits good soil sampling with split-spoon or thin-wall samplers • Water-quality sampling • Monitoring well installation in all unconsolidated formations • Can serve as temporary casing for coring rock • Can be used in stable formations to set surface casing (example: drill 12-inch borehole; remove augers; set 8-inch casing; drill 7 1/4-inch borehole with 3 1/4-inch ID augers to rock; core rock with 3-inch tools; install 1-inch piezometer; pull augers)	• Difficulty in preserving sample integrity in heaving formations • Formation invasion by water or drilling mud if used to control heaving • Possible cross contamination of aquifers where annular space not positively controlled by water or drilling mud or surface casing • Limited diameter of augers limits casing size • Smearing of clays may seal off aquifer to be monitored

SOLID-STEM AUGERS

Applications	Limitations
• Shallow soils investigations • Soil samples • Vadose zone monitoring wells (lysimeters) • Monitoring wells in saturated, stable soils • Identification of depth to bedrock • Fast and mobile	• Unacceptable soil samples unless split-spoon or thin-wall samples are taken • Soil sample data limited to areas and depths where stable soils are predominant • Unable to install monitoring wells in most unconsolidated aquifers because of borehole caving upon auger removal • Depth capability decreases as diameter of auger increases • Monitoring well diameter limited by auger diameter

CABLE TOOL DRILLING

Applications	Limitations
• Drilling in all types of geologic formations • Almost any depth and diameter range • Ease of monitoring well installation • Ease and practicality of well development • Excellent samples of coarse-grained materials	• Drilling relatively slow • Heaving of unconsolidated materials must be controlled • Equipment availability more common in central, north central and northeast sections of the United States

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TABLE 8

APPLICATIONS AND LIMITATIONS OF WELL DRILLING METHODS (ALLER, ET AL. (1989)) (continued)

AIR ROTARY DRILLING	
Applications	Limitations
• Rapid drilling of semi-consolidated and consolidated rock • Good quality reliable formation samples (particularly if small quantities of water and surfactant are used) • Equipment generally available • Allows easy and quick identification of lithologic changes • Allows identification of most water-bearing zones • Allows estimate of yields in strong water-producing zones with short "down time"	• Surface casing frequently required to protect top of hole • Drilling restricted to semi-consolidated and consolidated formations • Samples occur as small particles that are difficult to interpret • Drying effect of air may mask lower yield water producing zones, only allowing identification of significant water-bearing zones • Air stream requires contaminant filtration • Air may modify chemical or biological conditions; recovery time is uncertain

AIR ROTARY WITH CASING DRIVER DRILLING	
Applications	Limitations
• Rapid drilling of unconsolidated sands, silts and clays • Drilling in alluvial material (including boulder formations) • Casing supports borehole thereby maintaining borehole integrity and minimizing inter-aquifer cross contamination • Eliminates circulation problems common with direct mud rotary method • Good formation samples • Minimal formation damage as casing pulled back (smearing of clays and silts can be anticipated)	• Thin, low pressure water bearing zones easily overlooked if drilling not stopped at appropriate places to observe whether or not water levels are recovering • Samples pulverized as in all rotary drilling • Air may modify chemical or biological conditions; recovery time is uncertain

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TABLE 8 (CONTINUED)

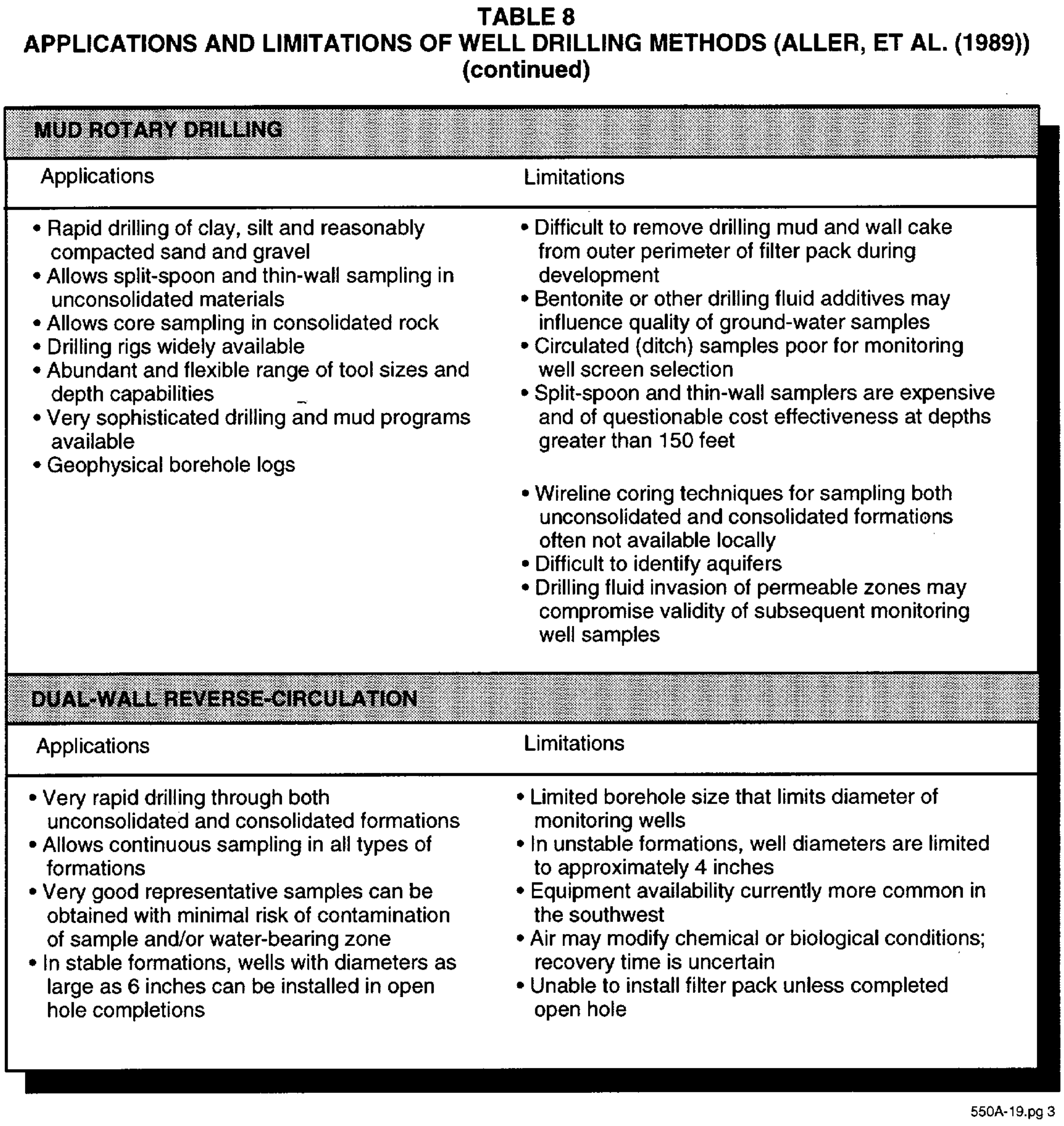

TABLE 8
APPLICATIONS AND LIMITATIONS OF WELL DRILLING METHODS (ALLER, ET AL. (1989))
(continued)

MUD ROTARY DRILLING	
Applications	Limitations
• Rapid drilling of clay, silt and reasonably compacted sand and gravel • Allows split-spoon and thin-wall sampling in unconsolidated materials • Allows core sampling in consolidated rock • Drilling rigs widely available • Abundant and flexible range of tool sizes and depth capabilities • Very sophisticated drilling and mud programs available • Geophysical borehole logs	• Difficult to remove drilling mud and wall cake from outer perimeter of filter pack during development • Bentonite or other drilling fluid additives may influence quality of ground-water samples • Circulated (ditch) samples poor for monitoring well screen selection • Split-spoon and thin-wall samplers are expensive and of questionable cost effectiveness at depths greater than 150 feet • Wireline coring techniques for sampling both unconsolidated and consolidated formations often not available locally • Difficult to identify aquifers • Drilling fluid invasion of permeable zones may compromise validity of subsequent monitoring well samples

DUAL-WALL REVERSE-CIRCULATION	
Applications	Limitations
• Very rapid drilling through both unconsolidated and consolidated formations • Allows continuous sampling in all types of formations • Very good representative samples can be obtained with minimal risk of contamination of sample and/or water-bearing zone • In stable formations, wells with diameters as large as 6 inches can be installed in open hole completions	• Limited borehole size that limits diameter of monitoring wells • In unstable formations, well diameters are limited to approximately 4 inches • Equipment availability currently more common in the southwest • Air may modify chemical or biological conditions; recovery time is uncertain • Unable to install filter pack unless completed open hole

550A-19.pg 3

TABLE 8 (CONTINUED)

TABLE 8
APPLICATIONS AND LIMITATIONS OF WELL DRILLING METHODS (ALLER, ET AL. (1989)) (continued)

DRIVEN WELLS	
Applications	Limitations
• Water-level monitoring in shallow formations • Water samples can be collected • Dewatering • Water supply • Low cost encourages multiple sampling points	• Depth limited to approximately 50 feet (except in sandy material) • Small diameter casing • No soil samples • Steel casing interferes with some chemical analysis • Lack of stratigraphic detail creates uncertainty regarding screened zones and/or cross contamination • Cannot penetrate dense and/or some dry materials • No annular space for completion procedures
JET PERCUSSION	
Applications	Limitations
• Allows water-level measurement • Sample collection in form of cuttings to surface • Primary use in unconsolidated formations, but may be used in some softer consolidated rock • Best application is 4-inch borehole with 2-inch casing and screen installed, sealed and grouted	• Drilling mud may be needed to return cuttings to surface • Diameter limited to 4 inches • Installation slow in dense, bouldery clay/till or similar formations • Disturbance of the formation possible if borehole not cased immediately

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TABLE 8 (CONTINUED)

zones, potentially resulting in a considerable decrease in aquifer hydraulic conductivity along the wall of the borehole. The smearing of clays and silts along the borehole wall may, depending on the site-specific properties of the geologic materials, significantly reduce well yield or produce unrepresentative ground-water samples even after the well has been developed; and

- Management of drill cuttings -- Control of contaminated drill cuttings is difficult with the auger method, especially when drilling below the water table.

6.1.2 Solid-Stem Augers

Drilling with solid-stem augers is similar to drilling with hollow-stem augers except solid-stem augers are made of solid steel, and therefore need to be removed from the borehole to collect "undisturbed" split-spoon or thin-wall samples and to install casing. Boreholes drilled in unconsolidated and poorly consolidated deposits in which solid-stem augers are used will typically not remain stable after saturated materials are encountered, and will collapse after the augers are removed. Consequently, "undisturbed" samples of the unconsolidated materials can generally be collected only above the water table. An alternative drilling method is generally used below the water table once the borehole is advanced through unsaturated deposits.

6.1.3 Cable Tool

Cable tool drilling is a versatile method for sampling and well installation. When the drill rig is equipped with fishing jars and a sampling barrel, continuous samples are retrieved and there is minimal disturbance to the borehole wall. Drilling progresses by raising and dropping the upper half of the jars (the jars are an interlocking set of steel hammers which slide independently of each other) while the lower half rests on the bottom of the borehole. There is a sampling tube attached to the bottom of the lower half of the jars. The hammering action of the jars drives the sampling barrel into the ground. This method will not work in consolidated bedrock but is applicable to virtually all overburden materials. Borehole instability can be overcome by using the jars to drive casing ahead of the sampling zone. Sand heaving can often be overcome by filling the casing with water to maintain a positive head.

The advantages of cable tool drilling include versatility, applicability to both hard and soft formations, minimal smearing, suitability for identifying thin subsurface zones, and usefulness over a wide range of depths. However, problems involving heaving may occur with cable tool drilling.

6.1.4 Air Rotary

Rotary drilling involves the use of circulating fluids (i.e., mud, water, or air) to remove the drill cuttings and to maintain an open hole as drilling progresses. Air rotary drilling forces air down the drill pipe and back up the borehole to remove the drill cuttings. The air rotary drilling technique is best suited for use in hard rock (versus unconsolidated or poorly consolidated materials).

Accurate detection of ground-water contamination at hazardous waste disposal sites is dependent on the generation of high-quality chemical data from the analysis of representative soil, unconsolidated material, rock, and ground-water samples. One of the most important goals of any method used to obtain samples is to create minimal effects on the media and contaminants of concern. The air rotary drilling method may jeopardize the collection of representative and accurate chemical data. For this reason, and for others listed below, the air rotary drilling method should be used with caution during environmental investigations:

- Air rotary does not allow collection of representative samples, therefore, the boring cannot be logged with accuracy. Moreover, air/ground water losses into fractures or other highly permeable zones cannot be measured.

- The injection of air into the borehole during air rotary drilling may alter the natural properties of the subsurface. Specifically, the following chemical and physical processes may occur:

    - Air-stripping of volatile organic constituents can occur during drilling, leading to erroneous chemical data for these compounds for both soil and ground-water samples;

    - Injection of air into the subsurface can significantly alter aquifer geochemistry. Alteration of such properties as pH and redox potential can often be irreversible, thus preventing the well from yielding ground-water samples that are representative of in situ conditions. Changes in pH can affect the solubility of metallic compounds; changes in oxidation state can result in the precipitation of metallic and organo-metallic compounds; and

    - The introduction of oxygen into the aquifer can initiate or greatly increase biodegradation of organic compounds in the aquifer near the vicinity of the borehole. Monitoring wells installed under these circumstances would be unable to yield representative ground-water samples.

- Unless an oil-less compressor is used, the risk exists for introducing some quantity of compressor oil into the borehole. This can occur even when oil-removing filters are used, because their effectiveness depends on careful maintenance. At best, the issue of whether oil has been introduced into the aquifer will remain suspect. There is generally no way to tell when compressor filters need changing because most drilling equipment has safety bypass valves that route the air around plugged filters.

- Control and containment of contaminated drill cuttings can be extremely difficult, and could result in the spread of contamination at the ground surface.

- Personnel safety considerations may require upgrading to higher levels of respiratory and dermal protection due to the generation of dusts, mists, and volatilization of organic compounds. Cuttings are difficult to contain and may pose a safety threat to drill crews working on contaminated sites.

Although use of the air rotary drilling method should not be completely rejected, owners/operators should take the following precautionary steps when using the air rotary drilling method:

- The air from the compressor should be filtered to ensure that compressor oil is not introduced into ground water. The QAPjP should specify when and how the filters will be monitored to prevent breakthrough.

- Air rotary drilling should not be used in areas where upper soil horizons are contaminated. In such settings, sloughing of the sidewalls of the borehole would likely result in contamination of the ground water.

- Air rotary drilling techniques should not be used in highly contaminated environments. When air rotary is used in an environment where even minor subsurface contamination is expected, shrouds, canopies, bluooey lines, or directional pipes should be used to contain and direct the drill cuttings away from the drill crew. Any contaminated materials (soil and/or water) should be collected and properly treated or disposed of in an approved waste disposal facility. Moreover, when drilling through potentially contaminated zones, contaminants carried in the air flow can be introduced into other layers and increase the zone of contamination. This problem can be lessened by installing casing as the borehole is advanced.

- The owner/operator should provide the Regional Administrator with a discussion of the potential impact of the air rotary drilling method on the physical and chemical characteristics of the subsurface and on ground-water quality.

Air rotary drilling requires that care be taken both to prevent cross-contamination of subsurface materials and to prevent contamination or chemical alteration of ground water or subsurface materials.

6.1.5 Mud Rotary and Water Rotary

The mud rotary and water rotary drilling methods involve the introduction of drilling fluids (various drilling muds or water) into the borehole through the drill pipe to maintain an open hole, provide lubrication to the drill bit, and remove drill cuttings.

Water rotary drilling is a rapid and effective drilling method for most geologic materials. However, the water used as a drilling fluid tends to react with the surrounding formation and ground water. For this reason, the utility of water rotary drilling is limited. In addition, there are other problems associated with water rotary drilling. The identification of water-bearing zones is hampered by the addition of water into the borehole. In clay-rich sediments, the water may form a slurry that can rapidly cause plugging of the formation, resulting in a well that is difficult to develop. In poorly consolidated sediments, drillers may have a problem with caving of the borehole prior to installation of the well screen and casing. In highly fractured rock, it may be difficult to maintain effective water circulation because of water losses to the subsurface. The drilling fluids used in rotary drilling can grossly contaminate upper or lower uncontaminated zones if a contaminated zone is penetrated. Driving casing as the borehole is advanced can help resolve this problem.

While there are hydrogeologic conditions where mud rotary drilling is the best option (e.g., where it is extremely difficult to maintain a stable borehole), mud rotary creates a high potential for affecting aquifer characteristics and ground-water quality. If the mud rotary method is used, the drilling mud(s) should not affect the chemistry of ground-water samples or samples from the borehole, or adversely impact the operation of the well. To minimize the influence to the surrounding formation and ground water, drilling muds should be limited to water-based, locally-occurring clays. The following describes the type of adverse affects that can occur to the aquifer, ground-water quality, and/or well performance as a result of using certain drilling muds. A more comprehensive review of the properties, applications, and impacts of drilling fluids is given in Aller et al. (1989):

- Bentonite muds form a filter cake on the sides of the borehole, thus reducing the effective porosity of formations in the borehole, and compromising the design of the well. Bentonite may also affect local ground-water pH. Additives to modulate viscosity and density may also introduce contaminants to the system or force large, unrecoverable quantities of mud into the formation.
- Some organic polymers and compounds provide an environment for bacterial growth, which reduces the reliability of sampling results.

- Bentonite muds may adsorb metals, potentially reducing contaminant concentrations and affecting the reliability of sampling results.

Direct mud rotary drilling is recommended by some investigators for use at heavily contaminated sites or at sites where the contaminants of concern are highly toxic and where proper containerization of drill cuttings and fluids is important. The technique requires creating a leak-proof seal in a portable mud pit, so that returned drilling fluids and cuttings will be contained within the pit. The cuttings may be transferred from the pit to drums as necessary. Heavy-gauge plastic sheeting may be used to cover the exclusion zone and to prevent equipment from contaminating surface soils. Obviously, owners/operators should ensure that this application of direct mud rotary drilling does not cause cross-contamination of subsurface materials.

6.1.6 Dual-Wall Reverse-Circulation

The dual-wall reverse-circulation rotary method utilizes a double-wall drill pipe, and has the reverse circulation of other conventional rotary drilling methods. Air or water is forced down the outer casing and is circulated up the inner drill pipe. Cuttings are lifted up to the surface through the inner drill pipe. Either a hammer or tricone bit can be used to cut the formation. A triple wall design, involving the placement of an additional single-wall casing around the dual-wall drill string, may be useful in situations where it is necessary to case a contaminated upper formation to install a well in an underlying formation.

The greatest advantage of dual-wall reverse-circulation drilling is that it allows continuous sampling of the subsurface, and largely eliminates or reduces problems associated with lost circulation and borehole stability. The disadvantages of dual-wall reverse-circulation drilling include the necessity of using larger drilling equipment and a large borehole to accommodate the dual-wall pipe.

6.1.7 Driven Wells

Driven wells consist of a steel well screen that is either welded or attached with drive couplings to a steel casing. The well screen and attached casing are forced into the ground by hand using a weighted drive sleeve, or with a heavy drive head mounted on a hoist. As the well is driven, new sections of casing are attached to the well in 4- or 5-foot sections.

Several problems are commonly associated with the installation of driven wells. First, it is difficult or impossible to drive a well through dense silts, clays or materials containing boulders. If penetration in these materials is accomplished, the well screen may be destroyed in the process. In addition, silts and/or clays can clog the well screen to the point where the well cannot be satisfactorily developed. Two techniques, described in Aller et al. (1989) have been employed in an attempt to alleviate these problems. Driven wells may be helpful as a tool for preliminary field studies requiring installation of shallow piezometers. However, in most cases, the Agency discourages the sole use of the driven well construction method for the purpose of installing monitoring wells. This is primarily because of the inability to collect representative samples of the materials that are penetrated during well installation, and of the inability to seal the well properly unless an outer casing is driven first. However, if samplers can be driven in advance of the casing to allow subsurface sample collection, the driven well method may be a viable well installation option.

6.1.8 Jet Percussion

The jet percussion drilling method uses a wedge-shaped drill bit attached to the end of the drill pipe. Water is forced under pressure down the drill pipe and is discharged through ports on the sides of the drill bit. The bit is lifted and dropped while rotating. The water is forced up the annular space between the drill pipe and the borehole wall, carrying cuttings to the surface. The method is limited to unconsolidated or soft consolidated formations. The disadvantages of this method include the inability to collect representative samples of ground-water, soil, or unconsolidated deposits during drilling and the potential for disturbing the formation.

6.1.9 Decontamination of Drilling Equipment

All drilling equipment that will encounter formation materials (e.g., augers, samplers, tremie pipes) should at a minimum be decontaminated between boreholes, and in the case of samplers, between samples. When cross-contamination between zones within a single borehole is a concern, equipment should be decontaminated more frequently. Aller et al. (1989) provide a comprehensive discussion of decontamination of drilling and formation-sampling equipment.

The types of drilling and sampling equipment that should be decontaminated (Aller et al., 1989) include:

- Drill bits;
- Auger sections;
- Drill-string tools;
- Drill rods;
- Sampling equipment (e.g., split spoons);
- Bailers used for well development or for the removal of fluids from the well;
- Tremie pipes;

- Clamps;
- Hand tools;
- Steel cable; and
- Drill rigs and support vehicles.

The general cleaning procedure for drilling equipment should include washing the equipment with potable water and/or hot pressurized potable water. For more contaminated equipment, this procedure should be followed by a wash with non-phosphate detergent and a final rinse with potable water (Moberly, 1985; Aller et al., 1989). Moberly (1985) presents a list of additional cleaning solutions that may be used to clean drilling and formation-sampling equipment, and provides their specific uses. If formation samples are being collected for chemical analysis, then the cleaning procedure followed for the samplers should be analogous to that provided for ground-water sampling equipment in Section 7.3.8.

6.1.10 Well Diameter

To avoid the possibility of having to handle large amounts of purged contaminated water, the Agency recommends the use of either 2-inch or 4-inch diameter wells. If an owner/operator believes that wells with diameters larger than 4 inches would improve sample integrity at some or all of the well locations, then he/she should submit substantive justification before installation of the larger diameter well(s). The use of larger diameter wells may be necessary where dedicated purging or sampling equipment is used or where the well is screened in a deep formation. When considering whether to install larger diameter wells, the investigator should recognize that the quantity of contaminated ground water that will require proper disposal, and in some settings the time required for well recovery, will increase with well diameter.

6.1.11 Stratigraphic Control

Adequate stratigraphic control is critical to the proper vertical placement of well screens. Samples should be collected from boreholes at all suspected changes in lithology. The deepest borehole drilled at the site should be continuously sampled. For boreholes that will be completed as monitoring wells, at least one sample should be collected from the interval that will be the monitoring well intake interval (i.e., screened interval or open (uncased) interval). EPA recommends that all boreholes be continuously sampled to ensure stratigraphic control. Borehole samples should be classified according to their lithology or pedology by an experienced professional in geology. Care should be taken to ensure that samples of every geologic formation, especially all confining layers, are collected, and that the nature of stratigraphic contacts is determined.

The owner/operator should construct a minimum of two representative cross-sections for each hazardous waste management unit, one in the direction of ground-water flow and one orthogonal to ground-water flow. Cross-sections should be based on both the monitoring well boring logs and on the boring logs from the subsurface boring program, and should depict significant stratigraphic and structural trends and reflect stratigraphic and structural features in relation to local and regional ground-water flow. Site stratigraphy represented on the cross-sections should be compared against known regional stratigraphy to verify the well/boring logs and to prepare an analysis of site-specific stratigraphy. In complex geologic settings, the Agency recommends that borehole geophysical logging, surface geophysical surveys, and/or cone penetrometer surveys be performed both to verify the logs of cuttings or samples and to assist in establishing stratigraphic control. When planning such surveys it is important to remember that drilling methods and well casings/screens will influence the selection of geophysical methods (e.g., electrical resistivity logging cannot be performed in cased wells).

6.2 Well Casing and Screen Materials

Figure 13 is a drawing of a monitoring well. A casing and well screen are installed in a ground-water monitoring well for several reasons: to provide access from the surface of the ground to some point in the subsurface, to prevent borehole collapse, to permit ground-water level measurements and ground-water sampling, and (for casing) to prevent hydraulic communication between zones within the subsurface. Access to the monitored zone is through the casing and into either an open borehole or the screened intake.

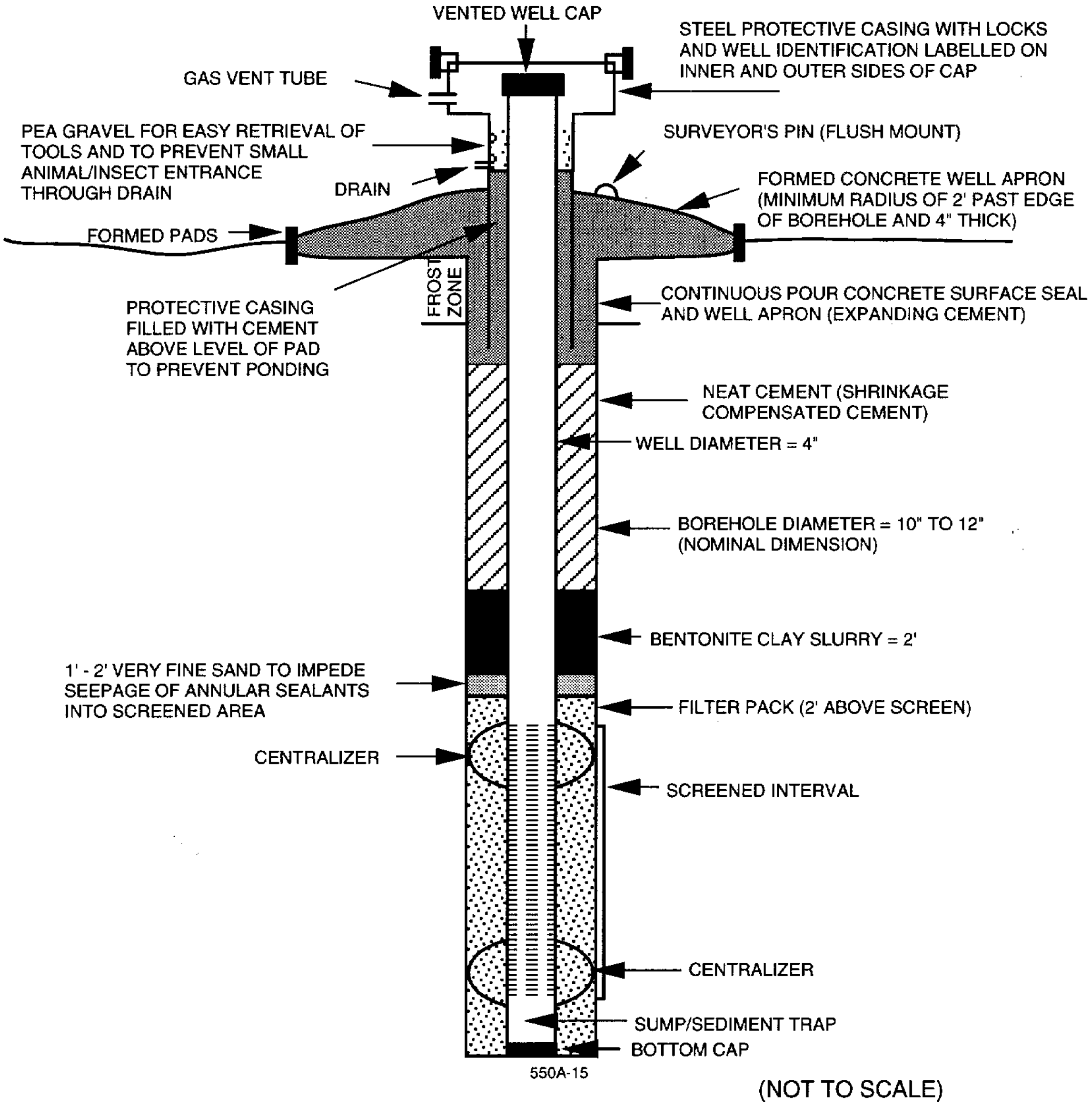
Monitoring well casing and screen materials should meet the following performance specifications:

- Monitoring well casing and screen materials should maintain their structural integrity and durability in the environment in which they are used over their operating life;

- Monitoring well casings and screens should be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters;

- Monitoring well casings and screens should be able to withstand the physical forces acting upon them during and following their installation, and during their use -- including forces due to suspension in the borehole, grouting, development, purging, pumping, and sampling, and forces exerted on them by the surrounding geologic materials; and

- Monitoring well casing and screen materials should not chemically alter ground-water samples, especially with respect to the analytes of concern, as a result of their sorbing, desorbing, or leaching analytes. For example, if a metal



CROSS-SECTION OF TYPICAL MONITORING WELL

FIGURE 13

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such as chromium is an analyte of interest, the well casing or screen should not increase or decrease the amount of chromium in the ground water. Any material leaching from the casing or screen should not be an analyte of interest, or interfere in the analysis of an analyte of interest.

In addition, monitoring well casing and screen materials should be relatively easy to install into the borehole during construction of the monitoring well.

Owners and operators also should consider the purpose of the well when determining the well's design. Will the well be used solely as a piezometer? Will the well be placed in an area where there is currently no contamination and where natural water quality is not likely to interact with it? Will the well be used to delineate the extent of a plume, but not used to determine compliance with cleanup levels? Will the well be used to extract contaminated ground water as part of corrective action activities? Will the well be used as a point-of-compliance well for which accurate information is crucial?

The following discussion of casing and screen materials comes from several sources, but the majority of it is directly from the EPA/EMSL-Las Vegas Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells (Aller et al., 1989), with additional information from various references, as cited. EPA believes that the use of this up-to-date technical guidance, along with the technical criteria provided below, aid in the selection of appropriate well materials. In addition to references cited by Aller et al. (1989) the following references also are available for consideration when choosing well casing and screen materials:

- Cowgill, U.M. 1988. The Chemical Composition of Leachate from a Two-Week Dwell-Time Study of PVC Well Casing and Three-Week Dwell-Time Study of Fiberglass Reinforced Epoxy Well Casing, in A.G. Collins and A.I. Johnson, eds., Ground-Water Contamination: Field Methods, ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 172-184.

- Gillham, R.W. and S.F. O'Hannesin. 1990. Sorption of Aromatic Hydrocarbons by Materials Used in Construction of Ground-Water Sampling Wells, in D.M. Nielsen and A.I. Johnson, eds., Ground-Water and Vadose Zone Monitoring, ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 108-122.

- Hewitt, A.D. 1989. Leaching of Metal Pollutants from Four Well Casings Used for Ground-Water Monitoring. CRREL Special Report 89-32, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755-1290.

- Hewitt, A.D. 1992. Potential of Common Well Casing Materials to Influence Aqueous Metal Concentrations. Ground Water Monitoring Review, Vol. 12, No. 2, pp. 131-136.

- Jones, J.N. and G.D. Miller. 1988. Adsorption of Selected Organic Contaminants onto Possible Well Casing Materials, in A.G. Collins and A.I. Johnson, eds., Ground-Water Contamination: Field Methods, ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 185-198.

- Parker, L.V. 1991. Discussion of "The Effects of Latex Gloves and Nylon Cord on Ground Water Sample Quality" by J.L. Canova & M.G. Muthig. Ground Water Monitoring Review, Vol. 11, No. 4, pp. 167-168.

- Parker, L.V., A.D. Hewitt, and T.F. Jenkins. 1990. Influence of Casing Material on Trace-Level Chemicals in Well Water. Ground Water Monitoring Review, Vol. 10, No. 2, pp. 146-156.

- Reynolds, G.W., J.T. Hoff, and R.W. Gillham. 1990. Sampling Bias Caused by Materials Used to Monitor Halocarbons in Groundwater. Environmental Science Technology, Vol. 24, No. 1, pp. 135-142.

Laboratory studies of the effects of well casing materials on either inorganic or organic dissolved constituents in ground water are still relatively inconclusive and incomplete; they serve solely to demonstrate the potential for well casing-related alteration of ground-water samples. The manipulation of raw data may allow investigators to reach conclusions that are unsupported given further evaluation of the raw data and test conditions.

Construction materials for piezometers that will be used solely for measuring water levels are not the focus of this section. For the purposes of water level monitoring during detection monitoring, thermoplastic materials are usually adequate. However, in compliance (or assessment) monitoring and corrective action, care should be taken to construct piezometers of materials that will not degrade or react with contaminated ground water.

6.2.1 General Casing and Screen Material Characteristics

Historically, well casings and screens were produced predominantly for water supply wells, and the selection of a well casing or screen material focused on structural strength, durability in long-term exposure to natural ground-water environments, and ease of handling. The selection of the most suitable well casing and screen materials should consider site-specific factors, including:

- Depth to the water-bearing zone(s) to be monitored and anticipated well depth;

- Geologic environment;

- Geochemistry of soil, unconsolidated material, and rock over the entire interval in which the well is to be cased;

- Geochemistry of the ground water at the site, as determined through an initial analysis of samples from both background wells and downgradient wells and including:

    - natural ground-water geochemistry,

    - nature of suspected or known contaminants, and

    - concentration of suspected or known contaminants; and

- Design life of the monitoring well.

The most frequently evaluated characteristics that directly influence the performance of casing and screen materials in ground-water monitoring applications are strength and chemical resistance/interference. These characteristics are discussed in more detail below.

Strength-Related Characteristics

Well casing and screen materials should maintain their structural integrity and durability in the environment in which they are used over their operating life. Monitoring well casings and screens should be able to withstand the physical forces acting upon them during and following their installation, and during their use, including forces due to suspension in the borehole, grouting, development, purging, pumping, sampling, and forces exerted on them by the surrounding geologic materials. When casing strength is evaluated, three separate yet related parameters should be evaluated:

- Tensile strength;

- Compressive strength; and

- Collapse strength.

The tensile strength of a material is defined as the greatest longitudinal stress the material can bear without pulling the material apart. Tensile strength of the installed casing varies with composition, manufacturing technique, joint type, and casing dimensions. For monitoring wells, the selected casing and screen materials should have a tensile strength capable of supporting the weight of the casing string when suspended from the surface in an air-filled borehole. The tensile strength of the casing joints is equally as important as the tensile strength of the casing. Because the joint is generally the weakest point in a casing string, the joint strength will determine the maximum axial load that can be placed on the casing. By dividing the tensile strength by the linear weight of casing, the maximum theoretical depth to which a dry string of casing can be suspended in a borehole can be calculated. When the casing is in a borehole partially filled with water, the buoyant force of the water increases the length of casing that can be suspended. The additional length of casing that can be suspended depends on the specific gravity of the casing material.

The compressive strength of a material is defined as the greatest compressive stress that a substance can bear without deformation. Unsupported casing has a much lower compressive strength than installed casing that has been properly grouted and/or backfilled, because vertical forces are greatly diminished by soil friction. This friction component means that the casing material properties are more significant to compressive strength than wall thickness. Casing failure due to compressive strength limitation is generally not an important factor in a properly installed monitoring well.

As important as tensile strength is the final strength-related property considered in casing and screen selection -- collapse strength. Collapse strength is defined as the capability of a casing to resist collapse by any and all external loads to which it is subjected both during and after installation. The resistance of casing to collapse is determined primarily by outside diameter and wall thickness. Casing collapse strength is proportional to the cube of the wall thickness. Therefore, a small increase in wall thickness provides a substantial increase in collapse strength. Collapse strength is also influenced by other physical properties of the casing material including stiffness and yield strength.

Casings and screens are most susceptible to collapse during installation before the placement of the filter pack or annular seal materials around the casing. Although the casing may collapse during development, once a casing is properly installed, collapse is seldom a concern (National Water Well Association and Plastic Pipe Institute, 1981). External loadings on casing that may contribute to collapse include:

- Net external hydrostatic pressure produced when the static water level outside of the casing is higher than the water level on the inside;
- Unsymmetrical loads resulting from uneven placement of backfill and/or filter pack materials;
- Uneven collapse of unstable formations;
- Sudden release of backfill materials that have temporarily bridged in the annulus;

- Weight of the cement grout slurry, and impact of the heat of hydration of the grout on the outside of a partially water-filled casing;

- Extreme drawdown inside the casing caused by overpumping;

- Forces associated with well development that produce large differential pressures on the casing; and

- Forces associated with improper installation procedures where unusual force is used either to counteract a borehole that is not straight or to overcome buoyant forces.

Of these stresses, only external hydrostatic pressure can be predicted and calculated with accuracy; the others can be avoided by common sense and good practice. To provide a sufficient margin against possible collapse by all normally-anticipated external loadings, a casing should be selected so that resistance to collapse is more than required to withstand external hydrostatic pressure alone. According to Purdin (1980), steps to minimize the possibility of collapse include:

- Drilling a straight, clean borehole;

- Uniformly distributing the filter pack materials at a slow, even rate;

- Avoiding the use of quick-setting (high temperature) cements for thermoplastic casing installation;

- Adding sand to cement to lower the heat of hydration; and

- Controlling negative pressures inside the well during development.

Nielsen and Schalla (1991) provide a discussion on the physical strength of various well casing and screen materials. Table 9 provides a summary of comparative strengths of well casing materials.

Chemical Resistance Characteristics

Monitoring well casing and screen materials should maintain their structural integrity and durability in the environment in which they are used over their operating life. Monitoring well casings and screens should be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters. Metallic casing and screen materials are subject to corrosion, and thermoplastic casing and screen materials are subject to chemical degradation by solvents. The extent to which these processes occur depends on water quality within the formation and changing chemical conditions such as

COMPARATIVE STRENGTHS OF WELL CASING MATERIALS[a] (NIELSEN AND SCHALLA, 1991)

Material	Casing Tensile Strength (lb)		Casing Collapse Strength (lb/in^2)	
	2-in. nominal	4-in. nominal	2-in. nominal	4-in. nominal
Polyvinylchloride (PVC)	7,500	22,000	307	158
PVC casing joint[b]	2,800	6,050	300	150
Stainless steel (SS)[c]	37,760	92,000	896	315
SS casing joint[b]	15,900	81,750	No data	No data
Polytetrafluoroethylene (PTFE)	3,800	No data	No data	No data
PTFE casing joints[b]	540	1,890	No data	No data
Epoxy fiberglass	22,600	56,500	330	250
Epoxy casing joints[d]	14,000	30,000	230	150
Acrylonitrile-butadiene-styrene (ABS)	8,830	22,000	No data	No data
ABS casing joints[d]	3,360	5,600	No data	No data

[a] Information provided by E. I. du Pont de Nemours & Company, Wilmington, DE.

[b] All joints are flush-threaded.

[c] Stainless steel casing materials are Schedule 5 with Schedule 40 joints; other casing materials (PVC, PTFE, epoxy, ABS) are Schedule 40.

[d] Joints are not flush-threaded, but are a special type that is thicker than Schedule 40.

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TABLE 9

fluctuations between oxidizing and reducing conditions. Casing materials should be chosen with a knowledge of existing and anticipated ground-water chemistry. Because subsurface conditions cannot be predicted without some preliminary sampling and analysis, the choice of appropriate well casing materials should be contingent upon preliminary water quality analyses, which will be critical to the success of a ground-water monitoring program. Information collected during interim status (see §265.92(b)) can assist in assessing ground-water quality. When anticipated water quality is unknown, it is prudent initially to use conservative materials (i.e., the most chemically inert). The "Chemical Resistance Chart" presented in the 1991-1992 catalog of the Cole-Parmer Instrument Company of Chicago (Appendix 3) may provide general information regarding the resistance of various well materials to degradation, although this chart is presumably reporting the effects of reagent grade chemicals on the various materials. General recommendations regarding the selection of well casing materials to minimize chemical interactions are presented in Table 10.

Chemical Interference Characteristics

Monitoring well casing and screen materials should not chemically alter ground-water samples as a result of their sorbing, desorbing, or leaching analytes, especially with respect to the analytes of concern. If a casing material sorbs selected constituents from the ground water, those constituents either will not be present in any water quality sample or the concentration of constituents will be reduced. Additionally, if ground-water chemistry changes over time, the chemical constituents that were previously sorbed onto the casing may begin to desorb and/or leach into the ground water. In either situation, the water-quality samples are not representative.

Sorptive solute-removal processes by interaction with casing materials or filter packs may reduce actual constituent concentrations below quantitation limits or regulatory thresholds, resulting in biased contaminant plume delineations, reduced sensitivity of detection, or false-negative assessments of ground-water contamination (Palmer et al., 1987). Proper well purging may minimize the impact of sorption or leaching effects; however, purging efficiency is difficult to document. Effective purging may rarely be achieved if bailers are used. The effectiveness of purging in minimizing sorption or leaching effects of well materials will be dependent on the relative rates and magnitudes of these processes in the borehole, filter pack, wells, and the actual time of sample exposure to the materials.

In the presence of chemically reactive aqueous solutions, certain chemical constituents can be leached from casing materials. If this occurs, chemical constituents that are not indicative of formation water quality may be detected in samples collected from the well. This phenomenon might be considered an indication of possible contamination when the constituents do not relate to ground-water contamination per se, but rather to water sample contamination contributed by the well casing material. The selection of a casing material should therefore consider potential interactions between the casing material and the natural and human-induced geochemical environment.

RECOMMENDATIONS REGARDING CHEMICAL INTERACTIONS WITH WELL CASINGS

	Best Choices		**Avoid if Possible**
If Monitoring for:	**1st Choice**	**2nd Choice**	
Metals	PTFE	PVC	SS 304 & SS 316[+]
Organics	SS 304 & SS 316	PVC	Galvanized steel and PTFE[*]
Metals & Organics	None	PVC & PTFE	SS 304 & SS 316

[*] Do not use PTFE for monitoring tetrachloroethylene. PTFE tends to be more sorptive of organics than PVC. Hydrophobic organics (Log Kow ≥ ~2) are most readily sorbed.

[+] Substantial concentrations of metals can be leached from SS if the contact time is 2 hours or longer.

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TABLE 10

With respect to well casings, there have been relatively few systematic studies of sorption and leaching, other than well-documented reports describing the persistent effects of PVC solvent cements (Sosebee et al., 1983) and the problems with corrosion of ferrous casings.

6.2.2 Types of Casing Materials

Casing materials widely available for use in ground-water monitoring wells can be divided into three categories:

1) Fluoropolymer materials, including polytetrafluoroethylene (PTFE), tetrafluoroethylene (TFE), fluorinated ethylene propylene (FEP), perfluoroalkoxy (PFA), and polyvinylidene fluoride (PVDF);

2) Metallic materials, including carbon steel, low-carbon steel, galvanized steel, and stainless steel (304 and 316); and

3) Thermoplastic materials, including polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS).

In addition to these three categories that are widely used, fiberglass-reinforced plastic (FRP) has been used for monitoring applications. Because FRP has not yet been used in general application across the country, very little data are available on their characteristics and performance. Gillham and O'Hannesin (1990) examined sorption of dissolved aromatics (ppm levels) by epoxy-impregnated fiberglass. Generally, fiberglass was more sorptive of these compounds than rigid PVC but less sorptive than PTFE. Fiberglass-reinforced materials are not included in the following discussion. However, owners/operators may conduct technically-based comparative studies between new well construction materials and standard alternatives (e.g., PVC, stainless steel, and PTFE) on a site-specific basis to demonstrate performance of well materials.

All well construction materials possess strength-related characteristics and chemical resistance/chemical interference characteristics that influence their performance in site-specific hydrogeologic and contaminant-related monitoring situations. The characteristics for each of the three categories of materials are discussed below.

Fluoropolymer Materials

Fluoropolymers are synthetic materials consisting of different formulations of monomers (organic molecules) that can be molded by powder metallurgy techniques or extruded while heated. Fluoropolymers are technically included among the thermoplastics, but possess a unique set of properties that distinguish them from other thermoplastics: fluoropolymers are resistant to chemical and biological attack, oxidation, weathering, and ultraviolet radiation; they have a broad useful temperature range (up to 550°F) and a high dielectric constant; they exhibit a low coefficient of friction; they have anti-stick properties; and they possess a greater coefficient of thermal expansion than most other plastics and metals.

A variety of fluoropolymer materials are marketed under a number of different trademarks. Polytetrafluoroethylene (PTFE) was discovered by E. I. Du Pont de Nemours in 1938. PTFE's properties include an extreme temperature range (from -400°F to +550°F in constant service) and the lowest coefficient of friction of any solid material (Hamilton, 1985). PTFE is by far the most widely-used and produced fluoropolymer. Fluorinated ethylene propylene (FEP) was also developed by E. I. Du Pont de Nemours and is perhaps the second most widely used fluoropolymer. It duplicates nearly all of the physical properties of PTFE except the upper temperature range, which is 100°F lower. Production of FEP-finished products is generally faster because FEP is melt-processible, but raw material costs are higher. Perfluoroalkoxy (PFA) combines the best properties of PTFE and FEP, but PFA costs substantially more than either PTFE or FEP. Polyvinylidene fluoride (PVDF) is tougher and has a higher abrasion resistance than other fluoropolymers, and is resistant to radioactive environments. PVDF also has a lower maximum temperature limit than either PTFE or PFA.

Care should be exercised in the use of trade names to identify fluoropolymers. Some manufacturers use one trade name to refer to several of their own different materials. For example, Du Pont refers to several of its fluorocarbon resins as Teflon®, although the actual products have different physical properties and different fabricating techniques. These materials may not always be interchangeable in service or performance.

Aller et al. (1989) provide an excellent summary of the research on PTFE materials performed by Hamilton (1985), Reynolds and Gillham (1985), Barcelona et al. (1985a), Lang et al. (1989), Dablow et al. (1988), and Barcelona et al. (1985b). The following advantages and disadvantages of PTFE are highlighted in Aller et al.'s (1989) summary and by Nielsen and Schalla (1991).

Advantages of PTFE well casing and screen materials:

- Can be used under a wide range of temperatures;
- Inert to attack by the environment, acids, and solvents;
- Fairly easily machined, molded, or extruded;
- Most inert casing for monitoring metals; and
- In terms of chemical inertness, best overall choice if only metallic analytes are of concern (Hewitt, 1992).

Disadvantages of PTFE well casing and screen materials:

- May sorb/desorb organic constituents from/into solution;
- Only slotted casing is available for screens;
- Ductile behavior of PTFE ("creep" or "cold flow") may result in the partial closing of well intake openings (i.e., screen slots);
- PTFE's extreme flexibility may result in non-plumb and bowed wells;
- Non-stick nature of PTFE may cause annular seal failure;
- Moderate weight and low strength per unit length;
- PTFE casing and screen is unsuitable for driven wells; and
- Higher cost relative to stainless steel and PVC.

Structural strength of screen materials is primarily a problem only with PTFE screen materials, which are affected by a phenomenon known as "creep" or "cold flow." Under constant stress through time, such as continuous loading of the entire length of casing, PTFE can deform plastically (i.e., it retains the deformed shape after the stress is removed), and in screened casings made of PTFE, the result can be partial or complete closure of the slots, thus effectively ruining the well's usefulness for monitoring purposes. This is a problem, however, only when the wells are relatively deep (250 feet or deeper); in shallow wells the physical resistance of PTFE to compression is greater than is its tendency to deform plastically (Du Pont, reference 1).

If PTFE is to be used in deeper wells, structural strength problems can be avoided by using slightly larger slots; larger slots may be narrowed slightly because of cold flow, however they will not be completely sealed shut. It also may be possible to obtain PTFE casing that has been modified by the use of fillers. Fillers can be used to increase the resistance to cold flow by approximately a factor of 2 (Du Pont, reference 1), thus limiting the deformation that will occur in the screened casing. More information about "cold flow" phenomena is available from the manufacturer (Du Pont, reference 2).

Metallic Materials

Metallic well casing and screen materials available for use in monitoring wells include carbon steel, low carbon steel, galvanized steel, and stainless steel. Well casings and screens made of any of these metallic materials are generally stronger, more rigid, and less temperature-sensitive than thermoplastics, fluoropolymer, or fiberglass-reinforced epoxy casing materials. The strength and rigidity of metallic casing materials are sufficient to withstand virtually any subsurface condition encountered in a ground-water monitoring situation, but metallic materials may be subject to corrosion during long-term exposure in certain subsurface geochemical environments.

Corrosion is defined as the weakening or destruction of a material by chemical action. Corrosion of metallic well casings and well intakes can both limit the useful life of the monitoring well installation and result in ground-water sample analytical bias. It is important, therefore, to select both casing and screen that are made from corrosion-resistant materials.

Several well-defined forms of corrosive attack on metallic materials have been observed. In all forms, corrosion proceeds by electrochemical action, and water in contact with the metal is an essential factor. According to Driscoll (1986), the forms of corrosion typical in environments where well casing and well intake materials are installed include:

- General oxidation or "rusting" of the metallic surface, resulting in uniform destruction of the surface with occasional perforation in some areas;

- Selective corrosion (dezincification) or loss of one element of an alloy, leaving a structurally weakened material;

- Bi-metallic corrosion, caused by the creation of a galvanic cell at or near the juncture of two different metals;

- Pitting corrosion, or highly-localized corrosion by pitting or perforation, with little loss of metal outside of these areas; and

- Stress corrosion, or corrosion induced in areas where the metal is highly stressed.

To determine the potential for corrosion of metallic materials, the natural geochemical conditions should first be determined. The following list of indicators can help recognize potentially corrosive conditions (modified from Driscoll, 1986):

- Low pH -- if ground-water pH is less than 7.0, water is acidic and corrosive conditions exist;

- High dissolved oxygen content -- if dissolved oxygen content exceeds 2 milligrams per liter, corrosive water is indicated;

- Presence of hydrogen sulfide (H_2S) -- presence of H_2S in quantities as low as 1 milligram per liter can cause severe corrosion;

- Total dissolved solids (TDS) -- if TDS is greater than 1000 milligrams per liter, the electrical conductivity of the water is great enough to cause serious electrolytic corrosion;

- Carbon dioxide (CO_2) -- corrosion is likely if the CO_2 content of the water exceeds 50 milligrams per liter; and

- Chloride (Cl^-), bromide (Br^-), and fluoride (F^-) content -- if the Cl^-, Br^-, and F^- concentrations together exceed 500 milligrams per liter, corrosion can be expected.

Combinations of any of these corrosive conditions generally increase the corrosive effect.

Carbon steels were produced primarily to provide increased resistance to atmospheric corrosion. Achieving this increased resistance requires that the material be subjected to alternately wet and dry conditions. In most monitoring wells, water fluctuations are not sufficient in either duration or occurrence to provide the conditions that minimize corrosion. Therefore, the difference between the corrosion resistance of carbon and low-carbon steels in the unsaturated or in the saturated zone is negligible, and both materials may be expected to corrode approximately equally.

Corrosion products include iron, manganese, and trace metal oxides as well as various metal sulfides (Barcelona et al., 1983). Under oxidizing conditions, the principal products are solid hydrous metal oxides; under reducing conditions, high concentrations of dissolved metallic corrosion products can be expected (Barcelona et al., 1983). While the electroplating process of galvanizing improves the corrosion resistance of either carbon or low-carbon steel, in many subsurface environments the improvement is only slight and short-term. The products of corrosion of galvanized steel include iron, manganese, zinc, and traces of cadmium (Barcelona et al., 1983).

The presence of corrosion products represents a high potential for the alteration of ground-water sample chemical quality. The surfaces where corrosion occurs also present potential sites for a variety of chemical reactions and adsorption. These surface interactions can cause significant changes in dissolved metal or organic compounds in ground-water samples (Marsh and Lloyd, 1980). According to Barcelona et al. (1983), even purging the well prior to sampling may not be sufficient to minimize this source of sample bias because the effects of the disturbance of surface coatings or accumulated corrosion products in the bottom of the well are difficult, if not impossible, to predict. On the basis of these observations, the use of carbon steel, low-carbon steel, and galvanized steel in monitoring well construction is not recommended in most natural geochemical environments.

Several different types of stainless steel alloys are available. The most common alloys used for well casing and screen are Type 304 and Type 316. Type 304 stainless steel is perhaps the most practical from a corrosion resistance and cost standpoint. It is composed of slightly more than 18 percent iron and not more than 0.08 percent carbon (Driscoll, 1986). Chromium and nickel give the Type 304 alloy resistance to corrosion; the low carbon content improves weldability. Type 316 stainless steel is compositionally similar to Type 304 with one exception -- Type 316 has a 2 to 3 percent molybdenum content and a higher nickel content that replaces the equivalent percentage of iron. This compositional difference provides Type 316 stainless steel with an improved resistance to sulfur-containing compounds and sulfuric acid solutions (Barcelona et al., 1983). Type 316 generally performs better than Type 304 under reducing conditions.

For either formulation of stainless steel, exposure to corrosive conditions may result in corrosion and the subsequent contamination of samples by metals such as chromium or nickel. According to Barcelona et al. (1983), Type 316 stainless steel is less susceptible to pitting or pinhole corrosion caused by organic acids or halide solutions. However, Laboratory studies by Hewitt (1989) and Parker et al. (1990) showed that rusting began within 1 to 2 days for pieces of both Type 304 and Type 316 casings exposed to well water with high dissolved oxygen. Recent work by Barcelona and Helfrich (1986, 1988) and Barcelona et al. (1988a) suggests that biological activity may alter geochemistry near stainless steel wells. Iron bacteria, which oxidize ferrous iron to ferric iron, can cause encrustation of any type of casing material, including PVC or PTFE, if the water contains ferrous iron (Lloyde and Heathcote, 1985). Encrustation can lead to failure of the screen due to blockage (Lloyde and Heathcote, 1985). Under anaerobic conditions, sulfate-reducing bacteria can actively cause corrosion of stainless steel (Lloyde and Heathcote, 1985).

The following advantages and disadvantages of stainless steel are highlighted by Aller et al. (1989) and by Nielsen and Schalla (1991):

Advantages of stainless steel well casing and screen materials:

- High strength in wide range of temperatures;
- Readily available;
- High open area screens available;
- Suitable for driven wells;
- Not degraded by organic solvents;
- Low potential for sorption of organic compounds; and
- Best material for monitoring trace-level organics.

Disadvantages of stainless steel well casing and screen materials:

- May corrode under some geochemical and microbiological conditions;
- May sorb cations and anions;
- May contribute metal ions (iron, chromium, nickel, manganese) to ground-water samples;
- High weight per unit length; and
- Type 304 and Type 316 stainless steel are unsuitable for use when monitoring for inorganic constituents.

Thermoplastic Materials

Thermoplastics are human-made materials that are composed of different formulations of large organic molecules. These formulations soften by heating and harden upon cooling, and therefore, can be easily molded or extruded into a wide variety of useful shapes including well casings, screens, fittings and accessories. The most common types of thermoplastic well casings and screens are polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS).

PVC plastics are produced by combining PVC resin with various types of stabilizers, lubricants, pigments, fillers, plasticizers and processing aids. The amounts of these additives can be varied to produce different PVC plastics with properties tailored to specific applications.

PVC materials are classified according to ASTM standard specification D-1785, which covers rigid PVC compounds (ASTM, 1986). This standard categorizes rigid PVC by numbered cells designating value ranges for certain pertinent properties and characteristics, including: impact strength, tensile strength, rigidity (modulus of elasticity), temperature resistance (deflection temperature), and chemical resistance. ASTM standard specification F-480 covers thermoplastic water well casing pipe and couplings made in standard dimension ratios. This standard specifies that PVC well casing can be made from only a limited number of cell classification materials, predominantly PVC 12454-B, but also including PVC 12454-C and PVC 14333-C and D (American Society for Testing and Materials, 1981).

ABS plastics are produced from three different monomers: 1) acrylonitrile, 2) butadiene, and 3) styrene. The ratio of the components and the way that they are combined can be varied to produce plastics with a wide range of properties. Acrylonitrile contributes rigidity, impact strength, hardness, chemical resistance, and heat resistance; butadiene contributes impact strength; styrene contributes rigidity, gloss, and ease of manufacturing (National Water Well Association and Plastic Pipe Institute, 1981). The ABS used for well casing is a rigid, strong unplasticized polymer formulation that has good heat resistance and impact strength.

Two ABS material types are used for well casings: 1) a higher strength, high rigidity, moderate impact resistance ABS, and 2) a lower strength and rigidity, high impact strength ABS. These two materials are identified as cell class 434 and 533, respectively, by ASTM standard specification F-480 (American Society for Testing and Materials, 1981). High temperature resistance and the ability of ABS to better retain other properties at high temperatures are advantages in wells where grouting with cement results in high temperature caused by the cement's heat of hydration.

Aller et al. (1989) describe some of the research that has been performed regarding degradation of thermoplastic materials and the adsorption/desorption of contaminants onto/from various thermoplastic materials. The potential sources of chemical interference from thermoplastic well casing materials, either from desorption or chemical degradation, are 1) the basic monomers from which the casing is made (e.g., vinyl chloride monomer), and 2) a variety of additives that may be used in the manufacture of the casing, including: plasticizers, stabilizers (e.g., PVC heat stabilizing compounds such as dimethyl tin and dibutyl tin), fillers, pigments, and lubricants. The significance and impact of these sources of chemical interference is not currently known, and may vary based on site-specific conditions. With respect to chemical interference effects, Aller et al. (1989) explain that another potential area of concern is the possibility that some chemicals could be sorbed by PVC well casing materials. Studies regarding sorption of chemical species onto PVC are inconclusive with respect to both the significance of contaminant sorption by PVC and the ability of well purging to correct any sample interferences.

The following advantages and disadvantages of PVC materials are highlighted in Aller et al.'s (1989) discussion and by Nielsen and Schalla (1991).

Advantages of PVC well casing and screen materials:

- Completely resistant to galvanic and electrochemical corrosion;
- Lightweight for ease of installation;
- High abrasion resistance;
- Requires low maintenance;
- Flexible and workable for ease of cutting and joining;
- High strength and low weight per unit length;

- Readily available;
- Lower cost than PTFE or metallic casing materials;
- High open area screens available; and
- Potentially best "compromise choice" when monitoring for low concentrations of both organic and inorganic constituents (Parker et al., 1990; Hewitt, 1992).

Disadvantages of PVC well casing and screen materials:

- May degrade in high concentrations of certain organic solvents, especially low molecular weight ketones, amines, aldehydes, and chlorinated alkenes and alkanes (Barcelona et al., 1983 and the Science Advisory Board of the USEPA);
- May fail if subjected to high differential pressures (i.e., during surging); weaker and less rigid than metallic casing materials;
- May fail if subjected to high temperatures (i.e., during grouting with neat cement);
- Long-term exposures of some formulations of thermoplastics to the ultraviolet rays of direct sunlight (above-ground portions of casings) and/or to low temperatures may cause brittleness and gradual loss of impact strength that may be significant; and
- Unsuitable for driven wells.

The National Sanitation Foundation (NSF) has set specifications for certain chemical constituents in PVC formulations. The purpose of these specifications as outlined in NSF Standard 14 (National Sanitation Foundation, 1988) is to control the amount of chemical additives in both PVC well casing and pipe used for potable water supply. Most of the maximum contaminant levels correspond to those set by the Safe Drinking Water Act for chemical constituents covered by the national Interim Primary Drinking Water Standards. Only PVC products that carry either the "NSF wc" (well casing) or "NSF pw" (potable water) designation have met the specifications set forth in Standard 14. Other non-NSF listed products may contain chemical additives not addressed by the specifications, or may contain concentrations of the listed chemicals that are higher than permitted by the specifications. In all cases, the material used should have been demonstrated to be compatible with the specific applications. For example, even though neither lead nor cadmium have been permitted as a compounding ingredient in United States-manufactured NSF-listed PVC well casing since

1970, PVC manufactured in other countries may be stabilized with lead or cadmium compounds that may leach from the PVC (Barcelona et al., 1983).

Composite Alternative Materials

In certain conditions it may be advantageous to design a well using more than one material for well components. For example, where stainless steel or fluoropolymer materials are preferred in a specific chemical environment, costs may be saved by using PVC in non-critical portions of the well. These savings may be considerable, especially in deep wells where only the lower portion of the well has a critical chemical environment, and where tens of feet of lower-cost PVC may be used in the upper portion of the well. In a composite well design, dissimilar metallic components should not be used unless an electrically-isolating design is incorporated (i.e., a dielectric coupling) (USEPA, 1986).

Conclusions

The available open and limited-distribution literature on materials used in well construction and sampling equipment for ground-water quality monitoring strongly suggest that well casing and screen material selection should be made carefully to prevent serious errors in analytical results. When performance studies (laboratory or field) are conducted by the owner or operator to demonstrate the appropriateness of a particular casing material, the studies should demonstrate chemical sorption characteristics, physical strength, and manufacturing tolerances on the inner diameter of the casing, at a minimum. Table 11 provides a summary of recommendations for the use of certain well casing materials under various physical and geochemical conditions which may be encountered.

The Agency discourages the practice of selecting well construction materials based on historical preference, unless supporting scientific studies or field data collected from facilities located in similar hydrogeologic settings and with similar wastes justify the preference. Consideration should be given to site specific factors such as: ground-water geochemistry, chemical characteristics of present or potential contaminants, structural integrity and chemical resistance of the well construction material, and site-specific comparative performance studies of various materials. In all cases, the Regional Administrator has the authority (40 CFR §270.32(b) and §3005(c)(3) of RCRA) to make the final determination regarding the appropriate well casing and screening materials for RCRA ground-water monitoring systems. Facilities may need to use combinations of screen and casing materials (either as a composite or independently) in a ground-water monitoring network, depending upon what constituents the wells will sample. Further, the owner or operator may need to conduct site-specific comparative performance studies to justify their preference for a particular well casing or screening material.

GENERAL RECOMMENDATIONS FOR SELECTION OF WELL CASING MATERIALS

	Do Not Use:	Use:
1.	PTFE if well depth exceeds 225-375' (68.6-114m).	PVC, ABS, SS.
2.	PVC or ABS if well depth exceeds 1200-2000' (366-610m).	SS.
3.	SS if $pH < 7.0$.	PVC, ABS, or PTFE.
4.	SS if D.O. > 2 ppm.	PVC, ABS, or PTFE.
5.	SS if $H_2S \geq 1$ ppm.	PVC, ABS, or PTFE.
6.	SS if T.D.S. > 1000 ppm.	PVC, ABS, or PTFE.
7.	SS if $CO_2 > 50$ ppm.	PVC, ABS, or PTFE.
8.	SS if $Cl^- > 500$ ppm.	PVC, ABS, or PTFE.
9.	PVC if a neat PVC solvent/softening agent* is present or if the aqueous concentration of the PVC solvent/softening agent exceeds 0.25 times its solubility in water.	SS, PTFE.
10.	Solvent bonded joints for PVC casings.	Threaded PVC casings.
11.	Welded stainless joints.	Threaded SS casings.
12.	Any PVC well casing that is not NSF-ASTM approved – D-1785 and F-480.	ASTM-NSF approved PVC well casings – D-1785 and F-480.
13.	Any stainless steel casing that is not ASTM approved – A312.	ASTM approved SS 304 and SS 316 casings – A312.
14.	Any ABS well casing that is not ASTM approved.	ASTM approved ABS casings – F-480.

*Known PVC solvents/softening agents include:

Tetrahydrofuran, cyclohexane, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, trichloromethane, 1,1-dichloroethane, 1,1,1-trichloroethane, trichloroethylene, benzene, toluene, acetone, and tetrachloroethylene.

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TABLE 11

6.2.3 Coupling Procedures for Joining Casing

Only a limited number of methods are available for joining lengths of casing or casing and screen together. The joining method depends on the type of casing and type of casing joint. Flush-joint, threaded flush-joint, plain square-end, and bell-end casing joints are typical of joints available for plastic casing; threaded flush-joint, bell-end, and plain square-end casing joints are typical of joints available for metallic casing.

Metallic Casing Joining

There are generally two options available for joining metallic well casings: 1) welding via application of heat, or 2) threaded joints. Both methods produce a casing string with a relatively smooth inner and outer diameter. With welding, it is possible to produce joints that are as strong or stronger than the casing, thereby enhancing the tensile strength of the casing string. The disadvantages of welding include: 1) greater assembly time, 2) difficulty in properly welding casing in the vertical position, 3) enhancement of corrosion potential in the vicinity of the weld, and 4) danger of ignition of potentially explosive gases that may be present.

Because of the disadvantages of welding, it is recommended that threaded joints be used with metallic casing and screen. Threaded joints provide inexpensive, fast, and convenient connections and greatly reduce potential problems with chemical resistance or interference (due to corrosion) and explosive potential. Wrapping the male threads with fluoropolymer tape prior to joining sections improves the watertightness of the joint. One disadvantage to using threaded joints is that the tensile strength of the casing string is reduced to approximately 70 percent of the casing strength. This reduction in strength does not usually pose a problem because strength requirements for small diameter wells (such as typical monitoring wells) are not as critical and because metallic casing has a high initial tensile strength.

Thermoplastic and Fluoropolymer Casing Joining

The most common method of mechanical joining of thermoplastic and fluoropolymer casing and screen is by threaded connections. Molded and machined threads are available in a variety of thread configurations including: acme, buttress, standard pipe thread, and square threads. Because most manufacturers have their own thread type, threaded casing may not be compatible between manufacturers. If the threads do not match and a joint is made, the joint can fail or leak either during or after casing installation.

Casing with threads machined or molded directly onto the pipe (without use of larger-diameter couplings) provides a flush joint between inner and outer diameters. Because the annular space is frequently minimal, casings that do not use couplings are best-suited for use in monitoring well construction. Joints should create a uniform inner and outer casing diameter in monitoring well installations. An inconsistent inner diameter causes problems when tight-fitting downhole equipment (development tools, sampling or purging devices, etc.) is used; an uneven outer diameter creates problems with filter pack and annular seal placement. The latter problem tends to promote water migration at the casing/seal interface to a greater degree than is experienced with uniform outer diameter casing (Morrison, 1984).

Because all joints in a monitoring well casing must be watertight, the extent to which the joints are tightened should comply with recommendations of the manufacturer. Overtightening casing joints can lead to structural failure of the joint (National Water Well Association and Plastic Pipe Institute, 1981). To maximize the watertightness of the joint where threaded joints are used, fluoropolymer tape may be wrapped around the threads prior to joining male and female sections; also, an O-ring may be added for extra security.

Solvent cementing of thermoplastic pipe should not be used in the construction of ground-water monitoring wells. In solvent cementing, a solvent primer is generally used to clean the two pieces of casing to be joined and a solvent cement is then spread over the cleaned surface areas. The two sections are assembled while the cement is wet. This allows the active solvent agent(s) to penetrate and soften the two casing surfaces that are joined. As the cement cures, the two pieces of casing are fused together; a residue of chemicals from the solvent cement remains at the joint. The cements used in solvent welding, which are organic chemicals, have been show to adversely effect the integrity of ground-water samples. (See Aller et al., 1989 for a summary of relevant research.)

6.2.4 Well Casing Diameter

While casing outside diameters are standardized, variations in wall thickness can cause casing inside diameters to vary. In "scheduled" casing, wall thickness increases as the scheduling number increases for any given diameter of casing. Nominal 2-inch casing is a standard 2.375 inches outside diameter; wall thicknesses vary from 0.065 inch for schedule 5 to 0.218 inch for schedule 80. This means that inside diameters for nominal 2-inch casings vary from 2.245 inches for schedule 5 thin-walled casings (typically of stainless steel) to only 1.939 inches for schedule 80 thick-walled casings (typically of PVC). Wall thickness also changes with pipe diameter in scheduling. Because schedule 80 PVC is thicker than schedule 40 PVC, schedule 80 PVC wells will extend the life of the monitoring system compared to schedule 40 PVC. The cost differential between these two schedules is fairly insignificant.

Another method of evaluating casing strength is by standard dimension ratios (SDR). A SDR is the ratio of the wall thickness to the casing diameter. The ratio is referenced to an internal pounds per square inch (psi) pressure rating such that all casings with a similar SDR will have a similar psi rating. Where strength of casing is important, scheduling and SDR numbers provide a means for choosing casing.

Although the diameter of the casing for a monitoring well depends on the purpose of the well, the casing size is generally selected to accommodate downhole equipment.

Additional casing diameter selection criteria include: 1) drilling or well installation method used, 2) anticipated depth of the well and associated strength requirements, 3) anticipated method of well development, 4) volume of water required to be purged prior to sampling, 5) rate of recovery of the well after purging, and 6) anticipated aquifer testing.

6.2.5 Casing Cleaning Requirements

Well casing and screen materials should be cleaned prior to installation to remove any coatings or manufacturing residues. Prior to use, all casing and screen materials should be washed with a mild non-phosphate detergent/potable water solution and rinsed with potable water. Hot pressurized water, such as in steam cleaning, should be used to remove organic solvents, oils, or lubricants from casing and screens composed of materials other than plastic. At sites where volatile organic contaminants may be monitored, the cleaning of well casing and screen materials should include a final rinse with deionized water or potable water that has not been chlorinated. Once cleaned, casings and screens should be stored in an area that is free of potential contaminants. Plastic sheeting can generally be used to cover the ground in the decontamination area to provide protection from contamination. Aller et al. (1989) describe the procedures that should be used to clean casing and screen materials.

6.3 Well Intake Design

The owner/operator should design and construct the intakes of monitoring wells to (1) accurately sample the aquifer zone that the well is intended to sample, (2) minimize the passage of formation materials (turbidity) into the well, and (3) ensure sufficient structural integrity to prevent the collapse of the intake structure.

6.3.1 Well Screen

The goal of a properly completed monitoring well is to provide low turbidity water that is representative of ground-water quality in the vicinity of the well. Although wells completed in rock often do not require screens, the majority of monitoring wells installed for RCRA purposes are completed in unconsolidated sediments.

6.3.1.1 Screen Length

The selection of screen length usually depends on the objective of the well. Piezometers and wells where only a discrete flow path is monitored (such as thin gravel interbedded with clays) are generally completed using short screens (2 feet or less). To avoid dilution, the Agency prefers that well screens be kept to the minimum length appropriate for intercepting a contaminant plume, especially in a high-yielding aquifer. The screen length should generally not exceed 10 feet. If construction of a water table well is the objective, either for defining gradient or detecting floating phases, then a longer screen is acceptable because the owner/operator will need to provide a margin of safety that will guarantee that at least a portion of the screen always contacts the water table regardless of its seasonal fluctuations. The owner or operator should not employ well intake designs that cut across hydraulically separated geologic units. Except in settings where DNAPLs may exist, wells may have a bottom sump to allow sediments that enter the well to settle, preventing "silting in" of the well. (See Section 5.1.2.3 for further guidance on selecting well screen length.)

6.3.1.2 Screen Slot Size

Well screen slot size should be selected to retain from 90% to 100% of the filter pack material (discussed below) in artificially filter packed wells, or from 50% to 100% of the formation material in naturally packed wells, unless the owner/operator can demonstrate that turbidity-free water (<5 nephelometric turbidity units) can be obtained using a larger slot size. Although this is a higher percentage than is usually required in a production well, the low withdrawal rates and the infrequent use of a monitoring well necessitate the higher percentage exclusion. EPA emphasizes that filtering a sample subsequent to its collection is not the solution for dealing with turbidity in an improperly designed well. Furthermore, well screens should be factory-slotted. Manually slotting screens in the field should not be performed under any circumstances.

6.3.2 Filter Packs/Pack Material

The annular space between the borehole wall and the screen or slotted casing should be filled in a manner that minimizes the passage of formation materials into the well. The driller should generally install an artificial filter pack around each well intake. As discussed above, wells in rock often do not require screens, and thus do not require filter packs. However, they are the exception; most wells will require filter packs and a screened length of casing. Aller et al. (1989) provide a comprehensive discussion of the purpose and selection of filter pack materials.

An artificial filter pack is appropriate in most geologic settings. In particular, an artificial filter pack should be used when: 1) the natural formation is poorly sorted; 2) a long screened interval is required and/or the intake spans highly stratified geologic materials of widely varying grain sizes; 3) the natural formation is a uniform fine sand, silt, or clay; 4) the natural formation is thin-bedded; 5) the natural formation is poorly cemented sandstone; 6) the natural formation is highly fractured or characterized by relatively large solution channels; 7) the natural formation is shale or coal that will act as a constant source of turbidity to ground-water samples; and 8) the diameter of the borehole is significantly greater than the diameter of the screen (Aller et al., 1989). Using natural formation material as filter pack is recommended only when the natural formation materials are relatively coarse-grained, permeable, and uniform in grain size (Aller et al., 1989).

Filter pack material should be chemically inert. The best filter packs are made from industrial grade glass (quartz) sand or beads (Barcelona, 1985a). Any other type of sand should be analyzed for cation exchange capacity and volatile organic compounds (VOCs) to determine whether it will interact with analytes of concern in the ground water. Commercially available pea gravel may be acceptable for use in gravel aquifers; however, to meet the Agency's requirement that the filter pack be chemically inert, the pea gravel itself should not be chemically active or coated with a chemically active metal oxide. Filters constructed from fabric should not be used as they tend to plug and may be chemically reactive.

The Agency recommends that filter pack material be well rounded and of uniform grain size. Aller et al. (1989) provide the following summary of methods for selecting the size of filter pack materials:

> "Although design techniques vary, all use the filter pack ratio to establish size differential between the formation materials and filter pack materials. Generally this ratio refers to either the average (50 percent retained) grain size of the formation material or the 70 percent retained size of the formation material. For example, Walker (1974) and Barcelona et al. (1985a [1985b in this document]) recommend using a uniform filter pack grain size that is 3 to 5 times the 50 percent retained size of the formation materials. Driscoll (1986) recommends a more conservative approach by suggesting that for fine-grained formations, the 50 percent retained size of the finest formation sample be multiplied by a factor of 2 to exclude the entrance of fine silts, sands, and clays into the monitoring well. The United States Environmental Protection Agency (1975) recommends that filter pack grain size be selected by multiplying the 70 percent retained grain size of the formation materials by a factor between 4 and 6. A factor of 4 is used if the formation is fine and uniform; a factor of 6 is used if the formation is coarser and non-uniform. In both cases, the uniformity coefficient of the filter pack materials should not exceed 2.5 and the gradation of the filter material should form a smooth and gradual size distribution when plotted. The actual filter pack used should fall within the area defined by these two curves. According to Williams (1981), in uniform formation materials, either approach to filter pack material sizing will provide similar results; however, in coarse, poorly sorted formation materials, the average grain size method may be misleading and should be used with discretion."

Filter pack material should be installed in a manner that prevents bridging and particle-size segregation. Filter pack material installed below the water table should generally be tremied into the annular space. Allowing filter pack material to fall by gravity (free fall) into the annular space is only appropriate when wells are relatively shallow, when the filter pack has a uniform grain size, and when the filter pack material can be poured continuously into the well without stopping.

At least two inches of filter pack material should be installed between the well screen and the borehole wall. The filter pack should extend at least two feet above the top of the well screen, as illustrated in Figure 13. In deep wells, the filter pack may not compress when initially installed, consequently, when the annular and surface seals are placed on the filter pack, the filter pack compresses sufficiently to allow grout into, or very close to, the screen. Consequently, filter packs may need to be installed as high as five feet above the screened interval in monitoring wells that are deep (i.e., greater than 200 feet). The precise volume of filter pack material required should be calculated and recorded before placement, and the actual volume used should be determined and recorded during well construction. Any significant discrepancy between the calculated volume and the actual volume should be explained.

Prior to installing the annular seal, a one- to two-foot layer of chemically inert fine sand may be placed over the filter pack to prevent the intrusion of annular or surface sealants into the filter pack. When designing monitoring wells, owners and operators should remember that the entire length of the annular space filled with filter pack material or sand is effectively the monitored zone. Moreover, if the filter pack/sand extends from the screened zone into an overlying zone, a conduit for hydraulic connection is created between the two zones.

6.4 Annular Sealants

Proper sealing of the annular space between the well casing and the borehole wall is required (§264.97(c)) to prevent contamination of samples and the ground water. Adequate sealing will prevent hydraulic connection within the well annulus. The materials used for annular sealants should be chemically inert with the highest anticipated concentration of chemical constituents expected in the ground water at the facility. In general, the permeability of the sealing material should be one to two orders of magnitude lower than the least permeable part of the formation in contact with the well. The precise volume of annular sealants required should be calculated and recorded before placement, and the actual volume used should be determined and recorded during well construction. Any significant discrepancy between the calculated volume and the actual volume should be explained. Aller et al. (1989) provide detailed discussions of the proper placement of sealants into the annular space.

When the screened interval is within the saturated zone, a minimum of two feet of sealant material such as raw (>10% solids) bentonite should be placed immediately over the protective sand layer overlying the filter pack. Granular bentonite, bentonite pellets, and bentonite chips may be placed around the casing by means of a tremie pipe in deep wells (greater than approximately 30 feet deep), or by dropping them directly down the annulus in shallow wells (less than approximately 30 feet deep). Dropping the bentonite pellets down the annulus presents a potential for bridging (from premature hydration of the bentonite), leading to gaps in the seal below the bridge. In shallow monitoring wells, a tamping device should be used to prevent bridging from occurring.

A neat cement or shrinkage-compensated neat cement grout seal should be installed on top of the bentonite seal and extend vertically up the annular space between the well casing and the borehole wall to within a few feet of land surface. Annular sealants in slurry form (e.g., cement grout, bentonite slurry) should be placed by the tremie/pump (from the bottom up) method. The bottom of the placement pipe should be equipped with a side discharge deflector to prevent the slurry from jetting a hole through the protective sand layer, filter pack, or bentonite seal. The bentonite seal should be allowed to completely hydrate, set, or cure in conformance with the manufacturer's specifications prior to installing the grout seal in the annular space. The time required for the bentonite seal to completely hydrate, set, or cure will differ with the materials used and the specific conditions encountered, but is generally a minimum of four to twenty-four hours. Allowing the bentonite seal to hydrate, set, or cure prevents the invasion of the more viscous and more chemically reactive grout seal into the screened area.

When using bentonite as an annular sealant, the appropriate clay should be selected on the basis of the environment in which it is to be used, such as the ion-exchange potential of the sediments, sediment permeability, and compatibility with expected contaminants. Sodium bentonite is usually acceptable. Other industrial grade clays without chemical additives that may affect ground-water quality can be used if sodium bentonite is incompatible with either the natural formation or the analytes of concern (e.g., calcium bentonite may be more appropriate in calcareous sediments and soils because of its reduced cation exchange capacity). The sealing properties of clays may be adversely affected by chlorine salts, acids, alcohols, ketones, and other polar compounds. If these materials are expected at the facility, alternative sealants should be considered.

When the annular sealant must be installed in the unsaturated zone, EPA recommends that neat cement or shrinkage-compensated neat cement mixtures be used for the annular sealant. Bentonite is not recommended as an annular sealant in the unsaturated zone because the moisture available is insufficient to fully hydrate bentonite. Adding calcium bentonite to cement should be avoided. Ca^{++} and OH^{-} ions in the cement cause flocculation of the clay, reducing its ability to swell. The bentonite also weakens the cement, reducing its compressive strength. A better solution for shrinkage control is to use shrinkage-compensating additives components: K, M, and S (ASTM C845). However, the high heat of hydration should be taken into account when these materials are used.

6.5 Surface Completion

The surface completion of monitoring wells is described in detail by Aller et al. (1989). In general, completing a monitoring well will involve installing the following components:

- Surface seal;
- Protective casing, utility vault, or meter box;
- Ventilation hole(s);
- Drain hole(s);
- Cap;
- Lock; and
- Guard posts.

Monitoring wells are commonly completed at the surface in one of two ways: as above-ground completions or as flush-to-ground completions. The purpose of both types of completion are to prevent infiltration of surface runoff into the well annulus and to prevent accidental damage or vandalism of the well.

A monitoring well surface seal should be installed on top of the grout seal (Section 6.4) and extend vertically up the well annulus between the well casing and the borehole to the land surface. Where appropriate, the lower end of the surface seal should extend at least one foot below the frost line to prevent damage from frost heaving. The composition of the surface seal should be neat cement or concrete. In above-ground well completions, the surface seal should form at least a two-foot wide, four-inch thick neat cement or concrete apron at the land surface. The apron should be constructed with a slight slope to drain surface water radially away from the well casing to prevent leakage down the outer casing wall.

A locking protective casing should be installed around the well casing to prevent damage or unauthorized entry. The protective casing should be anchored below the frost line (where applicable) into the surface seal and extend at least 18 inches above the surface of the ground. A 1/4-inch vent hole pipe is recommended to allow the escape of any potentially explosive gases that may accumulate within the well. In addition, a drain hole should be installed in the protective casing to prevent water from accumulating and, in freezing climates, freezing around the well casing. The space between the protective casing and the well casing may be filled with gravel to allow the retrieval of tools and to prevent small animal/insect entrance through the drain. A suitable cap should be placed on the well to prevent tampering or the entry of any foreign materials. A lock should be installed on the cap to provide security. To prevent corrosion or jamming of the lock, a protective cover should be used. Care should be taken when using lubricants such as graphite or petroleum-based sprays to lubricate the lock, as lubricants may introduce a potential for sample contamination. Locks should not be lubricated on the day the well is sampled, and gloves that are worn while lubricating the lock should be changed prior to initiating other activities at the well.

To guard against accidental damage to the well from facility traffic, the owner/operator should install concrete or steel bumper guards around the edge of the concrete apron. These should be located within 3 or 4 feet of the well and should be painted orange or fitted with reflectors to reduce the possibility of vehicular damage.

The use of flush-to-ground surface completions should be avoided because this design increases the potential for surface water infiltration into the well. In cases where flush-to-ground completions are unavoidable, such as in active roadways, a protective structure such as a utility vault or meter box should be installed around the well casing. In addition, measures should be taken to prevent the accumulation of surface water in the protective structure and around the well intake. These measures should include outfitting the protective structure with a steel lid or manhole cover that has a rubber seal or gasket, and ensuring that the bond between the cement surface seal and the protective structure is watertight.

6.6 Well Surveying

The location of all wells should be surveyed by a licensed professional surveyor (or equivalent) to determine their X-Y coordinates as well as their distances from the units being monitored and their distances from each other. A State Plane Coordinate System, Universal Transverse Mercator System, or Latitude/Longitude should be used, as approved by the Regional Administrator. The survey should also note the coordinates of any temporary benchmarks. A surveyed reference mark should be placed on the top of the well casing, not on the protective casing or the well apron, for use as a measuring point because the well casing is more stable than the protective casing or well apron (both the protective casing and the well apron are more susceptible to frost heave and spalling). The height of the reference survey datum, permanently marked on top of the inner well casing, should be determined within ±0.01 foot in relation to mean sea level, which in turn is established by reference to an established National Geodetic Vertical Datum. The reference marked on top of inner well casings should be resurveyed at least once every 5 years, unless changes in ground-water flow patterns/direction, or damage caused by freeze/thaw or desiccation processes, are noted. In such cases, the Regional Administrator may require that well casings be resurveyed on a more frequent basis.

6.7 Well Development

All monitoring wells should be developed to create an effective filter pack around the well screen, to rectify damage to the formation caused by drilling, to remove fine particles from the formation near the borehole, and to assist in restoring the natural water quality of the aquifer in the vicinity of the well. Development stresses the formation around the screen, as well as the filter pack, so that mobile fines, silts, and clays are pulled into the well and removed. The process of developing a well creates a graded filter pack around the well screen. Development is also used to remove any foreign materials (drilling water, muds, etc.) that may have been introduced into the well borehole during drilling and well installation, and to aid in the equilibration that will occur between the filter pack, well casing, and the formation water.

The development of a well is extremely important to ensuring the collection of representative ground-water samples. If the well has been properly completed, then adequate development should remove fines that may enter the well either from the filter pack or the formation. This improves the yield, but more importantly it creates a monitoring well capable of producing samples of acceptably low turbidity. Turbid samples from an improperly constructed and developed well may interfere with subsequent analyses.

When development is initiated, a wide range of grain sizes of the natural material is drawn into the well, and the well typically produces very turbid water. However, as pumping continues and the natural materials are drawn into the filter pack, an effective filter will form through a sorting process. Inducing movement of ground water into the well (i.e., in one direction) generally results in bridging of the particles. A means of inducing flow reversal is necessary to break down bridges and produce a stable filter.

The common methods for developing wells are described by Aller et al. (1989) and Driscoll (1986) and include:

- Pumping and overpumping;
- Backwashing;
- Surging with a surge block;
- Bailing;
- Jetting;
- Airlift pumping; and
- Air surging.

Aller et al. (1989) provide a detailed overview of well development and should be consulted when evaluating well development methods. Overall, the most effective and efficient method available for inducing flow reversal during well development is the careful use of a properly-constructed surge block. To be effective, the surge block may need to be lifted and lowered throughout the well screened interval for several hours, with periodic pumping or bailing of the fines. Bailers and pumps also have been used successfully to develop wells; however, depending on the depth of the water, the hydraulic conductivity of the aquifer, and the diameter of the well, pumping may effectively achieve well development.

The following is a general procedure for developing a well by surging and pumping of fines:

1. Record the static water level and total well depth.

2. Set the pump and record the pumping rate. Pump until turbidity reaches the desired level as measured using a turbidity meter.

3. Discontinue pumping and begin surging using a properly designed surge block and proper surging technique.

4. Measure and record well depth to determine the amount of fines, and repeat Step 2. If the well has been properly designed, the amount of pumping required to achieve the desired turbidity level will be substantially less than the amount of pumping required during the first pumping cycle.

5. Repeat surging and pumping until the well yields water of acceptable turbidity at the beginning of a pumping cycle. A good way to ensure that development is complete is to shut the pump off during the last anticipated pumping cycle, leaving the pump in place, and re-start it at a later time. The turbidity of the discharge water should remain low.

Effective and efficient well development is possible only with adequate flow rate during water withdrawal. Additionally, any fines that have been drawn into the well should be removed to the greatest degree possible. Therefore, the Agency recommends that one of the following pumping methods, listed in the order of preference, be used in conjunction with a properly designed surge block:

1. Centrifugal pump capable of removing fines if the water level is within suction-lift distance.

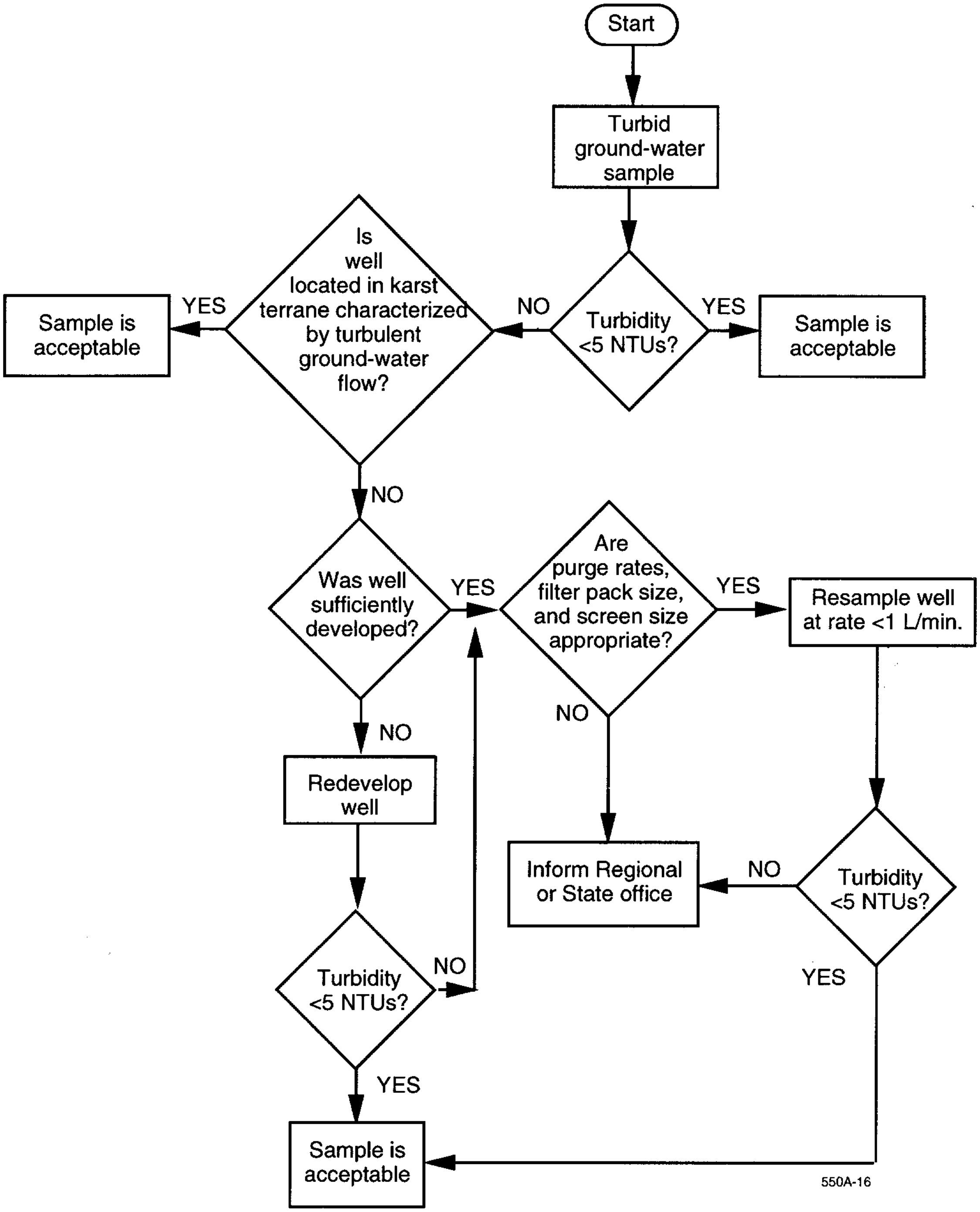
2. Electric submersible pump capable of pumping fines.

3. Properly designed and operated air-lift system (requires prior approval of the Regional Administrator).

Well development methods and equipment that alter the chemical composition of the ground water should not be used. Development methods that involve adding water (including water pumped from the well) or other fluids to the well or borehole, or that use air to accomplish well development, are rarely permissible. Consequently, methods that are unsuitable in most cases for monitoring well development include backwashing, jetting, airlift pumping, and air surging. Approval should be obtained from the Regional Administrator prior to introducing air, water, or other fluids into the well for the purpose of well development. Any water introduced into the well during well development should be chemically analyzed to determine its potential impact on water quality. The well development methods that will generally be approved by EPA are bailing, surging with a surge block, pumping, overpumping, or combinations of these methods. Airlift pumping may be approved if the owner/operator can demonstrate to the satisfaction of the Regional Administrator that appropriate measures will be taken to prevent air contact with the formation, and to prevent the entry of compressor oils into the well. Monitoring wells should not be developed before well sealant materials have set or cured.

Ground water should be collected and measured for turbidity periodically during well development, and at the completion of well development. The final turbidity measurement should be recorded on the well construction log. If a well yields turbid samples (turbidity greater than or equal to 5 NTUs) after development, the procedures shown in Figure 14 should be followed. A well that cannot be developed to the point of producing low turbidity water (e.g., <5 NTUs) may be considered by the Agency to have been improperly completed (e.g., mismatched formation materials/filter pack/screen slot size) depending on the geologic materials in which the well is screened. If a well is not producing low turbidity ground-water samples, the owner/operator should demonstrate to the satisfaction of the appropriate regulatory agency that proper well completion and development measures have been employed, and that the turbidity is an artifact of the geologic materials in which the well is screened, and not the result of improper well construction or development. Failure to make such a demonstration could result in a determination by the Agency that the well must be re-drilled.

The Agency emphasizes that proper well construction and development procedures, as well as proper sampling procedures (e.g., selection of appropriate well purging and sampling rates), are necessary to yield ground-water samples that are representative of ambient water quality. The Agency recognizes that ground water in some wells (both high and low yield) in fractured rock or karst aquifers may become muddy after periods of rainfall, even though during fair weather the water is free of turbidity. Careful attention to proper well installation and development should be exercised with wells completed in very silty geologic units. Information obtained from any aquifer tests conducted on the well should be used to establish



DECISION CHART FOR TURBID GROUND-WATER SAMPLES

FIGURE 14

the initial yield of the well, and these data can be used for periodic redevelopment and maintenance assessments.

If well drilling, installation, or completion have altered ground-water quality chemically in the vicinity of the well, well development should aid in restoring ground-water quality within the well to natural ground-water quality. The ability of a well development method to remove clays from the sides of the borehole should be considered, because clays retained in the borehole may alter the chemical composition of ground water in the well. The Agency recommends periodically monitoring ground water during well development for water quality parameters such as specific conductance and pH. The reproducibility of water quality results provides some indication that ground-water chemistry in the well has been restored to natural quality. In general, the Agency also recommends that the volume of water introduced into the well during well drilling, installation, and completion be withdrawn from the well during well development. The volume of water withdrawn from a well during development should be recorded.

6.8 Documentation of Well Design, Construction, and Development

Information on the design, construction, and development of each well should be compiled. Such information should include: (1) a boring log that documents well drilling and associated sampling, and includes the minimum required information presented in Table 3 and Section 4.2.1; and (2) a well construction log and well construction diagram ("as built"). The well construction log and well construction diagram should present the following information (including dimensions, as appropriate):

- Well name/number;
- Date/time of well construction;
- Borehole diameter and well casing diameter;
- Well depth (±0.1 ft);
- Casing length;
- Casing materials;
- Casing and screen joint type;
- Screened interval(s);
- Screen materials;

- Screen slot size/design;
- Filter pack material and size;
- Filter pack volume (calculated and actual);
- Filter pack placement method;
- Annular sealant composition;
- Annular seal placement method;
- Annular sealant volume (calculated and actual);
- Surface sealant composition;
- Surface seal placement method;
- Surface sealant volume (calculated and actual);
- Surface seal and well apron design/construction;
- Well development procedure and ground-water turbidity measured at the completion of well development;
- Type and design/construction of protective casing;
- Well cap and lock;
- Ground surface elevation (±0.01 ft);
- Survey reference point elevation (±0.01 ft) on well casing;
- Top of monitoring well casing elevation (±0.01 ft); and
- Top of protective steel casing elevation (±0.01 ft).

The owner/operator should document that the following well completion activities were performed appropriately:

- Selection of construction materials for the casing and screen;
- Selection of the well diameter, screen length, and screen slot size;

- Selection and emplacement of the appropriate filter pack;
- Selection and emplacement of the annular sealants;
- Providing proper security of the well;
- Surveying the locations and elevations of the tops of the casings; and
- Adequately developing the well.

All documents pertaining to the design, construction, and development of RCRA monitoring wells should be kept by the owner/operator in the facility operating record and submitted as part of the operating permit.

6.9 Specialized Well Designs

There are two cases where special monitoring well designs should be used:

- Where the owner/operator has chosen to use dedicated pumps to withdraw ground-water samples; or,
- Where separate low density and/or high density immiscible liquid phases may be present.

Dedicated pumps should be fluorocarbon resin or stainless steel positive gas displacement bladder pumps, or equivalent devices approved by the Regional Administrator. The design of the dedicated sampling system should allow access to the well for the purpose of conducting aquifer tests, maintaining the well (e.g., redevelopment procedures), and making water level measurements. Dedicated sampling systems should be periodically inspected to ensure that the equipment is functioning reliably. Samples should be withdrawn from the system to evaluate the operation of the equipment, and the equipment should be checked for damage.

Where light and dense-phase immiscible layers are present, or are determined to potentially occur after considering the waste types managed at the facility, specialized well systems should be designed to allow collection of discrete samples of both the light and dense phases. In certain cases, well screens that extend from above the water table to the lower confining layer may be appropriate, but more frequently the presence of immiscible phases will require that well clusters (or nests) or multilevel sampling devices be installed. Where well clusters are employed, one well in the cluster may be screened at horizons where floaters are expected, and another may be screened at horizons where dense phases are expected. Other wells may be screened within other portions of the aquifer.

6.10 Evaluation of Existing Wells

Existing monitoring wells should meet the performance standards presented in 40 CFR Part 264 Subpart F, as determined by the Regional Administrator. There are two situations in particular where wells may fail to meet the performance standards: (1) where existing wells are physically damaged; and (2) where the owner/operator can produce little or no documentation of how existing wells were designed and installed.

Wells that are physically damaged, or wells for which there is not sufficient documentation of design and construction, may need to be replaced. In addition, wells that produce consistently turbid samples (≥5 NTUs) and were not properly designed or constructed also may warrant replacement. In such cases, knowledge of site hydrogeology and professional judgment should be used in deciding when to replace wells.

When there is a question regarding whether or not the well casing material is negatively affecting the chemical quality of the ground-water samples, a side-by-side comparison at selected wells should be undertaken using the well construction materials in question. If analytical results are comparable, then it is likely that chemical bias is not a major issue at the time of the test.

When existing wells do not meet the performance standards, the wells should be properly decommissioned and, if required by the Regional Administrator, replaced. Pursuant to §264.97(c)(1), the design, installation, development, and decommissioning of any monitoring wells, piezometers and other measurement, sampling, and analytical devices must be documented in the operating record.

6.11 Decommissioning Ground-Water Monitoring Wells and Boreholes

Ground-water contamination resulting from improperly decommissioned wells and boreholes is a serious concern. Any borehole that will not be completed as a monitoring well should be properly decommissioned. The USEPA (1975) and the American Water Works Association (1985) provide the following reasons, summarized by Aller et al. (1989), as to why improperly constructed or unused wells should be properly decommissioned:

- To eliminate physical hazards;
- To prevent ground-water contamination;
- To conserve aquifer yield and hydrostatic head; and
- To prevent intermixing of subsurface water.

Should an owner or operator have a borehole or an improperly constructed or unused well at his or her facility, the well or borehole should be decommissioned in accordance with specific guidelines. Aller et al. (1989) provide comprehensive guidance on performing well decommissioning that can be applied to boreholes. This guidance should be consulted prior to decommissioning monitoring wells, piezometers, or boreholes. Lamb and Kinney (1989) also provide information on decommissioning ground-water monitoring wells.

Many states require that specific procedures be followed and certain paperwork be filed when decommissioning water supply wells. In some states, similar regulations may apply to the decommissioning of monitoring wells and boreholes. The EPA and other involved regulatory agencies, as well as experienced geologists, geotechnical engineers, and drillers, should be consulted prior to decommissioning a well or borehole to ensure that decommissioning is appropriately performed and to ensure compliance with state law. If a well to be decommissioned is contaminated, the safe removal and proper disposal of the well materials should be ensured by the owner/operator. Appropriate measures should be taken to protect the health and safety of individuals when decommissioning a well or borehole.

CHAPTER SEVEN

SAMPLING AND ANALYSIS

Federal regulations at §§270.14(c)(5), 270.14(c)(6)(iv), and 270.14(c)(7)(vi) require, as part of the permit application, both a written description of the ground-water monitoring program proposed to meet the requirements of §264.97 and a description of the proposed sampling, analysis, and statistical comparison procedures proposed for evaluating ground-water monitoring data. In addition, §§264.97(d) and 264.97(e) outline minimum procedures and techniques for ground-water monitoring programs implemented pursuant to 40 CFR Part 264 Subpart F. These regulations require that ground-water monitoring programs include measurement, sampling, and analytical methods that accurately assess ground-water quality, and that provide early detection of hazardous constituents released to ground water. Measurement, sampling, and analytical methods that are part of the ground-water monitoring program should be documented in the operating record and should include quality assurance and quality control procedures. These procedures are reviewed and revised by the regulatory agency, referenced in the permit (pursuant to §264.97), and included in the Quality Assurance Project Plan (QAPjP), as recommended in Chapter One of SW-846.

All procedures and techniques used for site characterization, ground-water monitoring well installation and development, sample collection, sample preservation and shipment, analytical procedures, chain-of-custody control, and implementing other monitoring programs (e.g., vadose zone monitoring and monitoring of springs in karst terranes) should be specified in a QAPjP and should conform with Chapter One of SW-846. The owner/operator and field personnel should follow the QAPjP while performing the site characterization, installing and developing monitoring wells, and collecting and analyzing ground-water samples. A proposed schedule, including dates anticipated for project initiation, project milestones, schedule of monitoring activities, and dates anticipated for completion of project, should be provided in the QAPjP. A milestone table or a bar chart consisting of project tasks and time lines is appropriate for inclusion in the QAPjP.

Section 7.1 describes important elements of QAPjPs. Sections 7.2 through 7.9 discuss each element in greater detail.

7.1 Elements of the Quality Assurance Project Plan

The QAPjP proposed by the owner/operator in the permit application should address the elements described in Chapter One of SW-846. At a minimum, the QAPjP should address:

- Sampling objectives;
- Pre-sampling activities;
- Sample collection;
- In-situ or field analyses;
- Sample preservation and handling;
- Chain-of-custody control and records management;
- Analytical procedures and quantitation limits for both laboratory and field methods;
- Field and laboratory quality assurance/quality control;
- Evaluation of data quality; and
- Health and safety.

The QAPjP also should include procedures for conducting the site characterization, installing and developing ground-water monitoring wells, and implementing other monitoring programs (e.g., vadose zone monitoring and monitoring of springs in karst terranes).

7.2 Pre-Sampling Activities

The following activities should be performed prior to collecting ground-water samples for analysis:

- Determining sampling frequency;
- Measurement of static water level elevation;
- Detection and sampling of immiscible layers; and
- Well purging.

These activities are discussed in greater detail in the following sections.

7.2.1 Determining Sampling Frequency

The frequency at which ground-water samples will be collected should be described in the QAPjP. Sampling frequency, in nearly all cases, should be based on the hydrogeology of the site. There is no maximum sampling frequency set by the Agency. The minimum frequency for sampling is at least semiannual (§§264.98(d) and 264.99(f)). As stated in §§264.97(g) and 264.99(f), the Regional Administrator will specify the frequency for sampling in the permit. Proposed sampling frequencies should be submitted by the owner or operator as part of the permit application. Furthermore, regulations at §264.97(h) require the owner/operator to use one of the several specified statistical procedures, or to use an alternative method that meets specified performance standards. The method chosen should be approved by the Regional Administrator, and specified in the operating permit. EPA’s guidance document "Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities," Interim Final Guidance (EPA/530-SW-89-026, NTIS PB-89-151-047; USEPA 1989a) suggests a method for choosing a sampling frequency that will reflect site-specific hydrogeologic conditions. The method uses the Darcy equation to determine the horizontal component of the average linear velocity of ground water for confined, semiconfined, and unconfined aquifers. This value is used to determine a sampling frequency that will yield an independent sample of ground water in diffuse flow regimes.

Recent research performed in the area of ground-water sampling frequency (Barcelona et al., 1989) indicates that ground-water monitoring data should be carefully collected over long periods of time (i.e., greater than two years) to determine optimal sampling frequency and to delineate seasonal trends in ground-water monitoring results. In Barcelona et al.’s study, ground water was collected biweekly for 18 months and analyzed for 26 water quality and geochemical constituents. The researchers determined that for the study site, ground-water sampling performed four to six times per year would result in an estimated information loss below 20% and would minimize redundancy. The researchers concluded that by using careful sampling and analytical procedures, sampling and analytical errors could be controlled to approximately ±20% of the annual mean inorganic chemical constituent concentrations in ground water.

Alternative methods should be employed to determine a sampling frequency in hydrogeologic settings where conduit flow predominates and where Darcy’s law is invalid (e.g., karst terrane). Section 4.5.5 discusses how to determine monitoring frequencies in these environments. More detailed information may be found in Quinlan and Alexander (1987).

In addition to the routine analyses to be performed as specified in the facility’s permit, all land disposal facilities applying for a RCRA operating permit that have contaminated ground water must identify the concentration of each Appendix IX constituent throughout the plume or identify the maximum concentrations of each Appendix IX constituent in the plume (§270.14(c)(4)(ii)). This analysis is conducted for the purpose of characterizing the chemistry of the background and downgradient ground water.

7.2.2 Measurement of Static Water Level Elevation

The QAPjP should include procedures for measuring the static water level elevation in each well prior to each sampling event, as required in §264.97(f). The QAPjP also should include procedures for measuring the depth of each well prior to each sampling event. Measuring water level elevations on a regular basis is important for determining whether horizontal and vertical components of the hydraulic gradient have changed since initial site characterization. A change in ground-water flow direction may necessitate modifying the design of the ground-water monitoring system.

Water level elevations typically have been measured using a number of devices and methods, including the following:

- Steel tape coated with carpenter's chalk (wetted-tape method);
- Float-type devices;
- Pressure transducers;
- Acoustic well probes;
- Electric sensors; and
- Air lines.

These devices and methods are described in more detail in Aller et al. (1989), USEPA (1987a), and Dalton et al. (1991). Dalton et al. (1991) provide the water level measurement accuracy of each of these devices. The QAPjP should specify the device to be used for water level measurements, as well as the procedure for measuring water levels.

Regardless of the method or device chosen to measure the water level elevation in a monitoring well or piezometer, the following criteria should be met when determining water level elevations:

- Prior to measurement, water levels in piezometers and wells should be allowed to recover for a minimum of 24 hours after well construction, well development, or well purging. In low yield aquifers, recovery may take longer than 24 hours. If necessary, several water level measurements should be made over a period of several days to ensure that recovery has occurred.
- Water levels should be measured with a precision of ±0.01 foot. Water levels should be measured from the surveyed datum on the top of the inner well

casing. In general, the wetted-tape method is the only method for water level measurement that is consistently accurate to 0.01 foot (Dalton et al., 1991).

- Water level measurements from boreholes, piezometers, or monitoring wells used to define the water table or a single potentiometric surface should be made within 24 hours. In certain situations, water level measurements should be made within an even shorter time interval. These situations typically include:

    - tidally influenced aquifers;

    - aquifers affected by river stage, bank storage, impoundments, and/or unlined ditches;

    - aquifers stressed by intermittent pumping of production irrigation or supply wells; and

    - aquifers being actively recharged because of recent precipitation.

- Water level measurement equipment should be constructed of materials that are chemically inert and not prone to sorption or desorption.

- Water level measurement equipment should be decontaminated prior to use at each well to ensure sample integrity and to prevent cross-contamination of ground water.

- Measuring tapes and marked cables that are used to measure water levels should be periodically checked for stretch.

Well depth should be measured each time ground water is sampled. Well depth may be measured using a weighted tape measure or marked cable constructed of materials that are chemically inert and not prone to sorption or desorption. The weight should be heavy enough to keep the tape measure straight and blunt enough so that it will not penetrate soft materials on the bottom of the well. The deeper the well, the heavier the weight has to be to "feel" the bottom of the well. Standing water level measuring devices are generally not appropriate for making well depth measurements. Equipment used to measure well depth should be decontaminated prior to use at each well. The measuring tape or marked cable used to measure well depth should be periodically checked for stretch.

7.2.3 Detection and Sampling of Immiscible Layers

The QAPjP should include procedures for detecting and measuring the thicknesses of immiscible contaminants (i.e., LNAPLs and DNAPLs) each time water level is measured, if immiscible contaminants are known to occur (or are determined to potentially occur after considering the waste types managed at the facility) in the subsurface at the facility. LNAPLs, also known as "floaters," are relatively insoluble organic liquids that are less dense than water and that spread across the water table. DNAPLs, also known as "sinkers," are relatively insoluble organic liquids that are more dense than water and tend to migrate vertically downward in aquifers toward underlying confining layers. The detection of immiscible contaminants requires specialized equipment, and should be performed before a well is purged for conventional sampling.

The QAPjP should specify the device(s) that will be used to detect LNAPLs and DNAPLs. The procedures for detecting LNAPLs and DNAPLs should include procedures for measuring depth to both the non-aqueous phase liquid (NAPL) layer and to the water surface. When opening wells that may contain LNAPLs or DNAPLs, the air above the well head should be monitored to determine the potential for fire, explosion, and safety hazards, or adverse health effects to workers. Air monitoring also serves as a first indication of the presence of LNAPLs. The presence of LNAPLs precludes the exclusive use of sounders or manometers to make a determination of static water level. A manometer or acoustical sounder (for very shallow wells) may provide an accurate reading of the depth to the surface of the liquid in the well, but neither is capable of differentiating between the water table and the surface of an immiscible layer. Often an interface gauging probe or a weighted tape coated with commercially available reactive indicator paste will be suitable for this purpose.

The interface probe serves two related purposes. First, as it is lowered into the well, the probe registers when it is exposed to an organic liquid and thus identifies the presence of LNAPLs. Careful recording of the depths of the air/LNAPL and LNAPL/water interfaces establishes a measurement of the thickness of the LNAPL in the well casing. Secondly, after passing through the LNAPL layer, the probe indicates the depth to the water level. Interface probes are available that can be used to measure the thickness of DNAPLs. The Regional Administrator should be notified when LNAPLs or DNAPLs have been detected in a well.

The QAPjP also should include the procedures that will be used to sample LNAPLs or DNAPLs. A sample of the LNAPL or DNAPL should be collected prior to well purging. The Agency understands that bailers typically must be used to collect LNAPLs and DNAPLs because immiscible phases do not often occur in thicknesses that can be satisfactorily sampled using recommended submersible pumps. The key to minimizing sample bias is controlled, slow lowering (and raising) of the bailer within the well.

The approach to sampling LNAPLs depends on the depth to the floating layer surface and the thickness of the layer. If the thickness of the LNAPL in the well casing is great enough, a double check valve (point source) bailer or a submersible pump (see Section 7.3) can be used. If a bailer is used, the bailer should be lowered slowly until contact is made with the surface of the LNAPL. The bailer should then be lowered to a depth less than the depth of the LNAPL/water interface, as determined beforehand using the interface probe. A double-check valve bailer also may be used to sample a DNAPL. A submersible pump also may be used to sample a DNAPL if the DNAPL layer is of sufficient thickness.

When the thickness of the LNAPL layer in the well casing is too small to be sampled with a double check valve bailer or pump, the bailer should be modified to allow filling only from the top. If a top-filling bailer is not available, sampling personnel can disassemble the bottom check valve of a bailer and insert a piece of fluorocarbon resin sheet between the ball and ball seat. This will seal off the bottom valve. The ball from the top check valve should be removed to allow the sample to enter from the top. The buoyancy that occurs when the bailer is lowered into the LNAPL can be overcome either by using a stainless steel bailer or by securing a length of 1-inch stainless steel pipe (Type 304, Type 316) below the bailer. The bailer should be lowered carefully into the well, measuring the depth to the surface of the LNAPL layer, until the top of the bailer is level with the top of the LNAPL layer. The bailer should be lowered an additional one-half thickness of the LNAPL layer and the sample should then be collected. This technique is the most effective method of sample collection if the LNAPL is only a few inches thick.

When the LNAPL layer in the well casing is less than approximately 2 inches thick, an alternative method is necessary. In this situation, a sample should be collected from the top of the water column using a bailer. The two-phase water/LNAPL sample should be appropriately containerized and submitted for laboratory analysis. The laboratory should be instructed to analyze the non-aqueous phase of the two-phase sample.

7.2.4 Well Purging

Because the water standing in a well prior to sampling may not represent in-situ ground-water quality, stagnant water should be purged from the well and filter pack prior to sampling. The QAPjP should include detailed, step-by-step procedures for purging wells, including the parameters that will be monitored during purging and the equipment that will be used for well purging.

The purging procedure should ensure that samples collected from the well are representative of the ground water to be monitored. Over the years, investigator opinions have varied widely regarding the most appropriate procedure for purging wells. Many investigators believe that a specified number of well volumes should be purged from a well, some investigators believe that purging procedures should be based on hydraulic performance of the well, others believe that wells should be purged until certain geochemical parameters have stabilized, and yet others believe that wells should not be purged at all. The Agency’s guidance regarding well purging is based on information based on research and studies described in Puls and Powell (1992), Puls and Barcelona (1989a), Puls et al. (1991), Barcelona, et al. (1990), Kearl et al. (1992), Puls et al. (1990), Puls and Barcelona (1989b), Barcelona et al. (1985b), Robin and Gillham (1987), Barcelona (1985b), Keeley and Boateng (1987), Puls and Eychaner (1990), and USEPA (1991).

Purging should be accomplished by removing ground water from the well at low flow rates using a pump. The use of bailers to purge monitoring wells generally should be avoided. Research has shown that the "plunger" effect created by continually raising and lowering the bailer into the well can result in continual development or overdevelopment of the well. Moreover, the velocities at which ground water enters a bailer can actually correspond to unacceptably high purging rates (Puls and Powell, 1992; Barcelona et al., 1990).

The rate at which ground water is removed from the well during purging ideally should be less than approximately 0.2 to 0.3 L/min (Puls and Powell, 1992; Puls et al., 1991; Puls and Barcelona, 1989a; Barcelona, et al., 1990). Wells should be purged at rates below those used to develop the well to prevent further development of the well, to prevent damage to the well, and to avoid disturbing accumulated corrosion or reaction products in the well (Kearl et al., 1992; Puls et al., 1990; Puls and Barcelona, 1989a; Puls and Barcelona, 1989b; Barcelona, 1985b). Wells also should be purged at or below their recovery rate so that migration of water in the formation above the well screen does not occur. A low purge rate also will reduce the possibility of stripping VOCs from the water, and will reduce the likelihood of mobilizing colloids in the subsurface that are immobile under natural flow conditions. The owner/operator should ensure that purging does not cause formation water to cascade down the sides of the well screen. At no time should a well be purged to dryness if recharge causes the formation water to cascade down the sides of the screen, as this will cause an accelerated loss of volatiles. This problem should be anticipated; water should be purged from the well at a rate that does not cause recharge water to be excessively agitated. Laboratory experiments have shown that unless cascading is prevented, up to 70 percent of the volatiles present could be lost before sampling.

To eliminate the need to dispose of large volumes of purge water, and to reduce the amount of time required for purging, wells may be purged with the pump intake just above or just within the screened interval. This procedure eliminates the need to purge the column of stagnant water located above the well screen (Barcelona et al., 1985b; Robin and Gillham, 1987; Barcelona, 1985b; Kearl et al., 1992). Purging the well at the top of the well screen should ensure that fresh water from the aquifer moves through the well screen and upward within the screened interval. Pumping rates below the recharge capability of the aquifer must be maintained if purging is performed with the pump placed at the top of the well screen, below the stagnant water column above the top of the well screen (Kearl et al., 1992). The Agency suggests that a packer be placed above the screened interval to ensure that "stagnant" casing water is not drawn into the pump. The packer should be kept inflated in the well until after ground-water samples are collected.

In certain situations, purging must be performed with the pump placed at, or immediately below, the air/water interface. If a bailer must be used to sample the well, the well should be purged by placing the pump intake immediately below the air/water interface. This will ensure that all of the water in the casing and filter pack is purged, and it will minimize the possibility of mixing and/or sampling stagnant water when the bailer is lowered down into the well and subsequently retrieved (Keeley and Boateng, 1987). Similarly, purging should be performed at the air/water interface if sampling is not performed immediately after the well is purged without removing the pump. Pumping at the air/water interface will prevent the mixing of stagnant and fresh water when the pump used to purge the well is removed and then lowered back down into the well for the purpose of sampling.

In cases where an LNAPL has been detected in the monitoring well, a stilling tube should be inserted into the well prior to well purging. The stilling tube should be composed of a material that meets the performance guidelines outlined in Section 7.3 for sampling devices. The stilling tube should be inserted into the well to a depth that allows ground water from the screened interval to be purged and sampled, but that is below the upper portion of the screened interval where the LNAPL is entering the well screen. The goal is to sample the aqueous phase (ground water) while preventing the LNAPL from entering the sampling device. To achieve this goal, the stilling tube must be inserted into the well in a manner that prevents the LNAPL from entering the stilling tube. One method of doing this is to cover the end of the stilling tube with a membrane or material that will be ruptured by the weight of the pump. Some investigators place a piece of aluminum foil over the end of the stilling tube. The stilling tube is lowered slowly into the well to the appropriate depth and then attached firmly to the top of the well casing. When the pump is inserted, the weight of the pump breaks the foil covering the end of the tube, and the well can be purged and sampled from below the LNAPL layer. The membrane or material that is used to cover the end of the stilling tube must be fastened firmly so that it remains attached to the stilling tube when ruptured. Moreover, the membrane or material must retain its integrity after it is ruptured. Pieces of the membrane or material must not fall off of the stilling tube into the well. Although aluminum foil is mentioned in this discussion as an example of a material that can be used to cover the end of the tube, a more chemically inert material may be required, based on the site-specific situation. Stilling tubes should be decontaminated prior to each use according to the procedures outlined for sampling equipment in Section 7.3.

For most wells, the Agency recommends that purging continue until measurements of turbidity, redox potential, and dissolved oxygen in in-line or downhole analyses of ground water have stabilized within approximately 10% over at least two measurements -- for example, over two successive measurements made three minutes apart (Puls and Powell, 1992; Puls and Eychaner, 1990; Puls et al., 1990; Puls and Barcelona, 1989a; Puls and Barcelona, 1989b; USEPA, 1991; Barcelona et al., 1988b). If a well is purged to dryness or is purged such that full recovery exceeds two hours, the well should be sampled as soon as a sufficient volume of ground water has entered the well to enable the collection of the necessary ground-water samples.

All purging equipment that has been or will be in contact with ground water should be decontaminated prior to use. Decontamination procedures outlined in Section 7.3.4 are generally adequate. If the purged water or the decontamination water is contaminated (e.g., based on analytical results), the water should be stored in appropriate containers until analytical results are available, at which time proper arrangements for disposal or treatment should be made (i.e., contaminated purge water may be a hazardous waste).

7.3 Ground-Water Sampling Equipment Selection and Use

There are three broad categories of ground water sampling devices: 1) grab samplers, 2) positive displacement (submersible) pumps, and 3) suction lift pumps (Pohlmann and Hess, 1988; Herzog et al., 1991). Gas contact pumps also are available but are not recommended for ground-water purging or sampling applications (Pohlmann and Hess, 1988). Table 12 is a useful guide for selecting devices for sampling. The Agency prefers that all sampling equipment be dedicated to a particular well. To encourage innovation, the Agency may allow the use of other devices that are not specifically mentioned above if the owner/operator demonstrates to the Agency's satisfaction (or to the authorized state's satisfaction) that the device will yield representative ground-water samples.

The following recommendations apply to the selection of sampling equipment:

- Sampling equipment should be chosen based on the analytes of interest and the characteristics and depth of the saturated zone from which the sample is withdrawn. For example, the choice of sampling equipment should reflect consideration of the potential for LNAPLs and DNAPLs (Section 7.2.3).

- Sampling equipment should be constructed of inert material. Sample collection equipment should not alter analyte concentrations, cause loss of analytes via sorption, or cause gain of analytes via desorption, degradation, or corrosion. Sampling equipment should be designed such that Viton®, Tygon®, silicone, or neoprene components do not come into contact with the ground-water sample. These materials have been demonstrated to cause sorptive losses of contaminants (Barcelona et al., 1983; Barcelona et al., 1985b; Barcelona et al., 1988b; Barcelona et al., 1990). Barcelona (1988b) suggests that sorption of volatile organic compounds on silicone, polyethylene, and PVC tubing may result in gross errors when determining concentrations of trace organics in ground-water samples. Barcelona (1985b) discourages the use of PVC sampling equipment when sampling for organic contaminants.

- Sampling equipment should cause minimal sample agitation and should be selected to reduce/eliminate sample contact with the atmosphere during sample transfer. Sampling equipment should not allow volatilization or aeration of samples to the extent that analyte concentrations are altered.

GENERALIZED GROUND-WATER SAMPLING DEVICE MATRIX

						GROUND-WATER PARAMETERS													
						INORGANIC							ORGANIC				RADIO-ACTIVE		BIOLOG-ICAL
		Device	Approximate Maximum Sample Depth	Minimum Well Diameter	Sample Delivery Rate or Volume†	EC	pH	Redox	Major ions	Trace metals	Nitrate Fluoride	Dissolved gasses	Non-volatile	Volatile	TOC	TOX	Radium	Gross alpha & beta	Coliform bacteria
PORTABLE SAMPLING DEVICES	GRAB	Open Bailer	no limit	1/2 in.	variable	●	¤	¤	●	●	●	¤	●	¤	¤	¤	●	¤	●
		Point-Source Bailer	no limit	1/2 in.	variable	●	●	●	●	●	●	¤	●	¤	●	●	●	¤	●
		Syringe sampler	no limit	1 1/2 in.	0.01-0.2 gal	●	●	●	●	●	●	¤	●	●	¤	¤	●	●	●
	POSITIVE DISPLACEMENT (SUBMERSIBLE)	Gear-drive	200 ft.	2 in.	0-0.5 gpm	●	●	●	●	●	●	●	●	●	●	●	●	●	¤
		Bladder pump	400 ft.	1 1/2 in.	0-2 gpm	●	●	●	●	●	●	●	●	●	●	●	●	●	●
		Helical rotor	160 ft.	2 in.	0-1.2 gpm	●	●	●	●	●	●	●	●	●	●	●	●	●	¤
		Piston pump (gas-drive)	500 ft.	1 1/2 in.	0-0.5 gpm	●	¤	¤	●	●	●	¤	●	●	¤	¤	●	●	¤
		Centrifugal (Low-rate)	variable	2 in.	variable	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SUCTION LIFT		Peristaltic	26 ft.	1/2 in.	0.01-0.3 gpm	●	¤	¤	●	●	●	¤	●	¤	¤	¤	●	¤	●
	GAS CONTACT	Gas-lift	variable	1 in.	variable	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
		Gas-drive	150 ft.	1 in.	0.2 gpm	●	¤	¤	●	¤	●	¤	●	¤	¤	¤	●	¤	¤
IN SITU SAMPLING DEVICES*		Pneumatic	no limit	no limit	0.01-0.13 gpm	●	●	●	●	●	●	¤	●	¤	¤	¤	●	●	●

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* Sampling devices on this chart are divided into two categories: 1. portable devices for sampling existing monitoring wells, and 2. in situ monitoring devices (often multilevel) that are permanently installed. Sampling device construction materials (including tubing, haul lines, etc.) should be evaluated for suitability in analyzing specific ground-water parameters. It is assumed on this chart that existing monitoring wells are properly installed and constructed of materials suitable for detection of the parameters of interest.

† Sample delivery rates and volumes are average ranges based on typical field conditions. Actual delivery rates are a function of diameter of monitoring well, size and capacity of sampling device, hydrogeologic conditions, and depth to sampling point. For all devices, delivery rate should be carefully controlled to prevent aeration or degassing of the sample.

• Indicates device is generally suitable for application (assuming device is cleaned and operated properly and is constructed of suitable materials).

¤ Indicates device may be unsuitable or is untested for application.

Source: Modified from Pohlmann and Hess, 1988
Based on Literature Review

TABLE 12

The following sections briefly discuss the various types of sampling mechanisms, and their relative advantages and disadvantages. More detailed discussions of the various types of sampling devices are provided in Nielsen and Yeates (1985), Pohlmann and Hess (1988), USEPA (1991a), and USEPA (1991b). Because new sampling devices will become available on a periodic basis, the Agency recommends that the manufacturer's performance testing data and results be reviewed before selecting a ground-water sampling device. It is expected that through design improvements, general operating ranges also will improve; therefore, some of the information contained in the following discussions may become outdated.

7.3.1 Grab Samplers

There are two types of grab samplers available: bailers and syringe devices. The following sections provide a general description of these devices.

7.3.1.1 Double and Single Check Valve Bailers

Bailers are among the simplest of ground-water sampling devices. A bailer is a rigid tube that fills with water when lowered into the well; when raised back out of the well, it is sealed on one or both ends, typically by a ball and seat mechanism. Bailers that seal only at the bottom are called single check valve bailers, bailers that seal at both ends are called double check valve bailers or point-source bailers. The ground-water sample is transferred into sample containers from the bailer. Bailers are relatively inexpensive to purchase or fabricate, easy to clean, portable, simple to operate, and require no external power source (USEPA, 1983).

Disadvantages of bailers are that their use can be time consuming and labor intensive and that the transfer of water to a sample container may significantly alter the chemistry of ground-water samples due to degassing, volatilization, or aeration (oxidation). Recent research focusing on the comparison of different types of ground-water sampling equipment demonstrates that significant loss of volatile organic compounds may occur when bailers are used to sample ground water (Pearsall and Eckhardt, 1987; Yeskis et al., 1988; Tai et al., 1991; Pohlmann et al., undated). Researchers also believe that the action of lowering and raising the bailer in the well may mobilize naturally immobile particulates, and that the velocity of ground-water entrance into the device may actually approach that of high-rate pumping methods (Puls and Powell, 1992; Barcelona et al., 1990; Puls and Barcelona, 1989a; Puls and Barcelona 1989b).

Studies have suggested that considerable imprecision is introduced into samples collected with bailers, possibly as a result of differences in operator technique (USEPA, 1991a; Tai et al., 1991; Pohlmann et al., undated). In addition, it is difficult to determine the exact location in the water column from which a bailed sample has been collected; inadequate sealing of the check valves often increases this imprecision (USEPA, 1991a). In a study comparing concentrations of volatile organic compounds detected using various sampling devices, Imbrigiotta et al. (1988) noted that the data for the samples collected with the bailers exhibited the lowest precision of the seven sampling devices investigated.

When sampling NAPLs, bailers should never be dropped into a well and should be removed from the well in a manner that causes as little agitation of the sample as possible. For example, the bailer should not be removed in a jerky fashion or be allowed to continually bang against the well casing as it is raised. When transferring the sample from a bailer to a container, it is preferable to use a bottom emptying device with a valve that allows the LNAPL or DNAPL to slowly drain from the bailer. Bailers should not be used if the well has not been purged by drawing water from the air/water interface because as the bailer is raised through the water column, the bailer may sample stagnant water located above the screened interval. When using bailers to collect LNAPL or DNAPL samples for inorganic analyses, the Agency recommends that the bailer be composed of fluorocarbon resin. Bailers used to collect LNAPL or DNAPL samples for organic analyses should be constructed of stainless steel. The cable used to raise and lower the bailer should be composed of an inert material (e.g., stainless steel) or coated with an inert material (e.g., PTFE).

7.3.1.2 Syringe Bailer

A syringe bailer is distinguished from other bailers by the means of water entry (Morrison, 1984). The syringe is lowered into a well and water is drawn into the chamber by activating a plunger via suction. To recover the sample, the syringe is withdrawn and the sample is transferred into a collection bottle or injected directly into an appropriate instrument for water quality analysis. The syringe bailer is often used as both a sampler and a sample container. The small syringe size is a limitation when large sample volumes are required. Moreover, researchers believe that in waters with high concentrations of suspended solids, syringe bailers may leak around the plunger. Imbrigiotta et al. (1988) concluded that for sampling volatile organic compounds, syringe samplers (bailers) were inferior in comparison to other sampling devices. Imbrigiotta et al. attributed the poor performance of the syringe sampler to exposure of the sample to widely fluctuating pressures during the sampling process caused by leakage of the seal between the piston and the syringe barrel.

7.3.2 Pumps

Pump mechanisms historically used for ground-water sampling include bladder pumps, helical rotor electric submersible pumps, gas-drive piston pumps, gear drive electric submersible pumps, centrifugal pumps, peristaltic pumps, gas-lift pumps, and gas-drive pumps. The following sections describe each of these types of pumps and their applications and limitations with regard to collecting ground-water samples.

7.3.2.1 Bladder Pumps

Bladder pumps (also referred to as gas squeeze pumps) are submersible mechanisms consisting of a flexible membrane (bladder) enclosed in a rigid (usually stainless steel) housing. The internal bladder can be compressed and expanded under the influence of gas (air or nitrogen). A strainer or screen attaches below the bladder to filter any material that could clog check valves located above and below the bladder. Water enters the bladder through the lower check valve; compressed gas is injected into the cavity between the housing and bladder. The sample is transported through the upper check valve and into the discharge line through compression of the bladder. The upper check valve prevents water from reentering the bladder. The process is repeated to cycle the water to the surface. Bladder volumes (e.g., volume per cycle) and sampler geometry can be modified to increase the sampling abilities of the pump. Automated control systems are available to control gas flow rates and pressurization cycles.

Bladder pumps prevent contact between the gas and water sample and can be fabricated entirely of fluorocarbon resin and stainless steel. Pohlmann and Hess (1988) determined that bladder pumps can be suitable for collecting ground-water samples for almost any given organic or inorganic constituent. Disadvantages of bladder pumps include the large gas volumes required (especially at depth), and potential bladder rupture. Bladder pumps are generally recognized as the best overall sampling device for both inorganic and organic constituents (Barcelona et al., 1985b; Barcelona, 1988b; USEPA 1991a).

7.3.2.2 Helical Rotor Electric Submersible Pumps

The helical rotor electric pump is a submersible pump consisting of a sealed electric motor that powers a helical rotor. The ground-water sample is forced up a discharge line by an electrically driven rotor-stator assembly by centrifugal action. Pumping rates vary depending upon the depth of the pump. Considerable sample agitation of water in the well may result from operating the pump at high rates, and this may cause alteration of the sample chemistry. In addition, high pumping rates can introduce sediments from the formation into the well that are immobile under ambient ground-water flow conditions, resulting in the collection of unrepresentative samples (Nielsen and Yeates, 1985). Tai et al. (1991) and Yeskis et al. (1988) indicate that helical rotor submersible pumps perform similarly to bladder pumps when collecting samples for volatile organics analysis.

7.3.2.3 Gas-Drive Piston Pumps

A piston pump uses compressed air to force a piston to raise a sample to the surface. A typical design consists of a stainless steel chamber between two pistons. The alternating chamber pressurization activates the piston, which allows water entry during the suction stroke of the piston, and forces the sample to the surface during the pressure stroke. The pump is connected to a tubing bundle which contains three tubes, an electric cord, and a stainless steel cable. The tubes convey the gases to and from the pump; the electric cable powers the water level indicator, and a steel cable supports the downhole assembly. Flow rate can be controlled by adjusting the driving pressure to the pump. The piston pump provides continuous sample withdrawal at depths that are greater than most other devices. The pump can be constructed of materials that minimize the possibility of chemical alteration of the sample.

The bulk of associated equipment may reduce the portability of the pump. The valving mechanism may cause a series of pressure drops in the sample that could cause sample degassing and pH changes. The tubing bundles may be difficult to decontaminate between wells. The pump intake should be filtered so that particulate matter does not damage the pump's valving. A study by Yeskis et al. (1988) indicates that gas-drive piston pumps perform similarly to bladder pumps when collecting samples for volatile organics analysis.

7.3.2.4 Gear-Drive Electric Submersible Pumps

Gear-drive submersible pumps are designed to be portable and easily serviceable in the field. A gear-drive pump operates using a small high-efficiency electric motor that is located within the pump housing. The electric motor rotates a set of PTFE gears from an intake screen at the top of the pump. The water is drawn through the gears and driven to a discharge line that transports the water to the surface. The pumps have self-contained power sources, however, external sources may be used. Flow rates cannot be controlled on conventional gear-drive submersible pumps. Wells that have high levels of suspended solids may cause the gears to require frequent replacement.

7.3.2.5 Centrifugal Pumps

Centrifugal (also called impeller) pumps transport fluid by accelerating it radially outward. Specifically, a motor shaft rotates an impeller that is contained within a casing. Water that is directed into the center of the rotating impeller is picked up by the impeller vanes, accelerated by the rotation of the impeller, and discharged by centrifugal force into the casing. A collection chamber within the casing converts much of the kinetic energy into head or pressure. Certain submersible centrifugal pumps are constructed for ground-water monitoring purposes. These pumps are fabricated of stainless steel and PTFE, and can be adjusted to achieve flow rates as low as 0.1 L/min. Studies conducted by Gass et al. (1991) concluded that low flow-rate submersible centrifugal pumps can deliver "representative" ground-water samples. A study conducted by Paul and Puls (1992) comparing a low flow-rate submersible centrifugal pump, a bladder pump, and a peristaltic pump concluded that the low flow-rate submersible centrifugal pump produced the least negative impacts when trying to obtain representative and reproducible ground-water samples at the particular site and wells investigated. Research performed by Yeskis et al. (1988) indicates that submersible impeller pumps perform similarly to bladder pumps when collecting samples for volatile organics analysis.

7.3.2.6 Peristaltic Pumps

A peristaltic pump (also called rotary peristaltic) is a low-volume pump that operates by suction lift. Plastic tubing is inserted around the pump rotor. Rotating rollers compress the tubing as the rollers revolve around the rotor, forcing fluid movement ahead and inducing suction behind each roller. As the rotor revolves, water is drawn into a sampling tube that has been inserted into the well, and discharged into the sample container. Peristaltic pumps often require the use of flexible silicone tubing, which is unsuitable for ground-water sampling purposes. The withdrawal rate of peristaltic pumps can be carefully regulated by adjusting the rotor head revolution. The use of a peristaltic pump is limited by the depth of sampling; the depth of sample collection is limited to situations where the potentiometric level is less than 25 feet below land surface (Herzog et al., 1991).

The Agency does not recommend the use of peristaltic pumps to sample ground water, particularly for volatile organic analytes. The method can cause sample mixing and oxidation resulting in degassing and loss of volatiles. Although Tai et al. (1991) indicated that peristaltic pumps may provide adequate recovery of volatile organic compounds, Imbrigiotta et al. (1988) concluded that for sampling volatile organic compounds, peristaltic pumps were inferior in comparison to other sampling devices. Imbrigiotta et al. attributed the poor performance of the peristaltic pump to degassing of volatile contaminants into the vacuum created by the pump. Puls and Barcelona (1989a) and Puls and Barcelona (1989b) indicated that vacuum pumps such as peristaltic pumps may significantly alter ground-water chemistry leading to colloid formation in the monitoring well.

7.3.2.7 Gas-Lift Pumps

An air- or gas-lift pump allows collection of ground-water samples by bubbling air or gas at depth in the well. Sample transport occurs primarily as a result of the reduced specific gravity of the water being lifted to the surface. Water is forced up a discharge pipe, which may be the outer casing or a smaller diameter pipe inserted into the well. The considerable pressures required for deep sampling can result in significant redox and pH changes. Gas-lift pumps should not be used for any purpose in ground-water investigations.

7.3.2.8 Gas-Drive Pumps

Gas drive (gas displacement) pumps are distinguished from gas-lift pumps by their method of sample transport. Gas-drive pumps force a column of water under linear flow conditions to the surface without extensive mixing of the pressurized gas and water. A vacuum also can be used to assist the gas. The disadvantages of a gas drive pump are that the drive gas comes into contact with the water and therefore, can be a source of contamination; also, the pump can be difficult to clean. Gas-drive pumps are not recommended for sampling monitoring wells.

7.3.3 Packer Assemblages

A packer assembly provides a means by which to isolate and sample a discrete interval in the subsurface. Hydraulic- or pneumatic-activated packers are wedged against the casing wall or screen allowing sample collection from an isolated portion of the well. The packers deflate for vertical movement within the well and inflate when the desired depth is attained. Packers are usually constructed from some type of rubber or rubber compound and can be used with submersible, gas-lift, and suction pumps.

If pumps are operated at a low rate, a packer assembly allows sampling of low-yielding wells, and wells that would otherwise produce turbid samples. A number of different samplers can be placed within the packers depending upon the analytical specifications for sample testing. One disadvantage is that vertical movement of water outside the well is possible with packer assemblages, depending upon the pumping rate and formation properties. Another possible disadvantage is that the packer material may be chemically reactive, causing gain or loss of organic contaminants through sorption or desorption.

7.3.4 Decontaminating Sampling Equipment

When dedicated equipment is not used for sampling (or well purging) or when dedicated equipment is stored outside of the well, the owner/operator's QAPjP should include procedures for disassembly and cleaning of equipment before each use at each well.

The recommended cleaning procedure for sampling equipment used when organic constituents are of interest is as follows (Barcelona et al., 1990; Keeley and Boateng, 1987; USEPA, 1986a):

1. Wash the equipment with a nonphosphate detergent.
2. Rinse the equipment with tap water.
3. Rinse the equipment with pesticide-grade hexane or methanol (methyl alcohol).
4. Rinse the equipment with reagent grade acetone.
5. Rinse the equipment with organic-free reagent water.

If acetone, hexane, or methanol are analytes of interest, a different solvent (which is not a target analyte) should be chosen (e.g., isopropanol).

The recommended cleaning procedure for sampling equipment used when inorganic constituents are of interest is as follows (Barcelona et al., 1990; Keeley and Boateng, 1987; USEPA, 1986a):

1. Wash the equipment with a nonphosphate detergent.

2. Rinse the equipment with tap water.

3. Rinse the equipment with dilute (0.1N) hydrochloric or nitric acid.

4. Rinse the equipment with reagent water.

Dilute hydrochloric acid is preferred over nitric acid when cleaning stainless steel because nitric acid may oxidize the steel.

In all cases, waste decontamination fluids should be containerized until the investigators determine (e.g., through analytical testing) whether the fluids should be treated or disposed of as hazardous waste.

All equipment should be allowed to dry thoroughly in a dust-free environment. If the equipment is not to be used again immediately, it should be packaged and properly stored to protect it from dust and dirt. Equipment may be wrapped in aluminum foil (shiny side on the outside) and placed in a plastic bag. A label should be affixed to the outside wrapping summarizing the decontamination procedure and stating the date of decontamination. Decontaminated sampling equipment should not be placed on the ground or on other contaminated surfaces prior to insertion in the well.

7.3.5 Collecting Ground-Water Samples

Monitoring well sampling should always progress from the well that is expected to be least contaminated to the well that is expected to be most contaminated, to minimize the potential for cross-contamination of samples that may result from inadequate decontamination of sampling equipment. Samples should be collected and containerized according to the volatility of the target analytes. The preferred collection order for some of the more common ground-water analytes is as follows (Barcelona et al., 1985b):

1. Volatile organics (VOAs or VOCs) and total organic halogens (TOX);

2. Dissolved gases and total organic carbon (TOC);

3. Semivolatile organics (SMVs or SVOCs);

4. Metals and cyanide;

5. Major water quality cations and anions;

6. Radionuclides.

The following recommendations apply to the use and operation of ground-water sampling equipment:

- Check valves should be designed and inspected to ensure that fouling problems do not reduce delivery capabilities or result in aeration of samples.

- Sampling equipment should never be dropped into the well, as this will cause degassing of the water upon impact.

- Contents of the sampling device should be transferred to sample containers in a controlled manner that will minimize sample agitation and aeration.

- Decontaminated sampling equipment should not be allowed to come into contact with the ground or other contaminated surfaces prior to insertion into the well.

- Ground-water samples should be collected as soon as possible after the well is purged. Water that has remained in the well casing for more than about 2 hours has had the opportunity to exchange gases with the atmosphere and to interact with the well casing material (USEPA, 1991b).

- The rate at which a well is sampled should not exceed the rate at which the well was purged. Ideally, the rate of sample collection should be approximately the same as the actual ground-water flow rate. Because this is typically not possible, low sampling rates, approximately 0.1 L/min, are suggested. Low sampling rates will help to ensure that particulates, immobile in the subsurface under ambient conditions, are not entrained in the sample and that volatile compounds are not stripped from the sample (Puls and Barcelona, 1989b; Barcelona, et al., 1990; Puls et al., 1991; Kearl et al., 1992; USEPA, 1991b). Pumps should be operated at rates less than 0.1 L/min when collecting samples for volatile organics analysis.

- Pump lines should be cleared at a rate of 0.1 L/min or less before collecting samples for volatiles analysis so that the samples collected will not be from the period of time when the pump was operating more rapidly.

- Pumps should be operated in a continuous, non-pulsating manner so that they do not produce samples that are aerated in the return tube or upon discharge.

- When sampling wells that contain LNAPLs, a stilling tube should be inserted in the well as described in Section 7.2.4. Ground-water samples should be collected from the screened interval of the well below the base of the tube.

- Ground-water samples collected for analysis for organic constituents or parameters should not be filtered in the field.

Currently, some hydrogeologists filter ground-water samples in the field using a 0.45 micron filter prior to chemical analysis of certain constituents. The Agency generally does not recommend that ground-water samples that will be used to determine if there is statistically significant evidence of ground-water contamination be filtered in the field. Nevertheless, the Agency understands that there may be circumstances where filtering ground-water samples is appropriate. For example, some wells may produce highly turbid ground water even though the wells have been appropriately installed and have been sampled using procedures intended to minimize sample turbidity. The Agency believes that in these circumstances filtering the ground-water samples in the field prior to their analysis for metals may be appropriate if filtering can be performed while still fulfilling the data quality objectives (DQOs) for the ground-water monitoring program.

There are several reasons why the Agency generally does not recommend filtering ground-water samples in the field prior to analysis for metals. One of the primary reasons is that data generated from filtered samples provide information on only the dissolved constituents that are present, because suspended materials are removed by the filtration process. As discussed in greater detail below, current research in ground-water sampling protocol indicates that hazardous constituents are mobile in the subsurface in both the aqueous (dissolved) phase and the solid phase. The research of Puls and Powell (1992), Puls and Barcelona (1989a), Puls and Barcelona (1989b), Penrose et al. (1990), and West (1990) are the primary sources of the discussion of field filtration that follows.

During ground-water sampling, every attempt should be made to minimize changes in the chemistry of the sample so that data representative of hazardous constituents that may be migrating to ground water can be collected. A sample that is exposed to the atmosphere as a result of field filtering is very likely to undergo chemical reactions (e.g., volatilization, precipitation, chemical flocculation) that alter constituent concentrations. These reactions can change the concentrations of organic compounds and metals if they are present in the sample. Volatile organic compounds (VOCs), for example, are likely to partition to the atmosphere, thereby resulting in ground-water monitoring data that are not representative of constituent concentrations. Further, precipitated and emulsion trapped constituents migrating from the waste management unit to ground water are lost through field filtering, because they are unable to pass through a standard 0.45 micron field filter.

Field filtration of ground-water samples that will be used for metals analysis may not provide accurate information concerning the mobility of metal contaminants. Field filtration of ground-water samples may be especially problematic in fractured or karst terranes. Facilitated transport phenomena are more likely to occur in these types of aquifer systems that are characterized by conduit flow, because colloidal particles can move easily through the larger channels formed by fractures or by the dissolution of carbonates. Some metals may move through fractured, karstic, and porous media not only as dissolved species, but also as precipitated phases, and/or polymeric species; some metals may be adsorbed to, or encapsulated in, organic or inorganic particles (e.g., colloid-size particles) that are likely to be removed by filtration. In addition, field filtration may expose a sample to the atmosphere, introducing oxygen into the sample that can oxidize dissolved ferrous iron to form a ferric hydroxide precipitate ($Fe(OH)_3$). The ferric hydroxide precipitate may enmesh other metals in the sample, removing them from solution. The precipitate and the entrapped constituents would be removed by field filtration. This phenomenon (which may be common because of the ubiquity of dissolved iron in ground water and iron colloidal particles, such as goethite, in the subsurface), also could result in an inaccurate measurement of metals concentrations in ground water at the facility. The Agency's position to prohibit field filtration of ground-water samples is even more crucial in fractured or karst terranes. Colloidal transport phenomena are more likely to occur in aquifer systems characterized by conduit flow, because colloidal particles can move easily through the larger channels formed by fractures and the dissolution of carbonates.

Several recent studies demonstrate that metals can migrate in ground water with colloidal particles (via a phenomenon known as facilitated transport), and that those colloids will not pass through a standard 0.45 micron field filter. Studies of the behavior of several persistent chlorinated organic compounds such as DDT, PCBs, and dioxin, also have demonstrated that the solubility of those substances is greatly increased by the presence of surfactants. Surfactants form a microemulsion in water, trapping the organic compounds while allowing them to stay dissolved in water and to continue moving throughout an aquifer. These emulsion-trapped organic compounds have similar contaminant fate and transport characteristics to that of metals bound up in colloids. Field filtering ground-water samples for organic compounds or metals analyses would remove these constituents and therefore lead to inaccurate measurements of their concentration in ground water.

The Agency is aware that many hydrogeologic field crews have routinely field filtered ground-water samples in an effort to decrease the sample turbidity. Some of this removed fraction may represent hazardous constituents that are mobile in ground water under natural conditions, and some of this fraction may represent immobile constituents. In many cases, however, proper well development and maintenance procedures (e.g., development of the well after installation to remove fine-grained materials, and periodic re-development of wells to counter the effects of siltation) are sufficient to reduce sample turbidity. In addition, the selection of an appropriate filter pack material (both composition and grain size) and screen slot size are important components of monitoring well design that can reduce sample turbidity. Further, lower well purging rates and sampling rates (e.g., less than 1.0 liter/minute) will minimize the amount of material flowing into the well without removing the fraction of the sample that may contain potential hazardous constituents that are mobile in the subsurface under natural conditions. Common sampling techniques often involve the use of bailers that do not allow low flow rate sampling.

The Agency recognizes that there are certain circumstances where it is necessary to filter or centrifuge a sample under controlled laboratory conditions prior to analysis to prevent instrument damage. Sample filtration in the laboratory is permissible if insoluble materials (e.g., silicates) remain after acid digestion of the sample, which could damage laboratory equipment. If this step is necessary, the filter and the filtering apparatus should be thoroughly cleaned and pre-rinsed with dilute nitric acid. Laboratory personnel should refer to Chapter Three of the EPA publication "Test Methods for Evaluating Solid Waste" (SW-846) for information concerning these procedures.

The Agency also realizes that data generated from unfiltered samples may result in higher concentrations of metals detected in ground-water samples at some facilities. Because background samples also will be unfiltered, however, false indications of contamination should be minimized. In all cases, owners and operators should ensure that all samples used in a statistical test are collected using the same procedures.

Ground-water sampling that is conducted to perform ion balance calculations or to classify ground water according to the amount of dissolved ions is not addressed in this Chapter, because these analyses are not part of the Subpart F requirements. Scientific studies that are performed to estimate aqueous concentrations of dissolved geochemical parameters have different data objectives than Subpart F ground-water monitoring, and commonly utilize other techniques and procedures to achieve the desired research goals.

7.4 In-Situ or Field Analyses

Physically or chemically unstable analytes should be measured in the field, rather than in the laboratory. Examples of unstable parameters include pH, redox potential, dissolved oxygen, and temperature. Although the specific conductance (i.e., electrical conductance) of a sample should be relatively stable, the Agency recommends that this analyte also be measured in the field. The Agency suggests that dissolved oxygen, turbidity, and specific conductance be determined in the field as soon as practicable after the well has been purged. Most conductivity instruments require temperature compensation; therefore, the temperature of the samples should be measured at the time conductivity is determined unless the monitoring equipment automatically makes this compensation.

Three methods are generally employed for measuring unstable parameters. The two preferred methods are to use either an in-line flow cell or specially designed analytical equipment that has probes that may be lowered down into the well. These methods provide results that typically are more precise than those obtained using the third method, collecting discrete samples and analyzing them at land surface. Specifically, the third method involves collecting a sample in a clean bottle or beaker in the same manner that a sample for laboratory analysis would be collected, and then analyzing the sample using a field test kit or meter at land surface. If down-hole probes (e.g., pH electrode, thermistor) are used to measure unstable parameters, the probes should be decontaminated in a manner that prevents the probe(s) from contaminating the water in the well. In no case should field analyses be performed directly on samples that will be submitted for laboratory analysis.

The QAPjP to be included in the permit application should list the specific parameters that will be measured in the field. The QAPjP should specify the types of instruments (e.g., in-line flow cells, downhole probes, meters) that will be used to make field measurements, and describe the procedures that will be followed in operating the instruments and recording the measurements. The QAPjP should describe all instrument calibration procedures, including the frequency of calibration. The description of calibration procedures should include: discussion of initial calibration, multi-level calibration for determination of usable range, periodic calibration checks, conditions that warrant re-calibration of instruments, acceptable control limits, and the maintenance of calibration records in the field log book. At a minimum, all field instruments should be calibrated at the beginning of each use and in accordance with the frequency suggested by the manufacturer. Field instruments should be calibrated using at least two calibration standards spanning the range of results anticipated during the sampling event. For example, if ground-water pH is expected to be near pH 7, the two standards used to calibrate the pH meter should be pH 4 or pH 5, and pH 9 or pH 10, respectively.

7.5 Sample Containers and Preservation

The procedures employed for sample containerization and preservation are nearly as important for ensuring the integrity of the samples as the collection device itself. Investigators should refer to Chapter Two of SW-846 for guidance relating to sample containers and sample preservation. Detailed procedures for sample containerization, preservation, packaging, and handling should be provided in the QAPjP. Regardless of the analytes of concern, exposure of the samples to the ambient air should be minimized.

7.5.1 Sample Containers

The Agency has identified several general performance standards that apply to the selection and use of sample containers relative to ground-water monitoring. These are as follows:

- The QAPjP should identify the types of sample containers that will be used to collect ground-water samples, as well as the procedures that the owner/operator will use to ensure that sample containers are free of contaminants prior to use. Chapters Three and Four of SW-846 discuss sample container selection and cleaning for inorganic and organic parameters, respectively.

- Clean sample containers should be sealed and stored in a clean environment to prevent any accumulation of dust or other contaminants. The cleanliness of a batch of precleaned bottles should be verified in the laboratory. The residue analysis should be available prior to sampling in the field.

- Samples should not be transferred from one sample container to another. Transferring samples between containers may result in losses of constituents onto the walls of the container or sample aeration.

- To minimize the possibility of volatilization of organic constituents, no headspace should exist in the containers of samples containing volatile organics. Immediately after samples designated for volatile organics analysis have been filled and capped, they should be checked for headspace. In most cases, the entire sample should be emptied from the container and the container should be refilled if headspace is noted in the sample. The container should not be "topped off" to fill the additional headspace. If headspace is observed after samples have been collected, field logs and laboratory analysis reports should note the headspace, if present, in the sample container(s) at the time of receipt by the laboratory, as well as at the time the sample was first transferred to the sample container at the wellhead.

- Splitting samples is a common practice. Normally, aliquots from the sampling device should be alternately emptied into each container receiving a split until the containers are full. When splitting samples for volatile organics analysis (VOAs), each VOA container (vial) should be completely filled and sealed -- vials should not be kept open while the sample is distributed between vials. Samples collected from a well should not be composited in one container for subsequent transfer to other containers.

7.5.2 Sample Preservation

The QAPjP should identify the methods that will be used to preserve ground-water samples. Methods of sample preservation are relatively limited, and are generally intended to 1) retard biological action, 2) retard chemical reactions such as hydrolysis or oxidation, and 3) reduce sorption effects. Preservation methods are generally limited to pH control, chemical addition, refrigeration, and protection from light. Chapter Two of SW-846 provides specific information on the required containers, preservation techniques, and holding times for aqueous matrices. Chemical preservatives should be added to samples in the field. No sample should be brought back to the laboratory for preservation.

Most commercial shipping containers ("coolers") leak when the interior water level reaches the lid-body interface. As a result, the carrier may refuse to ship the container. For this reason, the Agency recommends that two polyethylene overpack bags be used in shipping. The first will contain the sample bottles, the second the ice needed to keep the samples at 4°C. If the bags are taped shut, the melt water will not reach the bottle labels or escape from the cooler. This precaution may not be necessary if "blue" ice or other contained coolants are used.

As specified in Chapter One of SW-846, a temperature history of the samples should be maintained as a quality control measure. This is done by recording the temperature on the chain-of-custody record (Section 7.6) before the sample containers are sealed for shipment. Upon receipt of the shipment, the laboratory should record the temperature on the chain-of-custody record.

Holding time refers to the period that begins when the sample is collected from the well and ends with its extraction or analysis. Holding time is not measured from the time the laboratory receives the samples.

7.6 Chain-of-Custody and Records Management

A chain-of-custody procedure should be designed to allow the owner/operator to reconstruct how and under what circumstances a sample was collected, including any problems encountered. Chapter One of SW-846 contains a complete description of chain-of-custody and records management. The chain-of-custody procedure is intended to prevent misidentification of the samples, to prevent tampering with the samples during shipping and storage, to allow easy identification of any tampering, and to allow for the easy tracking of possession.

7.6.1 Sample Labels

To prevent sample misidentification, the owner/operator should affix a label to each sample container. Sample labels should be sufficiently durable to remain legible even when wet. Sample labels should contain, at a minimum, the following information:

- Sample identification number;
- Name and signature of collector;
- Date and time of collection;
- Place of collection; and
- Parameters requested (if space permits).

The samples can be labeled by recording the above information directly on the sample containers. Alternatively, the owner/operator may use multiple-part labels consisting of a unique identification number that is placed on the container. At least two copies of the descriptive information for the samples (referenced to the identification number) should be made. One copy should be kept in a separate file or logbook, and a second copy should be shipped with the samples to the laboratory.

7.6.2 Sample Custody Seal

In cases where samples leave the owner/operator’s immediate control (e.g., shipment to laboratory), a custody seal should be placed on the shipping container or on the individual sample bottles. Custody seals provide prevention or easy detection of sample tampering. The custody seal should bear the signature of the collector and the date signed. The custody seal can be placed on the front and back of a cooler, around the opening of a polyethylene overpack bag or on the lid of each sample container. Caution should be exercised in doing any of the above. Experience has shown that the seal may not always adhere to plastic coolers, and that the coolers may arrive at the destination without the appropriate seal. Sometimes the sample containers become wet from melting ice or condensation; thus, while their labels will stick, their custody seals may not. Taping over the seal with a transparent tape generally solves this problem. A similar solution can be applied to the cooler lids.

7.6.3 Field Logbook

If a sample analysis produces an unexpected or unexplainable result, it will be necessary to determine if the circumstances of sample collection, rather than a change in the ground-water quality, are responsible. Examination of the field logbook is critical in this process. A field log should be kept each time ground-water monitoring activities are conducted in the field. The field logbook should document the following:

- Well identification;
- Well depth;
- Static water level depth and measurement technique;
- Presence and thickness of immiscible layers and detection method;
- Well yield (high or low) and well recovery after purging (slow, fast);
- Well purging procedure and equipment;
- Purge volume and pumping rate;
- Time well purged;
- Collection method for immiscible layers;

- Sample withdrawal procedure and equipment;
- Date and time of collection;
- Well sampling sequence;
- Types of sample bottles used and sample identification numbers;
- Preservatives used;
- Parameters requested for analysis;
- Field observations of sampling event;
- Name of collector;
- Weather conditions, including air temperature; and
- Internal temperature of field and shipping containers.

7.6.4 Chain-of-Custody Record

The tracing of sample possession will be accomplished by use of a chain-of-custody record as described in Chapter One of SW-846. A chain-of-custody record should be completed and should accompany every sample shipment. The chain-of-custody record should contain enough copies so that each person possessing the shipment receives his/her own copy. At a minimum, the chain-of-custody record should contain the following information:

- Sample number;
- Signature of collector;
- Date and time of collection;
- Sample type (e.g., ground water);
- Identification of sampling point (well);
- Number of containers;
- Analyses requested;

- Preservatives used;
- Signature of persons involved in the chain of possession;
- Inclusive dates and times of possession;
- Internal temperature of shipping container when samples were sealed into the container for shipping;
- Internal temperature of container when opened at the laboratory; and
- Remarks section to identify potential hazards or to relay other information to the laboratory.

7.6.5 Sample Analysis Request Sheet

The sample analysis request sheet should accompany the sample(s) on delivery to the laboratory and clearly identify which sample containers have been designated for each requested parameter. The sample analysis request sheet may be included in, or be a part of, the chain-of-custody record. The addition of preservatives should be noted on the sample analysis request sheet. The sample analysis request sheet should include the following information:

- Name of person receiving the sample;
- Name and addresses of analytical laboratory;
- Laboratory sample number (if different from field number);
- Date of sample receipt;
- Analyses requested;
- Internal temperature of shipping container upon opening in the laboratory; and
- Preservatives added in the field.

7.6.6 Laboratory Logbook

Once the sample has been received in the laboratory, the sample custodian and/or laboratory personnel should clearly document the processing steps that are applied to the sample. All sample preparation techniques and instrumental methods used should be identified in the laboratory logbook. Experimental conditions, such as the use of specific reagents, temperatures, reaction times, and instrument settings, should be noted. The results of the analyses of all laboratory quality control samples should be identified, specific to each batch of ground-water samples analyzed. The laboratory logbook should include the time, date, and name of the person who performed each processing step.

7.7 Analytical Procedures

The QAPjP submitted as part of the permit application should describe in detail the analytical procedures that will be used to determine the concentrations of constituents or parameters of interest. These procedures should include suitable analytical methods as well as proper quality assurance and quality control protocols. Minimum procedures specified in Chapter One of SW-846 for QAPjPs should be satisfied.

The QAPjP included as part of the permit application should identify an analytical method that will be used for each specific parameter or target analyte, and that can achieve the required detection limits. The following should be addressed:

- For SW-846 analytical methods, reference SW-846 and the analysis methods (by method number), including all sample preparation methods. For modified SW-846, or other standard methods, the analytical procedure and method detection limits to be used should be documented in the format of a Standard Operating Procedure (SOP).

- For analysis by non-SW-846 methods, the following should be provided:

    - approval of the Regional Administrator for standardized methods;

    - for EPA or standardized methods, a reference to the source of the method; and

    - for non-standard methods, a complete SOP with method detection limit should be included as an integrated part of the S&A program to be approved by the Regional Administrator and specified in the permit. Minimum procedures specified in Chapter One of SW-846 for QAPjPs should be satisfied.

7.8 Field and Laboratory Quality Assurance/Quality Control

One of the fundamental responsibilities of the owner/operator is the establishment of continuing programs to ensure the reliability and validity of field and analytical laboratory data gathered as part of the overall ground-water monitoring program. Chapter One of SW-846 provides guidance on establishing and maintaining field and laboratory quality control programs. Specifically, Chapter One of SW-846 provides guidance for the following areas:

- Control samples;
- Acceptance criteria;
- Deviations;
- Corrective action for sampling and analysis procedures;
- Data handling;
- Laboratory control samples;
- Method blanks; and
- Matrix-specific effects.

The owner/operator's QAPjP should explicitly describe the QA/QC program that will be used in the field and laboratory. The Data Quality Objectives (DQOs) of the project should be described in terms of precision, accuracy, completeness, representativeness and comparability for field activities (sampling, measurements, and screening) and laboratory analyses, including the project required acceptance limits and means to achieve these QA objectives. Chapter One of SW-846 provides a discussion of DQOs. The QAPjP should specify the preventative maintenance procedures that will be used for field and laboratory instruments and ground-water monitoring wells. A table showing the type of maintenance to be performed and the frequency is appropriate. Many owner/operators use commercial laboratories to conduct analyses of ground-water samples. When commercial laboratories are contracted by the owner/operator to analyze ground-water samples, the owner/operator's QAPjP should be used by the laboratory analyzing the samples for the owner/operator.

As described in Section 3.4.1 of Chapter One of SW-846, both field and laboratory QC samples should be prepared during the sampling event. Chapter One of SW-846 recommends that the following samples be analyzed with each batch of samples (a batch may not exceed 20 samples):

- One field duplicate;

- One equipment rinsate (required only when non-disposable equipment is being used);

- One matrix spike (when appropriate for the method); and

- One duplicate sample (either a matrix duplicate or a matrix spike duplicate).

Chapter One of SW-846 recommends that a trip blank be prepared and analyzed when samples are being analyzed for volatile organic analytes. A trip blank should be submitted with samples each day that samples are collected.

Section 4.4.3 of Chapter One of SW-846 also recommends that the matrix-specific detection limit be determined. This determination does not need to be made on a sample batch basis, but should be made whenever the matrix is suspected to have altered, or as frequently as necessary to document that the matrix has not altered. For an aquifer with relatively static hydrogeological characteristics, this may mean making a matrix-specific detection limit determination twice annually.

7.8.1 Field QA/QC Program

The owner/operator's QAPjP should provide for the routine collection and analysis of QC samples to verify that the sample collection and handling process has not affected the quality of the ground-water samples. All field QC samples should be prepared exactly as regular investigation samples with regard to sample volume, containers, and preservation. The concentrations of any contaminants found in blank samples should not be used to correct the ground-water data. The contaminant concentrations in blanks should be documented, and if the concentrations are more than an order of magnitude greater than the field sample results, the owner/operator should resample the ground water. The owner/operator should prepare the QC samples as recommended in Chapter One of SW-846, at the frequency recommended by Chapter One of SW-846, and analyze them for all of the required monitoring parameters. Other QA/QC practices such as sampling equipment calibration, equipment decontamination procedures, and chain-of-custody procedures are discussed in other sections of this Chapter and should be described in the owner/operator's QAPjP.

7.8.2 Laboratory QA/QC Program

The owner/operator's QAPjP should provide for the use of control samples, as defined in Chapter One of SW-846. The owner/operator should use appropriate statistical procedures to monitor and document performance and to implement an effective program to resolve testing problems (e.g., instrument maintenance, operator training). Data from control samples (e.g., spiked samples, duplicates, and blanks) should be used as a measure of performance or as an indicator of potential sources of cross-contamination. All QC data should be submitted to the Agency with the ground-water monitoring sample results. Chapter One of SW-846 provides guidance for laboratory QA/QC programs.

7.9 Evaluation of the Quality of Ground-Water Data

A ground-water sampling and analysis program produces a variety of hydrogeological, geophysical, and ground-water analytical data. This section pertains primarily to the evaluation of analytical data. These data are required by the Subpart F regulations to be evaluated using the statistical tests outlined in §264.97(h). The results of these tests provide the fundamental evidence used to determine whether the facility is contaminating the ground water. Details regarding the specific protocols of these procedures are discussed in "Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities," Interim Final Guidance (USEPA, 1989a) and any subsequent addenda to this guidance. The analytical data may be presented to the owner or operator via electronic transmittal or on reporting sheets. These data then should be compiled and statistically analyzed by the owner/operator prior to submission to the state or to EPA. If data are to be transmitted electronically, the owner/operator should discuss the procedures with EPA regional or state staff to ensure that all software and hardware being used are compatible.

The following guidelines should help to ensure that units of measure associated with data values are reported consistently and unambiguously:

- The units of measure should accompany each target analyte. Laboratory data sheets that include the statement "values are reported in ppm unless otherwise noted" are discouraged, and at least should be examined in detail by the technical reviewer. It is common to find errors in the units of measure on this type of data reporting sheet, especially when the reporting sheets have been prepared manually.

- The units of measure for a given target analyte should be consistent throughout the report.

Owner/operators should ensure that during chemical analysis, laboratory reporting, computer automation, and report preparation, data are generated and processed to avoid mistakes, and that data are complete and fully documented. Analytical data submitted to the Agency should contain the date/time the sample was collected, the date/time the sample was received by the laboratory, the date/time the sample was extracted, and the date/time the sample was analyzed.

APPENDIX 1

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APPENDIX 2

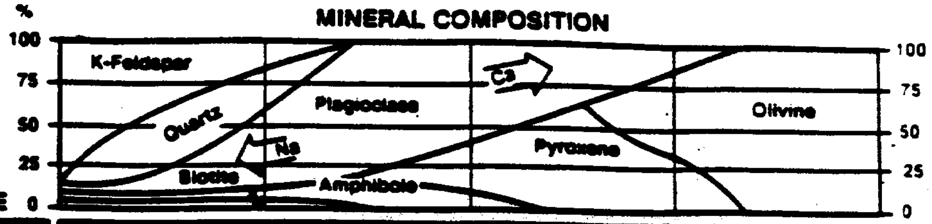
EXAMPLES OF CLASSIFICATION SCHEMES FOR IDENTIFICATION OF ROCK SAMPLES

November 1992

Percentage clay-size constituents			0-32	33-65	66-100
Field Adjective			Gritty	Loamy	Fat or Slick
NONINDURATED	Beds	Greater than 10 mm	BEDDED SILT	BEDDED MUD	BEDDED CLAYMUD
	Laminae	Less than 10 mm	LAMINATED SILT	LAMINATED MUD	LAMINATED CLAYMUD
INDURATED	Beds	Greater than 10 mm	BEDDED SILTSTONE	MUDSTONE	CLAYSTONE
	Laminae	Less than 10 mm	LAMINATED SILTSTONE	MUDSHALE	CLAYSHALE
METAMORPHOSED		Degree of metamorphism LOW	QUARTZ ARGILLITE	ARGILLITE	
		↓	QUARTZ SLATE	SLATE	
		HIGH	PHYLLITE AND/OR MICA SCHIST		

CLASSIFICATION OF SHALE (MORE THAN 50% GRAINS LESS THAN 0.062MM).
SOURCE: POTTER ET AL., 1980.

CLASSIFICATION OF IGNEOUS ROCKS

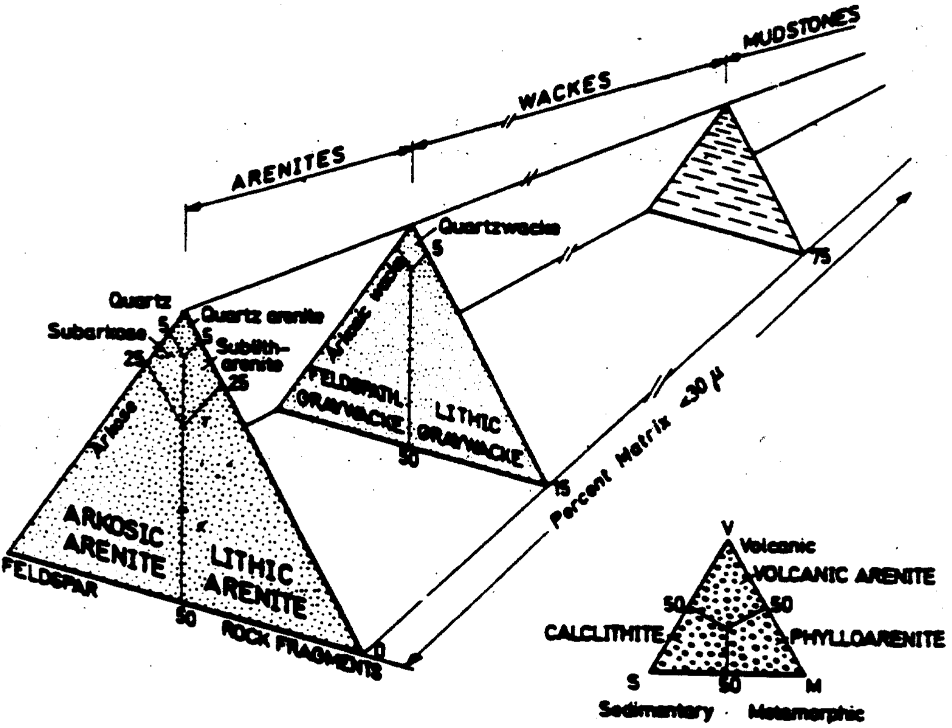


ORIGIN	TEXTURE				
EXTRUSIVE	APHANITIC	RHYOLITE	ANDESITE	BASALT	
INTRUSIVE	PHANERTIC	GRANITE	DIORITE	GABBRO	PERIDOTITE

SOURCE: HAMBLIN AND HOWARD (1975)

Depositional Texture recognizable					Depositional texture not recognizable
Original components not bound together during depositions				Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.	
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		Crystalline carbonate
Mud-supported		Grain-supported			
Less than 10% grains	More than 10% grains				(Subdivide according to classifications designed to bear on physical texture or diagenesis.)
Mudstone	Wackstone	Packstone	Grainstone	Boundstone	

CLASSIFICATION OF CARBONATE ROCKS ACCORDING TO DEPOSITIONAL TEXTURE



CLASSIFICATION OF TERRIGENOUS SANDSTONES
(MODIFIED FROM DOTT, 1964, FIG. 3)

APPENDIX 3

CHEMICAL RESISTANCE CHART SHOWING THE CHEMICAL EFFECT OF MANY CHEMICAL COMPOUNDS ON PVC, PTFE, AND STAINLESS STEEL

(MODIFIED FROM THE 1991-1992 CATALOG OF THE
COLE-PARMER INSTRUMENT COMPANY)

November 1992

Chemical resistance chart

Ratings-chemical effect

A - No effect - Excellent.
B - Minor effect - Good.
C - Moderate effect - Fair.
D - Severe effect - Not recommended.

Explanation of footnotes

1. Satisfactory to 72° F.
2. Satisfactory to 120° F.
3. Satisfactory for O-rings.

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Acetaldehyde	D	D	D	A	A	A	-	A
Acetamide	D	-	C	A	A	B	-	A
Acetate Solvent	D	-	A	A	A	A	A	A
Acetic Acid, Glacial	D	D	A^1	A	A	C	D	B
Acetic Acid 20%	D	C	A	A	A	B	D	A
Acetic Acid 80%	D	D	C	A	A	C	D	A
Acetic Acid	D	D	C	A	A	C	D	A
Acetic Anhydride	D	D	B^1	A	A	A	D	B
Acetone	D	D	D	A	A	A	B	A
Acetyl Bromide D	-	-	A	-	-	-	-	
Acetyl Chloride (dry)	C	D	A^2	A	A	A	-	D
Acetylene	A^1	-	A	A	A	A	A	A
Acrylonitrile	-	D	A^1	A	A^1	A^1	-	A
Alcohols: Amyl	A^2	-	A	A	A	A	-	A
Benzyl	D	D	A	A	A^1	A^1	-	B
Butyl	A^2	-	-	A	A	A	-	B
Diacetone	B^1	-	A^1	A	A	A	-	A
Ethyl	C	B	-	A	A	A	A	A
Hexyl	A^2	-	-	A	A	A	-	C
Isobutyl	A^1	B	-	A^2	A	A	-	A
Isopropyl	A^1	-	-	A^2	A	A	-	A
Methyl	A^1	D	A	A	A	A	A	B^1
Octyl	-	-	-	-	A	A	-	A
Propyl	A^2	A	A	A^2	A^1	-	C	B
Aluminum Chloride 20%	A^1	-	A	A	C^1	D	D	A
Aluminum Chloride	A^2	-	A	A	C^1	A^1	A^1	A
Aluminum Fluoride	A^2	-	A	A	C^1	B^1	D	A
Aluminum Hydroxide	A^2	-	A	A	C^1	A^1	A^1	A
Aluminum Potassium Sulfate 10%	A^2	-	B	A	B^2	C	B^1	A
Aluminum Potassium Sulfate 100%	A^2	-	-	A	B^2	C	D	A
Aluminum Sulfate	A^2	-	A	A	B^1	B	D	A
Alums	-	-	-	A	A	-	A	A
Amines	D	-	-	A^2	A	A	A	B
Ammonia 10%	B^1	-	A	A	A^1	A^1	A^1	A
Ammonia, anhydrous	A^2	-	A	A	A^1	A	A	A
Ammonia, liquid	A^2	-	A	A	A	B^2	B^2	A
Ammonia Nitrate	B	-	A	A	A	A	A	A
Ammonium Acetate	A	-	-	A	-	-	-	A
Ammonium Bifluoride	A^2	-	A	A	-	C	-	A^2
Ammonium Carbonate	A^2	-	A	A	B	B	B	A
Ammonium Caseinite	-	-	-	-	A	-	-	-
Ammonium Chloride	A^2	-	A	A	D	C	C	A
Ammonium Hydroxide	A	B	A	A	A^1	A^1	B	A
Ammonium Nitrate	A^2	-	A	A	A	A^1	A^1	A
Ammonium Oxalate	A	-	-	-	A	A	A	-
Ammonium Persulfate	A^2	-	A^1	A^1	B	A	A	A
Ammonium Phosphate, Dibasic	A^2	-	A	A^2	B	B	B	A
Ammonium Phosphate, Monobasic	A	-	-	A	C	B	B	A
Ammonium Phosphate, Tribasic	A	-	-	A	B	B	B	A
Ammonium Sulfate	A^2	-	A	A	B	B	B	A
Ammonium Thiosulfate	-	-	-	-	A	-	-	-
Amyl Acetate	C^1	-	A^2	A	A	A^1	B	A
Amyl Alcohol	A^2	-	A	A	A	A	-	A
Amyl Chloride	D	-	A	A	A^2	A^2	C^1	D
Aniline	C^1	D	A^1	A	B	A	B	B
Aniline Hydrochloride	D	-	-	A	D	D	D	B
Antifreeze	A	B	-	-	A	-	-	-
Antimony Trichloride	A^2	-	A	A	C^1	D	D	B^1
Aqua Regia (80% HCl, 20% HNO_3)	C^1	-	A^1	A	D	D	-	C
Arochlor 1248	-	-	-	A	B	B	-	B
Aromatic Hydrocarbons	D	-	-	-	C	-	-	D
Arsenic Acid	A^1	-	A	A	A^2	A^2	B	A^2
Arsenic Salts	A	-	-	-	-	-	-	-
Asphalt	A^2	-	-	A^1	A	B	B	D
Barium Carbonate	A^2	-	A	A	B	B^1	B^1	A
Barium Chloride	A^1	-	A	A	A^1	A^1	B	A
Barium Cyanide	D	-	-	A^1	A^1	A^1	-	A
Barium Hydroxide	A^2	-	A	A	B	B^1	B^1	A
Barium Nitrate	A	-	-	A^1	B	B^1	B	A
Barium Sulfate	B^1	-	A	A	B^1	B^1	B	A
Barium Sulfide	A^2	-	A	A	B^2	B^1	B^1	A
Benzaldehyde	D	B	A^2	A^1	B	B	-	A
Benzene	C	D	A^1	A	B	B	B	D
Benzene Sulfonic Acid	A	-	-	A	B	B	-	D
Benzoic Acid	A	-	A	A^2	B	B	B	D
Benzol	-	-	A	A	A^1	A^1	-	B
Bleaching Liquors	B	-	-	A	-	-	-	A
Borax (Sodium Borate)	B^1	-	A	A	A	A	A	A
Boric Acid	A^2	-	A	A	A^1	B^2	B	A
Brewery Slop	-	-	-	-	A	-	-	-
Bromine	C^1	D	A	A	D	D	D	D
Butadiene	C^1	-	A	A^2	A	A	A	C
Butane	C^1	B	A	A	A^2	A^2	A	D
Butanol (Butyl Alcohol)	B^1	-	-	A	A	C	-	A
Butylene	C^1	-	A	A	A	A	A	D
Butylacetate	D	-	B^2	A	A	B	B	B
Butyric Acid	B^1	D	B	A^2	B^2	B^2	C^1	B
Calcium Bisulfate	-	-	-	-	A	-	-	-
Calcium Bisulfide	A^1	-	-	A	B	B	-	C
Calcium Bisulfite	B	-	A	A	A	B	D	D
Calcium Carbonate	A^2	-	A	A	B	A^1	A	A
Calcium Chlorate	A^2	-	-	A	-	-	-	A
Calcium Chloride	A^2	B	A	A	B	C^1	C^1	A
Calcium Hydroxide	A^2	-	A	A	B	C	C	A
Calcium Hypochlorite	B^1	-	A	A	B	C	D	B^1
Calcium Oxide	B	D	-	A	A	A	-	A
Calcium Sulfate	A^1	C	A	A	B	B	B	A
Carbolic Acid (see Phenol)	C	-	A^2	A	B	B	B	B
Carbon Bisulfide	D	-	-	-	B	A	A	D
Carbon Dioxide	A	B	A	A	A^1	A	A	B
Carbon Dioxide (Dry)	A	B	A	A	A^1	A	A	B
Carbon Dioxide (Wet)	A	B	A	A	A^1	A	A	B
Carbon Disulfide	D	-	B^2	A	B	A^1	B	D
Carbon Monoxide	A^2	-	B	A	A	A	A	A
Carbon Tetrachloride	B^1	D	A	A	B	B	B	D
Carbonated Water	A	-	-	-	A	A	A	-
Carbonic Acid	A^2	-	A^1	A	A	A^1	B	A
Chloracetic Acid	B^1	-	A^1	A	A^1	-	D	B
Chlorobromomethane	D	-	-	A	-	-	-	B
Chloric Acid	A^1	-	-	A	C	D	D	-
Chlorinated Glue	-	-	-	-	A	-	-	B
Chlorine, anhydrous liquid	C^1	-	B	A	C	C^1	D	C
Chlorine, dry	A^2	-	A	A	B	C^1	C	A
Chlorine Water	A^2	-	B	A	C	C	D	C
Chlorobenzene (Mono)	D	D	A^1	A	A	D	A	D
Chloroform	D	D	A	A^1	A	B^1	A	D
Chlorosulfonic Acid	C	-	C^1	A	B^2	D	D	D
Chromic Acid 5%	A	B	A	A	A	B	B^1	A
Chromic Acid 10%	A^2	B	A	A	B	B	B^1	C
Chromic Acid 30%	C	C	A^2	A	B^2	B^1	C	B
Chromic Acid 50%	C^2	C	A^2	A	B^2	C^2	D	B
Chromium Salts	A	-	-	-	-	-	-	-
Citric Acid	B^2	C	A	A	A^2	B^2	C^2	A
Citric Oils	-	-	-	-	A	A	-	-
Clorox (Bleach)	A	B	-	A	A	A	-	B
Copper Chloride	A	-	-	A	D	D	B	A

Chemical resistance chart

Ratings-chemical effect

A - No effect - Excellent.
B - Minor effect - Good.
C - Moderate effect - Fair.
D - Severe effect - Not recommended.

Explanation of footnotes

1. Satisfactory to 72° F.
2. Satisfactory to 120° F.
3. Satisfactory for O-rings.

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Copper Cyanide	A^2	-	A	A	B	B	B	A
Copper Fluoborate	A	-	-	-	D	D	-	-
Copper Nitrate	B^2	-	A	A	B	A	B	-
Copper Sulfate 5%	A^2	-	A	A	B	B	B	A
Copper Sulfate >5%	A^2	-	A	A	B	B	B	A
Cresols	D	D	A^2	-	A	A^2	-	D
Cresylic Acid	C^1	-	B^1	A	A	A^1	A^1	D
Cyanic Acid	-	-	-	A	A	A	-	-
Cyclohexane	D	-	A	A	A	A	-	D
Cyclohexanone	D	D	B	A	A	A	-	C
Detergents	A	B	-	A	A^1	A^1	-	A
Diacetone Alcohol	D	-	-	A	A	A	-	A
Dichloroethane	D	-	A^1	A^1	B	B	-	-
Diesel Fuel	A^2	-	A	A	A	A	-	D
Diethylamine	D	-	A^1	A	B^1	-	A	B
Diethylene Glycol	A	B	-	A^2	A^2	A	A	A
Dimethyl Formamide	D	D	D	A	A	A	-	B
Diphenyl Oxide	D	-	B^2	A^1	B^1	B^1	A	D
Dyes	B	-	-	-	A	A	A	-
Epsom Salts (Magnesium Sulfate)	A^2	-	A	A	B	B^1	B	A
Ethane	D	-	A	A	A^1	-	A	D
Ethanolamine	D	-	C^1	A	A	A	A	B
$Ether^3$	D	-	B^1	A	B^1	B^1	B^1	C
Ethyl Acetate	C^1	C	A^1	A	B	B	B^1	B
Ethyl Chloride	D	D	A	A	A	A	A	A
Ethyl Sulfate	-	-	-	A	D	-	A	-
Ethylene Bromide	D	-	A	A	B	B	B	C
Ethylene Chloride	D	-	A	A	A^1	A^1	D	D
Ethylene Chlorohydrin	D	-	A	A	B		-	B
Ethylene Diamine	C	-	B	A	A	A	-	A
Ethylene Dichloride	D	D	A	A	A^1	A^1	A	C
Ethylene Glycol	A^1	B	A	A	A^1	A^1	B	A
Ethylene Oxide	C^1	-	A	A	C^1	C^1	-	C
Fatty Acids	B^1	-	A	A	A	B	B	D
Ferric Chloride	A^2	-	A	A	C^1	D	D	A
Ferric Nitrate	A^2	-	A	A	A^1	B^1	B^1	A
Ferric Sulfate	A^2	C	A	A	A^1	B	B	A
Ferrous Chloride	A^2	-	A	A	C^1	D	D	-
Ferrous Sulfate	A^2	-	A	A	B	B^1	B	A
Fluoboric Acid	A^2	-	A^1	A	C	B^1	-	A^2
Fluorine	D	-	A^1	A	C	C	C	A^1
Fluosilicic Acid	A^1	-	A^1	A	B^1	C	C	A^2
Formaldehyde 40%	A^1	-	A^2	A	A^1	A^1	B	A
Formaldehyde 100%	A	B	A	A	A	C	B	A
Formic Acid	A^1	B	A^2	A	C	B^1	B^1	A
Freon® 11	A^2	C	C	C	A	C	A	D
Freon 12	A^2	C	A	A	-	D	A	B
Freon 22	B	-	D	A	-	-	A	A
Freon 113	B	-	B	A	-	-	A	D
Freon TF	B	-	B	D	-	-	A	D
Fuel Oils	A^2	D	B	A	A	A	A	D
Furan Resin	A	-	D	A	A	A^1	A	C
Furfural	D	D	B^2	A	B	B	B	B
Gallic Acid	A^2	-	A^1	A	B	B	B	B
Gasoline	C^1	D	A	A	A	A	A	D
Glue, P.V.A.	C	-	-	A	A^2	A^1	A	A
Glycerin	A^1	C	A	A	A	A^2	A	A
Glycolic Acid	A^2	B	A^1	A	A	A	A	A
Gold Monocyanide	-	-	A	D	A	A	A	-
Heptane	C^1	D	A	A	A	A	A	D
Hexane	B^1	-	A	A	A	A	A	D
Hydraulic Oil (Petro)	A	-	A	A	A	A	A	D
Hydraulic Oil (Synthetic)	A	-	A	A	A	A	A	-

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Hydrazine	-	-	A	C	A	A	-	A
Hydrobromic Acid 20%	B^2	-	A	-	D	D	D	A
Hydrobromic Acid 100%	A^1	B	A	A	D	D	D	A
Hydrochloric Acid, Dry Gas	A^2	-	A	A	D	D	D	-
Hydrochloric Acid 20%	A^2	A	A	A	D	D	D	-
Hydrochloric Acid 37%	B	A	A	A	D	D	D	A
Hydrochloric Acid 100%	B^2	A	A	A	D	D	D	C
Hydrocyanic Acid	A^1	B	A	A	B^1	B^1	B^1	A
Hydrocyanic Acid (Gas 10%)	A	-	-	A	-	-	A	A
Hydrofluoric Acid 20%	B	C	A	A	D	D	D	A^1
Hydrofluoric Acid 50%	B^1	C	A	A	D	D	D	A^1
Hydrofluoric Acid 75%	C	C	A	A	D	D	D	C
Hydrofluoric Acid 100%	C	D	A	A	B^1	B^1	D	C
Hydrofluosilicic Acid 20%	A^2	-	A	A	B^1	C^2	D	A
Hydrofluosilicic Acid 100%	B^1	-	A^1	A	C^2	D	D	A
Hydrogen Gas	A^2	-	A	A	A	A	A	A
Hydrogen Peroxide 10%	A^1	A	A	A	B	B^1	B	-
Hydrogen Peroxide 30%	A^1	-	A	A	B	B^2	B	-
Hydrogen Peroxide 50%	A^1	-	A^1	A	A^2	B^2	B^1	-
Hydrogen Peroxide 100%	C^2	B	A^1	A	A^2	B^2	B^1	A
Hydrogen Sulfide (aqua)	B^1	B	A	A	C^1	C	C	A
Hydrogen Sulfide (dry)	A^2	-	A	A	B	C^1	C^1	A
Hydroquinone	B	D	-	A	-	-	-	D
Hydroxyacetic Acid 70%	D	-	A	-	-	-	-	A
Ink	C	B	A	D	C	C	-	-
Iodine	D	D	A^2	A	C	C	C	B
Iodine (in alcohol)	-	-	A	-	-	-	-	-
Iodoform	A	-	C	C	B	-	-	A
Isotane	A	-	A	-	-	-	A	-
Isopropyl Acetate	D	-	D	A	A	C	A	B
Isopropyl Ether	B	-	D	A^1	A	A	-	D
Jet Fuel (JP3, JP4, JP5)	A^1	-	A	A	A	A	A	D
Kerosene	A^2	D	A	A	A	A	A	D
Ketones	B	D	C^1	A	A	A	C	D
Lacquers	C	-	D	A	A	A^1	A	D
Lacquer Thinners	C	-	-	A	A	A^1	A	D
Latex	-	B	A	A	A^2	A^2	-	A
Lead Acetate	A^2	B	A	A	B	B	B	A
Lead Sulfamate	A^2	-	A	A^1	C	C	A	A
Ligroin	-	-	A	-	A	-	A	D
Lime	A^1	-	A	A^1	A	A	A	D
Lithium Hydroxide	-	-	-	A	B	B	B	-
Lubricants	B^2	-	A	A	A^2	A^2	A^2	D
Magnesium Carbonate	A^2	B	A	A^1	A^1	A^1	-	A
Magnesium Chloride	A^2	B	A	A	A^1	B	B	A
Magnesium Hydroxide	A^2	B	A	A	A^1	B	B	A
Magnesium Nitrate	A^2	B	A	A	A^1	A	A	A
Magnesium Oxide	-	-	-	-	A	-	A	-
Magnesium Sulfate	A^2	B	A	A	B	A	A	D
Maleic Acid	A^2	-	A	A	B	A	A	D
Maleic Anhydride	-	-	A	-	-	-	A	D
Malic Acid	A^2	-	A	A	A^2	A	B^1	D
Melamine	A^2	-	-	A	D	-	-	A
Mercuric Chloride (Dilute)	A^2	-	A	A	C	D	D	A
Mercuric Cyanide	B^2	-	A	A	B	B	D	-
Mercury	B	B	A	A	A	A	A	A
Methane	B	-	A	A	A	A	A	D
Methanol (Methyl Alcohol)	A^1	B	A	A	A	A	B	A
Methyl Acetate	D	-	D	A	A	A	-	B
Methyl Acrylate	-	-	D	-	-	-	A	B
Methyl Acetone	D	-	D	A	A	A	C	-
Methyl Alcohol 10%	A^1	-	A	A	A	A	B^1	A
Methyl Bromide	D	D	A	A	A	A	B	D

Chemical resistance chart

Ratings-chemical effect

A - No effect - Excellent. C - Moderate effect - Fair.
B - Minor effect - Good. D - Severe effect - Not recommended.

Explanation of footnotes

1. Satisfactory to 72° F.
2. Satisfactory to 120° F.
3. Satisfactory for O-rings.

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Methyl Butyl Ketone	A	-	D	-	A	-	B	A
Methyl Cellosolve	B[2]	-	A	A	A	A	C	B
Methyl Chloride	D	-	A	A	A	A	C	C
Methyl Dichloride	A	-	A	-	-	-	A	D
Methyl Ethyl Ketone	D	D	C[2]	A	A	A	B	A
Methyl Ethyl Ketone Peroxide	-	-	-	-	-	-	-	D
Methyl Isobutyl Ketone	D	D	D	A	A	A	-	B
Methyl Isopropyl Ketone	D	-	-	A	A	A	-	C
Methyl Methacrylate	-	-	D	-	-	-	A	D
Methylamine	A	-	-	A	A	-	A	A[1]
Methylene Chloride	D	D	B[2]	A	B	B	B	D
Mineral Spirits	A	D	-	A	A	A	A	D
Monoethanolamine	D	-	C	A	B	A	A	A
Naphtha	C	D	A	A	A	A	A	D
Naphthalene	D	D	A	A	A	A	A	D
Natural Gas	A	-	-	A	A	-	-	A
Nickel Chloride	A[2]	B	A	A	C	D	D	A
Nickel Sulfate	A[2]	B	A	A	B[1]	B	B	A
Nitrating Acid (≤15% H_2SO_4)	D	-	-	A	C	C	-	-
Nitrating Acid (≥15% H_2SO_4)	D	-	-	A	C	C	D	-
Nitrating Acid (≤1% Acid)	D	-	-	A	A	C	-	-
Nitrating Acid (≤15% HNO_3)	D	-	-	A	D	C	-	-
Nitric Acid (5-10%)	A[1]	B	A	A	A	A	B	B
Nitric Acid (20%)	A[1]	B	A	A	A	A	B	B
Nitric Acid (50%)	B[1]	C	A	A	A[1]	A	B	D
Nitric Acid (Concentrated)	D	D	A	A	A[1]	A	C	D
Nitrogen Fertilizer	-	-	-	A	-	-	-	-
Nitrous Acid	A	-	-	A	A	A	-	A
Nitrous Oxide	A	-	D	A	B	B	-	A
Nitrobenzene	D	D	A[1]	A	A	B	B	D
Oils: Aniline	D	D	A	A	A	A	A	B
Creosote	C	-	-	A	B	B	B	D
Diesel Fuel (20, 30, 40, 50)	A[2]	-	A	A	A	A	A	D
Fuel (1, 2, 3, 5A, 5B, 6)	A[2]	-	B	A	A	A	A	D
Hydraulic (see Hydraulic Oil)								
Mineral	A[1]	-	A	A	A	A	A	D
Silicone	A	-	A	A	A	B	A	A
Transformer	B	-	A	A	A	A	-	D
Turbine	A[1]	-	A	A	A	A	A	D
Oleic Acid	C[2]	D	A	A	B	B[1]	B[1]	B
Oleum 25%	D	-	C[1]	A	B	B[2]	A[2]	D
Oleum 100%	D	-	C[1]	A	B	B[2]	A[2]	D
Oxalic Acid (cold)	A[1]	A	A[2]	A[1]	B[1]	B	B	A
Paraffin	A[1]	-	A	A	A	A	A	D
Pentane	A	-	A	A	C	C	A	D
Perchloric Acid	A	-	A	A	-	-	-	B
Perchloroethylene	C[1]	-	A	A	A[1]	B[2]	A	D
Petroleum	B	-	A	C	A	-	A	A
Phenol (10%)	C[1]	-	A	A	B	B	B	B
Phenol (Carbolic Acid)	C[1]	D	A	A	B	B	B	B
Phosphoric Acid (≤40%)	B[2]	B	A	A	B	A	A[2]	B
Phosphoric Acid (>40%)	B[2]	C	A[1]	A	B	A[2]	B[2]	B
Phosphoric Acid Anhydride	-	-	D	-	-	-	-	-
Phosphoric Acid (crude)	B[2]	C	A	A	B	D	D	B
Phosphoric Acid (molten)	D	D	D	-	-	-	A	-
Photographic Developer	A	B	-	A	A	C	C	B
Phthalic Anhydride	D	-	A	A	A	A	A	A
Picric Acid	D	A	A[1]	A	B	B	B[1]	B
Plating Solutions								
Antimony Plating 130°F	A	-	A	A	A	A	B	-
Arsenic Plating 110°F	A	-	A	A	A	A	B	-

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Brass Plating:								
Regular Brass Bath 100°F	A	-	B	A	A	A	B	-
High Speed Brass Bath 110°F	A	-	B	A	A	-	B	-
Bronze Plating:								
Cu-Cd Bronze Bath R.T.	A	-	A	A	A	A	B	A
Cu-Sn Bronze Bath 160°F	D	-	A	A	A	A	C	A
Cu-Zn Bronze Bath 100°F	A	-	A	A	A	A	B	-
Cadmium Plating:								
Cyanide Bath 90°F	A	-	A	A	A	-	B	-
Fluoborate Bath 100°F	A	-	A	A	A	A	B	-
Chromium Plating:								
Chromic-Sulfuric Bath 130°F	A	-	C	A	C	-	D	-
Fluosilicate Bath 95°F	A	-	C	A	C	-	D	-
Fluoride Bath 130°F	A	-	C	A	D	-	D	-
Black Chrome Bath 115°F	A	-	C	A	C	-	D	-
Barrel Chrome Bath 95°F	A	-	C	A	D	-	D	-
Copper Plating (Cyanide):								
Copper Strike Bath 120°F	A	-	B	A	A	-	-	-
Rochelle Salt Bath 150°F	D	-	A	A	A	-	C	-
High Speed Bath 180°F	D	-	A	A	A	-	C	-
Copper Plating (Acid):								
Copper Sulfate Bath R.T.	A	-	A	A	D	-	D	-
Copper Fluoborate Bath 120°F	A	-	A	A	D	A	D	-
Copper Plating (Misc):								
Copper Pyrophosphate	A	-	A	A	A	-	B	-
Copper (Electroless)	A	-	A	A	-	-	B	-
Gold Plating:								
Cyanide 150°F	D	-	-	A	A	-	-	-
Neutral 75°F	A	-	-	A	C	-	-	-
Acid 75°F	A	-	-	A	C	-	-	-
Indium Sulfamate Plating R.T.	A	-	-	A	C	-	-	-
Iron Plating:								
Ferrous Chloride Bath 190°F	D	-	-	A	D	-	-	-
Ferrous Sulfate Bath 150°F	D	-	-	A	C	-	-	-
Ferrous Am Sulfate Bath 150°F	D	-	-	A	C	-	-	-
Sulfate-Chloride Bath 160°F	D	-	-	A	D	-	-	-
Fluoborate Bath 145°F	D	-	-	A	D	-	-	-
Sulfamate 140°F	A	-	-	A	D	-	-	-
Lead Fluoborate Plating	A	-	-	A	C	-	-	-
Nickel Plating:								
Watts Type 115-160°F	D	-	-	A	C	-	-	-
High Chloride 130-160°F	D	-	-	A	C	-	-	-
Fluoborate 100-170°F	A	-	-	A	C	-	-	-
Sulfamate 100-140°F	A	-	-	A	C	-	-	-
Electroless 200°F	D	-	-	A	-	-	-	-
Rhodium Plating 120°F	A	-	-	A	D	-	-	A
Silver Plating 80-120°F	A	-	-	A	A	-	-	A
Tin-Fluoborate Plating 100°F	A	-	-	A	C	-	-	-
Tin-Lead Plating 100°F	A	-	-	A	C	-	-	-
Zinc Plating:								
Acid Chloride 140°F	A	-	-	A	D	-	-	-
Acid Sulfate Bath 150°F	D	-	-	A	C	-	-	-
Acid Fluoborate Bath R.T.	A	-	-	A	C	-	-	-
Alkaline Cyanide Bath R.T.	A	-	-	A	A	-	-	-
Polish	C	-	-	-	A	A	-	-
Potassium Bicarbonate	A	C	B	A	B	B	B	-
Potassium Bromide	A	-	A	A	B	C	B	A
Potassium Carbonate	A	-	A	A	B[1]	B	B	A
Potassium Chlorate	A	-	A	A	B[1]	B	B	A
Potassium Chloride	A	C	A	A	B[1]	A[1]	B[1]	A
Potassium Chromate	A	-	B	A[1]	B[1]	B[1]	B[1]	A

Chemical resistance chart

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	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Potassium Cyanide Solutions	A	-	A	A	B^1	B^1	B^1	A
Potassium Dichromate	A	-	A	A	B	B^1	B	A
Potassium Ferrocyanide	B	-	A	A	B	B	C	A
Potassium Hydroxide (Caustic Potash)	A^1	C	A	A	B	B^1	B^1	A
Potassium Nitrate	A	-	A	A	B	B	B	A
Potassium Permanganate	A^1	C	A	A	B^1	B	B^1	A
Potassium Sulfate	A^2	-	A	A	B^1	B	B^1	A
Potassium Sulfide	A^2	-	-	A	A^1	B	B	A
Propane (liquified)	A^1	-	A	A	A	A	A	D
Propylene Glycol	C^1	B	-	A	B	B	-	-
Pyridine	D	-	C^2	A	A	A	B	B
Pyrogallic Acid	A	-	B	A	B^2	B	B	-
Rosins	C^1	-	-	-	A^1	A^1	B	-
Rust Inhibitors	-	-	-	-	A	A	-	-
Sea Water	A^2	-	A	A	A	C	C	A
Shellac (Bleached)	-	-	-	A	A	A	A	-
Shellac (Orange)	-	-	-	A	A	A	A	-
Silicone	A	-	-	A	A	B	-	A
Silver Bromide	-	-	-	A	A	D	D	-
Silver Nitrate	A^1	-	A	A	B	B	B	A
Soap Solutions	A	-	A^1	A	A	A^1	A	A
Soda Ash (see Sodium Carbonate)								
Sodium Acetate	B^1	-	A	A	B	B^1	B^1	A
Sodium Aluminate	-	-	-	A	A	A	-	A
Sodium Bicarbonate	A^2	B	A	A	B	A^1	B	A
Sodium Bisulfate	A^2	C	A	A	B^1	D	D	A
Sodium Bisulfite	A^2	B	A	A	B^1	B^1	C	A
Sodium Borate	A^2	-	A	A	B^2	C	A	A
Sodium Carbonate	A^2	C	A	A	A	B	B^1	A
Sodium Chlorate	A^1	-	A	A	B^1	B^1	B	A
Sodium Chloride	A^2	B	A	A	C	B	C	A
Sodium Chromate	-	-	-	A	B^1	B	B	-
Sodium Cyanide	A^2	-	A	A	A^1	B^1	A^1	A
Sodium Ferrocyanide	A	-	-	A	-	-	-	-
Sodium Fluoride	A^2	-	A	A^1	D	D	C^1	A
Sodium Hydrosulfite	C	-	-	A	-	-	-	-
Sodium Hydroxide (20%)	A	C	-	A	A	B^2	A^2	A
Sodium Hydroxide (50%)	A	C	A	A	B	B^1	B	A
Sodium Hydroxide (80%)	A	C	-	A^1	C	B^1	B	A
Sodium Hypochlorite (<20%)	A	-	A	A	C	C	D	B
Sodium Hypochlorite (100%)	C^2	-	A	A	D	D	D	B
Sodium Hyposulfate	-	-	-	A	A	A	-	-
Sodium Metaphosphate	B^2	-	-	A	A	A	B	A
Sodium Metasilicate	A	-	-	A	A	A	A	A
Sodium Nitrate	A^2	-	A	A	B^1	B^1	B^1	A
Sodium Perborate	A^2	-	-	A	B	B	B	A
Sodium Peroxide	B^2	-	A	A	A	A	B	A
Sodium Polyphosphate	A^1	-	A	A	B	B	B	A
Sodium Silicate	A^2	-	A	A	A	B	B	A
Sodium Sulfate	A^2	-	A	A	B	B^1	D	A
Sodium Sulfide	A^2	-	A	A	B	D	D	A

	PVC	Cycolac (ABS)	Kynar® (PVDF)	Teflon®	Stainless steel (316)	Stainless steel (304)	Stainless steel (440)	EPDM
Sodium Sulfite	A^2	-	A	A	B	A	C^1	A
Sodium Tetraborate	A^2	-	-	A	A^2	A	C	-
Sodium Thiosulfate (hypo)	A^2	-	A	A	A^2	B	C	A
Stannic Chloride	A^2	-	A	A	D	D	D	B
Stannic Fluoborate	-	-	-	-	A	-	-	-
Stannous Chloride	A^1	-	A	A	A^2	C^2	C^1	A
Stearic Acid	B^2	-	A	A	A	B	B	B
Stoddard Solvent	C^1	B	A	A	A	A	-	D
Styrene	D	-	-	A	A	A	-	D
Sulfate (Liquors)	B	-	A	A	B	B	A	A
Sulfur Chloride	C^1	-	A^1	A	D	D	D	D
Sulfur Dioxide	A^1	D	A	A	A^1	D	D	A
Sulfur Dioxide (Dry)	A^2	-	A	A	A	D	D	A
Sulfur Hexafluoride	B	-	-	-	-	-	-	A
Sulfur Trioxide	A	-	-	A	C	A	-	B
Sulfur Trioxide (Dry)	A^1	-	C^1	A	A	D	D	B
Sulfuric Acid (<10%)	A^1	B	A	A	A	D	D	B
Sulfuric Acid (10-75%)	A^1	B	A	A	D	D	D	B
Sulfuric Acid (75-100%)	D	-	A	A	D	C	D	B
Sulfuric Acid (Hot Conc)	D	-	C	A	C	D	B	D
Sulfuric Acid (Cold Conc)	D	-	A	A	B	C	C	B
Sulfurous Acid	A^2	-	A	A	B	B^1	B^1	B
Sulfuryl Chloride	-	-	-	A	-	-	-	-
Tannic Acid	A^1	-	B	A	A	B^1	B^1	A
Tanning Liquors	A^1	-	-	A	A^2	A^2	-	B
Tartaric Acid	A^1	-	B	A	C^2	C^2	C^1	B
Tetrachloroethane	C	-	A	A	A	B	-	-
Tetrachloroethylene	D	-	-	A	A	-	-	D
Tetrahydrofuran	D	-	B^1	A	A	A	-	B
Tin Salts	A	-	A	A	D	-	-	B
Toluene (Toluol)	D	D	A^1	A	A	A	A	D
Trichloroacetic Acid	B	-	B	A	C	D	D	B
Trichloroethane	C	-	A	A	A	B	-	D
Trichloroethylene	D	D	A^1	A	B	B^2	B	D
Trichloropropane	-	D	-	A^1	A	A	A	-
Tricresylphosphate	D	-	D	A	A^2	B	-	A
Triethylamine	A	-	A^2	A	A	-	-	-
Trisodium Phosphate	A	-	A	A	B	A	B	A
Turpentine	B^1	-	A	A	A	A	B	D
Urea	D	-	-	A	A	A	-	A
Varnish	D	-	-	A	A	A	A	D
Water, Acid, Mine	A^2	B	B	A	A	A	C	A
Water, Salt	A^2	-	A	A	B	B	C	A
Weed Killers	-	-	-	-	A	A	-	-
White Liquor (Pulp Mill)	A^2	-	A^1	A	A	B	-	-
White Liquor (Paper Mill)	A	-	-	-	A	A	-	-
Xylene	D	D	A	A	A	A	A	D
Zinc Chloride	A^2	-	A	A	D	D	D	A
Zinc Hydrosulfite	-	-	-	-	A	A	-	A
Zinc Sulfate	A^2	-	A	A	B	B^1	C^1	A

APPENDIX 4

SOURCES OF HYDROGEOLOGICAL INFORMATION

TABLE 1. INFORMATION SOURCES (modified from Waste Management, Inc., 1989)

GENERAL DATA SOURCES

Source	Information Obtainable	Comments
Libraries	Earth science bibliographic indices	Many of the types of information discussed below can be obtained from libraries. Excellent library facilities are available at the U.S. Geological Survey offices (USGS) in Reston, VA; Denver, CO; and Menlo Park, CA. Local university libraries can contain good collections of earth science and related information and typically are repositories for Federal documents. In addition, local public libraries normally have information on the physical and historical characteristics of the surrounding area.
Computer literature searches	Bibliographic indices	Perhaps one of the most useful and cost effective developments in the bibliographic indexes has been the increased availability of computerized reference searches. On-line computer searches save significant time and money by giving rapid retrieval of citations of all listed articles on a given subject and eliminate manual searching of annual cumulated indexes. A search is done by use of keywords, author names, or title words, and can be delimited by ranges of dates or a given number of the most recent or oldest references. The average search requires about 15 minutes of online searching and costs about $50 for computer time and offline printing of citations and abstracts.
Dialog Subscriptions and information: 1-800-3-DIALOG.	Accesses over 425 data bases from a broad scope of disciplines including such data bases as GEOREF and GEOARCHIVE.	Provides indexes to book reviews and biographes; directories of companies, people, and associations; and access to the complete text of articles from many newspapers, journals, and other original sources.
Master Directory (MD) User Support Office Suite 300 Hughes STX Corp. 7601 OraGlen Drive Greenbelt, MD 20771 (301) 513-1687 Span: BLAND NSSDCA. GSFC.NASA.GOV THIEMAN.NSSDCA. GSFC.NASA.GOV	The MD is a multidisciplinary data base that covers earth science (geology, oceanography, atmospheric science), space physics, solar physics, planetary science, and astronomy/astrophysics. It describes data generated by NASA, NOAA, USGS, DOE, EPA, and other agencies and universities, as well as international data bases.	MD is a free on-line data information service. Data available include personnel contact information, access procedures to other data bases, scientific campaigns or projects, and other data sources. Access Procedures: MD resides on a VAX at NSSDC and may be reached by several networks. MD is option #1 on the menu of NSSDC's On-line Data Information Services (NODIS) account. From span nodes: SET HOST NSSDA. USERNAME:NSSDC (no password). From Internet: TELNET NSSDCA.GSFC.NASA.GOV or TELNET 128.183.36.23. Via Direct Dial: Set modem to 8 bits, no parity, 1 stop bit, 300,1200 (preferable), or 2400 baud. Dial (301) 286-9000 ENTER NUMBER: MD, CALL COMPLETE: [CR], USERNAME: NSSDC (no password). For assistance or more information, contact the MD User Support Office (301) 513-1687.

Source	Information Obtainable	Comments
Alternative Treatment Technology Information Center (ATTIC) 4 Research Place Suite 210 Rockville, MD 20850 (301) 670-6294 (voice) (301) 670-3808 (on-line)	The ATTIC system is a collection of hazardous waste databases that are accessed through a computerized bulletin board system (BBS). The BBS features news items, bulletins, and special interest conferences. ATTIC users can access several databases including the ATTIC Database, which contains over 2,500 records dealing with alternative and innovative technologies for hazardous waste treatment; and the RREL Treatability Database, which provides data on characteristics and treatability of a wide variety of contaminants. Information from these sources consists of treatability information, case histories, transport and fate data, and other technical information. Also included are the abstracts of Superfund Innovative Technology Evaluation (SITE) reports, many Records of Decisions (RODs), State agency reports, international programs, and industry studies.	ATTIC is free of charge to all members of the federal, state and private sectors involved in site remediation. ATTIC can be accessed directly by a modem. Abstracts of reports can be downloaded from the system. Copies of complete reports are available on request. (Users register online the first time they access ATTIC.) A User's Manual is available and may be obtained by calling the ATTIC System Operator or leaving a message on the bulletin board.
Earth Science Data Directory (ESDD) U.S. Geological Survey (USGS) 801 National Center Reston, VA 22092 (703) 648-7112	ESDD is a data base that contains information related to the geologic, hydrologic, cartographic, and biological sciences.	Also included are data bases that reference geographic, sociologic, economic, and demographic information. Information comes from worldwide data sources and data includes that from NOAA, NSF, NASA, and EPA.
Local, State, Federal, and Regional Agencies	Site specific assessment data for dams, harbors, river basin impoundments, and Federal highways, soils, land use, flood plains, groundwater, aerial photographs, well records, geophysical borehole logs	Many states maintain a department of the environment or natural resources. Reports can be obtained by contacting the responsible agency. Surface water and geological foundation conditions such as fracture orientation, permeability, faulting, rippability, and weathered profiles are particularly well covered in these investigations.
University sources	Engineering and geology theses	College and university geology theses, in most instances, are well-documented studies dealing with specific areas, generally prepared under the guidance of faculty members having expertise in the subject under investigation. Most theses are not published.

Source	Information Obtainable	Comments
Comprehensive dissertation index	Doctoral dissertations	Citations began in 1861 and include almost every doctoral dissertation accepted in North America thereafter. The index is available at larger library reference desks and is organized into 32 subject volumes and 5 author volumes. Specific titles are located through title keywords or author names. Ph.D. dissertations from all U.S. universities are included.
AGI Directory of Geoscience Department	Faculty Members	Regular updates of faculty, specialties, and telephone date.
DATRIX II University Microfilms International 300 North Zeeb Rd. Ann Arbor, MI 48106 (800) 521-3042 ext. 732 (313) 761-4700 (in Alaska, Hawaii, and Michigan)	Dissertations and Masters theses	Using title keywords, a bibliography of relevant theses can be compiled and mailed to the user within two weeks. In addition, the DATRIX Alert system can automatically provide new bibliographic citations as they become available.
United States Geology: A Dissertation Bibliography by State	Ph.D. dissertation or Masters theses	Free index from University Microfilms International. Some universities do not submit dissertations to University Microfilms for reproduction or abstracting, however, and the dissertations from these schools do not appear in the United States Geology index. Citations for dissertations not abstracted must be located through DATRIX II or Comprehensive Dissertation Index.
Dissertation Abstracts International, Volume B - Science and Engineering, a monthly publication of University Microfilm International	Extended abstracts of dissertations from more than 400 U.S. and Canadian universities	Once the citation for a specific dissertation has been obtained from the Comprehensive Dissertation Index or from DATRIX II, the abstract can be scanned to determine whether it is relevant to the project at hand. Since some universities do not participate, some theses indexed in the two sources listed above must be obtained directly from the author or the university at which the research was completed. Abstracts of Masters theses available from University Microfilms are summarized in 150-word abstracts in Masters Abstracts and are indexed by author and title keywords. Both Dissertation Abstracts International and Masters Abstracts are available at many university libraries. A hard (paper) or microform (microfilm or microfiche) copy of any dissertation or thesis abstracted can be purchased from University Microfilms.

Source	Information Obtainable	Comments
USGS Publication Manuscripts System (PUBMANUS) Earth Science Information Center 507 National Center Reston, VA 22092 (703) 648-6045	This data base provides referral to all U.S. Geological Survey publications.	Flexible searching techniques enable users to find information in numerous ways. Currently, search requests are accepted through the USGS Earth Science Publication Office at no charge. (800) USA-MAPS. The "Guide to Obtaining USGS Information" (circular 900) is also an excellent source. It describes the services provided by USGS information offices. Includes addresses and telephone numbers, and lists types of publications and information products and their sources. Publication is free and may be ordered from USGS Book and Report Sales. This guide can be obtained from USGS, Book and Report Sales, Box 25286, Denver, CO 80225, (303) 236-7477.
U.S. Geological Survey (USGS) Earth Science Information Center (ESIC) Reston, VA (703) 648-6045 1-800-USA-MAPS	Detailed topographic, geologic, and hydrologic information is available from the USGS through the Earth Science Information Center. United States historical, physical divisions, Federal-aid highways, national atlas and scientific maps.	ESIC can be contacted to determine which map best meets your needs. Maps can be purchased from: USGS Map Sales Box 25286 Denver, CO 80225 (303) 236-7477
Electric Power Research Institute (EPRI) ATTN: EPRI Technical Information Specialists 3412 Hillview Ave. Palo Alto, CA 94304 (415) 855-2411 (510) 934-4212 (distribution center)	Up-to-date compilation of research relevant to utilities.	The EPRI manages a research and development program on behalf of the U.S. electric power industry. Its mission is to apply advanced science and technology to the benefits of its members and their customers.
RCRA/Superfund Hotline Office of Solid Waste (OS-305) U.S. EPA 401 M Street, SW Washington, DC 20460 (800) 424-9346 (toll free) (Washington, DC metropolitan area) (703) 920-9810	Information on RCRA, CERCLA, SARA, and UST statutes and corresponding regulations. Also provides document distribution service, including relevant Federal Register notices.	Team of information specialists maintains up-to-date information on the various regulations and rulemakings in progress. Hours of operation 8:30 a.m. to 7:30 p.m. (EST) Monday through Friday. Answer questions from wide range of callers - consultants, attorneys, generators, transporters, facility owner/operators, State and Federal regulatory agencies, trade associations, and the general public.

TOPOGRAPHIC DATA

Source	Information Obtainable	Comments
Branch of Distribution U.S. Geological Survey Maps Sales Box 25286, Federal Center Denver, CO 80225 (303) 236-7477	Index and quadrangle maps for the eastern U.S. and for states west of the Mississippi River, including Alaska, Hawaii, and Louisiana. Other scales are available.	A map should be ordered by name, series, and state. Mapping of an area is commonly available at two different scales. The quadrangle name is, in some instances, the same for both maps; where this occurs, it is especially important that the requestor specify the series designation, such as 7.5 minute (1:24,000), 15 minute (1:62,500), or two-degree (1:250,000).
Commercial map supply houses	Topographic and geologic maps.	Commercial map supply houses often have full state topographic inventories that may be out of print through national distribution centers.
Topographic Database National Geophysical Data at NOAA Code E/GCI 325 Broadway Boulder, CO 80303 (303) 497-6764	A variety of topography and terrain data sets available for use in geoscience applications.	The data were attained from U.S. government agencies, academic institutions, and private industries.
U.S. Geological Survey Topographic Map Names Database Attn. of Chief:GNIS USGS 523 National Center Reston, VA 22092 (703) 648-4544	This database contains descriptive information and official names for approximately 55,000 topographical maps prepared by the USGS, including out-of-print maps. Data includes the names of topographic maps, along with SE coordinates of the states in which they are located.	Printouts and searches are available on a cost recovery basis.
U.S. Geodata Tapes Dept. of the Interior Room 2650 18th & C Sts., NW Washington, DC 20240 (202) 208-4047	These computer tapes contain cartographic data in digital form. They are available in two forms. The graphic form can be used to generate computer-plotted maps. The topologically-structured form is suitable for input to geographic information system for use in spatial analysis and geographic studies.	Tapes are available for the entire US, including Alaska, and Hawaii, and are sold in 4 thematic layers: boundaries, transportation, hydrography and US Public Land Survey System. Each of the four layers can be purchased individually. US Geodata tapes can be ordered through Earth Science Information (ESIC) Center, as well as through the following ESIC offices. Anchorage, AK - (907) 786-7011; Denver, CO - (303) 236-7477 and 7476; Menlo Park, CA - (415) 329-4309; Reston, VA - (703) 860-6045; Rolla, MO - (314) 341-0851; Salt Lake City, UT - (801) 524-5652; Spokane, WA - (509) 456-2524; and Stennis Space Center, MS - (601) 688-3541 or (601) 353-2524.

Source	Information Obtainable	Comments
Geographic Information Retrieval and Analysis System (GIRAS) USGS Earth Science Information Center (ESIC) 507 National Center Reston, VA 22092 (800) USA-Maps (703) 648-6045	Land use maps, land cover maps, and associated overlays for the United States.	These maps have been digitized, edited and incorporated into a digital data base. The data is available to the public in both graphic and digital form. Statistics derived from the data are available also. Users are able to search for either locations or attributes. To obtain information from this data base, contact ESIC.
Topographic Maps Users Service Geographic Names Information System (GNIS) Reston, VA 22092 (703) 648-7112	Organized and summarized information about cultural or physical geographic entities.	GNIS provides a rapid means of organizing and summarizing current information about cultural or physical geographic name entities. The data base contains a separate file for each state, the District of Columbia, and territories containing all 7.5-min. maps published or planned.
Topography Data National Geophysical Data Center NOAA, Code E/GCI 325 Broadway Boulder, CO 80303 (303) 497-6764	This system contains a variety of topography and terrain data sets available for use in geoscience applications.	The data were obtained from U.S. Government agencies, academic institutions, and private industries. Data coverage is regional to worldwide; data collection methods encompass map digitization to satellite remote sensing.

GEOLOGIC DATA

Source	Information Obtainable	Comments
Geological Reference Sources: A Subject and Regional Bibliography of Publications and Maps in the Geological Sciences, Ward and others (1981)	Bibliographies of geologic information for each State in the U.S. and references general maps and groundwater information for many sites.	Provides a useful starting place for many site assessments. A general section outlines various bibliographic and abstracting services, indexes and catalogs, and other sources of geologic references.
A Guide to Information Sources in Mining, Minerals, and Geosciences, Kaplan (1965)	Describes more than 1,000 organizations in 142 countries. Its listings include name, address, telephone number, cable address, purpose and function, year organized, organizational structure, membership categories, and publication format. Federal and State agencies are listed for the U.S. as well as private scientific organizations, institutes, and associations.	An older useful guide. Part II lists more than 600 worldwide publications and periodicals including indexing and abstracting services, bibliographies, dictionaries, handbooks, journals, source directories, and yearbooks in most fields of geosciences.
Bibliography and Index of Geology	Includes worldwide references and contains listings by author and subject.	This publication is issued monthly and cumulated annually by the American Geological Institute (AGI), and replaces separate indexes published by the U.S. Geological Survey through 1970 (North American references only) and the Geological Society of America until 1969 (references exclusive of North America only). Both publications merged in 1970 and were published by the Geological Society of America through 1978, when AGI continued its publication.
KWIC (Keyword-in-Contents) Index of Rock Mechanics Literature	Engineering geologic and geotechnical references.	The KWIC index is available in two volumes at many earth science libraries (Hoek, 1969; Jenkins and Brown, 1979).
GEODEX Retrieval System with Matching Geotechnical Abstracts GEODEX International, Inc. P.O. Box 279 Sonoma, CA 95476	Engineering geological and geotechnical references.	The GEODEX is a hierarchically organized system providing easy access to the geotechnical literature and can be used at many university libraries. The GEODEX system can be purchased on a subscription basis.

Source	Information Obtainable	Comments
U.S. Geological Survey Branch of Distribution 604 S. Pickett St. Alexandria, VA 22304	The U.S. Geological Survey (USGS) produces annually a large volume of information in many formats, including maps, reports, circulars, open-file reports, professional papers, bulletins, and many others.	To simplify the dissemination of this information, the USGS has issued a Circular (No. 777) entitled A Guide to Obtaining Information from the USGS (Clarke, et al., 1981).
U.S. Geological Survey Library Database USGS Main Library National Center MS 950 12201 Sunrise Valley Drive Reston, VA 22092 (703) 648-4302	The Reston library contains more than 800,000 monographs, serials, maps, and microforms covering chemistry, environmental studies, geology, geothermal energy, mineralogy, oceanography, paleontology, physics, planetary geology, remote sensing, soil science, cartography, water resources, and zoology.	This library system is one of the largest earth science libraries in the world. Library staff and users may access the online catalog from terminals at each of the 4 USGS libraries. The data base can be searched by author, title, key words, subjects, call numbers, and corporate/conference names. The general public is welcome to conduct literature searches using various data bases. Regional libraries are located in Denver, CO; Flagstaff, AZ; and Menlo Park, CA.
Geologic Names of the United States (GEONAMES) Geologic Division USGS 907 National Center Reston, VA 22092	GEONAMES is an annotated index of the formal nomenclature of geologic units of the United States. Data includes distribution, geologic age, USGS usage, lithology, thickness, type locality, and references.	Printouts are not available. Diskettes containing data for 2 or more adjacent states are available from USGS Open-File and Publications, Box 25425 Federal Center, Denver, CO 80225. Magnetic tapes can be obtained from NTIS.
USDA Soil Conservation Service (202) 720-1820	Soil maps and description are available for about 75% of the country through the U.S. Soil Conservation Service office located in each state capital.	

GEOPHYSICAL DATA

Source	Information Obtainable	Comments
U.S. Geological Survey Water Supply Papers	The most common types of geophysical data are available from seismic and resistivity surveys.	Water Supply Papers for an area can be located by any of the computer searches or published indexes described in the first section of this paper. In addition, the USGS also publishes geophysical maps of various types at relatively small scales for many areas of the U.S. Aeromagnetic maps have been completed for much of the U.S., although the flight altitude of several thousand meters and scale of 1:24,000 make these maps too general for most site specific work.
Well Log Libraries Electric Log Services P.O. Box 3150 Midland, TX 79702 Tel: (915) 682-7773	Electric logs for many petroleum wells can be obtained from one of several well log libraries in the U.S.	The geophysical logs are indexed by survey section. To obtain information on wells in a given area, it is necessary to compile a list of the townships, ranges, and section numbers covering the area.
Geophysical Survey Firms	Specific geophysical logs	Proprietary geophysical data can sometimes be obtained from private survey firms. In general, the original client must approve the exchange of information, and preference is given for academic purposes. If the information cannot be released, firms may be willing to provide references to published information they obtained before the survey, or information published as a result of the survey.
NOAA National Geophysical Data Center (NGDC) Chief, Solid Earth Geophysics 325 Broadway Boulder, CO 80303 (303) 497-6521 Fax (303) 497-6513	NGDC maintains a computer database which contains information on earthquake occurrences from prehistoric times to the present. Historic U.S. earthquakes are included for the period starting in 1638. NGCD also maintains databases on other parameters, such as topography, magnetics, gravity, and other topics.	Site studies for many projects now require information regarding the seismicity of the region surrounding the site. The National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) is a focal point for dissemination of earthquake data and information for both technical and general users, except for information on recent earthquakes. (Information about recent earthquakes can be obtained by contacting the USGS.) For a fee, a search can be made for one of the following parameters: - Geographic area (circular or rectangular area) - Time period (staring 1638 for U.S.) - Magnitude range - Date - Time - Depth - Intensity (Modified Mercalli)

Source	Information Obtainable	Comments
Geomagnetism (GEOMAG) Branch of Global Seismology and Geomagnetism USGS Box 25046 Federal Center Mail Stop 968 Denver, CO 80225 (303) 273-8440 or (303) 273-8441	GEOMAG contains current and historical magnetic-declination information for the United States. It provides historical and current values of declination.	Current or historical values back to 1945 can be obtained over the telephone at no charge by calling (800) 358-2663. To access the full program via modem, contact the listed office for hook-up instructions. There is no subscription fee.

Source	Information Obtainable	Comments
USGS Earth Resources Observation Systems (EROS) Data Center User Service EROS Data Center U.S. Geological Survey Sioux Falls, SD 57198 (605) 594-6151	The EROS Program provides remotely-sensed data. To obtain publications, request further information, or place an order, contact the EROS Data Center.	The EROS Data Center, near Sioux Falls, South Dakota, is operated by the USGS to provide access primarily to NASA's Landsat imagery, aerial photography acquired by the U.S. Department of the Interior, and photography and multi-spectral imagery acquired by NASA from several satellite data systems sources. The primary functions of the Data Center are data storage and reproduction, user assistance, and training.
Landsat Data	Landsat satellites sensor images are found in spectral bands: - Band 4 (emphasizes sediment-laden and shallow water) - Band 5 (emphasizes cultural features) - Band 6 (emphasizes vegetation, land/water boundaries, and landforms) - Band 7 (as above, with best penetration of haze) - Band 5 gives the best general-purpose view of the earth's surface. Black and white images and false-color composites are available.	The Landsat satellites were designed to orbit the earth about 14 times each day at an altitude of 920 km, obtaining repetitive coverage every 18 days. The primary sensor aboard the satellites is a multi-spectral scanner that acquires parallelogram images 185 km per side in four spectral bands.
NASA Aerial Photography	Photography is available in a wide variety of formats from flight at altitudes ranging from one to 18 km. Photographs generally come as 230 mm by 230 mm prints at scales of 1:60,000 or 1:120,000, and are available as black and white, color, or false-color infrared prints.	NASA aerial photography is directed at testing a variety of remote-sensing instruments and techniques in aerial flights over certain preselected test sites over the continental U.S.
Aerial Mapping Photography	Aerial photography coverage obtained by the USGS and other Federal agencies (other than the Soil Conservation Service) for mapping of the U.S. is available as 230 mm by 230 mm black and white prints which are taken at altitudes of 600 m to 12 km. Scales range from 1:20,000 to 1:60,000.	Because of the large number of individual photographs needed to show a region on the ground, photomosaic indexes are used to identify photographic coverage of a specific area. The Data Center has more than 50,000 such mosaics available for photographic selection.

Source	Information Obtainable	Comments
Aerial Photography Field Office U.S. Department of Agriculture P.O. Box 30010 Salt Lake City, UT 84130 (801) 975-3503	Conventional aerial photography scales of 1:20,000 to 1:40,000.	Aerial photographs by the various agencies of the U.S. Department of Agriculture (Agricultural Stabilization and Conservation Service [ASCS], Soil Conservation Service [SCS], and Forest Service [USFS]) cover much of the U.S.
Photogrammetry Division of NOAA National Oceanic and Atmospheric Administration 6001 Executive Blvd. Rockville, MD 20852 (301) 443-8601 FTS 443-8601	The Coastal Mapping Division of NOAA maintains a file of color and black and white photographs of the tidal zone of the Atlantic, Gulf, and Pacific coasts. The scales of the photographs range from 1:20,000 to 1:60,000.	An index for the collection can be obtained by contacting the Coastal Mapping Division at (301) 443-8601 or the address listed.
U.S. Bureau of Land Management Aerial Photo Section Slyia Gorski (SC-67-C) P.O. Box 25047 Building 46 Denver, CO 80225-0047 (303) 236-7991	The Bureau of Land Management has aerial photographic coverage of over 50 percent of its lands in 11 western states.	For an index of the entire collection contact the U.S. Bureau of Land Management at (303) 236-7991 or the address listed.
National Archives and Records Admin. Cartographic and Architectural Branch 8 Pennsylvania Ave., N.W. Washington, DC 20408 (703) 756-6700	Airphoto coverage from the late 1930's to the 1940's obtained for portions of the U.S. Also, foreign airphoto coverage for the World War II period is available.	This service may be important for early documentation of site activities.
National Air Photograph Library 615 Booth St. Ottawa, Ontario K1A 0E9 Canada (613) 995-4560 Fax (613) 995-4568		Canadian airphoto coverage can be obtained from the National Aerial Photograph Library at (613) 995-4560 or the address listed.
Canada Center for Remote Sensing 588 Booth Street Ottawa, Ontario K1A 0W7 Canada (613) 990-8033		Canadian satellite imagery can be obtained from the Canada Center for Remote Sensing at (613) 990-8033 or from the address listed.
Commercial Aerial Photo Firms American Society for Photogrammetry and Remote Sensing 5410 Grosvenor Lane Suite 210 Bethesda, MD 20814 (301) 493-0290		In many instances, these firms retain the negatives for photographs flown for a variety of clients and readily sell prints to any interested users. For a listing of nearby firms specializing in these services, consult the yellow pages.

HYDROLOGIC DATA

Source	Information Obtainable	Comments
Water Publications of State Agencies, Giefer and Todd (1972, 1976)	This book lists state agencies involved with research related to water and also lists all publications of these agencies. In general, hydrologic data can be classified into four primary categories: stream discharge, stream water quality, groundwater level, and groundwater quality.	The trend for the past decade has been to compile such basic data in computerized data banks, and a number of such information systems are now available for private and public users. Many data now collected by Federal and state water-related agencies are available through computer files, but most data collected by private consultants, local and county agencies, and well drilling contractors remain with the organization that gathered them.
Local Assistance Center of the National Water Data Exchange (NAWDEX) U.S. Geological Survey 421 National Ctr. Reston, VA 22092 (703) 648-5663	NAWDEX identifies organizations that collect water data, offices within these organizations from which the data may be obtained, alternate sources from which an organization's data may be obtained, the geographic areas in which an organization collects data, and the types of data collected. Information has been compiled for more than 1,700 organizations, and information on other organizations is added continually. More than 450,000 data collection sites are indexed.	NAWDEX, which began operation in 1976 and is administered by the U.S. Geological Survey consists of a computer directory system which locates sources of needed water data. The system helps to link data users to data collectors. For example, the NAWDEX Master Water Data Index can identify the sites at which water data are available in a geographic area, and the Water Data Sources Directory can then identify the names and addresses of organizations from which the data may be obtained. In addition, listings and summary counts of data, references to other water data systems, and bibliographic data services are available.
WATSTORE Branch of Computer Technology USGS Reston, VA 22092 (703) 648-5686	WATSTORE maintains the storage of: 1) surface-water, quality-of-water, and ground-water data measured on a daily or a continuous basis; 2) annual peak values of stream flow stations; 3) chemical analyses for surface- and ground-water sites; 4) water-data parameters measured more frequently than daily; 5) geologic and inventory data for ground-water sites; and 6) summary data on water use.	Data can be retrieved in machine-readable form or as computer printed tables or graphs, statistical analyses, and digital plots. To retrieve WATSTORE data, contact: National Water Data Exchange (NAWDEX) Branch of Computer Technology USGS Mail Stop 421 Reston, VA 22092 (703) 648-5664

Source	Information Obtainable	Comments
Published Water-Supply Studies and Data	Stream discharge, groundwater level, and water quality data have been obtained during short-term, site-specific studies, and these data are typically available only in published or unpublished site reports. Data related to lakes, reservoirs, and wetlands are commonly found only in such reports.	Although significant progress has been made in computerizing surface- and groundwater data, the majority remains available only through published and unpublished reports.
Catalog of Information on Water Data	The reference consists of four parts: - Part A: Stream flow and stage - Part B: Quality of surface water - Part C: Quality of groundwater - Part D: Aerial investigations and miscellaneous activities.	Bibliographic publication indexes USGS sampling and measurement sites throughout the U.S. Maps are available that show a distinct numeric code assigned to each river basin and provide information on drainage, culture, hydrography, and hydrologic boundaries for each of the 21 regions and 222 subregions designated by the Water Resources Council. They also depict the boundaries and codes of 352 accounting units within the National Water Data Network and approximately 2,100 cataloging units of survey's Catalog of Information on Water Data.
Geologic and Water-Supply Reports and Maps (available for each state)		This publication lists references for each USGS division for each state or district, the listing, however, is by report number, requiring a scan of the entire list for information on a particular area.
Water Resources Investigations, by State Office of Water Data U.S. Geological Survey 417 National Ctr. 12201 Sunrise Valley Drive Reston, VA 22092	Listed are all agencies cooperating with the USGS in collecting water data, information on obtaining further information, and a selected list of references by both the USGS and cooperating agencies.	This booklet describes the projects and related publications for all current USGS work in a state or group of states. Also available is a useful summary folder with the same title that depicts hydrologic-data stations and hydrologic investigations in a district as of the date of publication. Additional assistance can be obtained by contacting: Hydrologic Information Unit, U.S. Geological Survey, 420 National Center, 12201 Sunrise Valley Drive, Reston, VA 22092.
Federal Flood Insurance Studies	To meet the provisions of the National Flood Insurance Act of 1968, the USGS, with funding by the Federal Insurance Administration, has mapped the 100-year floodplain of most municipal areas at a scale of 1:24,000.	Floodplain maps can be obtained from the nearest district office of the USGS and commonly from other agencies, such as the relevant city, town, or county planning office, or the Federal Insurance Administration. In some areas, more detailed "Flood Insurance Studies" have been completed for the Federal Emergency Management Agency; these maps include 100-year and 500-year floodplain maps. The complete studies are available at the nearest USGS office, the relevant city, town, or county planning office, or the Federal Emergency Management Agency.

Source	Information Obtainable	Comments
National Stream Quality Accounting Network (NASQAN) USGS Branch of Distribution 1200 South Ends St. Arlington, VA 22202	Regional and nationwide overview of the quality of our streams.	Consists of over 400 sampling sites. Data collection sties are located at or near the downstream end of hydrologic accounting units or at representative sites along coastal areas and Great Lakes.
Office of Water Data Coordination (OWDC) USGS 417 National Center Reston, VA 22092 (703) 648-5016	Publications including the "National Handbook of Recommended Methods for Water-Data Acquisition," indexes to the "Catalog of Information on Water Data," and other publications.	OWDC is the focal point for inter-agency coordination of current and planned water-data acquisition activities of all Federal agencies and many non-Federal organizations.
National Ground Water Information Center (National Ground Water Association) 6375 Riverside Drive Dublin, OH 43017 (800) 332-2104 (614) 761-3446 (fax)	Computerized, on-line bibliographic database that provides a variety of information on the quantity and quality of ground water resources worldwide. Also includes references on such ground water topics as ground water protection, waste remediation, well design and construction, drilling methods, water treatment, and flow and contaminant transport models. Photocopying service of most database references and interlibrary loan service available. Public information brochures on ground water available.	Databases are accessible through computer, modem, and telecommunications software. Members and nonmembers can gain access. Abstracts are relatively short and nontechnical.

CLIMATIC DATA

Source	Information Obtainable	Comments
National Climatic Data Center (NCDC) Federal Building 37 Battery Park Ave. Asheville, NC 28801-2733 (704) 259-0682 or (703) 259-0871	Readily available are data from the monthly publication *Climatological Data*, which reports temperature and precipitation statistics for all monitoring stations in a given state or region. An annual summary is also available.	The National Climatic Data Center (NCDC) collects and catalogs nearly all U.S. weather records. Climatic data (which are essential for construction planning, environmental assessments, and conducting surface and groundwater modeling) can be obtained from the NCC.
	In addition to collecting basic data, NCDC provides the following services:	NCC can provide data on file in hard (paper) copy, in microfiche, on magnetic tape, and on diskette.
	- Supply of publications, reference manuals, catalog of holdings, and data report atlases - Data and map reproduction in various forms - Analysis and preparation of statistical summaries - Evaluation of data records for specific analytical requirements - Library search for bibliographic references, abstracts, and documents - Referral to organizations holding requested information - Provision of general atmospheric sciences information.	For general summary statistics and maps, the publication *Climates of the States - NOAA Narrative Summaries, Tables, and Maps for Each State*, by Gale Research Company (1980) is helpful.