United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/625/R-93/003a
May 1993

EPA

Subsurface Characterization and Monitoring Techniques

A Desk Reference Guide

Volume I: Solids and Ground Water Appendices A and B

Technology Transfer EPA/625/R-93/003a

SUBSURFACE CHARACTERIZATION AND MONITORING TECHNIQUES:

A DESK REFERENCE GUIDE

Volume I: Solids and Ground Water
Appendices A and B

May 1993

Prepared by:

Eastern Research Group, Inc.
110 Hartwell Avenue
Lexington, MA 02173

Prepared for:

Center for Environmental Research Information
U.S. Environmental Protection Agency
26 West Martin Luther King Drive
Cincinnati, OH 45268

Environmental Monitoring Systems Laboratory
U.S. Environmental Protection Agency
Las Vegas, NV 89193-3478

CONTENTS

VOLUME I: SOLIDS AND GROUND WATER

VOLUME II: THE VADOSE ZONE, FIELD SCREENING, AND ANALYTICAL METHODS

NOTICE

This document has been reviewed in accordance with the U.S. Environmental Protection Agency's (EPA's) peer and administrative review policies. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is not intended to be a guidance or support document for a specific regulatory program. Guidance documents are available from EPA and must be consulted to address specific regulatory issues.

ACKNOWLEDGEMENTS

This document was prepared for EPA's Center for Environmental Research Information (CERI), Cincinnati, Ohio, and has benefitted from the input of the reviewers listed below. Every effort has been made to provide comprehensive coverage and up-to-date information. Due to the large number of techniques and references in this guide, errors or omission in citations might have occurred. These errors are the responsibility of the author, who would appreciate being informed of the need for any corrections or additions at the address indicated below.

Author:

J. Russell Boulding, Eastern Research Group, Inc. (ERG), 4664 N. Robs Lane, Bloomington, IN 47408

Project Management:

Susan Schock, EPA CERI, Cincinnati, OH
Heidi Schultz, ERG, Lexington, MA

Editing and Production:

Anne Donovan, ERG, Lexington, MA

Technical Reviewers (Chapters and appendices reviewed noted in parentheses):

Frederick Cornell, Environmental Liability Management, Princeton, NJ (10)
Lawrence Eccles, U.S. EPA, EMSL, Las Vegas, NV (9)
Lorne Everett, Metcalf and Eddy, Santa Barbara, CA (6,9)
Peter Haeni, U.S. Geological Survey, Hartford, CT (1)
Jan Hendrickx, Department of Geosciences, New Mexico Tech, Socorro, NM (4,7)
Paul C. Heigold, Illinois State Geological Survey, Champaign, IL (1,3)
Beverly Herzog, Illinois State Geological Survey, Champaign, IL (4,5,6,7,9,A)
David Kaminski, QED Ground Water Specialists, Walnut Creek, CA (5)
Peter Kearl, Oak Ridge National Laboratory, Grand Junction, CO (7,8)
Jack Keeton, U.S. Army Corps of Engineers, Omaha, NE (A)
W. Scott Keys, Geokeys, Inc., Longmont, CO (Tables 3-1 and 3-2)
Eric Koglin, U.S. EPA, EMSL, Las Vegas, NV (10)
Mark Kram, NEESA, Port Hueneme, CA (10)
Robert Powell, U.S. EPA, RSKERL, Ada, OK (5,B)
Robert Puls, U.S. EPA, RSKERL, Ada, OK (5,B)
James Quinlan, Nashville, TN (4)
Charles Riggs, Sverdrup Environmental, St. Louis, MO (2)
Ronald Schalla, Battelle Pacific Northwest Laboratory, Richland, WA (A,B)
Ronald Sims, Utah State University, Logan, UT (2,6,7,8,C,D)
James Ursic, U.S. EPA, Region 5 (1,3)
Mark Vendl, U.S. EPA, Region 5 (1,3)
John Williams, U.S. Geological Survey, Albany, NY (3)

American Geophysical Union, Washington, DC (Water Resources Research): Figure 1.6.2.

American Petroleum Institute, McLean, VA: from API Publication 4367, Figures 5.1.4c, 5.2.4, 5.3.1, 5.3.2a, 5.3.3c, 5.4.1, and 5.7.2c.

American Society for Testing and Materials (ASTM), Philadelphia, PA: Figures 1.3.5, 3.4.6, 5.5.2a and b, 5.6.2b, and A.1.

American Society of Agronomy/Soil Science Society of America, Madison, WI: Figures 1.6.3, 4.2.1b, 4.2.2, 4.2.3, 6.1.4b, 6.1.7, 6.2.4, 6.2.6, 6.2.7, 6.3.3b, 7.1.1, 7.2.1, 7.2.4, 7.2.2, 7.2.3, 7.2.6, 7.3.2, 7.3.5, 7.3.6, 7.3.7, 7.3.8, 7.5.4, 8.3.1d, 8.3.5a, 9.1.2a, 9.1.3, 9.2.5, 9.2.7, 9.4.4, 9.4.5a, 9.5.2, 10.3.5, 10.6.3, and 10.6.4.

American Society of Civil Engineers, New York, NY: Figures 1.4.4b and 3.4.4d.

American Water Resources Association, Bethesda, MD: Figure 9.3.2.

Electric Power Research Institute, Palo Alto, CA: Figures 1.2.2a and b, 1.4.6, 1.5.3, 1.5.1a, 2.3.2a and b, 2.3.3a, 2.4.1, 2.4.2, 3.4.4, 4.1.1, 4.1.3, 4.1.4, 4.1.6, 4.1.7, 5.5.3, 6.2.2b, and 7.3.4.

Elsevier Science Publishers, Amsterdam, The Netherlands (Journal of Hydrology): Figure 9.3.1.

Ground Water Publishing Company (formerly Water Well Journal Publishing Company), Dublin, OH: Figures 1.3.1c, 1.3.4, 1.4.2, 1.4.3a, 2.1.5b, 2.2.2a, 2.4.4, 3.5.7, 3.6.2b, 4.4.5b, 5.2.1d, 5.2.3, 5.5.1, 5.5.2c, 7.3.3, 9.2.1b, 9.4.2c, 9.4.5a, A.5b, and B.2a.

Hazardous Materials Control Research Institute, Greenbelt, MD: Figures 3.4.5a-c, 10.2.3b, and 10.3.4c.

International Association of Hydrogeologists/Verlag Heinz Heise, Hannover, Germany: Figures 3.1.3, 3.5.1, and 3.5.3.

John Wiley & Sons, Inc., New York, NY: Figures 2.1.4, 8.3.7, and 3.6.2a.

Johnson Filtration Systems/Wheelabrator Engineered Systems, St. Paul, MN: Figures 2.1.2a, 10.6.2, and Table 2-2.

Lewis Publishers, a subsidiary of CRC Press, Boca Raton, Florida: Figures 10.4.1b, A.2a and b, and A.3.

National Ground Water Association (formerly National Water Works Association), Dublin, OH: Figures 1.4.4a, 2.1.7, 2.1.12, 2.2.2b, 3.2.3, 3.4.5d, 3.5.5, 4.3.1b, 5.5.4, 5.5.5, 5.5.6c, 7.5.1, 8.1.1a, 8.1.2a, 9.3.6, 9.3.7, 9.4.2b, B.2, and Tables 7.1.1 and B-2.

Society of Exploration Geophysicists, Tulsa, OK (Geophysics): Figures 1.1.5, 1.2.1c, 3.1.6, and 3.2.2b.

Timco Manufacturing, Inc., Prairie du Sac, WI: Figures 1.6.1, 3.3.2, 4.1.10, 5.1.1b, 5.1.3, 5.1.5, 5.2.6b, 5.4.3b and c, 5.6.2a, 5.5.3a and b, 5.6.1a, 6.1.1, 6.1.2, 6.1.3, 6.1.4a, 6.1.5, 6.2.3, 6.2.2a, 6.2.5, 9.2.3, 9.2.4, and 9.3.1b.

Water Resource Publications, Highlands Ranch, CO: Figure 1.1.1b.

Williams and Wilkins, Baltimore, MD (Soil Science): Figure 9.3.3.

INTRODUCTION

Many EPA programs, including those under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Response, Compensation, and Liability Act (CERCLA), require subsurface characterization and monitoring to detect ground-water contamination and provide data to develop plans to prevent new contamination and remediate existing contamination. Hundreds of specific methods and techniques exist for characterizing, sampling, and monitoring the saturated and unsaturated zones at contaminated sites. Existing field methods are often refined and new methods are continually being developed. This guide is designed to serve as a single, comprehensive source of information on existing and developing field methods as of early 1993. Appendix C provides some suggestions on the best places to obtain information on new developments that occur after this guide is completed.

USE OF THIS GUIDE

As the title "Desk Reference Guide" implies, this is not a how-to handbook for the field. Instead, the guide provides, in a single document, enough information about specific techniques to make some judgements concerning their potential suitability for a specific site and also gives information on where to go to find more detailed guidance on how to use the technique. This guide can be used in two major ways:

1. **Development of Site Characterization and Monitoring Plans.** Each subsection listed in the table of contents represents a one-to-two page summary of a specific technique or several related techniques. A table at the beginning of each of the 10 major sections (summarized below), provides general comparative information on all methods covered in the sections, and cross-references relevant methods covered in other parts of the guide. In the summary tables, **boldfacing** is used to identify those techniques that are most commonly used. These tables might also be helpful in identifying new, or less common methods that might be of value for specific objectives or site conditions. Within a grouping of method summary sheets, techniques are listed in approximate order of frequency of use.

2. **Overview of Specific Methods.** Individuals who are unfamiliar with specific methods that are being used or proposed to be used at a hazardous waste site can find a concise description of the method, its applications, major advantages and disadvantages in its use, and major reference sources where more detailed information can be found about the method. To locate information on a specific method, the table of contents should be used to identify the section in which the method is located. If the term used to describe the method is not included in the table of contents, go to the summary table at the beginning of the appropriate section of the guide. If the summary table does not use the term, peruse the listing of alternative names for techniques in the individual summary sheets. For example, the **hydraulic percussion** drilling method is not listed in the table of contents, but appears in summary Table 2-1. The **hollow-rod** method, is listed in neither the table of contents or the summary, and requires looking through the individual summary sheets in Section 2.1 (Drilling Methods), until Section 2.1.6 is reached, which identifies the hollow-rod method as an alternative term for hydraulic percussion.

GUIDE ORGANIZATION AND FORMAT

Site characterization, monitoring, and field screening are related activities for which there might not be a clear dividing line. Generally, site **characterization** methods involve one-time field point measurements and sampling (or continuous measurements in the case of some geophysical methods) of physical and chemical properties of the subsurface, or multiple measurements to characterize seasonal variations at the site. **Monitoring** methods, on the other hand, involve sampling or measurements at a single point or the same area over time. Many methods can be used for both site characterization and monitoring, and site characterization activities can continue after monitoring begins to further refine subsurface interpretations. **Field screening** is a form of site characterization that involves the use of rapid, relatively low-cost field methods (typically chemical) in the field during site characterization to assist in the selection of locations for permanent monitoring well installations or for guiding remediation activities. **Field analytical** methods are distinguished from field screening methods by having a higher degree of precision and accuracy than field screening methods. This distinction in discussed further in the introduction to Section 10.

This guide includes two volumes. The first volume covers solids and ground water and the second volume covers the vadose zone. The site characterization, monitoring, and field screening methods covered in the guide are divided into 10 major sections, which are described below. Because site characterization generally precedes monitoring, earlier sections of the guide tend to cover site characterization methods, while later sections cover monitoring. Finally, field screening and analytical methods are covered in Section 10.

Section 1 (Remote Sensing and Surface Geophysical Methods) covers more than 30 airborne and surface geophysical methods that are often valuable during the initial phases of site characterization. These methods can provide preliminary information on the subsurface to provide guidance on placement of boreholes for direct observation of the subsurface and installation of permanent monitoring wells. A number of these methods can also be useful for monitoring the movement of contaminant plumes.

Section 2 (Drilling and Solids Sampling Methods) covers 20 drilling methods, and a variety of power-driven and hand-held devices for sampling soils and geologic materials. The section also briefly identifies important soil physical properties that are described in the field.

Section 3 (Geophysical Logging of Boreholes) covers more than 40 borehole logging and sensing techniques for the physical and chemical characterization of the subsurface.

Section 4 (Aquifer Test Methods) covers 10 methods for measuring ground-water well levels or pressure, pumping and slug tests, six categories of ground-water tracers, and several other techniques for measurement of aquifer properties that might be needed for modeling ground-water flow and contaminant transport.

Section 5 (Ground-Water Sampling Devices and Installations) covers more than 20 types of portable ground-water sampling devices and different types of permanent well installations for portable sampling devices. Appendix A **(Design and Installation of Monitoring Wells)** provides more detailed information on such installations. Section 5 also includes various types of portable and fixed in situ sampling devices and installations. General ground-water sampling methods are covered in Appendix B.

Section 6 (Vadose Zone Hydrologic Properties (I): Water State) covers over 20 methods for measuring vadose zone soil water potential, moisture content, and other soil hydrologic characteristics.

Section 7 (Vadose Zone Hydrologic Properties (II): Infiltration, Conductivity, and Flux) covers four approaches to measuring or estimating infiltration and approximately 30 methods for measuring unsaturated and saturated hydraulic conductivity and water flux in the vadose zone.

Section 8 (Vadose Zone Water Budget Characterization Methods) covers a large number of methods for obtaining data that might be required for water budget calculations to assess contaminant transport in the vadose zone. This includes 37 methods for obtaining various types of hydrometeorologic data, and 16 methods for measuring or estimating transpiration or evapotranspiration.

Section 9 (Vadose Zone Soil-Solute/Gas Sampling and Monitoring Methods) covers six indirect methods for monitoring soil solute movement, more than 20 methods for direct sampling of soil solutions, and a variety of methods for soil gas sampling and gaseous phase characterization in the vadose zone. The section also summarizes a number of methods to measure or estimate soil solute and gas flux in the vadose zone.

Section 10 (Field Screening and Analytical Methods) covers a large number of techniques and groups of techniques for field screening and analysis: Chemical field measurement (three summary sheets), sample extraction procedures (five summary sheets), gaseous phase analytical techniques (five summary sheets), luminescence/spectroscopic techniques (four summary sheets); wet chemistry methods (four summary sheets), and other techniques (five summary sheets).

More than 280 specific field methods are covered in this guide. The large number of methods precludes detailed coverage of any single method, which is often available from other sources. Instead, each method has a single-page summary in a uniform format that includes:

1. General method category title.
2. Method title.
3. Other names used to describe method.
4. Uses at contaminated sites.
5. Method/procedure/device description.
6. Method selection considerations.
7. Frequency of use.
8. Standard Methods/Guidelines (ASTM or other sources that give detailed instruction for use of the specific method).
9. Sources for additional information (which provides comparative information where other methods for similar applications are available).

The frequency of use ratings are very approximate, and actual usage might vary from region to region. Similarly, the summary tables at the beginning of each section should not be relied upon as definitive. Specific instrumentation or variants of techniques covered in this guide might have different characteristics than indicated in the summary tables. A specific method that has been rarely used might be suited for certain site-specific conditions. Conversely, site-specific conditions might make a widely-used technique a poor method of choice. When in doubt, obtaining the opinion of more than one person familiar with a particular technique is advisable.

Wherever possible, one or more figures or tables that illustrate instruments or how a method is used are included with summary sheets. These figures and tables have the same number as the section to which they are related (i.e., Figure 1.1.1 and Table 1.1.1 are located after Section 1.1.1 on visible and near infrared remote sensing). Each major section has a brief introduction that defines major concepts and provides an overview of methods covered in the section. Summary tables and figures at the beginning of each section, and index reference tables near the end of a section are numbered in sequence (i.e., Tables 1-1 to 1-3 provide summary information on remote sensing and geophysical methods, and Tables 1-4 and 1-5 provide an index to references contained at the end of the section).

SOURCES OF ADDITIONAL INFORMATION

As indicated above, two types of references are given for each method. First, if ASTM, EPA, or other standard methods, protocols, or guidelines related to the method have been promulgated, or are being developed, these are identified. Otherwise, references that give detailed instructions on how to use the method are cited, if available.

Secondly, major references that provide information on the use of the method in the context of ground-water and hazardous waste site investigations are listed. All references are in a single section. EPA documents are indicated (with EPA and NTIS numbers). Appendix C (Guide to Major References on Subsurface Characterization and Monitoring) provides annotated descriptions of more than 70 major books and reports and over 80 published conference and symposium proceedings that can serve as information sources for general and specific aspects of soil quality and ground-water field screening, characterization, and monitoring.

The following EPA documents are recommended for use as companions to this guide (all of which are available for no cost from U.S. EPA's Center for Environmental Research Information (see Appendix C for ordering address): **Ground-Water Handbook, Volume 1: Ground Water and Contamination; Volume 2: Methodology** (U.S. EPA, 1990 and 1991a), **Site Characterization for Subsurface Remediation** (U.S. EPA, 1991b), **Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells** (Aller et al., 1991), **Description and Sampling of Contaminated Soils: A Field Pocket Guide** (Boulding, 1991), and **Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide** (U.S. EPA, 1993). Other EPA documents that are available from NTIS and commercially published references that can be of potential value are too numerous to be named individually here. Appendix B should provide guidance concerning other publications that might be worth obtaining.

REFERENCES

Aller, L. et al. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. EPA/600/4-89/034, 221 pp. Also published in 1989 by the National Water Well Association, Dublin, OH in its NWWA/EPA series, 398 pp. [Nielsen and Schalla (1991) contain a more updated version of the material in this handbook that is related to design and installation of ground-water monitoring wells.]

Boulding, J.R. 1991. Description and Sampling of Contaminated Soils: A Field Pocket Guide. EPA/625/12-91/002, 122 pp.

Nielsen, D.M. and R. Schalla. 1991. Design and Installation of Ground-Water Monitoring Wells. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 239-331.

U.S. Environmental Protection Agency (EPA). 1990. Handbook Ground Water. Volume I: Ground Water and Contamination. EPA/625/6-90/016a, 144 pp.

U.S. Environmental Protection Agency (EPA). 1991a. Handbook Ground Water. Volume II: Methodology. EPA/625/6-90/016b, 141 pp.

U.S. Environmental Protection Agency (EPA). 1991b. Site Characterization for Subsurface Remediation. EPA/625/4-91/026, 259 pp.

U.S. Environmental Protection Agency (EPA). 1993. Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide. EPA/625/R-92/007.

SECTION 1

REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

Basic Concepts and Terminology

Geophysical techniques measure physical and chemical properties of soils, rock, and ground water by their response to either: (1) Various parts of the **electromagnetic spectrum** (EM), including gamma rays, visible light, radar, microwave, and radio waves (see Figure 1-1), (2) **acoustic** and/or **seismic** energy, or (3) other **potential** fields, such as gravity and the earth's magnetic field. Figure 1-2 shows typical ranges for parameters of various earth materials that can be measured by geophysical methods.

Most portions of the electromagnetic spectrum are used by one or more specific geophysical methods (Figure 1-1). In common usage, however the term **electromagnetic** is restricted to techniques that measure subsurface conductivities by low-frequency electromagnetic induction techniques (Benson et al., 1984). **Radioactive** or **radiation** methods refer to sensing involving the shortest wavelengths (x-rays and gamma rays). Terminology for methods using the radar and microwave portions of the EM spectrum varies considerably.

In the broadest sense most geophysical techniques involve remote sensing, the observation of an object or phenomenon without the sensor being in direct contact with the object being sensed. In common usage, however, the term **remote sensing** is often restricted to the use of airborne sensing methods in the visible and near-visible portions of the spectrum (see Figure 1-1). **Nondestructive testing** (NDT) is a term usually applied to laboratory test methods, but has also been used to describe geophysical methods in the context of detecting contained subsurface hazardous waste (Lord and Koerner, 1987). In this section the term **surface** geophysics is used broadly to include techniques used at or near land and water surfaces.

Overview of Techniques

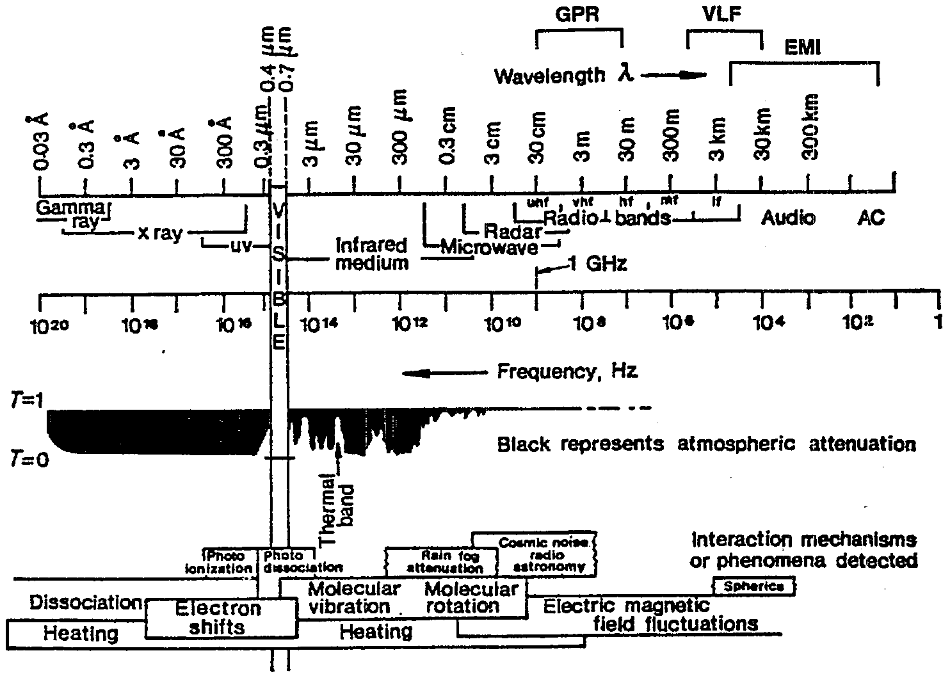
Table 1-1 provides summary information on over 30 remote sensing and surface geophysical methods and identifies where additional information can be found about specific methods in this handbook (several specific applications are covered in other sections of this handbook). This table provides general ratings concerning the potential applicability of individual techniques for characterization of (1) soils and geology, (2) conductive leachate plumes, (3) detection of buried wastes, and (4) detection of nonaqueous phase liquids (NAPLs). Table 1-1 also provides comparative information on cost and depth of penetration of each technique. Table 3-1 in Section 3 summarizes information on more than 30 **borehole** geophysical techniques.

A half dozen of the surface geophysical methods in Table 1-1 are routinely used at contaminated sites: (1) **Ground penetrating radar,** (2) **electromagnetic induction,** (3) **electrical resistivity,** (4) **seismic refraction,** (5) **metal detection,** and (6) **magnetometry.** Table 1-2 provides more detailed ratings of typical applications for these six methods.

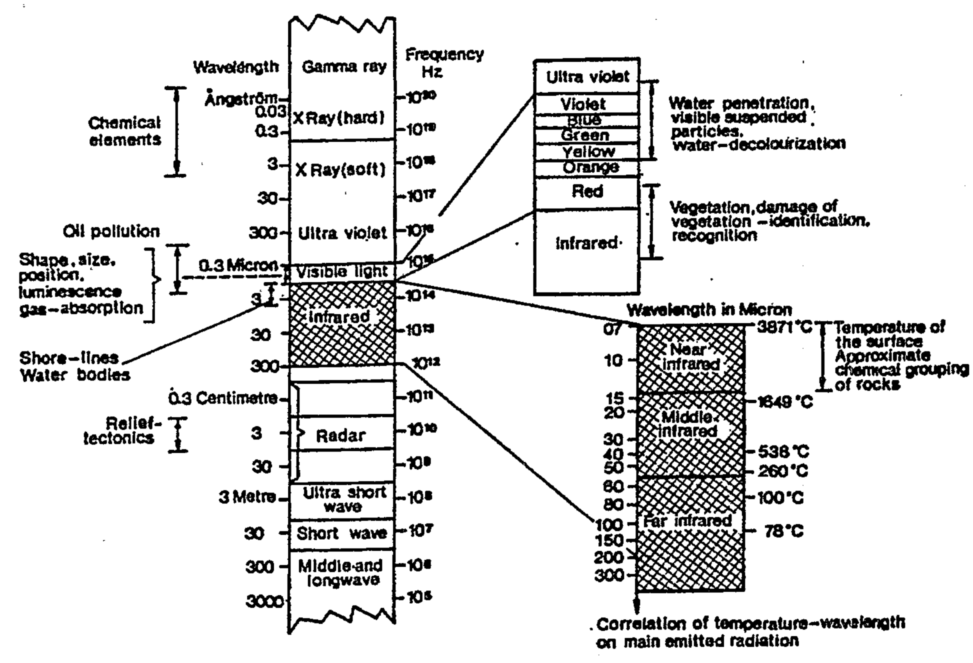
Selection of Remote Sensing and Surface Geophysical Techniques

Surface geophysical techniques are most commonly used early in site investigations for preliminary characterization of the geologic and hydrogeologic setting and contaminant plumes. This information serves as a valuable guide for placement of permanent monitoring wells for ground-water sampling and monitoring. The first four major surface geophysical methods identified above are likely candidates for almost any site (ground penetrating radar will not work where conductivity is high near the surface); metal detection and magnetometry are used whenever the presence of buried drums is suspected and to avoid buried pipelines or tanks when drilling. The Geophysical Advisor Expert System (Olhoeft, 1992) might be useful in determining which of these techniques (plus gravity and radiometric methods) are best suited for specific site and contaminant conditions.

The most basic requirement for successful use of surface geophysical methods is to select the method that is best at detecting the physical property contrasts of the target (i.e., buried waste, soil bedrock contact,



(a)



(b)

Figure 1-1 The Electromagnetic spectrum: (a) Customary divisions and portions used for geophysical measurements; (b) factors and phenomena influencing the radiation of electromagnetic waves (adapted from Erdélyi and Gálfi, 1988).

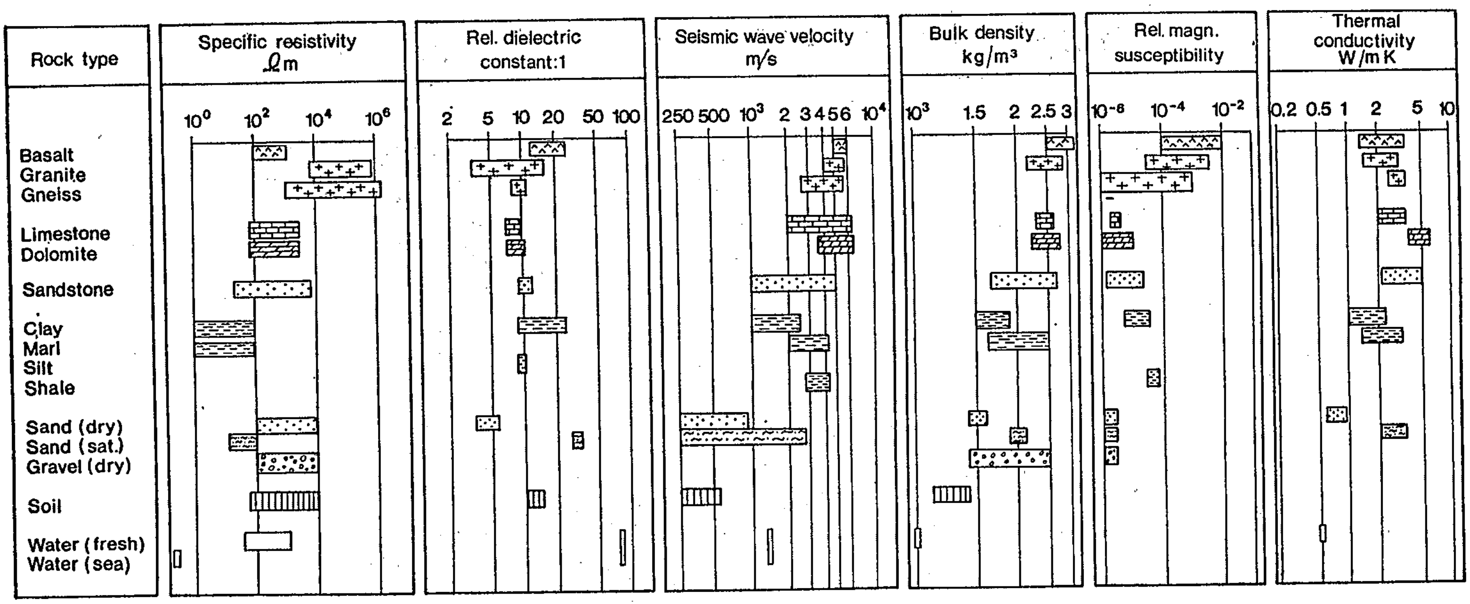


Figure 1-2 Ranges of geophysical measurements for selected earth materials (Erdélyi and Gálfi, 1988).

Table 1-1 Summary Information on Remote Sensing and Surface Geophysical Methods (all ratings are approximate and for general guidance only)

Technique	Soils/ Geology	Leachate	Buried Wastes	NAPLs	Penetration Depth (m)[a]	Cost[b]	Section/Tables
<u>Airborne Remote Sensing and Geophysics</u>							
Visible Photography +	yes	yes[c]	possibly[d]	yes[c]	Surf. only	L	1.1.1/Tb 1.1.1
Infrared Photography +	yes	yes[c]	possibly[d]	yes[c]	Surf. only	L-M	1.1.1/Tb 1.1.1
Multispectral Imaging	yes	yes[c]	no	yes[c]	Surf. only	L	1.1.1/Tb 1.1.1
Ultraviolet Photography	yes	yes[c]	no	yes[c]	Surf. only	L	1.1.2/Tb 1.1.1
Thermal Infrared Scanning	yes	yes (T)	possibly[d]	possibly	Surf. only	M	1.1.3
Active Microwave (Radar) +	yes	possibly	no	possibly	0.1-2	M	1.1.4
Airborne Electromagnetics	yes	yes (C)	yes	possibly	0-100	M	1.1.5
Aeromagnetics	yes	no	yes	no	10s-100s	M	1.1.6
<u>Surface Electrical and Electromagnetic Methods</u>							
Self Potential	yes	yes (C)	yes	no	S 10s	L	1.2.1
Electrical Resistivity +	yes	yes (C)	yes (M)	possibly	S 60 (km)	L-M	1.2.2, 9.1.1/Tbs 1-2, 1-3, 1.2.1
Induced Polarization	yes	yes (C)	yes	possibly	S km	L-M	1.2.3
Complex Resistivity	yes	yes (C)	yes	yes	S km	M-H	1.2.3
Dielectric Sensors	yes	yes (C)	no	possibly	S 2[e]	L-M	6.2.3/Tb 6-1
Time Domain Reflectometry	yes	yes (C)	no	yes	S 2[e]	M-H	6.2.4/Tb 6-1
Electromagnetic Induction +	yes	yes (C)	yes	possibly	S 60(200)/ C 15(50)	L-M	1.3.1/Tbs 1-2, 1-3, 1.3.1
Transient Electromagnetics	yes	yes (C)	yes	no	S 150 (2000+)	M-H	1.3.2/Tb 1.3.1
Metal Detectors	no	no	yes	no	C/S 0-3	L	1.3.3/Tbs 1-2, 1-3
VLF Resistivity	yes	yes (C)	yes	no	C/S 20-60	M-H	1.3.4
Magnetotellurics	yes	yes (C)	no	no	S 1000+	M-H	1.3.5
<u>Surface Seismic and Acoustic Methods</u>							
Seismic Refraction +	yes	yes	no	no	S 1-30(200+)	L-M	1.4.1/Tbs 1-2, 1-3
Shallow Seismic Reflection +	yes	no	no	no	S 10-30(2000+)	M-H	1.4.2
Continuous Seismic Profiling	yes	no	no	no	C 1-100	L-M	1.4.3
Seismic Shear/Surface Waves	yes	no	no	no	S 10s-100s	M-H	1.4.4
Acoustic Emission Monitoring	yes	no	no	no	S 2[e]	L	1.4.5
Sonar/Fathometer	yes	yes	no	no	C no limit	L-H	1.4.6
<u>Other Surface Geophysical Methods</u>							
Ground-Penetrating Radar +	yes	yes (C)	yes	yes	C 1-25 (100s)	M	1.5.1/Tbs 1-2, 1-3
Magnetometry +	no	no	yes (F)	no	C/S 0-20[f]	L-M	1.5.2/Tbs 1-2, 1-3
Gravity	yes	yes	no	no	S 100s+	H	1.5.3
Radiation Detection	no	no	yes (nuclear)	no	C/S near surface	L	1.5.4
<u>Near Surface Geothermometry</u>							
Soil Temperature	yes	yes (T)	no	no	S 1-2[e]	L	1.6.1
Ground-Water Detection	yes	yes (T)	no	no	S 2[e]	L	1.6.2
Other Thermal Properties	yes	no	no	no	S 1-2[e]	L-M	1.6.3

Boldface = Most commonly used methods at contaminated sites; + = covered in Superfund Field Operations Manual (U.S. EPA, 1987), (C) = plume detected when contaminant(s) change conductivity of ground water; (F) = ferrous metals only; (T) = plume detected by temperature rather than conductivity.

[a] S = station measurement; C = continuous measurement. Depths are for typical shallow applications; ( ) = achievable depths
[b] Ratings are very approximate L = low, M = moderate, H = high.
[c] If leachate or NAPLs are on the ground or water surface or indirectly affect surface properties—see Table 1.1.1; field confirmation required.
[d] Disturbed areas which may contain buried waste can often be detected on aerial photographs.
[e] Typical maximum depth, greater depths possible, but sensor placement is more difficult and cable lengths must be increased.
[f] For ferrous metal detection, greater depths require larger masses of metal for detection; 100s of meters depth can be sensed when using magnetometry for mapping geologic structure.

Table 1-2 Typical Applications of Six Commonly Used Geophysical Methods (all ratings are for general guidance only; *rating for a specific method* and application may differ depending on site specific conditions and instrumentation used)

Application	Ground Penetrating Radar	EM Induction	Electrical Resistivity	Seismic Refraction	Metal Detection	Magnetometry
Natural Conditions						
Layer thickness and depth of soil and rock	1	2	1	1	NA	NA[b]
Mapping lateral anomaly locations	1	1	1	1	NA	NA[b]
Determining vertical anomaly depths	1	2	1	1	NA	NA
Very high resolution of lateral or vertical anomalous conditions	1	1	2	2	NA	NA
Depth to water table and aquifer thickness	2	2	2	1	NA	NA
Water saturated fractures, shear and fault zones	2	2	2	2	NA	NA
Mapping clay layers	1	1	1	2	NA	NA
Cavity/sinkhole detection[d]	1	2	2	2	NA	NA
Subsurface Contamination Leachates/Plumes						
Existence of conductive contaminants Reconnaissance Surveys)	2[a]	1	1	NA	NA	NA
Mapping contaminant boundaries	2[a]	1	1	NA	NA	NA
Determining vertical extent of contaminant	2[a]	2	1	NA	NA	NA
Quantify magnitude of contaminants	NA	1	1	NA	NA	NA
Determine flow direction	2[a]	1	1	NA	NA	NA
Flow rate using two measurements at different times	NA	1	1	NA	NA	NA
Detection of organic contaminants above and floating on water table	2[a]	2[a]	2[a]	NA	NA	NA
Detection and mapping of conductive contaminants within unsaturated zone	2	1	1	NA	NA	NA
Location and Boundaries of Buried Wastes						
Bulk wastes	1	1	1	2	NA	NA
Nonmetallic containers	1	NA	NA	NA	NA	NA
Metallic containers						
- Ferrous	2	1	2	NA	1	1
- Nonferrous	2	1	2	NA	1	NA
Depth of burial	1	2	1	NA	2[a]	2[a]
Utilities						
Location of pipes, cables, tanks	1	1	2	NA	1	1
Identification of permeable pathways associated with loose fill in utility trenches	1	1	NA	NA	1	1
Abandoned well casings	2	2	2	NA	1	1
Safety						
Predrilling site clearance in order to avoid buried drums, breaching trenches, etc.	1	1	2	2	1	1
Typical Depth Range (meters)	<1-25	0.75-60[c]	0-100+	1-30+	0-3	0-5

1 - Denotes primary use.
2 - Denotes possible applications, secondary use; however, in some special cases, 2 may be the only effective approach due to circumstances.
NA - Not applicable.
\+ - Actual depth only limited by sources and length of wire available.

[a]Limited applications.
[b]Not applicable in the context used in this document.
[c]Deeper if using transient EM.
[d]Other principle methods include microgravity (ground survey) and sonar (water bottom survey).

Source: Modified from Benson et al. (1984)

conductive plume, etc.). Greenhouse and Monier-Williams (1985) identified six other considerations in the selection of geophysical methods at contaminated sites: (1) **Depth limits of detection and resolution** (see Table 1-1); (2) **susceptibility to electrical or vibrational noise** (Table 1-3 identifies susceptibilities for six major methods); (3) **corroboration** (confirmation of anomalies by multiple readings or use of more than one method); (4) **ties to borehole sampling** (i.e., confirmation of observations by drilling of monitor wells for direct observation); (5) **simplicity** (especially important if time series measurement are to be taken and there is a possibility of multiple contractors taking the measurements); and (6) **cost effectiveness.** To these considerations might be added: (7) **Operator experience** (most geophysical methods require specialized training for use and interpretation of results); and (8) **equipment availability.** For example, many of the less commonly used remote sensing and surface geophysical methods would probably be used more frequently if more contractors knew how to use them and/or the equipment was more readily available.

Most geophysical techniques require highly trained and experienced personnel for data collection and interpretation. When dealing with geophysical contractors, there should be a clear understanding about the services being performed. Many geophysical contractors just provide the raw geophysical data as their standard service, and charge extra for interpretation of data.

The summaries in this section identify common conditions that enhance or inhibit the success of specific techniques, but site specific conditions might cause problems for specific techniques, even when all other indications are that they should work well. As a general rule, **all** geophysical techniques should be checked by more direct observation and/or confirmed by a second geophysical method. Furthermore, well established techniques should be given preference to those less commonly used unless there is clear justification based on site conditions, cost, and the availability of trained and experienced personnel. When in doubt about the appropriateness of a specific technique, independent expert advice should be sought. EPA's Environmental Monitoring Systems Laboratory, Las Vegas, Nevada can provide such advice for EPA personnel.

Sources of Additional Information

Two useful EPA documents that contain more detailed information on commonly used surface geophysical techniques at contaminated sites are: **Geophysical Techniques for Sensing Buried Wastes and Waste Migration** (Benson et al., 1984), and the **Compendium of Superfund Field Operations Methods** (U.S. EPA, 1987). Table 1-4 (at the end of this section) identifies major references relating to geophysical methods in general, and specific applications for ground-water and contaminated-site studies. The document **Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide** (U.S. EPA, 1993), prepared as a companion to this guide, contains annotated descriptions of major geophysical texts and indexes about 1,400 literature references on the operation and applications of specific remote sensing and geophysical techniques in ground-water and contaminated site investigations. Tables 1-4 and 1-5 in this guide provide an index of remote sensing and geophysical texts only.

Table 1-3 Susceptibility of Major Geophysical Methods to Ambient "Noise"

Source of Noise	Ground Penetrating Radar	EM Induction	Electrical Resistivity	Seismic Refraction	Metal Detection	Magnetometry
Buried pipes[a]	2 Will detect but may affect data	1 Only if within several coil spacings	1 Only if survey line is parallel and close by	2 Only if survey is directly over	1 Any metal pipes unless buried below detection	1 Steel pipes only
Metal fences	2 May affect unshielded antenna if close to fence	1 Only if within several coil spacings	2 Only if survey line is parallel and close to fence	NA	2 Only if nearby	1 Steel fences only
Overhead wires (powerline)	2 Only if unshielded antennas are used	1 Only if within several coil spacings	NA	2 60 Hz filter may be required	NA	2 Some mags respond
Ground vibrations	NA	NA	NA	1	NA	NA
Airborne electromagnetic noise	NA	2	2	NA	2	1 to 2 (Earth's field changed)
FM radio transmission	1 to 2 depending on frequency	NA	NA	NA	NA	NA
Ground currents/voltage	NA	NA	2	NA	NA	NA
Trees	2 Only if unshielded antennas are used	NA	NA	2 (wind noise)	NA	NA
Metal from buildings, vehicles, etc.	2 Only if nearby and unshielded antennas are used	2 Only if nearby	2 Only if nearby	NA	2 Only if nearby	2 Only if nearby
Small metallic debris on or near surface (nails, wire coathangers)	2	NA	NA	NA	1	1 Ferrous metal only
Large metallic debris on or near surface (drums, drum covers, etc.)	2	1	2	NA	1	1 Ferrous metal only
Ground contact/ electrode problems	2	NA	1	1 to 2	NA	NA

1 - Very susceptible; 2 - Minor problem; NA - Not applicable.

[a] A small diameter pipe (1") will have little influence if a large mass of conducting material is in the immediate area.

Source: Modified from Benson et al. (1984)

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.1 Visible and Near Infrared

Other Names Used to Describe Method: Aerial photography, satellite photography, aerial remote sensing, satellite remote sensing, aerial imaging, satellite imaging, black-and-white imaging (panchromatic), color imaging (true and false), color and photographic infrared imaging, multiband imaging (multispectral), airborne television.

Uses at Contaminated Sites: Performing fracture trace analysis for potential zones of preferential ground-water flow; developing topographic maps; evaluating changes in land use and vegetation from aerial photographs taken at different times; detecting near-surface leachate/contamination; documenting preexisting physical conditions and monitoring progress of clean-up operations; (plan emergency response actions [airborne television]); locating abandoned wells.

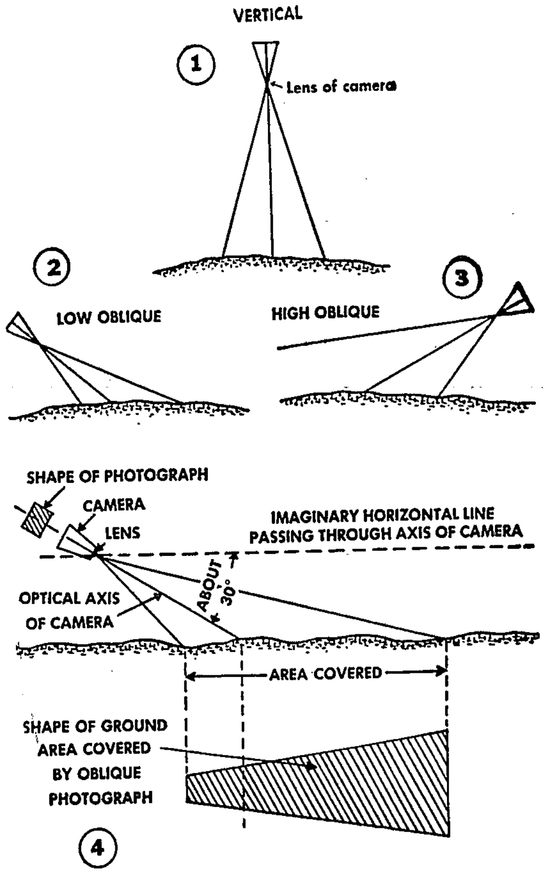
Method Description: Photographs record images on film that is sensitive to the visible and near-infrared portion of the electromagnetic spectrum, or images can be recorded electronically on tapes (video and multispectral scanning systems). Images can be black-and-white, true color, and false color (such as color infrared film, which records yellows and reds as green and the near infrared as red). Aerial photographs can be **vertical** or **oblique** (Figure 1.1.1a). They can record the full visible and near infrared (not visible to the human eye) or only portions of the spectrum (multiband images). Overlapping aerial photographs can be viewed three-dimensionally using a stereoscope, or used to develop topographic maps using photogrammetric techniques. Someone skilled in air-photo interpretation can develop preliminary interpretations about site geology, soils and hydrogeology that can assist in on-the-ground site evaluation. **Fracture trace analysis** is an especially useful technique that uses lineaments visible on air photos to identify potential zones of preferential movement of contaminants in ground water (Figure 1.1.1b). Table 1.1.1 identifies surface features that can be indicative of leachate or contaminants on the surface or in the shallow subsurface and the spectral bands that are most useful for identifying such features.

Method Selection Considerations: Should be used at all sites in one form or another, especially when litigation is involved. **Advantages:** (1) Relative to other site characterization activities, the cost of cameras, film, and image processing is small unless very specialized equipment is used; (2) color photographs or videotapes are a simple way to document on-ground conditions and activities; (3) existing aerial photography (usually black-and-white) taken by other government agencies, such as the Soil Conservation Service and the Agricultural Stabilization and Conservation Service is generally readily available and particularly useful in the site characterization stage and for fracture trace analysis; and (4) aerial documentation using hand-held cameras is relatively inexpensive. **Disadvantages:** (1) Aerial photography for stereoscopic interpretation or multispectral imaging requires more sophisticated equipment and is more expensive; and (2) availability of multispectral imagery from existing sources at the site scale is limited.

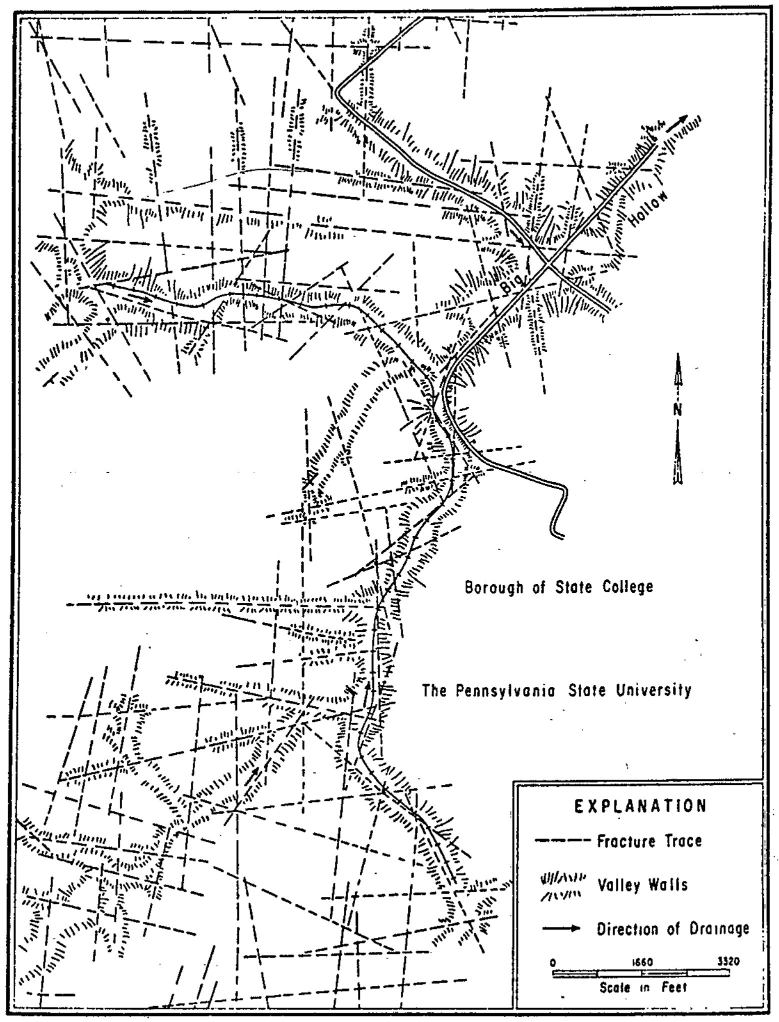
Frequency of Use: True color and black-and-white photographs are used at most, if not all, hazardous waste sites. Ongoing aerial photographic documentation of site activities is less common. Use of color infrared photography is uncommon, but would probably be useful at many sites. Use of false color and multispectral imagery is uncommon.

Standard Methods/Guidelines: ASTM (1993).

Sources for Additional Information: Aller (1984), Phillipson and Sangrey (1977), Rehm et al. (1985-near infrared), Sangrey and Phillipson (1979), U.S. EPA (1987, 1992-Chapter 2). See also, references on aerial photography in Table 1-4.



(a)



(b)

Figure 1.1.1 Aerial photography: (a) Orientation of aerial camera for vertical, and oblique photography (Avery, 1968); (b) Example of fracture trace analysis drawn from aerial photographs (Parizek, 1976, by permission).

Table 1.1.1 Spectral Bands for Detecting Leachate Through Reflected Radiation

Leachate Indicator	Primary Bands	Secondary Bands
<u>Gaps</u>		
Vegetation/Soil, Rock	Infrared, Red	
Snow/Soil, Rock	Blue, Green	
<u>Wetness</u>		
Soil	Infrared	Red
Soil with Grass	Infrared	
<u>Spectral Anomalies (Reflective or Emissive)</u>		
In Water	Red, Green	Blue
On Water (lipids)	Ultraviolet	Blue, Infrared
On Soil	Red, Green	Infrared
On Grass	Red	Infrared, Green
Stressed Vegetation	Infrared	Green, Red

Source: Phillipson and Sangrey (1977)

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.2 Photographic Ultraviolet

Other Names Used to Describe Method: Photographic UV.

Uses at Contaminated Sites: Mapping of oil spills on surface water bodies; sometimes used for geologic mapping of carbonate formations, such as limestones and dolomites; detecting surface contamination by explosives.

Method Description: Special films and filters are used to take photographs in the nonvisible ultraviolet portion of the electromagnetic spectrum (0.3 to 0.4 micrometers). Oil and carbonate minerals are fluorescent in UV bands when photostimulated by sunlight. Figure 1.1.2 illustrates a ground-portable UV video system for detecting surface contamination with explosives being tested by the U.S. Army Toxic and Hazardous Materials Agency (Barringer Research Limited, 1988).

Method Selection Considerations: **Advantages:** (1) Equipment is readily available and simple; and (2) ultraviolet is the best portion of the spectrum for detecting oil slicks on water surfaces (see Table 1.1.1). **Disadvantages:** The major drawback of photographic UV is high scattering of these wavelengths by the atmosphere results in low contrast images, especially when there is dust or haze.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: None.

Sources for Additional Information: Phillipson and Sangrey (1977), Redwine et al. (1985), Sangrey and Phillipson (1979).

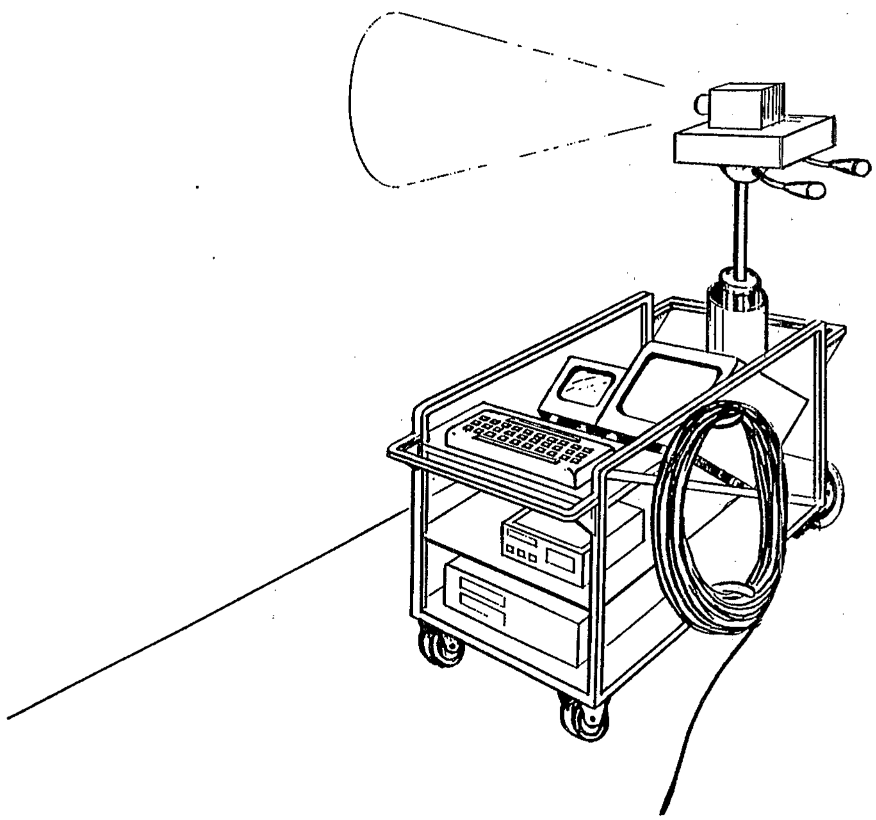


Figure 1.1.2 Ultraviolet video detection system (Barringer Research Limited, 1988).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.3 Thermal Infrared

Other Names Used to Describe Method: Medium and far infrared, infrared radiometry/thermography.

Uses at Contaminated Sites: Detecting discharge of ground-water from a contaminated site to nearby surface waters; detecting leaks from pipelines and underground storage tanks; monitoring soil moisture and evaporation; directly detecting seeps and springs; characterizing shallow ground-water flow (see Section 1.6.2); identifying water flow profiles in dams.

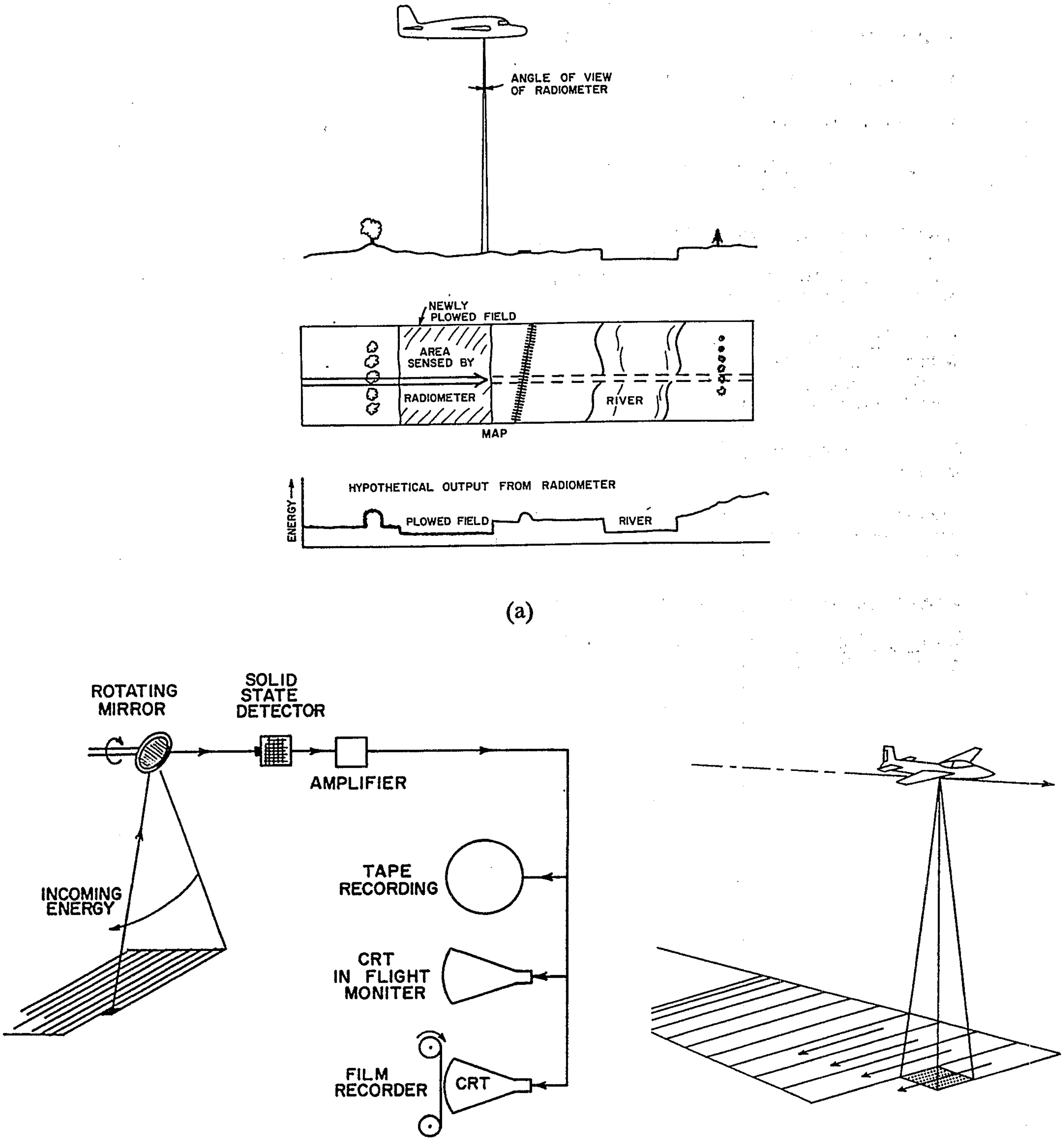
Method Description: Thermal infrared radiation lies between near-infrared (see Section 1.1.1) and the microwave portions of the electromagnetic spectrum (see Sections 1.1.3 and 1.1.4). An object emits infrared radiation as a function of the nature of its surface (emissivity) and its temperature, which can be sensed using a **radiometer** or an **infrared scanner**. A radiometer records the radiation received and generates an electrical signal based upon the difference between a standard reference in the instrument and the object being viewed (Figure 1.1.3a). An infrared scanner uses a detector that creates an image of the thermal environment on a television tube, magnetic tape, videotape or photographic film (Figure 1.1.3b). Infrared scanners can be used to detect ground-water discharges into surface waters because of the difference in temperature between the waters. They can also be used to detect variations in soil moisture content, and to monitor changes in soil moisture and evaporation over time. A microwave radiometer measure the thermal emissions from the surface, which at these wavelengths is essentially proportional to the product of the temperature and emissivity of the surface. This in turn can be related to moisture content by developing curves for a site that relate diurnal range of temperature to moisture content. Use of a radiometer for testing flaws in materials by measuring heat flow anomalies is a well established technique.

Method Selection Considerations: **Advantages:** (1) Cost effective where large areas must be evaluated, such as reconnaissance identification of ground water or contaminant plume discharge into large water bodies or along coastline; (2) thermal infrared imagery is available from existing sources and might be useful in the initial site characterization phase; (3) infrared radiometry is a well established nondestructive testing technique and commercial equipment is readily available. **Disadvantages:** (1) More complex and expensive than most other available methods for monitoring soil moisture content at the site-specific level (see Section 6.3); and (2) interpretation of thermal images is complicated by factors such as vegetation, presence of decaying organic matter, and climatological and micrometeorological effects.

Frequency of Use: Commonly used to detect ground-water discharge into rivers, lakes, and seas and as a nondestructive materials testing technique. Use to estimate soil moisture and evaporation is established, but not common. Use at contaminated sites rare, if at all.

Standard Methods/Guidelines: None.

Sources for Additional Information: **General:** Lord and Koerner (1987), Sharp (1970), Ulaby et al. (1982), U.S. EPA (1987, 1992-Chapter 2); **Applications:** Aller (1984-abandoned well location), Huntley (1978-shallow aquifers), Idso et al. (1975-evapotranspiration), Jackson and Schmugge (1986-soil moisture), U.S. Geological Survey (1982-evapotranspiration). See also, general references on remote sensing in Table 1-4.



SCHEMATIC OF SCANNING UNIT

LINE-SCANNING TECHNIQUE
USED BY MECHANICAL SCANNERS

(b) (c)

Figure 1.1.3 Thermal infrared: (a) Basic radiometer operation; (b) Thermal infrared scanning (Scherz and Stevens, 1970).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.4 Active Microwave (Radar)

Other Names Used to Describe Method: Radar (RAdio Detection And Ranging), side-looking airborne radar (SLAR), synthetic aperture radar.

Uses at Contaminated Sites: Limited. If continuous cloud-cover prevents obtaining good aerial photographic images of a site, SLAR could be used to develop black-and-white images. Possible applications in arid areas with little or no vegetation for characterization of grain size in alluvium and estimation of water table depth for relatively large areas and for soil moisture monitoring.

Method Description: Radar systems emit a radio wave in the microwave portion of the electromagnetic spectrum from a transmitter, and detect the weak reflected energy with a receiver that is amplified and modified to create an image. SLAR generates waves at an oblique angle that allows imaging of a much larger surface area than conventional aerial photography (Figure 1.1.4) and creates an image similar to a shaded relief map.

Method Selection Considerations: Unless site condition preclude other imaging methods, not likely to be method of choice.

Frequency of Use: Used infrequently in hydrogeologic studies. Main application is to develop images where cloud-cover or darkness prevents use of conventional photography. No reported cases of use at contaminated sites.

Standard Methods/Guidelines: None.

Sources for Additional Information: U.S. EPA (1987, 1992-Chapter 2). See also, general references on remote sensing in Table 1-4.

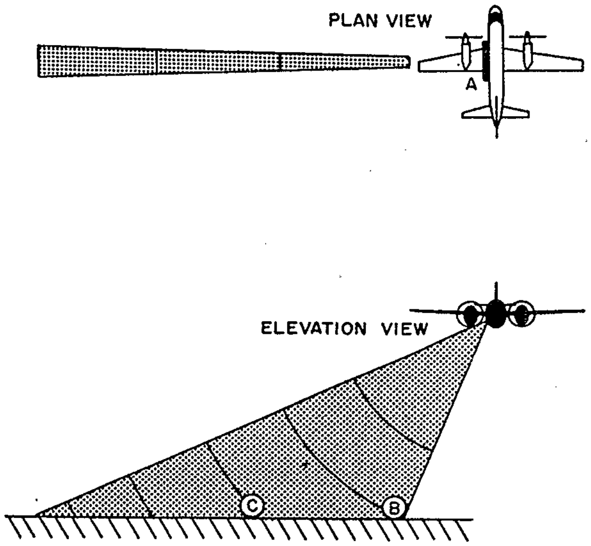


Figure 1.1.4 Side-looking radar antenna beam (Scherz and Stevens, 1970).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.5 Airborne Electromagnetics (AEM)

Other Names Used to Describe Method: Airborne EM, low frequency AEM.

Uses at Contaminated Sites: Detecting and monitoring conductive/brine contamination plumes and possible contamination sources of near-surface aquifers resulting from injection of brine into Class 2 wells; mapping of buried bedrock channels and variations in soil and rock types; locating shallow subsurface permafrost and aquifers; possibly locating unknown buried metal dump sites.

Method Description: Figure 1.1.5a shows the principle of airborne electromagnetic induction surveying using a transmitter in a plane, and a receiver in a towed bird. Section 1.3.1 provides additional discussion of the electromagnetic induction method. The transmitter can be **fixed** at the ground surface with an airborne receiver carried on a flight path that crosses the transmitter loop at specified intervals, or a **moving** transmitter can be used. Moving transmitter-receiver configurations include: (1) Placement in separate planes, (2) transmitter in a plane with receiver in a towed bird, and (3) rigid booms with transmitter and receiver attached to the tips of wings or combined in a single towed bird. Figure 1.1.5b illustrates a fixed transmitter arrangement and a number of moving transmitter arrangements.

Method Selection Considerations: Faster and might be more cost effective than surface EM methods where sites are inaccessible and large areas need to be evaluated.

Frequency of Use: Commonly used in mineral exploration, less frequently used in hydrogeologic studies. Currently being tested on the Brookhaven oil field in Mississippi.

Standard Methods/Guidelines: --

Sources for Additional Information: Palacky (1986), Palacky and West (1991), Smith et al. (1989), U.S. EPA (1992-Chapter 2).

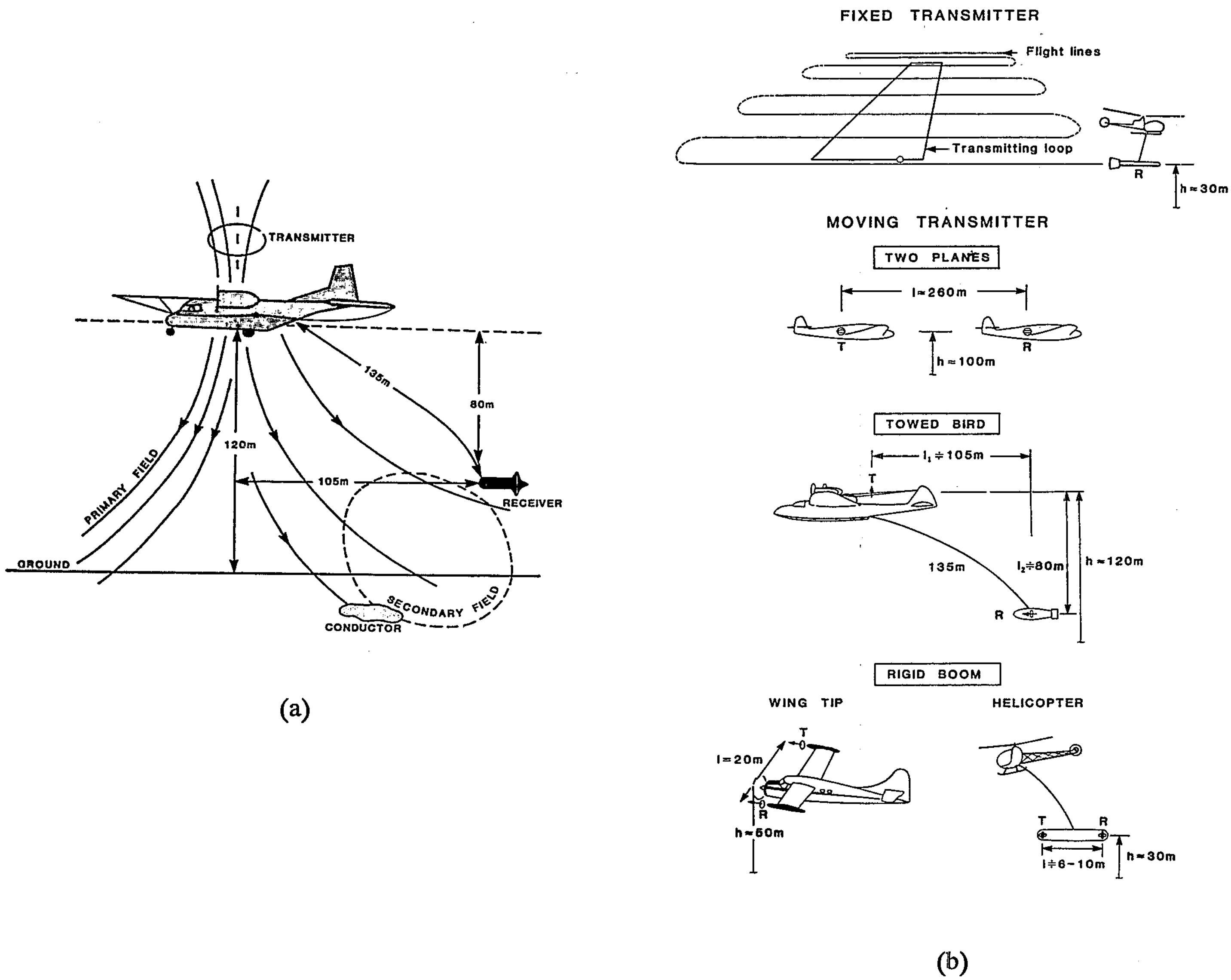


Figure 1.1.5 Airborne electromagnetics: (a) Principle of airborne electromagnetic surveying (towed bird); (b) Transmitter-receiver geometry of five basic types of active airborne electromagnetic systems (Palacky and West, 1991, by permission).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.1 AIRBORNE REMOTE SENSING AND GEOPHYSICS

1.1.6 Aeromagnetics

Other Names Used to Describe Method: Air magnetometer.

Uses at Contaminated Sites: Used in conjunction with airborne EM methods for delineating subsurface structures to evaluate brine contamination (see Section 1.1.5); locating abandoned wells.

Method/Device Description: Airborne magnetometers are used to measure variations in the earth's total magnetic field. See Section 1.5.2 for description of magnetic instrumentation. Relatively recent tests of aeromagnetic surveys (used in conjunction with other methods) for locating abandoned wells and associated brine contamination have had good results. Figure 1.1.6 shows aeromagnetic contour anomalies caused by wells in the Coon Creek oil field in Oklahoma. Photographically identified wells that do not appear on the map as anomalies are labeled with Roman numerals.

Method/Device Selection Considerations: Faster and can be more cost effective than surface EM methods where sites are inaccessible and large areas need to be evaluated. Use for abandoned well location requires complementary methods, such as air photo interpretation, because uncased wells will not be detected, and other features can create non-well related anomalies or mask magnetic anomalies associated with wells.

Frequency of Use: Commonly used in petroleum and mineral exploration to assist in with geological mapping and structural interpretations, less frequently used for hydrogeologic studies.

Standard Methods/Guidelines: --

Sources for Additional Information: Frischknecht (1990), Smith et al. (1989), U.S. EPA (1992-Chapter 2).

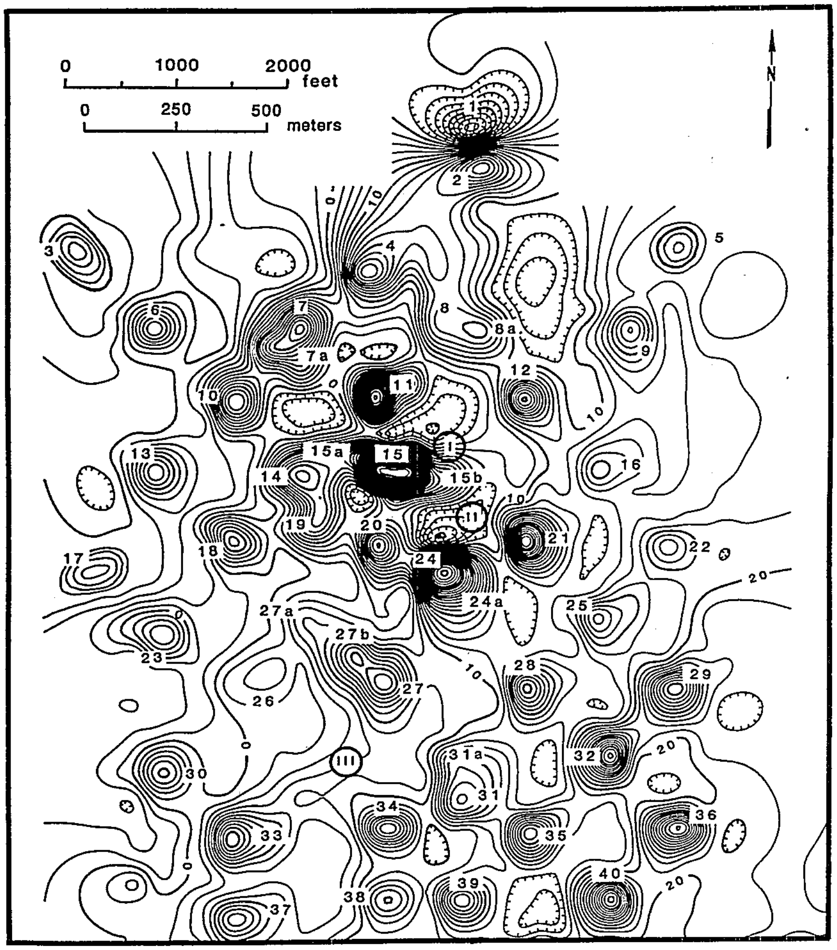


Figure 1.1.6 Aeromagnetic contour anomalies caused by wells in Coon Creek oil field, Oklahoma (Frischknecht, 1990).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.2 SURFACE ELECTRICAL METHODS

1.2.1 Electrical Resistivity (ER)

Other Names Used to Describe Method: Direct current resistivity, DC resistivity, galvanic resistivity, geo-electric resistivity.

Uses at Contaminated Sites: Mapping of conductive contaminant plumes and rate of plume movement; might be capable of detecting high resistivity subsurface hydrocarbons at some sites; locating abandoned wells; vertical and lateral mapping of stratigraphic and structural features, such as buried stream channels; mapping of fresh/salt-water interfaces; estimating depth to ground water/bedrock; detecting cavities/sinkholes (tri-potential). Azimuthal resistivity readings can be used for locating large or significant subsurface fractures and joint orientations. See also, Table 1-2.

Method Description: The resistivity of subsurface materials is measured by injecting an electrical current into the ground by a pair of surface electrodes (**current electrodes**) and measuring the resulting potential field (voltage) between a pair of second electrodes (**potential electrodes**) (see Figure 1.2.1a). DC methods are identified according to the arrangement of current and potential electrodes, with **Wenner**, **Schlumberger**, and **dipole-dipole** arrays being the most commonly used today (Figure 1.2.1b). Figure 1-2 shows typical resistivity ranges for various soil and geologic materials. Increasing the spacing between the current and potential electrodes increases the depth of the sounding measurement (in the Wenner array the spacing should be one to two times the depth of interest). **Tri-potential** DC resistivity is a relatively new method that involves taking readings from three electrode arrays (Wenner, dipole-dipole, and bipole-bipole) at each station and can allow resolution of ambiguities from single-array readings. **Azimuthal** resistivity measures the variations in electrical response to changes in the orientation of electrode arrays at a single location (Figure 1.2.1c). **Tomographic** imaging is an experimental surface DC resistivity method in which a grid of electrodes is established on the ground surface and controlled currents are introduced into a subset of electrodes in a prescribed sequence. The electrical response at other electrodes is then measured. Figure 3.1.6b in Section 3 illustrates a cross-borehole resistivity array that can also be used for tomographic imaging. Other methods using tomographic techniques are covered in Sections 3.4.5 and 6.3.7.

Method Selection Considerations: Table 1.2.1 provides comparative information for DC resistivity, EMI (Section 1.3.1), and time domain EM (Section 1.3.2). **Advantages:** (1) Well established method with many commercial sources of equipment available; (2) with horizontally layered earth, DC methods are better than EMI at resolving the layers (three or four layers compared to two); (3) superior to EM methods for detecting a thin, resistive layer; (4) tomographic imaging has the potential for high vertical and horizontal resolution of contaminant plumes, but grid-edge effects create difficulties in field application; (5) good capabilities for locating and mapping buried bulk wastes with and without metals, and vertical sounding might provide depth; (6) equipment is inexpensive, mobile, easy to operate, and provides relatively rapid areal coverage; (7) depth of penetration is limited only by the ability to extend electrode spacings (400 to 800 can be achieved relatively easily); and (8) results can be approximated in the field. **Disadvantages:** (1) The requirement for ground contact can cause problems in resistive material and in general makes the technique slower to use than EMI; (2) continuous profiling is not possible; (3) affected by cultural features (metal, pipes, buildings, and vehicles [see Table 1-3]); (4) interpretations of data are not unique; (5) dipping strata complicate interpretations and lateral heterogeneity is not easily accounted for; (6) cannot be used in paved areas, and use is limited in wet weather; (7) less sensitive to conductive pollutants than EMI; (8) deep soundings, where long wire lines must be laid, are labor and time intensive; and (9) slow and complicated computer programs are usually needed to resolve data from the field and complicated stratigraphy requires an expert to resolve data.

Frequency of Use: Conventional DC resistivity is commonly used for geologic/hydrogeologic characterization and preliminary mapping of contaminant plumes. DC resistivity is less commonly used for mapping changes in plume configuration. Tri-potential and azimuthal resistivity are relatively new methods with potential for wider use. Grid-edge effect problems need to be resolved before tomographic imaging using only surface electrodes is more widely used.

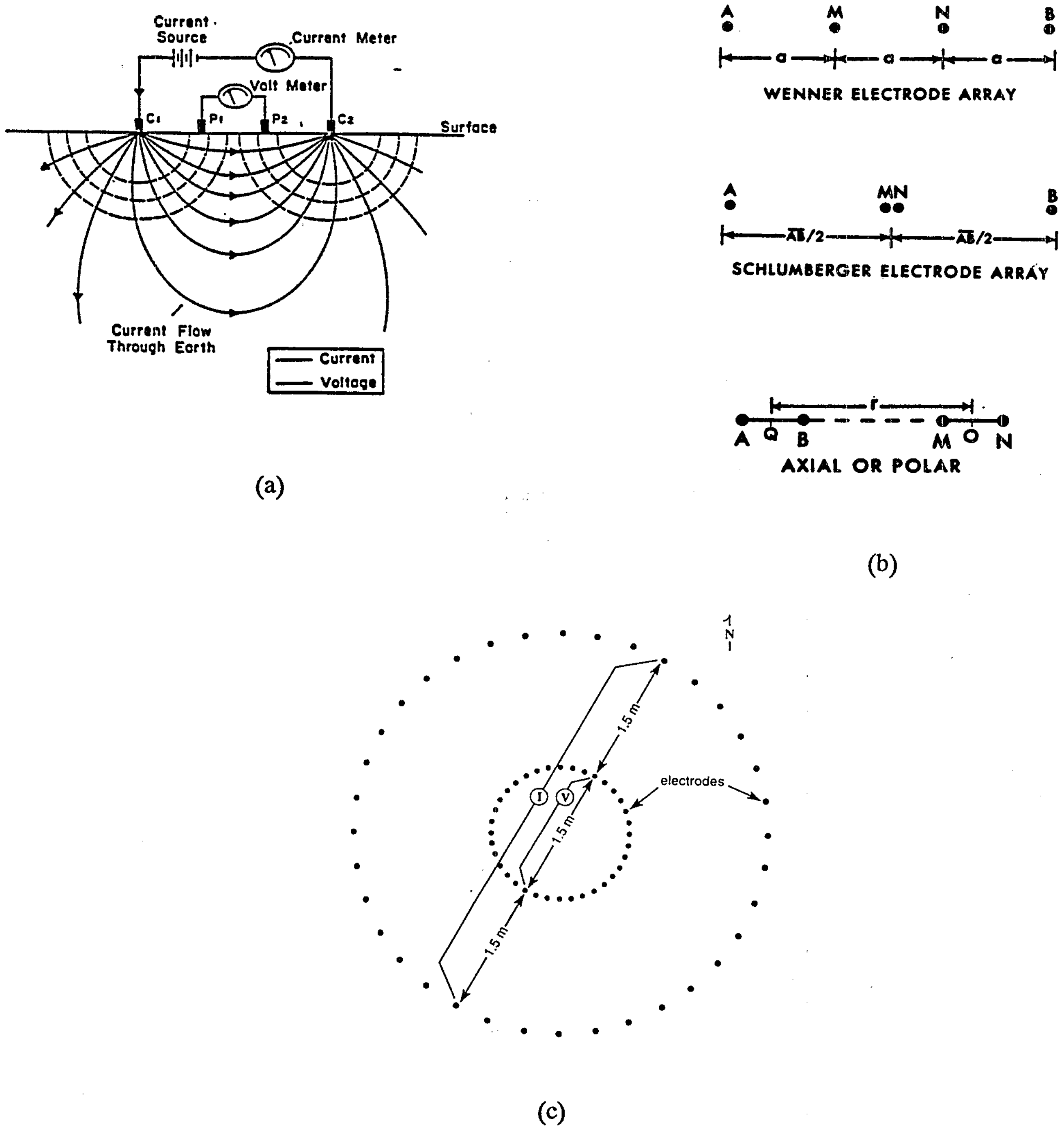


Figure 1.2.1 DC resistivity methods: (a) Diagram showing basic concept of resistivity measurement (Benson et al., 1984); (b) Wenner, Schlumberger, and axial/polar dipole-dipole electrode arrays (A and B are current electrodes, M and N are potential electrodes, a and AB/2 are electrode spacings) other dipole-dipole configurations are possible (Zohdy et al., 1974); (c) Layout of azimuthal resistivity array (a Wenner array is rotated 10 degrees clockwise and successive resistivities are measured) (Carpenter et al., 1991, by permission).

Table 1.2.1 Comparison of Resistivity and Electromagnetic Methods

		Electromagnetics	
	DC Resistivity	EMI	TDEM
Vertical sounding capability	Yes	To a limited extent (2 or 3 layers possible)	Yes, up to three layers or more
Depth of sounding measurement	Limited by array length	60 meters with equipment commonly used; 100s of meters possible	150 meters with equipment commonly used; 1000s of meters possible
Profile station measurements	Yes	Yes - to 60 meters depth	Yes - to 150 meters depth
Continuous profile measurement	No	Yes - to 15 meters depth and at speeds up to 8 km/hr	No
Relative lateral resolution[a]	Poor in profile mode	Good in profile mode with station measurements. Excellent in continuous profile mode	Excellent, particularly compared with exploration depth
Resolution for electrical equivalence[b]	Moderate	Poor	Excellent
Relative speed of measurement	Good	Very rapid	Rapid
Total site coverage	Not generally economical	Feasible at reasonable cost	Feasible at moderate cost
Susceptible to noise and buried pipes/cables	Yes	Yes (continuous measurements aid identification of pipes and cables)	Yes
Electrode contact problem	Yes	No (operates through dry sands, concrete blacktop, etc.)	No

[a]For a DC Wenner array, the array length is about three times the depth of exploration; for EMI the array length is of the order of the depth of exploration; for TDEM (in this case the length of the transmitter side) can be less than the depth of exploration.
[b]Electrical equivalence is the situation where more than one layered earth model will fit the measured data.

Source: Modified from Benson et al. (1984)

Standard Methods/Guidelines: Draft ASTM Standard Guide to Use of Surface Resistivity in Environmental Investigations (Nielsen, 1991).

Sources for Additional Information: Benson et al. (1984), Lord and Koerner (1987), Rehm et al. (1985), U.S. EPA (1987, 1992-Chapter 3), U.S. Geological Survey (1980), Zohdy et al. (1974). Most of the general geophysics texts identified in Table 1-4 also cover electrical methods. See also, electrical method texts identified in Table 1-5.

1.2.2 Self-Potential

Other Names Used to Describe Method: Spontaneous polarization, streaming potential.

Uses at Contaminated Sites: Identifying leaks in reservoirs and subsurface flow patterns in karst; monitoring ground-water flow at landfill sites; detecting leaks from membrane-lined sites; identifying conductive contaminant plumes.

Method Description: Electrodes are used to measure natural electrical potentials developed locally in the subsurface. Several types of natural potentials can be measured by this method. **Spontaneous polarization** is a natural voltage difference that occurs as a result of electric currents induced by disequilibria within the earth. **Streaming potential** is an electrokinetic effect related to movement of fluid containing ions through the subsurface. Figure 1.2.2a illustrates the use of the self-potential method to detect seepage into fissures in limestone and Figure 1.2.2b illustrates its use to locate a seepage zone in an earthen dam. A variant of self-potential, in which current is injected into the ground to enhance the streaming potential effect, has been developed to detect leaks in lined ponds (Figure 1.2.2c). Geomembrane liners have high resistivity and will give relatively uniform potential readings between two electrodes. If the liner is punctured, fluid flow through the leak provides a conductive path for the injected current to flow and produces anomalous readings in the moving potential electrodes near the leak.

Method Selection Considerations: **Advantages:** (1) Equipment is simple and easy to operate; (2) no source of injected current is required (does not apply to liner leak detection method); (3) useful method in karst areas where patterns of ground-water flow are difficult to predict; and (4) can locate leakage paths. **Disadvantages:** (1) Permanent installations might require placement large amounts of electrical cable; (2) other ER and EM methods generally are better for mapping of contaminant plumes; (3) interpretation is highly qualitative; and (4) susceptible to interferences dues to variations in lithology and vegetation.

Frequency of Use: Most commonly used in mineral exploration where ore bodies are in contact with solutions of different compositions. Use at contaminated sites is uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Bogoslovsky and Ogilvy (1973), Darilek and Parra (1988), Lord and Koerner (1987), Ogilvy and Bogoslovsky (1979), Redwine et al. (1985), U.S. EPA (1992-Chapter 3).

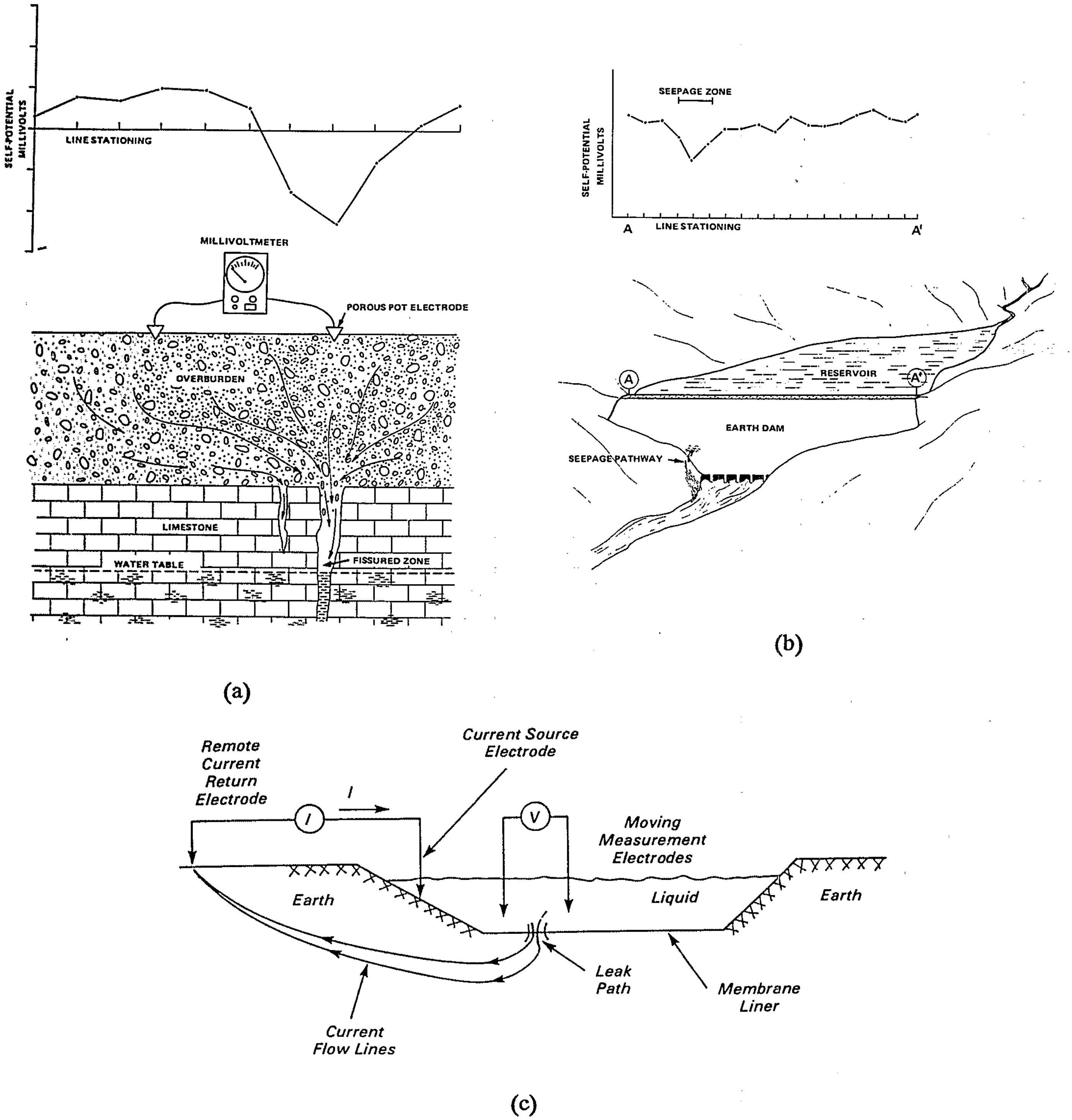


Figure 1.2.2 **Self-Potential: (a) Apparatus and graph of measurements over a fissured zone of limestone illustrating negative streaming potential induced by ground-water seepage (Modified by Redwine et al., 1985, from Ogilvy and Bogoslovsky, 1979, Copyright © 1985, Electric Power Research Institute, EPRI CS-3901, *Groundwater Manual for the Electric Utility Industry*, reprinted with permission); (b) Self-potential profile illustrating seepage zone in an earth dam (Redwine et al., 1985, from Bogoslovsky and Ogilvy, 1973, Copyright © 1985, Electric Power Research Institute, EPRI CS-3901, *Groundwater Manual for the Electric Utility Industry*, reprinted with permission); (c) Electrical leak detection using modified self-potential method (Darilek and Parra, 1988).**

1.2 SURFACE ELECTRICAL METHODS

1.2.3 Induced Polarization (IP)

Other Names Used to Describe Method: Complex resistivity.

Uses at Contaminated Sites: Conventional IP applications are similar to DC resistivity (Section 1.2.1), but can provide greater resolution for differentiation of clayey and nonclayey unconsolidated materials. Complex resistivity might be able to detect organic contaminant plumes.

Method Description: Induced polarization measures the electrochemical response of subsurface material (primarily clays) to an injected current. **Time domain** IP surveys measure the rate at which voltage decays after current injection stops (Figure 1.2.3) and **frequency domain** IP surveys measure the effect of changes in frequency on subsurface electrical resistivity. Equipment and field procedures are similar to that for DC electrical resistivity, in fact IP instrumentation can be used to conduct conventional ER surveys. **Complex resistivity** is similar to frequency domain IP using a larger frequency spectrum.

Method Selection Considerations: **Advantages:** (1) More sensitive than conventional DC resistivity in differentiating subsurface materials; and (2) might be superior to EM methods for organic contaminant plume detection when organic contaminants interact with clays. **Disadvantages:** (1) IP surveys are slower and more expensive than DC surveys and have many of the same disadvantages relative to EM methods; (2) a large amount of space is required to conduct the survey; (3) when clays are absent, ground penetrating radar (Section 1.5.1) is likely to be better for detecting organic contaminants; (4) injected currents might cause corrosion of buried metallic materials (pipelines, etc.); and (5) susceptible to interference from buried cultural features (pipelines and metallic containers).

Frequency of Use: Has been used infrequently, but with success in ground-water exploration. Use of conventional IP has not been reported at contaminated sites. Use of complex resistivity for detection of organic contaminant plumes is in developmental stages.

Standard Methods/Guidelines: None.

Sources for Additional Information: HRB Singer (1971), Lord and Koerner (1987), Pitchford et al. (1988), Rehm et al. (1985), Sumner (1979), Telford et al. (1990), U.S. EPA (1992-Chapter 3), U.S. Geological Survey (1980). See also, texts identified in Table 1-5.

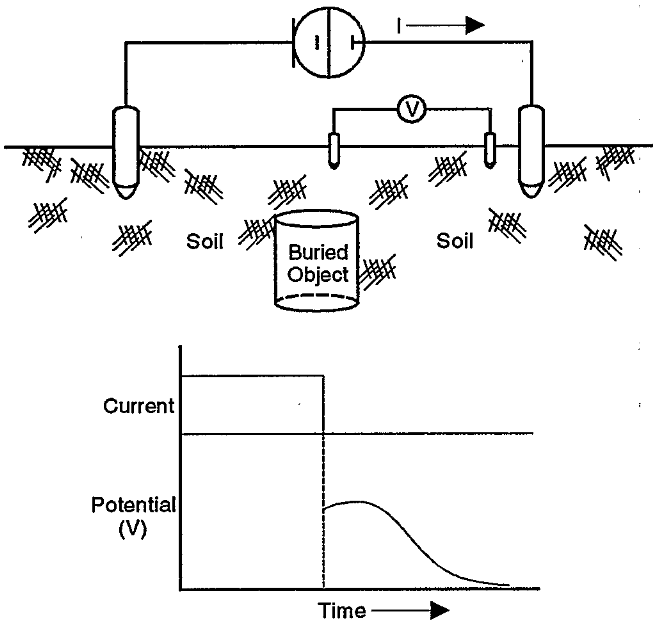


Figure 1.2.3 Principles of time domain induced polarization technique (Lord and Koerner, 1987).

1.3 SURFACE ELECTROMAGNETIC METHODS

1.3.1 Electromagnetic Induction (EMI)

Other Names Used to Describe Method: EM, terrain conductivity, frequency domain EM(I).

Uses at Contaminated Sites: Mapping conductive and possibly organic contaminant plume boundaries, and a variety of subsurface features with contrasting electrical properties; locating buried utilities, tanks and drums; subsurface stratigraphic profiling; locating abandoned wells. See also, Table 1-2.

Method Description: **Frequency domain EMI** uses a transmitter coil to generate an electromagnetic field that induces eddy currents in the earth below the instrument. Secondary electromagnetic fields created by the eddy currents are measured by a receiver coil that produces an output voltage that can be related to subsurface conductivity (Figure 1.3.1a). Conductivity readings represent the weighted cumulative sum of the conductivity variations from the surface to the effective depth of the instrument, which is determined by the spacing of the transmitting and receiving coils (Figure 1.3.1b). Near-surface readings, where the two coils are in one unit, can be made continuously, whereas deeper readings using a wider coil spacing require station measurements. Figure 1.3.1c illustrates the use of EMI over water with the transmitter towed in a raft behind a tow boat containing a receiver coil. The depth of penetration depends on the coil separation and the orientation. Coil separations in the horizontal position for commonly used equipment range from 3.7 meters (depth penetration of 3 meters) to 40 meters (depth penetration of 30 meters). Shifting the coil to a vertical orientation doubles the depth of penetration.

Method Selection Considerations: Table 1.2.2 provides comparative information on EMI, time domain EM, and electrical resistivity methods. U.S. EPA (1987) provides comparative information on commercially available EM systems. **Advantages:** (1) For mapping of shallow, conductive, contaminant plumes (up to 15 meters) EM surveys can usually be done faster (and hence more cheaply) than DC resistivity because direct contact with the ground is not required, sometimes allowing continuous operation; (2) equipment is readily available; (3) excellent capabilities for detection of buried bulk wastes with and without metal (to depths up to about 20 feet); (4) very good ability to detect single drums (6 to 8 feet) and metal tanks; and (5) rapid resolution and data interpretation. **Disadvantages:** (1) EMI is generally more susceptible to the presence of metal and powerlines on the surface than DC resistivity (see Table 1-3); (2) lacks the vertical resolution and depth penetration of electrical resistivity (where more than three major subsurface layers exist, and/or measurements to depths greater than 60 meters are required, DC resistivity [Section 1.2.1] or time domain EM [Section 1.3.2] will probably give better results); (3) data reduction is less refined than with electrical resistivity; (4) saline ground water can act to mask presence of steel drums; and (5) systems able to penetrate deeper than 60 meters are relatively expensive.

Frequency of Use: In the last decade, frequency domain EMI has replaced DC resistivity as the most commonly used surface geophysical method for contaminant plume detection.

Standard Methods/Guidelines: Draft Standard Guide for the Use of Electromagnetic Induction (Terrain Conductivity) in Environmental Investigations (Nielsen, 1991).

Sources for Additional Information: Aller (1984), Benson et al. (1984), Duran (1987), Rehm et al. (1985), U.S. EPA (1987, 1992-Chapter 4), U.S. Geological Survey (1980). See also, Table 1-5 and Table 9-3.

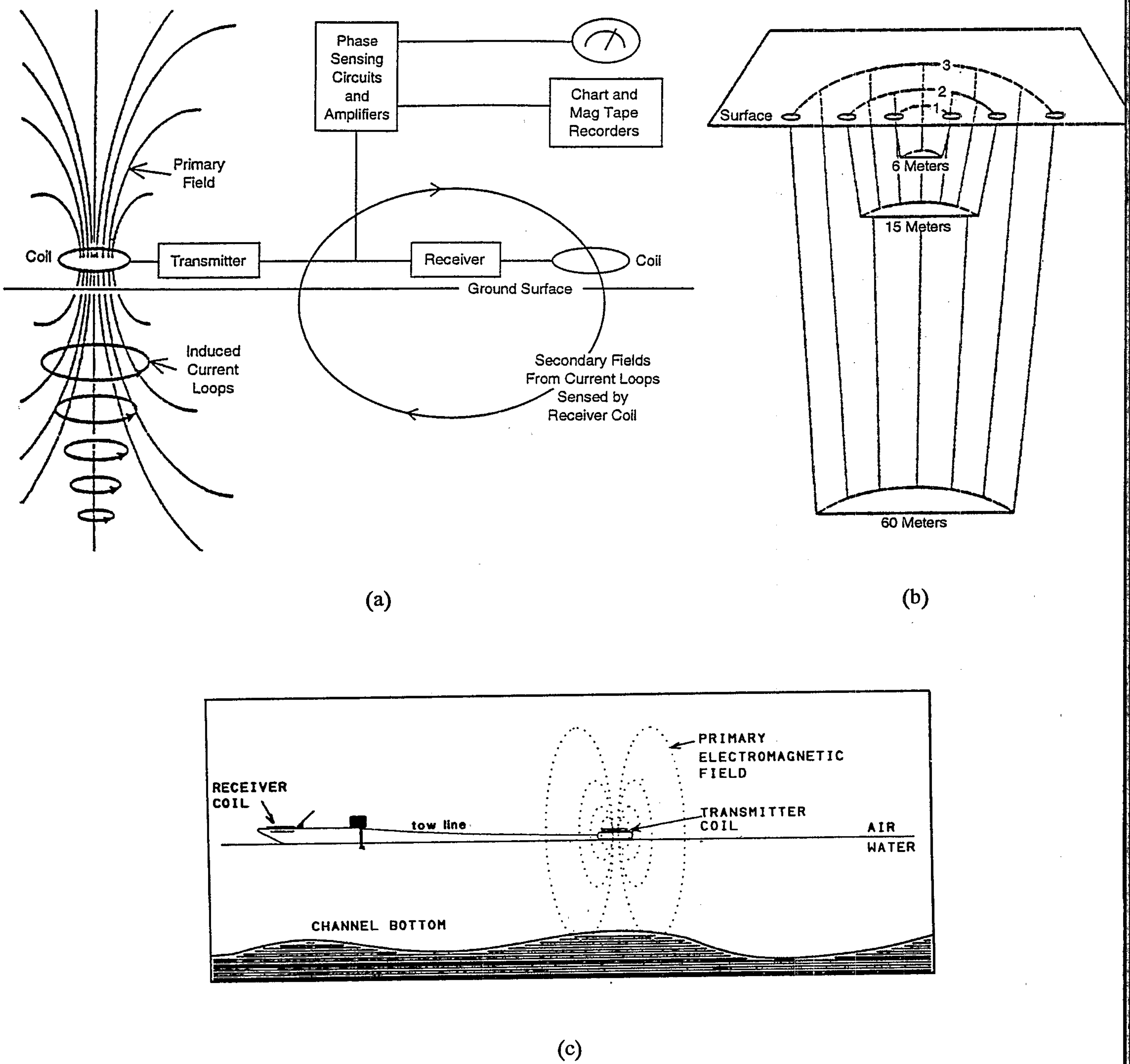


Figure 1.3.1 Electromagnetic induction: (a) Block diagram showing EMI principle of operation (adapted from Benson et al., 1984); (b) The depth of EMI soundings depends on coil spacing and orientation selected (Benson et al., 1984); (c) Use of EMI instrument over water with tow boat and raft (Duran, 1987, by permission).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.3 SURFACE ELECTROMAGNETIC METHODS

1.3.2 Time Domain Electromagnetics

Other Names Used to Describe Method: TDEM, transient electromagnetic sounding, geoelectric sounding.

Uses at Contaminated Sites: Same as EMI, except greater depth penetration possible (2,000+ meters) and greater resolution of layered earth possible (three layers or more).

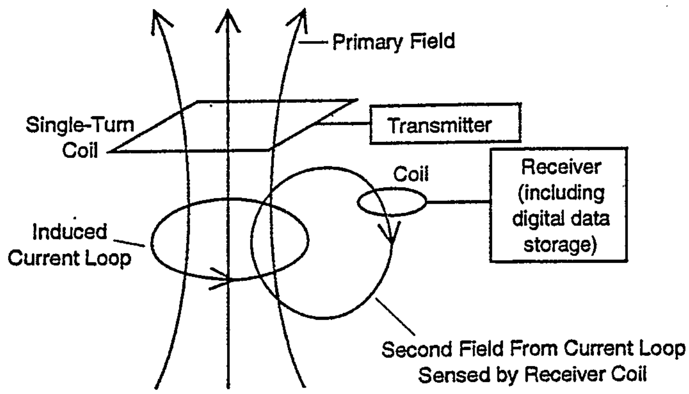
Method Description: **Time domain electromagnetic (TDEM)** instruments use a large transmitter loop on the ground and a receiving coil to measure the decaying magnetic field generated by a descending eddy current that is generated when the transmitter loop current is suddenly turned off (Figure 1.3.2a). These measurements can be interpreted in terms of the subsurface conductivity as a function of depth (Figure 1.3.2b).

Method/Device Selection Considerations: Table 1.2.2 provides comparative information on TDEM, EMI, and electrical resistivity methods. **Advantages:** (1) TDEM overcomes most of the disadvantages of EMI compared to DC resistivity, at a somewhat higher cost than EMI; and (2) able to penetrate to great depths (thousands of feet can be readily achieved). **Disadvantages:** (1) Site surface features might create difficulties in placement of the transmitter loop, which is typically 10 to 20 meters on a side; and (2) not suitable for very shallow applications (less than about 150 feet).

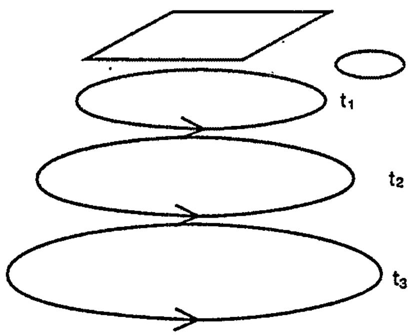
Frequency of Use: The development of TDEM equipment suitable for use at contaminated sites is relatively recent, but the increased depth of penetration and better resolution of layers is likely to result in greater use of this method.

Standard Methods/Guidelines: --

Sources for Additional Information: Felsen (1976), Fitterman and Stewart (1986), Goldman (1990), Kaufman and Keller (1983), Nabighian and Macnae (1991), U.S. EPA (1992-Chapter 4).



(a)



(b)

Figure 1.3.2 Time domain electromagnetics: (a) Block diagram showing TDEM principles of operations; (b) The depth of TDEM soundings depends on transmitter current, loop size, and time of measurement.

1.3 SURFACE ELECTROMAGNETIC METHODS

1.3.3 Metal Detection

Other Names Used to Describe Method: Eddy current.

Uses at Contaminated Sites: Locating buried metallic containers of various sizes; defining boundaries of trenches containing metallic containers; locating buried metallic tanks and pipes; avoiding buried utilities when drilling or trenching (not all instruments have adequate resolution for this application); evaluating integrity of deteriorating drums and tanks; locating abandoned wells. See also, Table 1-2.

Method Description: Metal detectors operate on the same principles as electromagnetic induction (Section 1.3.1), except that the instruments are specifically designed to sense increased conductivity resulting from either ferrous or nonferrous metals near the ground surface (Figure 1.3.3). Many different types of metal detectors are available and fall into three main classes: (1) Pipeline/cable locators, (2) conventional "treasure hunter" detectors, and (3) specialized detectors. The first two types are usually handheld, and require one person to operate. Specialized detectors are designed to handle for complex conditions, and often require two operators, or can be truck-mounted. Each class of detector is specific to certain applications and should not be used for other than its designed purpose.

Method Selection Considerations: **Advantages:** (1) MDs respond to both ferrous and nonferrous metals; (2) a wide range of commercial equipment is available, most of which is relatively easy to use; (3) all metal detectors allow continuous measurements, allowing rapid coverage; (4) less expensive and faster than ground-penetrating radar; and (5) equipment is light enough to be hand carried. **Disadvantages:** (1) Depth capability is limited to 1 to 3 meters for a single 55-gallon drum, and 3 to 6 meters for large masses of drums; (2) susceptible to a wide range of noise, including soils rich in iron minerals, metallic debris, pipes and cable, and nearby fences and metallic structures; (3) specialized equipment for difficult site conditions requires increased skill-levels to use and interpret data; (4) specialized MD equipment might not be readily available; (5) saline ground water (>15,000 mg/L total dissolved solids) can mask presence of buried steel containers; (6) unable to detect nonmetallic objects (i.e., plastic pipe with no metal detection strip) and detection of metal pipes with insulators at each pipe connection might be difficult; (7) determination of number or arrangement of buried objects is not possible; and (8) detection limits might be too high for use as a good screening device for selecting drilling locations.

Frequency of Use: EPA field investigation teams commonly use pipeline/cable locators. Specialized detectors might be desirable if available, and site conditions are complex.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller (1984), Benson (1991), Benson et al. (1984), EC&T et al. (1990), Evans and Schweitzer (1984), Lord and Koerner (1987), U.S. EPA (1992-Chapter 4).

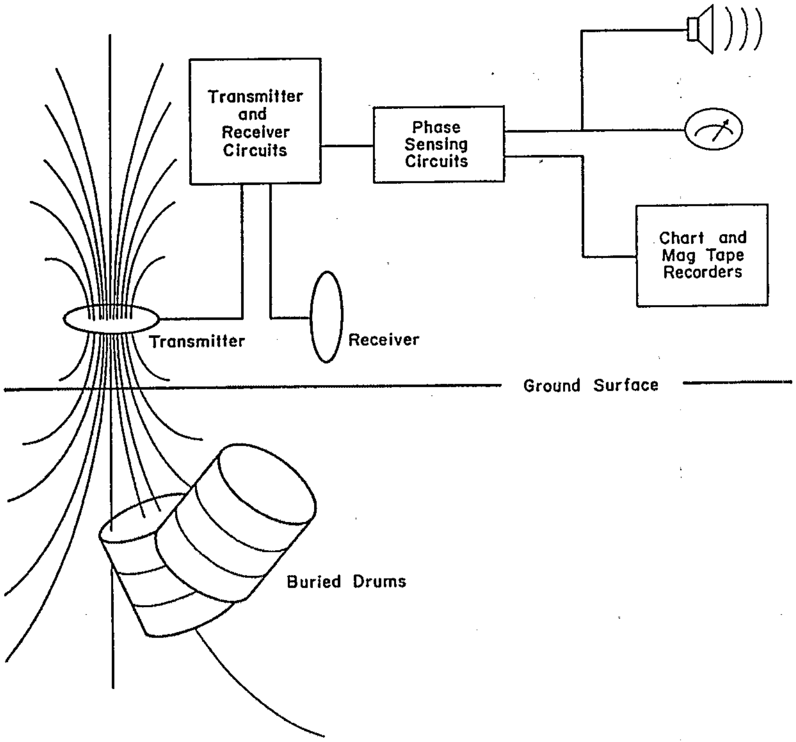


Figure 1.3.3 Simplified block diagram of a pipe/cable type metal detector system. Primary field from transmitter is distorted by buried metallic objects causing upset of null at receiver coil (Benson et al., 1984).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.3 SURFACE ELECTROMAGNETIC METHODS

1.3.4 Very-Low Frequency Electromagnetics (VLF)

Other Names Used to Describe Method: VLF resistivity.

Uses at Contaminated Sites: Similar to EM and DC resistivity.

Method Description: VLF resistivity instruments measure the ratio of electric to magnetic fields generated by military communication transmitters (around 15 to 25 kHz). Figure 1.3.4 illustrates the principal components of the VLF field. These are very low frequency **radio waves**, but are actually often higher than frequencies used in electromagnetic induction methods. The depth of penetration of these waves is related to the resistivity of the subsurface materials. Depth of penetration for contaminant plumes using the method is around 20 meters, with a maximum penetration depth of around 60 meters in saturated overburden with higher resistivities. Measurements are taken using potential electrodes driven into, or placed on, the ground at 10 meter spacing and both resistivity and the phase angle between the electric and magnetic fields are measured. Principles of data interpretation as similar to those used in magnetotelluric methods (Section 1.3.5).

Method Selection Considerations: **Advantages:** (1) Transmitting waves are generated off site at no cost; (2) the ease of taking measurements allows a high spatial density of readings; and (3) only potential electrodes are used, minimizing contact resistance problems that can occur with ER methods. **Disadvantages:** (1) Need to account for change in land surface (i.e., readings taken at different elevations are not comparable without adjustment); (2) resolution of two-layered earth requires that the resistivity of one of the layers be known or assumed.

Frequency of Use: Value has been demonstrated at contaminated sites, but used less frequently than DC resistivity and EMI.

Standard Methods/Guidelines: --

Sources for Additional Information: McNeill and Labson (1991), Stewart and Bretnall (1986), U.S. EPA (1992-Chapter 4).

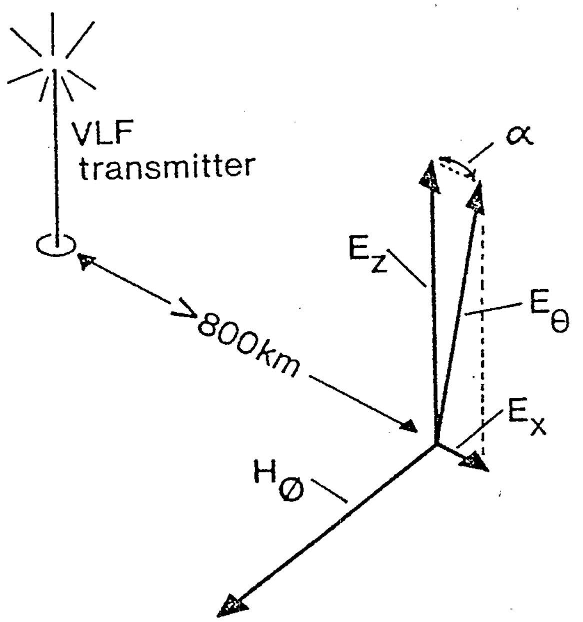


Figure 1.3.4 **Principal components of the primary VLF field at distances greater than 800 km from the transmitter. E_θ and H_ϕ are the electrical and magnetic components of the field, respectively, E_z and E_x are the vertical and horizontal components of E_θ. The angle α is the tilt of the electrical field from the vertical. Both α and E_x increase with increasing terrain resistivity (Stewart and Bretnall, 1986, by permission).**

1.3.5 Magnetotellurics (MT)

Other Names Used to Describe Method: Telluric current method, magnetotelluric method, audiofrequency MT, audiofrequency magnetic (AFMAG), MT array profiling (EMAP), controlled-source audiomagnetotellurics (CSAMT).

Uses at Contaminated Sites: Mapping of large geologic structures; regional ground water mapping; mapping of brine contamination from unplugged wells (CSAMT); water saturated fracture tracing in rock; detection of fault displaced masses of rock.

Method Description: Telluric currents are natural electric currents that flow in the subsurface in response to ionospheric tidal effects and lightning associated with thunderstorms. The **telluric current** method measures field intensity using four electrodes set in intersecting perpendicular lines and is, strictly speaking, an electrical method. **Magnetotelluric** (MT) geophysical methods involve the measurement of magnetic and electric fields associated with the flow of telluric currents. **Audiofrequency MT** (AMT) is the same as MT, except audio frequencies are measured. **Audiofrequency magnetic** (AFMAG) methods measure the tilt angle of total magnetic field on a surface or in the air. **MT array profiling** (EMAP) is MT with numerous measurements of a surface electric field to try to reduce static effect errors resulting from localized changes in conductivity of near-surface materials. These static effects can result in erroneous readings at all frequencies, which makes accurate interpretations of data difficult. The above-mentioned methods all measure natural currents. **Controlled-source audiomagnetotellurics** (CSAMT) uses a remote transmitter combined with an AMT receiver (Figure 1.3.5).

Method Selection Considerations: **Advantages:** (1) MT methods can reach depths much greater than can be reached effectively using artificially induced currents; and (2) CSAMT has been found to have excellent lateral resolution, good depth penetration (1 kilometer or more), and is relatively inexpensive for mapping oil field brine contamination. **Disadvantages:** (1) Static effect errors (see EMAP above) are a common problem with all MT methods; and (2) for shallow investigations, most other electrical and EM methods are more accurate and easier to use.

Frequency of Use: MT methods have been used primarily in connection with regional geological investigations related to mineral exploration. CSAMT has been used in regional ground-water investigations, and has recently been successfully used to detect the movement of formation brines into freshwater aquifers through improperly abandoned or plugged wells.

Standard Methods/Guidelines: None.

Sources for Additional Information: Kaufman and Keller (1981), Porstendorfer (1975), Tinlin et al. (1988-CSAMT), U.S. EPA (1992-Chapter 4), U.S. Geological Survey (1980), Vozoff (1986, 1991), Wait (1982), Zonge and Hughes (1991-CSAMT).

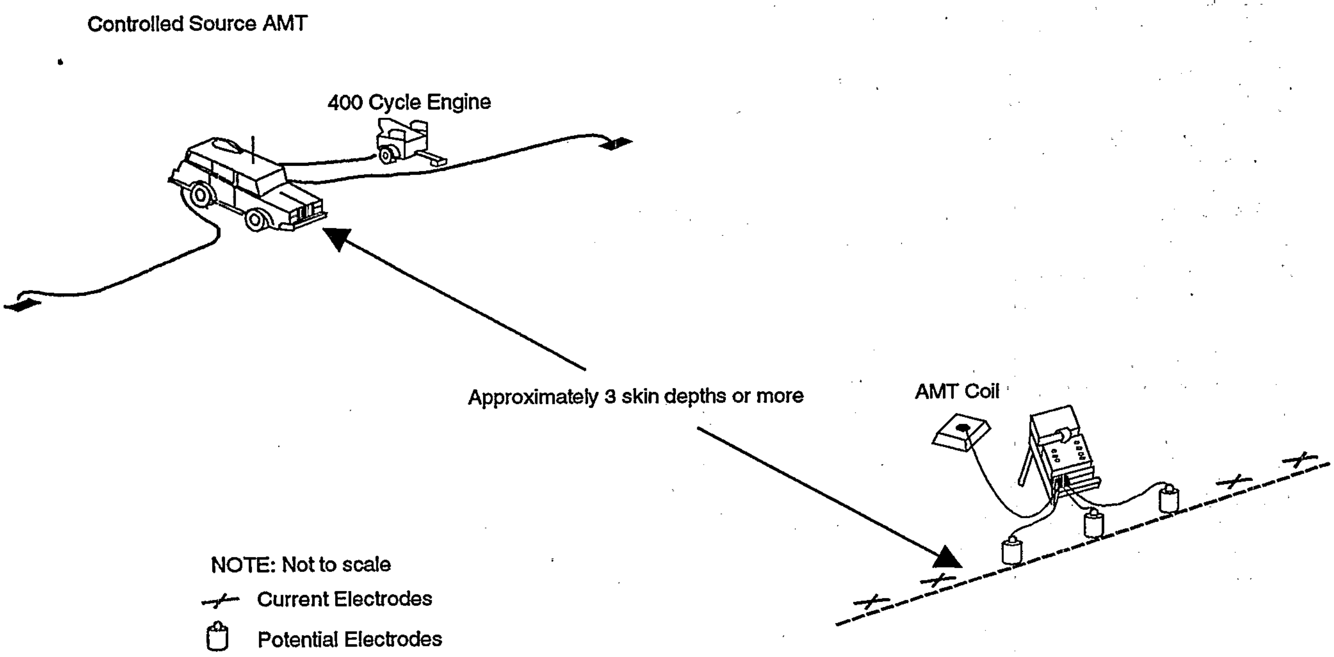


Figure 1.3.5 Layout for controlled source AMT survey (Tinlin et al., 1988, Copyright ASTM, reprinted with permission).

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.1 Seismic Refraction

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Ground-water and subsurface stratigraphic profiling (including the top of bedrock); mapping buried channels; measuring depth to ground water; mapping lateral facies variations in an aquifer; estimating porosity. See also, Table 1-2.

Method Description: An artificial seismic source (hammer, controlled explosive charge) creates direct compressional waves that are refracted by traveling along the contact between geologic boundaries before signals from the wave reach the surface again (Figure 1.4.1a). The refracted waves are sensed using electromechanical transducers, called geophones, which are attached to a seismograph. The seismograph records the time of arrival of all waves, using the moment the seismic source is set off as time zero. Travel time is plotted against source-to-geophone distance to produce a time/distance (T/D) plot. Line segments, slope and break points in the T/D plot, are then analyzed to identify the number of layers and depth of each layer. Figure 1.4.1b shows steps in processing and interpretation of seismic refraction data. Figure 1-2 shows typical seismic velocity ranges for various soil and rock types.

Method Selection Considerations: **Advantages:** (1) Equipment is readily available, portable, and relatively inexpensive; (2) provides depth of penetration of around 30 meters; (3) technique is accurate and provides rapid areal coverage; and (4) interpretation is generally straightforward (not exception below). **Disadvantages:** (1) Resolution might be obscured by layered sequences where velocity of layers decreases with depth (inversion), and thin layers, called blind zones, might not be detected; (2) susceptible to noise from urban development (such as ground vibrations from construction activity and electrical noise [see Table 1-3]); (3) use might be limited by cold or wet weather; (4) relatively time and labor intensive; (5) good data acquisition and resolution requires experience operator; (6) seismic sources for deep surveys require considerable energy; (7) only fair ability to detect buried bulk wastes, but might provide depth; and (8) does not detect contaminants in ground water.

Frequency of Use: Commonly used for near surface hydrogeologic studies and subsurface characterization of contaminated sites.

Standard Methods/Guidelines: Draft Standard Guide for the Use of Seismic Refraction in Environmental Investigations (Nielsen, 1991).

Sources for Additional Information: Redwine et al. (1985), Rehm et al. (1985), U.S. EPA (1987, 1992-Chapter 5), U.S. Geological Survey (1980), Zohdy et al. (1974). Most of the general geophysics texts identified in Table 1-4 also cover seismic methods. See also, seismic texts identified in Table 1-5.

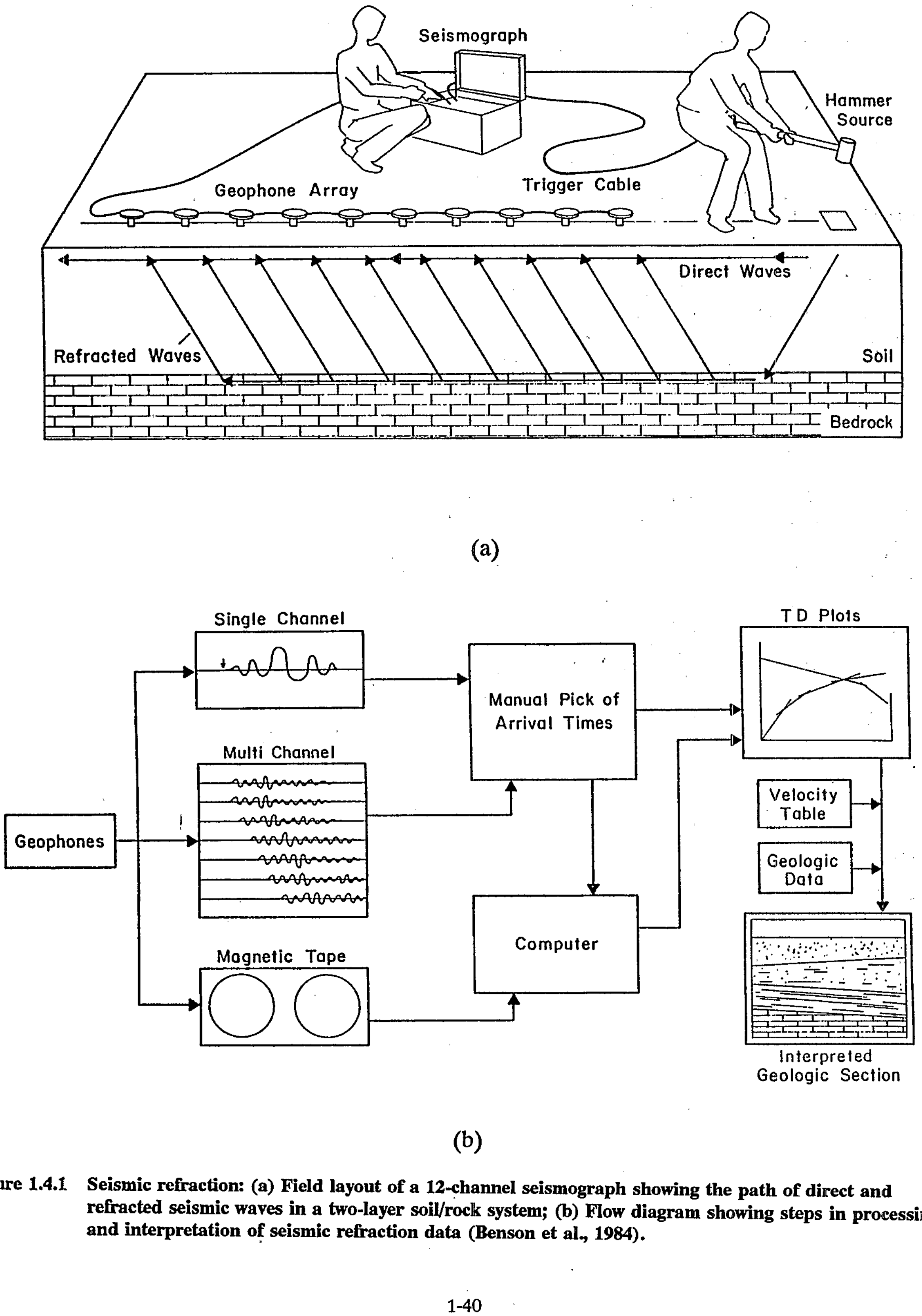


Figure 1.4.1 **Seismic refraction: (a) Field layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system; (b) Flow diagram showing steps in processing and interpretation of seismic refraction data (Benson et al., 1984).**

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.2 Seismic Reflection

Other Names Used to Describe Method: Shallow seismic reflection, common-offset reflection, common-depth point reflection, common midpoint (CMP) reflection.

Uses at Contaminated Sites: High resolution mapping of bedrock-unconsolidated contact at intermediate depths (typical minimum of 10 to 30 meters); high resolution mapping of stratigraphy and rock type at greater depths (more than 70 meters).

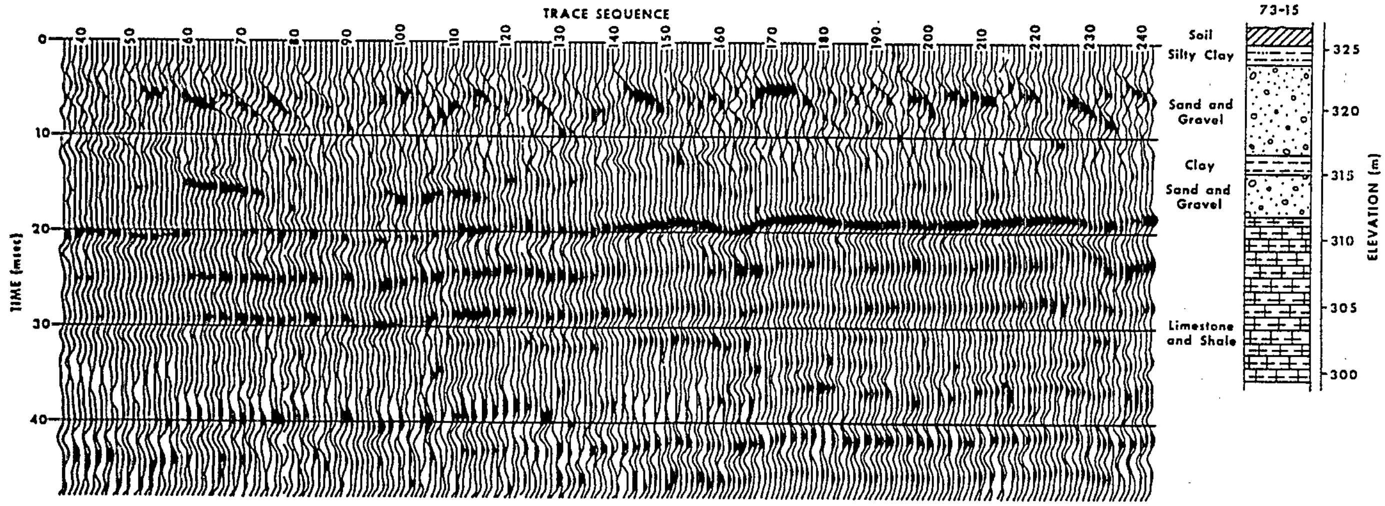
Method Description: Generally similar to seismic refraction (Section 1.4.1). Surveys are usually conducted with shorter spacing but with more geophones compared to a refraction survey for similar depths. In addition to recording the time of first arrival, numerous arrivals of reflected waves are recorded at each geophone, and multiple shots are used to create seismic waves (Figure 1.4.2.a), resulting in more data being recorded and requiring more complex data processing. Conventional reflection methods are designed for obtaining stratigraphic and structural data at depths greater than 70 meters. Relatively recent development of high resolution methods, such as the **common-depth-point** (CDP), can yield good data at depths as shallow as 15 to 30 meters (Figure 1.4.2b). The **common-offset** method has been successfully used at interfaces as shallow as 2.7 meters (but a more typical minimum depth would be around 10 meters).

Method Selection Considerations: **Advantages:** (1) Seismic reflection methods provide higher resolution than seismic refraction; (2) smaller energy sources are required; (3) shorter spacing of geophones allows greater areal coverage for any given spacing; (4) velocity inversions do not affect accuracy as with seismic refraction, and thin layers are easier to detect; and (5) data printout straightforward to interpret. **Disadvantages:** (1) Results are much more difficult to interpret and precise interpretation requires computer processing; (2) more complex instrumentation and data analysis results in generally higher costs than for seismic refraction; (3) steeply dipping boundaries create problems for interpretation; and (4) sensitive to vibrations and electrical noise. Seismic refraction is usually better for very shallow investigations, but should no longer be assumed to be the method of choice where depths greater than 3 to 15 meters are of interest.

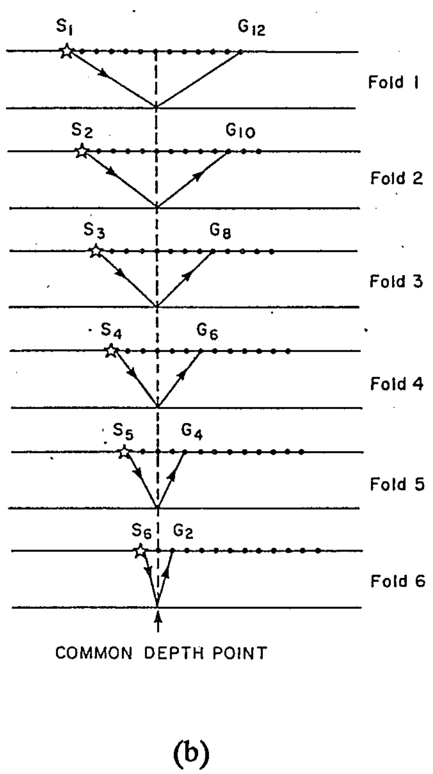
Frequency of Use: High resolution seismic reflection methods are a relatively new development that will probably become more widely used compared to seismic refraction because of higher resolution.

Standard Methods/Guidelines: --

Sources for Additional Information: Ayers (1989), Badley (1985), Hunter and Pullan (1989-common-offset), Kleyn (1983), Knapp and Steeples (1986a,b-CDP), Redwine et al. (1985), Steeples and Miller (1988-CDP), U.S. EPA (1987, 1992-Chapter 5), U.S. Geological Survey (1980), Waters (1981).



(a)



(b)

Figure 1.4.2 Shallow seismic reflection: (a) Example of CDP seismic time section and relationship to actual stratigraphic section; (b) Field procedure for obtaining sixfold CDP coverage with a single-ended 12-channel geophone spread moved progressively along the survey line (adapted from Kearey and Brooks, 1984, by Ayers, 1989, by permission).

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.3 Continuous Seismic Profiling (CSP)

Other Names Used to Describe Method: Acoustical/continuous high-resolution subbottom profiling, marine seismic reflection.

Uses at Contaminated Sites: Defining lithologic boundaries of shallow aquifers; assessing lithology of glacial deposits; determining unconsolidated material/bedrock contact. (Note: These uses are possible (provided that area of interest is crossed by rivers, large streams, or contains lakes, reservoirs, ponds or estuaries.)

Method Description: Continuous seismic profiling is adapted from methods originally used in deep-water marine geology investigations, and differs from land-based seismic techniques in that only one channel is used to detect signals. In shallow water, high-resolution, single-channel, continuous-seismic reflection equipment is towed through the water alongside or behind the survey boat (Figure 1.4.3a). The energy source (electromechanical transducers, sparkers, or airguns) emit sounds at a fixed frequency, or with a range of frequencies into the water. The receiver, called a hydrophone, detects the reflected acoustic signals to create a profile of the subsurface below the line of travel of the boat (Figure 1.4.3b). Usually the raw record can be used for direct interpretation with no further processing. The position of the boat must be established and maintained throughout the survey, using methods ranging from multiple land survey crews with ranging equipment to sophisticated microwave locationing systems. A grid pattern of survey lines allows a three dimensional representation of the subsurface. A fathometer survey (Section 1.4.6) is usually conducted simultaneously to provide an indication of water depth to assist in calculation of thicknesses of sub-bottom strata.

Method Selection Considerations: **Advantages:** (1) Relatively fast and inexpensive; (2) electromechanical transducers can emit a wide range of frequencies and provide good depth penetration and moderate to high resolution; low-frequency energy sources (sparkers and airguns) achieve deeper penetration into the subsurface but provide less resolution; (3) sediment types, such as sand and clay, can be differentiated with higher frequency systems; and (4) data printout is straightforward to interpret. **Disadvantages:** (1) Limited to water bodies that are large enough or continuous enough to provide the desired areal coverage; (2) steeply dipping boundaries create problems for interpretation; (3) sensitive to vibrations and electrical noise; and (4) material velocities must be known for depth calculations.

Frequency of Use: Uncommonly used for site specific investigations because of requirement for large water bodies.

Standard Methods/Guidelines: --

Sources for Additional Information: Haeni (1986), Redwine et al. (1985), U.S. EPA (1992-Chapter 5). See also, texts identified in Table 1-5.

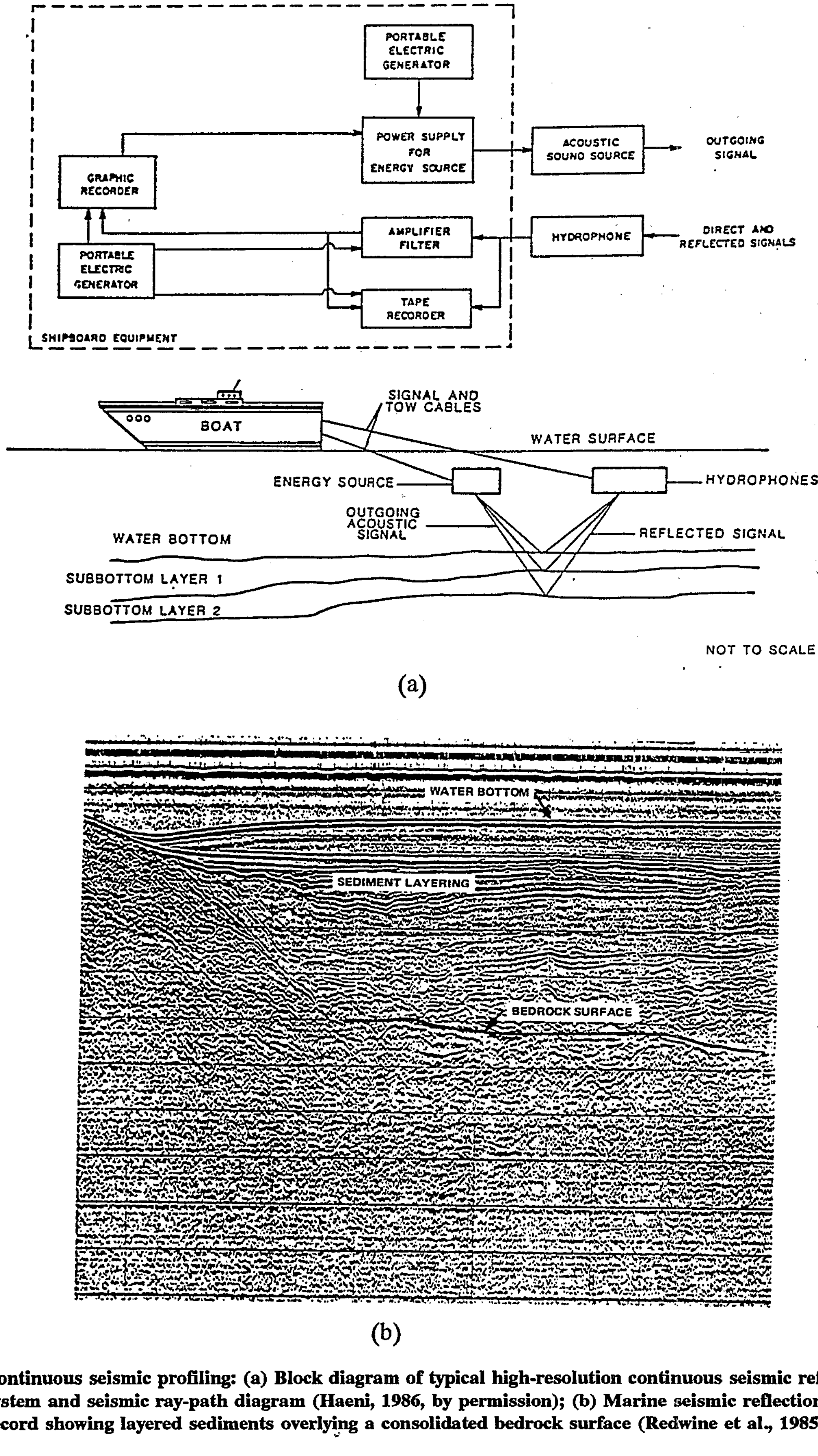


Figure 1.4.3 Continuous seismic profiling: (a) Block diagram of typical high-resolution continuous seismic reflection system and seismic ray-path diagram (Haeni, 1986, by permission); (b) Marine seismic reflection record showing layered sediments overlying a consolidated bedrock surface (Redwine et al., 1985).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.4 Seismic Shear and Surface Waves

Other Names Used to Describe Method: Spectral analysis of surface waves (SASW).

Uses at Contaminated Sites: **Seismic shear:** Detecting subsurface fissures caused by subsidence; differentiating water table from weathered bedrock (in combination with seismic refraction); potential for determining the distribution and orientation of fractures; **SASW:** Characterizing strength of soil materials.

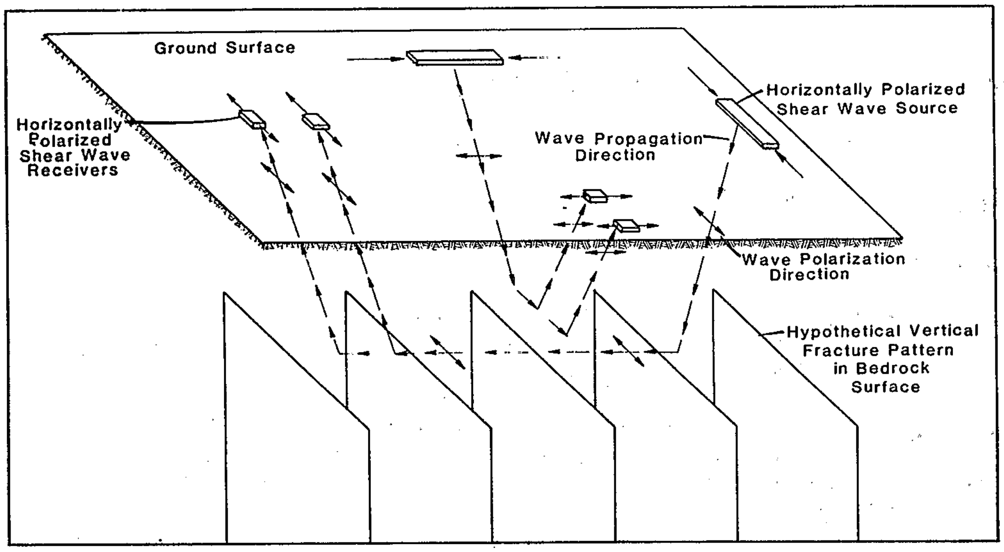
Method Description: **Seismic shear:** Basic instrumentation is similar to seismic refraction and reflection methods, except that layouts are modified to record the time of arrival of seismic shear waves (S waves), in which particles move transverse to the direction of propagation of the wave rather than back and forth as in a compressional (P wave), which is observed in seismic refraction and reflection. Figure 1.4.4a shows schematic receiver geometry for a shear wave refraction spread. Shear waves are commonly generated using a sledgehammer blow delivered to the soil at an angle to the ground surface, or by using a set of three sequential explosive shots. Both reflection and refraction of shear waves can be measured and analyzed. **SASW:** Method for measuring G_{max} of soil with depth, without the use of boreholes (see Section 3.4.6 for cross borehole methods). The technique uses two vertical transducers placed on the ground surface at equal distances from an imaginary centerline (Figure 1.4.4b). A vertical impulse is generated on the ground surface, and surface waves of the Rayleigh type are monitored as they propagate past the two transducers. Successive seismic impulses of different wavelengths allow sampling different depths of soil, with low frequency waves sampling greater depths.

Method Selection Considerations: **Seismic Shear Advantages:** (1) Has been found to be more successful than seismic refraction or reflection in detecting subsurface fissures that have developed where overpumping of ground water has caused subsidence; and (2) in combination with seismic refraction data, allows differentiation of a ground-water surface from other lithologic contacts. **Seismic Shear Disadvantages:** (1) Addition of shear wave generation and analysis to seismic surveys adds to the complexity and cost of surveys; and (2) applications such as mapping of water-table surface can usually done with simpler and less expensive methods. **SASW Advantages:** Boreholes are not required as with other methods for measuring G_{max}. **SASW Disadvantages:** (1) Relatively sophisticated computer programs, which are not readily available, are required to analyze data; and (2) results might be less accurate than crosshole method for layered soils with inclined boundaries and heterogenous soils.

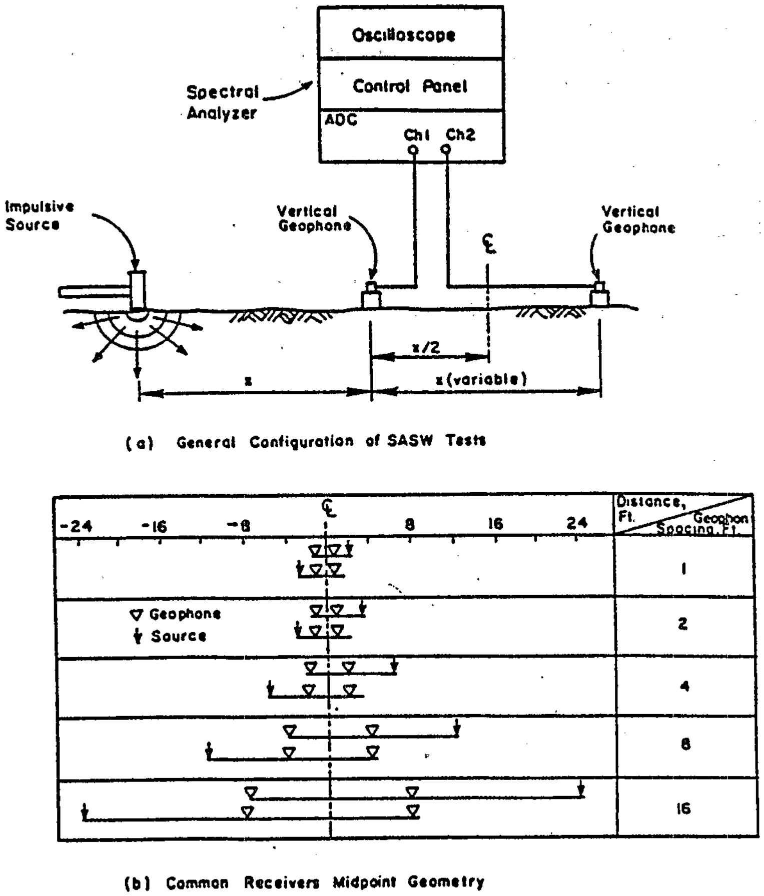
Frequency of Use: Uncommon.

Standard Methods/Guidelines: None.

Sources for Additional Information: Bates et al. (1991), CH2M Hill (1991-seismic shear, SASW), Danbom and Domenico (1987), Dohr (1985), Ensley (1987-bibliography), Stokoe and Nazarian (1985-SASW), U.S. EPA (1987-Chapter 5), Woods (1985-seismic shear, SASW).



(a)



(b)

Figure 1.4.4 Other seismic methods: (a) Schematic receiver geometry for shear wave refraction spreads (Bates et al., 1991, by permission); (b) Spectral analysis of surface waves test (CH2M Hill, 1991, after Stokoe and Nazarian, 1985, by permission).

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.5 Acoustic Emission Monitoring

Other Names Used to Describe Method: Microseismic method.

Uses at Contaminated Sites: Detecting sounds generated by instabilities in features such as dams and slopes, retaining walls, footings, underground tunnels, mines, and quarries. Provides early warning for instability in structures where remedial actions have been carried out.

Method Description: Subaudible sound waves cause the release of stored elastic-strain energy in stressed materials (such as dislocations, grain boundary movement and initiation, and propagation of fractures (between mineral grains) are monitored. A wave guide (steel rod or plastic pipe), inserted in the ground or lowered down a borehole, transmits signals to a sensor (Figure 1.4.5). The sensor, an accelerometer, converts the mechanical wave energy to an electrical signal, which is filtered and amplified. A signal counter records a count each time a the signal exceeds a threshold that is above the background noise level. Preliminary testing to determine background noise levels from such factors as wind, thunderstorms, barometric changes, power lines, operation of nearby machinery, passing airplanes, and vehicular traffic, is required. Monitoring can be continuous or periodic.

Method Selection Considerations: **Advantages:** (1) Acoustic emission monitoring is inexpensive and simple to carry out; (2) interpretation is generally uncomplicated; and (3) best of available methods for monitoring dike stability. **Disadvantages:** Intermittent sources of background noise (see method description above) can cause erroneous interpretations.

Frequency of Use: Relatively uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Davis et al. (1984), Lord and Koerner (1987), Redwine et al. (1985), U.S. EPA (1979, 1992-Chapter 5), Waller and Davis (1984).

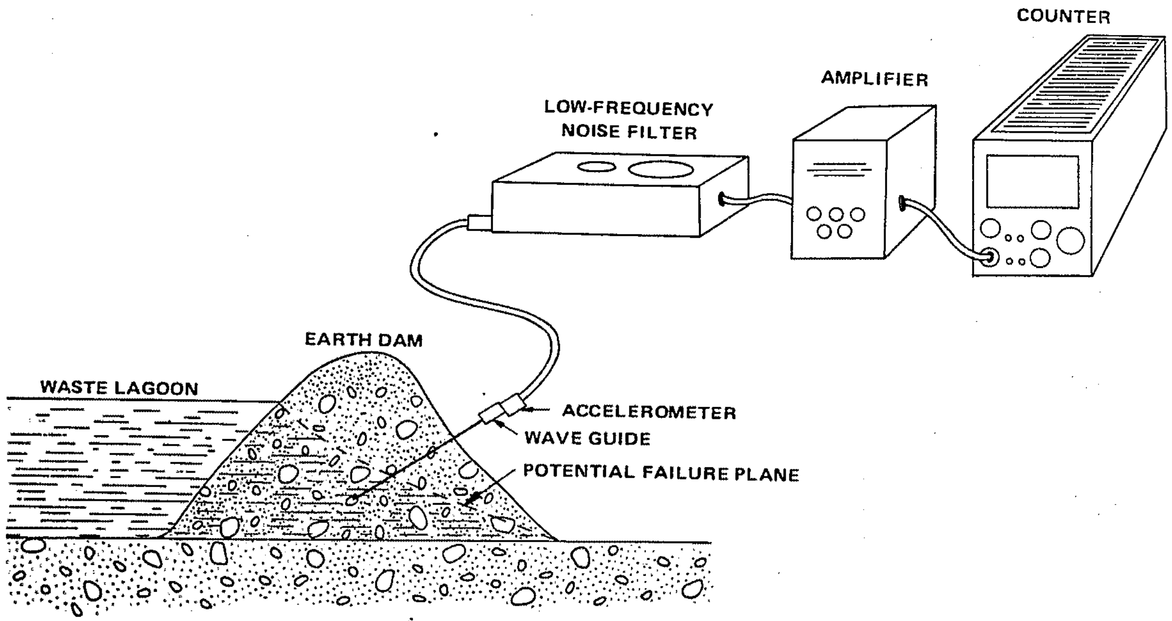


Figure 1.4.5 Acoustic emission monitoring system set up to detect acoustic emissions generated by a potential failure plane in a an earth dam (U.S. EPA, 1979).

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.6 Sonar

Other Names Used to Describe Method: Side-scan sonar, fathometer water bottom surveys, color fathometer.

Uses at Contaminated Sites: **Side-scan sonar:** Detecting leakage sources of sinkholes in water bodies (reservoirs and lakes, holding ponds, and waste disposal ponds); possible applications for detecting DNAPLs in water bodies. **Fathometer:** Constructing bottom-topography profiles or contour maps below water bodies to locate subsidence features and to assist in interpreting continuous-seismic reflection surveys.

Method Description: **Side-scan sonar:** A towfish containing transducers that send bursts of high-intensity, high-frequency acoustic signals and receive the echoes is pulled behind a boat (Figure 1.4.6). The signals are amplified and processed to create an image of the water bottom surface that can cover as much as several hundred meters on both sides of the survey line. Imagery resolution is sufficient to identify details such as bedrock outcrops, rough or smooth mud surfaces, sand surfaces, gravel or boulders, and collapse features. **Fathometer:** Similar to side-scan sonar, except that it only records bottom topography directly below the instrument. A fathometer survey is required for accurate interpretation of continuous-seismic profiles (Section 1.4.3). Both instruments can be used in conjunction with an underwater magnetometer to locate metal containers at or below the sediment surface.

Method Selection Considerations: **Side-Scan Sonar Advantages:** (1) Provides very high-resolution imagery; and (2) wide area of coverage allows for few survey lines without gaps in data and also allows rapid coverage. **Side-Scan Sonar Disadvantages:** (1) Relatively expensive due to cost of leasing equipment, boat, and operators; (2) does not provide water depths or sub-bottom information; and (3) cables might catch on underwater debris. **Fathometer Advantages:** (1) Inexpensive; and (2) data interpretation is easy. **Fathometer Disadvantages:** Records only surface directly below the instrument, and so it might miss features between survey lines.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Redwine et al. (1985), Saucier (1970), U.S. EPA (1992-Chapter 5).

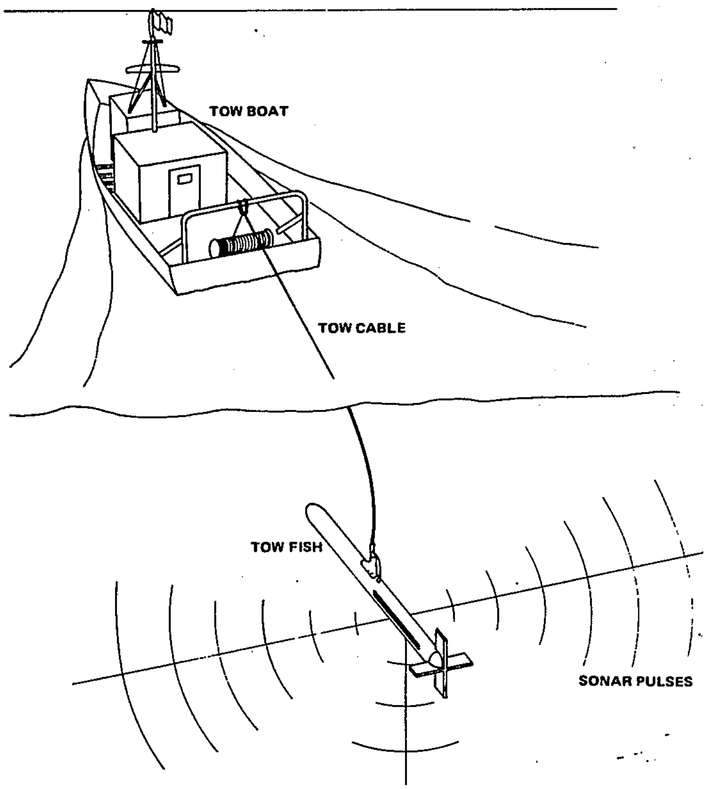


Figure 1.4.6 Side-scan sonar system (Redwine et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI CS-3901, *Groundwater Manual for the Electric Utility Industry*, reprinted with permission).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.4 SURFACE SEISMIC AND ACOUSTIC METHODS

1.4.7 Pulse-Echo Ultrasonics

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Monitoring of surface container corrosion, buried container stability, and buried pipeline leaks.

Method Description: A pulse of elastic energy, typically a few micro seconds long and a frequency of about 1 MHz, is beamed into the material being investigated. The elastic wave is reflected from cracks, and discontinuities within the material and the nature of the reflected pattern gives an indication of the depth and spatial extent of cracks and discontinuities (Figure 1.4.7).

Method Selection Considerations: **Advantages:** (1) Method is well-developed for testing integrity of surface containers; and (2) commercial equipment is readily available. **Disadvantages:** Limited actual field use experience at contaminated sites.

Frequency of Use: Uncommon at contaminated sites.

Standard Methods/Guidelines: --

Sources for Additional Information: Lord and Koerner (1980, 1987), McGonnagle (1961), Sharp (1970).

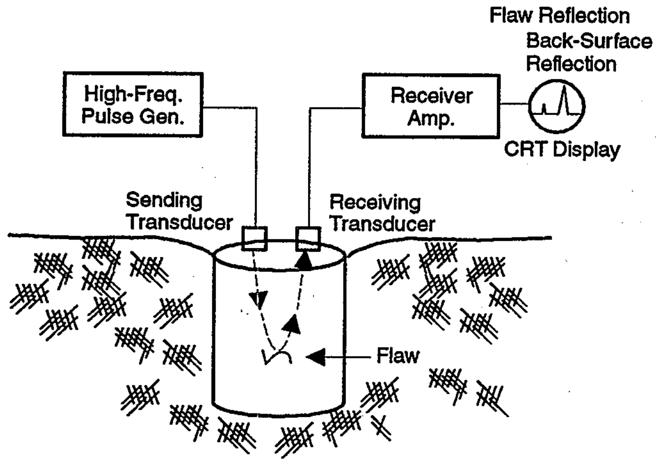


Figure 1.4.7 Principles of pulse-echo ultrasonics (Lord and Koerner, 1987).

1.5 OTHER SURFACE GEOPHYSICAL METHODS

1.5.1 Ground-Penetrating Radar (GPR)*

Other Names Used to Describe Method: Ground-piercing radar, ground-probing radar, subsurface impulse radar, pulsed microwave, pulsed radio frequency, electromagnetic subsurface profiling, continuous microwave.

Uses at Contaminated Sites: Locating buried objects (only reliable method for detecting buried plastic containers); mapping of depth to shallow water table; delineating soil horizons, bedrock subsurface, and structure; detecting buried containers and leaks; mapping of trench boundaries; delineating karst features; delineating physical integrity of manmade earthen structures; selecting locations for installation of suction samplers in the vadose zone. See also, Table 1-2.

Method Description: **GPR:** A transmitting and a receiving antenna are dragged along the ground surface. The small transmitting antenna radiates short pulses of high-frequency radio waves (ranging from 10 to 1,000 mHz) into the ground and the receiving antenna records variations in the reflected return signal (Figure 1.5.1a). The principles involved are similar to reflection seismology, except that electromagnetic energy is used instead of acoustic energy, and the resulting image is relatively easy to interpret (Figure 1.5.1b). **Continuous microwave:** Similar to GPR except that a range of frequencies is continuously emitted resulting in interference patterns between the emitted and reflected wave. The spacing (in frequency) between interference maxima or minima as the emitting frequency changes gives the depth of the reflecting surface.

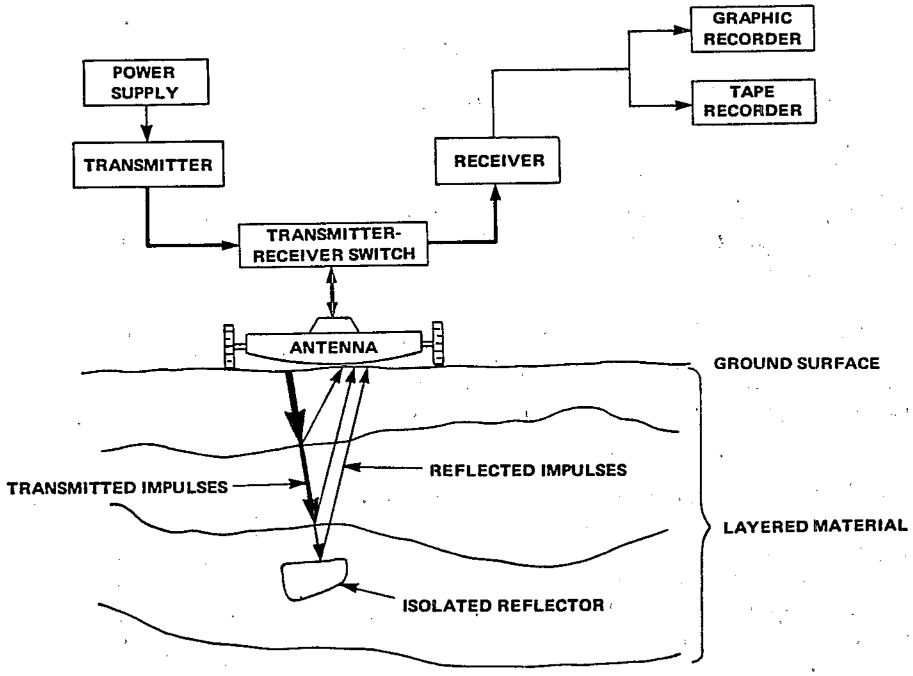
Method Selection Considerations: **GPR Advantages:** (1) Profiles give the greatest resolution of currently available surface geophysical methods; (2) best penetration is achieved in dry, sandy or rocky areas (up to 25 meters); and (3) where site conditions are favorable, rapid areal coverage is possible. **GPR Disadvantages:** (1) Depth of penetration (typically 1 to 15 meters) is less than DC resistivity and EM methods, and is further reduced in moist and/or clayey soils and soils with high electrical conductivity; (2) bulkiness of equipment limits use in rough and inaccessible terrain; (3) FM radio transmissions might interfere with signals depending on the frequency, and unshielded antennas are susceptible to interference by metallic materials (see Table 1-3); (4) bouldery till might scatter signal, masking underlying bedrock; and (5) unprocessed images give only approximate shapes and depths and require processing to obtain true shape and depth. **Continuous Microwave** methods are still in developmental stages.

Frequency of Use: Probably the most frequently used surface geophysical method after EMI and DC resistivity.

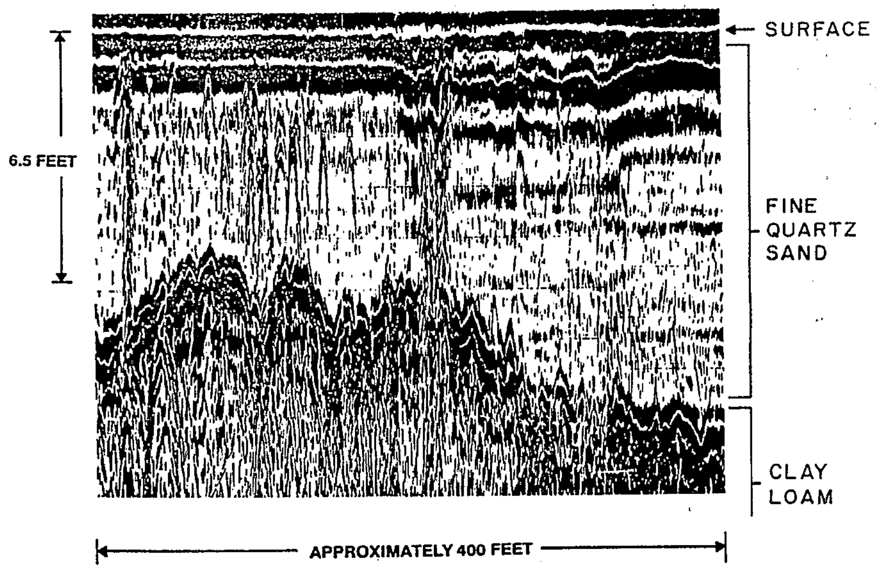
Standard Methods/Guidelines: Draft ASTM Standard Guide to the Use of Ground-Penetrating Radar in Environmental Investigations (Nielsen, 1991).

Sources for Additional Information: Benson et al. (1984), Beres and Haeni (1991), Daniels (1989), Douglas et al. (1992), Lord and Koerner (1987), Olhoeft (1988-bibliography), Pittman et al. (1984), Redwine et al. (1985), Trabant (1984), Truman et al. (1991), Ulriksen (1982), U.S. EPA (1987, 1992-Chapter 6). See also, Table 1-5. **Subsurface dielectric properties:** Figure 1-2, Akhadov (1980), Daniel (1967), Hasted (1974), Hoekstra and Delaney (1974), Kracchman (1970), Tareev (1975), van Beek (1965), von Hippel (1954a,b). See also, Table 6-2 listing for references on dielectric sensors.

*Following the convention of Benson et al. (1984), ground-penetrating radar is not placed in the section on electromagnetic methods (Section 1.3) due to the higher frequencies involved.



(a)



(b)

Figure 1.5.1 Ground-penetrating radar: (a) Ground-penetrating radar apparatus (Redwine et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI CS-3901, *Groundwater Manual for the Electric Utility Industry*, reprinted with permission); (b) GPR profile of quartz and over clay (Benson et al., 1984).

1.5 OTHER SURFACE GEOPHYSICAL METHODS

1.5.2 Magnetometry

Other Names Used to Describe Method: Fluxgate gradiometer/magnetometer, proton magnetometers/nuclear resonance magnetometer. Other names that are less commonly used include: Dip needles, deflection magnetometers, induction variometer.

Uses at Contaminated Sites: Locating buried steel containers, such as 55-gallon drums; defining boundaries of trenches filled with ferrous containers; locating ferrous underground utilities, such as iron pipe or tanks, and associated permeable pathways; selecting drilling locations that are clear of buried drums, underground utilities, and other obstructions; locating buried ferrous slag dumping areas; location of abandoned wells. See also, Table 1-2.

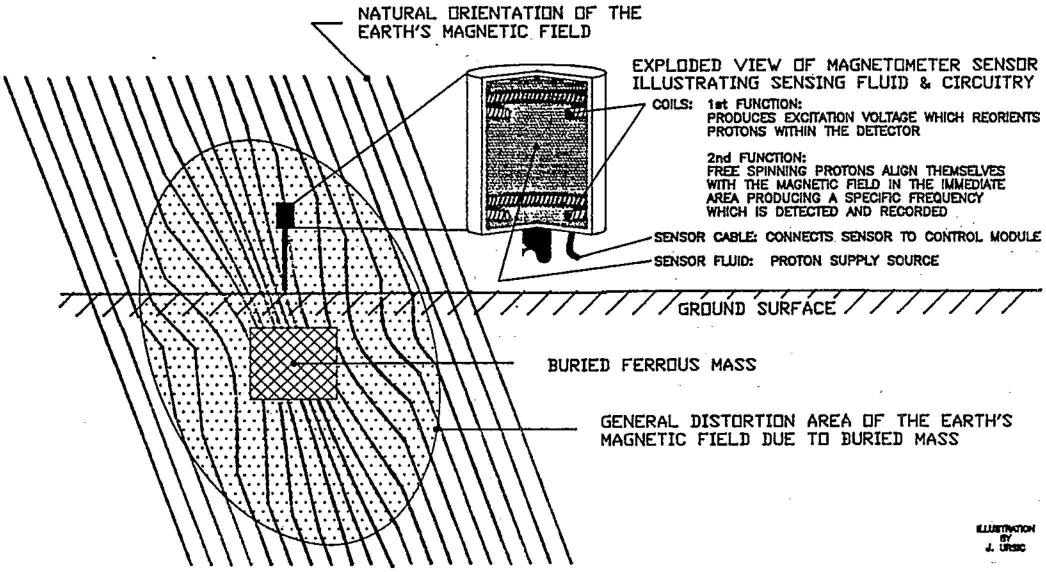
Method Description: Magnetometers measure either intensity of the earth's total magnetic field at a point or gradients in the magnetic field. **Proton magnetometers** are usually used to measure the strength of the earth's total magnetic field at a point, requiring a closely-spaced grid of station measurements to provide complete coverage of a site. **Fluxgate gradiometers** allow continuous measurement of the gradient in the magnetic field along a transect. Anomalous readings (measured as gammas) indicate the presence of ferrous metals (Figure 1.5.2). Typically, single drums can be detected at distances up to 6 meters and massive piles detected at distances of 20 meters or more. **Underwater** magnetometers can be used in conjunction with fathometers and sidescan sonar (Section 1.4.6) to detect metal containers that have been buried by sediments or shifting sand.

Method Selection Considerations: **Proton Magnetometer Advantages:** Provide the most sensitive reading variations in the magnetic field. **Proton Magnetometer Disadvantages:** (1) Require station measurements; and (2) more susceptible to noise than fluxgate gradiometers. **Fluxgate Gradiometer Advantages:** (1) Less susceptible to noise than proton magnetometers; and (2) generally less expensive to operate because continuous measurements provide more rapid coverage. **General Disadvantages:** (1) Depending on the distance from the interfering object, magnetometers are susceptible to noise from a number of different sources such as steel fences, vehicles, buildings, iron debris, and natural soil minerals (see Table 1-3); (2) will not detect nonferrous metals (metals other than iron, steel, and nickel); (3) estimating depth of burial is difficult; and (4) total field corrections and/or gradient readings might be required to compensate for solar interferences.

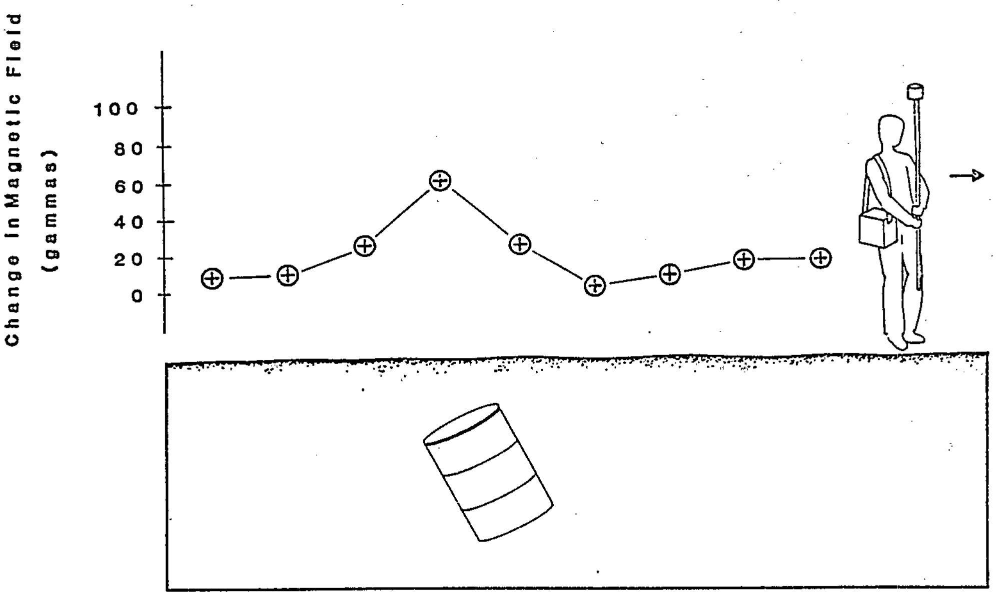
Frequency of Use: Common at sites where presence of ferrous metals in the subsurface is known or suspected.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller (1984), Benson et al. (1984), Bozorth (1951), Breiner (1973), Chikazumi (1964), EC&T (1990), Hinze (1988), Lahee (1961), Nettleton (1971, 1976), Rehm et al. (1985), U.S. EPA (1987, 1992-Chapter 6), Zohdy et al. (1974). Most of the general geophysics texts identified in Table 1-4 also cover magnetic methods.



(a)



(b)

Figure 1.5.2 Magnetometry: (a) Schematic illustrating basic magnetometer principle of operation (J. Ursic, U.S. EPA, Region 5); (b) Station measurements of a magnetic anomaly caused by a buried steel drum (Benson et al., 1984).

1.5 OTHER SURFACE GEOPHYSICAL METHODS

1.5.3 Gravimetrics

Other Names Used to Describe Method: Microgravity.

Uses at Contaminated Sites: Detecting variation of thickness of unconsolidated material over bedrock; mapping of landfill boundaries; detecting cavity, sinkholes, and subsidence.

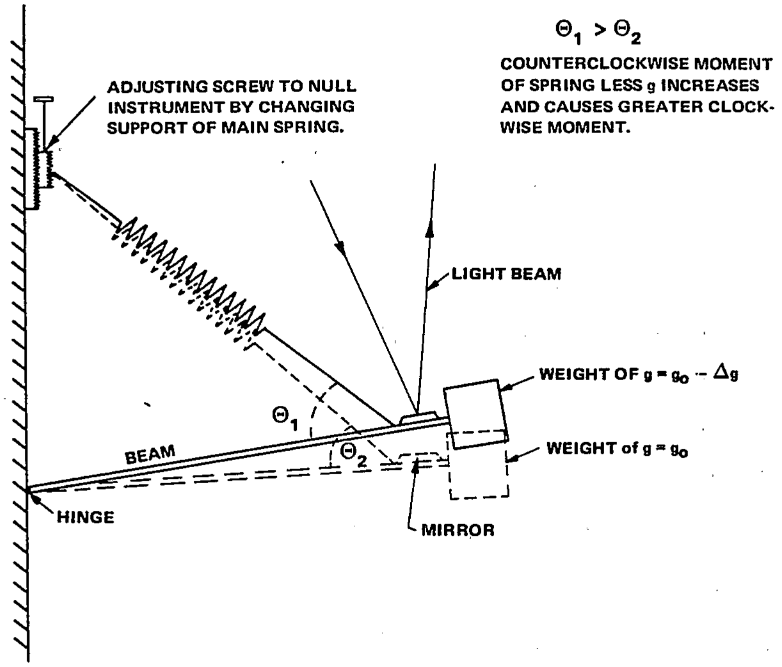
Method Description: Gravimetry involves measurement of variations in the intensity of the earth's gravitational field (expressed as acceleration in centimeters per second squared, or gals). Three principle classes of instruments are used in conventional gravity measurements: Torsion balance, pendulum, and gravity meter or gravimeter. All can detect anomalies as small as one-ten-millionth (milligals--10^{-3} gals) of the earth's gravitational field. **Microgravimeters,** measuring in units of microgals (10^{-6} gals) are sufficiently sensitive that they can delineate cavities in the subsurface (Figure 1.5.3a). Station measurements along a transect or on a grid require great care in setting up the instrument and the elevation of each station must be carefully surveyed. Gravity data obtained in the field must be corrected for elevation, rock density, latitude, earth-tide variations, and the influence of surrounding topographic variations. After corrections, measurements are plotted as Bouger anomaly maps, which look like topographic contour maps and are interpreted in terms of the size, shape and position of subsurface structures (Figure 1.5.3b).

Method Selection Considerations: **Advantages:** (1) Not adversely affected by urban influences that adversely affect EM methods, such as power lines, and radio broadcasts; (2) detailed surveys can delineate size and shape of cavity; and (3) existing data might be available locally from sources such as state geological surveys or the U.S. Geological Survey. **Disadvantages:** (1) Microgravity surveys tend to be expensive because extreme care is required in field procedures; (2) detailed elevation and location surveying of all stations is required; (3) instruments are very delicate and are very sensitive to temperature changes; (4) ground vibrations might adversely affect data; (5) microgravimeters are very expensive; (6) many corrections have to be applied to gravity data, which is time consuming; and (7) interpretations might be ambiguous.

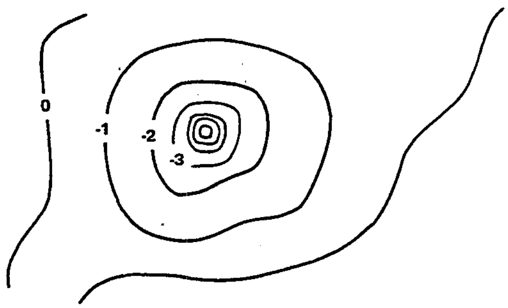
Frequency of Use: Widely used in mineral exploration. Most commonly used to detect bedrock valleys buried by unconsolidated glacial materials and regional-scale ground-water investigations. Not commonly used for site-specific investigations.

Standard Methods/Guidelines: --

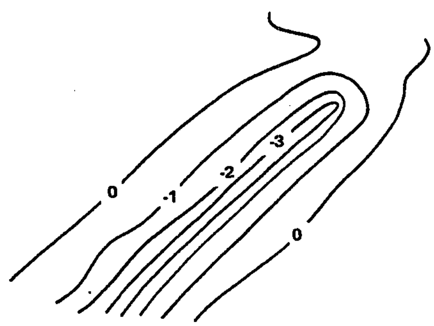
Sources for Additional Information: Butler (1977, 1984, 1991), Hinze (1988), Lahee (1961), Nettleton (1971, 1976), Redwine et al. (1985), Rehm et al. (1985), U.S. EPA (1992-Chapter 6), U.S. Geological Survey (1980), Zohdy et al. (1974). Most of the general geophysics texts identified in Table 1-4 also cover gravity methods.



(a)



A.) GRAVITY ANOMALY OF SPHERICAL CAVITY



B.) GRAVITY AND ANOMALY OF HORIZONTAL CYLINDRICAL CAVITY

(b)

Figure 1.5.3 **Microgravity surveys: (a) Schematic diagram of LaCoste and Romberg microgravimeter (Redwine et al, 1985, after Dobrin, 1960 [see Dobrin and Savit, 1988], Copyright © 1985, Electric Power Research Institute, EPRI CS-3901, *Groundwater Manual for the Electric Utility Industry*, reprinted with permission); (b) Contour maps illustrating negative gravity anomalies over spherical (A) and horizontal cylindrical (B) cavities in the subsurface (Butler, 1977).**

1.5 OTHER SURFACE GEOPHYSICAL METHODS

1.5.4 Radiation Detection

Other Names Used to Describe Method: **Radiation monitoring:** Personnel monitors and survey instruments (described below).

Uses at Contaminated Sites: Monitoring of radiation hazards using investigative techniques that involve ionizing radiation or detection of contamination by radioisotopes. See also, Section 10.6.1.

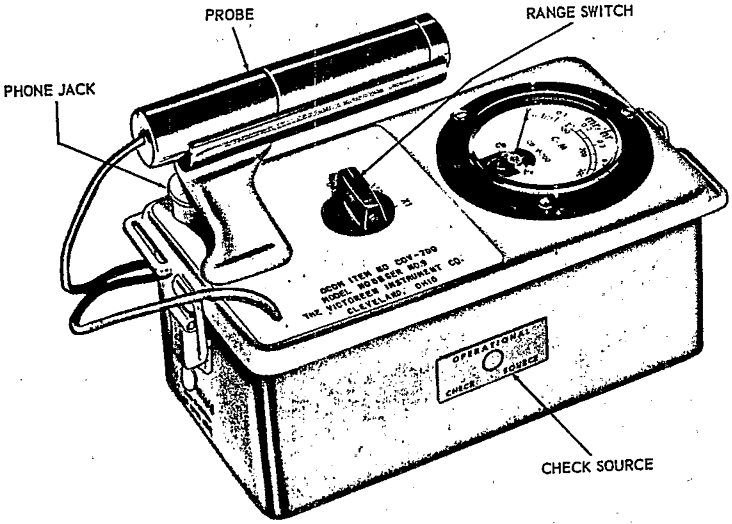
Method Description: **Radiation monitoring:** Various types of personnel monitors have been developed, such as **film badges** (records exposure on film), **thermoluminescent dosimeters** (store ionizing radiation in crystal lattice defects that can be measured as light output upon heating), and compact ionization chambers, such as **self-reading dosimeters** and **pocket ion chambers.** Most portable radiation survey instruments detect radiation by its interaction with gas in an ionization chamber. Conventional **ionization chambers** are used primarily for measuring high intensity beta, gamma, or x-radiation. **Proportional counters** can be used to discriminate between beta and gamma radiation. **Geiger-Mueller** counters (also called Geiger and G-M counters) are similar to ionization chambers except that the formation of secondary electrons greatly increases their sensitivity. Figure 1.5.4a shows a typical Geiger counter. **Scintillation** counters or detectors use a solid crystal that interacts with ionizing radiation to produce flashes of light that are converted to relatively large electrical pulses by a photomultiplier tube (Figure 1.5.4b). Scintillation detectors are extremely sensitive instruments that can be used to detect alpha, beta, gamma or x-radiation depending on the crystal that is used. ASTM (1990) covers standard terminology relating to radiation measurements.

Method Selection Considerations: Requires selection of an instrument or interchangeable detector tube that is consistent with the investigative requirements. Types of ionizing radiation most likely to be encountered at a hazardous waste sites and environmental spills are **alpha** and **beta** particles and **gamma** radiation, with gamma radiation being the most routinely monitored because of its penetration ability. Ford et al. (1984) summarize advantages and disadvantages of major types of personnel monitors and survey instruments.

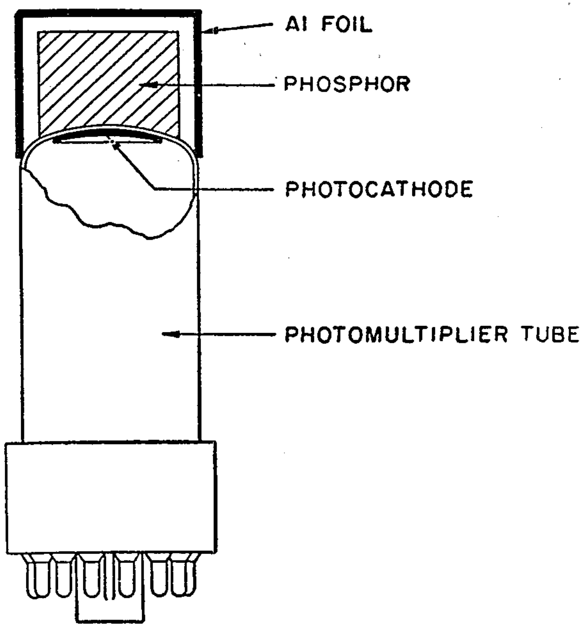
Frequency of Use: Radiation monitoring devices should be used in any situation that the presence of ionizing radiation is known or suspected.

Standard Methods/Guidelines: **Radiation survey instruments:** Ford et al. (1984), Marutzky et al. (1984); **low-level waste site monitoring:** EG&G Idaho (1990).

Sources for Additional Information: **General applications:** Duval (1980, 1989); **Radiation detection instruments:** Glasstone (1967-chapter 7), Steele et al. (1985). Geophysics texts covering radiometric methods: Beck (1981), Eve and Keys (1954), Morse (1977), Parasnis (1975), Sherriff (1989), Telford et al. (1990).



(a)



(b)

Figure 1.5.4 Radiation detection instruments: (a) Portable geiger tube detector; (b) Schematic of a simple scintillation counter (Glasstone, 1967).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.6 NEAR-SURFACE GEOTHERMOMETRY

1.6.1 Soil Temperature

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Evaluating volatilization of organic contaminants; evaluating soil microbial activity; delineating contaminant plume; characterizing shallow ground-water flow (see Section 1.6.2).

Method Description: Soil temperature is measured at the surface or below the ground surface using one or more methods for temperature measurement described in Sections 8.2.1 and 8.2.2 (Air thermometry). Thermocouples are the most commonly used methods for soil temperature measurement (Figure 1.6.1). Ground-water temperature gives a close estimate of mean annual soil temperature if monitoring wells are available with water at a depth of 10 to 20 meters. Alternatively, the average of four temperature measurements taken at a depth of about 50 centimeters equally spaced throughout the year gives a good estimate of mean annual soil temperature. Historical soil surface temperature data can be estimated from historical meteorological data using empirical relationships between soil and surface temperature or solving the energy balance equation for soil temperature (see Section 8.4.4). Pikul (1991) reviews and evaluates these methods.

Method Selection Considerations: See Sections 8.2.1 and 8.2.2 (Air Thermometry). See also, Section 3.5.2 (Temperature Logs).

Frequency of Use: Uncommon.

Standard Methods/Guidelines: Buchan (1991), Taylor and Jackson (1986a).

Sources for Additional Information: Brakensiek et al. (1979), Morrison (1983), Smith et al. (1960), U.S. EPA (1992-Chapter 6). See also, texts covering geothermal methods and soil thermal properties in Table 1-5.

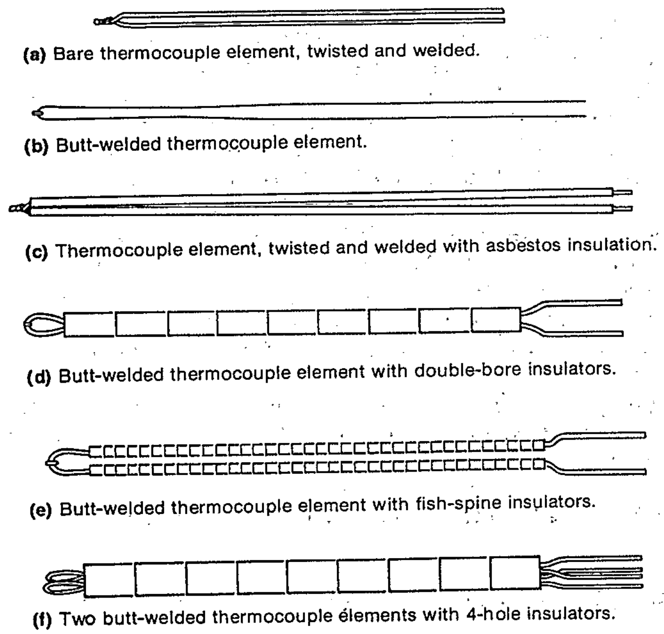


Figure 1.6.1 Typical thermocouple element assemblies for measuring soil temperature (Morrison, 1983, by permission).

1. REMOTE SENSING AND SURFACE GEOPHYSICAL METHODS

1.6 NEAR-SURFACE GEOTHERMOMETRY

1.6.2 Shallow Geothermal Ground-Water Temperature

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Detecting contaminant plumes from landfills; identifying areas of surface recharge, flow velocity, and permeability in shallow aquifers; measuring ground-water percolation; calculating ground-water flow and aquifer permeability.

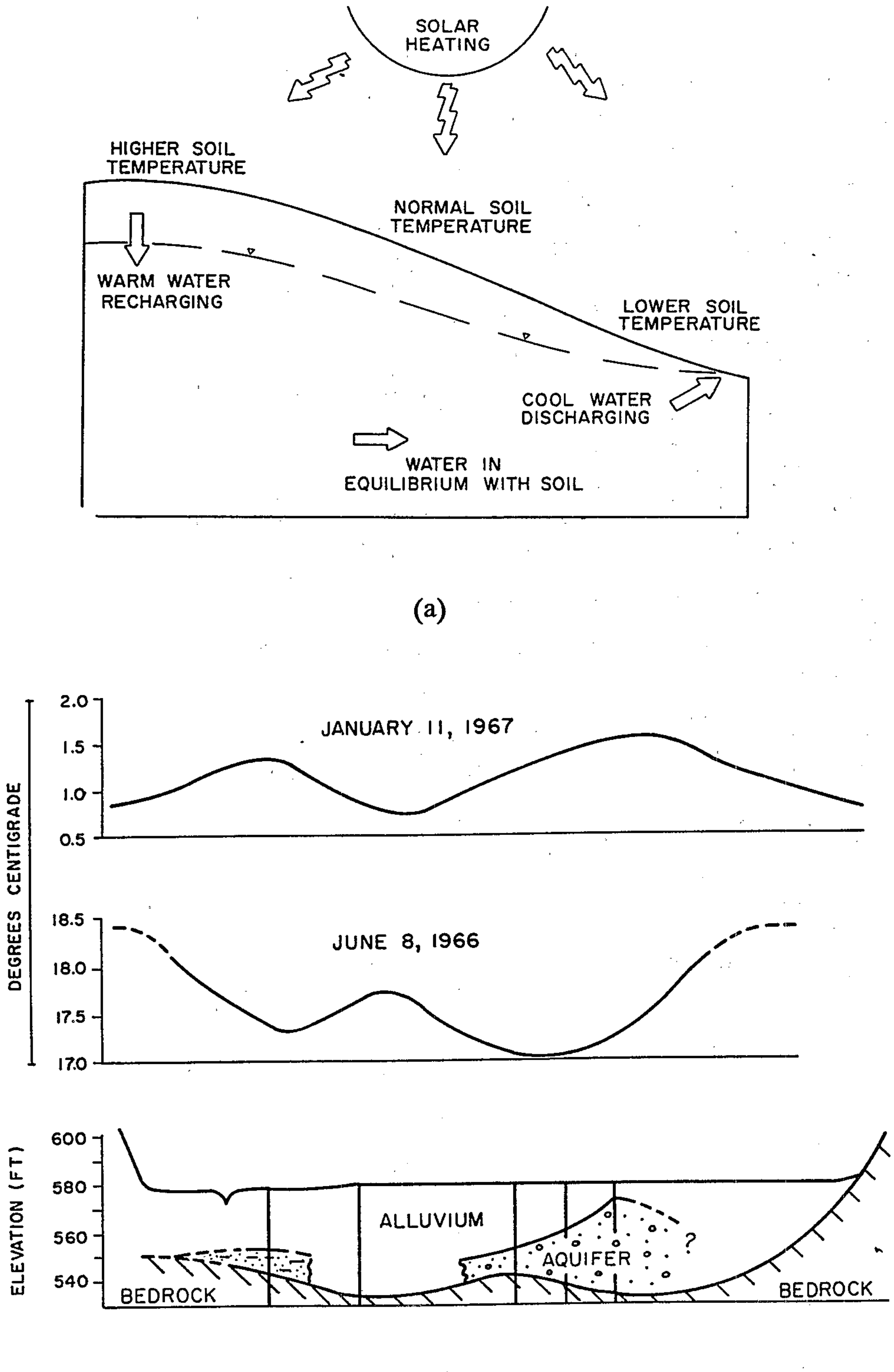
Method Description: Subsurface temperatures are measured at a selected depth (up to 40 inches) at a large number of stations over a short time span. Measurements are plotted on a map and contours of equal temperature interpolated between the data points. Interpretations are based on temperature hydrogeologic relationships such as: (1) Seasonal changes in soil temperatures associated with ground-water recharge and discharge (Figure 1.6.2a); (2) shallow moving ground water produces lower soil temperatures compared to shallow bedrock; and (3) landfill leachate tends to be warmer than native ground water. Figure 1.6.2b illustrates the use of summer and winter temperature profiles to detect discontinuous sand and gravel aquifers in fine-grained alluvium. Aquifer permeability can be calculated from head and temperature measurements. Brown et al. (1983) describe procedures for calculating ground-water flow from temperature in three situations: (1) Dipping aquifers; (2) vertical conductivity of confining beds; and (3) vertical flow near the land surface. The first two methods involve temperature measurements in boreholes (see Section 3.5.2). Surface or airborne thermal infrared measurements (Section 1.1.3) also can be used for shallow aquifer characterization.

Method Selection Considerations: Instrumentation is relatively simple and measurements are easy to make. Other methods, such as electromagnetic induction (Section 1.3.1) are easier, and probably more accurate for contaminant plume detection.

Frequency of Use: Occasionally used in near-surface ground water investigations; infrequently used at contaminated sites.

Standard Methods/Guidelines: Brown et al. (1983-Section 5.5), Stevens et al. (1975).

Sources for Additional Information: Bair and Parizek (1978), Gilkeson and Cartwright (1983), Jansen (1990), U.S. EPA (1992-Chapter 6). See also, texts covering geothermal methods in Table 1-5.



(b)

Figure 1.6.2 **Shallow geothermic method for ground-water detection: (a) Generalized temperature conditions in a small ground-water flow system during summer (conditions are reversed in winter) (Cartwright, 1974, by permission); (b) Temperature profiles (winter and summer) and geologic cross section of an alluvial valley where a discontinuous sand and gravel aquifer is contained within fine-grained alluvium (Cartwright, 1968, by permission).**

1.6 NEAR-SURFACE GEOTHERMOMETRY

1.6.3 Other Thermal Properties

Other Names Used to Describe Method: Heat capacity and specific heat, thermal conductivity and diffusivity, heat flux.

Uses at Contaminated Sites: Various thermal properties affect soil temperature which, in turn, influences rates of biological and chemical reactions, energy balance of the earth's surface, soil-water movement, and anthropogenic features such as roads, buried cables, and waterlines, which might be susceptible to damage by freeze-thaw action in the soil.

Method Description: Soil-water content is a critical factor affecting thermal properties and often needs to be measured (See Section 6.3). Various methods are used in the field to measure soil heat flux density (the amount of heat flowing in the soil per unit area per unit time) including: (1) Calorimetric method; (2) gradient method; (3) combination method using both calorimetric and gradient measurements; and (4) soil heat flux plate method. Other thermal properties are usually measured in the laboratory using soil samples: (1) **Heat capacity and specific heat** are measured using a calorimeter; (2) **thermal conductivity** is measured using a galvanometer; and (3) **thermal diffusivity** is measured using a sample container, heat exchanger in a temperature-controlled water bath. Figure 1.6.3 shows examples of field measured depth profiles of thermal conductivity, heat capacity, and heat flux. Figure 1-2 shows typical ranges of thermal conductivity for common rock and soil types.

Method Selection Considerations: Measurement of thermal properties generally is required in special situations, such as measurement of heat flux in the Energy Budget/Bowen Ratio Method. References listed below can give guidance on method selection for specific thermal properties.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: **Heat capacity and specific heat:** Taylor and Jackson (1986b); **thermal conductivity and diffusivity:** Jackson and Taylor (1986); **heat flux:** Fuchs (1986).

Sources for Additional Information: See texts covering geothermal methods and soil thermal properties in Table 1-5.

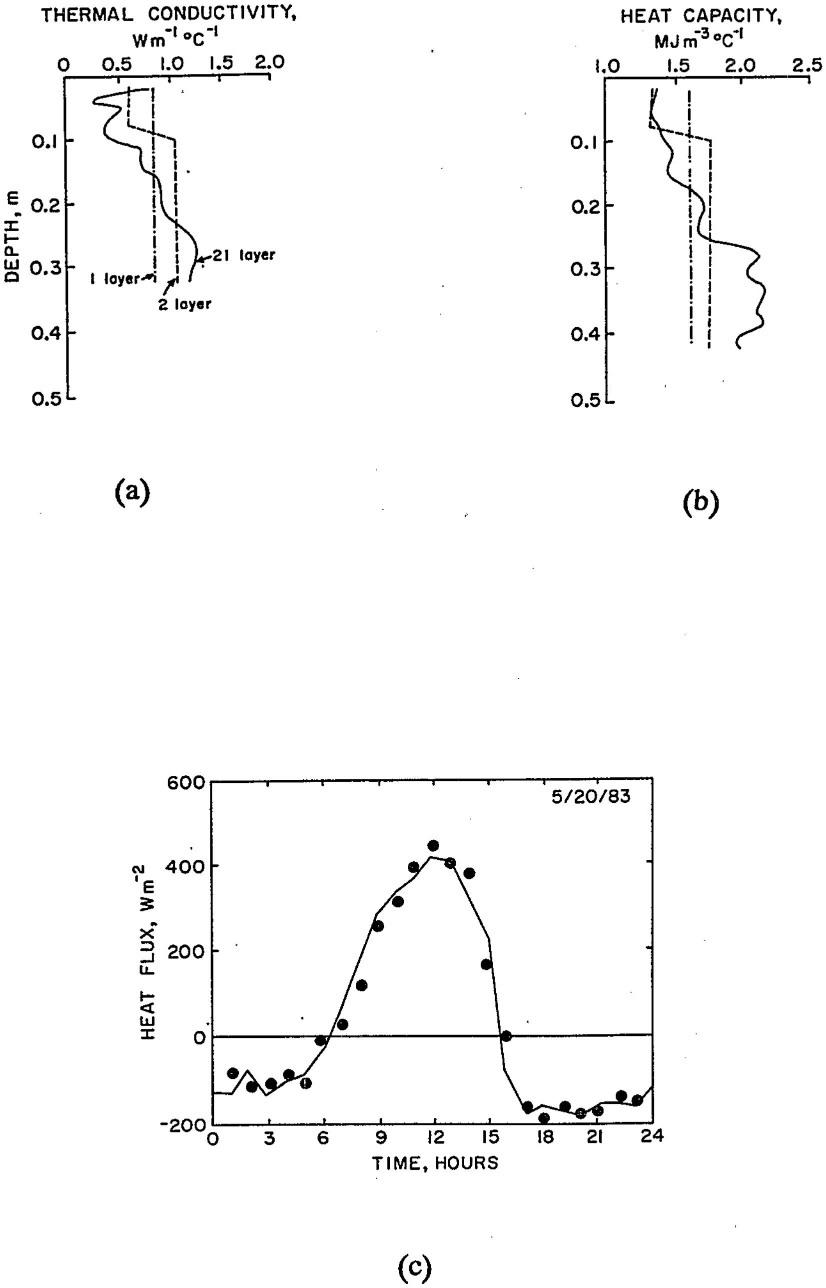


Figure 1.6.3 **Soil thermal properties: (a) Thermal conductivity; (b) Heat capacity; (c) Average soil heat flux (dashed lines in (a) and (b) and solid line in (c) represent theoretical values using various models) (Flint and Childs, 1987, by permission).**

Table 1-4 Reference Index for Texts on Remote Sensing and Surface Geophysical Methods

Topic	Reference
<u>Remote Sensing</u>	
General	ASTM (1993a), Colwell (1983), Dury (1990), Holz (1973), Johnson and Pettersson (1987), Kondratyev (1969), Rees (1990), Reeves (1968, 1975), Regan (1980), Sabins (1978), Ulaby et al. (1982-microwave), Watson and Regan (1983); <u>Hydrologic/Contamination Applications</u>: Burgy and Algaz (1974), Deutsch et al. (1979), Ellyett and Pratt (1975), Goodison (1985), Lund (1978), Reeves (1968), Scherz (1971), Scherz and Stevens (1970), Sers (1971), Thomson et al. (1973)
Aerial Photography	ASTM (1993), Avery (1968), Ciciarelli (1991), Denny et al. (1968), Johnson and Gnaedigner (1964-bibliography), Lattman and Ray (1965), Lueder (1959), Ray (1960), SCS (1973), Wolfe (1974-photogrammetry)
<u>General Geophysics</u>	
General Texts[a]	Beck (1981), d'Arnaud Gerkins (1989), Dobrin and Savit (1988), Eve and Keys (1954), Garland (1989), Grant and West (1965), Griffiths and King (1981), Hansen et al. (1967), Heiland (1940), Howell (1959), Jakosky (1950), Kearey and Brooks (1991), Milsom (1989), Nettleton (1940), Parasnis (1975, 1979), Robinson and Coruh (1988), Sharma (1986), Sheriff (1968, 1989, 1991), Telford et al. (1990), Valley (1965), Van Blaricom (1980), Ward (1990a)
Ground Water	Erdélyi and Gálfi (1988), Morely (1970), NWWA (1984, 1985, 1986), Redwine et al. (1985), Rehm et al. (1985), Taylor (1984), U.S. Geological Survey (1980), Ward (1990b), Zohdy et al. (1974); <u>Bibliographies</u>: Handman (1983), Johnson and Gnaedinger (1964), Lewis and Haeni (1987), Rehm et al. (1985), van der Leeden (1991)
Contaminated Sites	Aller (1984), API (1991), Benson et al. (1984), Costello (1980), EC&T et al. (1990), Frischknecht et al. (1983), HRB-Singer (1971), Lord and Koerner (1987), NWWA (1984, 1985, 1986), O'Brien & Gere (1988), Olhoeft (1992), Pitchford et al. (1988), SEMEG (1988-present), Technos (1992), U.S. EPA (1987), Waller and Davis (1984), Ward (1990b); <u>Review Papers</u>: Benson (1991), Evans and Schweitzer (1984), Hoekstra and Hoekstra (1990)
Engineering	Paillet and Saunders (1990), SEG (various dates), SEMEG (1988-present), U.S. Army Corps of Engineers (1979), Ward (1990c)
Nondestructive Testing Methods	ASTM (Annual), Lord and Koerner (1987), McGonnagle (1961), Sharp (1970)

[a]Most texts on geophysics cover electrical, electromagnetic, seismic, magnetic, and gravity methods. Check annotations for major topics covered by texts identified at the beginning of the table.

Table 1-5 Reference Index for Texts on Specific Surface Geophysical Methods

Topic	Reference
Electrical Resistivity	Texts: Bhattacharya and Patra (1968), Goldman (1990-nonconventional methods), Keller and Frishcknecht (1970), Kofoed (1979), Kunetz (1966), Mooney (1980), Patra and Mallick (1980), Roux (1978), Soiltest, (1968); Interpretation: Kalenov (1957), Mooney and Wetzel (1956), Orellana and Mooney (1966, 1972), Van Nostrand and Cook (1966), Verma (1980); Geoelectric Properties: Parkhomenko (1967), Wheatcraft et al. (1984)
Induced Polarization	Baizer and Lund (1983), Bertin and Loeb (1976), Bottcher (1952), Fink et al. (1990), Sumner (1976), Wait (1959, 1982), Wheatcraft et al. (1984)
Basic EM Theory	Jackson (1975), Kong (1975), Nabighian (1988), Stratton (1941), Wait (1985)
EM Wave Behavior	Chew (1990), Jordon (1963), Kong (1975), Lorrain and Carson (1970), Schelnukoff (1943), Wait (1970, 1981, 1985), Ward and Morrison (1971)
EM Induction	Hoyt (1974), Kaufman and Keller (1983), Kraus (1984), Nabighian (1988, 1991), Rokityanksi (1982), Verma (1982-three-layer interpretation data), Wait (1971, 1982)
Seismic Refraction	Texts: Badley (1985), Dix (1952-oil prospecting), Haeni (1988-hydrogeology), Mooney (1984), Musgrave (1967), Palmer (1986), Redpath (1973), Waters (1981); Analysis/Interpretation: Berkhout (1985, 1988), Fagin (1991), Palmer (1980), Russell (1988), Slotnick (1959), Tucker (1982), Tucker and Yorsten (1973); Wave Theory Texts: Auld (1990), Berkhkout (1987), Bland (1988), Davis (1988), White (1965); Rock Properties: Carmichael (1982)
Continuous Seismic Profiling	Texts: Burdic (1991), Coates (1989), EG&G Environmental Equipment Division (1977), Hassab (1989-signal processing), Hersey (1963), Sylwester (1983), Trabant (1984); Interpretation: Badley (1985), Ewing and Tirey (1961), Leenhart (1969), Roksandic (1978), Sangree and Widmier (1979), Tufekcic (1978)
Ground-Penetrating Radar	Hänninen and Autio (1992), Lucius et al. (1990), Pilon (1992), Rossiter and Bazely (1980), SCS (1988)
Geothermal Methods	Texts: Eve and Keys (1954), Gougel (1976), Howell (1959), Jessup (1990), Rehm et al. (1985), Sharma (1986), Sheriff (1989), Summers (1971-bibliography); Soil Thermal Properties: Carlslaw (1986), de Vries (1963, 1975), Farouki (1981), Kersten (1949), Lee (1965), Wechsler et al. (1965)

SECTION 1 REFERENCES

Akhadov, Y. 1980. Dielectric Properties of Binary Solutions. Pergamon, New York, NY, 475 pp.

Aller, L. 1984. Methods for Determining the Location of Abandoned Wells. EPA/600/2-83/123 (NTIS PB84-141530), 130 pp. Also published in NWWA/EPA Series, National Water Well Association, Dublin, OH. [Air photos, color/thermal IR, ER, EMI, GPR, MD, MAG, combustible gas detectors]

American Petroleum Institute (API). 1991. An Evaluation of Soil Gas and Geophysical Techniques for Detection of Hydrocarbons. API Publication No. 4509. API, Washington, DC, 110 pp. [GPR, EMI, ER, complex resistivity]

American Society for Testing and Materials (ASTM). Annual. Book of ASTM Standards: Metals Test Methods and Analytical Procedures, Volume 3.03: Nondestructive Testing. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1990. Terminology Relating to Radiation Measurements and Dosimetry. E170-90a, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993. Draft Standard Guide for Acquisition of File Aerial Photography and Imagery for Establishing Historic Site-Use and Surficial Conditions. D18.01 Subcommittee ballot. ASTM, Philadelphia, PA.

Auld, B.A. (ed.). 1990. Acoustic Fields and Waves in Solids, Vol. I and II, 2nd rev. Robert E. Krieger Publishing, Malabar, FL, (I) 435 pp., (II) 421 pp.

Avery, T.E. 1968. Interpretation of Aerial Photographs, 2nd ed. Burgess Publishing Company, Minneapolis, MN, 234 pp.

Ayers, J.F. 1989. Application and Comparison of Shallow Seismic Methods in the Study of an Alluvial Aquifer. Ground Water 27(4):550-563. [SRR, SRL] (See also, 1990 discussion by R.W. Lankston and reply in Ground Water 28(1):116-118.)

Badley, M.E. 1985. Practical Seismic Interpretation. International Human Resources Development Corporation, Boston, MA, 266 pp. [SRL, CSP]

Bair, E.S. and R.R. Parizek. 1978. Detection of Permeability Variations by a Shallow Geothermal Technique. Ground Water 16(4):254-263.

Baizer, M.M. and H. Lund (eds.). 1983. Organic Electrochemistry, 2nd edition. Marcel Dekker, New York, NY, 1166 pp. [IP]

Barringer Research Limited. 1988. UV Surface Sampling. USATHAMA CETHA-TS-CR-91074. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD. [UV video camera for detection of contaminants]

Bates, R., D. Phillips, and B. Hoekstra. 1991. Geophysical Surveys for Fracture Mapping and Solution Cavity Delineation. In: Ground Water Management, 7:659-673 (8th NWWA Eastern Ground-Water Conference). [Shear wave refraction, cross-borehole tomography]

Beck, A.E. 1981. Physical Principles of Exploration Methods. Macmillan, New York, NY, 234 pp. (Reprinted in 1982 with corrections.) [ER, SP, IP, GR, MAG, EMI, VLF, SRR, SRL, radiometric, BH]

Benson, R.C. 1991. Remote Sensing and Geophysical Methods for Evaluation of Subsurface Conditions. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 143-194. [GPR, EMI, TDEM, ER, SRR, SRL, GR, MAG, MD, BH]

Benson, R.C., R.A. Glaccum, and M.R. Noel. 1984. Geophysical Techniques for Sensing Buried Wastes and Waste Migration. EPA/600/7-84/064 (NTIS PB84-198449), 236 pp. Also published in NWWA/EPA series by National Water Well Association, Dublin, OH. [EMI, ER, GPR, MAG, MD, SRR]

Beres, Jr., M. and F.P. Haeni. 1991. Application of Ground-Penetrating Radar Methods in Hydrogeologic Studies. Ground Water 29:375-386.

Berkhout, A.J. 1985. Seismic Migration: Imaging of Acoustic Energy by Wave Field Extrapolation. A. Theoretical Aspects, 2nd edition; B. Practical Aspects. Elsevier, NY.

Berkhout, A.J. 1987. Applied Seismic Wave Theory. Elsevier, New York, NY, 377 pp.

Berkhout, A.J. 1988. Seismic Resolution: A Quantitative Analysis of the Resolving Power of Acoustical Echo Techniques. Pergamon, New York, NY, 228 pp.

Bertin, J. and J. Loeb. 1976. Experimental and Theoretical Aspects of Induced Polarization, 2 Volumes. Gebrüder Borntraeger, Berlin.

Bhattacharya, P.K. and H.P. Patra. 1968. Direct Current Geoelectric Sounding--Principles and Interpretation. Elsevier, New York, NY, 135 pp.

Bland, D.R. 1988. Wave Theory and Applications. Oxford University Press, New York, NY, 322 pp. [Seismic]

Bogoslovsky, V.V. and A.A. Ogilvy. 1973. Deformation of Natural Electric Fields Near Drainage Structures. Geophysical Prospecting 21(4):716-723. [SP]

Bottcher, C.F. 1952. Electric Polarization. Elsevier, NY.

Bozorth, R.M. 1951. Ferromagnetism. Van Nostrand Co., New York, NY, 968 pp.

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls (eds.). 1979. Field Manual for Research in Agricultural Hydrology. Agricultural Handbook No. 224, U.S. Department of Agriculture, Washington, DC.

Breiner, S. 1973. Applications Manual for Portable Magnetometers. Geometrics, Sunnyvale, CA, 58 pp.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7. UNESCO, Paris. (Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983.) [Thermal methods for evaluation of ground-water covered in Section 5.5]

Buchan, G.D. 1991. Soil Temperature Regime. In: Soil Analysis: Physical Methods, K.A. Smith and C.E. Mullins (eds.), Marcel Dekker, New York, NY, pp. 551-612.

Burdic, W.S. 1991. Underwater Acoustic System Analysis, 2nd ed. Prentice Hall, Englewood Cliffs, NJ, 445 pp. (1st edition, 1984.)

Burgy, R.H. and V.R. Algaz. 1974. An Assessment of Remote Sensing Applications in Hydrologic Engineering. U.S. Army Corps of Engineers Hydrologic Center, Davis, CA, 55 pp.

Butler, D.K. 1977. Geophysics Versus the Cavity Detection Problem. In: Symposium on Detection of Subsurface Cavities, U.S. Army Corps of Engineer, Water Experiment Station, Vicksburg, MS, pp. 27-43. [GR]

Butler, D.K. 1984. Microgravimetric and Gravity Gradient Techniques for Detecting Subsurface Cavities. Geophysics 49:1084-1096.

Butler, D.K. 1991. Engineering and Environmental Applications of Microgravimetry. In: Proc. (4th) Symp. on Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 139-246.

Carlslaw, H.S. 1986. Conduction of Heat in Solids, 2nd edition. Oxford University Press, New York, NY, 510 pp. (First edition by Carlslaw and Jaeger, published in 1960.)

Carmichael, R.S. 1982. Handbook of Physical Properties of Rocks, Vol. 2. CRC Press, Boca Raton, FL. [Seismic]

Carpenter, P.J., S.F. Calkin, and R.S. Kaufman. 1991. Assessing a Fractured Landfill Cover Using Electrical Resistivity and Seismic Refraction Techniques. Geophysics 56(11):1896-1904. [Azimuthal resistivity]

Cartwright, K. 1968. Thermal Prospecting for Ground Water. Water Resources Research 4(2):395-401.

Cartwright, K. 1974. Tracing Shallow Ground Water Systems by Soil Temperatures. Water Resources Research 10(4):847-855.

CH2M Hill. 1991. Proceedings: NSF/EPRI Workshop on Dynamic Soil Properties and Site Characterization, Vol. 1. EPRI NP-7337. Electric Power Research Institute, Palo Alto, CA. [Seismic shear, SASW]

Chew, W.C. 1990. Waves and Fields in Inhomogeneous Media. Van Nostrand Reinhold, New York, NY, 611 pp.

Chikazumi, S. 1964. The Physics of Magnetism. John Wiley & Sons, New York, NY.

Ciciarelli, J. 1991. A Practical Guide to Aerial Photography. Van Nostrand Reinhold, New York, NY, 176 pp.

Coates, R.F.W. 1989. Underwater Acoustic Systems. John Wiley & Sons, New York, NY, 188 pp.

Colwell, R.N. 1983. Manual of Remote Sensing, 2nd edition. American Society of Photogrammetry, Fall Church, VA. (1st edition by Reeves, published in 1975.)

Costello, R.L. 1980. Identification and Description of Geophysical Techniques. USATHAMA Report DRXTH-TE-CR-80084. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, 215 pp. (Superseded by EC&T et al., 1990.) [ER, GPR, SR, BH]

Danbom, S.H. and S.N. Domenico (eds.). 1987. Shear-Wave Exploration. Geophysical Developments No. 1. Society of Exploration Geophysicists, Tulsa, OK, 282 pp. (Last chapter contains an annotated bibliography on shear-wave exploration seismology--See Ensley, 1987.)

Daniel, V.V. 1967. Dielectric Relaxation. Academic Press, New York, NY.

Daniels, J.J. 1989. Technical Review: Ground Penetrating Radar. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems. Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 62-142.

Darilek, G.T and J.O. Parra. 1988. The Electrical Leak Location Methods for Geomembrane Liners. In: Proc. 14th Research Symp. (Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste), EPA/600/9-88/021 (NTIS PB89-174403), pp. 167-176.

d'Arnaud Gerkins, J.C. 1989. Foundations of Exploration Geophysics. Elsevier, NY, 667 pp. [SRR, SRL, GR, MAG, SP, TC, MT, IP, ER, EMI, TDEM, radiation]

Davis, J.L. 1988. Wave Propagation in Solids and Fluids. Springer Verlag, New York, NY, 400 pp.

Davis, J.L., R. Singh, B.G. Steman, and M.J. Waller. 1984. Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems: Acoustic Emission Monitoring and Time Domain Reflectometry. EPA/600/2-84/058 (NTIS PB84-161819), 105 pp.

Denny, C.S., C.R. Warren, D.H. Dow, and W.J. Dale. 1968. A Descriptive Catalog of Selected Aerial Photographs of Geologic Features of the United States. U.S. Geological Survey Professional Paper 590, 135 pp.

Deutsch, M., D.R. Wiosnet, and A. Ranjo (eds.). 1979. Satellite Hydrology (Fifth Annual William T. Pecora Memorial Symp. of Remote Sensing). American Water Resources Association, Minneapolis, MN, 730 pp.

de Vries, D.A. 1963. Thermal Properties of Soils. In: Physics of Plant Environment, W.R. Van Wijk (ed.), North-Holland Publishing Co., Amsterdam, pp. 210-235.

de Vries, D.A. 1975. Heat Transfer in Soils. In: Heat and Mass Transfer in the Biosphere, W.R. Van Wijk and N.A. Afgan (eds.), John Wiley & Sons, New York, NY, pp. 5-28.

Dix, G.H. 1952. Seismic Prospecting for Oil. Harper and Brothers, New York, NY, 213 p.

Dobrin, M.B. and C.H. Savit. 1988. Introduction to Geophysical Prospecting, 4th edition. McGraw-Hill, New York, NY, 867 pp. (Earlier editions by Dobrin: 1960, 1965, 1976.) [SRR, SRL, CSP, GR, MAG, ER, SP, IP, EMI]

Dohr, G. (ed.). 1985. Seismic Shear Waves, Part A. Theory, Part B. Applications. Handbook of Geophysical Exploration, Vols. 15A and 15B, Geophysical Press, London.

Douglas, D.G., A.A. Burns, C.L. Rino, and J.W. Maresca, Jr. 1992. A Study to Determine the Feasibility of Using A Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination. EPA/600/R-92/89 (NTIS PB92-169382), 115 pp.

Duran, P.B. 1987. The Use of Marine Electromagnetic Conductivity as a Tool in Hydrogeologic Investigations. Ground Water

25(2):160-166.

Dury, S.A. 1990. A Guide to Remote Sensing: Interpreting Images of the Earth. Oxford University Press, New York, NY, 208 pp.

Duval, J.S. 1980. Radioactivity Method. Geophysics 45(11):1690-1694.

Duval, J. 1989. Radiometrics in Geology. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems. Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 1-61.

EG&G Environmental Equipment Division. 1977. Fundamentals of High Resolution Seismic Profiling. TR760035. EG&G, 31 pp.

EG&G Idaho, Inc. 1990. Environmental Monitoring for Low-Level Waste-Disposal Sites, Revision 2 (2 Volumes). Low-Level Radioactive Waste Management Handbook Series, DOE/LLW-13Tg. National Low Level Waste Management Program, Idaho Falls, ID.

Ellyett, C.D. and D.A. Pratt. 1975. A Review of the Potential Applications of Remote Sensing Techniques to Hydrogeological Studies in Australia. Australian Water Resources Council Technical Paper No. 13, Canberra.

Ensley, R.A. 1987. Classified Bibliography of Shear-Wave Seismology. In: Shear-Wave Exploration, S.H. Danbom and S.N. Domenico (eds.), Society of Exploration Geophysicists, Tulsa, OK, pp 255-275.

Environmental Consulting & Technology (EC&T), Inc., Technos, Inc., and UXB International, Inc. 1990. Construction Site Environmental Survey and Clearance Procedures Manual. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD. [GPR, EMI, MAG, MD, soil gas]

Erdélyi, M. and J. Gálfi. 1988. Surface and Subsurface Mapping in Hydrogeology. Wiley-Interscience, New York, NY, 384 pp. [Chapter 5 covers remote sensing and Chapter 6 geophysical methods: GPR, ER, IP, EMI, SRR, SRL, GR, MAG, geothermal]

Evans, R.B. and G.E. Schweitzer. 1984. Assessing Hazardous Waste Problems. Environ. Sci. Technol. 18(11):330A-339A. [EMI, ER, GPR, MAG, MD, SRR]

Eve, A.S. and D.A. Keys. 1954. Applied Geophysics in the Search for Minerals, 4th edition. Cambridge University Press, New York, NY, 382 pp. (Earlier editions, 1929, 1931, 1938.) [MAG, ER, EM, GR, SRL, geothermal, radiometric]

Ewing, J.I. and G.B. Tirey. 1961. Seismic Profiles. J. Geophysical Research 66:2917-2927. [CSP]

Fagin, S.W. (ed.). 1991. Seismic Modeling of Geologic Structures. Geophysical Developments No. 2. Society of Exploration Geophysicists, Tulsa, OK, 288 pp.

Farouki, O.T. 1981. Thermal Properties of Soils. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory Monograph 81-1, Hanover, NH, 151 pp.

Felsen, L.B. (ed.). 1976. Transient Electromagnetic Fields. Springer-Verlag, New York, NY, 274 pp.

Fink, J.B., et al. (eds.). 1990. Induced Polarization. Society of Exploration Geophysicists, Tulsa, OK, 424 pp.

Fitterman, D.V. and M.T. Stewart. 1986. Transient Electromagnetic Sounding for Groundwater. Geophysics 51:995-1005.

Flint, A.L. and S.W. Childs. 1987. Field Procedures for Estimating Soil Thermal Environments. Soil Sci. Soc. Am. J. 51:1326-1331.

Ford, P.J., P.J. Turina, and D.E. Seely. 1984. Characterization of Hazardous Waste Sites--A Methods Manual, Vol. 2: Available Sampling Methods, 2nd edition. EPA/600/4-84/076 (NTIS PB85-521596).

Frischknecht, F.C. 1990. Application of Geophysical Methods to the Study of Pollution Associated with Abandoned and Injection Wells. In: Proc. of a U.S. Geological Survey Workshop on Environmental Geochemistry, B.R. Doe (ed.), U.S. Geological Survey Circular 1033, pp. 73-77. [Aeromagnetic, TDEM]

Frischknecht, F.C., L. Muth, R. Grette, T. Buckley, and B. Kornegay. 1983. Geophysical Methods for Locating Abandoned Wells. U.S. Geological Survey Open-File Report 83-702, 211 pp. Also published as EPA/600/4-84/065 (NTIS PB84-212711).

Fuchs, M. 1986. Heat Flux. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9.

American Society of Agronomy, Madison, WI, pp. 957-968.

Garland, G.D. (ed.). 1989. Proceedings of Exploration 87. Special Volume 3, Ontario Geological Survey, Toronto, Canada, 914 pp. [77 papers covering surface, borehole, and airborne EM, IP, remote sensing, radiometric, and seismic methods]

Gilkeson, R.H. and K. Cartwright. 1983. The Application of Surface Electrical and Shallow Geothermic Methods in Monitoring Network Design. Ground Water Monitoring Review 3(3):30-42.

Glasstone, S. 1967. Sourcebook on Atomic Energy, 3rd edition. Van Nostrand, Princeton, NJ, 883 pp.

Goldman, M.M. 1990. Non-Conventional Methods in Geoelectrical Prospecting. Prentice-Hall, New York, NY, 150 pp. [EM, TDEM, ER]

Goodison, B.E. (ed.). 1985. Hydrological Applications of Remote Sensing and Remote Data Transmission. Int. Ass. Hydrological Sciences Pub. No. 145.

Gougel, J. 1976. Geothermics. McGraw-Hill, New York, NY, 2090 pp.

Grant, F.S. and G.F. West. 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill, New York, NY, 583 pp. [ER, EM, SRL, SRR, GR, MAG, EMI]

Greenhouse, J.P. and M. Monier-Williams. 1985. Geophysical Monitoring of Ground Water Contamination Around Waste Disposal Sites. Ground Water Monitoring Review 5(4):63-69.

Griffiths, D.H. and R.F. King. 1981. Applied Geophysics for Engineers and Geologists: The Elements of Geophysical Prospecting, 2nd ed. Pergamon Press, New York, NY, 230 pp. (1st edition 1965.) [ER, EM, SRR, SRL, GR, MAG]

Haeni, F.P. 1986. Application of Continuous Seismic Reflection Methods to Hydrologic Studies. Ground Water 24:23-31.

Haeni, F.P. 1988. Application of Seismic Refraction Techniques to Hydrogeologic Studies. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 2-D2, 86 pp.

Handman, E.H. 1983. Hydrologic and Geologic Aspects of Waste Management and Disposal: A Bibliography of Publications by U.S. Geological Survey Authors. U.S. Geological Survey Circular 907, 40 pp. [15 references on geophysics]

Hänninen, P. and S. Autio (eds.). 1992. Fourth International Conference on Ground Penetrating Radar (June 8-13, 1992, Rovaniemi, Finland). Geological Survey of Finland Special Paper 16, 365 pp.

Hansen, D.A., W.E. Heinrichs, Jr., R.C. Holmer, R.E. MacDougall, G.R. Rogers, J.S. Sumner, and S.H. Ward (eds.). 1967. Mining Geophysics, Vol. II, Theory. Society of Exploration Geophysicists, Tulsa, OK, 708 pp. [EMI, ER, IP, MAG, GR]

Hassab, J.C. 1989. Underwater Signal and Data Processing. CRC Press, Boca Raton, FL, 320 pp.

Hasted, T. 1974. Aqueous Dielectrics. Chapman Hall, London.

Heiland, C.A. 1940. Geophysical Exploration. Prentice-Hall, New York, NY, 1013 pp. (Reprinted under the same title in 1968 by Hafner Publishing, New York, NY.) [S, ER, MAG, GR]

Hersey, J.B. 1963. Continuous Reflection Profiling. In: The Sea, Vol. 3. John Wiley & Sons, New York, NY, 963 pp.

Hinze, W.J. 1988. Gravity and Magnetic Methods Applied to Engineering and Environmental Problems. In: Proc. Symp. on the Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 1-108.

Hoekstra, P. and A. Delaney. 1974. Dielectric Properties of Soils at UHF and Microwave Frequencies. J. Geophys. Res. 79:1699-1708.

Hoekstra, B. and P. Hoekstra. 1990. Planning and Executing Geophysical Surveys. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:1159-1166. [EMI, ER, GPR, GR, MAG, SR]

Holz, R.K. (ed.) 1973. The Surveillant Science: Remote Sensing of the Environment. Houghton Mifflin, Boston, MA, 390 pp.

Howell, B.F. 1959. Introduction to Geophysics. McGraw-Hill, New York, NY, 399 pp. [S, GR, MAG, thermal]

Hoyt, Jr., W.H. 1974. Engineering Electromagnetics, 3rd edition. McGraw-Hill, New York, NY.

HRB-Singer, Inc. 1971. Detection of Abandoned Underground Coal Mines by Geophysical Methods. Project 14010, Report EHN. Prepared for U.S. Environmental Protection Agency and Pennsylvania Dept. of Env. Res. (Cited by Lord and Koerner, 1987.) [VLF, IP, SP]

Hunter, J. and S. Pullan. 1989. Optimum Offset Shallow Seismic Reflection Technique. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 143-174.

Huntley, D. 1978. On the Detection of Shallow Aquifers Using Thermal Infrared Imagery. Water Resources Research 14(6):1075-1083.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1975. Estimating Evapotranspiration: A Technique Adaptable to Remote Sensing. Science 189:991-992. [Thermal IR]

Jackson, J.D. 1975. Classical Electromagnetics. John Wiley & Sons, New York, NY.

Jackson, T.J. and T.J. Schmugge. 1986. Passive Microwave Remote Sensing of Soil Moisture. Advances in Hydroscience 14:123-159.

Jackson, R.D. and S.A. Taylor. 1986. Thermal Conductivity and Diffusivity. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 945-956.

Jakosky, J.J. 1950. Exploration Geophysics. Trija Publishing Co., Los Angeles, CA, 1195 pp. [S, ER, MAG, GR]

Jansen, J. 1990. Shallow Geothermal Exploration Techniques for Groundwater Studies. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:23-37.

Jessup, A.M. 1990. Thermal Geophysics. Elsevier, New York, NY, 306 pp.

Johnson, A.I. and J.P. Gnaedinger. 1964. Bibliography. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA, pp. 137-155. [Air photo interpretation (90 references), ER and seismic (60 references), electrical borehole logging (48 references), nuclear borehole logging (40 references), borehole camera (13 references), neutron moisture measurement (50 references)]

Johnson, A.I. and C.B. Pettersson (eds.). 1987. Geotechnical Applications of Remote Sensing and Remote Data Transmission. ASTM STP 967, American Society for Testing and Materials, Philadelphia, PA.

Jordon, E.D. (ed.). 1963. Electromagnetic Wave Theory. Pergamon, New York, NY.

Kalenov, E.N. 1957. Interpretation of Vertical Electrical Sounding Curves. Gostopekhizdat, Moscow, 472 pp.

Kaufman, A.A. and G.V. Keller. 1981. The Magnetotelluric Sounding Method. Elsevier, New York, NY, 686 pp.

Kaufman, A.A. and G.V. Keller. 1983. Frequency and Transient Soundings. Elsevier, New York, NY.

Kearey, P. and M. Brooks. 1991. An Introduction to Geophysical Exploration, 2nd edition. Blackwell Scientific Publications, Boston, MA, 296 pp. (1st edition, 1984.) [SRR, SRL, GR, MAG, ER, SP, IP, EMI, VLF, AFMAG, TC, MT, AEM]

Keller, G.V. and F.C. Frischknecht. 1970. Electrical Methods in Geophysical Prospecting, 2nd ed. Pergamon Press, New York, NY, 517 pp. (1st edition, 1966.)

Kersten, M.S. 1949. Thermal Properties of Soils. Univ. of Minn. Eng. Exp. Sta. Bulletin 28: 1-225.

Kleyn, A.H. 1983. Seismic Reflection Interpretation. Elsevier, New York, NY.

Kofoed, O. 1979. Geosounding Principles I, Resistivity Sounding Measurements. Elsevier, New York, NY, 276 pp.

Kondratyev, K.Y. 1969. Radiation in the Atmosphere. Academic Press, New York, NY, 912 pp.

Kong, J.A. 1975. Theory of Electromagnetic Waves. John Wiley & Sons, New York, NY, 339 pp.

Knapp, R.W. and D.W. Steeples. 1986a. High-Resolution Common Depth-Point Seismic Reflection Profiling Instrumentation. Geophysics 51:276-282.

Knapp, R.W. and D.W. Steeples. 1986b. High-Resolution Common Depth-Point Reflection Profiling: Field Acquisition Parameter Design. Geophysics 51:283-294.

Kracchman, M.B. 1970. Handbook of Electromagnetic Propagation in Conducting Media. U.S. Navy Material Command, NAVMAT P-2302, 128 pp.

Kraus, J.D. 1984. Electromagnetics, 3rd edition. McGraw-Hill, New York, NY, 775 pp.

Kunetz, G. 1966. Principles of Direct Current Resistivity Prospecting. Geoexploration Monograph Series No. 1, Gebrüder Borntraeger, Berlin, 103 pp.

Lahee, F.H. 1961. Field Geology. McGraw-Hill, New York, NY, 926 pp. [GR, MAG, S, ER, EM]

Lattman, L.H. and R.G. Ray. 1965. Aerial Photographs in Field Geology. Holt Rinehart and Winston, New York, NY, 221 pp.

Lee, W.H. (ed.). 1965. Terrestrial Heat Flow. Geophysical Monograph Series, American Geophysical Union, Washington, DC, 276 pp.

Leenhardt, O. 1969. Analysis of Continuous Seismic Profiles. International Hydrology Review 156(1):51-80.

Lewis, M.R. and F.P. Haeni. 1987. The Use of Surface Geophysical Techniques to Detect Fractures in Bedrock--An Annotated Bibliography. U.S. Geological Survey Circular 987. [31 English language and 12 foreign language references]

Lord, Jr., A.E. and R.M. Koerner. 1987. Nondestructive Testing (NDT) Techniques to Detect Contained Subsurface Hazardous Waste. EPA/600/2-87/078 (NTIS PB88-102405), 99 pp. [17 methods; EMI, GPR, MAG, MD best]

Lorraine, P. and D.R. Carson. 1970. Electromagnetic Fields and Waves, 2nd edition. W.H. Freeman, San Francisco, CA.

Lucius, J.E., G.R. Olhoeft, and S.K. Dukes (eds.). 1990. Third International Conference on Ground Penetrating Radar: Abstracts of the Technical Meeting, Lakewood, CO, May 14-18, 1990. U.S. Geological Survey Open File Report 90-414, 94 pp.

Lueder, D.R. 1959. Aerial Photographic Interpretation: Principles and Applications. McGraw-Hill, New York, NY, 462 pp.

Lund, T. 1978. Surveillance of Environmental Pollution and Resources by Electromagnetic Waves. NATO Advanced Study Institutes Series C, Vol. 45. Reidel Publishing Co., Boston, MA, 402 pp. [9 papers on land/water sensing using microwave and thermal IR]

Marutzky, S.J., W.D. Steele, and B.N. Key. 1984. Surface Gamma-Ray Measurement Protocol. GJ/TMC-06 (NTIS DE84-016085), U.S. Department of Energy Technical Measurements Center, Grand Junction, CO.

McGonnagle, W.J. 1961. Nondestructive Testing. Gordon and Breach Publ., New York, NY.

McNeill, J.D. and V. Labson. 1991. Geological Mapping Using VLF Radio Fields. In: Electromagnetic Methods in Applied Geophysics, Vol. 2: Applications, M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, Part B, pp. 521-640.

Milsom, J. 1989. Field Geophysics. Halsted Press, New York, NY, 182 pp.

Mooney, H.M. 1980. Handbook of Engineering Geophysics, Vol. 2: Electrical Resistivity. Bison Instruments, Minneapolis, MN, 83 pp.

Mooney, H.M. 1984. Handbook of Engineering Geophysics, Vol. 1: Seismic, 2nd edition. Bison Instruments, Minneapolis, MN, 195 pp. (1st edition published in 1973, reprinted in 1981; 2nd edition has new chapters added, but some planned chapters were not written due to death of the author.) [SRL, SRR]

Mooney, R.M. and W.W. Wetzel. 1956. The Potentials About a Point Electrode and Apparent Resistivity Curves for a Two-, Three- and Four-Layered Earth. University of Minnesota Press, Minneapolis, MN, 145 pp.

Morely, L.W. (ed.) 1970. Mining and Groundwater Geophysics/1967. Economic Geology Report 26. Geological Survey of Canada, Ottawa, Canada. [ER, EM, SRR, BH]

Morrison, R.D. 1983. Ground Water Monitoring Technology: Procedures, Equipment and Applications. Timco Mfg., Prairie Du Sac, WI, 111 pp.

Morse, J.G. (ed.). 1977. Nuclear Methods in Mineral Exploration and Production. Elsevier, New York, NY, 280 pp.

Musgrave, A.W. (ed.). 1967. Seismic Refraction Prospecting. Society of Exploration Geophysicists, Tulsa, OK, 604 pp.

Nabighian, M.N. (ed.). 1988. Electromagnetic Methods in Applied Geophysics, Vol. 1: Theory. Society of Exploration Geophysicists, Tulsa, OK, 528 pp.

Nabighian, M.N. (ed.). 1991. Electromagnetic Methods in Applied Geophysics, Vol. 2, Parts A and B: Applications. Society of Exploration Geophysicists, Tulsa, OK, (A) pp. 1-520, (B) pp. 521-992.

Nabighian, M.N. and J.C. Macnae. 1991. Time Domain Electromagnetic Prospecting Methods. In: Electromagnetic Methods in Applied Geophysics, Vol. 2: Applications, Part A. M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, pp. 427-520.

National Water Well Association (NWWA). 1984. NWWA/EPA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio, TX). NWWA, Dublin, OH.

National Water Well Association (NWWA). 1985. NWWA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (Fort Worth, TX). NWWA, Dublin, OH.

National Water Well Association (NWWA). 1986. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition (Denver, CO). NWWA, Dublin, OH.

Nettleton, L.L. 1940. Geophysical Prospecting for Oil. McGraw-Hill, New York, NY, 444 pp. [GR, MAG, SRR, SRL, ER]

Nettleton, L.L. 1971. Gravity and Magnetics for Geologists and Seismologists. Monograph No. 1. Society of Exploration Geophysicists, Tulsa, OK, 121 pp.

Nettleton, L.L. 1976. Gravity and Magnetics in Oil Prospecting. McGraw-Hill, New York, NY, 464 pp.

Nielsen, D.M. 1991. An Update on ASTM Subcommittee on Ground Water and Vadose Zone Investigations. Ground Water Monitoring Review 11(3):92-96.

O'Brien & Gere Engineering. 1988. Hazardous Waste Site Remediation: The Engineering Perspective. Van Nostrand Reinhold, New York, NY, 400 pp. [SRR, SRL, ER, EM, GPR, MAG]

Ogilvy, A.A. and V. Bogoslovsky. 1979. The Possibilities of Geophysical Methods Applied for Investigating the Impact of Man on the Geologic Medium. Geophysical Prospecting 27(4):775-789. [SP]

Olhoeft, G.R. 1988. Selected Bibliography on Ground Penetrating Radar. In: Proc. (1st) Symp. Application of Geophysics to Eng. and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 462-520.

Olhoeft, G.R. 1992. Geophysics Advisor Expert System, Version 2.0. U.S. Geological Survey Open File Report 92-526, 21 pp. plus floppy disk. (Also available from U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory, P.O. Box 93478, Las Vegas, NV, 89193-3478; Replaces Version 1.0 [EPA/600/4-89/023], released in 1989.) [ER, EMI, complex resistivity, SRR, SRL, GPR, GR, radiometric, soil gas]

Orellana, E. and H.M. Mooney. 1966. Master Tables and Curves for Vertical Electrical Sounding Over Layered Structures. Interciencia, Madrid, 150 pp. (Available from: Technical Information Center, U.S. Army Corps of Engineers Waterways Experiment Station, P.O. Box 631, Vicksburg, MS, 39180.)

Orellana, E. and H.M. Mooney. 1972. Two and Three Layers Master Curves and Auxiliary Point Diagrams for Vertical Electrical Sounding Using Wenner Arrangement. Interciencia, Madrid, 41 pp.

Paillet, F.L. and W.R. Saunders (eds.). 1990. Geophysical Applications for Geotechnical Investigations. ASTM STP 1101, American Society for Testing and Materials, Philadelphia, PA, 118 pp. [7 peer-reviewed papers on surface and borehole geophysics]

Palacky, G.J. (ed.), 1986. Airborne Resistivity Mapping. Canada Geological Survey Paper 86-22, 195 pp.

Palacky, G.J. and G.F. West. 1991. Airborne Electromagnetic Methods. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Part B: Applications. M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, pp. 811-880.

Palmer, D. 1980. Generalized Reciprocal Method of Seismic Refraction Interpretation. Society of Exploration Geophysicists, Tulsa, OK, 104 pp.

Palmer, D. 1986. Refraction Seismics. Handbook of Geophysical Exploration, Vol. 13. Geophysical Press, London, 269 pp.

Parasnis, D.S. 1975. Mining Geophysics, 2nd edition, revised and updated. Elsevier, New York, NY, 395 pp. (2nd edition, 1973.) [MAG, SP, EMI, TDEM, TC, ER, IP, GR, SRR, SRL, radiometric, BH]

Parasnis, D.S. 1979. Principles of Applied Geophysics, 3rd edition. Chapman and Hall, New York, NY, 269+ pp. (Earlier editions, 1962, 1972.) [MAG, GR, ER, IP, EM, S]

Parizek, R.R. 1976. On the Nature and Significance of Fracture Traces and Lineaments in Carbonate and Other Terranes. In: Karst Hydrology and Water Resources, Vol. 1, V. Yevjevich (ed.), Water Resources Publications, Fort Collins, CO, pp. 3-1 to 3-62.

Parkhomenko, E.I. 1967. Electrical Properties of Rocks. Plenum Press, New York, NY, 314 pp.

Patra, H.P. and K. Mallick. 1980. Geosounding Principles, Vol. 2: Time Varying Geoelectric Soundings. Elsevier, New York, NY.

Phillipson, W.R. and D.A. Sangrey. 1977. Aerial Detection Techniques for Landfill Pollutants. In: Proc. (3rd) Solid Waste Research Symp. (Management of Gas Leachate from Landfills), EPA/600/9-77/026 (NTIS PB272-595), pp. 104-114.

Pikul, Jr., J.L. 1991. Estimating Soil Surface Temperature from Meteorological Data. Soil Science 151:187-195.

Pilon, J.A. (ed.). 1992. Ground Penetrating Radar. Geological Survey of Canada Paper 90-4, Russell, 241 pp.

Pitchford, A.M., A.T. Mazzella, and K.R. Scarbrough. 1988. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination. EPA/600/4-88/019 (NTIS PB88-208194). [EMI, ER, complex resistivity, GPR, SRR, SRL, MAG, MD, AEM, radiometric]

Pittman, W.E., Jr., R.H. Church, W.E. Webb, and J.T. McLendon. 1984. Ground-Penetrating Radar: A Review of Its Application in the Mining Industry. U.S. Bureau of Mines Information Circular 8964, 23 pp.

Porstendorfer, G. 1975. Principles of Magneto-Telluric Prospecting. Gebrüder Borntraeger, Stuttgart.

Ray, R.G. 1960. Aerial Photographs in Geologic Interpretation and Mapping. U.S. Geological Survey Professional Paper 373, 320 pp.

Redpath, R. 1973. Seismic Refraction Exploration for Engineering Site Investigations. Technical Report E-73-4. (NTIS AD-768710), U.S. Army Corps of Engineers Explosive Excavation Research Laboratory, Livermore CA, 51 pp.

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA, Chapter 3. [SRR, SRL, CSP, sonar, ER, SP, EMI, GPR, GR, BH]

Rees, W.G. 1990. Physical Principle of Remote Sensing. Cambridge University Press, New York, NY 247 pp.

Reeves, R.G. 1968. Introduction to Electromagnetic Remote Sensing with Emphasis on applications to Geology and Hydrology. AGI Short Course Lecture Notes. American Geological Institute, Washington, DC.

Reeves, R.G. (ed.). 1975. Manual of Remote Sensing. American Society of Photogrammetry, Falls Church, VA, 2144 pp. (2nd edition, Colwell, 1983.)

Regan, R.D. 1980. Remote Sensing Method. Geophysics 45(11):1685-1689.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA. [Major methods: ER, EMI, SRR, BH; Other: IR, SP, IP/complex resistivity, SRR, GPR, MAG, GR, thermal]

Robinson, E.S. and C. Coruh. 1988. Basic Exploration Geophysics. John Wiley & Sons, New York, NY, 562 pp. [SRR, SRL, GR, MAG, ER, IP, SP, TC, EMI, BH]

Rokityanksi, I.I. 1982. Geoelectromagnetic Investigation of the Earth's Crust and Mantle. Springer-Verlag, New York, NY.

Roksandic, M.M. 1978. Seismic Facies Analysis Concepts. Geophysical Prospecting 26:383-398. [CSP]

Rossiter, J.R. and D.P. Bazeley (eds.). 1980. Proceedings of the International Workshop on the Remote Estimation of Sea Ice Thickness (St. John's, Newfoundland, September 25-26, 1979). C-CORE Publication No. 80-5, Centre for Cold Ocean Resources Engineering, St. John's, Newfoundland. [19 papers]

Roux, P.H. 1978. Electrical Resistivity Evaluations at Solid Waste Disposal Facilities. EPA/SW-729, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, DC, 93 pp.

Russell, B.H. 1988. Introduction to Seismic Inversion Methods. Course Notes No. 2. Society of Exploration Geophysicists, Tulsa, OK, 90 pp.

Sabins, Jr. F.F. 1978. Remote Sensing: Principles and Interpretation. W.H. Freeman, San Francisco, CA, 426 pp.

Sangree, J.B. and J.M. Widmier. 1979. Interpretation of Depositional Facies from Seismic Data. Geophysics 44(2):131-160. [CSP]

Sangrey, D.A. and W.R. Phillipson. 1979. Detecting Landfill Leachate Contamination Using Remote Sensors. EPA/600/4-79/060 (NTIS PB80-174295), 78 pp.

Saucier, R.T. 1970. Acoustic Subbottom Profiling Survey--A State-of-the-Art Survey. Miscellaneous Paper S-69-332. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 71 pp.

Schelkunoff, S.A. 1943. Electromagnetic Waves. Van Nostrand, New York, NY.

Scherz, J.P. 1971. Monitoring Water Pollution by Means of Remote Sensing Techniques. Remote Sensing Program Report No. 3. University of Wisconsin, Madison, WI, 27 pp.

Scherz, J.P. and A.R. Stevens. 1970. An Introduction to Remote Sensing for Environmental Monitoring. Remote Sensing Program Report No. 1, University of Wisconsin, Madison, WI, 80 pp.

Sers, S.W. 1971. Remote Sensing in Hydrology: A Survey of Applications with Selected Bibliography and Abstracts. Texas A&M University Remote Sensing Center, College Station, TX, 530 pp.

Sharma, P.V. 1986. Geophysical Methods in Geology, 2nd edition. Elsevier, New York, NY, 428 pp. (1st edition, 1976.) [S, GR, MAG, ER, GT]

Sharp, R.S. 1970. Research Techniques in Nondestructive Testing. Academic Press, New York, NY. [Thermal infrared sensing]

Sheriff, R.E. 1968. Glossary of Terms Used in Geophysical Exploration. Geophysics 33(1):181-228.

Sheriff, R.E. 1989. Geophysical Methods. Prentice Hall, Englewood Cliffs, NJ, 605 pp. [GR, MAG, ER, EM, SRR, geothermal, radiometric, BH]

Sheriff, R.E. 1991. Encyclopedic Dictionary of Exploration Geophysics, 3rd edition. Society of Exploration Geophysicists, Tulsa, OK, 376 pp. (1st edition, 1973; 2nd edition, 1984.)

Slotnick, M.M. 1959. Lessons in Seismic Computing. Society of Exploration Geophysicists, Tulsa, OK, 268 pp. [SRR]

Smith, G.D., F. Newhall, and L.H. Robinson. 1960. Soil-Temperature Regimes--Their Characterization and Predictability. SCS-TP-144. USDA Soil Conservation Service, 14 pp.

Smith, B., W. Heran, R. Bisdorf, and A.T. Mazzella. 1989. Evaluation of Airborne Geophysical Methods to Map Brine Contamination. EPA/600/4-89/003. U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory, Las Vegas, NV. [AEM, aeromagnetics]

Society of Engineering and Mineral Exploration Geophysicists (SEMEG). 1988-present. Symposium on the Application of Geophysics to Engineering and Environmental Problems (1st, 1988; 2nd, 1989; 3rd, 1990; 4th, 1991.) SEMEG, Golden, CO.

Society of Exploration Geophysicists (SEG). Various Dates. Annual Meeting Technical Program: Expanded Abstracts and Biographies. SEG, Tulsa, OK. (Publication for the 61st annual meeting in 1991 is a 2 volume set totaling 1707 pages.)

Soil Conservation Service (SCS). 1973. Aerial-Photo Interpretation in Classifying and Mapping Soils. U.S. Department of Agriculture Handbook 294.

Soil Conservation Service (SCS). 1988. Second International Conference on Ground Penetrating Radar (March 6-10, 1988, Gainesville, FL.) U.S. Department of Agriculture, 179 pp.

Soiltest, Inc. 1968. Earth Resistivity Manual. Soiltest, Inc., Evanston, IL, 46 pp.

Steele, W.D., D.C. George, and J.L. Burnham. 1985. Gamma-Ray Instrument Calibration Comparison Workshop. GJ/TMC-23. U.S. Department of Energy Technical Measurements Center, Grand Junction, CO.

Steeples, D.W. and R.D. Miller. 1988. Seismic Reflection Methods Applied to Engineering, Environmental and Ground-Water Problems. In: Proc. (1st) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 409-461.

Stevens, Jr., H.H., J.F. Ficke, and G.F. Smoot. 1975. Water Temperature--Influential Factors, Field Measurement, and Data Presentation. U.S. Geological Survey Techniques of Water-Resources Investigations TWRI 1-D1, 65 pp.

Stewart, M. and R. Bretnall. 1986. Interpretation of VLF Resistivity Data for Ground Water Contamination Surveys. Ground Water Monitoring Review 6(1):71-75.

Stokoe II, K.H. and S. Nazarian. 1985. Use of Rayleigh Waves in Liquefaction Studies. In: Measurement and Use of Shear Wave Velocity for Evaluation Dynamic Soil Properties, R.D. Woods (ed.), Proc., Geotechnical Eng. Division, ASCE, New York, NY, pp. 1-17.

Stratton, J.A. 1941. Electromagnetic Theory. McGraw-Hill, New York, NY.

Summers, W.K. 1971. The Annotated Indexed Bibliography of Geothermal Phenomena. New Mexico Institute of Mining and Technology, Socorro, NW. [More 14,000 references]

Sumner, J.S. 1976. Principles of Induced Polarization for Geophysical Interpretation. Elsevier, New York, NY, 277 pp.

Sumner, J.S. 1979. The Induced Polarization Exploration Method. In: Geophysics and Geochemistry in the Search of Metallic Ores, P.J. Hood (ed.), Economical Geology Report 31, Geological Survey of Canada, pp. 123-133.

Sylwester, R.E. 1983. Single-Channel, High-Resolution Seismic Reflection Profiling: A Review of the Fundamentals and Instrumentation. In: Handbook of Geophysical Exploration at Sea, A.A. Geyer (ed.), CRC Press, Boca Raton, FL, pp. 77-122.

Tareev, B. 1975. Physics of Dielectric Materials. Mir, Moscow.

Taylor, R.W. 1984. Evaluation of Geophysical Surface Methods for Measuring Hydrological Variables in Fracture Rock Units. U.S. Bureau of Mines, OFR-17-84 (NTIS PB84-158021), 145 pp.

Taylor, S.A. and R.D. Jackson. 1986a. Temperature. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 927-940.

Taylor, S.A. and R.D. Jackson. 1986b. Heat Capacity and Specific Heat. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 941-944.

Technos, Inc. 1992. Application Guide to the Surface Geophysical Methods. Technos, Miami, FL, 19 pp. [GPR, EMI, TDEM, VLF resistivity, ER, SRR, SRL, MAG, MD, GR, thermal, radiation]

Telford, W.M.N., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1990. Applied Geophysics, 2nd edition. Cambridge University Press, New York, NY, 770 pp. [1st edition, 1976; reprinted, 1982] [GR, MAG, SRR, SRL, ER, IP, SP, MT, EMI, TDEM, AEM, radioactive, BH]

Thomson, K.P.B., R.K. Lane, and S.C. Csallany (eds.). 1973. Remote Sensing and Water Resources Management. AWRA, Proceedings Series No. 17, American Water Resources Association, Urbana, IL, 436 pp.

Tinlin, R.M., L.J. Hughes, and A.R. Anzzolin. 1988. The Use of Controlled Source Audio Magnetotellurics (CSAMT) to Delineate Zones of Ground-Water Contamination. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 101-118.

Trabant, P.K. 1984. Applied High-Resolution Geophysical Methods--Offshore Geoengineering Hazards. International Human Resource Development Corp., Boston, MA, 265 pp. [CSP, GPR]

Truman, C.C., L.E. Asmussen, and H.D. Allison. 1991. Ground-Penetrating Radar: A Tool for Mapping Reservoirs and Lakes. J. Soil and Water Conservation 46(5):370-373.

Tucker, P.M. 1982. Pitfalls Revisited. Monograph No. 3. Society of Exploration Geophysicists, Tulsa, OK, 23 pp. (Expands on Tucker and Yorsten, 1973.)

Tucker, P.M. and H.J. Yorsten. 1973. Pitfalls in Seismic Interpretation. Monograph No. 2. Society of Exploration Geophysicists, Tulsa, OK, 56 pp.

Tufekcic, D. 1978. A Prediction of Sedimentary Environment from Marine Seismic Data. Geophysical Prospecting 26:329-336. [CSP]

Ulaby, F.T., R.K. Moore, and A.K. Fung. 1982. Microwave Remote Sensing: 3 Vols. Addison-Wesley, Reading, MA.

Ulriksen, P.F. 1982. Application of Impulse Radar to Civil Engineering. Geophysical Survey Systems Inc., Hudson, NH.

U.S. Army Corps of Engineers. 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Department of the Army, Washington, DC, 313 pp. [SRR, SRL, SASW, sonar, ER, GR, BH]

U.S. Environmental Protection Agency (EPA). 1979. Acoustic Monitoring to Determine the Integrity of Hazardous Waste Dams. EPA/625/2-79/024 (NTIS PB92-179928).

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557), 644 pp. [Remote sensing, EMI, ER, SRR, SRL, MAG, GPR, BH]

U.S. Environmental Protection Agency (EPA). 1993. Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide. EPA/625/R-92/007. Available from CERI.*

U.S. Geological Survey. 1980. Geophysical Measurements. In: National Handbook of Recommended Methods for Water Data Acquisition, Chapter 2 (Ground Water), Office of Water Data Coordination, Reston, VA, pp. 2-24 to 2-76. [TC, MT, AMT, EMI, ER, IP, SRR, GR, BH]

U.S. Geological Survey. 1982. Evaporation and Transpiration. In: National Handbook of Recommended Methods for Water Data Acquisition. USGS Office of Water Data Coordination, Reston, VA, pp 8-1 to 8-57. [Reviews thermal IR remote sensing methods for estimating evapotranspiration]

Valley, S.C. (ed.). 1965. Handbook of Geophysics and Space Environments. McGraw-Hill, New York, NY.

van Beek, L.K.H. 1965. Dielectric Behavior of Heterogeneous Systems. In: Progress in Dielectrics, Vol. 7, J.B. Birks (eds.), CRC Press, Boca Raton, FL, pp. 69-114.

Van Blaricom, R. 1980. Practical Geophysics for the Exploration Geologist. Northwest Mining Association, Spokane, WA, 303 pp.

van der Leeden, F. 1991. Geraghty & Miller's Groundwater Bibliography, 5th edition. Water Information Center, Plainview, NY, 507 pp.

Van Nostrand, R.G. and K.L. Cook. 1966. Interpretation of Resistivity Data. U.S. Geological Survey Professional Paper 499, 310 pp.

Verma, R.K. 1980. Master Tables for Electromagnetic Depth Sounding Interpretation. Plenum, New York, NY.

Verma, R.K. 1982. Electromagnetic Sounding Interpretation Data over Three-Layer Earth, Vols. 1 and 2. IFI/Plenum, New York, NY, (1) 338 pp., (2) 546 pp.

Von Hippel, A.R. 1954a. Dielectrics and Waves. MIT Press, Cambridge, MA, 284 pp.

Von Hippel, A.R. (ed.). 1954b. Dielectrics: Materials and Applications. MIT Press, Cambridge MA, 438 pp.

Vozoff, K. (ed.). 1986. Magnetotelluric Methods. Geophysics Reprint Series No. 5, Society of Exploration Geophysicists, Tulsa, OK, 800 pp.

Vozoff, K. 1991. The Magnetotelluric Method. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Part B: Applications, M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, pp. 641-712.

Wait, J.R. (ed.). 1959. Overvoltage Research and Geophysical Applications. Pergamon Press, New York, NY. [IP]

Wait, J.R. 1970. Electromagnetic Waves in Stratified Media, 2nd edition. Pergamon Press, New York, NY, 372 pp. (1st edition, 1962.)

Wait, J.R. (ed.). 1971. Electromagnetic Probing in Geophysics. The Golem Press, Boulder, CO, 391 pp.

Wait, J.R. 1981. Wave Propagation Theory. Pergamon Press, New York, NY, 349 pp.

Wait, J.R. 1982. Geo-Electromagnetism. Academic Press, New York, NY, 268 pp. [IP, EMI]

Wait, J.R. 1985. Electromagnetic Wave Theory. Harper and Row, New York, NY, 308 pp.

Waller, M.J. and J.L. Davis. 1984. Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failure. EPA/600/2-84/041 (NTIS PB84-157858), 148 pp. [28 methods assessed including ER, seismic, acoustic emission monitoring]

Ward, S.H. (ed.) 1990a. Geotechnical and Environmental Geophysics, Vol. I: Review and Tutorial. Society of Exploration Geophysicists, Tulsa, OK, 397 pp.

Ward, S.H. (ed.) 1990b. Geotechnical and Environmental Geophysics, Vol. II: Environmental and Groundwater. Society of Exploration Geophysicists, Tulsa, OK, 309 pp. [34 papers, including ER, EM multiple methods, thermal, others]

Ward, S.H. (ed.) 1990c. Geotechnical and Environmental Geophysics, Vol. III: Geotechnical. Society of Exploration Geophysicists, Tulsa, OK, 352 pp. [23 papers, including cross-borehole resistivity, seismic shear, radio imaging]

Ward, S.H. and H.F. Morrison (eds.). 1971. Special Issue on Electromagnetic Scattering. Geophysics 36(1):1-183.

Waters, K.H. 1981. Reflection Seismology--A Tool for Energy Resource Exploration, 2nd edition. John Wiley & Sons, New York, NY, 453 pp.

Watson, K., and R.D. Regan (eds.). 1983. Remote Sensing. Geophysics Reprint Series No. 3. Society of Exploration Geophysicists, Tulsa, OK, 581 pp.

Wechsler, A., P. Glaser, and R. McConnell. 1965. Methods of Laboratory and Field Measurements of Thermal Conductivity of Soils. CRREL Special Rept. 82. U.S. Army Cold Regions Res. and Eng. Lab., Hanover, NH, 31 pp.

Wheatcraft, S.W., K.C. Taylor, and J.G. Haggard. 1984. Investigation of Electrical Properties of Porous Media. EPA/600/4-84/089 (NTIS PB85-137156), 117 pp. [DC and complex resistivity]

White, J.E. 1965. Seismic Waves. McGraw-Hill, New York, NY, 200 pp.

Wolfe, P.R. 1974. Elements of Photogrammetry. McGraw Hill, New York, NY, 562 pp.

Woods, R.D. (ed.). 1985. Measurement and Use of Shear Wave Velocity for Evaluating Dynamic Soil Properties. Proc. Geotech. Eng. Div. ASCE, American Society of Civil Engineers, New York, NY.

Zohdy, A.A., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. U.S.

Geological Survey Techniques of Water-Resource Investigations, TWRI 2-D1, 116 pp. [ER, GR, MAG, SRR]

Zonge, K.L. and L.J. Hughes. 1991. Controlled Source Audio-Frequency Magnetotellurics. In: Electromagnetic Methods in Applied Geophysics, Vol. 2, Applications, M.N. Nabighian (ed.), Society of Exploration Geophysicists, Tulsa, OK, Part B, pp. 713-810.

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH 45268-0963 (513-569-7562).

SECTION 2

DRILLING AND SOLIDS SAMPLING METHODS

Drilling

Most subsurface investigations require the drilling of boreholes for one or more purposes: (1) Collection of solids samples or cores for lithologic logging and laboratory testing, (2) lithologic and hydrogeologic characterization using borehole geophysical logging, and (3) installation of piezometers or monitoring wells. Drilling methods are selected based on: (1) Availability and cost, (2) suitability for the type of geologic materials at a site (unconsolidated or consolidated), and (3) potential effects on sample integrity (influence by drilling fluids and potential for cross contamination between aquifers).

A wide variety of drilling methods have been developed that could be suitable for one or more of the purposes described above. Table 2-1 summarizes information on 18 drilling methods and explains where more detailed information on the method can be found in this section. The hollow-stem auger (Section 2.2.1) is by far the most commonly used method for well installation in unconsolidated deposits. Air rotary is probably the most commonly used method for well installation in consolidated formations (Section 2.1.2). Where cross contamination between aquifers is a concern, some kind of casing advancement methods is required, with drill-through methods (Section 2.1.5) and dual-wall reverse circulation (Section 2.1.6) being the most commonly used. Table 2-2 provides information on the relative performance of 11 of the drilling methods listed in Table 2-1 for different types of geologic formations.

Also included in this section is **cone penetrometry** (Section 2.2.2), which is not strictly a drilling method. This technology has been developed primarily in relation to geotechnical investigations, but is being used more frequently for subsurface characterization at contaminated sites.

Solids Sampling

Solids sampling methods can be broadly classified as **hand-held** and **power-driven.** Criteria for selection of hand-held equipment includes: (1) Whether an undisturbed core is required, (2) soil conditions at the site (cohesion, stones, moisture), (3) the sample size and depth desired, and (4) the number of required operators. Table 2-3 summarizes information on 12 types of hand-held samplers. More detailed information on these methods is covered in Sections 2.3.1 (Scoops, Spoons, and Shovels), 2.3.2 (Augers), and 2.3.3 (Tubes). Hand-held soil samplers are usually used for sampling the near surface (2 to 3 meters).

Power-driven samplers are usually operated in conjunction with drill rigs, although thin-wall tube samplers attached to hydraulic rigs for near-surface sampling can be attached to pickup trucks. Collection of soil cores is the preferred methods for sampling solids because much more accurate lithologic logging is possible than with cuttings from drill methods that do not obtain cores as part of the drilling process, such as diamond drilling (Section 2.1.10). The most common method for collection of disturbed cores is the split-barrel sampler (Section 2.4.1). Thin-wall open tube samples are the most common method for collecting undisturbed cores (Section 2.4.3). In consolidated geologic material, rotating core samplers are used (Section 2.4.2). Thin-wall piston samplers (Section 2.4.4) are usually used where poor cohesion prevents good recovery with conventional thin-wall samplers. Specially designed thin-wall samplers might be required for gravelly and very stiff or cemented unconsolidated deposits (Section 2.4.5).

ASTM (1987) provides general guidance on investigation and sampling of soil and rock. ASTM (1991) provides more specific guidance on soil sampling in the vadose zone.

Table 2-1 Summary Information on Drilling Methods

Drill Method	Casing/ Open Hole	Fluids Affect Chem.?	Core Samples?	Section Number	Tables
Hollow-Stem Auger	Open Hole	Usually No	Possible	2.1.1	2-2, 2.1.1
Open-Hole Rotary Methods					
Direct Air Rotary with Bit	Open Hole	Yes	Possible	2.1.2	2-2, 2.1.2
Direct Air Rotary with Downhole Hammer	Open Hole	Yes	Possible	2.1.2	2-2, 2.1.2
Direct Mud Rotary	Open Hole	Yes	Possible	2.1.3	2-2, 2.1.3
Reverse Rotary (no casing)	Open Hole	Yes	Possible	2.1.3	2-2
Cable Tool	Either	Usually No	Possible	2.1.4	2-2, 2.1.4
Rotary Drill-Through Methods					
Rotary Casing Driver	Casing	Yes	Possible	2.1.5	2-2, 2.1.5
Dual Rotary Advancement	Casing	Yes	Possible	2.1.5	
Reverse Circulation Methods					
Reverse Dual Wall Rotary	Casing	Yes	Possible	2.1.6	2-2, 2.1.6
Reverse Dual Wall Percussion	Casing	Yes	Possible	2.1.6	
Hydraulic Percussion	Casing	Yes	Possible	2.1.6	2-2
Downhole Casing Advancers	Casing	Yes	Possible	2.1.7	
Jet Percussion	Casing	Possible	Possible	2.1.8	2-2, 2.1.8
Jetting	Open Hole	Possible	No	2.1.8	
Solid Stem Auger	Open Hole	No	Possible	2.1.9	2-2, 2.1.9
Bucket Auger	Open Hole	No	Possible	2.1.9	
Rotary Diamond	Open Hole	Possible	Yes	2.1.10	
Directional Drilling	Either[a]	Possible	Possible[b]	2.1.11	
Sonic Drilling	Either	Possible	Yes	2.1.12	
Driven Wells	Either	No	No	2.2.1[c]	2-2
Cone Penetration	Open Hole	No	Possible[d]	2.2.2[c]	

Boldface = Most commonly used methods for monitoring well installation.

[a]EC rig uses casing advancement, other methods may involve open hole advancement.
[b]Sampling with a device resembling a split spoon may be possible with some directional rigs.
[c]Section includes cross references to other sections related to method.
[d]Geoprobe has developed a core sampler for use with a CPT rig.

Table 2-2 Relative Performance of Different Drilling Methods in Various Types of Geologic Formations

Type of Formation	Cable Tool	Direct Rotary (with fluids)	Direct Rotary (with air)	Direct Rotary (Down-the-hole air hammer)	Direct Rotary (Drill-through casing hammer)	Reverse Rotary (with fluids)	Reverse Rotary (Dual Wall)	Hydraulic Percussion	Jetting	Driven	Auger
Dune sand	2	5	Not recommended	Not recommended	6	5*	6	5	5	3	1
Loose sand and gravel	2	5	↓	↓	6	5*	6	5	5	3	1
Quicksand	2	5	↓	↓	6	5*	6	5	5	Not recommended	1
Loose boulders in alluvial fans or glacial drift	3-2	2-1	↓	↓	5	2-1	4	1	1	↓	1
Clay and silt	3	5	↓	↓	5	5	5	3	3	↓	3
Firm shale	5	5	↓	↓	5	5	5	3	Not recommended	↓	2
Sticky shale	3	5	↓	↓	5	3	5	3	↓	↓	2
Brittle shale	5	5	↓	↓	5	5	5	3	↓	↓	Not applicable
Sandstone—poorly cemented	3	4	↓	↓	Not applicable	4	5	4	↓	↓	↓
Sandstone—well cemented	3	3	5	↓	↓	3	5	3	↓	↓	↓
Chert nodules	5	3	3	↓	↓	3	3	5	↓	↓	↓
Limestone	5	5	5	6	↓	5	5	5	↓	↓	↓
Limestone with chert nodules	5	3	5	6	↓	3	3	5	↓	↓	↓
Limestone with small cracks or fractures	5	3	5	6	↓	2	5	5	↓	↓	↓
Limestone, cavernous	5	3-1	2	5	↓	1	5	1	↓	↓	↓
Dolomite	5	5	5	6	↓	5	5	5	↓	↓	↓
Basalts, thin layers in sedimentary rocks	5	3	5	6	↓	3	5	5	↓	↓	↓
Basalts—thick layers	3	3	4	5	↓	3	4	3	↓	↓	↓
Basalts—highly fractured (lost circulation zones)	3	1	3	3	↓	1	4	1	↓	↓	↓
Metamorphic rocks	3	3	4	5	↓	3	4	3	↓	↓	↓
Granite	3	3	5	5	↓	3	4	3	↓	↓	↓

*Assuming sufficient hydrostatic pressure is available to contain active sand (under high confining pressures)

Rate of Penetration:
1 Impossible
2 Difficult
3 Slow
4 Medium
5 Rapid
6 Very rapid

Source: Driscoll (1986), by permission

Table 2-3 Criteria for Selecting Hand-Held Soil Sampling Equipment

Type of Sampler/Section	Obtains Core	Required Soil Conditions			Sample		Number of Required Operators
		Cohesive	Stony	Moisture	Size	Depth	
Spoons, Scoops (2.3.1)	No	Either[a]	Yes	Either	Large	Shallow	1
Shovels (2.3.1)	No	Either	Yes	Either	Large	Deep	1
Post-Hole Digger	No	Yes	Yes	Moist	Large	Deep	1
Screw-Type Augers (2.3.2)	No	Either	No	Moist	Small	Deep	1
Barrel Augers (2.3.2)							
Dutch	No	Yes	Yes	Moist	Small	Deep	1
Regular	No	Yes	Yes	Either	Small	Deep	1
Sand	No	No[b]	Yes	Either	Large	Deep	1
Mud	No	Yes	Yes	Moist	Large	Deep	1
Tube Samplers (2.3.3)							
Soil probes							
Wet tips	Yes	Either	No	Moist	Small	Deep	1
Dry tips	Yes	Either	No	Dry	Small	Deep	2
Veihmeyer tube	Yes	Either	No	Either	Small	Shallow	1
Thin-wall tube samplers	Yes	Yes	No	Either	Large	Shallow	2
Peat samplers	Yes	Yes	No	Moist	Large	Deep	2

[a]Able to sample either cohesive or noncohesive soils.
[b]Designed to sample dry, sandy soils.

Source: Adapted from Brown et al. (1991)

Field Description of Soil Physical Properties

Field description of solids samples is an important part of the site characterization process. Major features that are described in the field include texture (Section 2.5.1) and color (Section 2.5.2). Numerous other features, such as moisture condition, and soil or sedimentary features that indicate zones of increased or reduced porosity or permeability, should also be described in the field (Section 2.5.3).

Sources of Additional Information

Table 2-4 provides sources of additional information on drilling methods and Table 2-5 presents other sources of information on solids sampling.

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.1 Hollow-Stem Auger

Other Names Used to Describe Method: Helical auger.

Uses at Contaminated Sites: Drilling for solids sampling and installation of ground-water monitoring wells in unconsolidated materials; drilling vadose monitoring wells (lysimeters); identifying depth to bedrock.

Method Description: A hollow-stem auger column (Figure 2.1.1) simultaneously rotates and axially advances using a mechanically or hydraulically powered drill rig. The hollow stem of the auger allows use of various methods for continuous (see Figure 2.4.3b) or intermittent sampling of soil material (see Figure 2.4.4b). Casing and screens for monitoring wells can be placed in the hollow stem when the desired depth has been reached, and gravel pack and grouting emplaced as the auger is gradually withdrawn from the hole. Use of different diameter augers allows use of casings to isolate near-surface contamination, and continuation of drilling with a smaller-diameter auger. Special screened auger sections allow ground-water sampling at different depths as drilling progresses (see Figure 5.2.7a).

Method Selection Considerations: Usually the favored method with moderately cohesive unconsolidated materials. **Advantages:** (1) Set-up time and drilling is fast and causes minimal damage to aquifer because no drilling fluids or lubricants are required; (2) high mobility rigs can reach most sites and equipment is generally readily available throughout the United States; (3) the hollow stem allows flexible choice of soil core sampling methods and use of natural gamma ray logging equipment; (4) depth to water table can usually be determined during drilling and formation waters can be sampled during drilling by using a screened lead auger or advancing a well point ahead of the augers; (5) auger flights act as temporary casing, stabilizing the hole for construction of small-diameter monitoring wells; and (6) usually less expensive than rotary or cable drilling. **Disadvantages:** (1) Cannot be used in consolidated deposits and might have to be abandoned if boulders are encountered; (2) heaving sands present problems, requiring special procedures to counteract; (3) generally limited to wells less than 150 feet in depth and works best to depths around 75 feet; (4) vertical mixing of formation water and geologic materials can occur; and (5) hollow stems might not be suitable for running a complete suite of geophysical logs. Aller et al. (1991) give hollow-stem augers top ratings compared to other drilling methods for: Up to 4-inch monitoring wells in unsaturated, unconsolidated material to 150 feet; up to 4-inch shallow monitoring wells (<15 feet) in saturated conditions; and for small (<2 inch) monitoring wells in saturated unconsolidated material to 150 feet (see Table 2.1.1).

Frequency of Use: The large majority of monitoring wells installed in unconsolidated materials in North America are constructed using hollow stem augers.

Standard Methods/Guidelines: ASTM (1993a), Appendix A in Aller et al. (1991).

Sources for Additional Information: Aller et al. (1991), Shuter and Teasdale (1989). See also, Table 2-4.

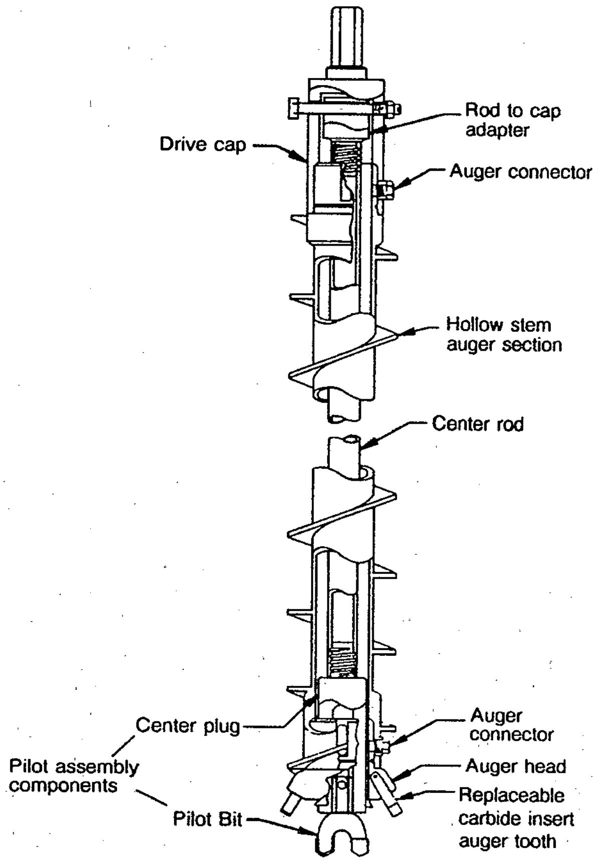


Figure 2.1.1 Typical components of a hollow-stem auger (Aller et al., 1991).

Table 2.1.1 Hollow-Stem Auger Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	**75**[a] (29-75)[b]	**75** (27-75)	**79** (32-79)	**75** (44-75)
	2-4"	**68** (30-68)	**72** (28-72)	**79** (24-79)	**77** (37-77)
	4-8"	NA	NA	**64** (48-64)	NA
15-150	<2"	**67** (23-67)	**69** (30-69)	**76** (24-76)	**79** (35-79)
	2-4"	59 (21-69)	64 (24-68)	72 (19-72)	73 (25-73)
	4-8"	NA	NA	NA	NA
>150	<2"	NA	NA	NA	NA
	2-4"	NA	NA	NA	NA
	4-8"	NA	NA	NA	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	NA	NA
--	4-8"	NA	NA

Boldface = Highest rating or within a few points of highest rating.
NA = Not applicable.
MW = Monitoring well diameter.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.2 Direct Air Rotary with Rotary Bit/Downhole Hammer

Other Names Used to Describe Method: Air rotary with roller-cone (tri-cone) bit, down-the-hole hammer, air-percussion rotary.

Uses at Contaminated Sites: **Air rotary bit:** Monitoring well installation in deeper, stable unconsolidated material, and sedimentary rocks. **Downhole hammer:** Monitoring well installation in very hard to hard geologic formations.

Method Description: **Air rotary bit:** The basic rig setup for air rotary with a tri-cone or roller-cone bit is similar to direct mud rotary (see Figure 2.1.3 in next section), except the circulation medium is air instead of water or drilling mud. Figure 2.1.2a illustrates the main components of a drill string using a tri-cone bit. Compressed air is circulated down through the drill rods to cool the bit, and carries cuttings up the open hole to the surface. A cyclone separator slows the air velocity and allows the cuttings to fall into a container. A roller cone drill bit is used for unconsolidated and hard to soft consolidated rock. In dry formations the cuttings are very fine-grained and a small amount of water and/or foaming surfactant can be added to increase the size of fragments discharged to the surface, allowing good characterization of the formation. **Downhole hammer:** A down-the-hole hammer, which operates with a pounding action as it rotates, replaces the roller-cone bit (Figure 2.1.2b). Other operational features are similar to those described for the rotary bit, except that small amounts of water or surfactants are needed for dust and bit temperature control.

Method Selection Considerations: Air rotary is often the method of choice for monitoring well installation in consolidated material, and deeper unconsolidated materials that form a stable hole. **Air Rotary Bit Advantages:** (1) Drilling is fast and can be used in both consolidated and unconsolidated formations, but is best suited for consolidated rock; (2) no drilling fluid is used, minimizing contamination of formation water; (3) depth is limited only by the capacity of the air compressor to deliver enough air downhole to maintain circulation; (4) cuttings can be recovered rapidly and are not contaminated by drilling mud (recovery is best in hard, dry formations); (5) major water-bearing zones can be identified when formation water is blown out of the hole along with cuttings and yields of strong water-producing zones can be estimated with a relatively short interruption of drilling; (6) well suited for highly fractured or cavernous rock because loss of drilling fluids is not a problem; (7) field analysis of water blown from the hole can provide information on changes in some basic water-quality parameters such as chlorides; and (8) drill rigs are readily available throughout most of the United States. **Air Rotary Bit Disadvantages:** (1) Oil contamination might result from the air compressor if air filters are not operating properly; (2) surfactant foams, if used, might react with formation water and affect representativeness of ground-water samples; (3) the drying effect of air can make lower yield water producing zones difficult to observe; (4) the air can modify chemical and biological conditions in an aquifer, with recovery time uncertain; (5) casing is required to keep the hole open when drilling in soft, caving formations below water table; (6) if hydrostatic pressures of water bearing zones are different, cross-contamination might occur between the time drilling is completed and the well casing is placed and grouted; (7) relatively expensive, might not be economical for small jobs; (8) requires a minimum 6-inch diameter hole; (9) cuttings and water blown from the hole can pose a hazard to crew and surrounding environment if toxic compounds are encountered; and (10) not suitable for soft, caving formations. Aller et al. (1991) give air rotary top ratings for all situations involving consolidated rock, and top ratings compared to other drilling methods for large diameter wells (4 to 8 inches) deeper than 15 feet in unsaturated, unconsolidated material where invasion of drilling fluid is not allowed (see Table 2.1.2). **Downhole Hammer Advantages:** (1) Downhole hammer provides better penetration in very hard geologic formations such as igneous and metamorphic rocks and very fast penetration in other formations; and (2) longer bit life, less drill collar wear, and easier to control deviation, while maintaining penetration rates compared to rotary bit. **Downhole Hammer Disadvantages:** (1) Oil is required in the air stream to lubricate the actuating device for the hammer, creating the possibility of hydrocarbon contamination of the monitoring well; (2) limited to systems using compressible circulating fluids (air, foam); and (3) use of surfactants might alter ground-water chemistry.

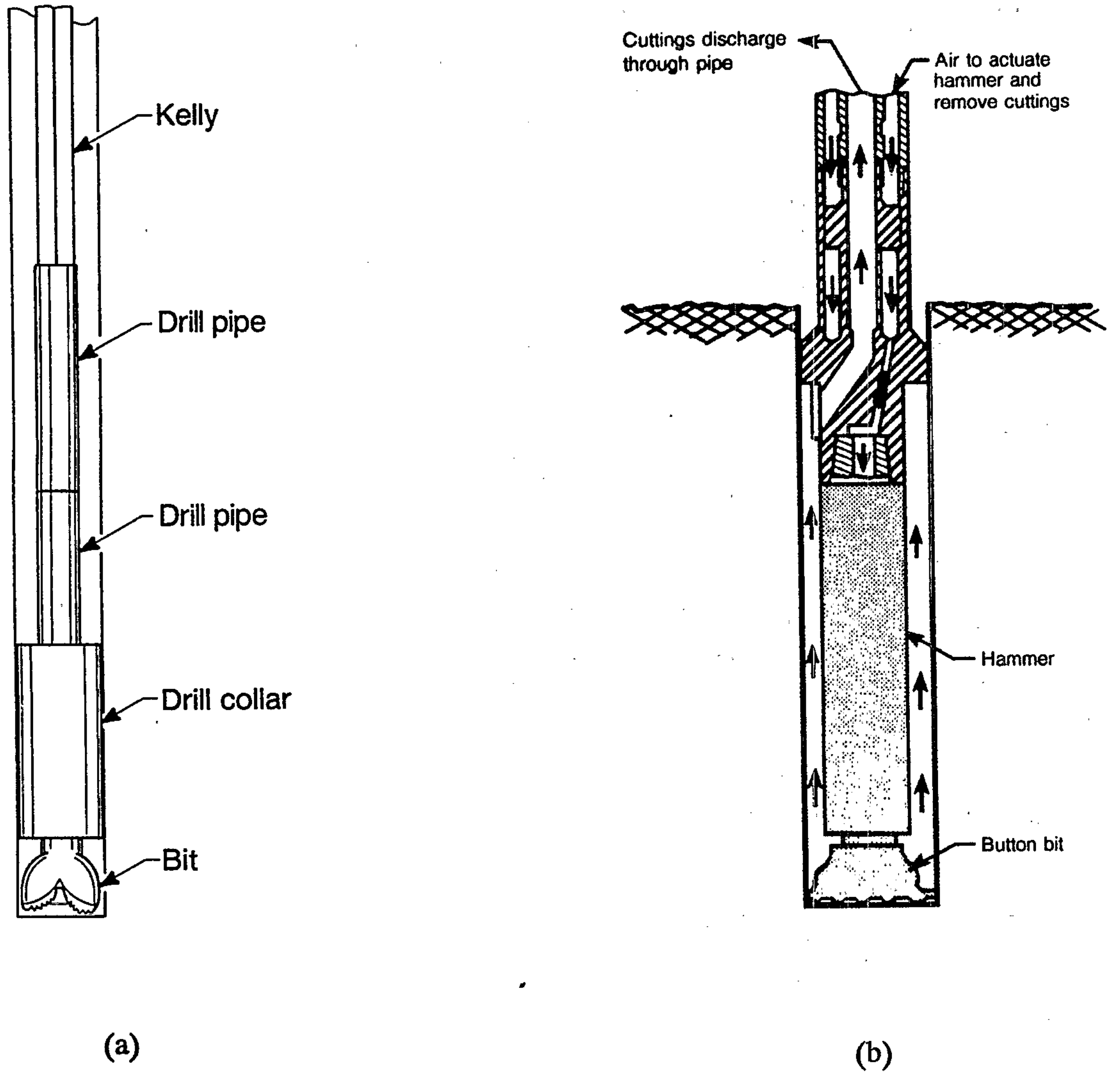


Figure 2.1.2 Air rotary drilling methods: (a) Drill string for a direct rotary rig with tri-cone bit (Driscoll, 1986, by permission); (b) Diagram of direct air rotary with downhole hammer (Aller et al., 1991).

Table 2.1.2 Direct Air Rotary Suitability Ratings

UNCONSOLIDATED MATERIALS

Depth (ft.)	MW Diameter	Saturated Invasion (+)	Saturated Invasion (-)	Unsaturated Invasion (+)	Unsaturated Invasion (-)
0-15	<2"	NA	NA	53 (32-79)[a]	53 (44-75)
	2-4"	NA	NA	53 (24-79)	53 (37-77)
	4-8"	NA	NA	48 (48-64)	58 (58-71)
15-150	<2"	NA	NA	56 (24-76)	56 (35-79)
	2-4"	NA	NA	51 (19-72)	52 (25-73)
	4-8"	NA	NA	NA (66-70)	**80** (80)
>150	<2"	NA	NA	55 (54-65)	65 (65-73)
	2-4"	NA	NA	58 (56-65)	60 (60-70)
	4-8"	NA	NA	NA	**80** (80)

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated Invasion (+)	Saturated/Unsaturated Invasion (-)
--	2-4"	**75** (55-75)	**74** (68-74)
--	4-8"	**77** (64-77)	**80** (80)

Boldface = Highest rating or within a few points of highest rating.
NA = not applicable.

[a]Range of numerical ratings of applicable methods (perfect score = 80).

Frequency of Use: Frequently used where monitoring wells must be installed in consolidated material.

Standard Methods/Guidelines: ASTM (1993b).

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986), Shuter and Teasdale (1989). See also, Table 2-4.

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.3 Direct Mud Rotary

Other Names Used to Describe Method: Direct (liquid) rotary, hydraulic rotary, reverse (circulation) rotary.

Uses at Contaminated Sites: Monitoring well installation in moderately deep to deep holes where invasion of drilling fluids is not a concern. Core sampling possible in both unconsolidated and consolidated rock.

Method Description: Figure 2.1.3 shows the major elements of a direct mud rotary drilling system. Drilling fluid, called mud, is pumped down hollow rotating drill rods and through a bit that is attached at the lower end of the drill rods. The fluid circulates back to the surface by moving up the annular space between the drill rods and the borehole wall, and is discharged at the surface through a pipe or ditch into a sedimentation tank, pond, or pit. Cuttings settle in the pond and the fluid overflows into a suction pit, where a pump recirculates the fluid back through the drill rods. The drilling fluid serves to: (1) Cool and lubricate the bit, (2) stabilize the borehole wall, and (3) prevent the inflow of formation fluids, thus minimizing cross contamination of aquifers. Samples can be obtained directly from the circulated fluid by placing a sample-collecting device, such as a shale shaker, in the discharge flow before the settling pit. For more accurate sampling, the flow of drilling fluid is interrupted and a split-spoon, thin-wall, or consolidated core sampler is inserted down the drill rod and the sample taken ahead of the bit. **Reverse circulation rotary** drilling is a variant of the mud rotary method in which drilling fluid flows from the mud pit down the borehole outside the drill rods; then passes upward through the bit, carrying cuttings into the drill rods; and then is discharged into the mud pit again. Equipment is similar to direct mud rotary, except that most pieces of equipment are larger.

Method Selection Considerations: **Direct Mud Rotary Advantages:** (1) A very flexible and rapid drilling method for a wide range of borehole diameters in both saturated and unsaturated conditions in consolidated and unconsolidated rock; (2) great depths can be reached (500 feet is the usual limit, but greater depths are possible depending on the borehole diameter, mudpump capacity, and ability to maintain circulation); (3) coring devices for detailed sampling are easy to use, but there is some risk of contamination by drilling fluids; (4) casing is not required during drilling; (5) complete suite of geophysical log can be run in mud-filled open hole; (6) flexibility in well construction; (7) smaller rigs can reach most sites and equipment is generally readily available throughout the United States; and (8) relatively inexpensive. **Direct Mud Rotary Disadvantages:** (1) Invasion of drilling fluid in permeable zones makes it difficult to identify aquifers, and compromises the validity of subsequent monitoring well samples; (2) contaminants might be circulated with the fluid; (3) collection of representative samples is difficult due to mixing of drill cuttings and sample lag time in deeper holes, unless split-spoon or thin-wall samplers are used in unconsolidated material or core bits are used in consolidated rock; (4) the filter pack is difficult to remove during development and disposing of contaminated drilling mud, and the large amount of water normally required to clean and develop the installation might be a problem; (5) no information on position of water table and only limited information on water producing zone is directly available during drilling; (6) measuring static water levels, taking representative water samples, and performing pump tests of individual aquifers is not practical; (7) generally not suited for use in fractured, cavernous, and very coarse material due to loss of drilling fluid (can be overcome by using casing); (8) bentonite fluids might absorb metals and might interfere with some other parameters; (9) organic fluids might interfere with bacterial analysis and/or organic-related parameters; (10) lubricants and metal parts might be a source of contamination; (11) placement of sand packs and seals is generally less certain than with auger methods; (12) requires experienced driller and fair amount of peripheral equipment; (13) might have to abandon holes if boulders are encountered; and (14) washout zones might develop in weaker formations. Aller et al. (1991) give mud rotary top ratings for saturated conditions deeper than 15 feet for all well diameters where invasion of drilling fluid is allowed (see Table 2.1.3). Where unconsolidated materials overlies a bedrock aquifer, mud rotary can be used to drill to the bedrock, the hole can be cased, and a less intrusive drilling method, such as air rotary, can be used to complete the well.

Frequency of Use: Mud rotary drilling rigs are widely available, but infrequently used for monitoring well installation because of the problems created by drilling fluids. **Reverse circulation rotary** is used primarily for the installation of large-diameter deep water wells, rather than monitoring wells.

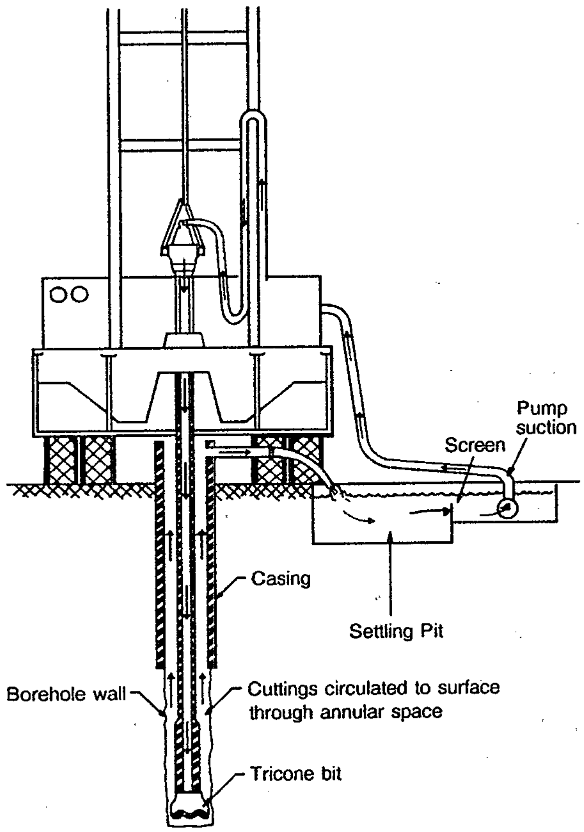


Figure 2.1.3 Diagram of direct mud rotary circulation system (Aller et al., 1991).

Table 2.1.3 Direct Liquid (Mud) Rotary Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	62[a] (29-75)[b]	NA	62 (32-79)	NA
	2-4"	60 (30-68)	NA	62 (24-79)	NA
	4-8"	**67** (61-69)	NA	**63** (48-64)	NA
15-150	<2"	**67** (23-67)	NA	67 (24-76)	NA
	2-4"	**69** (21-69)	NA	68 (19-72)	NA
	4-8"	**67** (67)	NA	**70** (66-70)	NA
>150	<2"	61 (60-69)	NA	61 (54-65)	NA
	2-4"	**66** (58-66)	NA	58 (56-65)	NA
	4-8"	**66** (63-66)	NA	**66** (65-66)	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	63 (55-75)	NA
--	4-8"	64 (64-77)	NA

Boldface = Highest rating or within a few points of highest rating.
NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

Standard Methods/Guidelines: ASTM (1993c).

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986), Shuter and Teasdale (1989). See also, Table 2-4.

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.4 Cable Tool

Other Names Used to Describe Method: Cable-tool percussion, percussion rig, spudder rig, open hole, reverse cable tool.

Uses at Contaminated Sites: Installing large-diameter monitoring wells.

Method Description: Cable tool drilling rigs operate by repeatedly lifting and dropping a heavy string of drilling tools attached to a cable into the borehole. Figure 2.1.4 illustrates the major components of a cable tool rig. Consolidated rock is broken or crushed into small fragments and unconsolidated material is loosened by the drill bit. The reciprocating action is caused by attaching the cable to an eccentric walking or spudding beam that also serves to mix the crushed or loosened particles with water to form a slurry at the bottom of the borehole. Periodically, the drilling string is removed and the slurry is removed by a sand pump or bailer. In unconsolidated formations, a casing is driven into the ground, often using hydraulic jacks as drilling and bailing proceeds. In consolidated formations, most boreholes are drilled "open hole," without the use of casing.

Method Selection Considerations: **Advantages:** (1) A very flexible drilling method that is suitable for all types of geologic formations (especially well suited to caving, large gravel-type formations, and drilling through boulders, fracture, fissured, broken, or cavernous rocks), and for wells of almost any depth and diameter range (depths exceeding 11,000 feet have been drilled with cable tool); (2) samples of coarse grained materials are of good quality and samples bailed from each interval represent about a 3 to 5 foot zone, allowing reasonably accurate geologic description; (3) typical casings are wide enough for easy installation of monitoring wells; (4) equipment is readily available in central, north-central and northeast sections of United States (in other part of the country, cable tool has been largely replaced by rotary drilling); (5) when casing is used, cross contamination is minimized; (6) changes in water level can be observed, water samples can be collected easily, and hydraulic conductivity tests can be made in different water-bearing zones; (7) good seal between casing and formation is virtually assured if flush-jointed casing is used; (8) rigs can reach most drilling sites; (9) relatively inexpensive; (10) little or no drilling fluid is required (small amounts of water are required, usually with no additives, above the water table; and (11) relative permeabilities and rough water quality data from the different water-bearing zones that are penetrated during drilling can be obtained by skilled operators. **Disadvantages:** (1) Drilling is slow because of the requirement for bailing; (2) heaving of material from the bottom of the casing upward might cause problems that require special measures; (3) casing costs are usually higher because heavier wall or larger diameter casing might be required and it might be difficult to pull back long strings of casing in some geologic formations; (4) difficult or impossible to obtain undisturbed cores; (5) slight potential for vertical mixing of materials as the casing is driven; (6) drill rigs not generally equipped to use borehole sampling devices other than bailers; (7) relatively large diameters are required (minimum 4-inch casing); (8) heavy steel drive pipe must be used and could be subject to corrosion under adverse contaminant conditions; (9) use of casing limits types of geophysical logs that can be run; (10) usually a screen must be set before a water sample can be taken; (11) heavy steel drive pipe used to keep hole open and drilling equipment can limit accessibility; (12) contamination possible if drilling fluid is used; and (13) it is difficult to place a positive grout seal above the drive shoe casing, consequently, wither the drive casing must be totally removed and the seal placed outside the permanent well casing, or a seal must be place above the screen but below the drive shoe, resulting in added costs and time for well completion. See Table 2.1.4 for ratings of cable drilling compared to other major drilling methods.

Frequency of Use: Not commonly used for monitoring well installation.

Standard Methods/Guidelines: API (1988a,b).

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Shuter and Teasdale (1989). See also, Table 2-4.

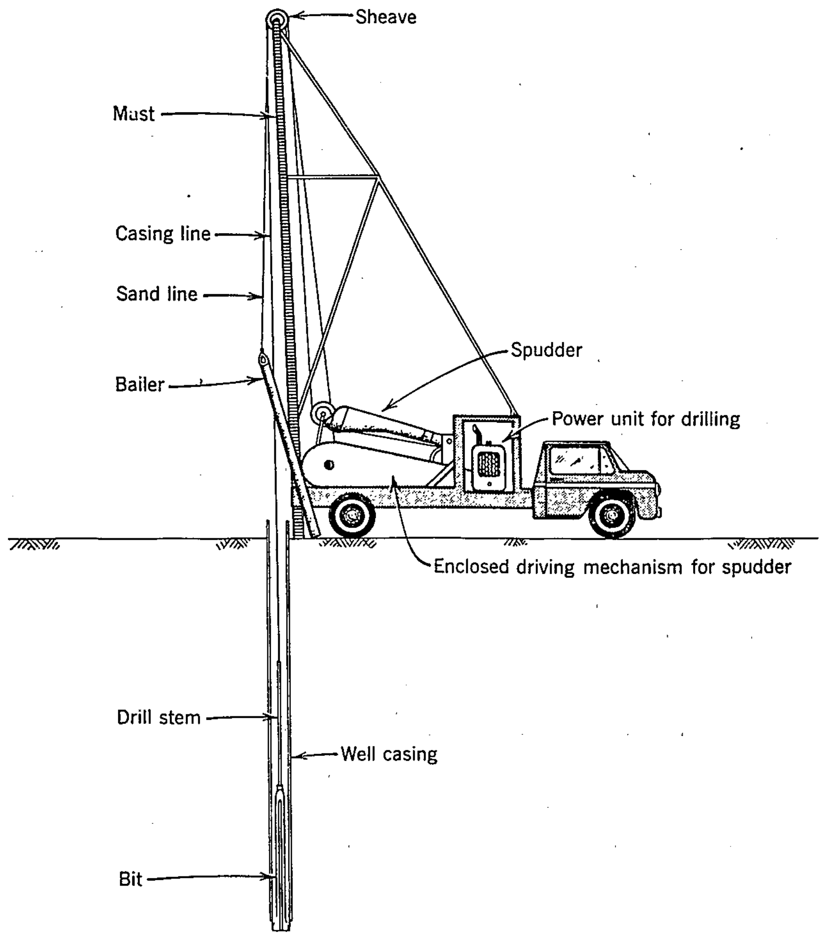


Figure 2.1.4 Truck-mounted cable tool rig; casing is commonly not used if well is being drilled in consolidated rock (Davis and DeWiest, 1966, reprinted by permission of John Wiley & Sons, Inc. from *Hydrogeology* by S.N. Davis and R.J.M. DeWiest, copyright © 1966).

Table 2.1.4 Cable Tool Drilling Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated Invasion (+)	Saturated Invasion (-)	Unsaturated Invasion (+)	Unsaturated Invasion (-)
0-15	<2"	65[a] (29-75)[b]	60 (27-75)	54 (32-79)	NA
	2-4"	65 (30-68)	66 (28-72)	60 (24-79)	NA
	4-8"	61 (61-69)	**74** (46-74)	61 (48-64)	NA
15-150	<2"	**66** (23-67)	66 (30-69)	57 (24-76)	NA
	2-4"	65 (21-69)	**68** (24-68)	66 (19-72)	NA
	4-8"	**67** (67)	**80** (80)	66 (66-70)	NA
>150	<2"	62 (60-69)	66 (66-72)	54 (54-65)	NA
	2-4"	60 (58-66)	67 (67-74)	56 (56-65)	NA
	4-8"	63 (63-66)	**80** (80)	**65** (65-66)	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated Invasion (+)	Saturated/Unsaturated Invasion (-)
--	2-4"	55 (55-75)	NA
--	4-8"	65 (64-77)	NA

Boldface = Highest rating or within a few points of highest rating.
NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

2.1.5 Casing Advancement: Rotary Drill-Through Methods (Drill-Through Casing Driver and Dual Rotary Advancement)

Other Names Used to Describe Methods: Air (mud) rotary drill or downhole hammer with casing drivers, air rotary casing hammer, air drilling with casing hammer.

Uses at Contaminated Sites: Monitoring well installation in unstable consolidated deposits, where loss of circulation of drilling fluids is a problem, and/or where prevention of cross contamination of aquifers is important.

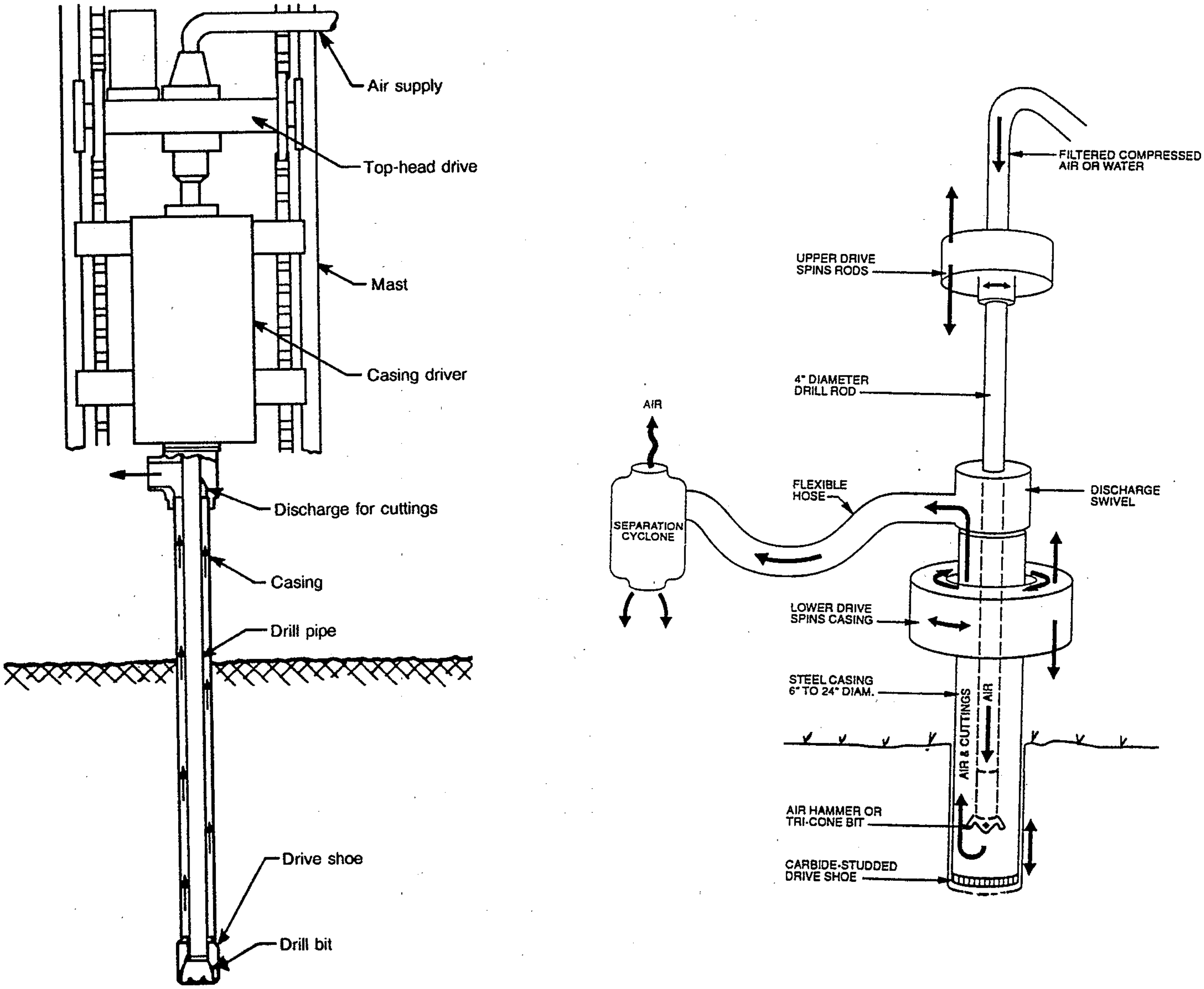
Method Description: **Casing driver advancement:** Conventional direct air (mud) rotary drill or downhole hammer equipment is used in combination with a driver that advances a casing as drilling proceeds (Figure 2.1.5a). Cuttings flow up between the annular space between the drill pipe and the casing. The diameter of the casing is slightly larger than the bit, so it can be removed when the desired depth is reached. **Dual rotary advancement:** Casing is advanced independently of the drill bit using a rotating steel casing equipped with a carbide studded drive shoe welded to the bottom of the first joint (Figure 2.1.5b). The carbide ring cuts its own way through the overburden material. Rotary drilling (usually air) takes place simultaneously using a downhole hammer or tri-cone bit. Drilling can proceed either inside or ahead of the casing. Monitoring well installation procedures are similar to for hollow-stem auger, but casing removal is a little more difficult.

Method Selection Considerations: **Advantages:** (1) Compared to open hole methods, holes are straighter and better geologic samples are collected because uphole erosion and contamination is eliminated; (2) drill-through casing methods work well in difficult conditions, such as unconsolidated deposits with cobbles and boulders; and (3) air requirements are also reduced compared to open hole air rotary and downhole hammer methods; (4) soft, caving formation can be drilled. **Disadvantages:** (1) Problems might be encountered in driving casing and pulling it back for well installation in consolidated rock; (2) more expensive due to added time and materials; (3) driving of the casing also is very noisy; (4) not in common use throughout the United States, so might not be available in some areas; (5) might be difficult to pull back casing if driven deeper than about 50 feet. Aller et al. (1991) give air rotary with casing hammer top ratings compared to other drilling methods for shallow (<15 feet) large-diameter (4 to 8 inch) monitoring wells in most categories, and for small to medium diameter (up to 4 inches) monitoring wells in unsaturated unconsolidated material greater than 150 feet (see Table 2.1.5).

Frequency of Use: With unconsolidated material, generally only used in situations where hollow-stem augers have problems (coarse gravels, cobbles, boulders) or where prevention of cross-contamination between aquifers is critical. Casing advancement methods in consolidated rock are being used with increasing frequency as a means of insuring integrity of well installation.

Standard Methods/Guidelines: --

Sources for Additional Information: **Rotary casing driver:** Aller et al. (1991), Driscoll (1986), Hix (1991), Woessner (1987, 1988); **Dual rotary:** Hix (1991).



(b)

(a)

Figure 2.1.5 Drill through methods: (a) Diagram of rotary drill-through casing driver (Aller et al., 1991); (b) Diagram of dual rotary method (Hix, 1991, by permission).

Table 2.1.5 Air Rotary with Casing Hammer Drilling Method Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	57[a] (29-75)[b]	59 (27-75)	59 (32-79)	59 (44-75)
	2-4"	58 (30-68)	62 (28-72)	60 (24-79)	62 (37-77)
	4-8"	**69** (61-69)	64 (46-74)	**63** (48-64)	**71** (58-71)
15-150	<2"	60 (23-67)	65 (30-69)	64 (24-76)	63 (35-79)
	2-4"	60 (21-69)	**67** (24-68)	65 (19-72)	63 (25-73)
	4-8"	NA	NA	NA	NA
>150	<2"	60 (60-69)	69 (66-72)	**65** (54-65)	**73** (65-73)
	2-4"	60 (58-66)	**74** (67-74)	**65** (56-65)	68 (60-70)
	4-8"	NA	NA	NA	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	NA (55-75)	NA (68-74)
--	4-8"	NA (64-77)	NA (80)

Boldface = Highest rating or within a few points of highest rating.
NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.6 Casing Advancement: Reverse Circulation (Rotary, Percussion Hammer, and Hydraulic Percussion)

Other Names Used to Describe Method: Numerous terms are used to describe reverse circulation methods. Two casings (dual-wall or dual-tube) or three casings can be used (triple-wall). Reverse circulation rotary drilling methods can use air rotary with bit or downhole hammer (Section 2.1.2), or mud rotary (Section 2.1.3). The percussion hammer method should not be confused with the air rotary with downhole hammer method (Section 2.1.2). Hydraulic percussion is also called the hollow-rod method.

Uses at Contaminated Sites: Installing monitoring wells where unconsolidated formation materials are unstable, coarse alluvium, and/or the interaquifer cross-contamination must be minimized.

Method Description: **Reverse circulation dual-wall rotary:** Similar to air rotary roller-cone bit or downhole hammer with casing driver (Section 2.1.2), except that air is circulated down the annular space between the casing and the drill pipe to the bit, and cuttings are brought to the surface through the drill pipe (Figure 2.1.6). **Reverse circulation dual-wall percussion hammer:** The percussion hammer operates on the same principle of reverse circulation as the dual-wall rotary method but the drive method is distinctly different. Either dual- or triple-wall casing configurations can be used. The top of the dual pipe string is attached to the drive spout, which allows compressed air to be delivered to the annulus between the outer and inner pipes, and cuttings to be discharged from the inner pipe through a flexible hose to a cyclone. A tempered-steel anvil mounted on top of the drive spout assembly receives the blows of the percussion hammer mounted on the mast of the drill rig. Special dual-wall or triple-wall drill bits are used for cutting into the formation and no rotation of the bit occurs, which is a primary distinguishing feature from dual-wall rotary drilling. **Hydraulic percussion:** Similar to the jet-percussion methods (Section 2.1.8), except that a ball check valve exists between the bit and lower end of the drill pipe. The annular space between the drill rods and well casing is filled with water and the drill rods and bit are lifted and dropped with quick, short strokes. When the bit drops and strikes bottom, water with cuttings in suspension enters the ports of the bit, and the water and cuttings are trapped inside the drill pipe by the check valve when the bit is lifted. This reciprocating motion produces a pumping action that brings the water and cuttings to the surface where they are discharge into a settling tank. Water is returned to the hole from the settling tank. Casing is driven as drilling proceeds.

Method Selection Considerations: **Reverse Dual-Wall Rotary Advantages:** In addition to the advantages of other casing advancement methods of providing borehole support, minimizing cross-contamination, and minimizing problems with lost circulation, the method: (1) Produces larger sized chip particles than conventional rotary equipment resulting in very good continuous, representative formation samples with minimal risk of contamination of samples and/or water-bearing zones; (2) drilling is very rapid (usually between 40 and 80 feet per hour) in both unconsolidated and consolidated formations; (3) excellent for drilling and sampling in formations which are highly fractured and/or have voids and cavities; (4) aquifers can be readily identified when drilling with air; (5) large diameter wells can be easily installed using triple-wall percussion hammer; (6) estimates of aquifer yield can be made easily at many depths in the formation; (7) washout zones are reduced or eliminated; and (8) relatively deep wells are possible (up to 1400 feet in alluvial deposits, although works best up to 600 feet and generally up to 2,000 feet in hard rocks). **Reverse Dual-Wall Rotary Disadvantages:** (1) Monitoring well installation can be tricky with the dual-wall configuration due to limitations in the annular space; (2) open hole completion is required for installation of a filter pack; (3) formation might become contaminated with oil if air filter is not working properly on air rotary rigs; (4) limited to holes greater than 9 to 10 inches in diameter; (5) well-trained drilling crews are needed, and equipment has limited availability; (6) drilling costs are high due to high cost of drilling rig and equipment; and (7) placing cement grout around the outside of the casing above the screen of the permanent well is difficult, especially when the screen and casing are placed down through the inner drill pipe before it is pulled out. Aller et al. (1991) give dual-wall reverse rotary highest ratings compared to other drilling methods for deep wells (>150 feet) in unconsolidated material and the following situations: (1) Small diameter monitoring wells (<2 inches) in saturated conditions, and (2) medium monitoring wells (2 to 4 inches) in unsaturated conditions (see Table 2.1.6). **Percussion Hammer Advantages:** (1) Able to penetrate alluvial formation with sands, gravels, and boulders at rapid speed; (2) provides continuous

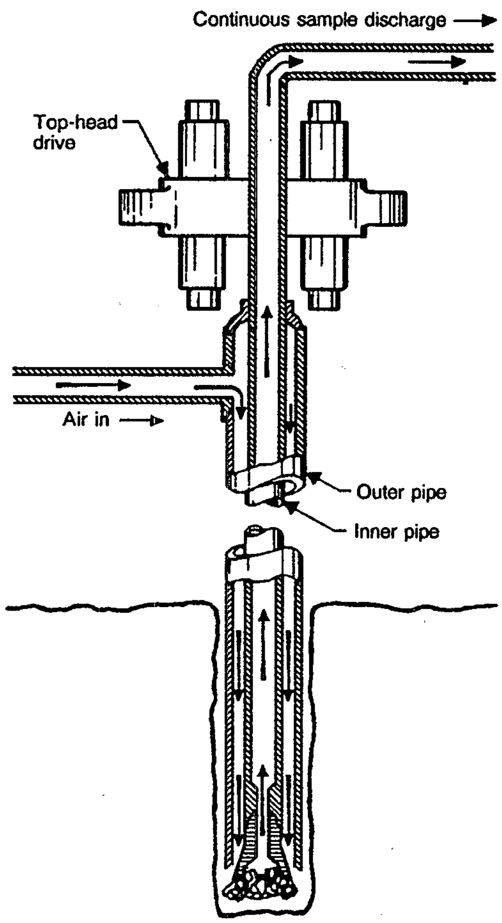


Figure 2.1.6 Diagram of dual-wall reverse circulation rotary (Aller et al., 1991).

Table 2.1.6 Dual-Wall Rotary Drilling Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	56[a] (29-75)[b]	56 (27-75)	57 (32-79)	64 (44-75)
	2-4"	56 (30-68)	54 (28-72)	57 (24-79)	59 (37-77)
	4-8"	NA	NA	NA	NA
15-150	<2"	63 (23-67)	64 (30-69)	61 (24-76)	64 (35-79)
	2-4"	61 (21-69)	57 (24-68)	62 (19-72)	52 (25-73)
	4-8"	NA	NA	NA	NA
>150	<2"	**69** (60-69)	**72** (66-72)	**64** (54-65)	69 (65-73)
	2-4"	58 (58-66)	70 (67-74)	**65** (56-65)	**70** (60-70)
	4-8"	NA	NA	NA	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	68 (55-75)	68 (68-74)
--	4-8"	NA (64-77)	NA (80)

Boldface = Highest rating or within a few points of highest rating.
NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

and accurate geological samples--soft seams, organic layers, and whole rock cobbles up to 4 inches in diameter can be lifted without prior crushing; (3) split spoon samples can be taken through the hollow center of the dual wall pipe; and (4) location of aquifers can be pinpointed with high precision because once the drive bit has progressed beyond the aquifer, the sample become dry again. **Percussion Hammer Disadvantages:** (1) Dual-wall pipe that is used is expensive and has limited inside diameter; and (2) diesel soot expelled by the pile driving hammer might result in some downhole contamination. **Hydraulic Percussion:** The main advantage is that relatively simple equipment is required, but use is limited to drilling small-diameter wells through clay and sand formations that are relatively free of cobbles and boulders.

Frequency of Use: Reverse dual-wall rotary is most commonly used in the southwestern United States. Percussion hammer has become quite popular for drilling monitoring wells in the west. The hydraulic percussion method has rarely been used to monitor well construction.

Standard Methods/Guidelines: ASTM (1993d).

Sources for Additional Information: **Reverse dual-wall rotary:** Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986); **Percussion hammer:** Hix (1991); **Hydraulic percussion:** Driscoll (1986). See also, Table 2-4.

2.1.7 Casing Advancement: Downhole Casing Advancers (ODEX, TUBEX)

Other Names Used to Describe Method: Down-the-hole hammer drill with underreaming capability, downhole hammer with eccentric bit.

Uses at Contaminated Sites: Monitoring well installation in bouldery glacial till or hard or fractured bedrock, and where prevention of cross contamination of aquifers is important.

Method Description: Downhole casing advancers are similar to drill-through casing drivers using downhole air hammer (see Section 2.1.5), except that eccentric (off-centered) bits drill a hole larger than the casing. Figure 2.1.7 illustrates major elements of the ODEX drilling assembly and method of operation. The weight of the casing, plus blows from the hammer (which are directed onto a drive shoe welded to the leading edge of the casing) are enough to advance the casing through hard formations. When the desired depth has been reached, the eccentric bit is rotated briefly in the reverse direction, causing it to become smaller than the casing, so that it can be removed. Monitoring well installation procedures are similar to for hollow-stem auger, but casing removal is a little more difficult.

Method Selection Considerations: **Advantages:** (1) Compared to open hole methods, holes are straighter and better geologic samples are collected because uphole erosion and contamination is eliminated; (2) most methods can advance through difficult formations such as cobbles, boulders, caliche, heaving sands, weathered bedrock, and clay; and (3) air requirements also are reduced for air rotary and percussion methods. **Disadvantages:** (1) Relatively expensive due to slower drilling and materials; and (2) casing removal after well installation might be difficult.

Frequency of Use: In unconsolidated material, generally only used in situations where hollow-stem augers have problems (coarse gravels, cobbles, boulders, and heaving sands) or where prevention of cross-contamination between aquifers is critical. Casing advancement methods in consolidated rock are being used with increasing frequency as a means of insuring integrity of well installation.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Baker et al. (1987-ODEX), Hix (1991), Murphy (1991-ODEX/TUBEX).

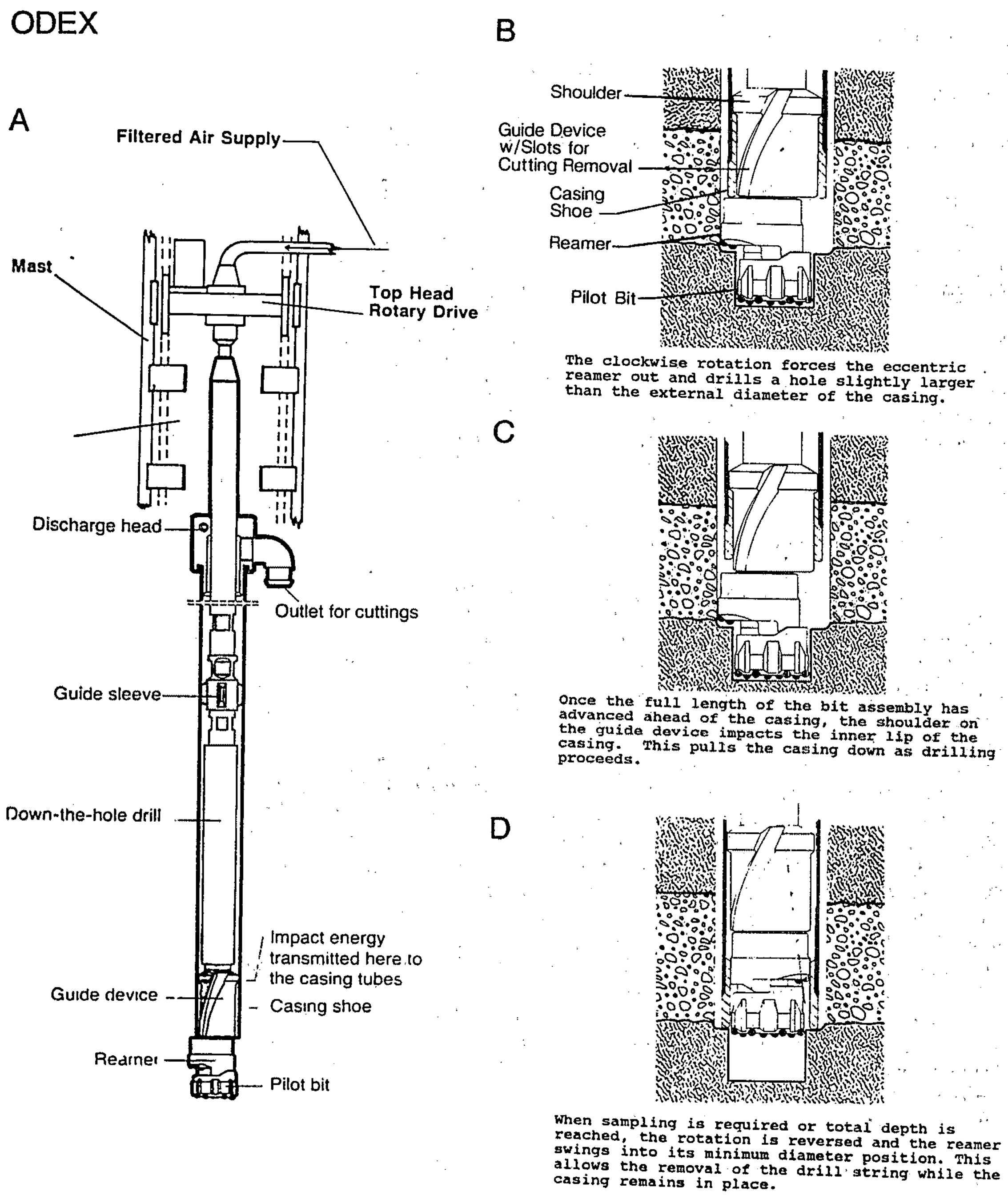


Figure 2.1.7 Diagram of ODEX downhole casing advancer drilling assembly and operations (Murphy, 1991, by permission).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.8 Jetting Methods

Other Names Used to Describe Method: **Jetting:** Wash boring*; **Jet percussion:** Wash boring*.

Uses at Contaminated Sites: Monitoring well/piezometer installation in unconsolidated deposits.

Method Description: The **jetting** or **wash drilling** method (Figure 2.1.8a) involves a wash pipe placed inside a well screen, or a string of 2-inch pipe is set adjacent to the well point. Water is pumped into the casing (in the first instance) or into the pipe string (in the second instance) and the resulting jet of water allows the well screen and casing to sink into the water-bearing formation by its own weight. Cuttings are brought to the surface by water rising outside the casing/jet pipe. At depths below 25 feet or so, a drilling fluid additive must be mixed with the jetting water to suspend cuttings and stabilize the borehole when circulation is interrupted. The **jet percussion** or **wash boring** method uses a wedge-shaped drill bit at the end of a drill pipe attached to a cable, which is alternately raised and dropped to loosen unconsolidated material or to break up rock at the bottom of a borehole (Figure 2.1.8b). The drill pipe is rotated by hand at the surface. A casing is advanced by a drive pipe as the depth of the hole increases. Water or drilling fluid is pumped down the drill pipe under pressure, is discharged through ports on each side of the drill bit to lubricate the bit, carries cuttings up the annular space between the drill-pipe and casing to the surface, and deposits the cuttings in a settling pit. The drilling fluid is then recirculated down the drill pipe.

Method Selection Considerations: **Jetting Advantages:** (1) Simple, light equipment eliminates need for a drilling contractor; (2) fast and inexpensive for shallow boreholes in unconsolidated sediments; (3) vertically spaced ground-water samples can be obtained if drive points are forced ahead of borehole and pumped; (4) drilling equipment can reach almost any site; and (5) numerous well points can be placed as an inexpensive method to determine water table contours/flow direction. **Jetting Disadvantages:** (1) Slow, especially at depth; (2) maximum depth of 100 to 150 feet; (3) can only be used in unconsolidated sediment and cannot penetrate boulders or wash up coarse gravel; (4) wash water can dilute formation water, affecting representativeness of samples; (5) interpretation of geology from wash samples is difficult (in cohesive soils and silts it might be possible to use sampling devices to obtain representative or undisturbed samples); (6) only short screens can be easily set; (7) water must be supplied under enough pressure to penetrate the geologic materials present and large quantities of water might be required; (8) use of drilling fluid additives and entrained air might affect sample quality; (9) not possible to place grout seal above the screen to assure depth-discrete sampling or isolation of different water-bearing zones; and (10) diameter of casing usually limited to 2 inches, which places some limitation on sampling tools that can be used. **Jet Percussion Advantages:** (1) Most effective in unconsolidated sands and best application is a cinch borehole with 2-inch casing and screen installed, sealed, and grouted; and (2) equipment and operation are simple and relatively inexpensive. **Jet Percussion Disadvantages:** (1) Slow and not effective in dense clay/till or bouldery material and drilling mud might be required to return cuttings to the surface; (2) use of water during drilling can dilute formation water and cause cross-contamination; (3) no formation water sample can be taken during drilling; (4) poor soil samples as a result of fines being washed out of sample; and (5) monitoring-well diameter limited to 4 inches and to depths of about 200 feet. Aller et al. (1991) gave this method consistently the lowest ratings compared to other drilling methods in their matrices for selecting appropriate drilling methods (see Table 2.1.8).

Frequency of Use: Uncommon for monitoring well installation.

Standard Methods/Guidelines: --

Sources for Additional Information: **Jetting:** Driscoll (1986), Mickelson et al. (1961), Moulder and Klug (1963); **Jet percussion:** Aller et al. (1991), Driscoll (1986), Matlock (1970).

*The term "wash boring" can be used to describe the jetting method in water well applications (Driscoll, 1986) and to describe the jet percussion method in geotechnical applications. This guide uses the terms jetting and

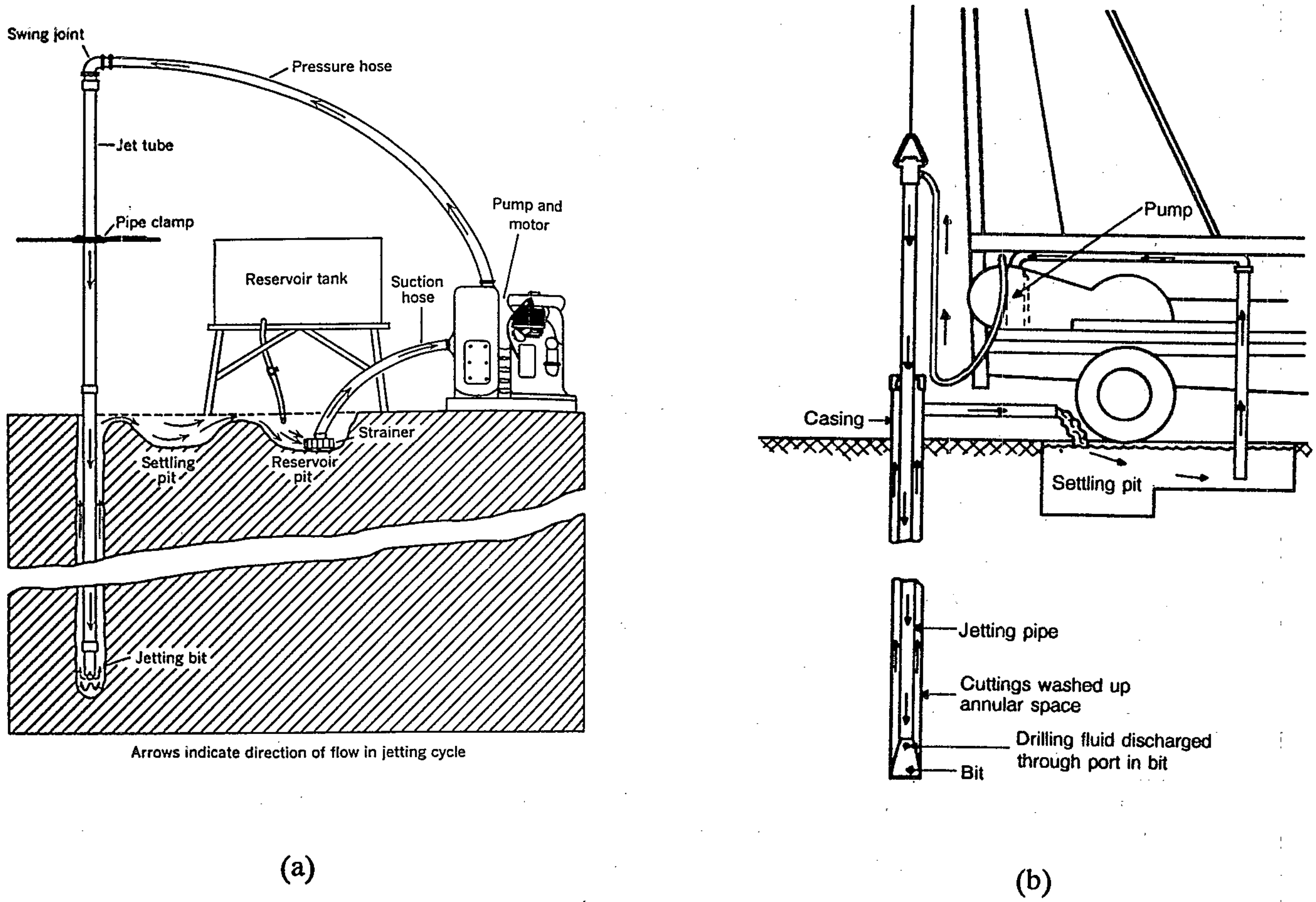


Figure 2.1.8 Jetting methods: (a) Single-pipe wash boring method for small-diameter wells (Moulder and Klug, 1963); (b) Jet percussion (Aller et al., 1991).

Table 2.1.8 Jet Percussion Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	29[a] (29-75)[b]	NA	32 (32-79)	NA
	2-4"	30 (30-68)	NA	24 (24-79)	NA
	4-8"	NA	NA	NA	NA
15-150	<2"	23 (23-67)	NA	24 (24-76)	NA
	2-4"	21 (21-69)	NA	19 (19-72)	NA
	4-8"	NA	NA	NA	NA
>150	<2"	NA	NA	NA	NA
	2-4"	NA	NA	NA	NA
	4-8"	NA	NA	NA	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	NA	NA
--	4-8"	NA	NA

NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

jet percussion to avoid possible confusion. Whenever this term is encountered, the operation of the method should be evaluated to determine whether jetting or jet percussion is involved.

2.1.9 Solid Flight and Bucket Augers

Other Names Used to Describe Method: Solid-stem auger, solid-core auger, continuous flight auger, helical/worm-type auger, disk auger, rotary bucket drilling.

Uses at Contaminated Sites: Investigating shallow soil and vadose monitoring wells (lysimeters); monitoring wells in saturated, stable soils; identifying depth to bedrock.

Method Description: **Solid flight augers:** Auger sections with a solid stem and flighting (the curve corkscrew-like blades) are connected in a continuous string to the lowermost section with a cutting head that is approximately 2 inches larger in diameter than the flighting (Figure 2.1.9a). Cuttings are rotated upward to the surface by moving along the continuous flighting as the cutting head advances into the earth (Figure 2.1.9b), making it difficult to obtain reliable depth-specific soil samples from the cuttings that are brought to the surface. In stable soils, rotation can be stopped at the desired depth, the augers removed from the borehole, and samples taken from the bottom flight. Use of different diameter augers allows placement of casing to isolate near-surface contamination, and continuation of drilling with a smaller-diameter auger. Recovery of samples from the saturated zone is difficult. The only way to collect undisturbed samples is to remove the auger string, attach a split-spoon or thin-wall sampler to the end of the drill rod and put the entire string back into the borehole. A **disk auger** is similar to a solid flight auger except that it has a larger diameter and the flighting only goes around the stem once. **Bucket augers** (8-inch minimum diameter and typically 2 feet long) have a cutting edge on the bottom that is slowly rotated by a square telescoping Kelley of drill stem. When the bucket fills with cuttings, it is brought to the surface to be emptied. Figure 2.1.9c illustrates several types of bucket augers. Other variants in include the **spoon auger** and the **Vicksburg hinged auger.**

Method Selection Considerations: **Solid Stem Auger Advantages:** (1) In unconsolidated material, drilling rigs are fast and mobile; and (2) minimal damage to aquifer and no drilling fluids or lubricants required. **Solid Stem Auger Disadvantages:** (1) Soil samples are unreliable unless split-spoon or thin-wall samples are taken, slowing drilling speed, and those can only be taken where stable soils exist; (2) generally unsuitable for monitoring-well installation in the saturated zone because of borehole caving upon auger removal; (3) depth generally restricted to 30 meters or less; (4) because auger must be removed before well can be set, vertical mixing can occur between water-bearing zones; (5) can only be used in unconsolidated materials; (6) depth to water table might be difficult to determining accurately in deep borings; and (7) drilling through a contaminated soil zone might result in downward transport of contaminants. Aller et al. (1991) give consistently low ratings compared to other drilling methods in unconsolidated saturated material, and the methods usually rate second highest, after hollow-stem auger, for most unsaturated conditions (see Table 2.1.9). **Bucket Auger Advantages:** (1) Good for construction wells just into the water table in unconsolidated formations that form stable borehole walls, such a clayey sediments walls; (2) after hole has been drilled, the setting of casing with screen and grouting outside to casing is relatively easy; (3) soil samples taken with a bucket auger are disturbed, but representative, unless caving of the borehole has occurred; and (4) depth specific sampling and detailed in situ soil descriptions might be possible if the diameter of the boring is large enough to let a person work in the hole. **Bucket Auger Disadvantages:** (1) Large diameter holes create a large annular space when small-diameter casing is used, necessitating a large volume of grout, and special care in grout placement and backfilling; (2) in caving formations below the water table, water must be added continuously to prevent caving; (3) restricted to depths less than about 50 feet; and (4) rigs might not be readily available.

Frequency of Use: **Solid stem auger:** Most commonly used for geotechnical investigations in unconsolidated material. Less commonly used for monitoring well installation because most installations need to be completed into the saturated zone. **Bucket auger:** Most commonly used for large-diameter borings associated with foundations and building structures.

Standard Methods/Guidelines: --

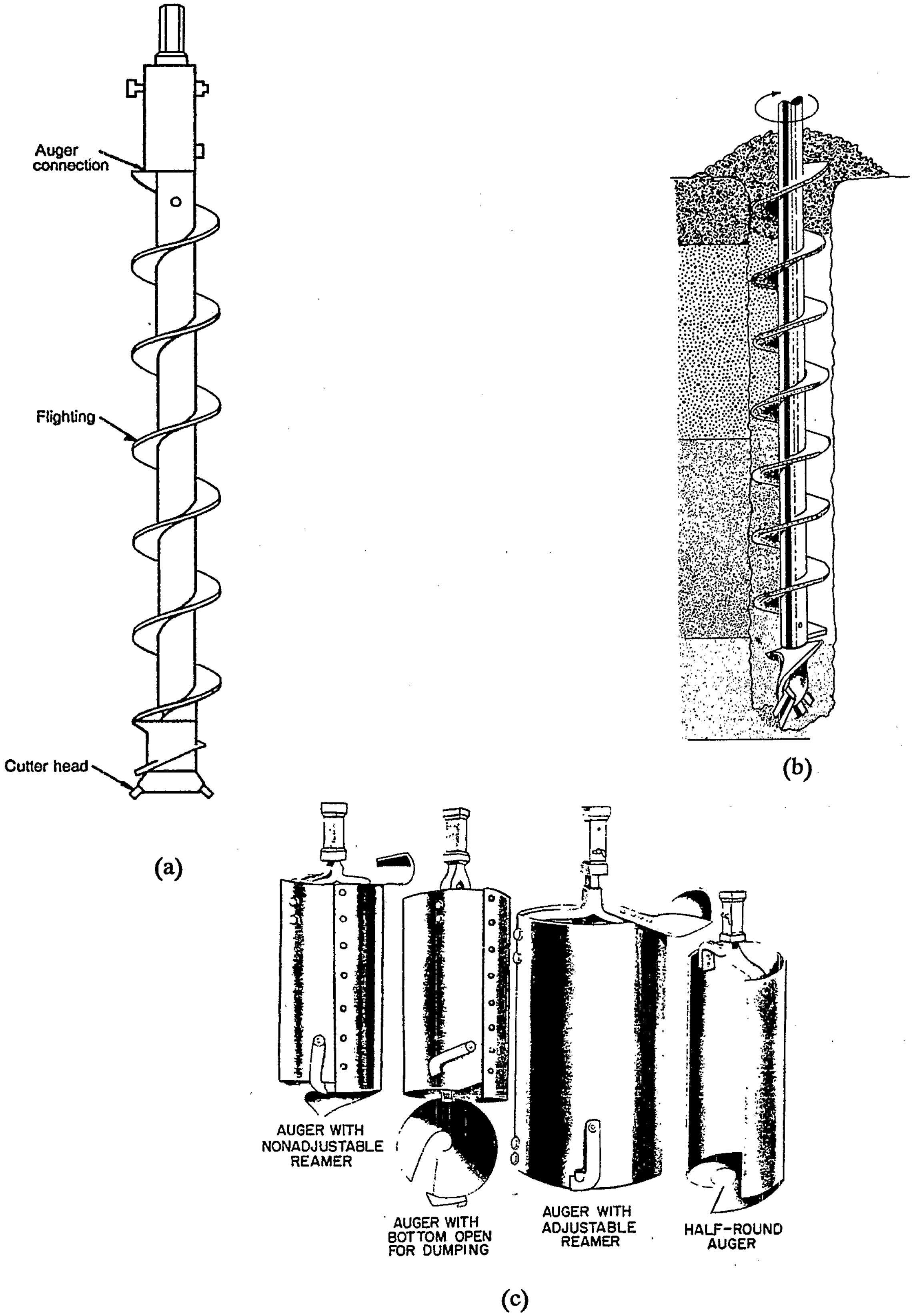


Figure 2.1.9 Power-driven augers: (a) Diagram of solid-flight auger (Aller et al., 1991); (b) Relationship of surface cuttings and subsurface (Scalf et al., 1981); (c) Bits for power bucket augers (U.S. Army, 1981).

Table 2.1.9 Solid Flight Auger Suitability Ratings

UNCONSOLIDATED MATERIAL

Depth (ft.)	MW Diameter	Saturated		Unsaturated	
		Invasion (+)	Invasion (-)	Invasion (+)	Invasion (-)
0-15	<2"	44[a] (29-75)[b]	27 (27-75)	70 (32-79)	70 (44-75)
	2-4"	41 (30-68)	28 (28-72)	70 (24-79)	68 (37-77)
	4-8"	NA	46 (46-74)	60 (48-64)	NA
15-150	<2"	37 (23-67)	NA	69 (24-76)	70 (35-79)
	2-4"	32 (21-69)	24 (24-68)	59 (19-72)	58 (25-73)
	4-8"	NA	NA	NA	NA
>150	<2"	NA	NA	NA	NA
	2-4"	NA	NA	NA	NA
	4-8"	NA	NA	NA	NA

CONSOLIDATED MATERIAL

Depth	MW Diameter	Saturated/Unsaturated	
		Invasion (+)	Invasion (-)
--	2-4"	NA	NA
--	4-8"	NA	NA

NA = Not applicable.

[a]Numerical rating for drilling method in Appendix B, Aller et al. (1991).
[b]Range of numerical ratings of applicable methods (perfect score = 80).

<u>Sources for Additional Information</u>: **Solid flight auger:** Aller et al. (1991), Driscoll (1986), Geeting (1990-enclosed auger), Scalf et al. (1981), Shuter and Teasdale (1989), U.S. EPA (1987); **Bucket auger:** Driscoll (1986), Scalf et al. (1981), U.S. EPA (1987).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.10 Rotary Diamond Drilling

Other Names Used to Describe Method: Diamond drilling.

Uses at Contaminated Sites: Borehole drilling and coring in consolidated rock.

Method Description: Rotating bit consists of a tube 10 to 20 feet long, with a diamond-studded ring fitted to the end of the core barrel. Figure 2.1.10 illustrates a typical diamond drilling rig. The bit can also be attached to either an air or a mud rotary rig (Sections 2.1.2 and 2.1.3). Typically water circulates through the bit to cool the cutting surface. The diamond bit cuts through rock, with a solid core remaining in the tube. In soft and medium formations sawtooth or carbide tips can be used.

Method Selection Considerations: **Advantages:** (1) Can drill to any depth; (2) provides continuous cores of geologic material for accurate geologic logging; (3) especially useful for locating and characterizing fracture zones; and (4) can be used with mud or air rotary rigs. **Disadvantages:** (1) Limited primarily to use in consolidated bedrock, but can also be used in highly compacted tills; (2) cooling water or drilling fluids might alter chemistry of ground-water samples, especially when it penetrates deeply into highly fractured rock (placement of tracers in drilling fluid can be used to determine whether ground-water samples have been influenced by the drilling water; (3) diamond bits are more expensive than conventional roller bits; and (4) slow compared to most other methods.

Frequency of Use: Commonly used for mineral exploration in crystalline rock; less commonly used for monitoring well installation.

Standard Methods/Guidelines: ASTM (1983b), DCDMA (1991).

Sources for Additional Information: Barrett et al. (1980), Bowman (1911), Christensen Diamond (1970), Cumming and Wickland (1965), Gillham et al. (1983), Heinz (1985), Shuter and Teasdale (1989), World Oil (1970).

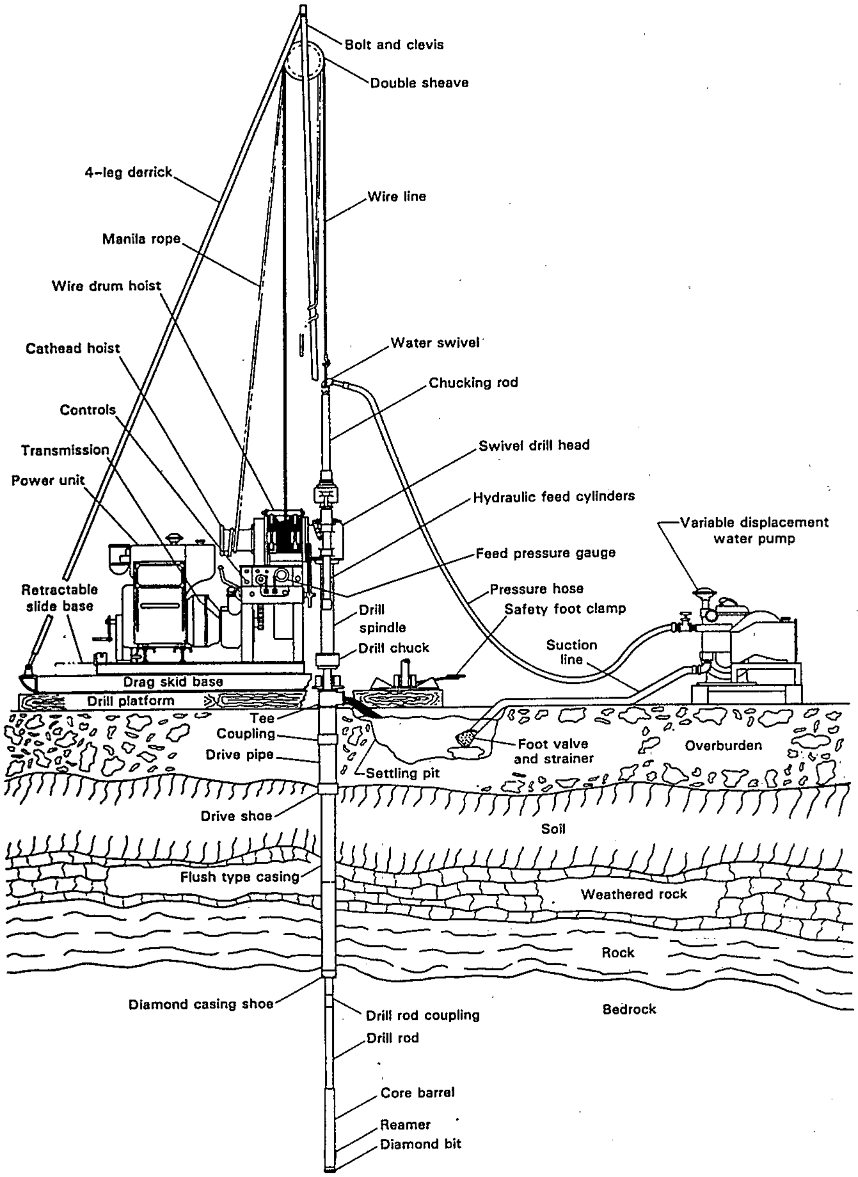


Figure 2.1.10 Typical diamond drilling rig (Shuter and Teasdale, 1989).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.11 Directional Drilling

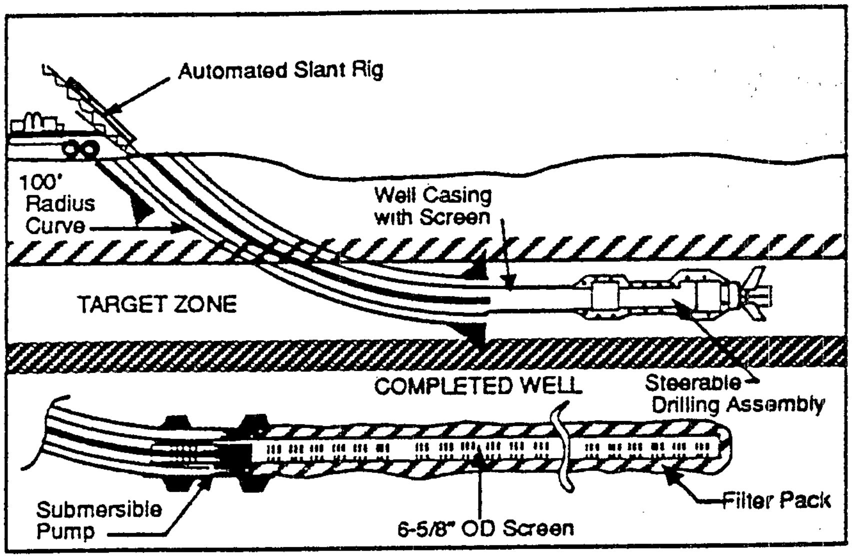
Other Names Used to Describe Method: Radial/horizontal drilling, conical jet drilling, slant rig drilling.

Uses at Contaminated Sites: Installing horizontal or slanting wells for geophysical measurement or vadose zone monitoring; conducting soil and ground-water remediation (pump-and-treat, grouting, soil gas vacuum extraction, bioventing, in situ remediation, and soil flushing).

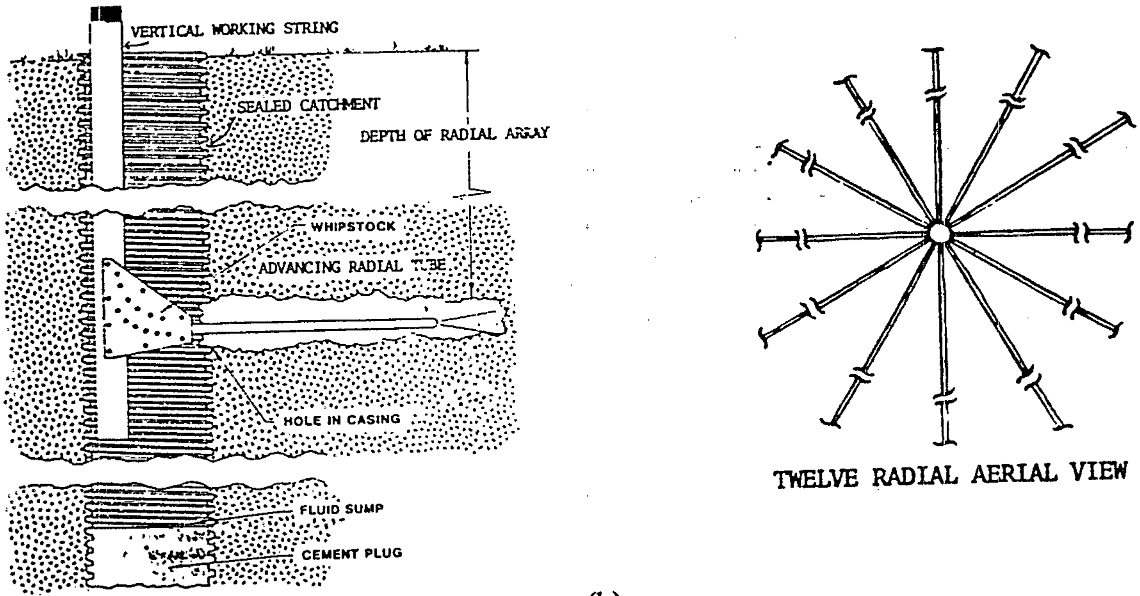
Method Description: **Directional drilling** involves use of drilling equipment located at the ground surface to drill slanting or horizontal holes in the subsurface. All directional drilling systems require: (1) A steerable drill stem, and (2) the capability to detect the location of the drill head or trajectory of the borehole. Directional drilling equipment with potential for applications at contaminated sites range in size from scaled-down rigs developed for the oil industry to relatively compact, simple equipment used to install utilities. Eastman-Christensen (EC) has developed a custom-equipped drill rig with a slanting rig mast capable of being oriented from the vertical, to 60 degrees from vertical, which can drill horizontally on a 100-foot radius (Figure 2.1.11a). The drilling assembly consists of a dual-wall drill string and an expandable bit, which drills a hole large enough to permit casing to be advanced during drilling. The drill bit is guided using measurement from a tool face indicator, which records the inclination of the drilling assembly. When the well is drilled to the desired length, the inner drilling assembly is withdrawn and the well screen installed. A horizontal section of screen greater than 500 feet in length can be accurately placed at target depths from around 10 feet to greater than 300 feet. Several **radial drilling** systems have been developed. In these systems a relatively large diameter vertical hole is first drilled and cased. Specific systems vary somewhat, but have the common elements of a vertical drilling string or assembly with a nonrotating orientation assembly or whipstock at the depth of interest that guides a flexible drive pipe from the vertical to horizontal direction (Figure 2.1.11b). Two types of drilling methods have been reported for radial drill holes: (1) A mud rotary system with a top-drive hydraulic rotary rig (Kaback et al., 1989), and (2) Petrolphysics conical jet drilling system, which uses a nozzle designed to produce a conical shell of high velocity water that also serves to advance the drill pipe. With the jet drilling system, multiple laterals (as many as 12) up to 200 feet or more can be placed at several levels using the same vertical well (Figure 2.1.11b). **Utility rigs** use an initially inclined borehole and develop a trajectory that is similar to the EC rig described above, except that the equipment is smaller and less sophisticated. Boring methods include jet-assisted rotary, above-ground hydraulic percussion, water jet, down-hole pneumatic percussion, or down-hole pneumatic motor. Drill head location is monitored using a radio transmitter in the drill head and a receiver at the surface over the drill head. Boring lengths greater than 500 feet at depths of 3 to 20 feet are possible. Greater depths require specialized monitoring equipment. Equipment can be mobilized behind a pickup truck.

Method Selection Considerations: **Advantages:** (1) Allows borehole access to subsurface areas such as beneath buildings, tanks, landfills, and impoundments where vertical drill rigs cannot go; (2) reduces potential for cross-contamination between aquifers; (3) excellent for remediation techniques that require maximum horizontal access to contaminated zone or contaminant plumes that are not vertically dispersed; (4) production from horizontal wells generally is higher than from vertical wells due to greater possible screen length; (5) Petrolphysics radial jet drilling is very rapid in bedrock (1/2 foot per minute in granite, more than 1 foot per minute in sedimentary rock); and (6) cost of drilling with utility rigs is similar to vertical drilling with an auger rig. **Disadvantages:** (1) There has been relatively little actual experience using directional drilling methods at contaminated sites, and value for site characterization and monitoring (as opposed to remediation) has yet to be demonstrated; (2) drilling costs are high for petroleum industry-related equipment (100 to several hundred dollars a foot); (3) utility rigs, although less expensive than petroleum rigs, have more limited depth capabilities (around 20 feet compared to 300 feet for EC slant rig)*; (4) equipment that uses water or other fluids to advance the well bore might affect quality of samples; (5) sampling capabilities are currently limited.

Frequency of Use: Small-scale equipment is widely used to install underground utilities. Use of large scale drilling is well established in the petroleum industry. At contaminated sites, test applications have focussed on remedial activities, but good potential exists for use with geophysical and other vadose monitoring methods.



(a)



(b)

Figure 2.1.11 Directional drilling methods: (a) Eastman-Christensen slant rig (Metcalf and Eddy, 1991); (b) Petrolphysics rig with a shallow radial system (U.S. EPA, 1992).

Standard Methods/Guidelines: --

Sources for Additional Information: See Table 2-4.

*Depth limitations of utility rigs are a result of locating methods. New locators that send signals up the drill steel are expected to expand the depth capabilities of small rigs.

2. DRILLING AND SOLIDS SAMPLING METHODS

2.1 DRILLING METHODS

2.1.12 Sonic Drilling

Other Names Used to Describe Method: Vibratory drilling, rotosonic drilling.

Uses at Contaminated Sites: Continuous sampling and monitoring well installation in unconsolidated and soft/fractured bedrock.

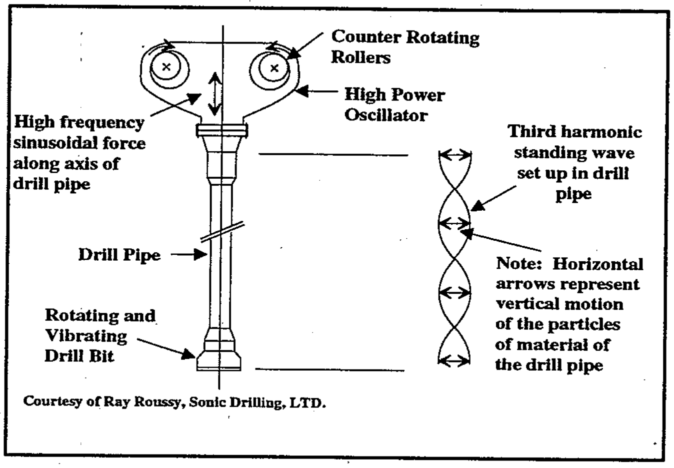
Method Description: A sonic rig uses an oscillator, or head, with eccentric weights driven by hydraulic motors, to generate high sinusoidal force in a rotating drill pipe (Figure 2.1.12a). The frequency of vibration (generally between 50 and 120 cycles per second) of the drill bit or core barrel can be varied to allow optimum penetration of subsurface materials. A dual string assembly allows advancement of casing with the inner casing used to collect samples. Small amounts of air or water can be used to remove the material between the inner and outer casing. Very rapid rates of drilling are possible; Dustman et al. (1992) report 160 feet/day in sandy terrace deposits over glacial till and weathered sandstone. When a drill bit is used, most of the cuttings are forced into the borehole wall. A thin-wall or split spoon sampler can be used to obtain continuous samples. The head of the rig tilts outward to allow easy access for threading and sample extraction (Figure 2.1.12b). Research in vibratory drilling techniques date back to the late 1940s, but it is only relatively recently that improvements in equipment design have made the technique a viable option for investigation of contaminated sites.

Method Selection Considerations: **Advantages:** (1) Collection of continuous, relatively undisturbed unconsolidated and bedrock cores possible; (2) higher drilling rates than conventional methods (around twice as fast as air rotary and 8 to 10 times faster than hollow-stem auger and cable tool); and (3) produces about one-tenth the cuttings of hollow-stem auger and cable tool. **Disadvantages:** (1) Higher operation, maintenance, and tooling costs compared to conventional drilling methods; (2) present equipment limited to depths of about 300 feet; (3) drilling in hard rock generally not recommended; (4) driving of material into borehole wall might create problems for borehole logging and aquifer testing; and (5) limited equipment availability.

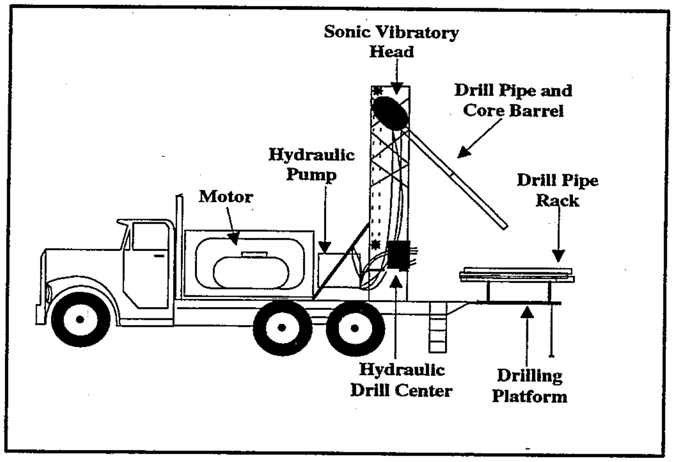
Frequency of Use: Uncommon; relatively recent improvements in equipment design will probably lead in increased use in the future.

Standard Methods/Guidelines: --

Sources for Additional Information: Dustman et al. (1992), Godsey (1993).



(a)



(b)

Figure 2.1.12 Sonic drilling: (a) Basic principles of operation; (b) Drill rig (Dustman et al., 1992, by permission).

2. DRILLING AND SOLIDS SAMPLING METHODS

2.2 DRIVE METHODS

2.2.1 Driven Wells

Other Names Used to Describe Method: Driven wellpoint, piezometers, driven pile.

Uses at Contaminated Sites: Water level monitoring in shallow formations and small-diameter shallow water quality monitoring wells.

Method Description: A screened well-point attached to metal casing (usually 1.25 to 2 inches in diameter) is driven by hand or with drive heads mounted on a hoisting device (Figure 2.2.1). Section 6.1.10 provides additional information on the use of drive points for piezometric measurements, and Section 5.5.3 provides additional information on driven devices for collection of ground-water samples. A **driven pile** method has been described that involves simultaneously driving two 10- to 12-inch diameter steel cylinder piles with 0.5 inch wall thickness, one inside the other. The assembly is driven to the desired depth, or until it can be driven no further. The inner pile is withdrawn, allowing space for installation of a 5-inch diameter well. following installation, the 12-inch diameter pile is removed. A variant of this method has also been used to install relatively shallow leachate collection wells at a landfill (Miller and Hornsby, 1991).

Method Selection Considerations: **Wellpoint Advantages:** (1) Relatively low cost of installation allows multiple observation points; (2) well suited for water level measurements; (3) water samples can be collected at closely spaced intervals during drilling; and (4) no drilling fluids are introduced into the formation. **Wellpoint Disadvantages:** (1) Limited to unconsolidated material without coarse fragments; (2) cannot penetrate dense and/or some dry materials; (3) generally limited to depth of 30 to 50 feet; (4) lack of stratigraphic detail resulting from the lack of soil samples create uncertainty regarding screened zones and/or cross contamination (penetration rate can provide some stratigraphic information); (5) steel casing might affect quality of samples and there is no annular space for completion procedures (a good seal between casing and formation can only be expected if drilling through loose, well-sorted material that collapses around the well); (6) only small-diameter ground-water sampling equipment can be used (2.5-inch diameter casing is the usual maximum); and (7) drive point screen might become clogged with clay if driven through a clay unit. **Driven Pile Advantages:** (1) Casing reduces potential for cross contamination; and (2) no drilling fluids are involved. **Driven Pile Disadvantages:** (1) Pile might reduce formation permeability by smearing or compaction; (2) unconsolidated material that can be penetrated by piles is required; and (3) casing is expensive.

Frequency of Use: Commonly used for water level observations.

Standard Methods/Guidelines: See Section 6.1.10 for piezometer installation.

Sources for Additional Information: **Wellpoint:** Aller et al. (1991), Driscoll (1986); **Driven pile:** Kaufman et al. (1981), Miller and Hornsby (1991).

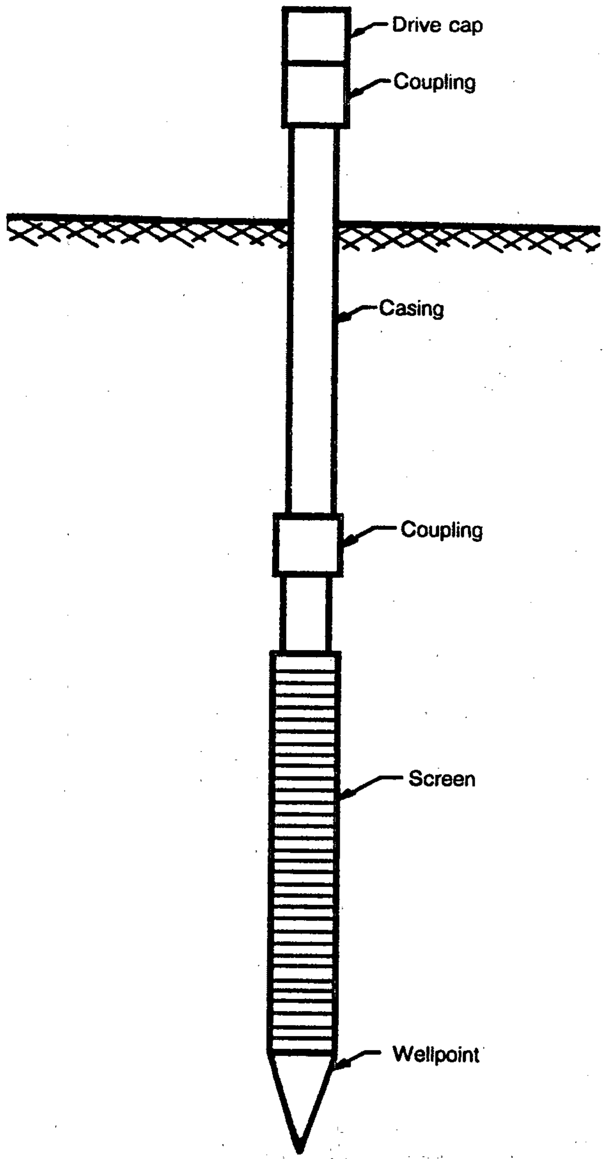


Figure 2.2.1 Diagram of driven wellpoint (Aller et al., 1991).

2.2.2 Cone Penetration

Other Names Used to Describe Method: CPT (cone penetration test), cone penetrometry.

Uses at Contaminated Sites: Stratigraphic logging in soft soils. When instrumented for pore pressure measurements, subsurface hydraulic characteristics can be measured (pressure head, soil permeability, and water bearing zones), and sampling cones allow in-situ sampling of liquids and gases (see Sections 5.5.1 and 5.5.2). Measuring stress-strain soil properties affecting site seismic response (see Section 3.3.4).

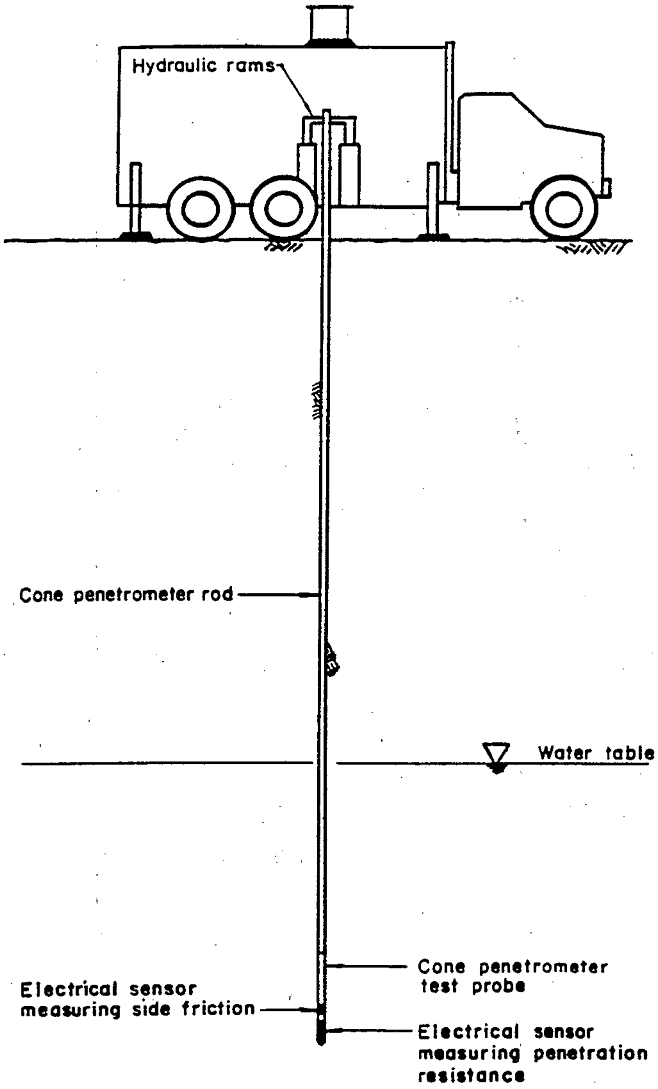
Method/Device Description: The cone penetration test (CPT) involves hydraulically pushing a cone-shaped instrument into the soil and measuring its resistance to penetration (Figure 2.2.2a). Resistance is measured by sensitive strain gauges that transmit electronic signals to an automatic data acquisition system (Figure 2.2.2b). Use of a four-channel piezocone allows estimation of hydraulic properties of the soil by measuring pore pressure changes in response to the stresses created by the CPT. **Porous probe permeameters** can be used in a falling-head or constant-head mode, as a relatively simple and inexpensive method for determining hydraulic conductivity in the vicinity of the probe. The seismic cone penetration test is described in Section 3.4.4. Special porous sampling cones can be used with conventional cone-penetration equipment, which allow collection of soil-gas or ground-water samples from a desired depth by lowering specially designed vials down the casing to the cone (see descriptions of Hydropunch in Sections 5.5.1 and the BAT system in section 5.5.2).

Method/Device Selection Considerations: Best used in initial site characterization to help in siting of monitoring wells. Works most efficiently in soft soils. Continuous measurement of soil properties minimizes the possibility of overlooking thin strata that could influence soil behavior. No contaminated fluids are produced by measurements of hydraulic properties. One-time samples helpful for characterizing the extent of contaminant plumes, but not suitable for ongoing monitoring.

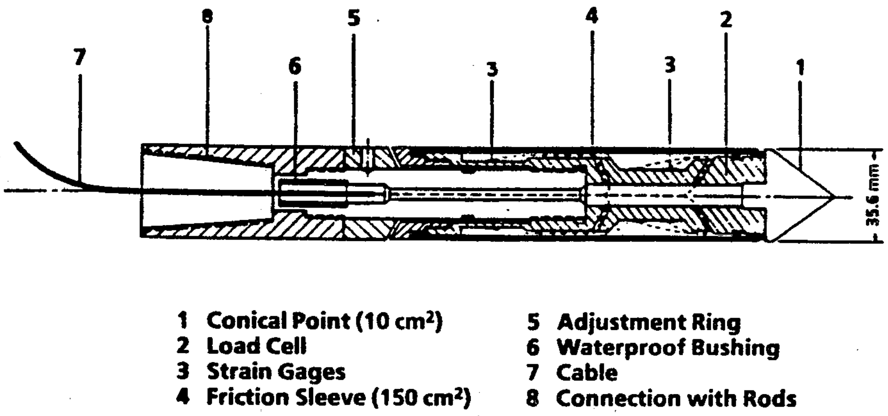
Frequency of Use: Commonly used in geotechnical investigations. Use at hazardous waste investigations should become more common as experience is gained in using cone penetration equipment for hydrologic characterization and sampling for preliminary site characterization.

Standard Methods/Guidelines: ASTM (1986a,b).

Sources for Additional Information: See Table 2-4. **Hydraulic conductivity testing:** Petsonk (1985), Sai and Anderson (1991). See also, Sections 5.5.1 and 5.5.2 and Table 5-5.



(a)



(b)

Figure 2.2.2 **Cone penetrometry: (a) Typical cone penetrometer test rig (Smolley and Kappmeyer, 1991, by permission); (b) Electric friction-cone penetrometer tip (Chiang et al., 1989a, by permission).**

2.3 HAND-HELD SOIL SAMPLING DEVICES

2.3.1 Scoops, Spoons, and Shovels

Other Names Used to Describe Method: Trowels, spades, soil punch, soil moisture tin.

Uses at Contaminated Sites: Sampling of near surface soils.

Method Description: Spoons (from 10 to 100 gram capacity), scoops (with capacity typically ranging from 300 to 2000 grams), and shovels or shovel-like instruments, such as trowels, can be used separately or in combination to collect samples. Stainless steel is the most common type used; plastic or Teflon-coated are also available. A shovel is usually used to remove the top cover of soil to the desired depth, and spoons or scoops are used for actual sampling. Use of **trenches** to provide a vertical exposure allows use of **soil punches** or **soil moisture tins,** either vertically or horizontally, to collect samples of a known volume (see Figure 2.3.1).

Method Selection Considerations: **Scoops and Spoons Advantages:** (1) Inexpensive and readily available; (2) can be easily decontaminated, or discarded to reduce sampling time; (3) can be transported to remote areas; and (4) easy to obtain relatively large sample volumes. **Scoops and Spoons Disadvantages:** (1) Samples are disturbed, so measurements requiring undisturbed soil cannot be taken; (2) reproducibility of sample sizes might be poor when area and/or volume are critical for accurately characterizing the degree of contamination; and (3) limited to near-surface sampling (deeper than 50 centimeters becomes very labor intensive). **Shovels:** Similar to scoops and spoons except they are more expensive. **Soil punches** have the advantage that a precise volume of soil is sampled, which allows for the calculation of other properties, such as bulk density. See also, Table 2-3.

Frequency of Use: Commonly used for near-surface sampling for initial screening purposes.

Standard Methods/Guidelines: Boulding (1991), Ford et al. (1984).

Sources for Additional Information: --

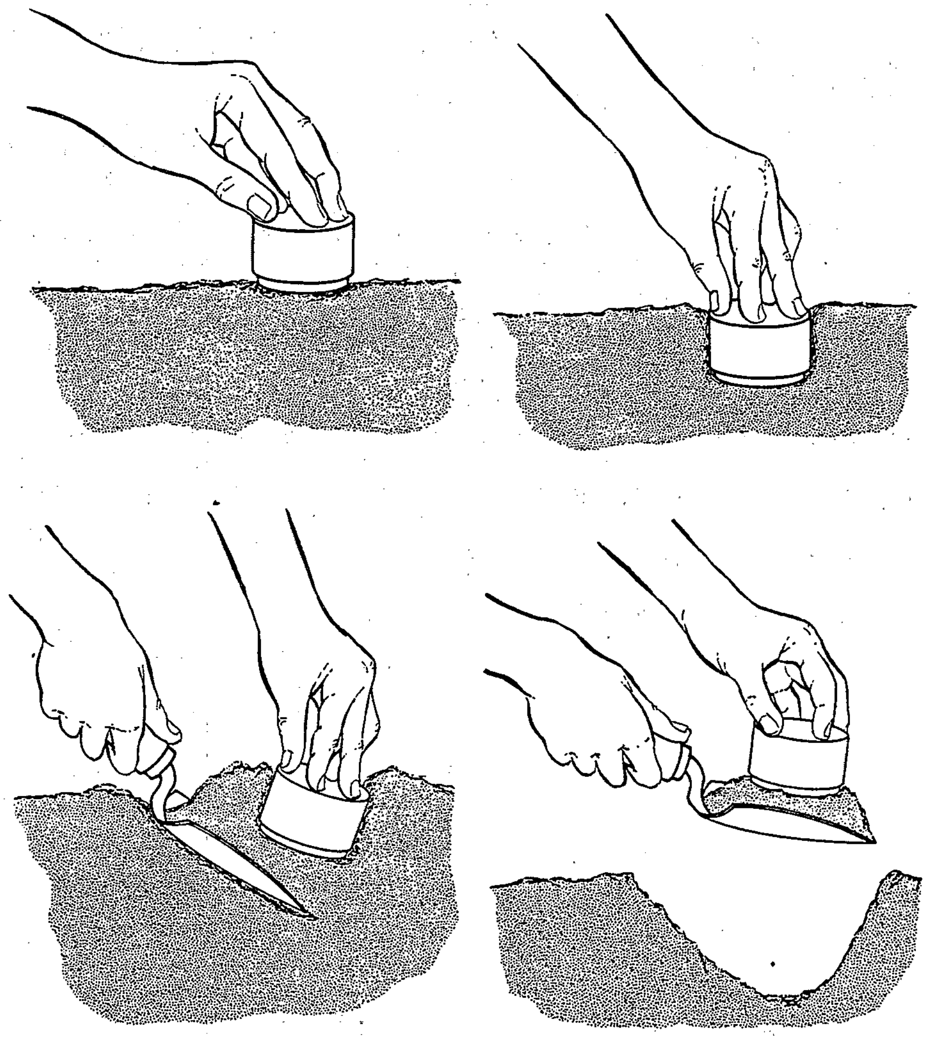


Figure 2.3.1 Procedure for collecting sample with soil moisture tin (Cameron et al., 1966).

2.3 HAND-HELD SOIL SAMPLING DEVICES

2.3.2 Augers

Other Names Used to Describe Method: Screw auger, helical auger, closed spiral auger, opern spiral auger, worm auger, bucket auger, barrel auger (standard, sand, mud/clay, dutch, in situ soil recovery, stony soil, planer, post-hole/Iwan-type, silage), spiral auger, ram's horn auger.

Uses at Contaminated Sites: Collecting disturbed soil samples; used in combination with tube samplers for collecting undisturbed soil samples.

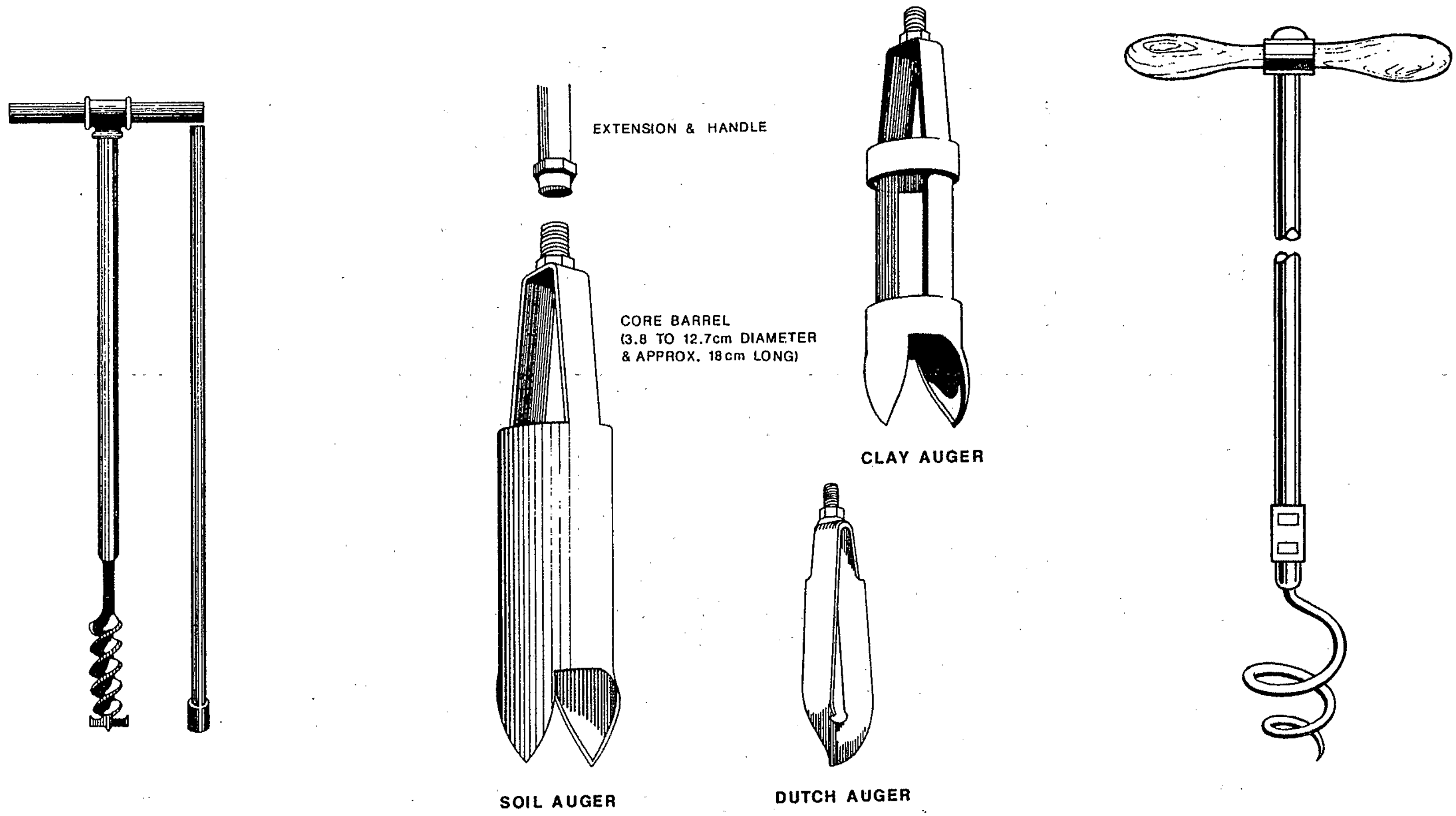
Method Description: Hand-held augers consist of an auger bit, a solid or tubular drill rod, and a "T" handle (Figure 2.3.2a). When the drill rod is threaded, extensions can be added or auger bits interchanged. The auger tip bites into the soil as the handle is rotated, and soil retained on the auger tip is brought to the surface and used as the soil sample. Alternatively, augers can be used to bore to the desired sampling depth, and a tube sampler replaced for collection of the actual sample. Many types of auger bits are available: Screw-type (Figure 2.3.2a), bucket-type (Figure 2.3.2b), and spiral-type (Figure 2.3.2c). Table 2.3.2 describes the applications and special limitations of ten types of augers. Hand-held power screw augers, requiring one or two people to operate, can also be used. ASTM (1980) provides descriptions of about a dozen types of hand-held and machine-operated augers.

Method Selection Considerations: **General Advantages:** (1) Relatively inexpensive, readily available, and most types can be easily operated by one person; and (2) depending on the type, larger volumes of soil can be obtained compared to hand-held tube samplers (Section 2.3.3). **General Disadvantages:** (1) Difficult to know the exact depth from which sample comes; (2) cross-contamination of samples from lower depths by cave-in or sloughing of borehole walls is common (can be reduced by use of in situ soil recovery auger); (3) samples are disturbed, so measurements requiring undisturbed soil cannot be taken, and accurate soil profile description is difficult; (4) disturbance of exposure of soil to air makes most types unsuitable for sampling volatile contaminants; (5) sampling depth is usually limited to 1 or 2 meters, but up to 3 meters is possible under favorable conditions using extensions. **Screw Auger Advantages:** (1) Hand-held types usually penetrate more rapidly than bucket augers in moist soil; (2) power-driven hand held screw augers allow deep and rapid penetration in cohesive, soft, or hard soils; (3) open thread provides easy access to sample; and (4) fairly easy to decontaminate. **Screw Auger Disadvantages:** (1) Will not retain dry, loose, or granular material; and (2) only suitable for obtaining composite samples. **Truck-driven solid flight augers** (Section 2.1.9) yield samples similar to screw augers and have the same advantages and disadvantages. **Bucket Auger Advantages:** Variety of types allows selection of auger head for much wider variety of soil conditions than screw auger and tube sampler. **Bucket Auger Disadvantages:** (1) Extraction of sample from closed bucket-types cumbersome; and (2) more difficult to decontaminate than screw augers.

Frequency of Use: Commonly used for collection of composite near surface samples, and in combination with tube samplers to collect undisturbed samples.

Standard Methods/Guidelines: ASTM (1980), Boulding (1991), Ford et al. (1984), U.S. EPA (1986b-also covers sampling from solid flight augers).

Sources for Additional Information: See Table 2-5.



(a) (b) (c)

Figure 2.3.2 **Hand-held augers: (a) Screw auger (Rehm et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission); (b) Examples of bucket augers (Rehm et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission); (c) Spiral or ram's horn auger (U.S. Army, 1981).**

Table 2.3.2 Summary of Hand-Held Soil Augers[a]

Auger Type	Applications	Limitations
Screw Auger	Cohesive, soft, or hard soils or residue	Will not retain dry, loose, or granular material
Standard Bucket Auger	General soil or residue	Might not retain dry, loose, or granular material
Sand Bucket Auger	Bit designed to retain dry, loose, or granular material (silt, sand, and gravel)	Difficult to advance boring in cohesive soils
Mud Bucket Auger	Bit and bucket designed for wet silt and clay soil or residue	Will not retain dry, loose, or granular material
Dutch Auger	Designed specifically for wet clayey, fibrous, or rooted soils (marshes)	
In-Situ Soil Recovery Auger	Collection of soil samples in reusable liners; closed top reduces contamination from caving sidewalls	Similar to standard bucket auger
Eijkelcamp Stony Soil Auger	Stony soils and asphalt	
Planer Auger	Used to clean out and flatten the bottom of predrilled holes	
Post-Hole/Iwan Auger	Cohesive, soft, or hard soils; readily available	Will not retain loose material
Silage Auger	Silage pits and peat bogs	
Spiral Auger	Used to remove rock from auger holes so that borings can continue with other auger-type	

[a]Suitable for soils with limited coarse fragments; only the stony soil auger will work well in very gravelly soil.

2.3 HAND-HELD SOIL SAMPLING DEVICES

2.3.3 Tubes

Other Names Used to Describe Method: Soil probe, thin-walled tubes, soil recovery probe, Veihmeyer tube, peat sampler.

Uses at Contaminated Sites: Collecting undisturbed soil core samples in the near surface.

Method Description: Basic equipment is similar to augers, except that a closed or open tube with a cutting tip is attached to the drill rod. Rather than being rotated, the tube is pushed into the soil to obtain a relatively undisturbed core. Various types of tube samplers are available. **Soil probes** are usually single units designed for near-surface sampling. **Thin-walled** tube samplers are designed to be interchangeable with auger tips, and for sampling at greater depths by the addition of extensions (Figure 2.3.3a). **Veihmeyer tubes** are designed to be driven into the ground, and pulley jacks with grips are available for pulling the sampler out of the ground (Figure 2.3.3b). The cutting tip on most types of samplers can be replaced if it is damaged by hitting a rock or when it wears out. Different types of tips are available for use in standard, wet, and dry soils. Tube samplers are often used in combination with augers, with the augers used to bore a larger diameter hole to the depth of interest, and the tube sampler used to collect the actual sample. Table 2.3.3 provides additional information on major types of hand-held tube samplers.

Method Selection Considerations: **Advantages:** (1) Relatively inexpensive, readily available, and most types can easily be operated by one person; (2) a relatively undisturbed core can be obtained, from which a soil profile descriptions can be made; (3) better than augers for sampling volatile contaminants; and (4) when combined with an auger, depths up to 6 meters can be reached in stable, unconsolidated material without rocks. **Disadvantages:** (1) Extraction of core from the tube might be difficult; (2) not suitable for rocky, dry, loose, or granular material, or very wet soil; (3) might be difficult to drive into dense or hard material, and sometimes difficult to pull from the ground; and (4) sampling depth is usually limited to 1 or 2 meters.

Frequency of Use: Commonly used for near-surface soil sampling, especially where volatile contaminants are present.

Standard Methods/Guidelines: Boulding (1991), U.S. EPA (1986b).

Sources for Additional Information: See Table 2-5.

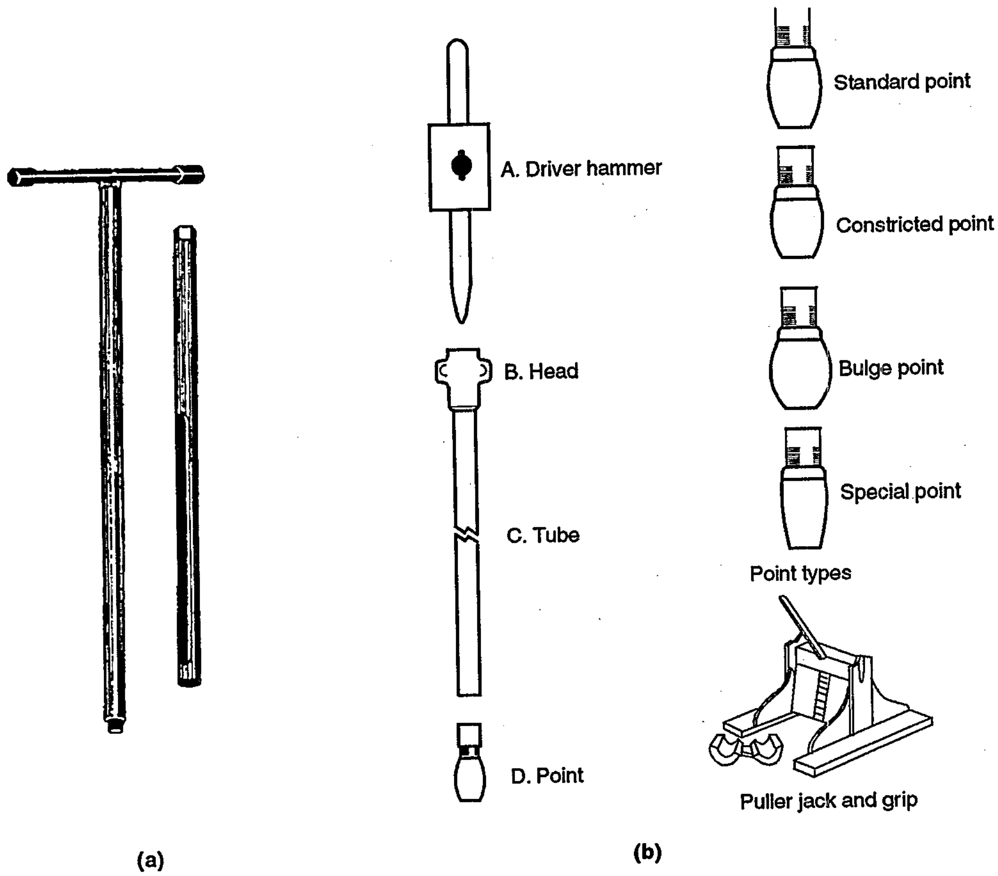


Figure 2.3.3 Hand-held thin-wall samplers: (a) Thin-wall tube probe (Rehm et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission); (b) Veihmeyer tube (Brown et al., 1991).

Table 2.3.3 Summary of Hand-Held Tube Samplers[a]

Tube Type	Applications	Limitations
Soil Probe	Cohesive, soft soils or residue; representative samples in soft to medium cohesive soils and silts	Sampling depth generally limited to less than 1 meter
Thin-Walled Tubes	Cohesive, soft soils or residue; special tips for wet or dry soils available	Similar to Veihmeyer tube
Soil Recovery Probe	Similar to thin-wall tubes; cores are collected in reusable liners, minimizing contact with the air	Similar to Veihmeyer tube
Veihmeyer Tube	Cohesive soils or residue to depth of 3 meters (maximum of 4.9 meters)	Difficult to drive into dense or hard material; will not retain dry, loose, or granular material; might be difficult to pull from ground
Peat Sampler	Wet, fibrous, or organic soils	Use limited to organic soils

[a]Not suitable for soils with coarse fragments.

Source: Adapted from Boulding (1991)

2.4 POWER-DRIVEN SOIL SAMPLING DEVICES

2.4.1 Split and Solid Barrel

Other Names Used to Describe Method: Split-spoon, split barrel, Maine-type split barrel, split barrel with liner.

Uses at Contaminated Sites: Collecting disturbed cores in unconsolidated material.

Method Description: **Split-spoons** are tubes constructed of high strength alloy steel with a tongue and groove arrangement running the length of the tube, allowing it to be split in half. The two halves are held together by a threaded drive head assembly at the top, and a hardened shoe at the bottom, with a beveled cutting tip (Figure 2.4.1). The sampler is driven by a 140-pound weight dropped through a 30-inch interval (ASTM, 1984a), and the number of blows required to drive the sampler provides an indication of the compaction/density of the formation being sampled. When the split-spoon is brought to the surface, it is disassembled and the core removed. Some models have a liner that allows removal of the sample with minimum contact with the air. A basket or spring retainer can be placed inside the tube near the tip to reduce loss of sample material to the borehole as the sampler is being withdrawn. Standard geotechnical investigations sample an 18-inch interval for each 5 feet penetrated. Continuous samples can be taken by augering or drilling to the bottom of the previously sampled interval, and repeating the sampling operation. **Barrel samplers** are similar to split-spoons, except they cannot be taken apart. A core extruder might be required to remove the core from the barrel. Table 2.4.1 provides additional information on split-spoon and barrel samplers. **Ring-lined barrel** samplers combine a split-barrel of a barrel sampler with a thin-walled extension for the collection of minimally disturbed samples.

Method Selection Considerations: **Advantages:** (1) Sampling depth limited only by the capabilities of the drill rig and depth to consolidated rock; (2) split-spoon samplers are readily available; (3) provide good samples for stratigraphic interpretation; and (4) ring-lined barrel samplers can sometimes be used to obtain undisturbed cores where conventional thin-wall samplers (Section 2.4.3) will not work. **Disadvantages:** (1) Disturbance of core samples prevent use for laboratory measurement of formation properties; and (2) collection of continuous samples is time consuming.

Frequency of Use: Split-spoons are widely used during drilling for stratigraphic characterization, solid barrels are less commonly used.

Standard Methods/Guidelines: **Split spoon:** ASTM (1984a), U.S. EPA (1986b); **Ring-lined barrel:** ASTM (1984b).

Sources for Additional Information: Aller et al. (1991), Barrett et al. (1980), Rehm et al. (1985), Shuter and Teasdale (1989).

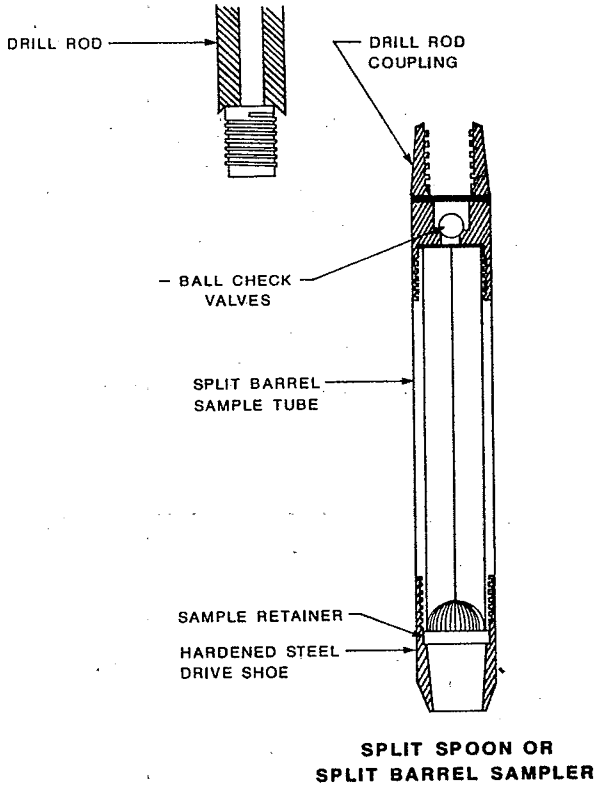


Figure 2.4.1 Split-spoon sampler (Rehm et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission).

Table 2.4.1 Summary of Major Types of Power-Driven Disturbed-Core Samplers

Sampler Type	Applications	Limitations
<u>Barrel Samplers</u> (Section 2.4.1)		
Solid Barrel	Sand, silts, or clays	Disturbed core, questionable recovery and quality below water table
Split-Spoon	Disturbed samples from cohesive soils	Ineffective in cohesionless sands; not suitable for collection of samples for laboratory tests requiring undisturbed soil
<u>Rotating Core</u> (Section 2.4.2)		
Single Tube	Dense, unconsolidated and consolidated formations	
Double-Tube	Friable, erodible, soluble, or highly fractured formations	

Source: Adapted from Rehm et al. (1985) and Aller et al. (1991)

2.4 POWER-DRIVEN SOIL SAMPLING DEVICES

2.4.2 Rotating Core

Other Names Used to Describe Method: Core barrels, single-tube/wall, double-tube/wall core barrels.

Uses at Contaminated Sites: Collecting disturbed cores in dense, unconsolidated and consolidated formations; characterizating joints and fractures.

Method Description: See Section 2.1.10 for basic description of diamond coring process. In **single-wall** tubes, drilling fluid circulates around the core that has been cut and around the barrel, and exits through the bit (Figure 2.4.2). In **double-wall** tubes, the drilling fluid circulates between the two walls of the core barrel and does not come in direct contact with the core being cut (Figure 2.4.2).

Method Selection Considerations: **Advantages:** (1) Can provide continuous cores; and (2) double-tube barrels can provide good recovery even in unconsolidated clays and silts. **Disadvantages:** (1) Poor recovery of single-barrel cores in soft, friable, poorly consolidated materials, or soluble or fractured formations due to erosion by the drilling fluid; (2) rotation results in disturbance of cores (double-barrel sampler reduces disturbance); (3) use of water or drilling fluids might alter the chemistry of the sample; and (4) time-consuming and high cost of equipment makes the method expensive. Table 2.4.1 provides additional comparative information on rotating core samplers.

Frequency of Use: Commonly used in mineral exploration, uncommon at contaminated sites.

Standard Methods/Guidelines: ASTM (1983b), DCDMA (1991).

Sources for Additional Information: Aller et al. (1991), Barrett et al. (1980), Rehm et al. (1985), Shuter and Teasdale (1989).

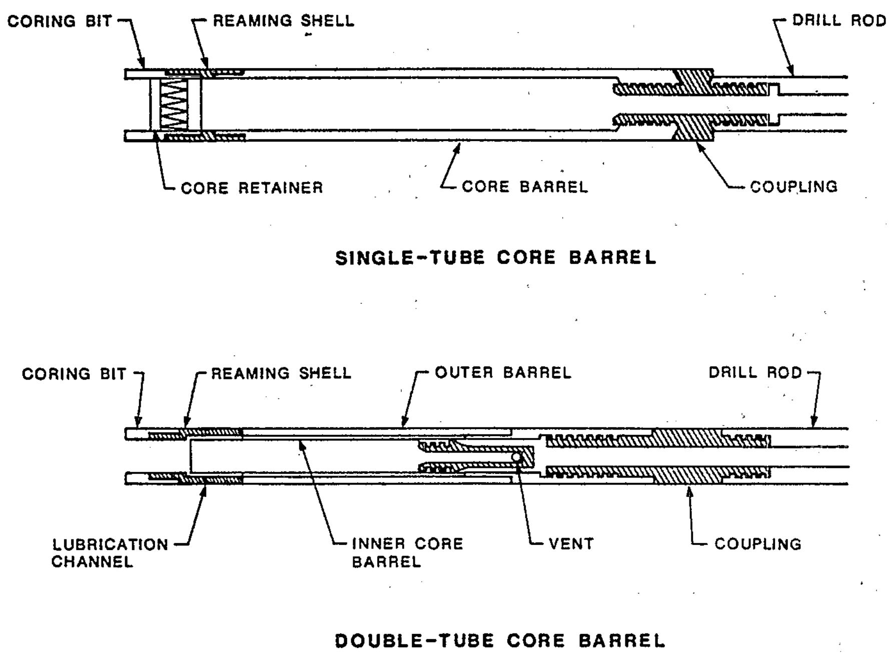


Figure 2.4.2 Single-tube and double-tube core barrels (Rehm et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission).

2.4.3 Thin-Wall Open Tube

Other Names Used to Describe Method: Shelby tube, thin-wall sampler, continuous sample tube, ring-lined barrel sampler. See also, ring-lined barrel sampler in Section 2.4.1

Uses at Contaminated Sites: Collecting undisturbed soil and unconsolidated core samples.

Method Description: Thin-wall samplers must meet the following criteria: (1) A clearance ratio of 0.5 to 1.5 (inside diameter of tube, minus the inside diameter of the opening, divided by the inside diameter of the opening), and (2) an end area ratio--total area of the sampler (outside diameter) to the wall thickness area should be less than 10 percent (Figure 2.4.3a). Sample collection procedure is similar to split-spoon sampling, except that the tube is pushed into the soil using the weight of the drill rig, rather than driven. The use of a **continuous** thin-wall sampler with a hollow-stem auger (Section 2.1.1) avoids the time delays involved in collection of continuous cores from conventional thin-wall samplers. A 5-foot thin-wall tube is placed down the stem of the auger. The tube is attached to a nonrotating sampling rod, or a wireline assembly that allows the auger to rotate while the tube remains stationary, and undisturbed material enters the tubes and the auger flights advance (Figure 2.4.3b). The sample is collected every 5 feet before a new auger flight is added.

Method Selection Considerations: **Advantages:** (1) Equipment is readily available; and (2) collects undisturbed sample. **Disadvantages:** (1) Might not be strong enough to penetrate compact sediments (can be overcome with specialized samplers [see Section 2.4.5]); (2) collection of continuous samples with conventional thin-wall samplers is very time consuming, especially when the depth exceeds around 100 feet (continuous sampling tube system can overcome this); and (3) gravel or cobbles can disturb sample during collection, or damage walls of the sampler (sample tube should be at least 6 times the diameter of the longest particle size of the sample to minimize physical disturbance). Table 2.4.3 provides comparative information on power-driven thin-wall samplers.

Frequency of Use: Most common method for collection of undisturbed core samples.

Standard Methods/Guidelines: ASTM (1983a), U.S. EPA (1986b).

Sources for Additional Information: See Table 2-5.

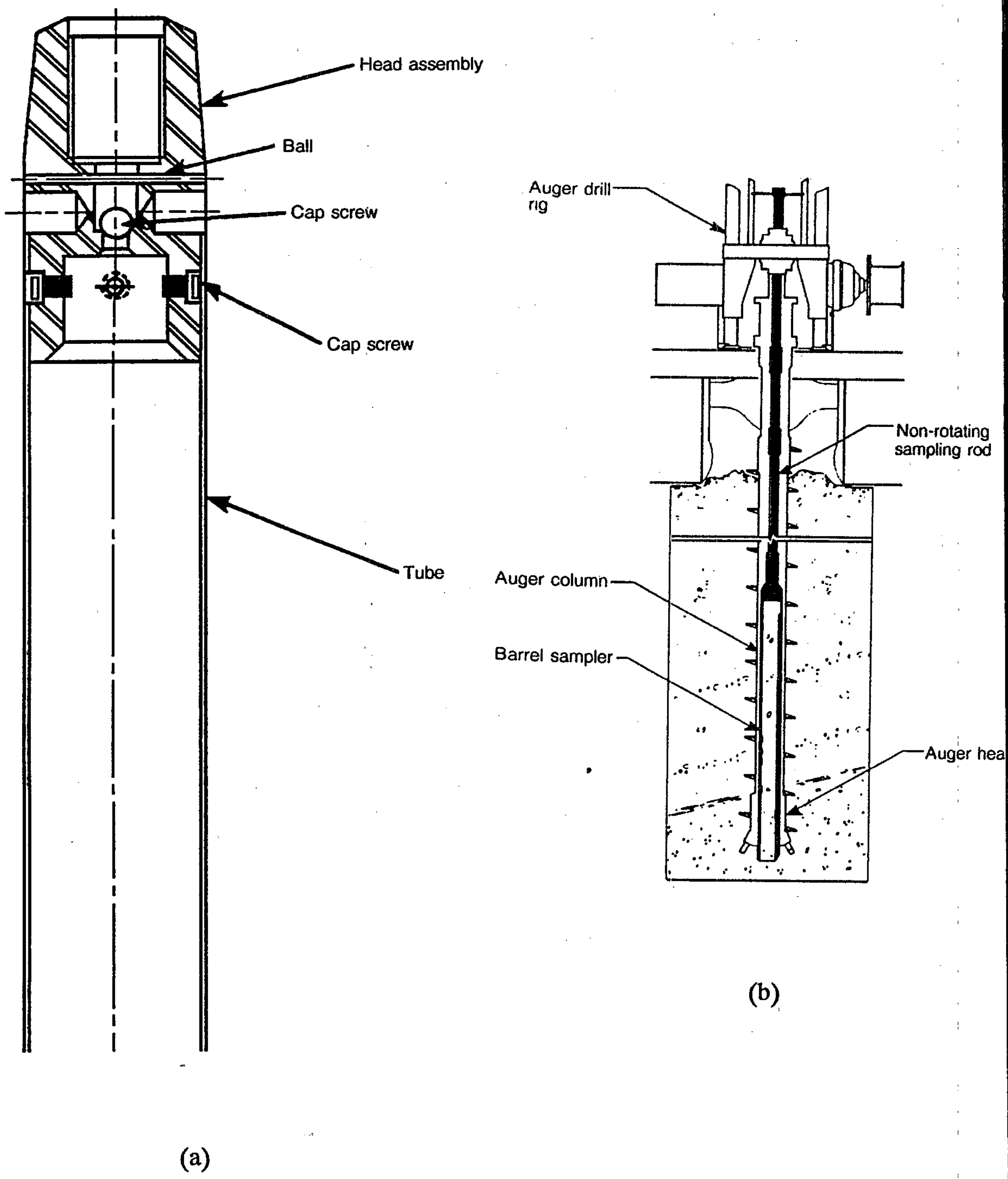


Figure 2.4.3 Thin-wall samplers: (a) Shelby tube; (b) Continuous sampling tube system (Aller et al., 1991).

Table 2.4.3 Summary of Major Types of Power-Driven Undisturbed-Core Samplers

Sample 1 Type	Applications	Limitations
Thin-Wall Open Tube Samplers (Section 2.4.3)		
Shelby Tube	Undisturbed samples in cohesive soils, silt, and sand above water table	Ineffective in cohesionless sands or stony soil
Continuous Tube	Same as Shelby tube, except longer barrel designed to operate inside the column of a hollow-stem auger	Same as Shelby tube
Thin-Wall Piston Samplers (Section 2.4.4)		
Internal Sleeve Piston	Collection of sample in heaving sands; used with hollow-stem auger with clamshell bit	Requires use of water or drilling mud for hydrostatic control; only one sample per borehole can be obtained
Wireline Piston	Undisturbed samples in cohesive soils and noncohesive sands; used with clam shell device on hollow-stem auger	In heaving sands, only one sample per borehole can be collected because clamshell remains open after sampling
Fixed-Piston	Undisturbed samples in cohesive soils, silt, and sand above or below water table	Ineffective in cohesionless sands
Hydraulic Piston (Osterberg)	Similar to fixed-piston sampler	Not possible to limit the length of push or to determine amount of partial sampler penetration during push
Stationary Piston	Undisturbed samples in stiff, cohesive soils; representative samples in soft to medium cohesive soils, silts, and some sands	
Free Piston	Similar to stationary piston sampler	Not suitable for cohesionless soils
Open Drive	Similar to stationary piston sampler	Not suitable for cohesionless soils

Table 2.4.3 (cont.)

Sampler Type	Applications	Limitations
Specialized Thin-Wall Sampler (Section 2.4.5)		
Pitcher	Undisturbed samples in hard, brittle, cohesive soils and cemented sands; representative samples in soft to medium cohesive soils, silts, and some sands; variable success with cohesionless soils	Frequently ineffective in cohesionless soils; requires use of drilling fluid that might affect quality of sample
Denison	Undisturbed samples in stiff to hard cohesive soils, cemented sands, and soft rocks; variable success with cohesionless materials	Not suitable for undisturbed sampling of loose, cohesionless soils or soft cohesive soils; requires use of drilling fluid that might affect quality of sample
Vicksburg	Similar to Shelby tube, but able to sample denser and coarser material	

Source: Adapted from Aller et al. (1991), Barrett et al. (1980), Boulding (1991), and Rehm et al. (1985)

2.4 POWER-DRIVEN SOIL SAMPLING DEVICES

2.4.4 Thin-Wall Piston

Other Names Used to Describe Method: Fixed piston, hydraulic piston (Osterberg), wireline piston, free piston, open drive sampler, internal sleeve piston.

Uses at Contaminated Sites: Collecting samples in unconsolidated formations and heaving sands (internal sleeve and wireline piston).

Method Description: Piston samplers are similar to thin-wall samplers except that they are equipped with internal pistons to generate a vacuum within the sampler as it is withdrawn from the soil (Figure 2.4.4a). Figure 2.4.4b illustrates sampling procedures using a wireline piston sampler with a hollow-stem auger. Numerous types of piston samplers have been developed and Table 2.4.3 summarizes information on seven types.

Method Selection Considerations: **Advantages:** (1) Vacuum might improve sample recovery compared to conventional thin-wall samplers; and (2) models are available that are designed especially for sampling heaving sands, which are difficult to sample using conventional thin-wall samplers. **Disadvantages:** (1) Not as widely available as regular thin-wall samplers; and (2) more complex construction increases possibility of malfunction.

Frequency of Use: Usually used where soil conditions are unfavorable for use of conventional thin-wall samplers.

Standard Methods/Guidelines: U.S. EPA (1986b).

Sources for Additional Information: Aller et al. (1991), Barrett et al. (1980), Rehm et al. (1985). See also, Table 2-5.

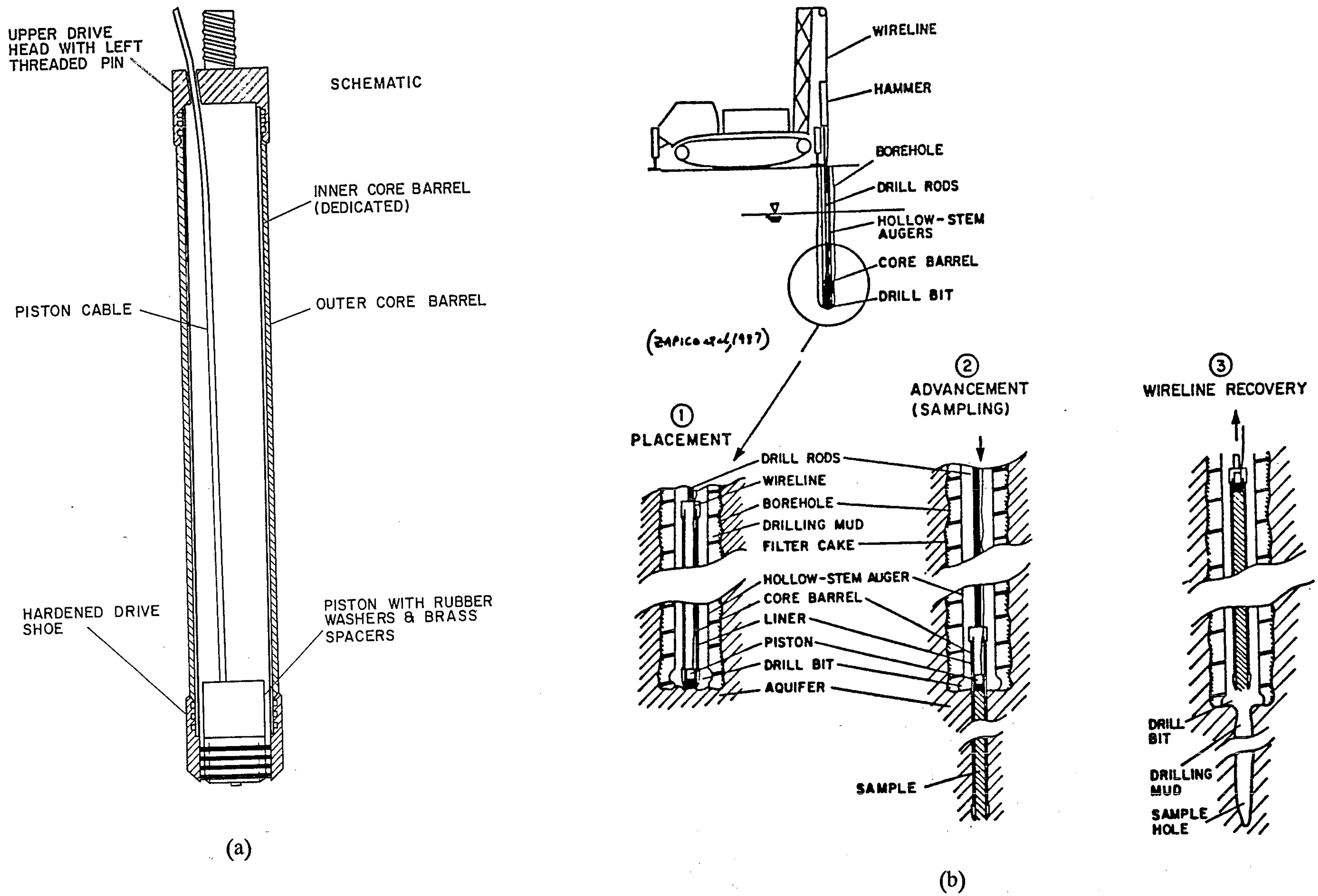


Figure 2.4.4 Wireline piston sampler: (a) Sampling device; (b) Sampling procedure (Zapico et al, 1987, by permission).

2.4.5 Specialized Thin-Wall

Other Names Used to Describe Method: Pitcher sampler, Denison sampler, Vicksburg sampler.

Uses at Contaminated Sites: Collecting undisturbed samples where specific soil conditions are unfavorable for use of conventional or piston samplers.

Method Description: Basic sampling procedures are generally the same as for thin-wall samplers. The **Vicksburg** sampler has a 5.05-inch inside diameter by 5.25-inch outside diameter, which qualifies as a thin-wall sampler but is structurally much stronger than a Shelby tube (Figure 2.4.5a). The **denison** sampler (Figure 2.4.5b) and **pitcher** sampler (Figure 2.4.5c) have a double-tube core design with an inner tube that qualifies as a thin-wall sampler. The rotating outer tube allows penetration in extremely stiff deposits or highly cemented unconsolidated materials, while the stationary inner tube collects a minimally disturbed sample. Table 2.4.3 provides comparative information on specialized thin-wall samplers.

Method Selection Considerations: **Advantages:** Greater structural strength allows collection of undisturbed samples in dense formations. **Disadvantages:** Less readily available than conventional thin-wall samplers.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Rehm et al. (1985), Shuter and Teasdale (1989).

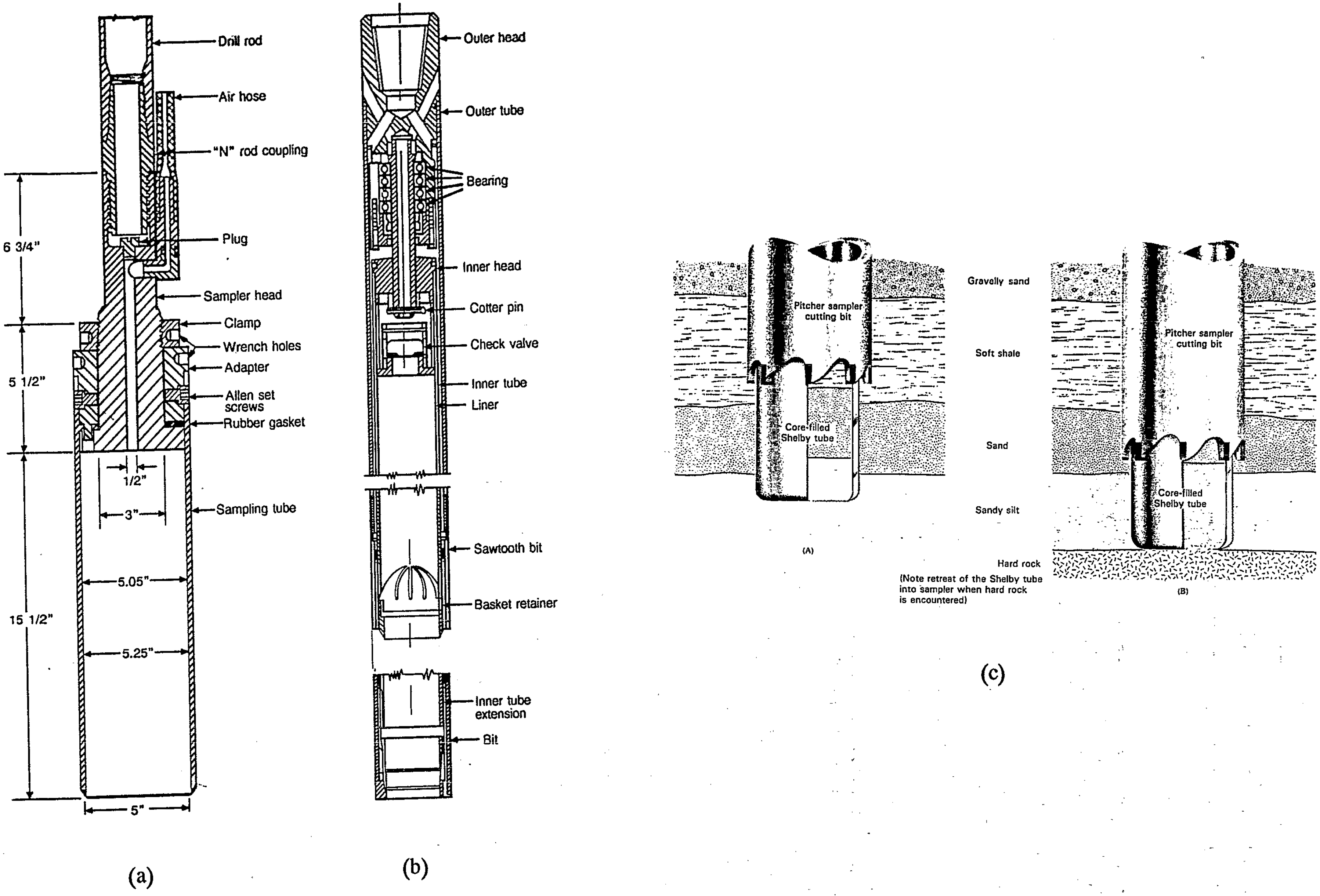


Figure 2.4.5 Special thin-wall samplers: (a) Vicksburg sampler (Aller et al., 1991); (b) Denison sampler (Aller et al., 1991); (c) Pitcher sampler operation: Shelby tube extends beyond cutting bit in soft formations (A) and retracts into cutting barrel when hard rock is encountered (B) (Shuter and Teasdale, 1989).

2.5 FIELD DESCRIPTION OF SOIL PHYSICAL PROPERTIES

2.5.1 Texture

Other Names Used to Describe Method: Particle-size distribution. There are numerous systems for classifying soil according to particle-size distribution. The most common are those used by the Soil Conservation Service of the U.S. Department of Agriculture (USDA), and the Unified Soil Classification System (USCS), used by the American Society for Testing and Materials (ASTM). Other systems, all of which have slight to major differences, include: AASHTO (American Association of State Highway and Transportation Officials), FAA (Federal Aviation Administration), U.S. Army Corps of Engineers, U.S. Public Roads Administration, International Society of Soil Science, British Standards Institution, and Canadian Soil Survey Committee.

Uses at Contaminated Sites: Texture is a basic soil property that affects numerous hydrologic, engineering, and contaminant transport characteristics of the soil.

Method Description: **USDA:** Particle-size classes of the fine fraction (<2 mm) are determined by estimating the relative proportions of sand-, silt-, and clay-sized particles based on feel. Accurate classification requires laboratory analysis of samples, but repeated "calibration" of field classification by feel with laboratory analyses allows accurate field determinations, except in borderline cases. Particle-size class names using the USDA soil texture triangle are shown in Figure 2.5.1. **USCS:** A series of field tests to determine the nature of the coarse and fine fractions, and properties such as plasticity, liquid limit, clod strength, dilatancy, toughness, and stickiness, allow field estimation of unified soil type. Laboratory analysis is required to ensure accurate classification. **Rock classification:** Bedrock materials are classified according to origin (igneous, metamorphic, and sedimentary), particle or mineral grain size, mineralogy, and other features, such as hardness, degree of fracture development, etc.

Method Selection Considerations: USDA classification method is best for interpretations relating to hydrologic and contaminant transport properties. USCS is best for evaluating engineering properties.

Frequency of Use: USCS is commonly used; USDA is less commonly used, but should probably be used more for reasons mentioned above.

Standard Methods/Guidelines: **Unified (ASTM) field estimation:** ASTM (1990), Boulding (1991); **Unified laboratory classification:** ASTM (1992); **USDA field description:** Boulding (1991); **Rock:** Dunham (1962), Pettijohn et al. (1972), Potter et al. (1980).

Sources for Additional Information: Boulding (1991). Other references discussing classification of texture: Casagrande (1948), Emerson (1967), Folk and Ward (1957), Irani and Callis (1963), Propkopovich (1977), Shepard (1954), Williamson (1984)

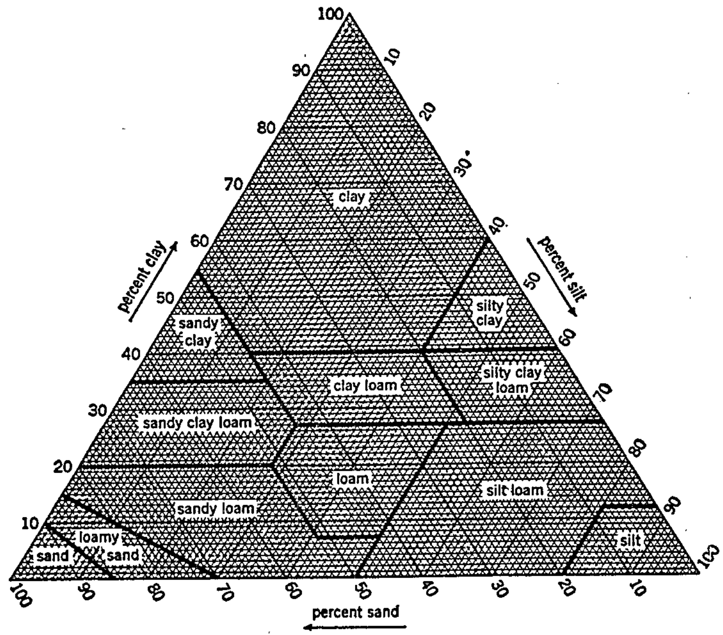


Figure 2.5.1 USDA soil texture triangle (Soil Survey Staff, 1975).

2.5.2 Color

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Color of soil horizons and other unconsolidated material serves as an indicator of zone of saturation and seasonal fluctuations in the water table, organic matter content, and soil mineralogy.

Method Description: Soil matrix, mottles, and concentrations of minerals are described according to hue, value, and chroma using Munsell Soil Color Charts (Figure 2.5.2). A simple ignition test that can be carried out in the field allows evaluation of the contribution of organic matter, iron oxides, ferrous (reduced) iron, and manganese oxides to soil color.

Method Selection Considerations: Should be standard procedure for description of soil/unconsolidated material cores and soil samples.

Frequency of Use: Common.

Standard Methods/Guidelines: **Soil color:** Munsell Soil Color Charts (available from Munsell Color Company, 2441 N. Calvert St., Baltimore, MD 21218); **Color ignition test:** Boulding (1991).

Sources for Additional Information: Boulding (1991).

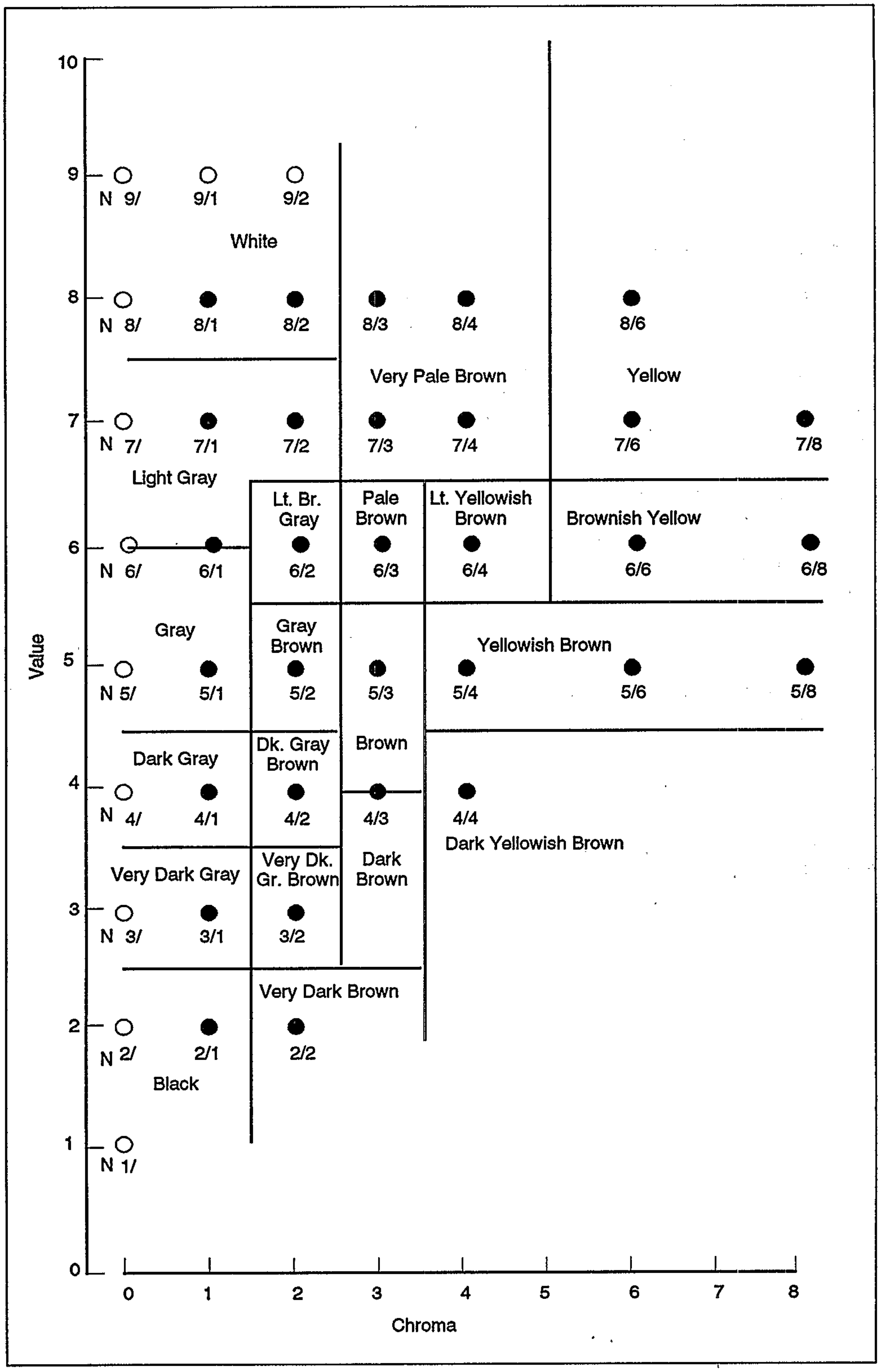


Figure 2.5.2 Soil color names for several combinations of value and chroma and hue 10YR (Soil Survey Staff, 1975).

2.5 FIELD DESCRIPTION OF SOIL PHYSICAL PROPERTIES

2.5.3 Other Features

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Characterizating variability of soil properties; identifying near surface zone of increased and reduced permeability for contaminant transport.

Method Description: Trenches are dug to a depth of 1 to 2 meters, or cores from hand-held or power driven thin-wall tube samplers are visually observed and felt for signs of pedogenic (soil-weathering), such as: (1) Soil horizons, (2) porosity, (3) other features indicating increased porosity or permeability (soil structure, extrastructual cracks, roots, and surface and sedimentary features), (4) other features indicating zones of reduced porosity or permeability (slowly permeable genetic horizons, high rupture resistance, root restricting layers, and compaction), and (5) soil moisture conditions. Soil profile description procedures should follow those developed by the U.S. Soil Conservation Service. Figure 2.5.3 illustrates major types of soil structure, a form of secondary porosity that facilitates transport of contaminants in the subsurface. Section 10.6.2 describes field procedures for measurement or collection of samples for bulk density, an important property affecting transport of contaminants in the subsurface.

Method Selection Considerations: **Advantages:** (1) Relatively inexpensive method for initial characterization of soil characteristics and variability when cores are obtained using a hand-held thin-wall tube probe, or truck-mounted tube probe; and (2) information is useful for design of soil sampling plan and for selection of monitoring well locations. **Disadvantages:** (1) Special training is required to obtain consistent soil-profile descriptions; and (2) provides qualitative rather than quantitative information and more complex field or laboratory measurements are required for quantitative data.

Frequency of Use: Uncommon, but should probably be used more frequently.

Standard Methods/Guidelines: **Visual/tactile observation:** Boulding (1991); **Bulk density:** See section 10.6.2

Sources for Additional Information: --

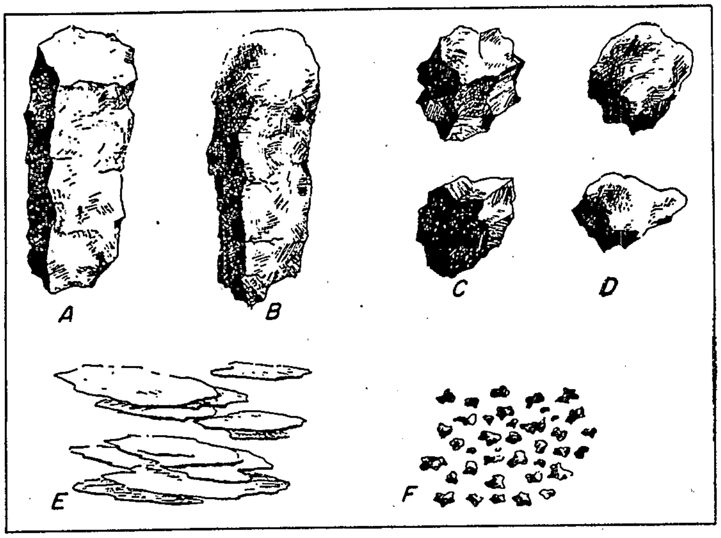


FIGURE 44.—Drawings illustrating some of the types of soil structure: *A*, prismatic; *B*, columnar; *C*, angular blocky; *D*, subangular blocky; *E*, platy; and F, granular.

Figure 2.5.3 Major types of soil structure (Soil Survey Staff, 1975).

Table 2-4 Reference Index for Drilling Methods

Topic	References
General	
General Drill Method Texts	Aller et al. (1991), Australian Drilling Association (1992), Bowman (1911), Campbell and Lehr (1973), Driscoll (1986), Gaitlin (1960), Gibson and Singer (1969, 1971), Ingersoll-Rand (1985-terminology), Lehr et al. (1988), McCray and Cole (1958-oil well drilling), Moore (1974), Ruda and Bosscher (1990), Shuter and Teasdale (1989), U.S. Army (1981), USATHAMA (1982); Regional Water Well Drilling Trends: Hindall and Eberle (1989), Meyer and Wyrick (1966)
Ground-Water Texts Covering Drilling Methods	Barrett et al. (1980), Bureau of Reclamation (1981), Davis and DeWiest (1966), Devinny et al. (1990), GeoTrans (1989), Gillham et al. (1983), Rehm et al. (1985), Scalf et al. (1981)
Review Papers	Carlson (1943), Davis et al. (1991), Hix (1991), Luhdorff and Scalmanini (1982), McIlvride and Weiss (1988), Nielsen (1991-status of ASTM method development), Smith (1990), Stow (1963)
Water Quality Effects	Gillham et al. (1983), Herzog et al. (1991), Lolcama (1988), Russell et al. (1989), U.S. EPA (1975); See also, references on drilling mud chemical effects (below)
Decontamination	Hix (1992)
Specific Drilling Methods	
Hollow Stem Auger	Hackett (1987, 1988), Hodges and Teasdale (1991), Huntoon-Pecak (1989), Kresse (1985), Leach et al. (1988), McIlvride and Weiss (1988), Nickens et al. (1988), Vroblesky et al. (1988-remote controlled drilling), Weinstock (1990)
Air Rotary	Texts: Brantley (1961), Hughs Tool (1966-drill bits), Petroleum Extension Service (various dates); Papers: Angel (1968), Bates (1965), Bennett et al. (1988), Cooper et al. (1977), Hodges and Teasdale (1991), Kaufman et al. (1981), Mason and Woolley (1981), McEllhinney (1960), Russell et al. (1989-cross contamination prevention), Schalla (1986-effect on pump test results), Seikan and Deyling (1989); Logging of Cuttings: Hooper and Earley (1961)
Mud Rotary	Texts: API (1973), Brantley (1961), Hughs Tool (1966-drill bits), Petroleum Extension Service (various dates); Papers: Hodges and Teasdale (1991), Kaufman et al. (1981), Millison et al. (1989), Russell et al. (1989), Schalla (1986-effect on pump test results), White (1990); Drill Mud/Fluids: API (1968, 1991a, 1991b), Baroid Division (1954, 1966), Dreeszen (1959), Ericsen et al. (1985), Gray (1972), Gray and Darley (1981), Grichor (1983), Imco Services (1975), Magcobar (1977), McEllhinney (1960), Petroleum Extension Service (1969), Rogers (1963), Shew (1975), Tschirley (1978); Drill Mud Toxicity/Water Chemistry Effects: Brobst and Buszka (1986), Ericsen et al. (1985), Graham and Johnson (1991), Graham et al. (1985), Russell et al. (1989), Senum and Dietz (1991), Shew and Keeley (1975), U.S. EPA (1984a,b)
Cable Tool	Texts: API (1988b), Decker (1968), Gordon (1958), Sanderson Cyclone (1966); Papers: Bonham (1955), Stevens (1963), Treadway (1991)

Table 2-4 (cont.)

Topic	References
Reverse Circulation	Percussion Hammer: Bates (1965), Massarenti (1964), Paules et al. (1990), Sale and Rhoades (1987), Shirley and Hay (1988); Reverse Dual-Tube Rotary: Holsten and Morgan (1989), Riddle and Johnson (1991), Strauss et al. (1989)
Casing Advance Drilling	Boyle (1992)
Directional Drilling	Dickinson et al. (1987), Kaback et al. (1991), Karlsson and Bitto (1990), Langseth (1990), Losonsky et al. (1992), Metcalf and Eddy (1991), Morgan (1992), Speake et al. (1991), Summers (1972), U.S. Bureau of Mines (1968)
Penetrometry	ASTM (1966, 1986a,b), Campbell and O'Sullivan (1991), Chiang et al. (1989a, 1989b, 1992), Christy and Spradlin (1992), Cooper et al. (1988a,b), Ehrenzeller et al. (1991), Fritton (1990), Gillespie and Campanella (1981), Klopp et al. (1989), Lithland et al. (1985), Olson and Farr (1986), Robertson and Campenalla (1986), Robertson et al. (1986), Saines et al. (1989), Sangerlat (1972), Schmertmann (1978), Smolley and Kappmeyer (1989, 1991), Smythe et al. (1988), Strutynsky and Sainey (1990), Strutynsky et al. (1992), Wahls (1975); See also, reference for Sections 5.5.1 and 5.5.2

Table 2-5 Reference Index for Solids Sampling Methods

Topic	References
<u>General</u>	
Soil/Solids Sampling Texts	Acker (1974), Barth et al. (1989), Brown (1986), Brown et al. (1991), Bureau of Reclamation (1974, 1990), Cameron et al. (1966), Corps of Engineers (1972), deVera (1980), Goodwin et al. (1982), Hodgson (1978), Hvorslev (1948, 1949), ISSMFE (various dates), Mason (1992), McKeague (1978), Mooij and Roovers (1978), Mori (1979), SCS (1971, 1984), U.S. EPA (1986a)
Other Texts with Sections Covering Soil Sampling	Aller et al. (1991), Barrett et al. (1980), Devinny et al. (1990), Everett et al. (1976), Fenn et al. (1977), Ford et al. (1984), GeoTrans (1989), Rehm et al. (1985), Scalf et al. (1981), U.S. EPA (1986b)
Review Papers	Broms (1980), Busche and Burden (1991), Davis et al. (1991)
Logging/Sampling of Cuttings	Hooper and Earley (1961), Johnson UOP (1967), Maher (1963), Shuter and Teasdale (1989), Stevens (1963-cable tool and rotary), USATHAMA (1982)
Characterization and Sampling of Contaminated Soils	Boulding (1991), Breckinridge et al. (1991), Cameron (1991), Fleischauer (1985-radium), Kostecki and Calabrese (1990), Leach and Draper (1991), Ostendorf et al. (1991), Zirschky and Gilbert (1984); <u>Aseptic Sampling</u>: Leach and Ross (1991), Leach et al. (1988), Russell et al. (1989); <u>Volatiles</u>: API (1992), Jackson et al. (1991), Parolini et al. (1991), Siegcrist and Jenssen (1990), Sims et al. (1991), Slater and McLaren (1983), Spittler et al. (1988)
Sample Handling	Bartlett and James (1980), Kluitenberg et al. (1991-sealing of cores in shrinking soil), Mullins and Hutchison (1982), Nevo and Hagin (1966), Parolini et al. (1991), Plumb (1981), Qian and Wolt (1990), Wilson et al. (1991); <u>Sample Mixing/Compositing</u>: Mroz and Reed (1991), Raab et al. (1991), Schumacher (1990), Schumacher et al. (1991)
<u>Specific Sampling Devices/Methods</u>	
Undisturbed Core Samplers	Begemann (1974), Brown and Thilenius (1977), Buchele (1961), Byrnes (1975), Chong et al. (1982), Hayden and Heinemann (1968), Hayden and Robbins (1975), Hendrickx et al. (1991-portable motor driven), Hipp et al. (1968), Holtzclaw et al. (1975-bulk density), Jamison et al. (1950), Kelley et al. (1947-truck mounted), LaRochelle et al. (1981), Lutz (1947), Mielke and Wilhelm (1983), Myers et al. (1989), Parsons (1961), Pikul et al. (1979), Rhotan and McChesney (1991), Riggs (1983), Robertson et al. (1974-truck mounted), Rogers and Carter (1987), Ruark (1985), Russell et al. (1989), Schickedanz et al. (1973), Sieczka et al. (1982), Starr and Ingelton (1992-piston sampler), Stolt et al. (1991-modified bucket auger), Tackett et al. (1965), Tanner et al. (1953), Terry et al. (1974), Tuttle et al. (1984), Vaughn et al. (1984), Viehmeyer (1929), Vepraskas et. al (1990), Watson and Lees (1975), Wires and Sheldrick (1987); <u>Freezing Methods</u>: Blevins et al. (1968), Buchter et al. (1984); <u>Coated Cores/Samples</u>: Bondurant et al. (1969), Economy and Bowman (1993), Mielke (1973), Tomer and Ferguson (1989); See also, references for Section 7.3.8

Table 2-5 (cont.)

Topic	References
Noncohesive Soil Samplers	Arthur and Shamash (1970), Barton (1974), Bishop (1948), Marcuson and Franklin (1980-undisturbed samples), Munch and Killey (1985), Murphy et al. (1981), Schuh (1987), Zapico et al. (1987)
Wireline Samplers	API (1983), Armstrong et al. (1988), Clark (1988), McElwee et al. (1991), Millison et al. (1989), Zapico et al. (1987)
Special Sampling Situations	Rocky Soils: Buchter et al. (1984), Lewis et al. (1990), Tuttle et al. (1984); Underwater Sediments: Ali (1984), Anastasi and Olinger (1991), ASTM (1993e), Barth and Starks (1985-quality assurance), Darmody et al. (1976), Edwards and Glysson (1988), Fleischauer and Engelder (1985), Palmer (1985), Plumb (1981), U.S. EPA (1989)

SECTION 2 REFERENCES

Acker, W.L. 1974. Basic Procedures for Soils Sampling and Core Drilling. Acker Drill Co., Scranton, PA.

Ali, A. 1984. A Simple and Efficient Sediment Corer for Shallow Lakes. J. Environ. Quality 13:63-66.

Aller, L., et al. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. EPA/600/4-89/034, 221 pp. Available from CERI.* (Also published in 1989 by National Water Well Association, Dublin, OH, in its NWWA/EPA series, 398 pp.)

American Petroleum Institute (API). 1968. Principles of Drilling Fluid Control. API, Dallas, TX, 215 pp. (In cooperation with University of Texas and Am. Ass. of Oil Well Drilling Contractors.)

American Petroleum Institute (API). 1973. Procedures for Selecting Rotary Drilling Equipment, 2nd edition. API Bulletin D10. API, Washington, DC. (Reissued 1982; reaffirmed, 1990.)

American Petroleum Institute (API). 1983. Wireline Operations and Procedures, 2nd edition. API, Washington, DC, 58 pp. (Book 5 in Vocational Training Series.)

American Petroleum Institute (API). 1988a. Recommended Practice for Care and Use of Cable Drilling and Fishing Tools, 2nd edition. API RP3. API, Washington, DC.

American Petroleum Institute (API). 1988b. Specification for Cable Drilling Tools, 13th edition. API Spec 3. API, Washington, DC.

American Petroleum Institute (API). 1991a. Recommend Practice Standard Procedure for Field Testing Oil-Based Drilling Fluids, 2nd edition. API RP 13B-2. API, Washington, DC.

American Petroleum Institute (API). 1991b. Specifications for Drilling Fluid Materials, 14th edition. API Spec 13A. API, Washington, DC.

American Petroleum Institute (API). 1992. Sampling and Analysis of Gasoline Range Organics in Soil. API Publication 4516. API, Washington, DC, 132 pp.

American Society for Testing and Materials (ASTM). 1966. Vane Shear and Cone Penetration Resistance Testing of In-Situ Soils. In: ASTM STP 399, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1980. Standard Practice for Soil Investigation and Sampling by Auger Borings. D1452-80, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1983a. Standard Practice for Thin-Walled Tube Sampling of Soils. D1587-83, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1983b. Standard Practice for Diamond Core Drilling for Site Investigation. D2113-83, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1984a. Standard Method for Penetration Test and Split-Barrel Sampling of Soils. D1586-84, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1984b. Standard Practice for Ring-Lined Barrel Sampling of Soils. D3550-84, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1986a. Standard Test Method for Stress Wave Energy Measurement for Dynamic Penetrometer Testing Systems. D4633-86, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1986b. Standard Test Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests of Soil. D3441-86, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1987. Standard Guide for Investigation and Sampling Soil and Rock. D420-87, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1989. Standard Practices for Preserving and Transporting Soil Samples. D4220-89, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1990. Standard Practice for Description and Identification of Soils (Visual-Manual Procedures). D2488-90, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991. Guide for Soil Sampling from the Vadose Zone. D4700-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992. Standard Test Method for Classification of Soils for Engineering Purposes. D2487-92, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993a. Draft Standard Guide for the Use of Hollow-Stem Augers for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices. D18.21 Ballot 93-03, April 28. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993b. Draft Standard Guide for the Use of Direct Air-Rotary Drilling for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices. D18.21 Ballot 93-03, April 28. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993c. Draft Standard Guide for the Use of Direct Rotary Drilling with Water-Based Drilling Fluid for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices. D18.21 Ballot 93-03, April 28. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993d. Draft Standard Guide for the Use of Dual-Wall Reverse Circulation Drilling for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices. D18.21 Ballot 93-03, April 28. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993e. Standard Guide for a Complete Data Set for Non-Cohesive Sediments. D5387-93, (Vol 11.02), ASTM, Philadelphia, PA.

Anastasi, F.S. and L.W. Olinger. 1991. A Method for Collecting Soil Samples Beneath Lake-Bottom Sediments. In: Proc. 15th Annual Army Environmental R&D Symp. (1990), CETHA-TS-CR-91077, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 153-160.

Angel, R.R. 1968. Volume Requirements for Air-Gas Drilling. Gulf Publishing Co., Houston, TX. [Air foam drilling, oriented toward petroleum industry]

Armstrong, J.M., W. Korreck, L.E. Leach, R.M. Powell, S.V. Vandegrift, and J.T. Wilson. 1988. Bioremediation of a Fuel Spill: Evaluation of Techniques for Preliminary Site Characterization. In: Proc. (5th) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 931-948. [Wireline sampling]

Arthur, J.R.F. and S.J. Shamash. 1970. Sampling of Cohesionless Soils Without Disturbing the Particle Packing. Geotechnique 20(4):439-440.

Australian Drilling Association. 1992. Australian Drillers Manual. Available from S.A. Smith Consulting Service, P.O. Box, Ada, OH 45810, 550+ pp. [Goetechnical, environmental, well drilling]

Baker, J.A., T.J. Holdredge, D.J. Buck, and E.J. Hubbard. 1987. Use of ODEX Drilling System for Monitoring Well Installation in Aquifer Containing Glacial Boulders. In: 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 363-372.

Baroid Division. 1954. Baroid Drilling Mud Data Book. Baroid Division, National Lead Corporation, 471 pp.

Baroid Division. 1966. What's New with Mud? Baroid Division Special Report, National Lead Corporation, 35 pp. (Updates Baroid Division, 1954.)

Barrett, J. et al. 1980. Procedures Recommended for Overburden and Hydrologic Studies of Surface Mines. GTR-INT-71. U.S. Department of Agriculture Forest Service, Intermountain Forest and Experiment Station, Ogden, UT, 106 pp.

Barth, D.S. and T.H. Starks. 1985. Sediment Sampling Quality Assurance User's Guide. EPA/600/4-85/048 (NTIS PB85-233542).

Barth, D.S., B.J. Mason, T.H. Starks, and K.W. Brown. 1989. Soil Sampling Quality Assurance User's Guide, 2nd ed. EPA/600/8-89/046 (NTIS PB89-189864), 225+ pp.

Bartlett, R. and B. James. 1980. Studying Dried, Stored Soil Samples--Some Pitfalls. Soil Sci. Soc. Am. J. 47:721-724.

Barton, C.M. 1974. Bore Hole Sampling of Saturated Uncemented Sands and Gravels. Ground Water 12(3):170-181.

Bates, Jr., R.E. 1965. Economics of Percussion vs. Air Rotary Drilling. World Oil (February):51-59.

Begemann, H.K.S. 1974. The Delft Continuous Soil Sampler. Bull. Int. Ass. Eng. Geol. 10:35-37.

Bennett, D.B., M. Busacca, and E.E. Clark. 1988. The Modified Reverse-Circulation Air Rotary Drilling Technique for Development of Observation and Monitoring Wells at Ground-Water Contamination Sites. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 137-145.

Bishop, A.W. 1948. A New Sampling Tool for Cohesionless Sands Below Ground Water Level. Geotechnique 1:125-131.

Blevins, R.L., G.M. Aubertin, and N. Holowaychuk. 1968. A Technique for Obtaining Undisturbed Soil Samples by Freezing In-Situ. Soil Sci. Soc. Am. Proc. 32:741-742.

Bondurant, J.A., R.V. Worstell, and C.E. Brockway. 1969. Plastic Casings for Soil Cores. Soil Science 107:70-71.

Bonham, C.F. 1955. Engineering Analysis of Cable Tool Drilling. Petrol. Eng. (December):B-93 to B-100.

Boulding, J.R.. 1991. Description and Sampling of Contaminated Soils: A Field Pocket Guide. EPA/625/12-91/002, 122 pp. Available from CERI.*

Bowman, I. 1911. Well Drilling Methods. U.S. Geological Survey Water Supply Paper 257, 139 pp. [Cable tool, hydraulic rotary, jetting, diamond core]

Boyle, D.R. 1992. A Multilevel Ground Water Monitoring System for Casing Advance and Bedrock Drilling Methods. Ground Water Monitoring Review 12(2):105-115.

Brantley, J.E. 1961. Rotary Drilling Handbook, 6th edition. Palmer Publications, Fort Lee, NJ, 825 pp.

Breckenridge, R.P., J.R. Williams, and J.F. Keck. 1991. Characterizing Soils for Hazardous Waste Site Assessments. Superfund Ground-Water Issue Paper. EPA/600/8-91/008. Environmental Monitoring Systems Laboratory, Las Vegas, NV, 89193-3478, 16 pp.

Brobst, R.B. and M. Buszka. 1986. The Effects of Three Drilling Fluids on Groundwater Sample Chemistry. Ground Water Monitoring Review 6(1):62-70.

Broms, B.B. 1980. Soil Sampling in Europe: State-of-the-Art. J. Geotechnical Engineering Division (ASCE) 106(GT1):65-98. [Focus on engineering applications]

Brown, K.W. 1986. Efficiency of Soil Core and Soil-Pore Water Sampling Systems. EPA/600/2-86/083 (NTIS PB87-106100).

Brown, G.R. and J.F. Thilenius. 1977. A Tool and Method for Extracting Plant-Root-Soil Cores on Remote Sites. J. Range Management 30:72-74.

Brown, K.W., R.P. Breckenridge, and R.C. Rope. 1991. Soil Sampling Reference Field Methods. In: U.S. Fish and Wildlife Service Lands Contaminant Monitoring Operations Manual, Appendix J. Prepared by Center for Environmental Monitoring and Assessment, Idaho National Engineering Laboratory, Idaho Falls, ID. (Final publication pending revisions resulting for field testing of manual.)

Buchele, W.F. 1961. A Power Sampler of Undisturbed Soils. Trans Am. Soc. Agric. Eng. 4(2):185-187.

Buchter, B., J. Leuenberger, P.J. Wierenga, and F. Richard. 1984. Preparation of Large Core Samples from Stony Soils. Soil Sci. Soc. Am J. 48:1460-1462.

Bureau of Reclamation. 1974. Earth Manual, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

(First 3 chapters reprinted in 1990, 326 pp.; remaining chapters superseded by 1990 3rd edition.)

Bureau of Reclamation. 1981. Ground Water Manual--A Water Resources Technical Publication, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 480 pp.

Bureau of Reclamation. 1990. Earth Manual, 3rd ed, Part 2. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 1270 pp. (Part 1 consists of a 1990 reprint of the first 3 chapters of the 1974 2nd edition.)

Busche, F.D. and D.S. Burden. 1991. Sampling of Contaminated Sites. Hazardous Material Control 4(3):35-40.

Byrnes, B.H. 1975. A Hydraulically Driven Soil Auger for Sampling Fine-Textured and Wet Soils. Soil Sci. Soc. Am. Proc. 39:156.

Cameron, R.E. 1991. Guide To Site and Soil Description for Hazardous Waste Sites, Volume 1: Metals. EPA/600/4-91/029 (NTIS PB92-146158).

Cameron, R.E., G.B. Blank, and D.R. Gensel. 1966. Sampling and Handling of Desert Soils. NASA Technical Report No. 32-908. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 37 pp.

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill, New York, NY, 681 pp. [Annotated bibliography contains 673 references]

Campbell, D.J. and M.F. O'Sullivan. 1991. The Cone Penetrometer in Relation to Trafficability, Compaction, and Tillage. In: Soil Analysis: Physical Methods, K.A. Smith and C.E. Mullins (eds.), Marcel Dekker, New York, NY, pp. 399-429.

Carlson, C.W. 1943. Early History of Water Well Drilling in the United States. Economic Geology 38(3):119-136.

Casagrande, A. 1948. Classification and Identification of Soils. Trans. ASCE 113(2351):901-992.

Chiang, C.Y., C.C. Stanley, L. Hekma, and G.F. Boehm. 1989a. Characterization of Ground Water and Soil Conditions by Cone Penetrometry. In: Proc. (6th) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 141-157.

Chiang, C.Y., K.R. Loos, R.A. Klopp, and M.C. Beltz. 1989b. A Real-Time Determination of Geological/Chemical Properties of an Aquifer by Penetration Testing. In: Proc. (6th) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 175-189.

Chiang, C.Y., K.R. Loos, and R.A. Klopp. 1992. Field Determination of Geological/Chemical Properties of an Aquifer by Cone Penetrometry and Headspace Analysis. Ground Water 30:428-436.

Chong, S.K., M.A. Khan, and R.E. Green. 1982. Portable Hand-Operated Soil Core Sampler. Soil Sci. Soc. Am. J. 46:433-434.

Christensen Diamond. 1970. Diamond Drilling Handbook. Christensen Diamond Products Co., Salt Lake City, UT.

Christy, T.M. and S.C. Spradlin. 1992. The Use of Small Diameter Probing Equipment for Contaminated Site Investigations. Ground Water Management 11:87-101 (6th NOAC). [Geoprobe, soil vapor, solids, ground-water sampling]

Clark, R.R. 1988. A New Continuous-Sampling Wireline System for Acquisition of Uncontaminated, Minimally Disturbed Cores. Ground Water Monitoring Review 8(4):66-72.

Cooper, L.W., R.A. Hook, and B.E. Payne. 1977. Air Drilling Techniques. Am. Inst. Mining, Metall. Eng. Paper No. SPE 6435. AIMME, Dallas, TX, 16 pp.

Cooper, S.S., P.G. Malone, R.S. Olsen, and G.B. Morhman. 1988a. Use of an Instrumented Cone Penetrometer in Monitoring Land Disposal Sites. In: HWHM '88 (Proc. 5th Nat. Conf. on Hazardous Wastes and Hazardous Materials), Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 424-427.

Cooper, S.S., P.G. Malone, R.S. Olsen, and D.H. Douglas. 1988b. Development of a Computerized Penetrometer System for Hazardous Waste Site Soils Investigations. Report No. AMXTH-TR-TE-88242, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, 58 pp.

Corps of Engineers. 1972. Soil Sampling. EM 1110-2-1907. COE, Department of the Army, Washington, DC.

Cumming, J.D. and A.P. Wickland. 1965. Diamond Drill Handbook. J.K. Smith and Sons, Diamond Products, Ltd., Toronto, 547 pp.

Darmody, R.G., M.C. Rabenhorst, and J.E. Foss. 1976. Bucket Auger Modification for Tidal Marsh Soil Sampling. Soil Sci. Soc. Am. J. 40:321-322.

Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogeology. John Wiley & Sons, New York, NY.

Davis, H.E., J. Jehn, and S. Smith. 1991. Monitoring Well Drilling, Soil Sampling, Rock Coring, and Borehole Logging. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 195-237.

Decker, M.G. 1968. Cable Tool Fishing. Water Well Journal Publishing Co., Columbus, OH, 70 pp.

deVera, E.R. 1980. Samplers and Sampling Procedures for Hazardous Waste Streams. EPA/600/2-80/018 (NTIS PB80-135353).

Devinny, J.S., L.G. Everett, J.C.S. Lu, and R.L. Stollar. 1990. Subsurface Migration of Hazardous Wastes. Van Nostrand Reinhold, New York, NY. [Chapter 7-Soil Core Monitoring]

Diamond Core Drill Manufacturers Association (DCDMA). 1991. DCDMA Technical Manual. DCDMA, Columbia, SC.

Dickinson, W., R.W. Dickinson, P.A. Mote, and J.S. Nelson. 1987. Horizontal Radials for Geophysics and Hazardous Waste Remediation. In: Superfund '87 (Proc. 8th Annual Conf.), Hazardous Material Control Research Institute, Silver Spring, MD, pp. 371-375.

Dreeszen, V.H. 1959. Rotary Drilling Muds. Water Well Journal 13(9):18-19, 26, 29-30.

Driscoll, F.G. 1986. Groundwater and Wells, 2nd ed. Johnson Filtration Systems, Inc., St. Paul, MN, 1089 pp.

Dunham, R.J. 1962. Classification of Carbonate Rocks According to Depositional Texture. In: Classification of Carbonate Rocks, W.E. Ham (ed.), Am. Ass. Pet. Geol. Memoir 1, pp. 108-121.

Durnford, D., J. Brookman, J. Billica, and J. Milligan. 1991. LNAPL Distribution in Cohesionless Soil: A Field Investigation and Cryogenic Sampler. Ground Water Monitoring Review 11(3):115-122.

Dustman, J., R. Davis, and T. Oothoudt. 1992. Soil, Bedrock and Groundwater Sampling Using Rotasonic Drilling Techniques. Ground Water Management 11:179-187 (6th NOAC). [Vibratory drilling/sampling]

Economy, K. and R.S. Bowman. 1993. Fiberglass Encasement Method for Undisturbed Soil Cores. Soil Sci. Soc. Am. J. 57:39-41.

Edwards, T.K. and G.D. Glysson. 1988. Methods for Measurements of Fluvial Sediment. U.S. Geological Survey Open File Report 86-531, 118 pp.

Ehrenzeller, J.L., F.G. Baker, and V.E. Keys. 1991. Using the Cone Penetrometer and Hydropunch Method to Collect Reconnaissance Ground Water Samples. Ground Water Management 5:733-746 (5th NOAC).

Emerson, W.W. 1967. A Classification of Soil Aggregates Based on Their Cohesion in Water. Australian J. of Soil Research 2:211-217.

Ericsen, W.A., J.E. Brinkman, and P.S. Dar. 1985. Types and Uses of Drilling Fluids Utilized to Install Monitoring Wells Associated with Metals and Radionuclide Ground Water Studies. Ground Water Monitoring Review 5(1):30-33.

Everett, L.G., K.D. Schmidt, R.M. Tinlin, and D.K. Todd. 1976. Monitoring Groundwater Quality: Methods and Costs. EPA/600/4-76/023 (NTIS PB257 133).

Fenn, D., E. Cocozza, J. Isbister, O. Braids, B. Yare, and P. Roux. 1977. Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities. EPA/SW-611 (NTIS PB84-174820).

Fleischauer, H.L. 1985. Procedures for Sampling Radium-Contaminated Soils. GJ/TMC-13 (NTIS DE86-006185). U.S. Department of Energy Technical Measurements Center, Grand Junction, CO.

Fleischauer, H.L. and P.R. Engelder. 1985. Procedures for Reconnaissance Stream-Sediment Sampling. GJ/TMC-14 (NTIS DE85-009789). Department of Energy Technical Measurements Center, Grand Junction, CO.

Folk, R.L. and W.C. Ward. 1957. Brazos River Bar: A Study in the Significance of Grain-Size Parameters. J. Sed. Pet. 27:3-27.

Ford, P.J., P.J. Turina, and D.E. Seely. 1984. Characterization of Hazardous Waste Sites--A Methods Manual, Vol. II: Available Sampling Methods, 2nd ed. EPA/600/4-84/076 (NTIS PB85-521596).

Fritton, D.D. 1990. A Standard for Interpreting Soil Penetrometer Measurements. Soil Science 150:542-551.

Gaitlin, C.G. 1960. Petroleum Engineering, Drilling and Well Completions. Prentice-Hall, Engelwood Cliffs, NJ, 341 pp.

Geeting, M.D. 1990. Maintaining Displacement Integrity as an Installation Procedure. In: Ground Water Management 2:165-175 (4th NOAC).

GeoTrans. 1989. Groundwater Monitoring Manual for the Electric Utility Industry. Edison Electric Institute, Washington, DC.

Gibson, U.P. and R.D. Singer. 1969. Small Wells Manual. U.S. Agency for International Development, Washington, DC.

Gibson, U.P. and R.D. Singer. 1971. Water Well Manual. Premier Press, 156 pp. (Reprint of Gibson and Singer [1969].)

Gillespie, D. and R.G. Campanella. 1981. Consolidation Characteristics from Pore Pressure Dissipation After Piezometer Cone Penetration. Soil Mechanics Series No. 47, Dept. of Civil Engineering, The Univ. of British Columbia, Vancouver, Canada.

Gillham, R.W., M.J.L. Robin, J.F. Barker, and J.A. Cherry. 1983. Groundwater Monitoring and Sample Bias. API Publication 4367. American Petroleum Institute, Washington, DC, 206 pp.

Godsey, K.D. 1993. The (Sonic) Wave of the Future. Water Well Journal 47(5):86-90.

Goodwin, B.E., J.R. Aronson, R.P. O'Neil, M.A. Randel, and E.M. Smith. 1982. Surface Sample Techniques. USATHAMA DRXTH-TE-CR-82179. U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, 91 pp. [Includes annotated bibliography with 47 citations]

Gordon, R.W. 1958. Water Well Drilling with Cable Tools. Bucyrus-Erie Co., S. Milwaukee, WI, 230 pp.

Graham, D.L. and V.G. Johnson. 1991. Effects of Fluid Rotary Drilling on Hydrochemical Sampling Results from Deep Boreholes in Fractured Columbia River Basalt. J. Hydrology 128:171-212.

Graham, D.L., R.W. Bryce, and D.J. Halko. 1985. A Field Test to Assess the Effects of Drilling Fluids on Groundwater Chemistry Collected from Columbia River Basalts. In: Proc. Int. Ass. Hydrogeologists 17th Int. Congress, Hydrogeology of Rocks of Low Permeability (Tucson, AZ), pp. 383-394.

Gray, E.R. 1972. Drilling with Mud: Simple Tests Save Time and Money. Water Well Journal 26(3):33-35.

Gray, G.R. and H.C.H. Darley. 1981. Composition and Properties of Oil Well Drilling Fluids, 2nd ed. Gulf Publishing Co., Houston, TX, 630 pp.

Grichor, C. 1983. The Mechanical Treatment of Solids in Drilling Fluids. Water Well Journal 37(11):46-54.

Hackett, G. 1987. Drilling and Constructing Monitoring Wells with Hollow Stem Auger: Part 1. Ground Water Monitoring Review 7(4):51-62.

Hackett, G. 1988. Drilling and Constructing Monitoring Wells with Hollow-Stem Augers: Part 2. Monitoring Well Installation. Ground Water Monitoring Review 8(1)60-68.

Hayden, C.W. and W.H. Heinemann, Jr. 1968. A Hand-Operated Undisturbed Core Sampler. Soil Science 106:153-156.

Hayden, C.W. and C.W. Robbins. 1975. Mechanical Snake River Undisturbed Soil Core Sampler. Soil Science 120(2):153-155.

Heinz, W.F. 1985. Diamond Drilling Handbook. South African Drilling Association, Johannesburg.

Hendrickx, J.M.H., C.J. Ritsema, O.H. Boersma, L.W. Dekker, W. Homminga, and J.W.H. van der Kolk. 1991. Motor-Driven Portable Soil Core Sampler for Volumetric Sampling. Soil Sci. Soc. Am. J. 55:1792-1795.

Herzog, B., J. Pennino, and G. Nielsen. 1991. Ground-Water Sampling. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 449-499.

Hindall, S.M. and M. Eberle. 1989. National and Regional Trends in Water-Well Drilling in the United States, 1964-84. U.S. Geological Survey Circular 1029, 15 pp.

Hipp, B., C.J. Gerard, and B. Edwards. 1968. A Machine for Taking Soil Samples and Placing Access Tubes for Soil Moisture and Density Measurements. Soil Sci. Soc. Am. Proc. 32:886-887.

Hix, G.L. 1991. Casing Advancement Methods for Drilling Monitoring Wells. Water Well Journal 45(5):60-64.

Hix, G. 1992. Squeaky Clean Drill Rigs. Ground Water Monitoring Review 12(3):94-97.

Hodges, R.E. and W.E. Teasdale. 1991. Considerations Related to Drilling Methods in Planning and Performing Borehole-Geophysical Logging for Ground-Water Studies. U.S. Geological Survey Water Resource Investigations Report 91-409 (NTIS PB92-155688), 22 pp. [Auger, air and mud rotary drilling]

Hodgson, J.M. 1978. Monograph on Soil Survey, Soil Sampling and Soil Description. Oxford University Press, New York, NY, 241 pp.

Holsten, D.B. and J. Morgan. 1989. The Dual-Tube Air Percussion Drilling Method for Installation of Ground Water Monitoring Wells. In: 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1-14.

Holtzclaw, K.M., J.M. Rible, and P.F. Pratt. 1975. Bulk Density Sampler for Deep Profiles. Soil Sci. Soc. Am. Proc. 39:1220-1223.

Hooper, W.F. and J.W. Earley. 1961. Compositional Logging of Air-Drilled Wells. Am. Ass. Petrol. Geol. Bull. 45(11):1870-1883.

Hughes Tool. 1966. Rotary Drilling Bits. Hughes Tool Co., Houston, TX, 31 pp.

Huntoon-Pencak, L. 1989. Auger Drilling for Monitoring Wells. Ground Water Age 24(1).

Hvorslev, M.J. 1948. Subsurface Exploration and Sampling of Soils. Engineering Foundation, New York, NY.

Hvorslev, J.J. 1949. Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS (Reprinted by the Engineering Foundation in 1962 and 1965.)

Imco Services. 1975. Applied Mud Technology. Imco Services Division of Halliburton Co., Houston, TX.

Ingersoll-Rand. 1985. Drilling Terminology. Ingersoll-Rand, Rotary Drill Division, Garland, TX, 125 pp.

International Society of Soil Mechanics and Foundation Engineers (ISSMFE). Various Dates. 5th International Conference (Paris, 1961); Seventh International Conference (Mexico City, 1969); Fourth Asian Conference (Bangkok, 1971); Tenth International Conference (Rotterdam, 1981). [Proceedings contain papers given at special sessions on soil sampling]

Irani, R.R. and C.F. Callis. 1963. Particle Size: Measurement, Interpretation, and Applications. John Wiley & Sons, New York, NY.

Jackson, J., N. Thomey, and L.F. Dietlein. 1991. Degradation of Hydrocarbons in Soils Samples Analyzed Within Accepted Analytical Holding Times. Ground Water Management 5:567-576 (5th NOAC).

Jamison, V.C., H.A. Weaver, and I.F. Reed. 1950. A Hammer-Driven Soil Core Sampler. Soil Science 69:487-496.

Johnson UOP. 1967. Taking Representative Formation Samples. Bulletin 638-S. Johnson UOP, St. Paul, MN.

Kaback, D.S., B.B. Looney, J.C. Corey, L.M. Wright, III, and J.L. Steele. 1989. Horizontal Wells for In-Situ Remediation of Groundwater and Soils. In: Proc. Third Nat. Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 121-135.

Kaback, D.S., B.B. Looney, C.A. Eddy, and T.C. Hazen. 1991. Innovative Groundwater and Soil Remediation: In Situ Air Stripping Using Horizontal Wells. Ground Water Management 5:47-58 (5th NOAC).

Karlsson, H. and R. Bitto. 1990. New Horizontal Wellbore System for Monitor and Remedial Wells. In: Superfund '90, Hazardous

Waste Materials Control Research Institute, Silver Spring, MD, pp. 357-362.

Kaufman, R.F., T.A. Gleason, R.B. Ellwood, and G.P. Lindsey. 1981. Ground-Water Monitoring Techniques for Arid Zone Hazardous Waste Disposal Sites. Ground Water Monitoring Review 1(3):47-54. [Air and mud rotary]

Kelley, O.J., J.A. Hardman, and D.S. Jennings. 1947. A Soil Sampling Machine for Obtaining Two-, Three-, and Four-Inch Diameter Cores of Undisturbed Soils at a Depth of Six Feet. Soil Sci. Soc. Am. Proc. 12:85-87.

Klopp, R.A., A. M. Petsonk, and B.-A. Torstensson. 1989. In-Situ Penetration Testing for Delineation of Ground Water Contaminant Plumes. In: 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 329-343.

Kluitenberg, G.J., J.R. Bilskie, and R. Horton. 1991. Rubberized Asphalt for Sealing Cores of Shrinking Soils. Soil Sci. Soc. Am. J. 55:105-1507.

Kostecki, P.T. and E.J. Calabrese. 1990. CHESS-A National Coalition to Standardize Approaches to Contaminated Soil Problems. In: Proc. 14th Annual Army Environmental R&D Symp. (1989), CETHA-TE-TR-90055, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 249-264.

Kresse, F.C. 1985. Exploration for Ground-Water Contamination. Bull. Ass. Eng. Geol. 22:275-280. [Hollow-stem auger]

Langseth, D.E. 1990. Hydraulic Performance of Horizontal Wells. In: Superfund '90, Hazardous Waste Materials Control Research Institute, Silver Spring, MD, pp. 398-408.

LaRochelle, P., et al. 1981. Causes of Sampling Disturbance and Design of a New Sampler for Sensitive Soils. Canadian Geotechnical J. 18(1):52-66.

Leach, L.L. and D.C. Draper. 1991. Advances in Hazardous Waste Site Alluvial Sampling. In: Proceedings: Design and Construction Issues at Hazardous Waste Sites, EPA/600/D-91/214 (NTIS PB91-233320), pp. 681-700.

Leach, L.E. and R.R. Ross. 1991. Aseptic Sampling of Unconsolidated Heaving Soils in Saturated Zones. In: Groundwater Residue Sampling, R.G. Nash and A.R. Leslie (eds.), ACS Symp. Series 465, American Chemical Society, Washington, DC.

Leach, L.W., F.P. Beck, J.T. Wilson, and D.H. Kampbell. 1988. Aseptic Subsurface Sampling Techniques for Hollow-Stem Auger Drilling. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 31-51.

Lehr, J., S. Hurlburt, B. Gallagher, and J. Voyteck. 1988. Design and Construction of Water Wells: A Guide for Engineers. Van Nostrand Reinhold, New York, NY, 224 pp.

Lewis, T.E., B. Blasdell, and L.J. Blume. 1990. Collection of Intact Cores from a Rocky Desert and a Glacial Till Soil. Soil Sci. Soc. Am. J. 54:938-940.

Lithland, S.T., T.W. Hoskins, and R.L. Boggess. 1985. A New Ground-Water Survey Tool: The Combined Cone Penetrometer/Vadose Zone Vapor Probe. In: Proc. (2nd) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Groundwater--Prevention, Detection, and Restoration, National Water Well Association, Dublin, OH, pp. 322-330.

Lolcama, J.L. 1988. Reconciliation of Hydrochemistry of Ground Water Affected by Drilling and Sampling in Deep Boreholes. In: Proc. of the Groundwater Geochemistry Conference, National Water Well Association, Dublin, OH, pp. 405-426.

Losonsky, G., G.E. Jacques, and M.S. Beljin. 1992. Ground Water Monitoring with Horizontal Wells. Ground Water Management 11:189-204 (6th NOAC).

Luhdorff, Jr., E.E. and J.C. Scalmanini. 1982. Selection of Drilling Method, Well Design and Sampling Equipment for Wells to Monitor Organic Contamination. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 359-365.

Lutz, J.F., 1947. Apparatus for Collecting Undisturbed Soil Samples. Soil Science 64:399-401.

Magcobar. 1977. Drilling Fluid Engineering Manual. Magcobar Division, Dresser Industries, Inc., Houston, TX.

Maher, J.C. 1963. Logging Drill Cuttings. Oklahoma Geological Survey Guide Book XIV, 2nd edition, 48 pp.

Marcuson, III, W.F. and A.G. Franklin. 1980. State-of-the-Art of Undisturbed Sampling of Cohesionless Soils. Geotechnical Engineering 11:31-53.

Mason, B.J. 1992. Preparation of Soil Sampling Protocols: Sampling Techniques and Strategies. EPA/600/R-92/128 (NTIS PB92-220532). (Supersedes 1983 edition titled, Preparation of Soil Sampling Protocol: Techniques and Strategies, EPA/600/4-03/020 [NTIS PB83-206979], 102 pp.)

Mason, K.L. and S.T. Woolley. 1981. How to Air Drill--From Compressor to Blooey Line: Part I. Petroleum Engineer International v. 40, March, pp. 53.

Massarenti, M. 1964. Percussion-Reverse Circulation Water Well Drilling System Designed and Developed in Italy. Ground Water 2(2):25-27.

Matlock, W.G. 1970. Small Diameter Wells Drilled by Jet Percussion Method. Ground Water 8(1):6-9.

McCray, A.W. and F.W. Cole. 1958. Oil Well Drilling Technology. University of Oklahoma Press, Norman, OK, 492 pp.

McEllhiney, W.A. 1960. Application of Rotary Drilling to Water Wells. Am. Water Works Ass. J. 52(3):351-355.

McElwee, C.D., J.J. Butler, Jr., and J.M. Healy. 1991. A New Sampling System for Obtaining Relatively Undisturbed Samples of Unconsolidated Coarse Sand and Gravel. Ground Water Monitoring Review 11(3):182-191.

McIlvride, W.A. and R.B. Weiss. 1988. Drilling Method Effects on Well Performance. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 277-287.

McKeague, J.A. (ed.). 1978. Manual on Soil Sampling and Methods of Analysis, 2nd edition. Canadian Society Soil Science, Ottawa.

Metcalf & Eddy. 1991. Handbook: Stabilization Technologies for RCRA Corrective Actions. EPA/625/6-91/026, 62 pp. Available from CERI.*

Meyer, G. and G.G. Wyrick. 1966. Regional Trends in Water Well Drilling in the United States. U.S. Geological Survey Circular 533, 8 pp.

Mickelson, R.H., L.C. Benz, C.W. Carlson, and F.M. Sandoval. 1961. Jetting Equipment and Techniques in a Drainage and Salinity Study. Trans. Am. Soc. Agric. Eng. 4:222-228.

Mielke, L.N. 1973. Encasing Undisturbed Soil Cores in Plastic. Soil Sci. Soc. Am. Proc. 37:325-326.

Mielke, L.N. and W.W. Wilhelm. 1983. Mast Anchor for Hydraulic Soil Sampling Machines. Soil Sci. Soc. Am. J. 47:1263-1264.

Miller, M.S. and R.G. Hornsby. 1991. Zero Air Emission and Zero Drilling Waste Landfill Leachate Collection Well Installation Method. Ground Water Management 8:631-648 (8th NWWA/API Conf.). [Driven wells]

Millison, D., T. Eckard, J. Muller, and E. Vander Velde. 1989. Use of a Continuous Sampling Wireline System and Telescopic Casing to Optimize Well Construction and Prevent Cross-Contamination in Deep Monitor Well Installations. In: 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 273-287.

Mooij, H. and F.A. Roovers. 1978. Recommended Ground Water and Soil Sampling Procedures. Report EPA-4-EC-76-7. Environment Canada Solid Waste Management Bureau.

Moore, P.L. 1974. Drilling Practice Manual. The Petroleum Publishing Co., Tulsa, OK, 448 pp.

Morgan, J.H. 1992. Horizontal Drilling Applications of Petroleum Technologies for Environmental Purposes. Ground Water Monitoring Review 12(3):98-102

Mori, H. (ed.). 1979. State of the Art on Current Practice of Soil Sampling. Proceedings of the International Symposium of Soil Sampling, Int. Soc. Soil Mech. and Foundation Engineering, New York, NY.

Moulder, E.A. and M.L. Klug. 1963. Jetting Method of Installing Small-Diameter Wells. In: U.S. Geological Survey Water-Supply Paper 1544-H, pp. H14-H30.

Mroz, G.D. and D.D. Reed. 1991. Forest Soil Sampling Efficiency: Matching Laboratory Analyses and Field Sampling Procedures. Soil Sci. Soc. Am. J. 55:1413-1416. [Optimization of sample compositing]

Mullins, C.E. and B.J. Hutchison. 1982. The Variability Introduced by Various Subsampling Techniques. J. Soil Science 33:547-561.

Munch, J.H. and R.W.D. Killey. 1985. Equipment and Methodology for Sampling and Testing Cohesionless Sediments. Ground Water Monitoring Review 5(1):38-42.

Murphy, Jr., J. 1991. Application of ODEX/TUBEX Drilling Method in a Variably Fractured Volcanic/Igneous Environment. Ground Water Management 5:799-814 (5th NOAC).

Murphy, J.B., E.H. Grissinger, and W.C. Little. 1981. Fiberglass Encasement of Large, Undisturbed, Weakly Cohesive Soil Samples. Soil Science 131:130-134.

Myers, R.G., C.W. Swallow, and D.E. Kissel. 1989. A Method to Secure, Leach and Incubate Undisturbed Soil Cores. Soil Sci. Soc. Am. J. 53:467-471.

Nevo, Z. and J. Hagin. 1966. Changes Occurring in Soil Samples During Air-Dry Storage. Soil Science 102:157-160.

Nickens, D.A., M.S. Turner, and M.T. Morrow. 1988. Characterization of Groundwater Contamination by Direct Sampling Through Hollow Stem Augers. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 255-276.

Nielsen, D.M. 1991. An Update on ASTM Subcommittee on Ground Water and Vadose Zone Investigations. Ground Water Monitoring Review 11(3):92-96.

Olsen, R.S. and J.V. Farr. 1986. Site Characterization Using the Cone Penetrometer Test. In: Proc. of the ASCE Conf. on Use of In-Situ Testing in Geotechnical Engineering, American Society of Civil Engineer, New York, NY.

Ostendorf, D.W., L. Leach, E.S. Henlein, and Y. Xie. 1991. Field Sampling of Residual Aviation Gasoline in Sandy Soil. Ground Water Monitoring Review 11(2):107-120.

Palmer, M. 1985. Methods Manual for Bottom Sediment Sample Collection. EPA/905/4-85/004 (NTIS PB86-107414), 52 pp.

Parolini, J.R., V.G. King, T.W. Nail, and T.E. Lewis. 1991. The Investigation of Soil Sampling Devices and Shipping and Holding Time Effects on Soil Volatile Organic Compounds. In: 2nd Int. Symp. Field Screening Methods for Hazardous Wastes and Toxic Chemicals. EPA/600/9-91/028 (NTIS PB92-125764), pp. 725-728.

Parsons, P.J. 1961. Multiple Soil Sampler. J. Soil Mech. Div. (ASCE) 87(SMG):19-27.

Paules II, M.S., J.F. Mednick, and D.E. Callahan. 1990. Installation of Large Diameter Recovery Wells Utilizing Triple-Wall Percussion Hammer Drilling. Ground Water Management 4:491-505 (7th NWWA/API Conf.).

Perry, C.A. and R.J. Hart. 1985. Installation of Observation Wells on Hazardous Waste Sites in Kansas Using a Hollow-Stem Auger. Ground Water Monitoring Review 5(4):70-73.

Petroleum Extension Service. Various Dates. Lessons in Rotary Drilling--Unit I, Lesson 2: The Bit (1966, 50 pp.); Unit I, Lesson 3: The Drill String (1965, 58 pp.); Unit II, Lesson 1: Making Hole (1968, 55 pp.); Unit II, Lesson 2: Drilling Mud (1968, 48 pp.); Unit II, Lesson 4: Casing and Cementing (1968, 81 pp.); Unit II, Lesson 5: Testing and Completing (1968, 64 pp.). University of Texas, Austin, TX.

Petroleum Extension Service. 1969. Principles of Drilling Fluid Control. University of Texas, Austin, TX, 215 pp.

Petsonk, A.M. 1985. A Device for In Situ Measurement of Hydraulic Conductivity. Presented at the American Geophysical Union Symposium on Advance in Hydraulic Testing and Tracers Methods (San Francisco, December 10, 1985). (Cited in Sai and Anderson [1991].)

Pettijohn, F.J., P.E. Potter, and R. Siever. 1972. Sand and Sandstone. Springer-Verlag, New York, NY, 618 pp.

Pikul Jr., J.L., R.R. Allmaras, and G.E. Fischbacher. 1979. Incremental Sampler for Use in Summer-Fallowed Soils. Soil Sci. Soc. Am. J. 43:425-552.

Plumb, Jr., R.H. 1981. Procedures for Handling and Chemical Analysis of Sediment and Water Samples. Technical Report EPA/CE-81-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 71 pp.

Potter, P.E., J.B. Maynard, and W.A. Pryor. 1980. Sedimentology of Shale. Springer-Verlag, New York, NY, 306 pp.

Propkopovich, N.P. 1977. Discussion: The Unified Soil Classification System. Ass. Eng. Geol. Bull. 14(3):183-185.

Qian, P. and J.D. Wolt. 1990. Effects of Drying and Time of Incubation on the Composition of Displace Soil Solution. Soil Science 149(6):367-374.

Raab, G.A., M.H. Bartling, M.A. Stapanian, W.H. Cole, III, R.L. Tidwell, and K.A. Cappo. 1991. The Homogenization of Environmental Soil Samples in Bulk. In: Hazardous Waste Measurements, M.S. Simmons (ed.), Lewis Publishers, Chelsea, MI, pp. 35-51.

Rehm, B.W., T.R. Stolzenburg, D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA.

Rhotan, F.E. and D.S. McChesney. 1991. System for Collecting Undisturbed Cores from Surface Soils for Micromorphological Analysis. Soil Sci. Soc. Am. J. 55:1796-1797.

Riddle, J. and R.J. Johnson. 1991. Dual Tube, Reverse Circulation Drilling: Effective Exploration of Ground Water Conditions. Ground Water Management 5:787-798 (5th NOAC).

Riggs, C. 1983. Continuous Soil Sampling in the Vadose Zone. In: Proc. NWWA/EPA Conf. on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Dublin, OH, pp. 611-622.

Robertson, P.K. and R.G. Campenalla. 1986. Guidelines for Use, Interpretation and Application of CPT and CPTU. Hogentogler and Company, Inc., Gaithersburg, MD.

Robertson, W.K., P.E. Poper, and R.T. Tomlinson. 1974. Sampling Tool for Taking Undisturbed Soil Cores. Soil Sci. Soc. Am. Proc. 38:855-857.

Robertson, P.K., R.G. Campanella, D. Gillespie, and J. Grieg. 1986. Use of Piezometer Cone Data. In: Proc. of In-Situ '86, ASCE Specialty Conf. (Blacksburg, VA), American Society of Civil Engineers, New York, NY.

Rogers, W.F. 1963. Composition and Properties of Oil Well Drilling Fluids, 3rd edition. Gulf Publishing Co., Houston, TX, 878 pp.

Rogers, J.S. and C.E. Carter. 1987. Soil Core Sampling for Hydraulic Conductivity and Bulk Density. Soil Sci. Soc. Am. J. 51:1393-1394.

Ruark, G.A. 1985. A Refined Soil Coring System. Soil Sci. Soc. Am. J. 49:278-281.

Ruda, T.C. and P.J. Bosscher (eds.). 1990. Drillers Handbook. National Drilling Contractors Association, Columbia, SC.

Russell, B.F., J.M. Hubbell, and S.C. Minkin. 1989. Drilling and Sampling Procedures to Minimize Borehole Cross-Contamination. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 81-93. [Air and mud rotary]

Sai, J.O. and D.C. Anderson. 1991. State-of-the-Art Field Hydraulic Conductivity Testing of Compacted Soils. EPA/600/2-91/022 (NTIS PB91-206243), 95 pp. [Cone penetration porous probes]

Saines, M., A.I. Strutynsky, and G. Lytwynshyn. 1989. Use of Piezometric Cone Penetration Testing in Hydrogeologic Investigations. In: Proc. 1st USA/USSR Hydrogeology Conference, National Water Well Association, Dublin, OH.

Sale, T.C. and S.E. Rhoades. 1987. Installation of Monitoring Wells Using the Dual Wall Hammer Drilling Technique. In: Superfund '87 (Proc. of the 8th National Conference), Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 358-361.

Sanderson Cyclone. 1966. Cable Tool Drilling Manual. Sanderson Cyclone Drill Co., Orrville, OH, 50 pp.

Sangerlat, G. 1972. The Penetrometer and Soil Exploration. Elsevier, New York, NY.

Scalf, M.R., J.F. McNabb, W.J. Dunlap, R.L. Cosby, and J. Fryberger. 1981. Manual of Ground-Water Quality Sampling Procedures. EPA/600/2-81/160, (NTIS PB82-103045). Also published in NWWA/EPA Series, National Water Well Association, Dublin OH.

Schalla, R. 1986. A Comparison of the Effects of Rotary Wash and Air Rotary Drilling Techniques on Pumping Test Results. In: Proc. 6th Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 7-26.

Schickedanz, D.M., A.B. Onken, T. Cummings, and R.M. Jones. 1973. A Tractor-Mounted Hydraulically-Operated Soil Sampler for Rapid Soil Coring. Agronomy J. 65:339-340.

Schmertmann, J.H. 1978. Guidelines for Cone Penetration Test Performance and Design. FHWA-TS-78-209. Federal Highway Adminstration, Washington, DC, 145 pp.

Schuh, W.M. 1987. Apparatus for Extraction of Undisturbed Samples on Noncohesive Subsoils. Soil Sci. Soc. Am. J. 51:1678-1679.

Schumacher, B.A., K.C. Shines, J.V. Burton, and M.L. Papp. 1990. Comparison of Three Methods for Soil Homogenization. Soil Sci. Soc. Am. J. 54:1187-1190.

Schumacher, B.A., K.C. Shines, J.V. Butron, and M.L. Papp. 1991. A Comparison of Soil Sample Homogenization Techniques. In: Hazardous Waste Measurements, M.S. Simmons (ed.), Lewis Publishers, Chelsea, MI, pp. 53-68.

Seikan, D.I., and M.A. Deyling. 1989. Ground Water Monitoring Network Installation at the Fall River, Massachusetts Municipal Landfill. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 179-189. [Air rotary]

Senum, G.I. and R.N. Dietz. 1991. Perfluorocarbon Tracer Tagging of Drilling Muds for the Assessment of Sample Contamination. In: Proc. 1st Int. Symp. on the Microbiology of the Deep Subsurface, C.B. Fliermans and T.C. Hazen (eds.), Westinghouse Savannah River Co., Aiken, SC, pp. 7/145-7/149.

Shepard, F.P. 1954. Nomenclature Based on Sand-Silt-Clay Ratios. J. Sediment. Petrol. 24(3):151-158.

Shew, D.C. 1975. Ground-Water Problems Associated with Well-Drilling Additives. In: Conf. Proc. Environmental Aspects of Chemical Use in Well-Drilling Operations. EPA/560/1-75/004 (NTIS PB246-947), pp. 223-230.

Shew, D.C. and J.W. Keeley. 1975. Ground-Water Problems Associated with Well-Drilling Additives. EPA/560/1-75/004 (NTIS PB-246 947), pp. 223-230.

Shirley, D.S. and S.M. Hay. 1988. Using the Percussion Hammer to Install Groundwater Monitor Wells in Coarse Alluvial Deposits. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 289-301.

Shuter, E. and W.E. Teasdale. 1989. Application of Drilling, Coring, and Sampling Techniques to Test Holes and Wells. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-F1, 96 pp.

Sieczka, J.B., W.H. Gutenmann, and D.J. Lisk. 1982. Soil Sampling Method for Use in Pesticide Leaching Studies. Bull. Environ. Contam. Toxicol. 28(3):358-359.

Siegrist, R.L. and P.D. Jenssen. 1990. Evaluation of Sampling Method Effects on Volatile Organic Compounds Concentrations in Contaminated Soils. Environ. Sci. Technol. 24:1387-1392.

Sims, W.R., B.B. Looney, and C.A. Eddy. 1991. Evaluation of a Rapid Headspace Analysis Method for Analysis of Volatile Constituents in Soils and Sediments. In: Ground Water Management 5:655-668 (5th NOAC).

Slater, J.P. and F.R. McLaren. 1983. Sampling and Analysis of Soil for Volatile Organic Compounds. In: Proc. NWWA/EPA Conf. on Characterization and Monitoring of the Vadose (Unsaturated) Zone (Las Vegas, NV), National Water Well Association, Dublin, OH, pp. 623-658.

Smith, S.A. 1990. Monitoring Well Drilling and Testing in Urban Environments. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp.

55-63.

Smolley, M. and J.C. Kappmeyer. 1989. Cone Penetrometer Tests and Hydropunch (TM) Sampling: An Alternative to Monitoring Wells for Plume Definition. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 717-724.

Smolley, M. and J.C. Kappmeyer. 1991. Cone Penetrometer Tests and Hydropunch Sampling: A Screening Technique for Plume Definition. Ground Water Monitoring Review 11(2):101-106.

Smythe, J.M., P.B. Bedient, and R.A. Klopp. 1988. Cone Penetrometer Technology for Hazardous Waste Site Investigations. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 71-94.

Soil Conservation Service (SCS). 1971. Handbook of Soil Survey Investigations Procedures.

Soil Conservation Service (SCS). 1984. Procedures for Collecting Soil Samples and Methods of Analysis for Soil Survey. Soil Survey Investigations Report No. 1. U.S. Government Printing Office. (Supersedes report by the same title dated 1972.)

Soil Survey Staff. 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Department of Agriculture Agricultural Handbook No. 436, 754 pp.

Speake, Jr., R.C., M. Trogan, and Z.Z. Wang. 1991. Modeling the Performance of a Horizontal Groundwater Recovery Well. Ground Water Management 5:399-415 (5th NOAC).

Spittler, T.M., M.J. Cuzzupe, and J.T. Griffith. 1988. A Field Method for Determination of Volatile Organics in Soil Samples. In: Proc. 1st Int. Symp. Field Screening Method for Hazardous Waste Site Investigations, EPA/600/D-89/189 (NTIS PB90-132572), pp. 155-157.

Starr, R.C. and R.A. Ingleton. 1992. A New Method for Collecting Core Samples Without a Drilling Rig. Ground Water Monitoring Review 12(1):91-95. [Piston sampler]

Stevens, P.R. 1963. Examination of Drill Cuttings and Application of Resulting Information to Solving Field Problems on the Navajo Indian Reservation, New Mexico and Arizona. U.S. Geological Survey Water-Supply Paper 1544-H, pp. H3-H13.

Stolt, M.H., J.C. Baker, and T.W. Simpson. 1991. Bucket Auger Modification for Obtaining Undisturbed Samples of Deep Saprolite. Soil Science 151:179-182.

Stow, G.R.S. 1963. Modern Water Well Drilling Techniques Used in the United Kingdom. Ground Water 1(3):3-12.

Strauss, M.F., S.L. Story, and N.E. Mehlhorn. 1989. Application of Dual Wall Reverse Circulation Drilling in Ground Water Exploration and Monitoring. Ground Water Monitoring Review 9(2):63-71.

Strutynsky, A.I. and T.J. Sainey. 1990. Use of Piezometric Cone Penetration Testing and Penetrometer Groundwater Sampling for Volatile Organic Contaminant Plume Detection. Ground Water Management 4:71-84 (7th NWWA/API Conf.).

Strutynsky, A.I., R.E. Sandiford, and D. Cavaliere. 1992. Use of Piezometric Cone Penetration Testing with Electrical Conductivity Measurements (CPTU-EC) for the Detection of Hydrocarbon Contamination in Saturated Granular Soils. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 169-182.

Summers, W.K. 1972. Horizontal Wells and Drains. Water Well Journal 26(6):36-38.

Tackett, J.L., E. Burnett, and D.W. Fryear. 1965. A Rapid Procedure for Securing Large, Undisturbed Soil Cores. Soil Sci. Soc. Am. Proc. 29:218-220.

Tanner, C.B., W.E. Hanks, and R.J. Hanks. 1953. A Core-Type Soil Sampler for Small Undisturbed Samples. Agronomy J. 45:512-513.

Terry, D.L., C.B. McCants, and F.G. Averette. 1974. A Sampler for Taking Soil Samples from Specific Soil Zones. Soil Science 118(6):402-404

Tomer, M.D. and A.H. Ferguson. 1989. Rubber Latex Encasement of Undisturbed Cores for Water Flow and Potential

Measurements. Soil Sci. Soc. Am. J. 53:305-308.

Treadway, C. 1991. Cable Tool Drilling: A Viable Drilling Method for Constructing Monitoring Wells. Water Well Journal 45(5):56-59.

Tschirley, N.K. 1978. Manual of Drill Fluids Technology. Baroid Petroleum Service Co., Houston, TX, 200 pp.

Tuttle, C.L., M.S. Golden, and D.L. Sirois. 1984. A Portable Tool for Obtaining Soils Cores in Clayey or Rocky Soils. Soil Sci. Soc. Am. J. 48:1453-1455.

U.S. Army. 1981. Well Drilling Operations. Department of Army Technical Manual FM5-1161/AFR 85-23. Reprinted by National Water Well Association, Dublin, OH, 249 pp. (Supersedes TM 5-297/AFR 85-23, published in 1965.)

U.S. Army Toxic and Hazardous Material Agency (USATHAMA). 1982. Minimum Requirement for Boring Logs, Drilling Procedures, Monitoring Well Installation, and Associated Data Management System Entries. USATHAMA, Aberdeen Proving Ground, MD.

U.S. Bureau of Mines. 1968. Horizontal Boring Technology: A State-of-the-Art Study. U.S. Bureau of Mines Information Circular 8392, 86 pp. [Utility rigs]

U.S. Environmental Protection Agency (EPA). 1975. Conference Proceedings, Environmental Aspects of Chemical Use in Well-Drilling Operations. EPA/5670/1-75/004 (NTIS PB246-947), 582 pp. [35+ papers]

U.S. Environmental Protection Agency (EPA). 1984a. Drill Mud Assessment Chemical Analysis Reference Volume. EPA/600/3-84/048 (NTIS PB84-170000).

U.S. Environmental Protection Agency (EPA). 1984b. A Survey of the Toxicity and Chemical Composition of Used Drilling Muds. EPA/600/3-84/071 (NTIS PB84-207661).

U.S. Environmental Protection Agency (EPA). 1986a. Test Methods for Evaluating Solid Waste, 3rd edition, Vol. II: Field Manual Physical/Chemical Methods. EPA/530/SW-846 (NTIS PB88-239223); First update, 3rd edition. EPA/530/SW-846.3-1 (NTIS PB89-148076). (2nd edition published in 1982 (NTIS PB87-1200291); current edition and updates available on a subscription basis from U.S. Government Printing Office, Stock #955-001-00000-1.)

U.S. Environmental Protection Agency (EPA). 1986b. Permit Guidance Manual on Unsaturated Zone Monitoring for Hazardous Waste Land Treatment Units. EPA/530/SW-86/040. (NTIS PB87-215463).

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557), 644 pp.

U.S. Environmental Protection Agency (EPA). 1989. Sediment Classification Methods Compendium, Final Draft Report. Office of Water Regulations and Standards, Washington, DC. [Compendium of 10 methods for assessing chemically contaminated sediments]

Vaughn, D.H., C.B. Muralik, and J.H. Wilson. 1984. Soil Sampler Minimizes Soil Disturbance. Agric. Eng. 64:24-25.

Vepraskas, M.J., M.T. Hoover, J.L. Beeson, M.S. Carpenter, and J.B. Richards. 1990. Sampling Device to Extract Inclined Undisturbed Soil Cores. Soil Sci. Soc. Am. J. 54:1192-1195.

Viehmeyer, F.J. 1929. An Improved Soil Sampling Tube. Soil Science 27:147-152.

Vroblesky, D.A., S.W. Phillips, and J. Stefano. 1988. Remote-Controlled Drilling Operations at Hazardous-Waste Sites, Aberdeen Proving Ground, Maryland. In: 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 17-30.

Wahls, H.E. (ed.). 1975. In Situ Measurement of Soil Properties. Proc. Specialty Conf. of the Geotechnical Engineering Division, American Society of Civil Engineers, New York, NY.

Watson, K.K. and S.J. Lees. 1975. A Procedure for the Sampling and Testing of Large Soil Cores. Soils Sci. Soc. Am. Proc. 39:589-590.

Weinstock, E.A. 1990. Installing Monitoring Wells with Hollow Stem Augers--Breaking the "100-Foot" Barrier. Water Well Journal

44(1):49.

White, A.E. 1990. Design/Installation of Deep Groundwater Monitoring Wells in an Arid Region. Ground Water Management 4:101-109 (7th NWWA/API Conf.).

Williamson, D.A. 1984. Unified Rock Classification System. Bull Ass. Eng. Geol. 21(3):345-354.

Wilson, S.A., K. Keehan, and R.T. Williams. 1991. The Physical Preparation and Chemical Analysis of Soil/Compost Samples. In: Proc. 15th Annual Army Environmental R&D Symp. (1990), CETHA-TS-CR-91077, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 143-146.

Wires, K.C. and B.H. Sheldrick. 1987. A Soil Sampling Procedure for Micromorphological Studies. Can. J. Soil Science 67:693-695.

Woessner, W.W. 1987. Using the Drill Through Casing Hammer Method for Monitoring Well Construction and Water Quality Characterization in a Metal Contaminated Gravel, Cobble and Boulder Aquifer. In: 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 373-397.

Woessner, W.W. 1988. Drill-Through Casing Driver Drilling Method for Construction of Monitoring Wells in Coarse, Unconsolidated Sediments. Ground Water Monitoring Review 8(1):69-72.

World Oil. 1970. Guidelines for Optimum Diamond Bit Performance, Parts I to IV. World Oil, Vol. 171, No. 4 (September), pp. 63-66; No. 5 (October), pp. 94-96; No. 6 (November), pp. 113-116; No. 7 (December), pp. 75-77.

Zapico, M.M., S. Vales, and J.A. Cherry. 1987. A Wireline Piston Core Barrel for Sampling Cohesionless Sand and Gravel Below the Water Table. Ground Water Monitoring Review 7(3):74-82.

Zirschky, J. and R.O. Gilbert. 1984. Detecting Hot Spots at Hazardous-Waste Sites. Chemical Engineering July 9, pp. 97-100.

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH, 45268-0963 (513-569-7562).

SECTION 3

GEOPHYSICAL LOGGING OF BOREHOLES

Overview of Borehole Techniques

Methods for geologic and hydrogeologic characterization using boreholes most commonly use **probes** or **sondes** that are lowered on a cable. These probes transmit signals to surface instruments that generate logs or charts, which relate changes in the parameter being measured with depth. However, any method that involves a signal transmitter and separate receivers can use boreholes in a variety of configurations: (1) **Cross-borehole** (transmitter in one borehole and receiver[s] in one or more other boreholes), (2) **borehole-to-surface** (transmitter in a borehole and receiver[s] on the surface), and (3) **surface-to-borehole** (transmitter at the surface and receivers in the borehole[s]).

Most borehole geophysical techniques for characterizing rock fall into three categories: (1) **Electrical/electromagnetic** methods, which measure resistivity and conductivity of fluids and surrounding rocks (Sections 3.1 and 3.2), (2) **nuclear** methods, which use natural or artificial sources of radiation and radiation detectors to characterize rock and fluid properties (Section 3.3), and (3) **acoustic/seismic** methods, which measure the elastic response of subsurface rock to a seismic source (Section 3.4). Miscellaneous logging methods, such as **caliper, temperature**, and **fluid flow** logging are covered in Section 3.5, and **well construction** logs are covered in Section 3.6. Section 5.5 covers probes used for fluid characterization, such as dissolved oxygen, Eh and pH probes (Section 5.5.4), and ion-selective electrodes (Section 5.5.5).

Selection of Borehole Techniques

The type of borehole (cased or uncased), and whether it is filled with fluid or is dry, are major considerations in the selection of borehole techniques. For example, most electrical methods require an uncased borehole and either drilling fluid or water in the hole. Table 3-1 provides summary information on casing and borehole fluid requirements for more than 40 borehole techniques covered in this guide. This tables also indicates the approximate radius of measurement of each technique and required corrections or calibrations, and other logs that might be required for accurate interpretation of a log. Typically, several different types of logs are run on the same borehole and compared to facilitate stratigraphic interpretations. A typical suite of logs in a fluid filled borehole would include: (1) **Spontaneous potential** (Section 3.1.1), (2) **single-point resistance** (Section 3.1.2) and/or **normal resistivity** (Section 3.1.4), (3) **natural gamma** (Section 3.3.1), (4) **neutron** (Section 3.3.3), (5) **caliper** (Section 3.5.1), (6) **fluid conductivity** (Section 3.1.3), (7) **temperature** (Section 3.5.2), and, possibly, (8) **acoustic velocity** (Section 3.4.1). Figure 3-1 illustrates a typical response to sedimentary rocks (Figure 3-1a) and altered or fractured crystalline rock (Figure 3-1b) with commonly used logging methods. Measurement of ground-water flow in boreholes (Sections 3.5.3 to 3.5.6) is an especially useful technique for locating zones of high permeability within a borehole.

Depending on site conditions and the availability of equipment and experienced operating personnel, all of the techniques covered in this section have potential for use at contaminated sites. Table 3-2 provides more detailed guidance on techniques for specific subsurface parameters. The ASTM Subcommittee on Ground Water and Vadose Zone Investigations has prepared a Draft Standard Guide for Borehole Geophysical Investigations (Nielsen, 1991), and this will provide useful additional guidance when it is completed.

In shallow boreholes, or where a hole is completed a short distance below a desired point, tool **length** might be an important consideration, particularly if a detector is housed in the middle of a long tool. A special consideration in the selection of borehole techniques at contaminated sites is the requirement that the instrument usually be decontaminated after each use.

Table 3-1 Characteristics of Borehole Logging Methods (information for general guidance only)

Log Type/Section	Casing[a]	Min. Diam.[b]	Borehole Fluid	Radius of Measurement	Required Correction
Electrical Logs					
Spontaneous Potential (3.1.1)	Uncased only	1.5-3.0"	Conductive fluid	Near borehole surface	Drilling fluid resistivity and borehole diameter for quantitative uses
Single-Point Resistance (3.1.2)	Uncased only	1.5-2.0"	Conductive fluid	Near borehole surface	Not quantitative; hole diameter effects significant
Fluid Conductivity (3.1.3)	Uncased or screened	2.0-2.5"	Conductive fluid	Within borehole	Calibration with fluid of known salinity; temperature correction
Resistivity (3.1.4)	Uncased only	2.0-5.5"	Conductive fluid	<1.0-60"	Drilling fluid resistivity, borehole diameter, and temperature log for quantitative uses
Dipmeter (3.1.5)	Uncased only	6.0"	Conductive fluid	Near borehole surface	Orientation; minimum of 6" diam. required for accurate joint/fracture characterization
Induced Polarization (3.1.6)	Uncased only	2.0"	Conductive fluid	2.0-4.0'	Hole diameter
Cross-Well AC Voltage (3.1.6)	Uncased only	?	Wet or dry	10s to 100s of meters	Borehole deviation
Electromagnetic Logs					
Induction (3.2.1)	Uncased or nonmetallic	2.0-4.0"	Wet or dry	30"	Effect of hole diameter and mud negligible
Borehole Radar (3.2.2)	Uncased or nonmetallic	2.0-6.0"	Wet or dry	meters	Borehole deviation (crosshole)
Dielectric (3.2.3)	Uncased or nonmetallic	5.0"	Wet or dry	30"	Conductive material skin depth, chlorine interference
Nuclear Magnetic Resonance (3.2.4)	Uncased only	7.0"	Required	1.5'	Borehole fluid
Surface-Borehole CSAMT (3.2.4)	Uncased only (?)	?	Wet or dry(?)	?	?
Nuclear Logs					
Natural Gamma (3.3.1)	Uncased or cased	1.0-2.0"	Wet or dry	6.0-12.0"	None for qualitative uses; hole diameter, casing (thickness, composition, and size), and drilling fluid density for quantitative uses
Gamma-Gamma (3.3.2)	Uncased or cased	2.5"	Wet or dry	6.0"	Same as natural gamma with addition of formation fluid and matrix density corrections
Neutron (3.3.3)	Uncased or cased	1.5-4.5"	Wet or dry	6.0-12.0"	Same as natural gamma with addition of temperature, fluid salinity, and matrix composition corrections
Gamma-Spectrometry (3.3.4)	Uncased or cased	2.0-4.0"	Wet or dry	6.0-12.0"	Similar to natural gamma

Table 3-1 (cont.)

Log Type/Section	Casing[a]	Min. Diam.[b]	Borehole Fluid	Radius of Measurement	Required Correction
Nuclear Logs (cont.)					
Neutron-Activation (3.3.5)	Uncased or cased	2.0-4.0"	Wet or dry	< Neutron	?
Neutron-Lifetime (3.3.6)	Uncased or cased	2.0-4.0"	Wet or dry	< Neutron	?
Acoustic and Seismic Logs					
Acoustic-Velocity/[c] Sonic (3.4.1)	Uncased or bonded metallic	2.0-4.0"	Required	Depends on frequency and rock velocity; several feet	Hole diameter, formation fluid, and matrix velocity corrections for quantitative uses
Acoustic-Waveform[c] (3.4.2)	Uncased or bonded metallic	2.5-3.0"	Required	> sonic	Same as sonic
Acoustic-Televiewer (3.4.3)	Uncased only	3.0" min 16.0" max	Required	Borehole surface	Large number of equipment adjustments required during operation (calibration of magnetometer), borehole diameter response, borehole deviation
Surface-Borehole Seismic (3.4.4)	Uncased or bonded cased	2.5-4.0"	Wet or dry	Depends on geophone configuration	Borehole deviation, correction for geometric spreading of source energy; geophones must be locked in dry holes
Geophysical Diffraction Tomography (3.4.5)	Uncased or nonmetallic	2.5-4.0"	Wet	100'	Borehole deviation
Cross Borehole Seismic (3.4.6)	Cased or uncased	2.0-3.0"	Wet or dry	Depends on borehole spacing	Borehole deviation
Miscellaneous Logging Methods					
Caliper (3.5.1)	Uncased or cased	1.5"+	Wet or dry	Arm limit (usually 2.0-3.0')	None
Temperature (3.5.2)	Uncased or cased[d]	2.0"	Required	Within borehole	Calibration to known standard
Mechanical Flowmeter (3.5.3)	[e]	2.0-4.0"	Required	[e]	Borehole diameter for velocity and volumetric logging
Thermal Flowmeter (3.5.4)	[e]	2.0"	Required	[e]	Borehole diameter for velocity and volumetric logging
EM Flowmeter (3.5.5)	[e]	2.0"	Required	[e]	Borehole diameter for velocity and volumetric logging
Single-borehole flow tracing (3.5.6)	[e]	1.75"+	Required	[e]	Changes in flow field with time
Colloidal Boroscope (3.5.7)	[e]	2.0"	Required	[e]	None

Table 3-1 (cont.)

Log Type/Section	Casing[a]	Min. Diam.[b]	Borehole Fluid	Radius of Measurement	Required Correction
Miscellaneous Logging Methods (cont.)					
Television/Photography (3.5.7)	Uncased or cased	2.0"+	Wet or dry	Borehole surface	None
Gravity (3.5.8)	Uncased best	6.0"	Wet or dry	10s to 100s of meters	Borehole diameter/inclination; other usual gravity corrections
Magnetic/Magnetic Susceptibility (3.5.8)	Uncased or nonmetallic	?	Wet or dry	1.0-2.0'	Hole diameter correction
Well Construction Logs					
Casing Collar Locator (3.6.1)	Steel Casing	2.0"+	Wet or dry	Casing collar, thickness	None
Cement and Gravel Pack Logs (3.6.2)	Cased	See specific logging methods discussed in Section 3.6.2			
Borehole Deviation (3.6.3)	Uncased	Varies	Wet or dry	Borehole Surface	Magnetic declination
Fluid/Gas Chemical Sensors					
Eh, Ph Probes (5.5.4)	Uncased/screened	1.0"	Required	Within borehole	Calibration to known standards
Ion-Selective Electrodes (5.5.5)	Uncased/screened	1.0"	Required	Within borehole	Calibration to known standards
Fiber Optic Chemical Sensors (5.5.6)	Uncased/screened	<2.0"	Wet or dry	Within borehole	Calibration to known standards
Other Chemical Sensors (10.6.5)	Uncased/screened	<1.0"-2.0"	Wet or dry	Within borehole	Calibration to known standards

Boldface = Most frequently used techniques in ground-water investigations.

[a] Unless otherwise specified, either plastic or steel casing is possible.
[b] Indicates the range of minimum diameters for commercially available probes based on best available information. Various sources were used, with the survey by Adams et al. (1983) being the main source.
[c] Wheatcraft et al. (1986) indicate that acoustic logs are suitable only for uncased boreholes. However, Thornhill and Benefield (1990) report using them for mechanical integrity tests of steel-cased injection wells.
[d] Wheatcraft et al. (1986) indicate that casing is allowable for temperature logs, Benson (1991) indicates that casing should not be used. Uncased holes are required for identification of high permeability zones. Cased hole uses would include measurement of geothermal gradient and cement bond logs (see Section 3.6.2).
[e] Flow measurements are usually made in uncased holes or screened intervals of cased holes. Radius of measurement depends on the permeability and whether natural or induced flow is measured. Natural flow will measure the properties of several well diameters; pumping will measure properties up to 25 to 35 well diameters (Taylor, 1989).

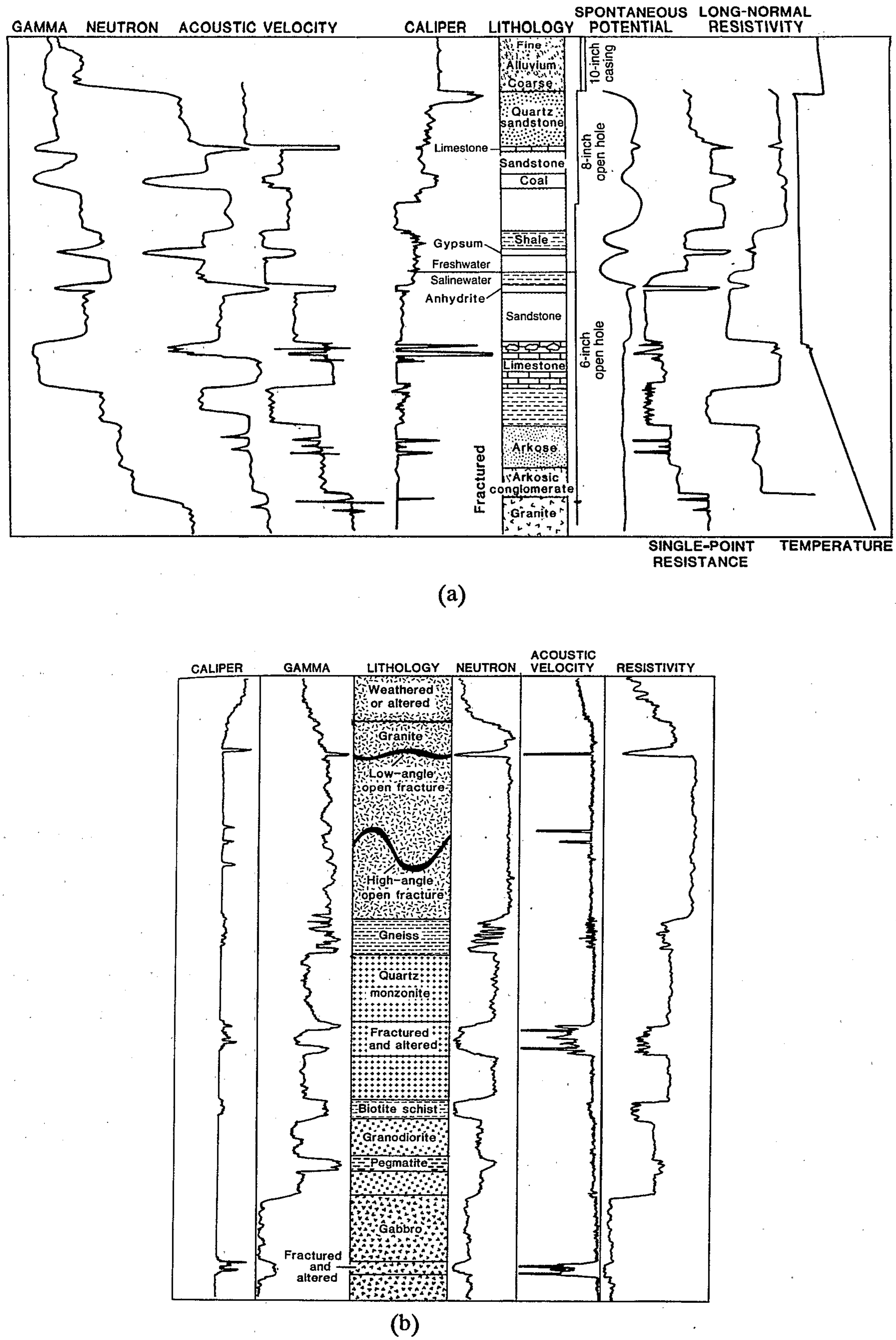


Figure 3-1 Well log suites: (a) Typical response to a sequence of sedimentary rocks; (b) Typical response to various altered and fractured crystalline rocks (Keys, 1990).

Table 3-2 Summary of Borehole Log Applications

Required Information	Logging Techniques Which Might Be Used
<u>Lithology, Stratigraphy, Formation Properties</u>	
General lithology and stratigraphic correlation.	Electric (SP, single point resistance, normal and focused resistivity, dipmeter, IP, cross-well AC voltage); EM (induction, dielectric); all nuclear (open or cased holes); caliper logs made in open holes, borehole television.
Bed thickness	Single point resistance, focused resistivity (thin beds), gamma, gamma-gamma, neutron, acoustic velocity.
Cavity detection	Caliper, acoustic televiewer, crosshole radar, crosshole seismic.
Sedimentary structure orientation	Dipmeter, borehole television, acoustic televiewer.
Large geologic structures	Gravity, surface-borehole/crosshole seismic, crosshole radar.
Total porosity/bulk density.	Calibrated dielectric, sonic logs in open holes; crosshole radar; calibrated neutron, neutron lifetime, gamma-gamma logs, computer assisted tomography (CAT) in open or cased holes; nuclear magnetic resonance, induced polarization, crosshole seismic.
Effective porosity.	Calibrated long-normal and focused resistivity or induction logs.
Clay or shale content.	Gamma log, induction log, IP log.
Relative sand-shale content	Gamma, SP log.
Grain size/pore size distribution.	<u>Grain size</u>: Possible relation to formation factor derived from electric, induction or gamma logs; <u>Pore size distribution</u>: Nuclear magnetic resonance; <u>Soil macroporosity</u>: Computerized axial tomography (CAT).
Compressibility/stress-strain properties.	Acoustic waveform, uphole/downhole seismic, crosshole seismic
Geochemistry	Neutron activation log, spectral-gamma log.
<u>Aquifer Properties</u>	
Location of water level or saturated zones.	Electric, induction, acoustic velocity, temperature or fluid conductivity in open hole or inside casing. Neutron or gamma-gamma logs in open hole or outside casing.
Moisture content.	Calibrated neutron logs, gamma-gamma logs, nuclear magnetic resonance, computerized axial tomography (CAT).
Permeability/hydraulic conductivity.	No direct measurement by logging. May be related to porosity, single borehole tracers methods (injectivity), 2-wave sonic amplitude, temperature, nuclear magnetic resonance. Estimation may be possible using vertical seismic profiling.
Secondary permeability--fractures, solution openings.	Caliper, temperature, flowmeters (mechanical, thermal, EM), sonic, acoustic waveform/televiewer, borehole television logs, SP resistance, induction logs, cross-well AC voltage, surface-borehole CSAMT, vertical seismic profiling, crosshole seismic.
Specific yield of unconfined aquifers.	Calibrated neutron logs during pumping.
<u>Ground-Water Flow and Direction</u>	
Infiltration.	Temperature logs, time-interval neutron logs under special circumstances or radioactive tracers.

Table 3-2 (cont.)

Required Information	Logging Techniques Which Might Be Used
Ground-Water Flow and Direction (cont.)	
Direction, velocity, and path of ground-water flow.	Thermal flowmeter; single-well tracer techniques--point dilution and single-well pulse; multiwell tracer techniques.
Source and movement of water in a well.	Injectivity profile; mechanical, thermal, EM flowmeters; tracer logging during pumping or injection; temperature logs.
Borehole Fluid Characterization	
Water Quality/Salinity	Calibrated fluid conductivity and temperature; SP log, Single point resistance, normal/multielectrode resistivity; neutron lifetime.
Water Chemistry	Dissolved oxygen, Eh, pH probes; specific ion electrodes.
Pore Fluid Chemistry	Induced polarization log, neutron activation (if matrix effects can be accounted for).
Mudcake Detection	Microresistivity, caliper, acoustic televiewer.
Contaminant Characterization	
Conductive Plumes	Induction log, resistivity, surface-borehole CSAMT.
Contaminant Chemistry	Specific ion electrodes, fiber optic chemical sensors.
Hydrocarbon Detection	Dielectric log, IP log.
Radioactive Contaminants	Spectral-gamma log.
Dispersion, dilution, and movement of waste.	Fluid conductivity and temperature logs, gamma logs for some radioactive wastes, fluid sampler.
Buried Object Detection	Geophysical diffraction tomography.
Borehole/Casing Characterization	
Determining construction of existing wells, diameter and position of casing, perforations, screens.	Gamma-gamma, caliper, collar, and perforation locator, borehole television.
Guide to screen setting.	All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers.
Borehole deviation	Deviation log, dipmeter, single-shot probe, dolly and cage tests.
Cementing/gravel pack.	Caliper, temperature, gamma-gamma; acoustic-waveform for cement bond; noise/Sonan log.
Casing corrosion/integrity.	Borehole television/photography; under some conditions caliper or collar locator.
Casing detection/logging	Casing collar locator, borehole television/photography; various electric, nuclear and acoustic logs.
Casing leaks and/or plugged screen.	Tracer and flowmeters.
Behind casing flow	Neutron activation and neutron lifetime logs.

The summaries in this section identify common conditions that enhance or inhibit the success of specific techniques, but site specific conditions might cause problems for specific techniques, even when all other indications are that the technique should work well. As a general rule, all geophysical techniques should be checked against more direct observation and/or confirmed by a second geophysical method. Furthermore, well established techniques should be given preference to those less commonly used, unless there is clear justification based on site conditions, cost, and the availability of trained and experienced personnel. When in doubt about the appropriateness of a specific technique, independent expert advice should be sought. EPA's Environmental Monitoring Systems Laboratory, Las Vegas, Nevada, can provide such advice for EPA personnel.

Sources of Additional Information

Table 3-3 (at the end of this section) identifies 16 general texts on logging methods, 20 texts of log interpretation, a number of texts focusing on electric and nuclear methods, and over 20 texts focusing on ground-water applications and contaminated sites, and identifies major published symposia and symposium series devoted to borehole geophysical methods. Where possible, text references are annotated to indicate techniques that are covered. In addition, many of the conferences and symposia proceedings identified in Table A-2 of Appendix A contain papers on use of geophysical methods. Probably the best references on borehole geophysics, which focus on ground-water applications, are the U.S. Geological Survey publications **Borehole Geophysics Applied to Ground-Water Investigations** (Keys, 1990), and **Applications of Borehole Geophysics to Water Resource Investigations** (Keys and MacCary, 1971). U.S. EPA (1992) provides an index of over 300 technical papers related to specific borehole geophysical methods, focusing primarily on applications in ground-water and contaminated-site investigations. Table 3-3 also identifies several documents that contain major bibliographies on borehole geophysical methods as they relate to hydrogeology. **Neutron moisture logging** is one of the most frequently used borehole technique because it is well suited for both near-surface and deep characterization. Table 3-4 (also at the end of this section) provides a comprehensive index of over 100 references related to neutron logging.

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1 ELECTRICAL BOREHOLE LOGGING

3.1.1 SP Logs

Other Names Used to Describe Method: Spontaneous potential, self-potential.

Uses at Contaminated Sites: Identifying variations in lithology (permeable beds, relative sand and shale content or strata), bed thickness, water quality, and casing detection.

Method/Device Description: A logging device that records the potentials or voltages that develop at the contacts between different lithologies, or with change in water quality. Figure 3.1.1 illustrates how the flow of current at bed contacts results in changes in the spontaneous potential curve. SP logs are commonly made at the same time as single-point resistance logs (see Figure 3.1.2 in the next section). Figure 3-1a illustrates an SP log.

Device Selection Considerations: **Advantages:** (1) Useful as supplemental information for interpretation of other types of logs; and (2) better adapted for locating the tops and bottoms of beds than conventional resistivity logs. **Disadvantages:** (1) Requires uncased hole filled with water or drilling fluid; (2) unreliable for estimating dissolved solids in aquifers less than 10,000 mg/L; and (3) noise and anomalous potentials are a common problem (usually caused when there is a poor insulator between the probe electrode and the cable).

Frequency of Use: Widely used for logging deep holes, especially by the petroleum industry; commonly used in association with rotary drilling methods; use of SP/single pint probe is also very common in ground-water studies.

Standard Methods/Guidelines: --

Sources for Additional Information: Brown et al. (1983), Bureau of Reclamation (1981), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Everett (1985), Keys (1990), Keys and MacCary (1971), Redwine et al. (1985), Respold (1989), U.S. EPA (1992), Wheatcraft et al. (1986). Most of the general borehole logging texts indexed in Table 3-3 cover SP logs, and texts focussing on electrical methods are also indexed in Table 3-3.

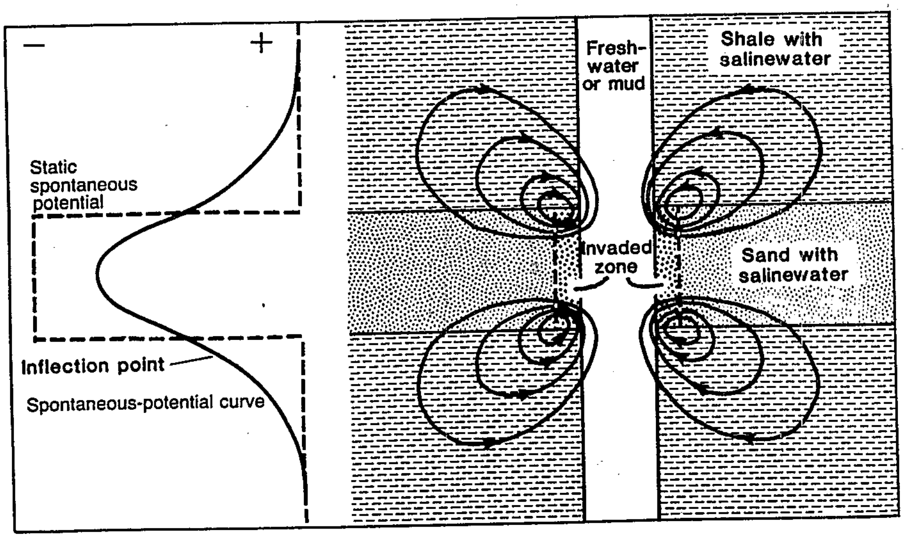


Figure 3.1.1 The flow of current at typical bed contacts and the resulting spontaneous-potential curve and static values (Keys, 1990).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1 ELECTRICAL BOREHOLE LOGGING

3.1.2 Single-Point Resistance

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Identifying changes in lithology and water quality.

Method Description: There are two types of single-point resistance logs. **Conventional** single-point resistance logs measure the resistance in ohms between an electrode as it is lowered down a well and an electrode at the land surface (Figure 3.1.2). **Differential** single-point resistance logs measure the resistance between two electrodes on a single probe as it is lowered down a borehole. Figure 3-1a illustrates a single-point resistance log.

Method Selection Considerations: **Advantages:** (1) Instrumentation is simple; (2) excellent for information about changes in lithology because it is not influenced by bed thickness; and (3) very good for fracture detection in crystalline bedrock. **Disadvantages:** (1) Cannot be used for quantitative interpretation of porosity and salinity; (2) readings are affected by borehole diameter and borehole fluid resistivity; (3) shallow radius of investigation; (4) noise and anomalous potentials are a common problem; and (5) require uncased borehole filled with fluid.

Frequency of Use: Use has been reported at a contaminated sites, but probably not used frequently.

Standard Methods/Guidelines: --

Sources for Additional Information: Keys (1990), Keys and MacCary (1971), Rehm et al. (1985), U.S. EPA (1992), Wheatcraft et al. (1986). Most of the general borehole logging texts indexed in Table 3-3 cover single-point resistance logs, and texts focussing on electrical methods also are indexed in Table 3-3.

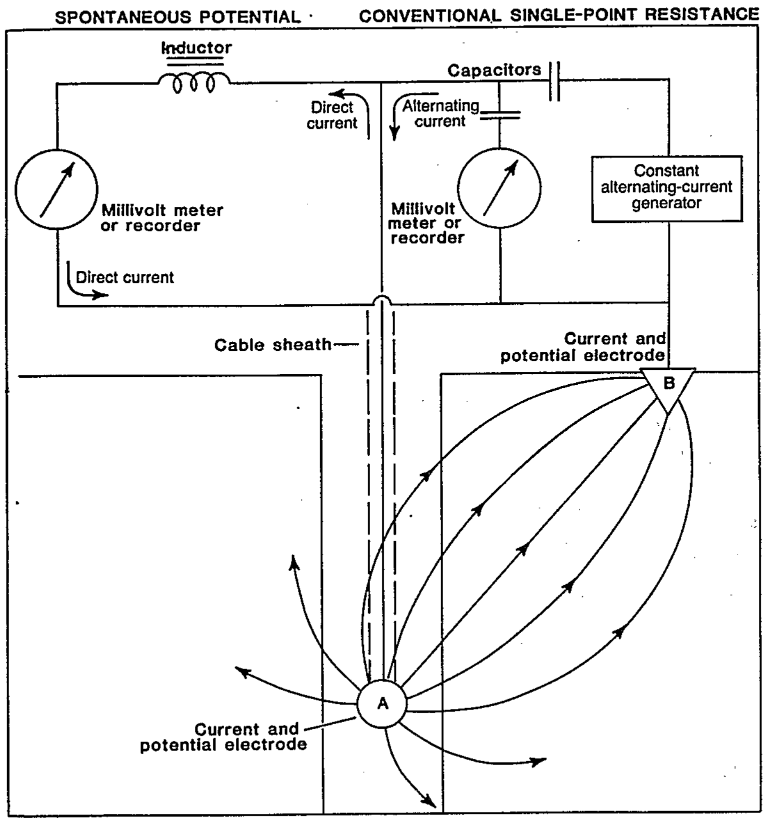


Figure 3.1.2 System used to make conventional single-point resistance and spontaneous potential logs (Keys, 1990).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1. ELECTRICAL BOREHOLE LOGGING

3.1.3 Fluid Conductivity

Other Names Used to Describe Method: Fluid resistivity, salinometer.

Uses at Contaminated Sites: Obtaining information on the concentration of dissolved solids in borehole fluid; locating sources of saltwater leaking into artesian wells; aiding in interpretation of electric logs.

Method Description: A specially designed probe that records only the electrical conductivity of the borehole fluids by placing electrodes inside a protective housing (Figure 3.1.3). The most common type of probe measures the AC-voltage drop across two closely spaced electrodes, which is a function of the resistivity of the fluid between the electrodes. Although resistance is actually measured, the term conductivity log is usually used to avoid confusion with resistivity logs, which measure the rocks and their interstitial fluids (Section 3.1.3). Commonly, the probes include temperature sensors that allow simultaneous measurement of temperature and fluid resistivity because temperature corrections are usually required for the readings (Figure 3.1.3). Combined logs are also useful for defining zones of inflow and outflow in bedrock wells. Figure 5.5.4 illustrates a combined conductivity-temperature log. Tellam (1992) describes the **reversed flow test** (RFT), which uses a fluid conductivity log to obtain information on pore water quality and inflow rates along the length of an uncased borehole.

Method Selection Considerations: **Advantages:** (1) Relatively simple and inexpensive type of log; and (2) interpretation is relatively straightforward (failure to consider disadvantage numbers 2 and 3 might result in erroneous interpretations). **Disadvantages:** (1) Calibration required with fluids of known conductance and measurements need to be corrected to standard temperature; (2) disturbance in the borehole by drilling, cementing, fluid density differences, and thermal convection will affect measurements and might require months to reestablish chemical equilibrium; and (3) setting of screens at the wrong depth can cause the measurement of fluid conductivities that are not representative of fluid in the aquifer.

Frequency of Use: Commonly used in logging uncased bedrock wells.

Standard Methods/Guidelines: --

Sources for Additional Information: Brown et al. (1983), Keys (1990), Keys and MacCary (1971), Respold (1989), U.S. EPA (1992), Wheatcraft et al. (1986). Most of the general borehole logging texts indexed in Table 3-3 cover fluid conductivity logs, and texts focussing on electrical methods also are indexed in Table 3-3.

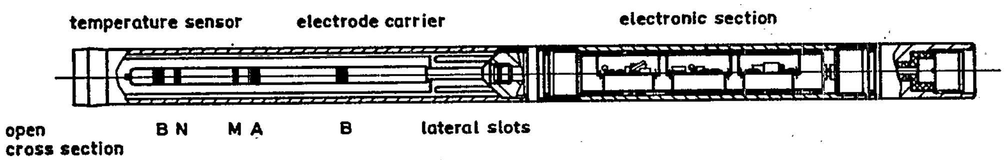


Figure 3.1.3 Combined salinometer/temperature probe (Respold, 1989, by permission).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1 ELECTRICAL BOREHOLE LOGGING

3.1.4 Resistivity Logs

Other Names Used to Describe Method: **Normal:** Short normal, long normal. **Focused:** Guard log, laterolog, dual laterolog. **Lateral:** --. **Microresistivity:** Microlog, contact log, micro-survey, microlateral, micronormal.

Uses at Contaminated Sites: **Normal:** Evaluating water quality. **Focused:** Measuring resistivity of thin beds or resistive strata in wells containing conductive fluids; detecting fractures in crystalline bedrock. **Lateral:** Performing lithologic characterization. **Microresistivity:** Determining presence or absence of mudcake.

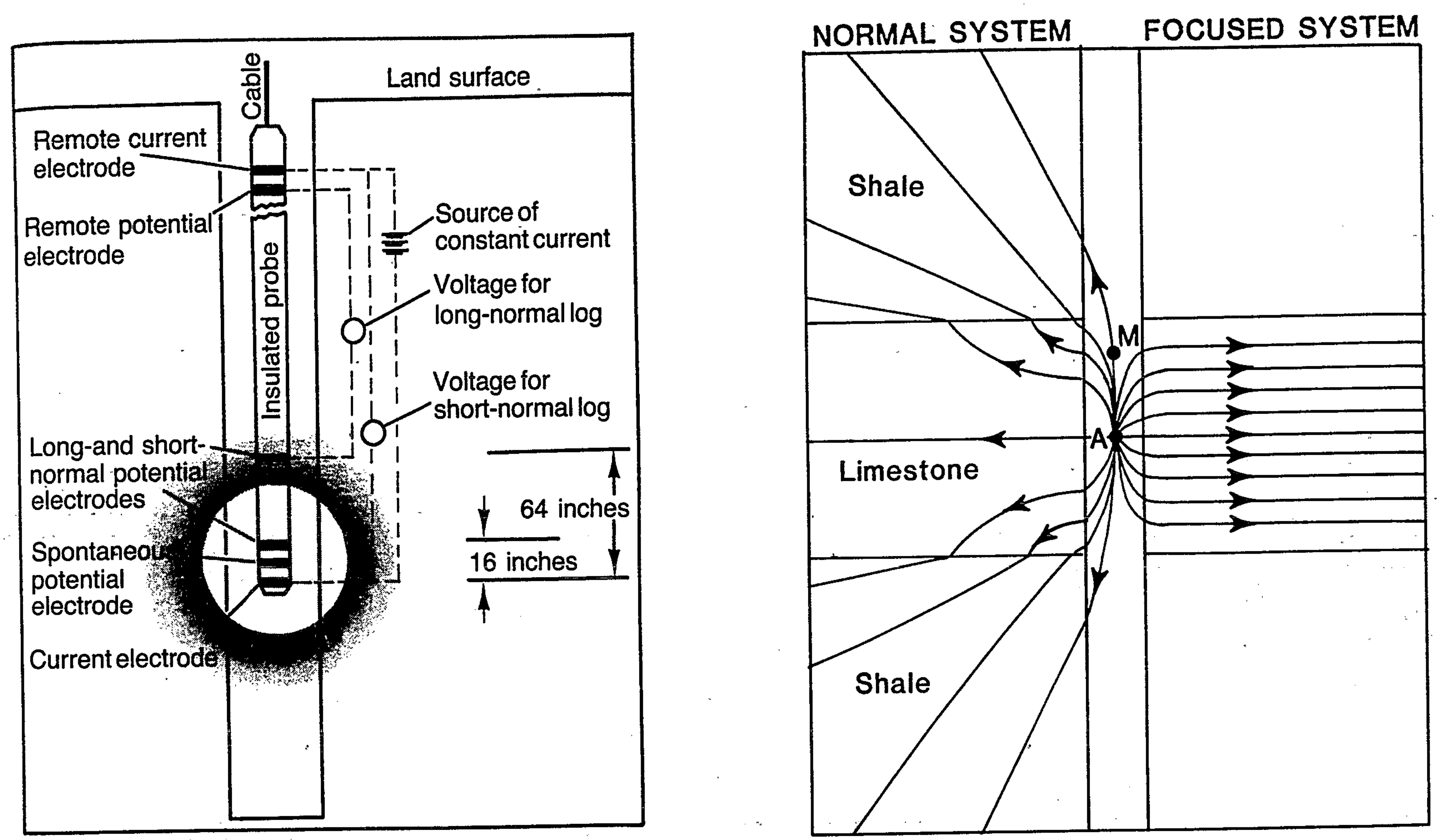
Method Description: The principal components of an electric resistivity logging instrument include: (1) An electronic unit that feeds electric current to a down-the-hole electrode and measures resistivity of the entire circuit, (2) a hoist or reel with conductor cable, (3) an electrode or probe from which current passes to the drilling fluid and formation surrounding the borehole, and (4) a recorder for automatically plotting values of resistivity against depth as a continuous curve. There are four main types of resistivity probes. **Normal:** Resistance is measured using four electrodes at various spacing on a single probe that is lowered down the hole (Figure 3.1.4a). Figures 3-1a and 3-1b illustrate normal resistivity logs. **Focused:** Uses guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the borehole (Figure 3.1.4b). **Lateral:** Similar to the normal resistivity logging tool, except electrodes are more widely spaced on the probe in order to measure resistivity of rock farther out from the borehole. **Microresistivity:** There are numerous variations of this type of probe, which uses short electrode spacing and pads or some kind of contact electrode to decrease the effect of borehole fluid.

Method Selection Considerations: All resistivity logs require an uncased hole with borehole fluid. There is a general tradeoff between increasing depth of penetration and resolution of beds. **Normal:** Equipment is generally available. Quantitative interpretations required corrections for bed thickness, borehole diameter, and other factors. **Focused:** Specialized logs generally are not available to water well loggers. Primarily for use in deep boreholes where ground-water has high dissolved solids. Also good for fracture detection in crystalline bedrock (Williams and Conger, 1990). **Lateral:** Suitable only for thick beds (>40 feet); marginal for highly resistive rocks. **Microresistivity:** Specialized log for evaluation of mudcake; might be of value in deep boreholes where drilling mud has been used.

Frequency of Use: **Normal:** Widely used in hydrogeologic investigations to evaluate water quality. **Other resistivity logs:** Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: **General:** Brown et al. (1983), Bureau of Reclamation (1981), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Everett (1985), Keys (1990), Keys and MacCary (1971), Redwine et al. (1985), Rehm et al. (1985), Respold (1989), U.S. EPA (1992); **Focused resistivity:** Moran and Chemali (1985), Roy (1982). Most of the general borehole logging texts indexed in Table 3-3 cover resistivity logs, and texts focussing on electrical methods are also indexed in Table 3-3.



(a)

(b)

Figure 3.1.4 **Resistivity logs: (a) System used to make 16- and 64-inch normal-resistivity logs (shaded area indicated relative size of volume investigations; (b) Current distribution around a normal-electrode system and a focused-electrode system (Keys, 1990).**

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1 ELECTRICAL BOREHOLE LOGGING

3.1.5 Dipmeter

Other Names Used to Describe Method: Diplog, formation micro-scanner.

Uses at Contaminated Sites: Measuring location and orientation of sedimentary structures and fractures. Also provides indication of borehole deviation.

Method Description: This method includes a variety of wall-contact microresistivity probes. The electrodes are on pads located 90 or 120 degrees apart and oriented with respect to magnetic north by a magnetometer in the probe (Figure 3.1.5).

Method Selection Considerations: **Advantages:** Can be used in boreholes in sedimentary rocks over a wide variety of hole conditions to obtain data on strike and dip of bedding planes; fractures can also be identified, but with less precision. **Disadvantages:** (1) Very expensive well logging method; (2) might not work well in less consolidated rock where strata do not have clear contrasts in resistivity; and (3) for accurate detection of joints and fractures, borehole diameters of at least 6 inches are required.

Frequency of Use: Uncommon, but potentially useful for deep boreholes in sedimentary rock.

Standard Methods/Guidelines: --

Sources for Additional Information: Bigelow (1985), Brown et al. (1983), Keys (1990), Respold (1989), U.S. EPA (1992). Many of the general borehole logging texts indexed in Table 3-3 cover resistivity logs, and texts focussing on electrical methods are also indexed in Table 3-3.

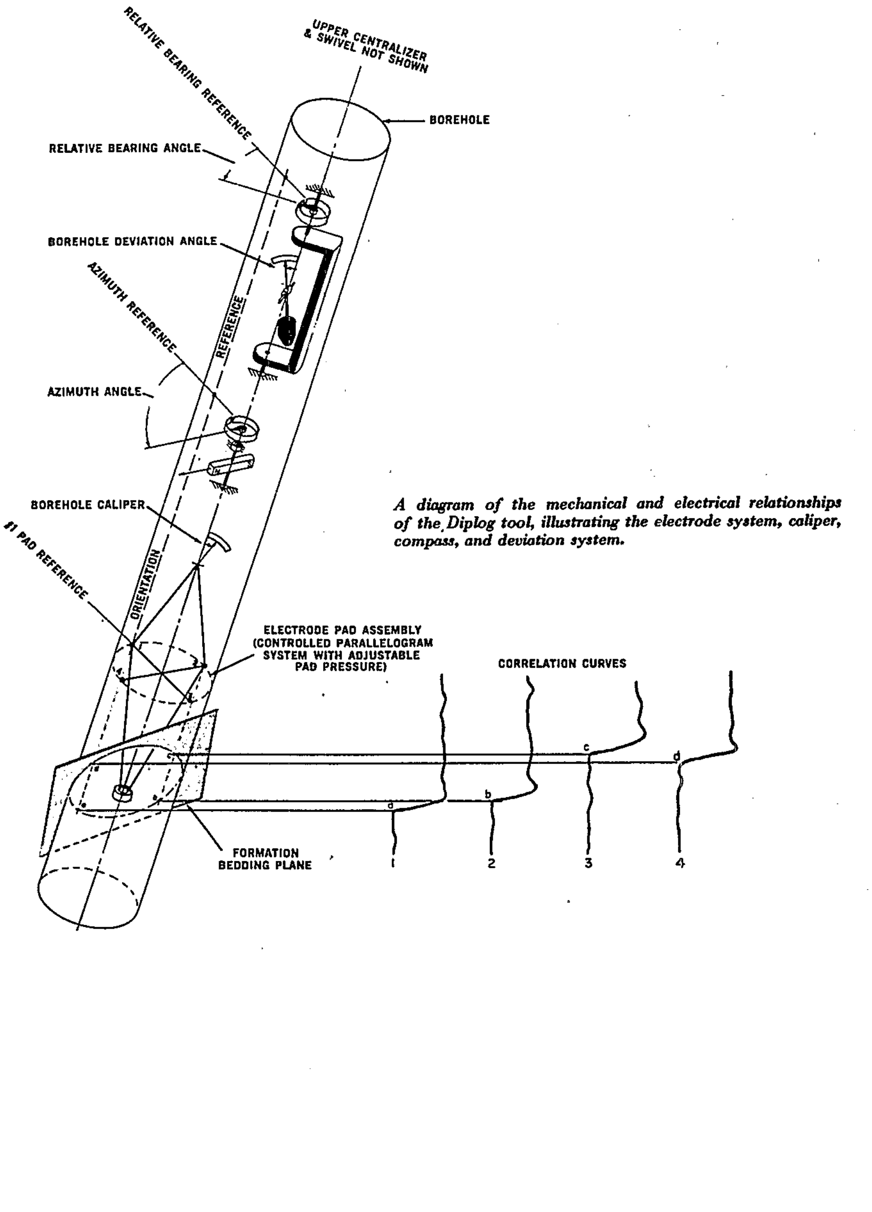


Figure 3.1.5 Diagram of the mechanical and electrical relationships of the diplog tool, illustrating the electrode system, caliper, compass and deviation system (Dresser Atlas, 1974).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.1 ELECTRICAL BOREHOLE LOGGING

3.1.6 Other Electrical Methods

Other Names Used to Describe Method: Hole-to-surface/hole-to-hole resistivity, induced polarization (IP), cross-well AC voltage.

Uses at Contaminated Sites: **Induced polarization:** Characterizing stratigraphy and porosity; measuring clay content and pore fluid chemistry. **Hole-to-surface/hole-to-hole resistivity:** Three dimensional modeling of resistivity data to define geoelectric inhomogeneities. **Cross-well AC voltage:** Characterizing spatial variation in subsurface fracture systems.

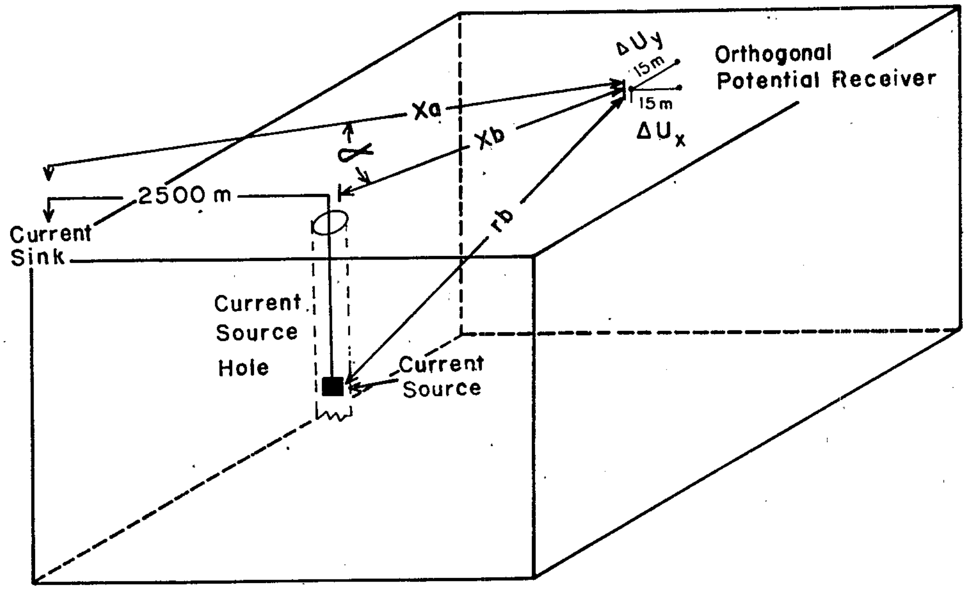
Method Description: **Hole-to-surface/hole-to-hole resistivity:** Numerous configurations of source and receiver electrodes are possible: Hole-to-surface (current source in the borehole--see Figure 3.1.6a), surface-to-hole (current source at the surface), and hole-to-hole (fixed source, moving pole, or bipole source). Figure 3.1.6b provides a schematic of resistivity measurements made between two boreholes. Electrodes in each borehole make electrical contact with the formation and current is driven through the formation from two adjacent electrodes (right-hand side of Figure 3.1.6b) as the potential difference is measured between all other adjacent electrode pairs. The procedure is repeated for all combinations of adjacent source and receiver electrode positions. **Induced polarization:** Probe measures the response of formation to an injected current (see Section 1.2.3). The same hole-to-hole and hole-to-surface configurations used for resistivity measurements can also be used for induced polarization. **Cross-well AC voltage:** A low-frequency alternating current is introduced into the fracture system of two wells and the voltage between the current electrodes and observation wells is measured.

Method Selection Considerations: All methods require uncased and fluid-filled borehole. **Hole-to-surface/hole-to-hole resistivity:** Main advantage is the possibility for three-dimensional modeling of the subsurface. The main disadvantages is the greater complexity compared to surface resistivity surveys. **Induced polarization:** Specialized log that is mainly used for differentiation of clayey and non-clayey deposits. **Cross-well AC voltage:** Relatively new method that might be useful for characterization of fracture systems. Equipment availability might be a problem.

Frequency of Use: **Hole-to-surface/hole-to-hole resistivity:** Has been primarily used in mineral exploration to locate ore bodies. **Induced polarization:** Uncommon. **Cross-well AC voltage:** Uncommon.

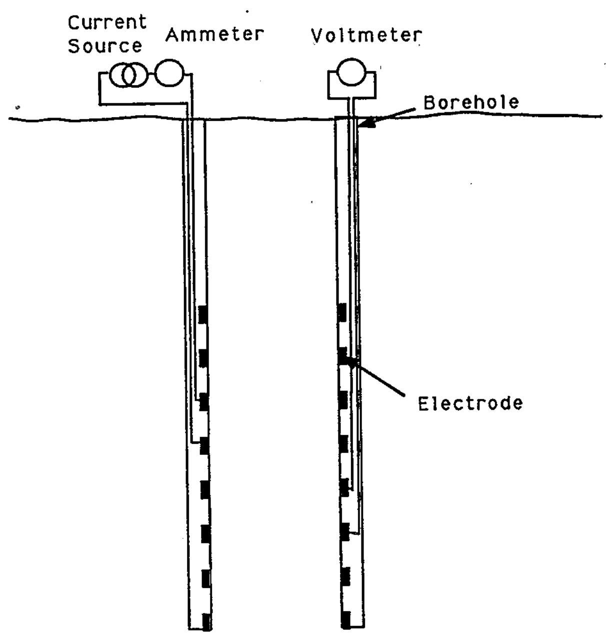
Standard Methods/Guidelines: --

Sources for Additional Information: **Hole-to-surface/hole-to-hole resistivity:** Daniels (1983), U.S. EPA (1992); **Induced polarization:** Rehm et al. (1985), U.S. EPA (1992); **Cross-well AC voltage:** Robbins and Hayden (1988).



Field measurement configuration. The total electric field is calculated from the orthogonal dipole potential measurements. $E_t = [(\Delta U_x / 15)^2 + (\Delta U_y / 15)^2]^{1/2}$. The distances X_b, r_b, and X_a ($r_a = X_a$) are used in the apparent resistivity calculation.

(a)



(b)

Figure 3.1.6 Other electrical methods: (a) Example configuration for hole-to-surface resistivity measurements (Daniels, 1983, by permission); (b) Schematic of crossbore resistivity measurement array (Daily and Owen, 1991, by permission).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.2 ELECTROMAGNETIC BOREHOLE LOGGING

3.2.1 Induction

Other Names Used to Describe Method: Slimhole EM probe (Geonics EM39 borehole conductivity meter), electromagnetic (EM) induction, dual induction, surface-to-borehole EM method.

Uses at Contaminated Sites: Performing lithologic characterization; locating the zone of saturation; performing physical and chemical characterization of formation fluids/ground-water quality.

Method Description: The **slimhole EM probe** is a relatively new tool designed specifically for use in fresh water. The probe contains a transmitter coil on the upper part, which induces eddy current in the formation around the borehole, and a receiver on the lower part (Figure 3.2.1). Conductivity is measured using same principles as surface EM induction measurement (Section 1.3.1). **Conventional induction probes** are designed for use in boreholes with no conductive material (such as oil-based drilling muds) between the probe and the formation. **Surface-to borehole EM method:** This variant uses a surface EM source (grounded bipole or large ungrounded loop) and a subsurface electric field or magnetic field sensor.

Method Selection Considerations: **Slimhole EM probe:** A major advantage of this probe is that can be used in wet or dry holes (2 inches minimum diameter) and can be used in PVC cased holes. See also, general advantages and disadvantages of surface EM methods (Section 1.3.1). **Conventional induction probe:** Requires holes filled with non-conducting drilling mud.

Frequency of Use: **Slimhole EM probe:** Relatively recent tool that has gained rapid acceptance for use in ground-water studies. **Conventional induction probe:** Uncommon for reason mentioned above. **Surface-to-borehole EM methods:** Have been used infrequently for mineral exploration.

Standard Methods/Guidelines: --

Sources for Additional Information: **Slimhole EM probe:** McNeill (1986), McNeill et al. (1990); **Conventional induction probe:** Everett (1985), Kaufman and Keller (1989), Keys (1990), Keys and MacCary (1971), Respold (1989), U.S. EPA (1992); **Surface-to-borehole:** Ross and Ward (1984).

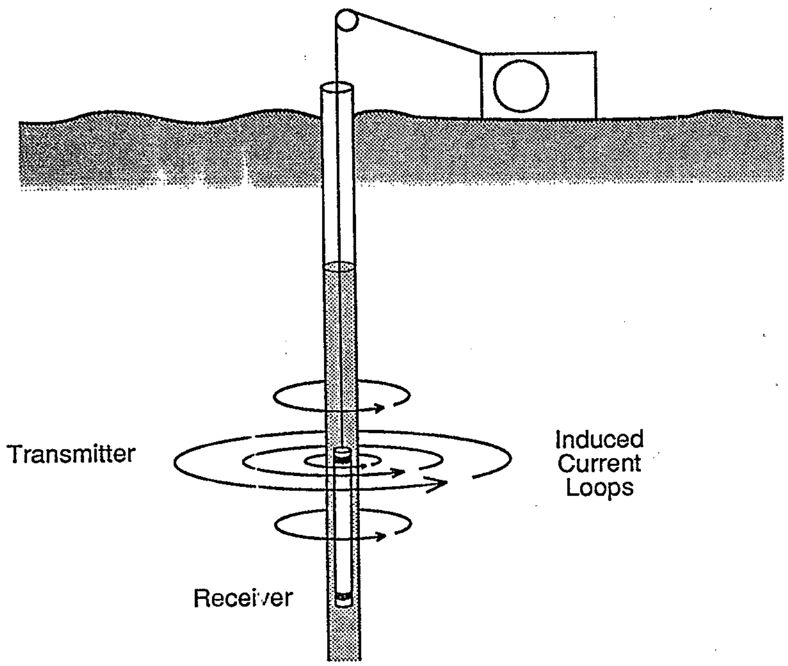


Figure 3.2.1 Slimhole EM-induction logger for ground-water investigations (McNeill, 1986).

3.2 ELECTROMAGNETIC BOREHOLE LOGGING

3.2.2 Borehole Radar

Other Names Used to Describe Method: Radar logging, single-hole borehole radar, cross-borehole radar/ electromagnetic probing.

Uses at Contaminated Sites: Characterizing stratigraphy, porosity, bedrock fractures; locating cavities and tunnels.

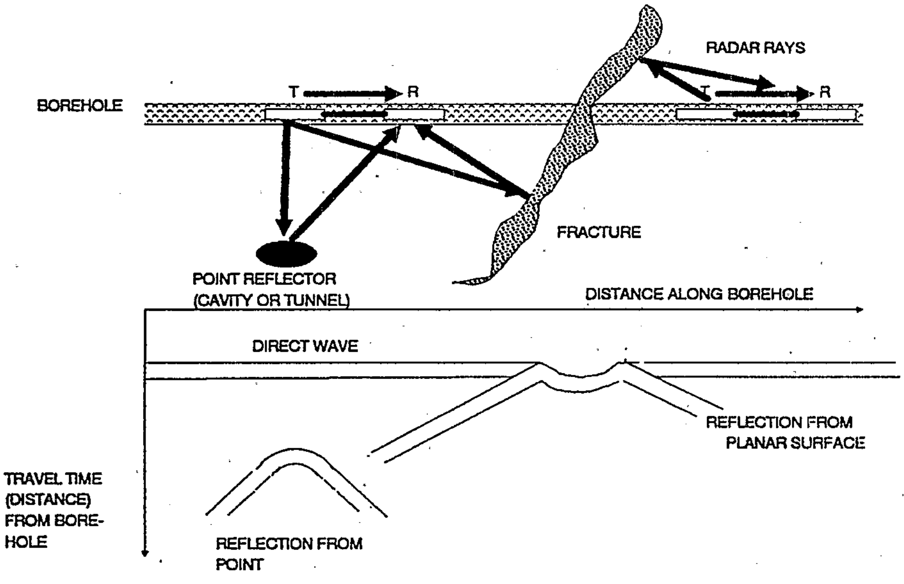
Method Description: Two major types of borehole radar have been developed. **Radar logging** involves a pulsed microwave system similar to ground-penetrating radar (Section 1.5.1) except that instrumentation is designed for use in a single borehole. This type has most commonly been used to map stratigraphy in salt domes, which readily transmit microwave signals. A relatively recent development is the **directional** borehole radar system (Figure 3.2.2a) which has the ability to detect cavities and fractures in a single borehole. **Cross-borehole** radar involves the use of a **continuous-wave** transmitter in one hole and receivers in one or more holes in line with the transmitter hole. Different "views" of a geophysical anomaly are obtained by placing the transmitter in one location in the borehole and measuring the signals as the receiver is lowered down the receiver borehole. Geophysical anomalies are recorded as signal minima. Multiple logs of the same receiver borehole with the transmitter at different depths can be graphically plotted to locate the area of the geophysical anomaly (Figure 3.2.2ba).

Method Selection Considerations: **Advantages:** (1) Relatively large area of measurement (tens of meters or more in favorable materials) compared to most borehole methods; (2) horizontal and vertical position of high-contrast geophysical anomalies can be determined with reasonable accuracy using cross-borehole probing with continuous-wave EM transmission; (3) cross-borehole field data on contrasting geophysical anomalies can be interpreted quickly and simply if the correct frequency is used (which depends on the wavelength of the surrounding medium and the dimension of the anomaly); and (4) radar can be used in open-hole or PVC cased wells. **Disadvantages:** (1) Penetration limited by moist and/or clayey soils or rock and soils with high electrical conductivity; and (2) equipment might not be readily available.

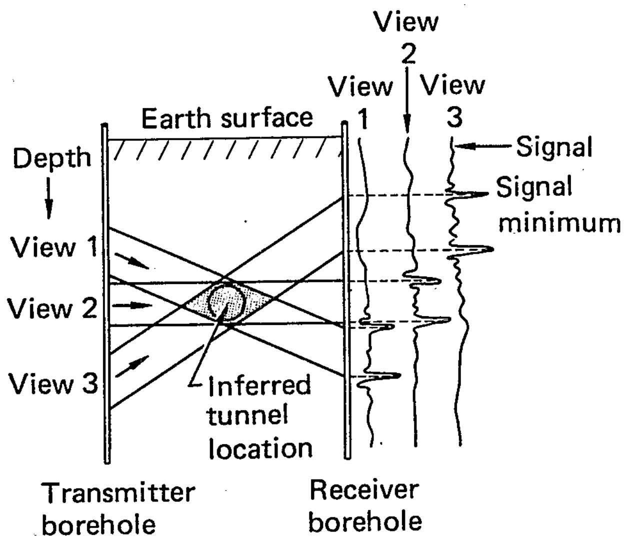
Frequency of Use: Most common reported applications are for characterizing salt domes and locating tunnels.

Standard Methods/Guidelines: --

Sources for Additional Information: Lytle et al. (1979), U.S. EPA (1992).



(a)



(b)

Figure 3.2.2 Borehole radar: (a) Single-hole radar reveals fractures, cavities, dikes and other reflectors (ABEM AB, Terraplus USA, Inc., Highlands Ranch, Colorado); (b) Principle of tunnel location using signal minima of different views (Lytle et al., 1979, by permission).

3.2 ELECTROMAGNETIC BOREHOLE LOGGING

3.2.3 Dielectric

Other Names Used to Describe Method: Electromagnetic propagation tool (EPT), deep propagation tool (DPT), low frequency dielectric log (LFD), dielectric constant log (DCL), continuous pulse microwave log.

Uses at Contaminated Sites: Measuring formation porosity; measuring hydrocarbon thickness on ground water.

Method Description: Dielectric tools use electromagnetic waves to measure the dielectric permittivity (or dielectric constant) of a formation. This is a measure of the relative ability of electrically charge particles in a formation to be polarized by an electric field. Dielectric logging devices are to two types: (1) Low frequency (20-47 MHz) mandrel tools, and (2) high frequency (200 MHz - 1.1 GHz) pad tools, which have an antenna pad with two transmitters and two receivers in a borehole compensated array (Figure 3.2.3). Note that the low frequency tools still use frequencies about an order of magnitude higher than electromagnetic induction tools (see Sections 1.3.1 and 3.2.1). The tool uses transmitting antennas to generate an electromagnetic waves and receiving antennas to measure phase shift and attenuation. Measurements can be used to calculate porosity in the saturated zone, and relative water and hydrocarbon saturation.

Method Selection Considerations: This is a relatively new method that was developed by the petroleum industry to distinguish between fresh water and oil. It can be used: As an alternative to density and neutron logs if the radioactive sources are a concern, in a wider range of conditions than sonic logs for measuring porosity, and in fresh water (use of resistivity logs for measuring porosity require brackish or saline waters). Dielectric logs have great potential for characterization of NAPLs in the subsurface. Low-frequency tools penetrate 15 to 45 inches, are relatively insensitive to borehole irregularities, and can be run in open or nonmetallic cased holes. High frequency tools penetrate 1 to 5 inches, are very sensitive to borehole irregularities, and work only in uncased holes. Minimum hole size for currently available tools ranges from 5 to 6.5 inches, considerably larger than typical monitoring wells.

Frequency of Use: Uncommon. This is a relatively new tool with great potential for characterization of hydrocarbon contaminated sites and porosity, if equipment and large diameter wells are available.

Standard Methods/Guidelines: --

Sources for Additional Information: Collier (1989), Keech (1988), Serra (1984a), U.S. EPA (1992).

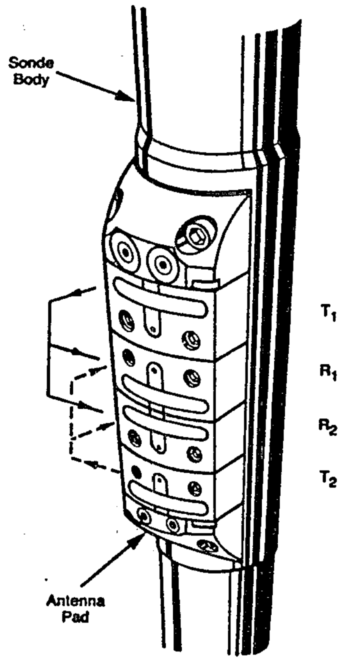


Figure 3.2.3 Antenna pad of the electromagnetic propagating tool (EPT) sonde (Collier, 1989, by permission).

3.2 ELECTROMAGNETIC BOREHOLE LOGGING

3.2.4 Other Electromagnetic Methods

Other Names Used to Describe Method: Nuclear magnetic resonance (NMR), nuclear magnetic logging, Surface-to-Borehole Controlled-Source Audiomagnetotelluric (CSAMT).

Uses at Contaminated Sites: **NMR:** Evaluating porosity, permeability, moisture content, pore-size distribution, and available water. **Surface-borehole CSAMT:** Potential for mapping of subsurface conductive zones and three-dimensional characterization of fracture zones in deep boreholes.

Method Description: **NMR:** Uses the same principle as the proton precession magnetometer (Section 1.5.2), except that the precession of protons (hydrogen atoms) in water molecules is measured in the formation after an induced magnetic field has been turned off. Section 6.2.5 provides additional description of this method as used for measuring near-surface soil moisture. Borehole units contain instrumentation for creating a magnetic field and measuring the precession of protons after it is turned off in a single probe. Nuclear magnetic resonance is commonly classified as a nuclear method (Morrison, 1983; Keys, 1990). However, no radioisotopes are involved in using the method, and it is classified here as an electromagnetic method because the magnetic field is electrically induced. **CSAMT** involves measurement the response of magnetotelluric currents (see Section 1.3.5) using sensors in a borehole to an artificially created audiofrequency signal at the surface.

Method Selection Considerations: **NMR Advantages:** More precise characterization of free and bound water and porosity than other logging methods. **NMR Disadvantages:** (1) Use limited to large boreholes (generally >7 inches) filled with drilling mud (magnetite powder usually has to be added to the mud to eliminate the borehole contribution to the log); and (2) equipment availability might be a problem. **Surface-Borehole CSAMT Advantages:** (1) For deep boreholes, the advantage over other magnetotelluric methods is that the signal is much larger than the level of natural-field noise; and (2) the high frequency of the source also allows rapid data acquisition. **Surface-Borehold CSAMT Disadvantages:** (1) Other proven methods are likely to give better results in near-surface investigations; (2) problems can develop if the borehole sensor is not kept vertically oriented; and (3) geologic noise cannot always be identified and effectively separated from the secondary response of the target.

Frequency of Use: **NMR:** Not widely used for petroleum applications and relatively unknown for ground-water borehole applications. Potentially very useful if borehole diameter is large enough. **Surface-borehole CSAMT:** Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: **NMR general:** Abragam (1961), Schlichter (1963); **NMR borehole applications:** Jackson (1984), Keys (1990), Wyllie (1963); **NMR soil moisture applications:** Morrison (1983). See also, Section 6.2.5, and references indexed in Table 6-2. **Surface-borehole CSAMT:** West and Ward (1988). See also, texts identified in Section 1.3.5.

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.3 NUCLEAR BOREHOLE LOGGING

3.3.1 Natural Gamma

Other Names Used to Describe Method: Gamma, gamma-ray log.

Uses at Contaminated Sites: Identifying lithology (clay and shale particularly) and stratigraphic correlation.

Method Description: Records total natural gamma radiation (primarily from K-40, U-238, and Th-232) from a borehole that is within a selected energy range. Different formations can be distinguished by differing levels of natural radioactivity (Figure 3.3.1). Figures 3-1a and 3-1b illustrate gamma logs for sedimentary and crystalline rocks.

Method Selection Considerations: **Advantages:** (1) Instrumentation is relatively simple and inexpensive; and (2) involves radiation detection only, so no radioactive sources required for the instrumentation. **Disadvantages:** (1) Only qualitative analysis is possible; (2) the smaller the diameter of the probe, the higher the signal-to-noise ratio; and (3) sensitivity of the probe is reduced by large diameter holes, drilling fluid, and casing (generally not feasible with cemented casing or two uncemented steel casings).

Frequency of Use: Probably the most commonly used nuclear log for stratigraphic mapping in ground-water studies.

Standard Methods/Guidelines: API (1974).

Sources for Additional Information: **Major references:** Guyod (1965), Keys (1990), Keys and MacCary (1971), Killeen (1982-review paper), Patten and Bennett (1963), Respold (1989), SPWLA (1978a), U.S. EPA (1992); **Other references:** Brown et al. (1983), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Everett (1985), Rehm et al. (1985), Wheatcraft et al. (1986). Most of the general borehole logging texts indexed in Table 3-3 cover gamma logs, and other texts focussing on nuclear methods are also indexed in Table 3-3.

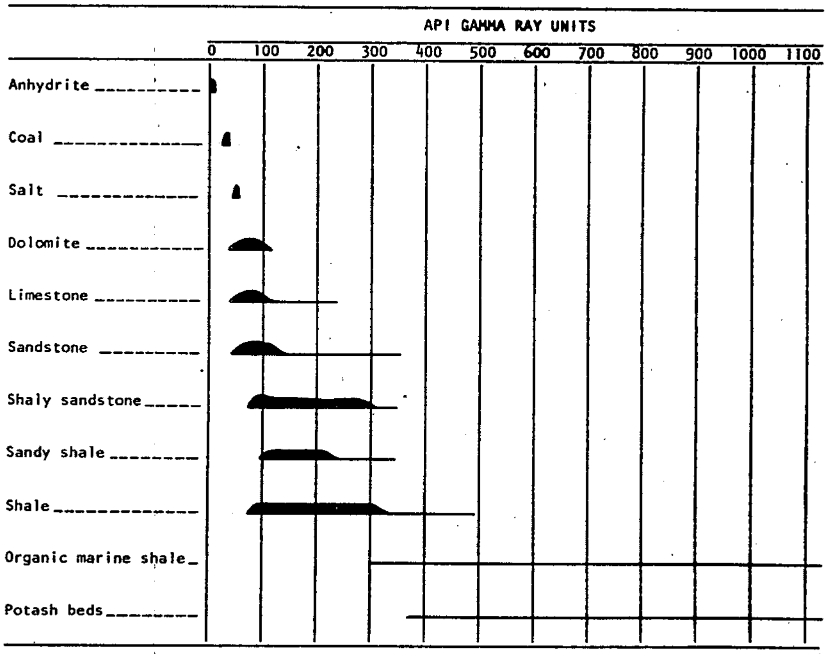


Figure 3.3.1 Range of radioactivity of selected sedimentary rocks (Keys and MacCary, 1971).

3.3 NUCLEAR BOREHOLE LOGGING

3.3.2 Gamma-Gamma

Other Names Used to Describe Method: Density log, transmittance log, gamma ray attenuation, gamma ray transmission, gamma ray absorption, gamma ray scattering.

Uses at Contaminated Sites: Measuring bulk density, porosity, and moisture content.

Method Description: A beam of gamma photons (typically cobalt-60, cesium-137, and/or americium-241) is directed at the borehole sides and a detector records the radiation that is attenuated and scattered in the borehole and surrounding rock. For deep boreholes, the **scattering** method is usually used, with a **single-probe** configuration that has the source and detector on the same unit (Figure 3.3.2). These probes can use either a **single-source** or a **dual-source** (which emit gamma radiation at different energy levels). For near surface monitoring of soil moisture, the **double tube transmission** method is more commonly used, in which the source and detector are lowered down two parallel boreholes (see Figure 6.2.2b).

Method Selection Considerations: **Advantages:** (1) Good method for measuring formation properties (bulk density, porosity, and moisture content); (2) data can be obtained over very small horizontal or vertical distances (layers of soil as thin as 1 centimeter); (3) average moisture contents can be determined with depth; (4) the system can be interfaced to accommodate automatic recording; (5) temporal soil moisture changes can be easily monitored with high accuracy and precision; (6) measurements are nondestructive once access tubes are installed; (7) can be used to calculate porosity when the fluid and grain densities are known; (8) can be used under almost any borehole conditions; and (9) near-surface measurements are more accurate than for neutron depth probes. **Disadvantages:** (1) Field instrumentation is expensive, difficult to use, and requires frequent maintenance; (2) the active radioactive source requires special handling for health and safety reasons, and might be unacceptable to regulatory authorities; (3) large variations in bulk density and moisture content can occur in highly stratified soils and limit spatial resolution; (4) unreliable in soils that swell and shrink with water content changes or with freeze and thaw; (5) instruments are susceptible to electronic drift and instabilities in the count rate; (6) soil temperature variations might affect accuracy of measurements; (7) failure to install equidistant dual access tubes will introduce errors in measurements; (8) double-tube method limited to relatively shallow depths because of difficulties in installing equidistant tubes to greater depths; (9) installation of equidistant tubes for double-tube method also difficult in steep terrain and in rocky materials; (10) accurate measurement of moisture requires independent measurement of dry bulk density; (11) leakage of water from perched layers along the wall of the casing might cause erroneous moisture measurement; (12) mixtures of water and other liquids will yield erroneous logs unless calibrated for the mixture; and (13) water moving through the sampling area at a constant rate will not change water content resulting in erroneous interpretation that there is no water movement in the soil profile.

Frequency of Use: Widely used in the petroleum industry; less frequently used for ground-water applications. More commonly used for laboratory measurement of soil core properties than directly in the field.

Standard Methods/Guidelines: **Density measurement:** ASTM (1991a-deep boreholes), ASTM (1991b-shallow depth). **Moisture measurement:** Gardner (1986).

Sources for Additional Information: **Major borehole references:** Keys (1990), Keys and MacCary (1971), Respold (1989), SPWLA (1978a); **Other borehole references:** Brown et al. (1983), Driscoll (1986), Everett (1985), Redwine et al. (1985), Rehm et al. (1985), Thompson et al. (1989), U.S. EPA (1992), Wheatcraft et al. (1986); **Vadose zone/soil moisture:** Bouwer and Jackson (1974), Brakensiek et al. (1979), Everett et al. (1983), Gardner and Roberts (1967), Morrison (1983), Poeter (1988), Schmugge et al. (1980), van Bavel and Underwood (1957), Vomocil (1954), Wilson (1980, 1981). Most of the general borehole logging texts indexed in Table 3-3 cover gamma-gamma logs, and references focusing on soil moisture and bulk density applications are indexed in Table 3-4.

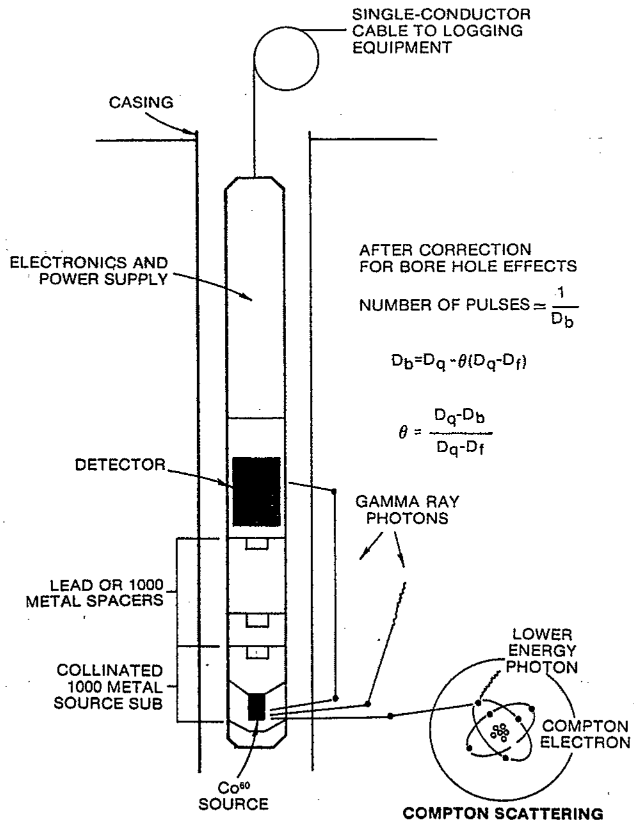


Figure 3.3.2 Principles and interpretation of single probe gamma transmission equipment (Morrison, 1983, after Keys and MacCary, 1971, by permission).

3.3 NUCLEAR BOREHOLE LOGGING

3.3.3 Neutron

Other Names Used to Describe Method: Neutron probe, neutron moisture meter, neutron moisture gage, neutron moderation, neutron thermalization, neutron scattering, neutron-gamma log, neutron attenuation.

Uses at Contaminated Sites: Measuring saturated porosity and moisture content in the unsaturated zone; soil moisture monitoring; locating perched water tables; measuring specific yield of unconfined aquifers.

Method Description: Probe contains a source of neutrons and detectors that are arranged so that the output is primarily a function of the hydrogen content of the borehole environment. The various available probe designs can be broadly classified as **surface** probes (which do not require a borehole [see Figure 6.2.2a]) and **depth** probes, which are used in boreholes. Figure 3.3.3 shows a depth probe and illustrates types of interactions between neutrons and hydrogen atoms. Fast neutrons (>0.1 Mev), which have been slowed to energies of less than 0.25 ev, are said to be **thermalized.** Neutron reactions also result in the emission of **gamma** rays by neutron capture. Neutron **moderation** involves the slowing of fast neutrons to **epithermal** electrons (0.1 to 100 ev). Neutron devices can be described by the type of radiation that causes most of the measured response. **Neutron-gamma** logs detect primarily gamma photons resulting from neutron reactions. **Neutron-thermal-neutron** probes respond mainly to thermal neutrons (<0.25 ev), and **neutron-epithermal-neutron** probes respond chiefly to neutrons between 0.1 and 100 ev. Figures 3-1a and 3-1b illustrate neutron logs for sedimentary and crystalline rocks. **Neutron attenuation** is a different technique similar to gamma attenuation (Section 3.3.2), but requires high neutron fluxes not readily available outside of a reactor facility, and is consequently not practical for field use (Gardner, 1986).

Method Selection Considerations: **Advantages:** (1) Rapid method of measuring soil moisture that is largely independent of temperature and pressure; (2) average moisture contents can be determined with depth; (3) the system can be interfaced to accommodate automatic recording; (4) temporal soil moisture changes can be easily monitored; (5) rapid changes in soil moisture can be detected; (6) readings are directly related to soil moisture; (7) measurements can be made repeatedly at the same site; (8) measurements are nondestructive once access tubes are installed; (9) can be used under almost any borehole conditions; and (10) moisture can be measured regardless of its physical state. **Disadvantages:** (1) Inadequate depth resolution makes measurement of absolute soil moisture content difficult and limits its use in studying evaporation, infiltration, percolation, and placement of the phreatic water surface; (2) the moisture measurement depends on many physical and chemical properties of the soil which are, in themselves, difficult to measure; (3) radioactive sources require special care in handling for health and safety reasons; (4) the sphere of influence of depth probes does not allow accurate measurements of soil water at or near the soil surface, unless special instruments designed specifically for use on the soil surface are used; (5) boron, cadmium, chloride, hydrocarbons, and other fast neutron moderators can interfere with moisture determinations; (6) difficult to define horizontal distribution of water since moisture close to the neutron source has a more pronounced effect on counting rate than pore water at a greater distance; (7) might not be accurate enough to detect slight water content changes in the dry range to infer water movement; (8) less accurate for monitoring water movement than measurement of matric potential heads, especially when water flow is in channels that transmit water without detectable changes in water content; and (9) chemical might cause deterioration of some access tubes (e.g., aluminum).

Frequency of Use: Most commonly used nuclear method for measurement of soil moisture.

Standard Methods/Guidelines: API (1974), ASTM (1988, 1992), Gardner (1986).

Sources for Additional Information: **Ground-water texts covering the method:** Brown et al. (1983), Driscoll (1986), Keys (1990), Keys and MacCary (1971), Redwine et al. (1985), Rehm et al. (1985), Respold (1989), Thompson et al. (1989), U.S. EPA (1992), Wheatcraft (1986); **Vadose zone/soil moisture:** Bouwer and Jackson (1974), Brakensiek et al. (1979), Everett et al. (1983), Gairon and Hadas (1973), Hendrickx (1990), Hillel (1971), Holmes et al. (1967), Morrison (1983), Schmugge et al. (1980), Wilson (1980, 1981). See also, reports and other

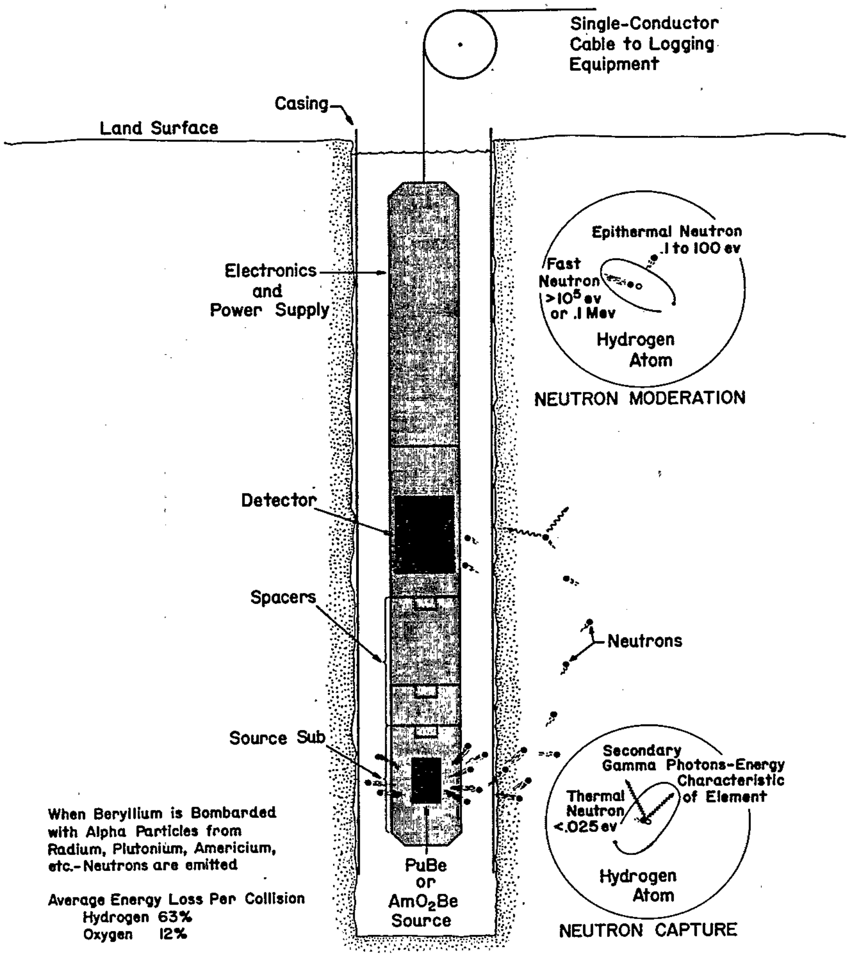


Figure 3.3.3 The equipment and principles of a depth neutron probe (Keys and MacCary, 1971).

references indexed in Table 3-4, and Section 6.2.2. Most of the general borehole logging texts indexed in Table 3-3 also cover neutron logs.

3.3 NUCLEAR BOREHOLE LOGGING

3.3.4 Gamma-Spectrometry

Other Names Used to Describe Method: Spectral-gamma log, spectra-gamma log, spectro-gamma log, spectromic-gamma log.

Uses at Contaminated Sites: Performing lithology and stratigraphic correlation; identifying artificial radioisotope contaminants in the subsurface.

Method Description: A spectral-gamma probe is similar to a gamma probe except that a channel analyzer with a variable threshold or "window" adjustment is used, which allows adjustment of the energy range of pulses to be recorded per unit time on the log. Figure 3.3.4 shows the gamma spectra of potassium, uranium, and thorium. Recording all pulses between thresholds A and B in this figure gives a value that is related to the potassium-40 content, if uranium and thorium contributions are removed. Similarly, the count rate between thresholds B and C are primarily related to uranium, and the count rate above threshold C is related to thorium. The amount and energy level of gamma photons can be recorded on either a **continuous** log or at selected depths with a **stationary** probe.

Method Selection Considerations: **Advantages:** (1) Gamma spectrometry allows more precise identification of lithology than a regular gamma log (Section 3.3.1); (2) types and amounts of radioisotopes can be measured; and (3) involves radiation detection only, so no radioactive sources required for the instrumentation. **Disadvantages:** (1) Equipment is expensive; and (2) substantial errors in quantitative results are common because of the complexity of the real-time calculations to produce a spectral log.

Frequency of Use: Widely used in the petroleum industry and should probably be used more frequently in ground-water investigations.

Standard Methods/Guidelines: --

Sources for Additional Information: Adams and Gasparini (1970), Keys (1990), Keys and MacCary (1971), Rider (1986), Schlumberger (1989b), Schneider (1982), Serra (1984a), U.S. EPA (1992).

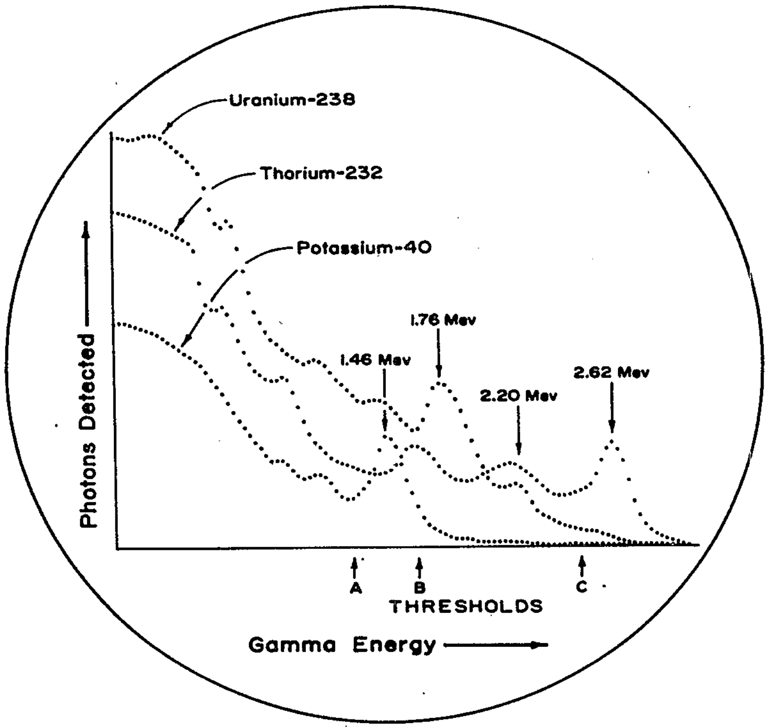


Figure 3.3.4 Gamma spectra for potassium, uranium, and thorium with energy "window" threshold for differentiating the three elements (Keys and MacCary, 1971).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.3 NUCLEAR BOREHOLE LOGGING

3.3.5 Neutron Activation

Other Names Used to Describe Method: Activation, cyclic activation tool.

Uses at Contaminated Sites: Performing remote identification of elements present in the ground-water and adjacent rocks; detecting flow of fluids behind casing.

Method Description: Uses neutrons to "activate" stable isotopes in the borehole and identify the activated element by measuring the amount and energy level of emissions (see gamma spectroscopy, Section 3.3.4). A large number of elements can be detected with this method, with sensitivities ranging from parts per million to percentage levels, depending on the element (Figure 3.3.5). A procedure similar to the neutron activation borehole technique (Section 3.3.5) has been used at the surface to determine cement content in soil-cement mixtures and concrete (Iddings et al., 1979).

Method Selection Considerations: **Advantages:** (1) Can be used in a wide variety of borehole conditions; (2) the same probe can be used to create a standard gamma log and for neutron thermalization measurements; (3) semi-quantitative analysis of major elements is possible; (4) measuring variations in the concentration of aluminum provides information on clay content; and (5) carbon-to-oxygen ratios and silicon-to-calcium ratios from neutron activation logs can be interpreted in terms of lithology and in-situ hydrocarbons. **Disadvantages:** (1) Instrumentation is complex; (2) larger neutron source is required compared to conventional neutron logging in order to keep neutron activation time within practical limits; (3) radioactive sources require special care in handling for health and safety reasons and generally limits use to deep boreholes (a neutron generator has the advantage of emitting no radioactivity when it is turned off); (4) equipment might not be readily available; (5) quantitative analysis is not likely to be as accurate as laboratory analysis using the same technique; and (6) logging slow if neutron source is weak or elements of interest require a long activation time.

Frequency of Use: Relatively new method with potential for wide application in ground-water hydrology.

Standard Methods/Guidelines: --

Sources for Additional Information: Keys (1990), Schneider (1982), Serra (1984a), U.S. EPA (1992).

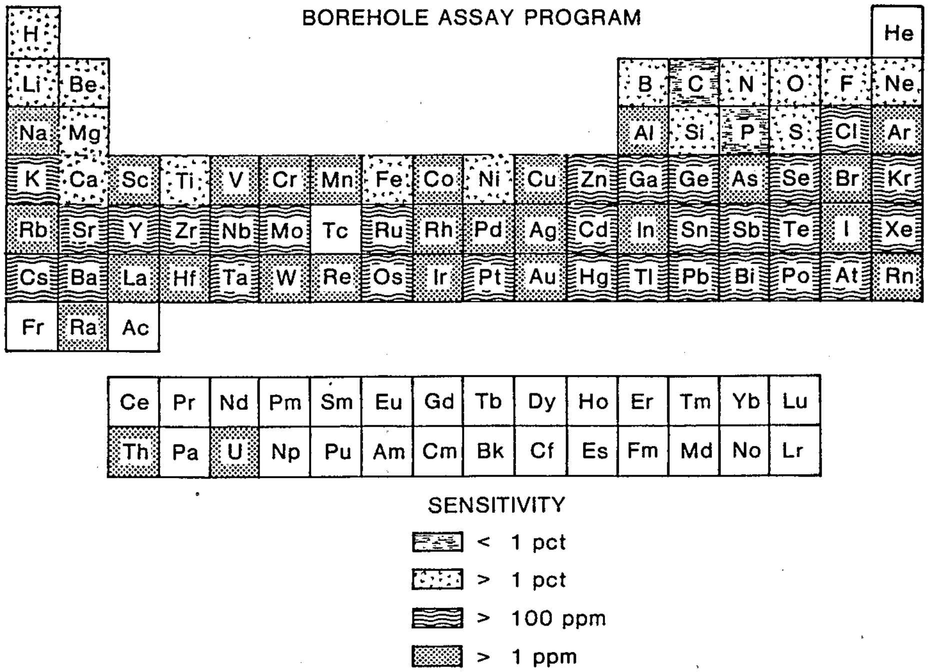


Figure 3.3.5 Estimated sensitivity that can be expected with neutron activation methods for various elements (Schneider, 1982).

3.3 NUCLEAR BOREHOLE LOGGING

3.3.6 Neutron Lifetime

Other Names Used to Describe Method: Pulsed-neutron decay, pulsed-neutron lifetime log.

Uses at Contaminated Sites: Measuring salinity and porosity; detecting flow of fluids behind casing.

Method Description: A variant of the neutron activation technique, which uses a pulsed-neutron generator and a synchronously gated neutron detector to measure the rate of decrease of the neutron population. The rate of neutron decay is greatly affected by the chlorine concentration, providing a measurement of salinity and porosity similar to resistivity logs. This method also can be used to detect flowing water behind casings as part of mechanical integrity testing. In this application, neutrons interact with oxygen nuclei in the water to produce nitrogen-16, which decays with a half-life of 7.13 seconds, emitting gamma radiation. If water is flowing behind the casing, the flow can be calculated from the energy and intensity response of two gamma ray detectors mounted in the logging probe. Thornhill and Benefield (1990) describe use of a neutron lifetime logs with packers in EPA's leak test well near Ada, Oklahoma.

Method Selection Considerations: **Advantages:** (1) Borehole effects can be greatly decreased compared to conventional neutron logs by delaying the measuring gate; (2) can provide useful data through casing and cement; and (3) neutron generator does not emit radiation when it is turned off. **Disadvantages:** (1) More expensive than conventional neutron log; (2) equipment availability might be a problem; and (3) radioactive sources requires special care in handling for health and safety reasons and generally limits use to deep boreholes.

Frequency of Use: Used by petroleum industry to distinguish between oil, gas, and saltwater in cased wells; use to date in ground-water investigations has been limited.

Standard Methods/Guidelines: --

Sources for Additional Information: Dresser Atlas (1974), Keys (1990), Schlumberger (1989b), Serra (1984a), Thornhill and Benefield (1990), U.S. EPA (1992).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.4 ACOUSTIC AND SEISMIC LOGGING

3.4.1 Acoustic-Velocity (Sonic)

Other Names Used to Describe Method: Acoustic log, sonic log, transmit time log.

Uses at Contaminated Sites: Performing lithologic characterization; measuring porosity.

Method Description: An acoustic-velocity probe records the travel time of an acoustic wave from one or more transmitters to receivers in the probe. Two general types of measurements can be made in acoustic logging: (1) Interval transit time, which is the reciprocal of velocity, and (2) amplitude, which is the reciprocal of attenuation. **Single-** and **two-receiver** probes (Figure 3.4.1a) provide **uncompensated** logs, which are prone to errors resulting from tilting of the probe or variations in borehole diameter (Figure 3.4.1b). **Compensated** acoustic logs require a probe with two transmitters and two or four receivers, which allow identification of variations in borehole diameter by analyzing different arrival times of the two separate pulses at the two receivers (Figure 3.4.1c). Figures 3-1a and 3-1b illustrate acoustic-velocity logs for sedimentary and crystalline rocks.

Method Selection Considerations: **Advantages:** (1) Compensated logs provide useful information on secondary porosity in consolidated rock; and (2) formation porosity can be calculated if the velocity of the rock matrix and pore liquids is known; **Disadvantages:** (1) Difficult to obtain good results in unconsolidated materials that have low velocities; (2) requires fluid-filled boreholes; (3) cycle skipping can result from excessive attenuation by the fluid, the formation (deep fractures), or by equipment malfunction; and (4) variability in environmental factors affecting the transmission and attenuation of elastic waves make interpretation of logs difficult.

Frequency of Use: Beginning to be more widely used in ground-water studies.

Standard Methods/Guidelines: --

Sources for Additional Information: Brown et al. (1983), Driscoll (1986), Everett (1985), Guyod and Shane (1969), Keys (1990), Keys and MacCary (1971), Rehm et al. (1985), Respold (1989), Thornhill and Benefield (1990), U.S. EPA (1992), Wheatcraft et al. (1986); **Acoustic logging texts:** Guyod and Shane (1969), Paillet and Cheng (1991), SPWLA (1978b). Most of the general borehole logging texts indexed in Table 3-3 cover acoustic logs.

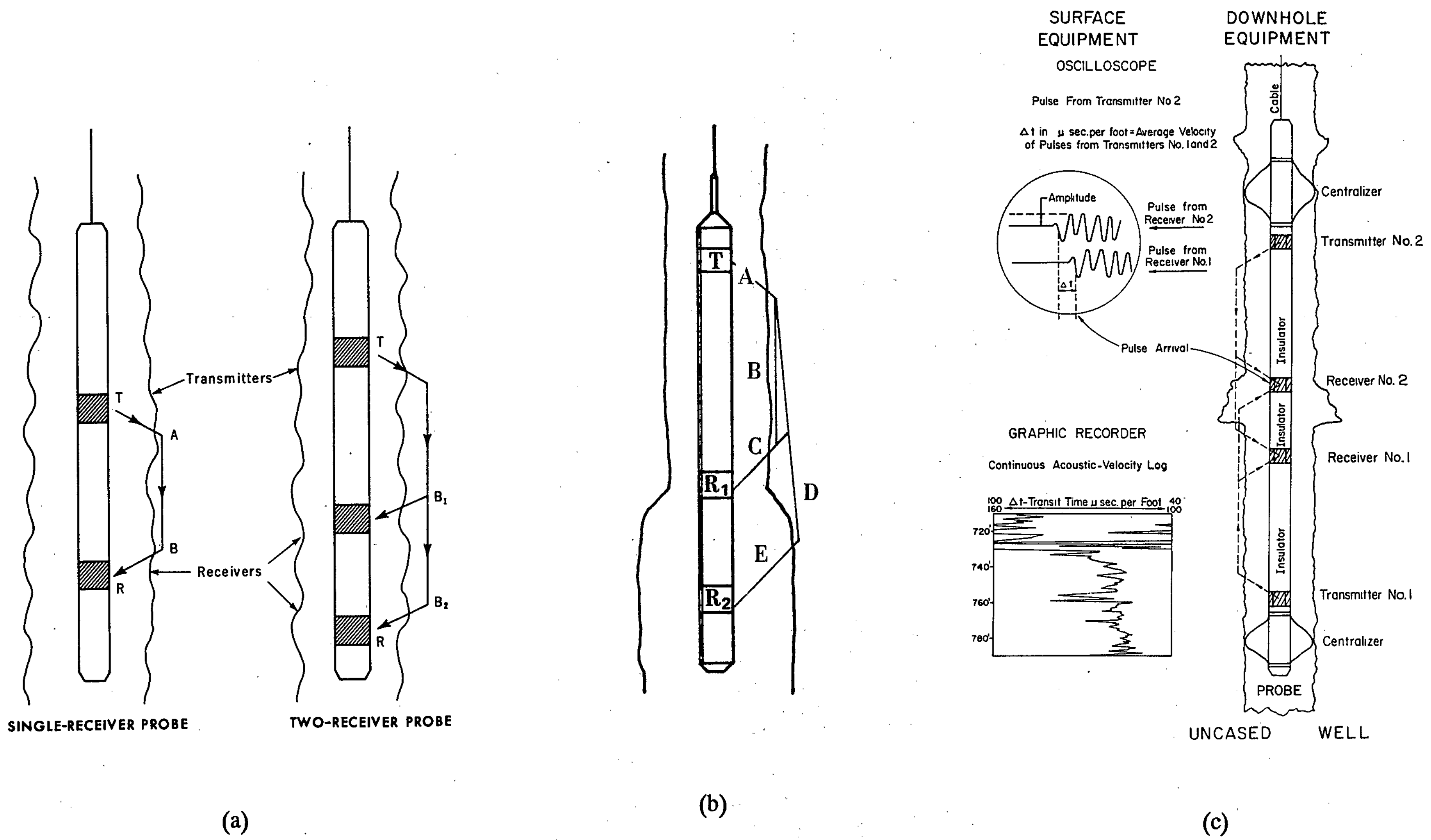


Figure 3.4.1 Acoustic velocity probes: (a) Single- and two-receiver uncompensated probes (Keys and MacCary, 1971); (b) Error in travel time measurements by two-receiver probe introduced by variation in borehole diameter (Dresser Atlas, 1974); (c) Principles and equipment for making borehole adjusted acoustic-velocity logs (Keys and MacCary, 1971).

3.4 ACOUSTIC AND SEISMIC LOGGING

3.4.2 Acoustic-Waveform

Other Names Used to Describe Method: Variable density, three-dimensional velocity, 3-D velocity.

Uses at Contaminated Sites: Providing information on lithology and structure; measuring elastic properties (vertical compressibility of an aquifer, prediction of subsidence and fracturing characteristics); characterizing fracture permeability; interpreting cement bond logs.

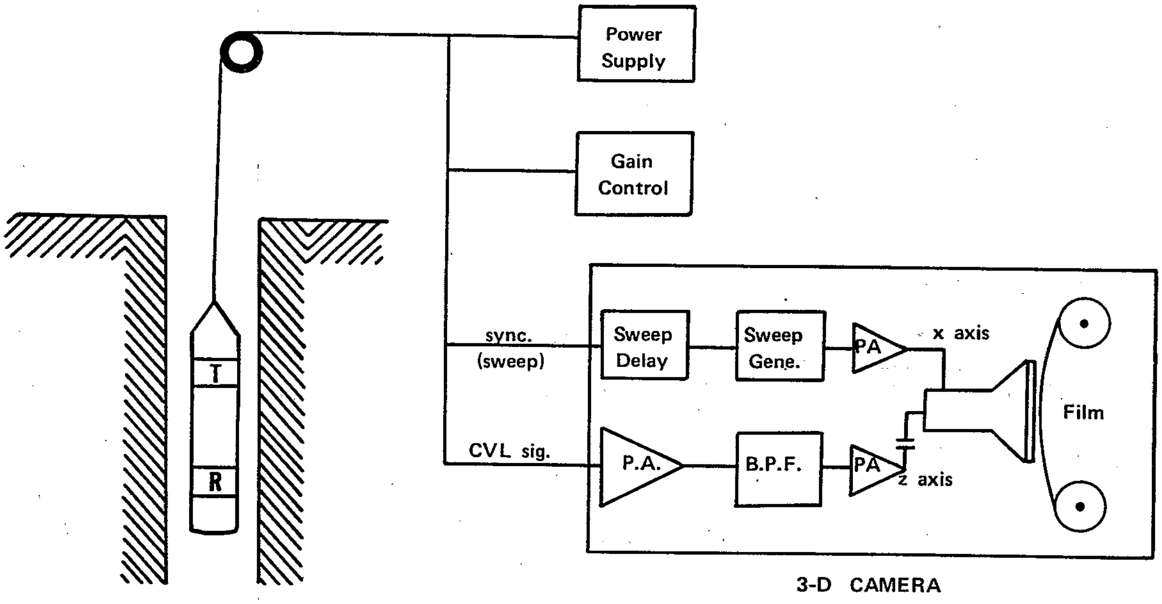
Method Description: An acoustic-waveform probe includes an acoustic signal transmitter and a receiver (Figure 3.4.2a), which is sensitive to the complete acoustic wave train (compressional, shear, and boundary or surface waves). These waves are recorded photographically using an oscilloscope display (Figure 3.4.2b) or are recorded digitally (Figure 3.4.2c). Various interpretations can be made from analysis of amplitude changes and velocity ratios of the wave forms.

Method Selection Considerations: **Advantages:** (1) One of the few down-hole methods the provides a complete record of the acoustic wave train so its greatest value is in situations where measurement of elastic properties is required (aquifer compressibility, and subsidence prediction); and (2) acoustic-waveform logs are required for accurate interpretation of some cement bond logs (acoustic-waveform logs for this purpose do not give comparable information to 3-D velocity logs). **Disadvantages:** (1) Limited to consolidated materials in fluid-filled boreholes; (2) other methods are probably better if the primary interest is in porosity or secondary permeability (see Table 3-2); and (3) tilting of the probe or irregular surfaces on the borehole will cause errors in the measured transit time of the compressional wave (see discussion of compensated and uncompensated acoustic logs [Section 3.4.1]).

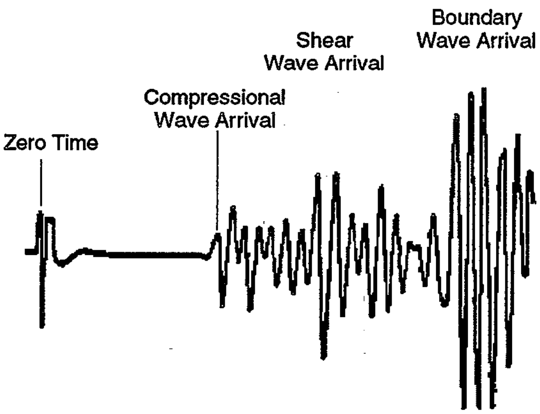
Frequency of Use: Not yet widely used in hydrogeologic studies, but has considerable potential for uses described above.

Standard Methods/Guidelines: --

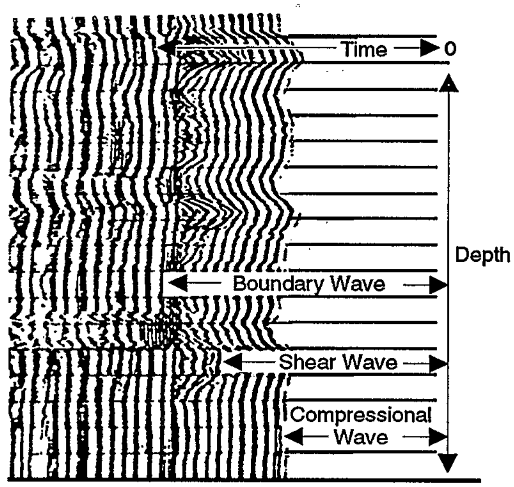
Sources for Additional Information: Everett (1985), Guyod and Shane (1969), Keys (1990), Thornhill and Benefield (1990), U.S. EPA (1992). See also, acoustic logging texts identified in Section 3.4.1. Most of the general borehole logging texts indexed in Table 3-3 cover acoustic waveform logs.



MEASURING SYSTEM



Variable Deflection Trace



3-D Velocity Log

Note: Time is shown increasing to the right on the variable deflection trace and to the left on the 3-D presentation. The right to left presentation is in keeping with other porosity logs.

Figure 3.4.2 Acoustic-waveform (3-D velocity) logging system (Hamilton and Myung, 1979).

3.4.3 Acoustic Televiewer*

Other Names Used to Describe Method: ATV probe, borehole televiewer, seismic televiewer, acoustical seisviewer.

Uses at Contaminated Sites: Characterizing fractures and solution openings; measuring strike and dip of fractures and bedding planes.

Method Description: An ATV probe uses a rotating transducer that serves as both transmitter and receiver of high-frequency acoustic pulses. An oscilloscope and light sensitive paper are used to create a 360 degree scan of the borehole wall and provide high-resolution images of fractures and solution openings. Figure 3.4.3 shows how a dipping fracture that intersects a borehole appears on an ATV scan. A flux-gate magnetometer mounted on the vertical axis of the probe senses the earth's magnetic field and indicates the orientation of features on the log (Figure 3.4.3).

Method Selection Considerations: **Advantages:** Excellent method for characterizing secondary porosity (fractures and solution features). **Disadvantages:** (1) Equipment is complex and expensive; (2) requires experienced operator; (3) logging speed for high resolution is slow (about 5 feet/min.), creating excessively long logging runs for deep wells; and (4) viscous drilling fluids and oblong or over-gage borehole diameters attenuate the signal.

Frequency of Use: Uncommon in ground-water studies because of cost and complexity.

Standard Methods/Guidelines: --

Sources for Additional Information: Everett (1985), Guyod and Shane (1969), Hamilton and Myung (1979), Keys (1990), Serra (1984a), U.S. EPA (1992).

*The term televiewer also is sometimes used for borehole television, so care should be used when running across this term to determine what type of instrument is being referred to.

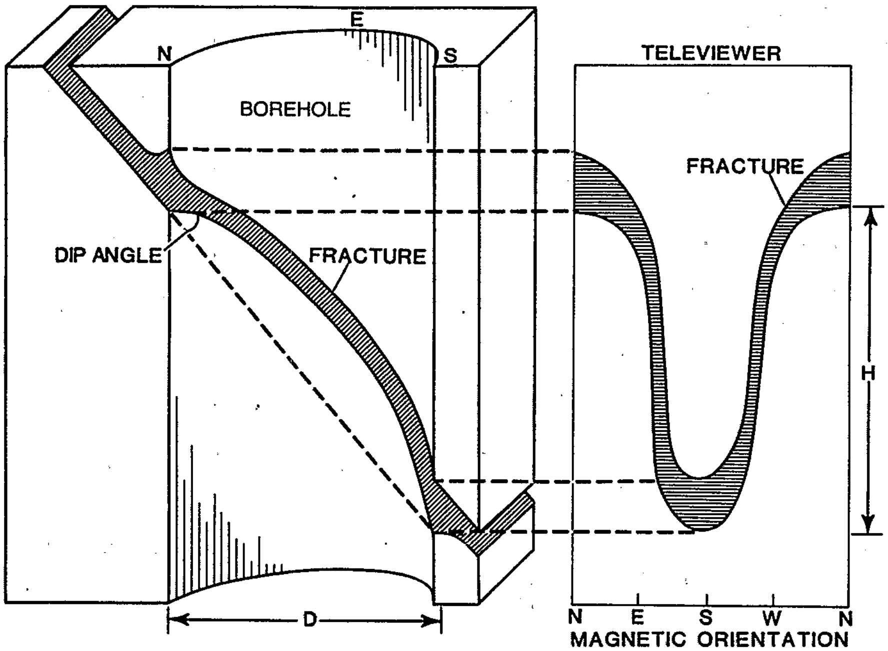


Figure 3.4.3 Three-dimensional view of a fracture intersecting a borehole and appearance of the same fracture on an acoustic televiewer log (Keys, 1990).

3.4.4 Surface-Borehole Seismic Methods

Other Names Used to Describe Method: Vertical seismic profiling (VSP); downhole/uphole methods.

Uses at Contaminated Sites: **VSP:** Detecting isolated inclusions, lithologic boundaries, and homogeneous areas; detectiing fractures; estimating permeability and hydraulic conductivity. **Downhole/uphole:** Measuring soil stiffness and stress-strain properties affecting site response to earthquakes.

Method Description: Seismic borehole surveys measure the velocities of compressional (P) waves (see Section 1.4.1) and shear (S) waves (see Section 1.4.4) at various depths below the ground surface. P- and S-wave velocities are used to calculate dynamic soil and rock properties such as: (1) Shear modulus, (2) Young's modulus, (3) bulk modulus, and (4) Poisson's ratio. **VSP:** Principles are the same as for surface seismic refraction and reflection (Sections 1.4.1 and 1.4.2). Geophone arrays are placed vertically in one or two boreholes, and arrival times of seismic waves from a surface source are measured (Figure 3.4.4a). When the primary seismic energy waves intersect a fluid-filled fracture zone, part of the energy is reflected back to the surface and a secondary seismic wave is created in the fluid. This secondary wave travels in the fluid along the fracture, and if the fracture intersects the borehole, a **tube** wave is created in water in the borehole (Figure 3.4.4a). VSP also can be used as a cross borehole method (Section 3.4.6). **Downhole/uphole methods:** Downhole measurement of P-wave (compressional) and S-wave (shear) velocities are made using a fixed surface source and string of geophones placed in a borehole (Figure 3.4.4b) or a single downhole triaxial sensor that is moved to various measurement depths within the borehole (usually 5 to 10 foot increments). In uphole measurement, the positions of the source and seismometer/geophone array are interchanged (Figure 3.4.4c). A variant of the downhole method is to use a **seismic cone penetrometer** (Figure 3.4.4d). In this test a cone penetrometer containing a triaxial receiver system is pushed into the soil. Seismic shear waves are generated at the surface in the vicinity of the cone and wave velocities and moduli are inferred from the travel times of the waves between the source and the cone. See Section 2.2.2 for additional information on cone penetrometers.

Method Selection Considerations: **VSP Advantages:** Use of VSP in conjunction with surface seismic measurements allows more accurate three-dimensional interpretation of seismic data. **VSP Disadvantages:** (1) Equipment is more complicated to set up than surface seismic methods; and (2) equipment might be less readily available than surface seismic instrumentation. **Downhole/Uphole Advantages:** (1) Provides higher resolution of subsurface layers of soil and rock for the area surrounding a borehole than is possible with a surface refraction survey; (2) especially good at detecting thin layers or a low velocity layer beneath a higher velocity layer; and (3) simpler than the crosshole seismic shear method. **Downhole/Uphole Disadvantages:** Less accurate than cross borehole seismic methods (uncertainties in compressional and shear wave velocities can be 10 to 20 percent). **Seismic Cone Penetrometer Advantages:** (1) Does not require drilling of a borehole; (2) cone penetrometer rigs also can be used for stratigraphic testing (see Section 2.2.2) and soil-gas/ground-water sampling (see Section 5.5.2).

Frequency of Use: **VSP** has been reported at several sites with sufficient success to probably justify more widespread use of this method. **Downhole/uphole** methods are used routinely in geotechnical investigations to determine soil stiffness, and are commonly used to augment data from surface seismic surveys. **Seismic cone penetrometers** are commonly used in geotechnical investigations and the versatility of cone penetration rigs has resulted in increased use in contaminant site investigations (see Section 2.2.2).

Standard Methods/Guidelines: --

Sources for Additional Information: **VSP texts:** Balch and Lee (1984), Gal'perin (1974), Hardage (1985), Toksoz and Stewart (1984); **VSP (other):** Labo (1987), Redwine et al. (1985), Schlumberger (1989a), Serra (1984a), U.S. EPA (1992); **Downhole/uphole:** CH2M Hill (1991), Redwine et al. (1985); **Seismic cone penetrometer:** CH2M Hill (1991), Robertson et al. (1986).

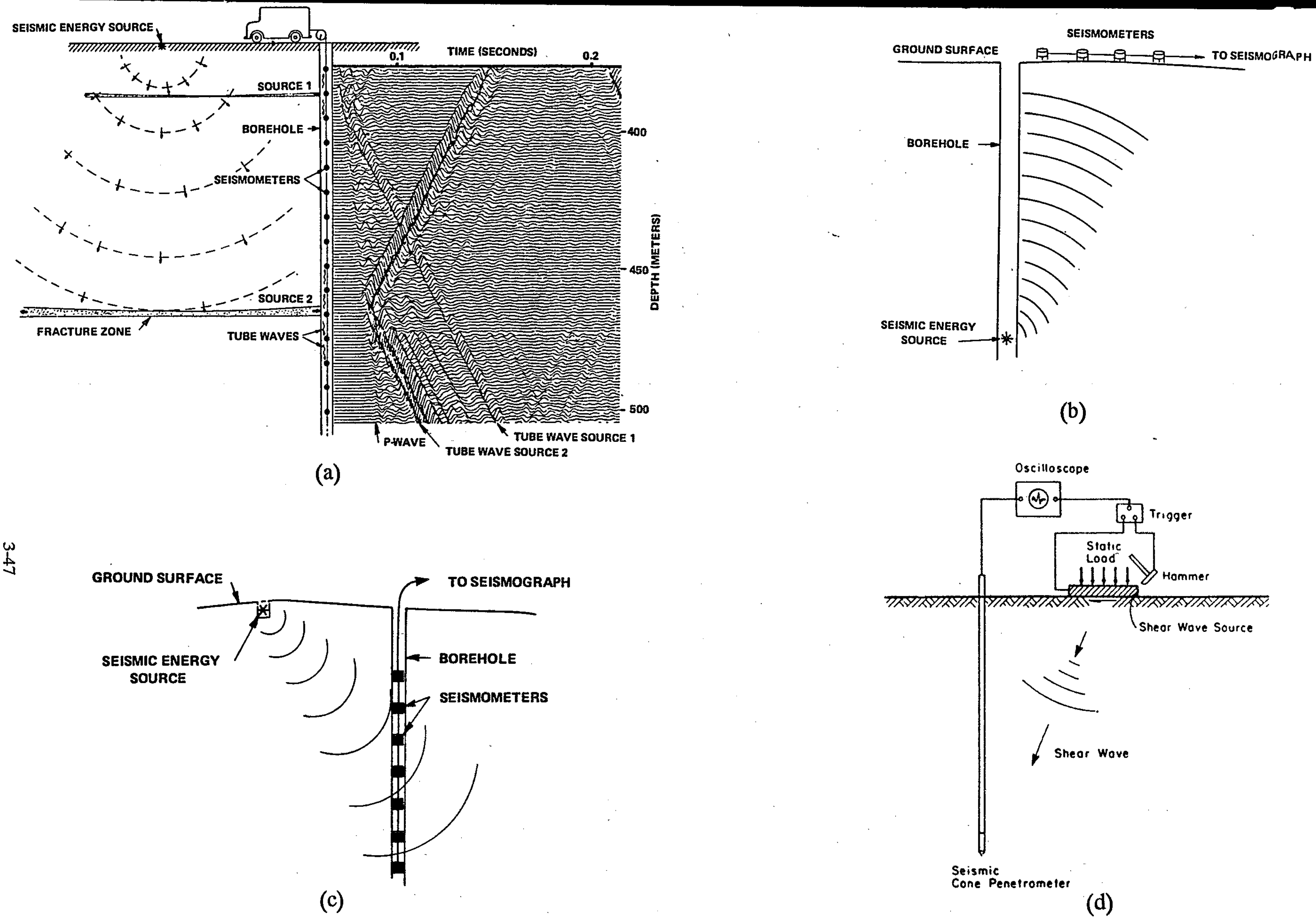


Figure 3.4.4 Surface-borehole seismic techniques: (a) Vertical seismic profiling (Redwine et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission); (b) Downhole seismic survey (Redwine et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission); (c) Uphole seismic survey (Redwine et al., 1985, Copyright © 1985, Electric Power Research Institute, EPRI EA-4301, *Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature*, reprinted with permission)); (d) Seismic cone used in a downhole test (CH2M Hill, 1991, after Robertson et al., 1986, by permission).

3.4 ACOUSTIC AND SEISMIC LOGGING

3.4.5 Geophysical Diffraction Tomography

Other Names Used to Describe Method: GDT, variable density acoustic tomography, seismic tomography.

Uses at Contaminated Sites: Obtaining high resolution subsurface cross-sectional images for identification of buried objects, define clean areas, and stratigraphic mapping.

Method Description: The field layout for geophysical diffraction tomography is similar to that for vertical seismic profiling. Typically, a hydrophone array is placed down a borehole with a seismic source at the surface, but cross-borehole and surface-to-two-borehole configurations also are possible (Figure 3.4.5a). The seismic source is typically an acoustic gun that is moved along a line on the ground surface and fired at fixed intervals (3.4.5b). GDT differs from other seismic method in the way seismic signals are used and how the data received by the hydrophones is processed (Figure 3.4.5c). GDT is a form of analysis of wave motion similar to that used for CT scanners in medicine (see also, Section 6.2.7 for use of CT methods for soil moisture measurement). Imaging algorithms are able to analyze the diffraction of waves caused by inhomogeneities and to create a high resolution cross-sectional image of the transect across which the acoustic gun is moved. Objects in the soil as small as about 1 foot in diameter can be located with a 2-foot seismic source spacing on the transect. Figure 3.4.5d shows a source-receiver configuration using both simultaneous surface and borehole seismic signals.

Method Selection Considerations: **Advantages:** (1) Relatively new method that shows great promise for high resolution imaging of buried wastes; and (2) might provide results when conventional surface geophysical methods are not working well due to unfavorable site conditions. **Disadvantages:** (1) New technique with limited operational and field experience; and (2) equipment and personnel familiar with procedures for data collection and analysis might not be available.

Frequency of Use: Limited use to date, but good potential for wider application.

Standard Methods/Guidelines: --

Sources for Additional Information: Anderson and Dziewinski (1984), Mahannah et al. (1988), U.S. EPA (1992). See also, texts on borehole imaging and tomography indexed in Table 3-3.

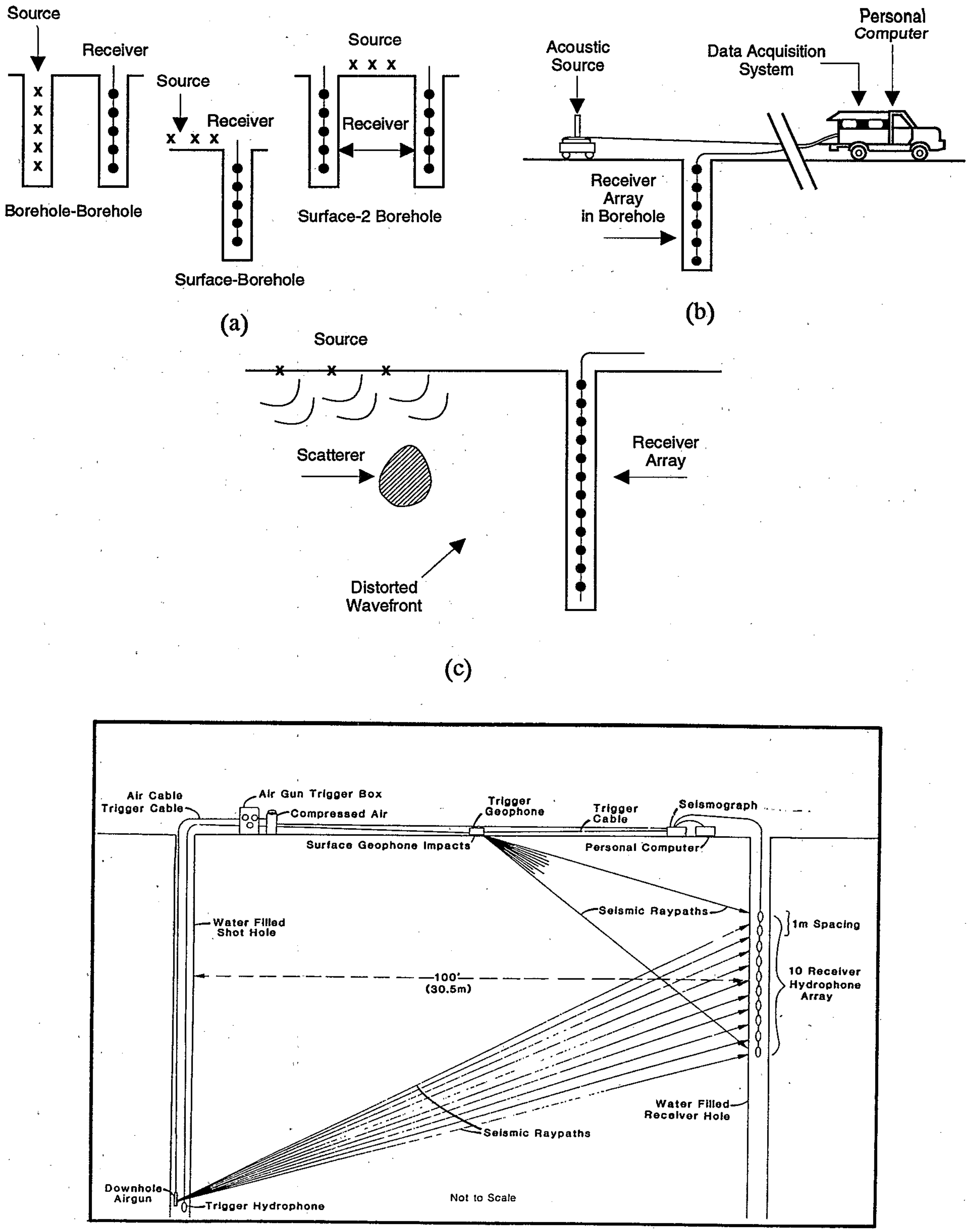


Figure 3.4.5 **Geophysical diffraction tomography: (a) Source-receiver configurations; (b) Configuration of test system; (c) Conceptual example of GDT (Mahannah et al., 1988, by permission); (d) Source-receiver configuration using both surface and downhole seismic sources (Bates et al., 1991, by permission).**

3.4.6 Cross-Borehole Seismic Methods

Other Names Used to Describe Method: Cross-borehole shear, crosshole vertical seismic profiling (VSP).

Uses at Contaminated Sites: Evaluating stratigraphy and porosity; detecting cavities, open fractures, zones of weakness, and other discontinuities; measuring dynamic moduli for safety evaluations of major structures, such as dams; designing vibration-sensitive engineered structures.

Method Description: **Crosshole seismic shear:** An energy source is placed in one borehole and geophones are placed in nearby borings at the same depth (Figure 3.4.6). Typically, three boreholes separated by 3 to 5 meters in line with a seismic source borehole are used. Borehole deviation surveys (Section 3.6.3) are required within each drill hole to determine accurate distances between boreholes at all depths. 3-D velocity transducers are wedged in at the same elevation in each borehole and arrival times of both P-and S- waves from the subsurface seismic source are measured. Repeated measurements at different levels in the boreholes allow development of shear wave velocity profiles using the travel time of first arrivals (direct-wave arrival) and the result of the borehole deviation data. **Crosshole VSP:** Similar to surface-borehole vertical seismic profiling (Section 3.4.4), except that the seismic source is used to generate seismic waves in a borehole.

Method Selection Considerations: **Crosshole Seismic Shear Advantages:** (1) Most reliable method for in situ measurement of shear wave velocity because of the small height of soil sampled at each depth; (2) very little interpretation of field data is required because the travel path of the seismic signal is predominantly horizontal. **Crosshole Seismic Shear Disadvantages:** Complicated to set up. **Crosshole VSP:** Similar to advantages and disadvantages discussed in Section 3.4.4.

Frequency of Use: Use in geotechnical investigations is well established; has been infrequently used at contaminated sites.

Standard Methods/Guidelines: ASTM (1991c).

Sources for Additional Information: Butler and Curro (1981), CH2M Hill (1991), Gal'perin (1974), Redwine et al. (1985), U.S. EPA (1992), Wheatcraft et al. (1986).

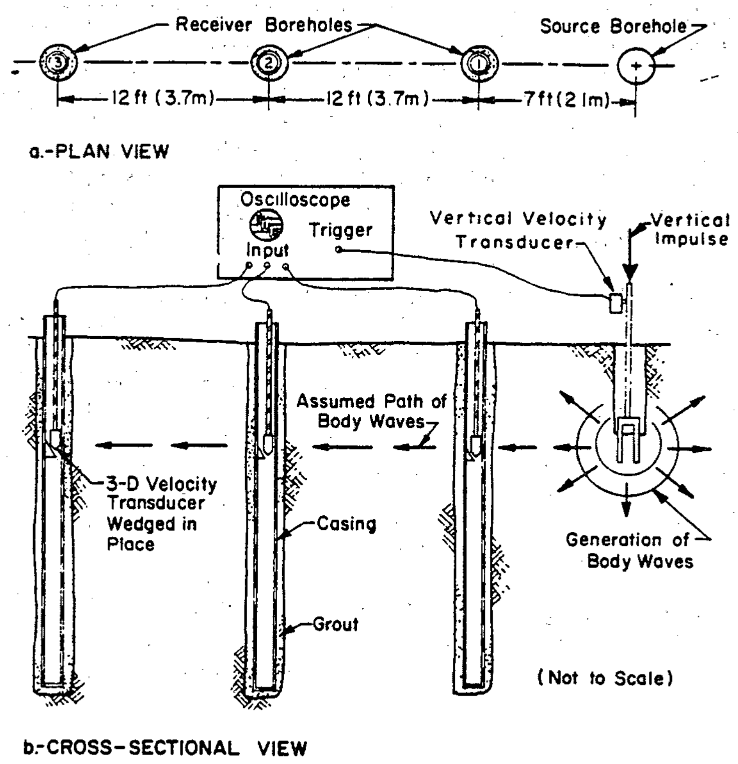


Figure 3.4.6 Cross-borehole seismic method (Hoar and Stokoe, 1977, Copyright ASTM, reprinted with permission).

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.1 Caliper

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Obtaining information on borehole configuration, lithology, and secondary porosity (fracture and solution zones); correlating with other geophysical logs; approximating estimates of mudcake thickness.

Method Description: Caliper logs are made by a probe that measures borehole diameter. Many types are available, including mechanical, electric, and acoustic. **Mechanical caliper** tools are the most common type and logs are made by first lowering the device to the hole's bottom with the arms resting against the body of the probe. The arms are opened, usually with an electric motor, and the probe, with the arms touching the sides of the borehole, is raised. Deflections of the arms are transmitted to the precision potentiometer and the signal passed to the surface over the cable. Mechanical caliper tools have from one to six arms and can measure variations as small as 1/4 inch in borehole diameter. Figure 3.5.1 illustrates a three-arm caliper probe, and Figure 3-1 shows caliper logs for holes in sedimentary rocks with decreasing hole diameter (Figure 3-1a) and fractured crystalline rock (Figure 3-1b).

Method Selection Considerations: **Advantages:** (1) Caliper logs are an essential complement to guide the interpretation of other types of logs that are affected by borehole diameter (gamma, gamma-gamma, resistivity, self potential, and flowmeters); (2) equipment is readily available; and (3) interpretation is easy (diameter can be read directly from the log). **Disadvantages:** (1) Failure to center properly in holes that are as little a few degrees off from vertical can result in erroneous readings (diameter less than it actually is); and (2) special types are required for measuring diameter of inclined or horizontal boreholes

Frequency of Use: Commonly used in conjunction with other logging methods.

Standard Methods/Guidelines: --

Sources for Additional Information: Brown et al. (1983), Bureau of Reclamation (1981), Driscoll (1986), Everett (1985), Keys (1990), Keys and MacCary (1971), Redwine et al. (1985), Respold (1989), U.S. EPA (1992). Most of the general borehole logging texts indexed in Table 3-3 cover caliper logs.

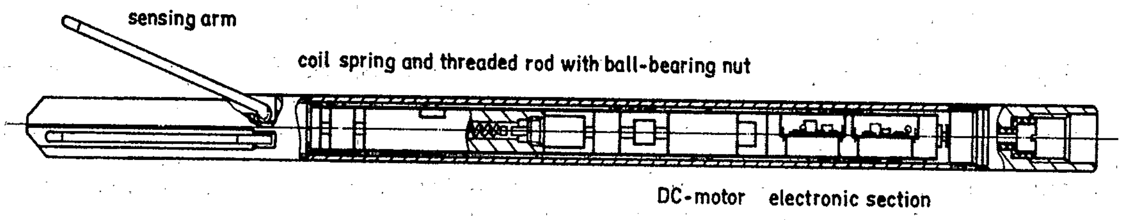


Figure 3.5.1 Three-arm caliper probe (Respold, 1989, by permission).

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.2 Temperature Logs

Other Names Used to Describe Method: Differential temperature log, radial differential temperature (RDT) survey.

Uses at Contaminated Sites: Detecting contaminant plumes (where temperature differs from the natural ground-water); obtaining information on movement of natural or injected water, permeability distribution, and relative hydraulic head; locating fracture/solution zones; monitoring infiltration/ground-water recharge; locating cement grout; detecting gas leaking into a well.

Method Description: A **temperature log** records temperature versus depth with a temperature sensor, usually a thermistor (Section 8.2.2) mounted inside a cage or tube to protect it and to channel the fluid past the sensor. Temperature logs taken in an open borehole, at time intervals after drilling has stopped, often provide an indication of the location of permeable strata (Figure 3.5.2). Temperature logs often are made in combination with fluid conductivity logs (see Section 3.1.3 and Figure 5.5.4). In bedrock open-hole wells, changes in slope can indicate inflow or outflow. Isothermal slopes indicates borehole flow between fractures under different pressure heads. In the absence of borehole flow, the temperature approaches the geothermal gradient (Williams and Conger, 1990). A **differential-temperature log** records the rate of change in temperature versus depth and can be obtained by computer calculation from a temperature log or by using a specially designed logging probe with either two sensors with a vertical spacing, or one sensor and an electronic memory that compares the temperature at one time with selected previous times. A **radial differential temperature** tool uses two highly sensitive temperature probes that extend from the probe to contact the casing. As the probes are rotated, they measure any difference in temperature at two points on the casing 180 degrees apart and can detect cooler water flowing behind a casing that has not been properly sealed.

Method Selection Considerations: **Advantages:** (1) Equipment is widely available; (2) rapid and inexpensive technique; (3) a differential-temperature log is more sensitive to changes in temperature gradient; and (4) interpretation is relatively straightforward. **Disadvantages:** (1) Temperature recorded is only that of the fluid surrounding the sensor, which might not be representative of the surrounding rocks due to disturbance by drilling, cementing and testing; and (2) thermal lag, self-heating, and drift of electronics might affect accuracy of readings.

Frequency of Use: Widely used in ground-water studies.

Standard Methods/Guidelines: Stevens et al. (1975).

Sources for Additional Information: Brown et al. (1983), Bureau of Reclamation (1981), Driscoll (1986), Everett (1985), Keys (1990), Keys and MacCary (1971), Redwine et al. (1985), Respold (1989), Thornhill and Benefield (1990), U.S. EPA (1992), Wheatcraft et al. (1986). See also, Section 1.6.2 and related references indexed in Table 1-5.

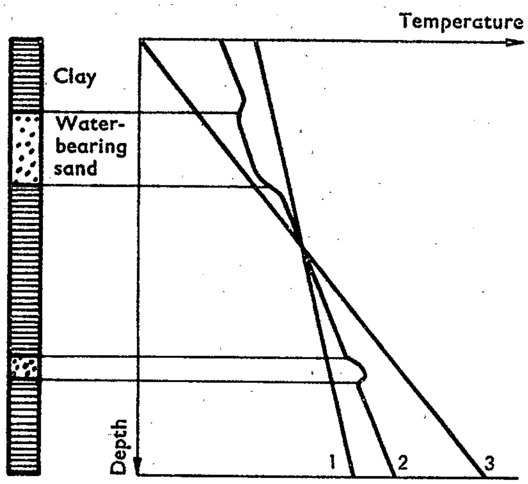


Figure 3.5.2 Temperature log showing water-bearing sands: Curve 1, immediately after stopping mud circulation; Curve 2, a few hours later; Curve 3, a few days later (Brown et al., 1983).

3.5.3 Mechanical Flowmeter

Other Names Used to Describe Method: Current flowmeter, impeller flowmeter, spinner log.

Uses at Contaminated Sites: Measuring vertical flow in boreholes; locating intervals of leakage in artesian wells; identifying fractures or permeable zones producing and accepting water.

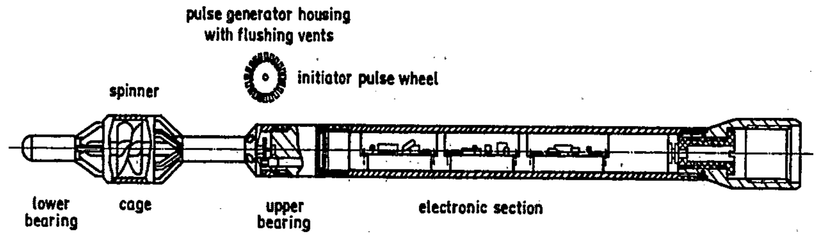
Method Description: Various designs have been developed. Most use a lightweight, three- or four-bladed impeller mounted on a shaft that rotates a magnet mounted on the same shaft (Figure 3.5.3a). The magnet actuates a switch, which generates electric signals that record the number of rotations of the impeller. Calibration of the instrument allows calculation of velocity of flow, and when combined with cross-sectional area, the amount of flow. Mechanical flowmeters usually required flow rates of at least 4 feet/minute, but velocities as low as 2 feet/minute can sometime be measured. Mechanical flowmeters can require pumping of the well to increase the flow rate sufficiently to identify zones of higher permeability (Figure 3.5.3b).

Method Selection Considerations: **Advantages:** Equipment is relatively inexpensive and readily available. **Disadvantages:** (1) Generally require larger diameter boreholes than other thermal and electromagnetic flowmeters (see next sections); (2) limited to measuring vertical flow; (3) the magnet and switch are placed in an oil-filled housing that create the possibility of contaminating monitoring-wells (minor consideration); and (4) turbulent flow near zones of high transmissivity can cause erratic response, reducing the accuracy of permeability calculations.

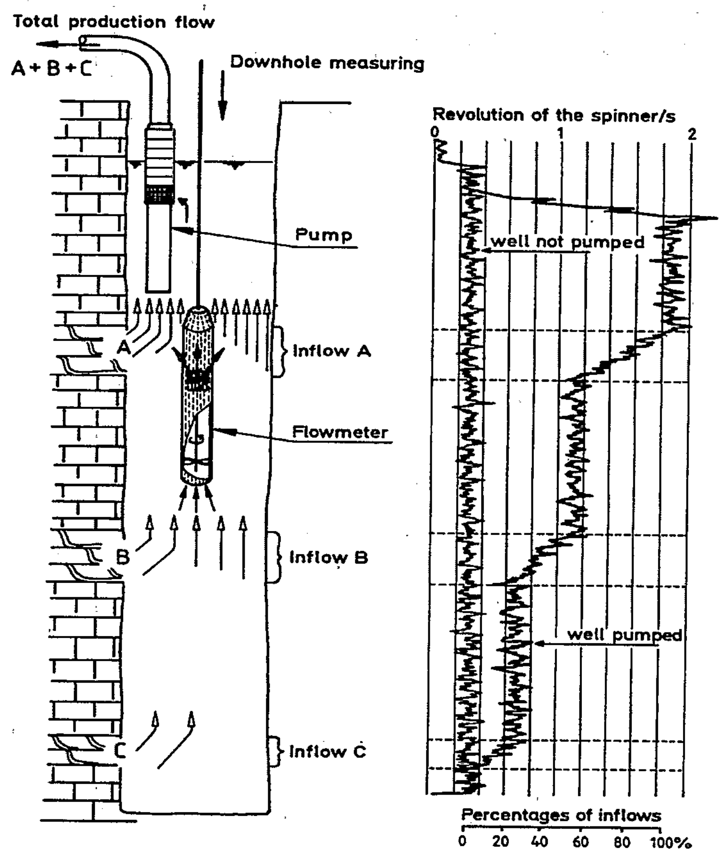
Frequency of Use: Commonly used in the water well industry.

Standard Methods/Guidelines: --

Sources for Additional Information: Brown et al. (1983), Driscoll (1986), Everett (1985), Hess and Wolf (1991), Keys (1990), Keys and MacCary (1971), Respold (1989), Schlumberger (1989b), U.S. EPA (1992).



(a)



(b)

Figure 3.5.3 Impeller flowmeter: (a) Probe; (b) Effect of pumping on flow from fracture zones on an impeller flowmeter log (Respold, 1989, by permission).

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.4 Thermal Flowmeter

Other Names Used to Describe Method: Heat-pulse flowmeter.

Uses at Contaminated Sites: Measuring vertical and/or horizontal flow (depending on the instrument) in boreholes; locating intervals of leakage in artesian wells; identifying fractures and zones of high permeability producing and accepting water for characterization of spatial variability of the subsurface.

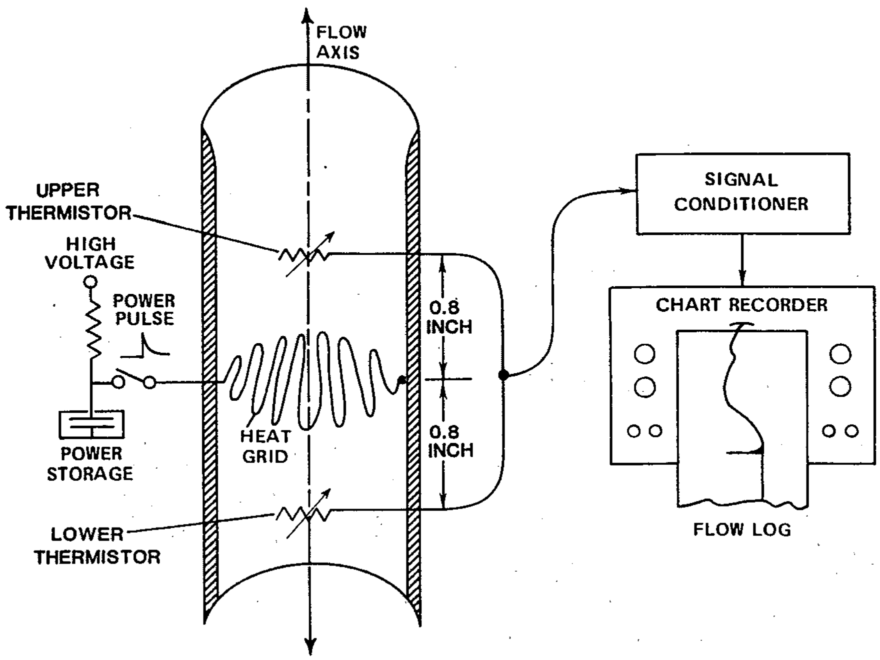
Method Description: Water passing through the flowmeter is suddenly heated and the time it takes the pulse of heated water to pass thermistors that are located either above or below the heat source (vertical flow, Figure 3.5.4a), or horizontal to the source (lateral flow), is recorded. When used with a packer and pump that concentrates flow, measurements at different levels in a borehole allow characterization of vertical changes in relative permeability in consolidated material and detection of fracture zones in boreholes in bedrock (Figure 3.5.4b).

Method Selection Considerations: **Advantages:** (1) More sensitive than mechanical flowmeters (able to measure vertical velocities as low as 0.1 feet/minute); (2) can measure either vertical or horizontal flow; (3) relatively recent refinements have made them the flowmeter of choice in most situations. **Disadvantages:** Channelizing of flow near slotted casing can give misleading readings.

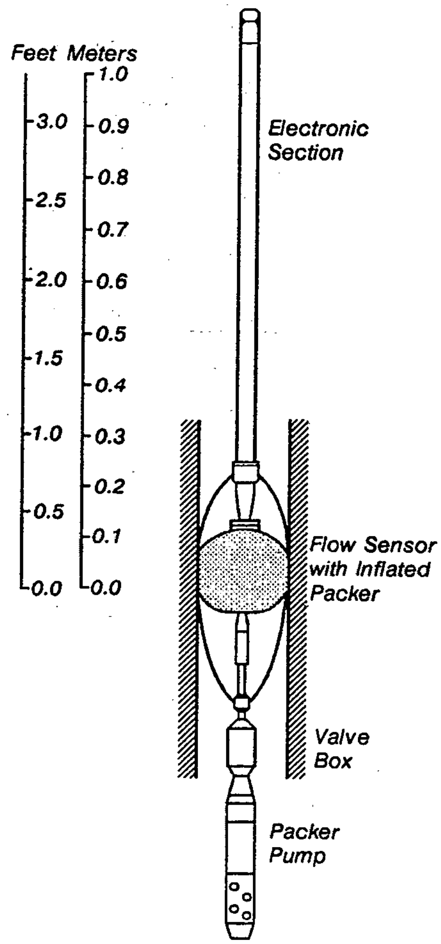
Frequency of Use: Common. Although relatively recent, they have gained rapid acceptance.

Standard Methods/Guidelines: --

Sources for Additional Information: Keys (1990), Keys and MacCary (1971), Molz et al. (1990), U.S. EPA (1992-18 references on thermal flowmeters), Wheatcraft et al. (1986).



(a)



(b)

Figure 3.5.4 Thermal flowmeter: (a) Equipment for making heat-pulse flowmeter logs (Keys, 1990); (b) The U.S. Geological Survey's thermal flowmeter with inflated flow-concentrating packer (Molz et al., 1990).

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.5 Electromagnetic (EM) Flowmeter

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Measuring vertical flow in boreholes; locating intervals of leakage in artesian wells; identifying fractures and zone of high permeability producing and accepting water for characterizing spatial variability of the subsurface.

Method Description: The EM flowmeter consists of an electromagnet and two electrodes placed 180 degrees apart and all cast in a durable epoxy (Figure 3.5.5). Water flowing past the magnetic field generated by the electromagnet creates voltage changes between the two electrodes, which transmit a signal to the surface that is directly proportional to the velocity of the water in accordance with Faraday's Law of Induction. The EM flow meter can be used in combination with a short-duration single well pump and/or an injection test in a fully screened borehole. Flow measurements are taken at around 0.3 meter intervals and hydraulic conductivity calculated for each interval based on flow rates.

Method Selection Considerations: **Advantages:** (1) Very sensitive to measurement of low flow rates (about 1 centimeter/minute compare to 3 centimeter/minute for thermal flowmeters, and an order of magnitude lower than impeller flowmeters); (2) measures flow rates with better accuracy and precision and require less calibration than impeller flowmeters; (3) equally well suited for pumping or injection test; (4) no moving parts means instrument is more durable and requires less maintenance than impeller flowmeters; and (5) shows less erratic flow response than impeller flowmeters in zones of high transmissivity. **Disadvantages:** The general disadvantages that are associated with a new method: (1) Limited operational and field experience; (2) limited equipment availability.

Frequency of Use: Relatively new method being developed by the Tennessee Valley Authority that shows considerable potential. Currently being tested by EPA at several Superfund sites.

Standard Methods/Guidelines: --

Sources for Additional Information: Young and Pearson (1990), Young and Waldrop (1989).

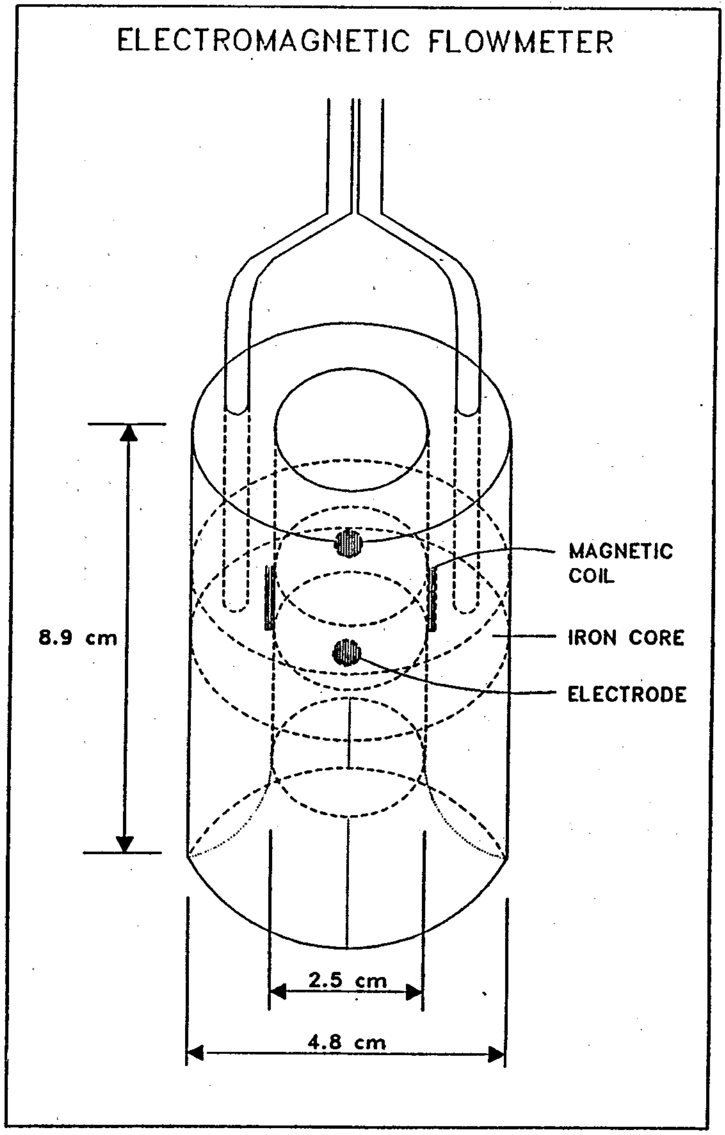


Figure 3.5.5 Electromagnetic flowmeter (Young and Waldrop, 1989, by permission).

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.6 Single-Borehole Tracer Methods

Other Names Used to Describe Method: Injector-detector probes, trace-injector probes, brine tracing, salt-injection, injection/withdrawal (pulse) technique, borehole dilution, colorimetric borehole dilution.

Uses at Contaminated Sites: Measuring vertical and/or horizontal (using ground-water velocities and direction), estimation of hydraulic conductivity (borehole dilution); well integrity testing.

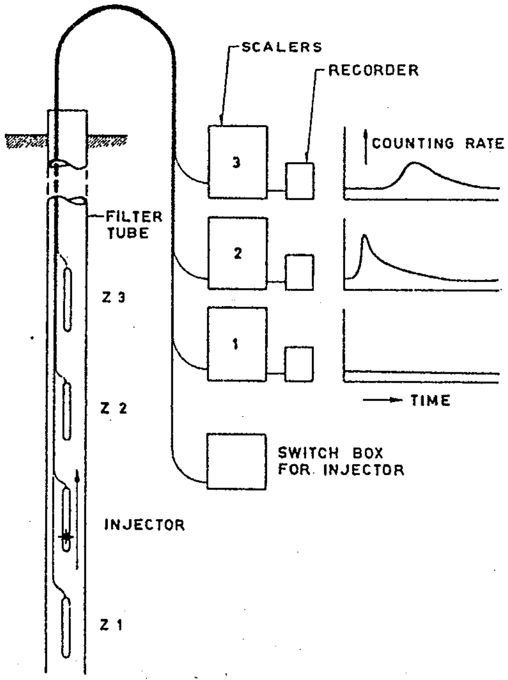
Method Description: **Injector-detector probes** have the injector in the middle and detectors (either fluid conductivity or gamma detectors, depending on the tracer that is injected) above and below. Alternatively, separate injector and detector probes can be used. Velocity is determined based on how long it takes the injected tracer to reach the detector. Figures 3.5.6a shows an arrangement of multiple detectors in a borehole using a radioactive tracer, and Figure 3.5.6b shows an single injector-detector probe and resulting logs when brines or different chemical composition are used. **Injection/withdrawal** tracer tests allow estimation of pore velocity (provided that porosity is know or can be estimated with reasonable accuracy) and longitudinal dispersion coefficient. A known amount of tracer is instantaneously added to the borehole, mixed, and then two to three borehole volumes of fresh water are pumped in to force the tracer to penetrate the aquifer. After a certain time, the borehole is pumped at a constant rate, which is large enough to overcome the natural ground-water flow, and the tracer concentration is measured with time or pumped volume. **Borehole dilution** can be used to measure the magnitude and direction of horizontal tracer velocity and vertical flow. A known quantity of tracer is introduced into the borehole, mixed, and then the concentration decrease is measured with time for velocity measurement. Packers often are required if measurement of horizontal flow is the main concern. Direction of flow is measured by slowly introducing a tracer (often radioactive) without mixing into a section of the borehole that has a compartmental sample (four to eight compartments) isolated by packers. After some time the sampler is opened, and the relative concentrations in the different compartments indicate flow direction. **Colorimetric borehole dilution** is a new method in which the change in concentration of an injected dye is measured by light transmitted by a colorimeter via fiber optics (Section 5.5.6).

Method Selection Considerations: **Advantages:** Very low flow velocities (as low as a few feet a day) can be measured using tracer methods. **Disadvantages:** (1) Salt solutions cannot be detected in water with similar salt concentration and the greater specific gravity introduces some errors; (2) health concerns associated with use of radioactive tracers limits their use in potable aquifers; and (3) turbulence associated with high flow rates in very permeable formations might affect accuracy of measurements by dispersing the tracer.

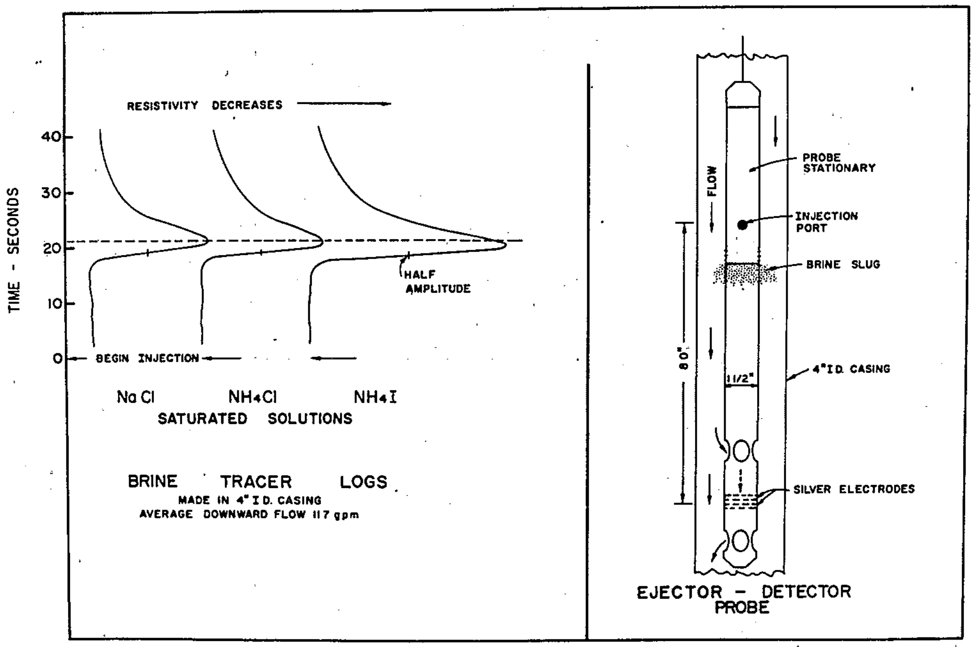
Frequency of Use: Use not commonly reported at hazardous waste sites.

Standard Methods/Guidelines: --

Sources for Additional Information: Bennett et al. (1960), Davis et al. (1985), Everett (1985), Hall (1993), Keys (1990), Keys and MacCary (1971), Patten and Bennett (1962), U.S. EPA (1992).



(a)



(b)

Figure 3.5.6 Single-borehole tracer techniques: (a) Arrangement of multiple detectors for determining vertical flow in a borehole using a radioactive tracer (Brown et al., 1983); (b) Brine ejector-detector probe (right) and logs of three different salts used as tracers (left) (Keys and MacCary, 1971).

3.5.7 Television/Photography

Other Names Used to Describe Method: Borehole camera, TV camera, televiewer*, colloidal boroscope, single vertical photo survey, stereo photo survey, motion picture survey.

Uses at Contaminated Sites: Performing lithologic/stratigraphic characterization; providing information on frequency, size, and orientation of fractures; performing vertical correlation of rock cores where voids are present; inspecting casing/monitoring well integrity; performing remote inspection of integrity of nuclear and chemical waste storage tanks (remote tank inspection robotic system); assessing local ground-water flow velocity and colloidal transport potential (colloidal boroscope).

Method Description: **Television:** Television cameras (black-and-white or color) are attached to a flexible multilead underwater video cable and lowered down the borehole for visual inspection of the borehole walls and downward (Figure 3.5.7a). Depth of the probe is measured and displayed on the monitor. The **colloidal boroscope** is a recently developed waterproof video camera capable of viewing indigenous colloids in a monitoring well. Optical magnification allows observation of the density, flow direction, and velocity of colloidal particles in monitoring wells (Figure 3.5.7b). A **remote tank inspection** (RTI) system, using high resolution video cameras attached to a robotic arm with 6 feet of articulated reach for inspection of tank walls of high level nuclear waste tanks, is in developmental stages (see Fromme et al., 1991). **Stereo photo survey:** 35-mm photographs (color or black-and-white) are taken simultaneously by two cameras set in the same place with the optical lenses set at a slight angle to obtain overlapping coverage of the area 3 to 5 feet below the camera. The resultant film can be examined through a stereoscopic viewer to obtain a three-dimensional axial image, which is readily interpreted and which provides good data on corrosion indications, encrustation, casing breaks, partings, collapse, and other casing features. **Single vertical photo surveys** have generally been superseded by television and stereo photo surveys. **Motion picture survey:** Movie cameras with lens attachments for taking either side hole pictures or vertical pictures along the well axis provide a continuous borehole log. Images can be either color or black-and-white.

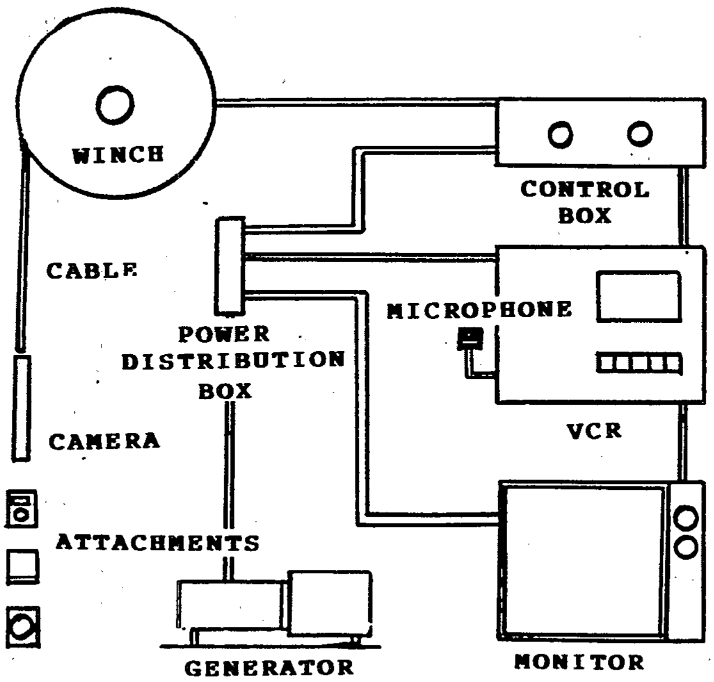
Method Selection Considerations: Valuable in any borehole where features, such as secondary porosity and casing condition, can be interpreted visually. **Television/Camera Advantages:** (1) Allow direct observation of borehole or casing; (2) television equipment has been developed for inspection of boreholes as small at 2 inches in diameter; (3) black-and-white stereo photo films can be developed on-site in about 45 minutes (color photographs require about a week for processing and delivery). **Television/Camera Disadvantages:** (1) Use limited to boreholes with clear water and clean walls; (2) cannot be used with standard logging cable; (3) photo and motion picture surveys are limited to relatively large diameter holes (6 inches or larger for stereo photo surveys and 10 inches or more for motion picture surveys); (4) interpretation of black-and-white stereo film negatives requires some experience; (5) motion picture surveys are not as flexible in operation as television surveys and do not permit detailed examination of critical areas; (6) 2-inch television logging equipment is relatively complex and delicate; and (7) color television equipment cannot be operated as deeply as black-and-white units. **Colloidal Boroscope:** New instrument that is being used primarily in research to evaluate ground-water sampling methods, but has potential for wider applications in contaminated site investigations.

Frequency of Use: Not widely used, but potentially very useful.

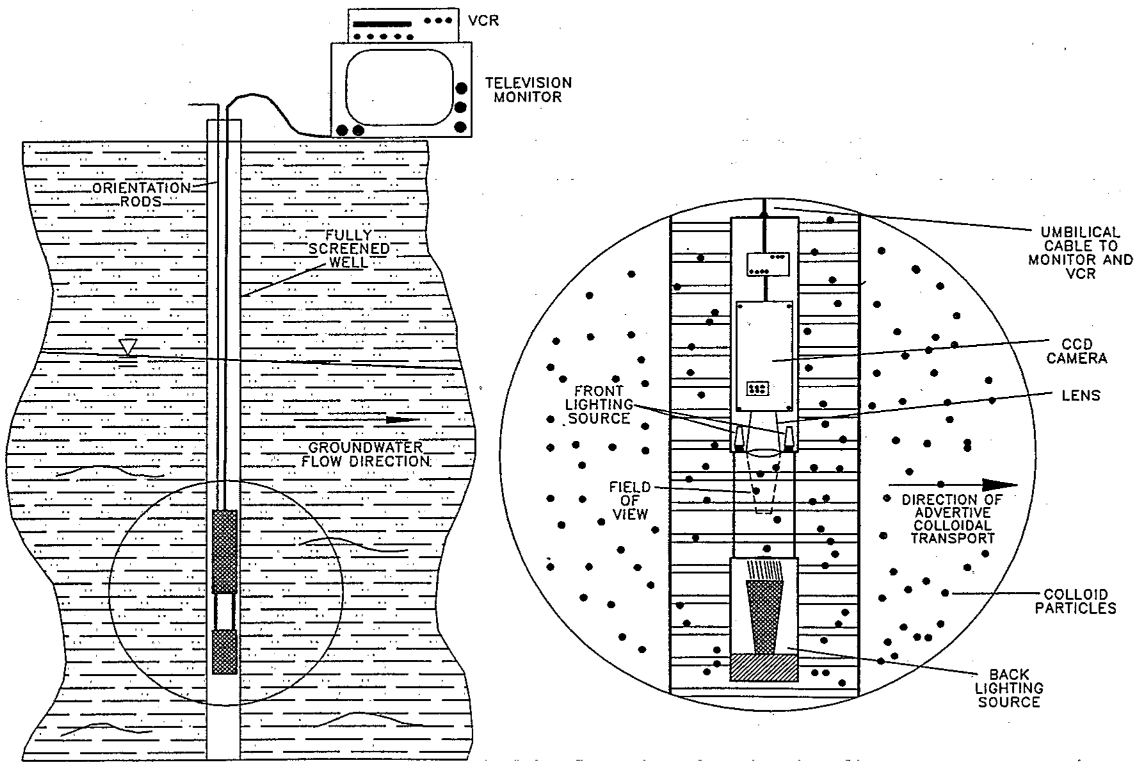
Standard Methods/Guidelines: --

Sources for Additional Information: **Borehole television:** Campbell and Lehr (1973), Morahan and Dorrier (1984), Respold (1989), U.S. EPA (1992), Wheatcraft (1986); **Photographic and motion picture surveys:** Bureau of Reclamation (1981); **Colloidal boroscope:** Cronk and Kearl (1991), Kearl et al. (1992).

*The term televiewer is more commonly used to refer to the acoustic televiewer (Section 3.4.3), so care should be used when running across this word to determine what type of instrument is being referred to.



(a)



(b)

Figure 3.5.7 Visual inspection of boreholes: (a) Schematic diagram of a borehole television system (Morahan and Dorrier, 1984, by permission); (b) Schematic diagram of the colloidal boroscope (Kearl et al., 1992, by permission).

3. GEOPHYSICAL LOGGING OF BOREHOLES

3.5 MISCELLANEOUS BOREHOLE LOGGING

3.5.8 Magnetic and Gravity Logs

Other Names Used to Describe Method: --

Uses at Contaminated Sites: **Magnetic:** Detecting buried metals in advance of drilling. **Magnetic susceptibility:** Performing stratigraphic correlation. **Gravity:** Possible use for performing structural and stratigraphic interpretation in association with surface gravity measurements.

Method Description: **Magnetic:** Borehole magnetometers operate on the same principle as surface fluxgate gradiometers described in Section 1.5.2, except that they are attached to a cable that allows testing of boreholes to a depth of 25 feet (Figure 3.5.8).* **Gravity:** Borehole gravimetry is a fairly recent extension of surface gravimetry. Microgravity instrumentation (see Figure 1.5.3a), specially designed for use in boreholes, measures vertical changes in gravity. Clamping the logging cable and clamping or spring-loading the probe to the borehole wall often is required to eliminate vibrations. The basic corrections required for surface gravity readings are required (see Section 1.5.3), although specific calculations can differ because measurements are taken vertically rather than horizontally.

Method Selection Considerations: **Magnetic Advantages and Disadvantages:** See Section 1.5.2. **Gravity Advantages:** (1) Can extend conventional surface gravity measurements to a third dimension, allowing more precise interpretations; and (2) can be used in cased wells. **Gravity Disadvantages:** (1) Instruments are expensive and availability is limited; (2) temperature sensitivity might be a problem; (3) many corrections have to be applied to gravity data, which is time consuming; (4) interpretations are ambiguous (i.e., for any set of gravity measurements, more than one model usually can explain gravity and density differences); (5) invasion of drilling fluid into formations might reduce the accuracy of gravity interpretation; and (6) errors in depth measurement often are the largest source of error in a borehole gravity survey.

Frequency of Use: **Magnetic:** Commonly used when presence of buried metals is suspected in the area of drilling. **Gravity:** Relatively common for oil and gas exploration; use in ground-water studies is not commonly reported.

Standard Methods/Guidelines: --

Sources for Additional Information: **Magnetic:** Schonsted Instrument Company (undated); **Gravity:** Head and Kososki (1979), Hearst and Carlson (1982), Labo (1987), Robbins (1986).

*The magnetic susceptibility log (see Section 10.6.3 for principles involved) has been used for mineral exploration (Scott et al., 1981), but its use has not been reported for ground-water or contaminated site investigations.

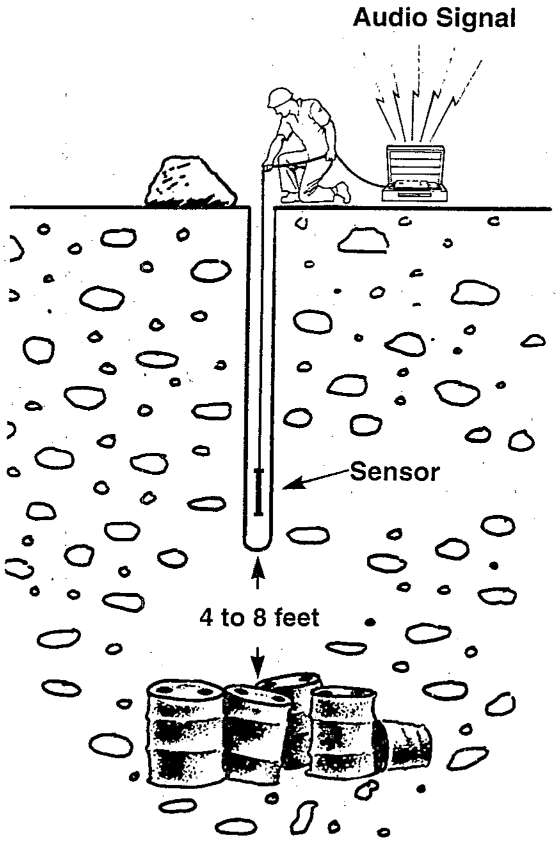


Figure 3.5.8 Use of borehole magnetometer to detect buried ferrous containers (Schonstedt Instrument Company, undated).

3.6 WELL CONSTRUCTION LOGS

3.6.1 Casing Logging

Other Names Used to Describe Method: Casing collar locator (CCL), electromagnetic casing logs. Other logging methods that can be used to evaluate casing include: Electric logs (steel casing), gamma-gamma logs, neutron and gamma logs, caliper logs, acoustic velocity, acoustic waveform, and acoustic televiewer.

Uses at Contaminated Sites: Evaluating the location and condition of different types of casing and screens.

Method Description: **Casing collar locator:** Probe that can be operated on other logging tools that uses a magnet wrapped in a coil of wire, which causes a current to flow in response to changes in the magnetic properties of casing. The collar of steel casing cause a fluctuation in the field, which is readily discerned compared to the main part of the casing. Several types of **electromagnetic casing log** tools are available that measure the change in mass of metal between two coils and are used to measure corrosion of steel casings. **Television** and **photographic** surveys (Section 3.5.7) also can be used to evaluate the condition of the interior surface of a casing.

Method Selection Considerations: Casing logging methods are used mainly in deeper boreholes where metal casing has been used. The CCL is a useful and relatively inexpensive probe and its standard mode of operation is to record event marks along the margin of other logs to represent the location of collars in steel casing.

Frequency of Use: Commonly used when the integrity of wells is a concern, such as large diameter water wells, injection wells, and ground-water monitoring wells.

Standard Methods/Guidelines: --

Sources for Additional Information: Keys (1990), Keys and MacCary (1971), Nielsen and Aller (1984), Respold (1989), Thornhill and Benefield (1990), U.S. EPA (1992).

3.6 WELL CONSTRUCTION LOGS

3.6.2 Cement and Gravel Pack Logs

Other Names Used to Describe Method: Cement bond logs. Various logging methods discussed earlier can be used singly or in combination.

Uses at Contaminated Sites: Locating cement and gravel pack outside of casing in the annular space, and determining whether the annular space has been completely filled; detecting interzone fluid communication behind casing.

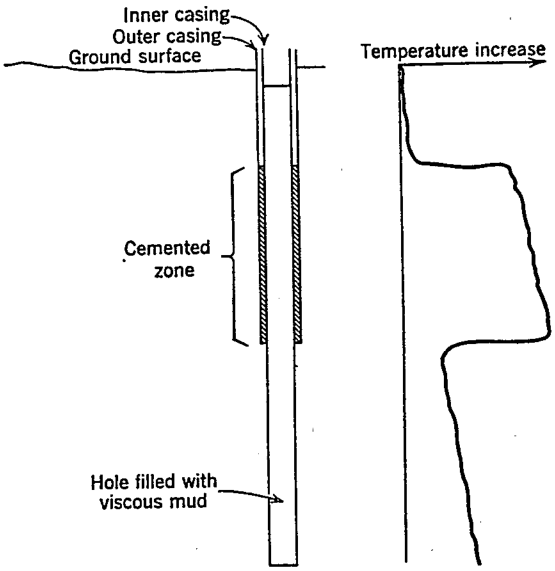
Method Description: Specific cement bond logging tools can combine different logging methods described above, usually including **gamma-gamma** (Section 3.3.2), and **casing collar locator** (Section 3.6.1) for depth control, and various types of **acoustic** logs (Sections 3.4.1 and 3.4.2). **Temperature** logs (Section 3.5.2) can be used to locate cement grout while it is still warm from chemical reactions during curing (Figure 3.6.2a). **Caliper** logs (Section 3.5.1), which are run before grouting, usually are required to interpret whether the annular space is filled. **Gamma-gamma** logs run on casing before grouting and then again after grouting, can be used to estimate whether the annular space has been filled completely (Figure 3.6.2b). A **noise** or **Sonan** log monitors and records sounds at seven frequencies (200 to 8,000 Hertz), and can be used to detect flow of air and/or water behind a casing.

Method Selection Considerations: **Advantages:** Essential for evaluating the adequacy of grouting of the annular space of monitoring wells, especially where there is a potential for cross-contamination. **Disadvantages:** (1) Interpretation of some logs might be ambiguous unless careful logs of the borehole are completed before and after grouting; and (2) noise logs are susceptible to extraneous sources of sound, such as surface equipment noise, inadvertent flow past the sonde, or continued movement of the logging tool during measurement.

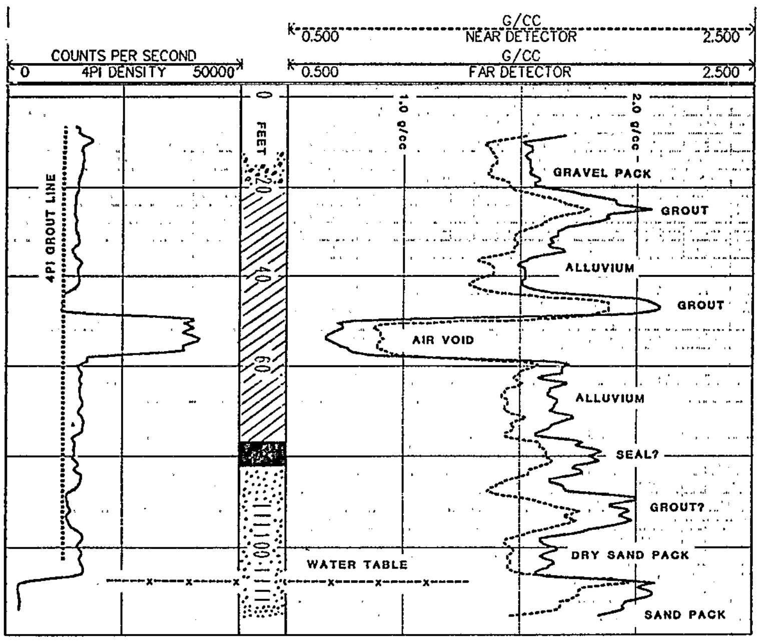
Frequency of Use: Not commonly used, but probably should be.

Standard Methods/Guidelines: --

Sources for Additional Information: Gearhart Industries (1982), Keys (1990), Nielsen and Aller (1984), Respold (1989), Schlumberger (1989b), Thornhill and Benefield (1990), U.S. EPA (1992), Wyllie (1963); **Noise log:** Thornhill and Benefield (1990).



(a)



(b)

Figure 3.6.2 Well completion logs: (a) Schematic diagram showing heat given off by cement as it hardens (Davis and DeWiest, 1966, reprinted by permission of John Wiley & Sons, Inc. from *Hydrogeology* by S.N. Davis and R.J.M. DeWiest, Copyright © 1966); (b) Identification of air void using gamma-gamma log with near and far detectors (Yearsley et al., 1991, by permission).

3.6 WELL CONSTRUCTION LOGS

3.6.3 Borehole Deviation

Other Names Used to Describe Method: Plumbness/alignment tests, single-shot probe, deviation log, dipmeter log, cage/cable suspended cage test, dolly test.

Uses at Contaminated Sites: Identifying potential problems in well completion due to borehole deviations; providing data to calculate the true vertical depth of water levels and other features of interest, and to correct the strike and dip of fractures of bedding planes.

Method Description: **Single-shot probes** provide one measurement of the deviation angle and azimuth at one point in the borehole. Multiple measurements require bringing the probe to the surface and resetting it after each reading. **Deviation logs** provide continuous measurements with a probe that includes an inclinometer for measuring deviation and a magnetometer for determining direction. **Dipmeter logs** (see Section 3.1.5) usually include a continuous record of the azimuth (magnetic north) and the magnitude of deviation. Continuous logs of borehole deviation usually are made by companies that specialize in this method. The **dolly** test uses a 40-foot long rigid dolly fitted with rings that are a 1/2 inch smaller than the inside diameter of the casing. If the dolly hangs up, it is an indication the casing is not plumb and/or is out of alignment. the **cage** test involves setting up a tripod above the well casing from which a plumb line can be centered and lowered into the casing (Figure 3.6.3). Deviations of casing from the vertical and direction of deviation can be determined by measuring the distance and direction of movement of the cable from the center of the casing using a template that is placed on the top of the casing.

Method Selection Considerations: Borehole deviation primarily is a concern in deep boreholes, although it is possible for auger borehole less than 100 feet deep to deviate enough to adversely affect gamma-gamma transmittance logs. Single-shot probes are the least expensive and can be used to determined whether more expensive continuous logs might be required.

Frequency of Use: Infrequently, probably should be used more.

Standard Methods/Guidelines: --

Sources for Additional Information: Bureau of Reclamation (1981), Keys (1990), Respold (1989), U.S. EPA (1992).

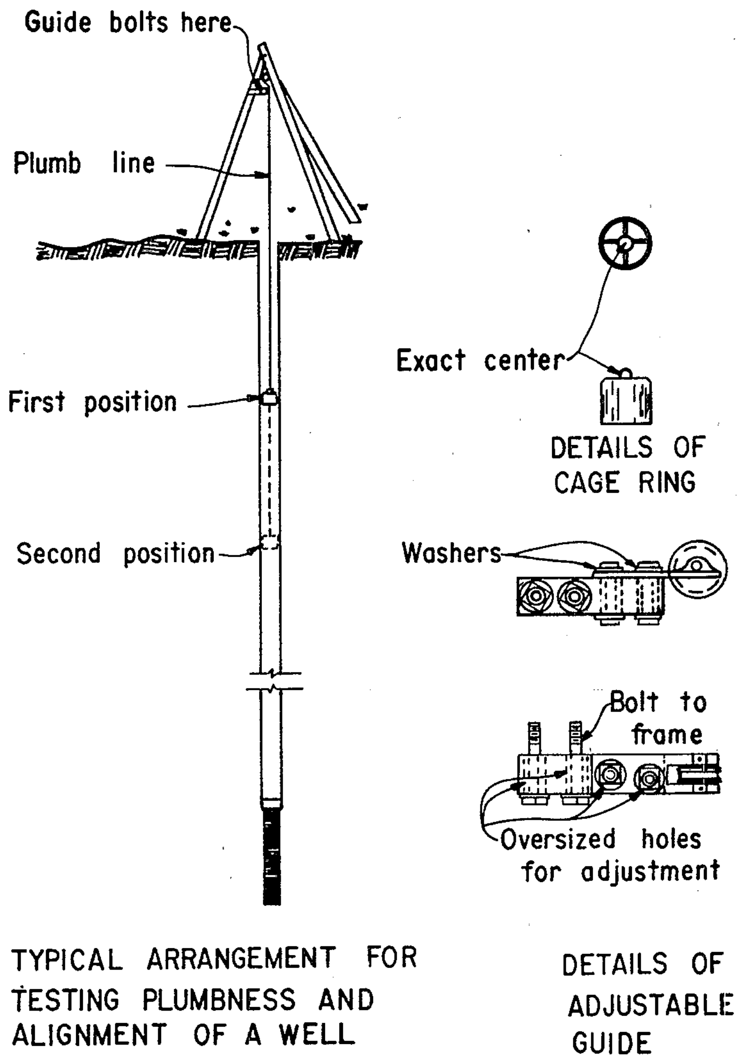


Figure 3.6.3 Cable suspended cage for checking straightness and plumbness of wells (Bureau of Reclamation, 1981).

Table 3-3 Index for General References on Borehole Geophysics

Topic	References
Bibliographies	Prensky (various dates), Rehm et al. (1985), Taylor and Dey (1985), Johnson and Gnaedinger (1964), van der Leeden (1991)
Glossary	Society of Professional Well Log Analysts (1975)
General Texts/Reports	
Log Method Texts	Dresser Atlas (1974, 1982), Ellis (1987), Guyod and Shane (1969), Hallenberg (1983), Hamilton and Myung (1979), Hearst and Nelson (1985), Helander (1983), Kelly (1969), Labo (1987), LeRoy et al. (1987), Lynch (1962), Nelson (1985), Scott and Tibbets (1974), Serra (1984a), Telford et al. (1990), Tittman (1986)
Log Interpretation	Asquith and Gibson (1982), Birdwell Division (1973), Doveton (1986), Dresser Atlas (1975, 1979, 1982), Foster and Beaumont (1990), Hallenberg (1984), Hilchie (1982a,b), Pirson (1963, 1970), Rider (1986), Schlumberger (1972, 1974, 1989a,b, 1991), Serra (1984b), Tearpock and Bischke (1991), Wyllie (1963)
Imaging/Tomography	Borehole Imaging: Lines and Scale (1997), SPWLA (1990-borehole imaging); Tomography: Davis (1989), Desaubies et al. (1990), Stewart (1991), Lines and Scales (1987), Tweeton (1988)
Log Quality Control	Bateman (1985), Theys (1991)
Borehole Logging Symposia	Canadian Well Logging Society (various dates), Killeen (1985), Minerals and Geotechnical Logging Society (1985-91), NWWA (1984, 1985, 1986), SPWLA (1960 to present)
Texts for Specific Log Types	
Electrical Logging Texts	Guyod (1952, 1957a, 1958, 1965), Guyod and Pranglin (1959), Hilchie (1979), Keller and Frischknecht (1970), Patten and Bennett (1963), Ross and Ward (1984); Bibliograpy: Johnson and Gnaedinger (1964)
Nuclear Logging	IAEA (1968, 1971); Protection: Blizard (1958), U.S. Nuclear Regulatory Commission (1985); Bibliography; Johnson and Gnaedinger (1964)
Ground-Water Applications	
Texts/Reports	Bennett and Patten (1960), Emerson and Webster (1970), Hodges and Teasdale (1991), Johnson (1968), Jorgenson (1989), Keys (1990), Keys and MacCary (1971), Patten and Bennett (1963), Respold (1989), Taylor and Dey (1985)
Ground-Water Texts with Sections on Borehole Geophysics	Brown et al. (1983), Beesley (1986), Bureau of Reclamation (1981), Campbell and Lehr (1973), Davis and DeWiest (1966), Driscoll (1986), Everett (1985), Redwine et al. (1985), Rehm et al. (1985), U.S. Army Corps of Engineers (1979)
Contaminated Sites	Benson (1991-review paper), Stowell (1989-review paper), Taylor et al. (1990), Technos (1992), U.S. EPA (1987), Wheatcraft et al. (1986)
Well Integrity Testing	Nielsen and Aller (1984), Thornhill and Benefield (1990)

Table 3-4 Index for References on Neutron and Gamma-Gamma Logging Methods

Topic	References
Neutron	
General	Texts/Reports: Beck (1981), Belcher et al. (1950), Bell (1973), Gardner and Roberts (1967), Greacen (1981), Institute of Hydrology (1981), IAEA (1970), Johnson (1962), SPWLA (1978a), van Bavel (1958, 1963a); Review Papers: Belcher (1952), Hodnett (1986), van Bavel (1963b), van Bavel and Underwood (1956), Visvalingam and Tandy (1972), Zuber and Cameron (1966); Theory: McHenry (1963), Olgaard (1965), Tittle (1961), Weinberg and Wignor (1958)
Non-moisture applications	Jones and Schneider (1969-specific yield), Meyer (1962--storage coefficient), Poeter (1988-perched water table), Schimschal (1981-hydraulic conductivity), Senger (1985-glacial stratigraphy)
Soil Moisture/Vadose Zone Monitoring	Brose and Shatz (1987), Franklin et al. (1992), Kramer et al. (1991, 1992), McGowan and Williams (1980), Unruch et al. (1990), Wilson (1971), Wilson and DeCook (1968); Evapotranspiration: Bowman and King (1965), van Bavel and Stirk (1967)
Neutron Depth Probes	Bell (1969), Bell and McCulloch (1966), Black and Mitchell (1968), deVries and King (1961), Gardner and Kirkham (1952), Holmes and Jenkinson (1959), Holmes and Turner (1958), Kozachyn and McHenry (1964), Long and French (1967), Luebs et al. (1968), McHenry (1963), Pierpoint (1966), Poeter (1988), Scholl and Honey (1983), Stewart and Taylor (1957), Stolzy and Cahoon (1957), Stone et al. (1955), Tyler (1985), van Bavel et al. (1956, 1961); Neutron-Gamma: Belcher (1952), Belcher et al. (1950), Couchat et al. (1979), van Bavel and Underwood (1956)
Surface Neutron Probe	Belcher et al. (1952), Cope and Trickett (1965), Phillips et al. (1960), van Bavel (1961)
Access Tube Installation/ Tube/Grout Effects	Amoozegar et al. (1989), Glenn et al. (1980), Hanks and Bowers (1960), Keller et al. (1990), Kozachyn and McHenry (1964), Kramer et al. (1990), Myhre et al. (1969), Rawitz (1969), Richardson (1966), Teasdale and Johnson (1970)
Accuracy/Calibration/ Errors	Abeele (1979), Bell and Eeles (1967), Carneiro and De Jong (1985), Cohen (1964), Douglass (1966), Gornat and Goldberg (1972), Greacen and Hignett (1979), Greacen and Schrale (1976), Greacen et al. (1981), Halvorson (1986), Hammermeister et al. (1985), Hauser (1984), Haverkamp et al. (1984), Hewlett et al. (1964), Hodnett and Bell (1991), Holland (1969), Holmes (1956, 1966), Hsieh and Enfield (1974), Lal (1974, 1979), Lawless et al. (1963), McCauley and Stone (1972), Mortier et al. (1960), Nakayama and Reginato (1982), Olgaard and Haahr (1968), Parks and Siam (1979), Rawitz (1969), Rawls and Asmussen (1973), Reginato and Nakayama (1988), Shirazi and Isobe (1976), Sinclair and Williams (1979), Stewart and Taylor (1957), Stolzy and Cahoon (1957), Stone et al. (1960), Troxler (1964), Tyler (1988), Ursic (1967), Vachaud et al. (1977), van Bavel (1962), van Bavel et al. (1961)
Neutron Attenuation	Gardner and Calissendorff (1967), Stewart and Gardner (1969)

Table 3-4 (cont.)

Topic	References
Gamma-Gamma	
Basic Theory	Davidson et al. (1963), Dmitriyev (1966), Gurr (1962), Ferguson and Gardner (1962), Fritton (1969), van Bavel et al. (1957); Temperature Effects: Kriz (1969), Ligon (1969), Reginato and Jackson (1971), Reginato and Stout (1970), Smith et al. (1967)
Applications	Dual Gamma Attenuation: Corey et al. (1971), Gardner and Calissendorff (1967), Gardner et al. (1969, 1972), Goit et al. (1978), Mansell et al. (1973), Nofziger (1978), Nofziger and Swartzendruber (1974), Soane (1967), Wood and Collis-George (1980); Single-Gamma Attenuation: Ashton (1956), Ferguson and Gardner (1962--laboratory), Gurr (1962--laboratory), Hsieh et al. (1972), Reginato (1974), Reginato and van Bavel (1964); Double-Probe: Fleming et al. (1993), Ryhiner and Pankow (1969), Soane and Hensall (1979)

SECTION 3 REFERENCES

Abeele, W.V. 1979. Influence of Access Hole Parameters on Neutron Moisture Probe Readings. LA-8094-MS. Los Alamos Scientific Laboratory, Los Alamos, NM.

Abragam, A. 1961. The Principles of Nuclear Magnetism. Clarendon Press, Oxford, England, 599 pp.

Adams, J.A.S. and P. Gasparini. 1970. Methods in Geochemistry and Geophysics: Gamma Ray Spectrometry of Rocks. Elsevier, New York, NY, 280 pp.

Adams, W.M., S.W. Wheatcraft, and J.W. Hess. 1983. Downhole Sensing Equipment for Hazardous Waste Site Investigations. In: Proc. (4th) Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 108-113.

American Petroleum Institute (API). 1974. Recommended Practice for Standard Calibration and Format for Nuclear Logs. API RP 33. API, Washington, DC. [Gamma neutron]

American Society for Testing and Materials (ASTM). 1988. Standard Test Method for Water Content of Soil and Rock In Place by Nuclear Methods (Shallow Depth). D3017-88, (Vol. 4.08), ASTM, Philadelphia, PA. [Neutron probe]

American Society for Testing and Materials (ASTM). 1991a. Standard Test Method for Density of Soil and Rock In-Place at Depths Below the Surface by Nuclear Methods. D5195-91, (Vol. 4.08), ASTM, Philadelphia, PA. [Gamma-gamma]

American Society for Testing and Materials (ASTM). 1991b. Standard Test Methods for Density of Soil and Soil-Aggregate In Place by Nuclear Methods (Shallow Depth). D2922-91, (Vol. 4.08), ASTM, Philadelphia, PA. [Gamma backscatter and direct transmission methods]

American Society for Testing and Materials (ASTM). 1991c. Standard Test Method for Crosshole Seismic Testing. D4428/D4428M-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992. Standard Test Method for Water Content of Soil and Rock In-Place by the Neutron Depth Probe Method. D5220-92, (Vol 4.08), ASTM, Philadelphia, PA.

Amoozegar, A., K.C. Martin, and M.T. Hoover. 1989. Effect of Access Hole Properties on Soil Water Content Determination by Neutron Thermalization. Soil Sci. Soc. Am. J. 53:330-335.

Anderson, D.L. and A.M. Dziewonski. 1984. Seismic Tomography. Scientific American 251(4):60.

Ashton, F.M. 1956. Effects of a Series of Cycles of Alternating Low and High Soil Water Content on the Rate of Apparent Photosynthesis of Sugar Cane. Plant Physiol. 31:266-274. [Single-gamma attenuation]

Asquith, G. and C. Gibson. 1982. Basic Well Log Analysis for Geologists. American Association of Petroleum Geologists, Tulsa, OK, 216 pp.

Balch, A.H. and M.W. Lee (eds.). 1984. Vertical Seismic Profiling: Techniques, Applications, and Case Histories. International Human Resource Development Corporation, Boston, MA, 488 pp.

Bateman, R.M. 1985. Log Quality Control. Boston International Human Resources Development Corporation, Boston, MA, 398 pp.

Bates, R., D. Phillips, and B. Hoekstra. 1991. Geophysical Surveys for Fracture Mapping and Solution Cavity Delineation. In: Ground Water Management 7:659-673 (8th NWWA Eastern GW Conference). [Shear wave refraction, cross-borehole tomography]

Beck, A.E. 1981. Physical Principles of Exploration Methods. Macmillan, New York, NY, 234 pp. (Reprinted in 1982 with corrections). [Neutron probe]

Beesley, K. 1986. Downhole Geophysics. In: Ground Water: Occurrence, Development and Protection. T.W. Brandon (ed.), Institute of Water Engineers and Scientists Water Practice Manual 5, London, Chapter 9.

Belcher, D. 1952. The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering. In: Frost Action in Soils, A Symposium. Highway Res. Board Special Report No. 2. National Res. Council Publ. 213, Washington, DC, pp. 98-110.

Belcher, D.J., T.R. Cuykendall, and H.S. Sack. 1950. The Measurement of Soil Moisture and Density by Neutron and Gamma Ray Scattering. Civil Aeronautics Administration Technical Development Report No. 127, Washington, DC, 20 pp.

Belcher, D.J., T.R. Cuykendall, and H.S. Sack. 1952. Nuclear Methods for Measuring Soil Density and Moisture in Thin Soil Layers. Civil Aeronautics Administration Technical Development Report No. 161, Washington, DC, 8 pp.

Bell, J. 1969. A New Design Principle for Neutron Soil Moisture Gages: The "Wallingford" Neutron Probe. Soil Science 198:160-164.

Bell, J.P. 1973. Neutron Probe Practices. Institute of Hydrology Report No. 19, Wallingford, Oxon, U.K.

Bell, J. and C. Eeles. 1967. Neutron Random Counting Error in Terms of Soil Moisture for Nonlinear Calibration Curves. Soil Science 103:1-3.

Bell, J. and J. McCulloch. 1966. Soil Moisture Estimation by the Neutron Scattering Method in Britain. J. Hydrology 4:254-263.

Bennett, G.D. and E.P. Patten, Jr. 1960. Borehole Geophysical Methods for Analyzing Specific Capacity of Multiaquifer Wells. U.S. Geological Survey Water Supply Paper 1536-A.

Benson, R.C. 1991. Remote Sensing and Geophysical Methods for Evaluation of Subsurface Conditions. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 143-194.

Bigelow, E.L. 1985. Making More Intelligent Use of Log Derived Dip Information, Parts I-V. Log Analyst 26(1):41-51; 26(2):25-41; 26(3):18-31; 26(4):21-43; 26(5):25-64.

Birdwell Division. 1973. Geophysical Well Log Interpretation. Birdwell Division, Seismograph Service Corporation, Tulsa, OK, ed. (Birdwell Division is no longer in operation.) [SP, resistivity, gamma, gamma-gamma, neutron, fluid conductivity, temperature, 3-D velocity].

Black, J. and P. Mitchell. 1968. Near Surface Soil Moisture Measurement with a Neutron Probe. J. Aust. Inst. Agric. Sci. 34:181-182.

Blizard, E.P. 1958. Nuclear Radiation Shielding. In: Nuclear Engineering, H. Etherington (ed.), McGraw-Hill, New York, NY.

Bouwer, H. and R.D. Jackson. 1974. Determining Soil Properties. In: Drainage for Agriculture, J. van Schilfgaarde (ed.), ASA Agronomy Monograph No. 17, American Society of Agronomy, Madison, WI, pp. 611-672. [Gamma-gamma, neutron probe]

Bowman, D.H. and K.M. King. 1965. Determination of Evapotranspiration Using the Neutron Scattering Method. Can. J. Soil Science 45:117-126.

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls. 1979. Field Manual for Research in Agricultural Hydrology. U.S. Department of Agriculture Handbook No. 224. [Gamma-gamma, neutron probe]

Brose, R.J. and R.W. Shatz. 1987. Neutron Monitoring in the Unsaturated Zone. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 455-465.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7. UNESCO, Paris. (Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983.) [Section 9 covers borehole geophysical techniques]

Bureau of Reclamation. 1981. Ground Water Manual--A Water Resources Technical Publication, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 480 pp.

Butler, D.K. and J.R. Curro, Jr. 1981. Crosshole Seismic Testing--Procedures and Pitfalls. Geophysics 46(1):23-29.

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill, New York, NY, 681 pp. [Annotated bibliography contains over 600 references]

Canadian Well Logging Society. (Various dates). Biannual Formation Evaluation Symposium Series. Canadian Well Logging Society, Calgary. (Published symposia include: 2nd [1968], 6th [1977], 7th [1979], 8th [1981], 9th [1983], 11th [1987], 12th [1989], and 13th [1991].)

Carneiro, C. and E. De Jong. 1985. In Situ Determination of the Slope of the Calibration Curve of a Neutron Probe Using a Volumetric Technique. Soil Science 139:250-254.

CH2M Hill. 1991. Proceedings: NSF/EPRI Workshop on Dynamic Soil Properties and Site Characterization, Vol 1. EPRI NP-7337. Electric Power Research Institute, Palo Alto, CA. [Chapter 3 Low- and High-Strain Cyclic Material Properties covers uphole-downhole seismic methods]

Cohen, O.P. 1964. A Procedure for Calibrating Neutron Moisture Probes in the Field. Israel J. Agric. Res. 14:169-178.

Collier, H.A. 1989. Assessment of the Dielectric Tool as a Porosity Log. In: Proc. Third Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 151-165.

Cope, F. and E. Trickett. 1965. Measuring Soil Moisture. Soil and Fertilizers 28:201-208. [Surface neutron probe]

Corey, J.C., S.F. Peterson, and M.A. Wakat. 1971. Measurement of Attenuation of ^{137}Cks and ^{241}Am Gamma Rays for Soil Density and Water Content Determinations. Soil Sci. Soc. Am. Proc. 35:215-219.

Couchat, P., P. Moutonnet, and M. Puard. 1979. The Application of the Gamma Neutron Method for Transport Studies in Field Soils. Water Resources Research 15:1583-1588.

Cronk, T.A. and P.M. Kearl. 1991. The Colloidal Boroscope: A Means of Assessing Local Colloidal Flux and Ground water Velocity in Porous Media. In: 2nd Int. Symp. Field Screening Methods for Hazardous Wastes and Toxic Chemicals. EPA/600/9-91/028 (NTIS PB92-125764), pp. 631-632.

Daily, W. and E. Owen. 1991. Cross-Borehole Resistivity Tomography. Geophysics 56(8):1228-1235.

Daniels, J.J. 1983. Hole-to-Surface Resistivity Measurements. Geophysics 48(1):87-97.

Davidson, J.M., J.W Biggar, and D.R. Nielsen. 1963. Gamma Radiation Attenuation for Measuring Bulk Density and Transient Water Flow in Porous Media. J. Geophys. Res. 68:4477-4783.

Davis, R.W. 1989. Developments in Cross Borehole Tomography. In: Proc. (2nd) Symp. on the Application of Geophysics to Engineering and Environmental Problems, Soc. Eng. and Mineral Exploration Geophysicists, Golden, CO, pp. 262-274.

Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogeology. John Wiley & Sons, New York, NY, 463 pp. [Chapter 8 covers surface and borehole geophysical methods]

Davis, S.N., D.J. Campbell, H.W. Bentley, and T.J. Flynn. 1985. Introduction to Ground Water Tracers. EPA/600/2-85/022 (NTIS PB86-100591). Also published under the title Ground Water Tracers in NWWA/EPA Series, National Water Well Association, Dublin, OH, 200 pp. (See also, 1986 discussion by J.F. Quinlan in Ground Water 24(2):253-259 and 24(3):396-397 and reply by S.N. Davis in Ground Water 24(3):398-399.)

Desaubies, Y., A. Tarantola, and J. Zinn-Justin (eds.). 1990. Oceanographic and Geophysical Tomography. Elsevier, New York, NY, 463 pp.

deVries. J. and K.M. King. 1961. Note on the Volume of Influence of a Neutron Surface Moisture Probe. Can. J. Soil Science 41:253-257.

Dmitriyev, M.T. 1966. Gammascopic Measurement of Soil Moisture. Soviet Soil Science (Pchvovedenie) 2:208-217.

Douglass, J.E. 1966. Volumetric Calibration of Neutron Moisture Probes. Soil Sci. Soc. Am. Proc. 30:541-544.

Doveton, S.H. 1986. Log Analysis of Subsurface Geology: Concepts and Computer Models. John Wiley & Sons, New York, NY, 273 pp.

Dresser Atlas. 1974. Log Review 1. Dresser Atlas Division, Dresser Industries, Houston, TX. [Induction, resistivity, acoustic velocity, gamma-gamma, neutron-gamma, diplog, neutron lifetime]

Dresser Atlas. 1975. Log Interpretation Fundamentals. Dresser Atlas Division, Dresser Industries, Houston, TX, 125 pp.

Dresser Atlas. 1979. Log Interpretation Charts. Dresser Atlas Division, Dresser Industries, Houston, TX.

Dresser Atlas. 1982. Well Logging and Interpretation Techniques: The Course for Home Study. Dresser Atlas Division, Dresser Industries, Houston, TX, 350 pp.

Driscoll. F.G. 1986. Groundwater and Wells, 2nd edition. Johnson Filtration Systems Inc., St. Paul, MN, 1089 pp. [Chapter 8 covers borehole geophysical methods: resistivity, SP, gamma, gamma-gamma, neutron, acoustic, temperature, caliper and fluid velocity]

Ellis, D.V. 1987. Well Logging for Earth Scientists. Elsevier, New York, NY, 532 pp. [SP, resistivity, induction, gamma, neutron, acoustic]

Emerson, D.W. and S.S. Webster. 1970. Interpretation of Geophysical Logs in Bores in Unconsolidated Sediments. Australian Water Resources Council Research Project 68/7-Phase I, 212 pp.

Everett, L.G. 1985. Groundwater Monitoring Handbook for Coal and Oil Shale Development. Elsevier, New York, NY. [Section 8 covers borehole geophysical methods: temperature, caliper, gamma, flow, radioactive tracer, 3-D velocity (acoustic waveform), acoustic, gamma-gamma, electric, acoustic-televiewer]

Everett, L.G., L.G. Wilson, and E.W. Hoylman. 1983. Vadose Zone Monitoring for Hazardous Waste Sites. EPA/600/X-83/064 (NTIS PB84-212752). Also published in 1984 by Noyes Data Corporation, Park Ridge, NJ.

Ferguson, J. and W.H. Gardner. 1962. Water Content Measurement in Soil Columns by Gamma Ray Absorption. Soil Sci. Soc. Am. Proc. 26:11-18.

Fleming, R.L., T.A. Black, and N.R. Eldridge. 1993. Water Content, Bulk Density, and Coarse Fragment Content Measurement in Forest Soils. Soil Sci. Soc. Am. J. 57:261-270. [Double probe gamma-gamma]

Foster, N.H. and E.A. Beaumont (eds.). 1990. Formation Evaluation I: Log Evaluation; II: Log Interpretation. Reprint Series Nos. 16 and 17, American Association of Petroleum Geologists, Tulsa, OK, (I) 742 pp., (II) 600 pp. [Resistivity, SP, gamma, porosity, dip meter, other logs]

Franklin, J.J., M.E. Unruh, and V. Suryasasmita. 1992. Neutron Probe Monitoring in the Unsaturated Zone: Case Histories from Several Sites Comparing Problems and Utility of Horizontal and Vertical Access Tube Installations. Ground Water Management 11:103-117 (6th NOAC).

Fritton, D.D. 1969. Resolving Time, Mass Absorption Coefficient and Water Content with Gamma Ray Attenuation. Soil Sci. Soc. Am. Proc. 33:651-655.

Fromme, C., B.P. Knape, and B. Thompson. 1991. Development of Remote Tank Inspection (RTI) Robotic System. In: 2nd Int. Symp. Field Screening Methods for Hazardous Wastes and Toxic Chemicals. EPA/600/9-91/028 (NTIS PB92-125764), pp. 197-204.

Gairon, S. and A. Hadas. 1973. Measurement of Water Status in Soils. In: Arid Zone Irrigation, B. Yaron, E. Danfoss, and Y. Vaadia (eds.), Springer-Verlag, New York, NY, pp. 215-226. [Neutron probe]

Gal'perin, E.I. 1974. Vertical Seismic Profiling. Society of Exploration Geophysicists, Tulsa, OK, 278 pp.

Gardner, W.H. 1986. Water Content. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 493-544. [Gamma-gamma, neutron]

Gardner, W.H. and C. Calissendorff. 1967. Gamma Ray and Neutron Attenuation Measurement of Soil Bulk Density and Water Content. In: Isotopes and Radiation Techniques. Proc. of Symp. Techniques in Soil Physics and Irrigation Studies (Istanbul), International Atomic Energy Agency, Vienna, pp. 101-113.

Gardner, W.H. and D. Kirkham. 1952. Determination of Soil Moisture by Neutron Scattering. Soil Science 73:391-401.

Gardner, R.P. and K.F. Roberts. 1967. Density and Moisture Content Measurement by Nuclear Methods. Nat. Coop. Highway Res. Program Report 43.

Gardner, W.H., G.S. Campbell, and C. Calissendorff. 1969. Water Content and Soil Bulk Density Measurement Concurrently Using Two Gamma Photon Energies. AEC Report RLO-1543-6. Washington State University, Pullman, WA, 42 pp.

Gardner, W.H., G.S. Campbell, and C. Calissendorff. 1972. Systematic and Random Errors in Dual Gamma Energy Soil Bulk Density and Water Content Measurements. Soil Sci. Soc. Am. Proc. 36:393-398.

Gearhart Industries. 1982. Basic Cement Bond Log Evaluation. Gearhart Industries, Inc., Charleston, WV, 36 pp.

Glenn, D., R. Henderson, and F. Bolton. 1980. A Retractable Neutron-Probe Access Tube. Agronomy J. 72:1067-1068.

Goit, J.B., P.H. Groenevelt, B.D. Kay, and J.G.P. Loch. 1978. The Applicability of Dual Gamma Scanning to Freezing Soils and the Problem of Stratification. Soil Sci. Soc. Am. J. 42:858-863.

Gornat, B. and D. Goldberg. 1972. The Relation Between Moisture Measurements With a Neutron Probe and Soil Texture. Soil Science 114:254-258.

Greacen, E.L. (ed.). 1981. Soil Water Assessments by the Neutron Method. ISBN 0 643 004 14 9. CSIRO, East Melbourne.

Greacen, E.L. and C.T. Hignett. 1979. Sources of Bias in the Field Calibration of a Neutron Meter. Aust. J. Soil Res. 17:405-415.

Greacen, E.L. and G. Schrale. 1976. The Effect of Bulk Density on Neutron Meter Calibration. Aust. J. Soil Res. 14:159-169.

Greacen, E.L., R.L. Correll, R.B. Cunningham, G.G. Johns, and K.D. Nicolls. 1981. Calibration. In: Soil Water Assessments by the Neutron Method, E.L. Greacen (ed.), CSIRO, East Melbourne, pp. 50-81.

Gurr, C. 1962. Use of Gamma Rays in Measuring Water Content and Permeability in Unsaturated Columns of Soil. Soil Science 94:224-229.

Guyod, H. 1952. Electrical Well Logging Fundamentals. Well Instruments Developing Co., Houston, TX, 164 pp.

Guyod, H. 1957. Resistivity Determination from Electric Logs. (Published by) Hubert Guyod, Houston, TX.

Guyod, H. 1958. Electric Analogue for Resistivity Logging. (Published by) Hubert Guyod, Houston, TX.

Guyod, H. 1965. Interpretation of Electric and Gamma Ray Logs in Water Wells. Am. Geophysical Union Technical Paper. Mandrel Industries, Inc. Houston, TX.

Guyod, H. and J.A. Pranglin. 1959. Analysis Charts for the Determination of True Resistivity from Electric Logs. (Published by) Hubert Guyod, Houston TX, 202 pp.

Guyod, H. and L.E. Shane. 1969. Geophysical Well Logging, Vol. I: Introduction to Geophysical Well Logging and Acoustical Logging. (Published by) Hubert Guyod, Houston TX, 256 pp. [Part I covers general well logging equipment principles, Part II covers acoustical logging]

Hall, S.H. 1993. Single Well Tracer Tests in Aquifer Characterization. Ground Water Monitoring and Remediation 13(2):118-124.

Hallenberg, J.K. 1983. Geophysical Logging for Mineral and Engineering Applications. Penn Well Books, 264 pp.

Hallenberg, J.K. 1984. Formation Evaluation Programs. Penn Well Books, 120 pp.

Halvorson, G.A. 1986. Neutron Moisture Meter Calibration for Minespoils Containing Coal. Soil Sci. Soc. Am. J. 50:496-498.

Hamilton, R.G. and J.I. Myung. 1979. Summary of Geophysical Well Logging. Birdwell Division, Seismograph Service Corporation, Tulsa, OK, 32 pp.

Hammermeister, D.P., C.R. Kneiblher, and J. Klenke. 1985. Borehole Calibration Methods Used in Cased and Uncased Test Holes to Determine Moisture Profiles in the Unsaturated Zone, Yucca Mountain, Nevada. In: Proc. Conf. on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Dublin, OH, pp. 542-563.

Hanks, R.J. and S.A. Bowers. 1960. Neutron Meter Access Tube Influences Soil Temperature. Soil Sci. Soc. Am. Proc. 24:62-63.

Hardage, B.A. 1985. Vertical Seismic Profiling, Part A: Principles, 2nd enlarged edition. Seismic Exploration Volume 14A, Geophysical Press, London, 450 pp. (1st edition 1982.)

Hauser, V.L. 1984. Neutron Meter Calibration and Error Control. Trans. Am. Soc. Agric. Eng. 27:722-728.

Haverkamp, R., M. Vauclin, and G. Vachaud. 1984. Error Analysis in Estimating Soil Water Content from Neutron Probe Measurements: 1. Local Standpoint. Soil Science 135:78-90.

Head, W.J. and B.A. Kososki. 1979. Borehole Gravity: A New Tool for the Ground-Water Hydrologist (Abstract). Trans. Am. Geophys. Union 60:248.

Hearst, J.R. and R.C. Carlson. 1982. Measurement and Analysis of Gravity in Boreholes. Developments in Geophysical Exploration Methods 4:269-303.

Hearst, J.R. and P.H. Nelson. 1985. Well Logging for Physical Properties. McGraw-Hill, New York, NY, 571 pp.

Helander, D.P. 1983. Fundamentals of Formation Evaluation. Oil & Gas Consultants International Publications, Tulsa, OK, 332 pp. [SP, resistivity, acoustic, radiation]

Hendrickx, J.M.H. 1990. Determination of Hydraulic Soil Properties. In: Process Studies in Hillslope Hydrology, M.G. Anderson and T.P. Burt (eds.), John Wiley & Sons, New York, NY, pp. 43-92. [Neutron probe]

Hess, K.M. and S.H. Wolf. 1991. Techniques to Determine Spatial Variations in Hydraulic Conductivity of Sand and Gravel. EPA/600/2-91/006 (NTIS PB91-109123). [Laboratory core permeability tests and impeller flowmeter]

Hewlett, J.D., J.E. Douglass, and J.L. Clutter. 1964. Instrumental and Soil Moisture Variance Using the Neutron-Scattering Method. Soil Science 97:19-24.

Hilchie, D.W. 1979. Old (Pre-1958) Electrical Log Interpretation. Institutes for Energy Development, Tulsa, OK.

Hilchie, D.W. 1982a. Applied Open Hole Log Interpretation for Geologists and Engineers, 2nd edition. D.W. Hilchie, Inc., Golden, CO, 400+ pp. [SP, induction, acoustic, gamma, gamma-gamma, neutron, dipmeter]

Hilchie, D.W. 1982b. Advanced Well Log Interpretation. D.W. Hilchie, Inc., Golden, CO, 353 pp.

Hillel, D. 1971. Soil and Water: Physical Principles and Processes. Academic Press, New York, NY. [Neutron probe]

Hoar, R.J. and K.H. Stokoe, II. 1977. Generation and Measurement of Shear Waves In Situ. In: Dynamic Geotechnical Testing, ASTM STP 654, American Society for Testing and Materials, Philadelphia, PA, pp. 3-29.

Hodges, R.E. and W.E. Teasdale. 1991. Considerations Related to Drilling Methods in Planning and Performing Borehole-Geophysical Logging for Ground-Water Studies. U.S. Geological Survey Water Resource Investigations Report 91-409 (NTIS PB92-155688), 22 pp. [Caliper, gamma, gamma-spectral, gamma-gamma, neutron, electric, acoustic velocity, acoustic televiewer, temperature, flowmeters]

Hodnett, M.G. 1986. The Neutron Probe for Soil Moisture Measurements. In: Advanced Agricultural Instrumentation, W. Gensler (ed.), Martinus Nijhoff, Dordrecht, The Netherlands.

Hodnett, M.G. and J.P. Bell. 1991. Neutron Probe Standards: Transport Shields or a Large Drum of Water? Soil Science 151:113-120.

Holland, D.A. 1969. The Construction of Calibration Curves for Determining Water Content from Radiation Counts. J. Soil Science 20:132-140.

Holmes, J.W. 1956. Calibration and Field Use of the Neutron Scattering Method of Measuring Soil Water Content. Aust. J. Appl. Sci. 7:45-58.

Holmes, J.W. 1966. Influence of Bulk Density of the Soil on Neutron Moisture Meter Calibration. Soil Science 102:355-360.

Holmes, J.W. and A.F. Jenkinson. 1959. Techniques for Using the Neutron Moisture Meter. J. Agric. Eng. Res. 4:100-109.

Holmes, J.W. and K.G. Turner. 1958. The Measurement of Water Content of Soils by Neutron Scattering: A Portable Apparatus for Field Use. J. Agric. Eng. Res. 3:199-204.

Holmes, J.W., S.A. Taylor, and J.J. Richards. 1967. Measurement of Soil Water. In: Irrigation of Agricultural Lands, R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.), Agronomy Monograph No. 11, American Society of Agronomy, Madison, WI, pp. 275-298. [Neutron probe]

Hsieh, J.J.C. and C.G. Enfield. 1974. Steady State Methods of Measuring Unsaturated Hydraulic Conductivity. Communications in Soil Survey and Plant Analysis 5(2):123-129. [Neutron probe calibration]

Hsieh, J.J.C., W.H. Gardner, and G.S. Campbell. 1972. Experimental Control of Soil Water Content in the Vicinity of Root Hairs. Soil Sci. Soc. Am. Proc. 36:418-421. [Single-gamma attenuation]

Iddings, F.A., L.W. Miller, C.E. Pepper, and G.A. Keller. 1979. Determination of Cement Content in Soil-Cement Mixtures and Concrete by Neutron Activation Analysis. In: Interm. Adv. Nondest. Test. 6:199-237.

Institute of Hydrology. 1981. User's Handbook for the Institute of Hydrology Neutron Probe System. Institute of Hydrology Report No. 79, Wallingford, Oson, U.K.

International Atomic Energy Agency (IAEA). 1968. Guidebook of Nuclear Techniques in Hydrology. Technical Report No. 91. IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1970. Neutron Moisture Gauges. Technical Report No. 112. IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1971. Nuclear Well Logging in Hydrology. Technical Report No. 126. IAEA, Vienna, 92 pp.

Jackson, J.A. 1984. Nuclear Magnetic Resonance Well Logging. The Log Analyst 25(5):16-30.

Johnson, A.I 1962. Methods of Measuring Soil Moisture in the Field. U.S. Geological Survey Water-Supply Paper 1919-U, 25 pp.

Johnson, A.I. 1968. An Outline of Geophysical Logging Methods and their Uses in Hydrogeological Studies. U.S. Geological Survey Water-Supply Paper 1892, pp. 158-164.

Johnson, A.I. and J.P. Gnaedinger. 1964. Bibliography. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA, pp. 137-155. [Electrical borehole logging (48 refs); nuclear borehole logging (40 refs), borehole camera (13 refs); neutron moisture measurement (50 refs)]

Jones, O.R. and A.D. Schneider. 1969. Determining Specific Yield of The Ogallala Aquifer by the Neutron Method. Water Resources Research 5(6):1267-1272.

Jorgensen, D. 1989. Using Geophysical Logs to Estimate Porosity, Water Resistivity, and Intrinsic Permeability. U.S. Geological Survey Water-Supply Paper 2321, 24 pp.

Kaufman, A.A. and G.V. Keller. 1989. Induction Logging. Elsevier, New York, NY.

Kearl, P.M., N.E. Korte, and T.A. Cronk. 1992. Suggested Modifications to Ground Water Sampling Procedures Based on Observations from the Colloidal Boroscope. Ground Water Monitoring Review 12(2):155-161.

Keech, D.A. 1988. Hydrocarbon Thickness on Groundwater by Dielectric Well Logging. In: Proc. (5th) NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 275-289.

Keller, G.V. and F.C. Frischknecht. 1970. Electrical Methods in Geophysical Prospecting, 2nd edition. Pergamon Press, New York, NY, 517 pp. (First edition 1966.)

Keller, B.R., L.G. Everett, and R.J. Marks. 1990. Effects of Access Tube Material and Grout on Neutron Probe Measurements in the Vadose Zone. Ground Water Monitoring Review 10(1):96-100.

Kelly, D.R. 1969. A Summary of Geophysical Logging Methods. Pennsylvania Geological Survey Bulletin M61, 88 pp.

Keys, W.S. 1990. Borehole Geophysics Applied to Ground-Water Investigations. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-E2, 150 pp. (Supersedes report originally published in 1988 under the same title as U.S. Geological Survey Open-File Report 87-539, 303 pp., which was published in 1989 with the same title by the National Water Well Association, Dublin, OH, 313 pp.) (Complements Keys and MacCary [1971].)

Keys, W.S. and L.M. MacCary. 1971. Application of Borehole Geophysics to Water Resource Investigations. TWRI 2-E1. U.S. Geological Survey Techniques of Water-Resources Investigations, 126 pp. (Reprinted, 1990; see, also Keys, 1990.)

Killeen, P.G. 1982. Gamma-Ray Logging and Interpretation. Developments in Geophysical Exploration Methods 3:95-150.

Killeen, P.G. (ed.). 1985. Borehole Geophysics for Mining and Geotechnical Applications. Geological Survey of Canada Paper 85-27.

Kozachyn, J. and J. McHenry. 1964. A Method for Installation of Access Tubes and the Development of Field Equipment for Measuring Soil Moisture by Neutron Scatter. Agronomy J. 56:443-444.

Kramer, J.H., L.G. Everett, and L.A. Eccles. 1990. Effect of Well Construction Materials on Neutron Probe Readings with Implications for Vadose Zone Monitoring Strategies. Ground Water Management 2:1303-1317 (4th NOAC).

Kramer, J.H., L.G. Everett, and S. Cullen. 1991. Innovative Vadose Zone Monitoring at Landfill Using the Neutron Probe. Ground Water Management 5:135-149 (5th NOAC).

Kramer, J.H., J. Cullen, and L.G. Everett. 1992. Vadose Monitoring with the Neutron Moisture Probe. Ground Water Monitoring Review 12(3):177-187. (See also, discussion by M.A. Williams and reply by J.H. Kramer in Ground Water Monitoring & Remediation 13(1):159-162.)

Kriz, G.J. 1969. Temperature Effects on Gamma-Ray Attenuation Equipment. Trans. Am. Soc. Agric. Eng. 12(6):870-873.

Labo, J. 1987. A Practical Introduction to Borehole Geophysics. Society of Exploration Geophysicists, Tulsa, OK, 336 pp. [Gamma-gamma, gravity, acoustic, VSP, dipmeter]

Lal, R. 1974. The Effect of Soil Texture and Density on the Neutron Density Probe Calibration for Some Tropical Soils. Soil Science 117:183-190.

Lal, R. 1979. Concentration of Size of Gravel in Relation to Neutron Moisture and Density Probe Calibration. Soil Science 127:41-50.

Lawless, G., N. MacGillivray, and P. Nixon. 1963. Soil Moisture Interface Effects Upon Readings of Neutron Soil Moisture Probes. Soil Sci. Soc. Am. Proc. 27:7-502-507.

LeRoy, L.W., D.O. LeRoy, S.D. Schwochow, and J.W. Raese (eds.). 1987. Subsurface Geology, 5th edition. Colorado School of Mines, Golden, CO. (1st edition: LeRoy and Cran [1947], 2nd edition: LeRoy [1951], 3rd edition: Huan and LeRoy [1958], and 4th edition [1977].)

Ligon, J.T. 1969. Evaluation of the Gamma Transmission Method for Determining Soil-Water Balance and Evapotranspiration. Trans. Am. Soc. Agric. Eng. 12:121-126.

Lines, L.R. and J.A. Scales (eds.) 1987. Geophysical Imaging. Symposium of the Geophysical Society of Tulsa, available from Society of Exploration Geophysicists, Tulsa, OK, 225 pp. [Tomography, inversion, migration, computer-related issues]

Long, I.F. and B.K. French. 1967. Measurement of Soil Moisture in the Field by Neutron Moderation. J. Soil Science 18:149-166.

Luebs, R.E., M.J. Brown, and A.E. Laag. 1968. Determining Water Content of Different Soils by the Neutron Method. Soil Science 106:207-212.

Lynch, E.J. 1962. Formation Evaluation. Harper and Row, New York, NY, 422 pp.

Lytle, R.J., E.F. Laine, D.L. Lager, and D.T. Davis. 1979. Cross-Borehole Electromagnetic Probing to Locate High-Contrast Anomalies. Geophysics 44(10):1167-1676.

Mahannah, J.L., A.J. Witten, and W.C. King. 1988. Use of Geophysical Diffraction Tomography for Hazardous Waste Site Characterization. In: Superfund '88, Hazardous Materials Control and Research Institute, Silver Spring, MD, pp. 152-156.

Mansell, R.S., L.C. Hammond, and R.M. McCurdy. 1973. Coincidence and Interference Corrections for Dual-Energy Gamma Ray Measurements of Soil Density and Water Content. Soil Sci. Soc. Am. Proc. 37:500-504.

McCauley, G.N. and J.F. Stone. 1972. Source-Detector Geometry Effect on Neutron Probe Calibration. Soil Sci. Soc. Am. Proc. 36:246-250.

McGowan, M. and J.B. Williams. 1980. The Water Balance of an Agricultural Catchment. I: Estimation of Evaporation for Soil Water Records. J. Soil Science 31:217-230. [Neutron probe]

McHenry, J.R. 1963. Theory and Application of Neutron Scattering in the Measurement of Soil Moisture. Soil Science 95:294-307.

McNeill, J.D. 1986. Geonics EM39 Borehole Conductivity Meter--Theory of Operations. Technical Note 20, Geonics Ltd., Mississauga, Ontario, 11 pp.

McNeill, J.D., M. Bosnar, and F.B. Snelgrove. 1990. Resolution of an Electromagnetic Borehole Conductivity Logger for Geotechnical and Ground Water Applications. Technical Note TN-25. Geonics Limited, Mississauga, Ontario.

Meyer, W.R. 1962. Use of a Neutron Moisture Probe to Determine the Storage Coefficient of an Unconfined Aquifer. U.S. Geological Survey Professional Paper 450-E, pp. 174-176.

Minerals and Geotechnical Logging Society Symposia Series. 1985-1991. Proc. 1st Int. Symp. Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications (Ottawa, 1985); 2nd (Golden, CO, 1987); 3rd (Las Vegas, NV, 1989); 4th (Ontario, 1991). Available from SPWLA.

Molz, F.J., O. Güven, and J.G. Melville. 1990. A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers. EPA/600/2-90/002 (NTIS PB90-187063).

Morahan, T. and R. C. Dorrier. 1984. The Application of Television Borehole Logging to Ground Water Monitoring Programs. Ground Water Monitoring Review 4(4):172-175.

Moran, J.H. and R. Chemali. 1985. Focused Resistivity Logs. Developments in Geophysical Exploration Methods 6:225-260.

Morrison, R.D. 1983. Groundwater Monitoring Technology. Timco Mfg., Inc. Prairie du Sac, WI, 105 pp. [Gamma-gamma, neutron probe, nuclear magnetic resonance]

Mortier, P., M. DeBoodt, W. Donsercoer, and L. DeLeenheer. 1960. The Resolution of the Neutron Scattering Method for Soil Moisture Determination. Trans. 7th Int. Cong. Soil Science I:321-329.

Myhre, D., J. Sanford, and W. Jones. 1969. Apparatus and Technique for Installing Access Tubes in Soil Profiles to Measure Soil Water. Soil Science 108:296-299.

Nakayama, F.S. and R.J. Reginato. 1982. Simplifying Neutron Moisture Meter Calibration. Soil Science 133:48-52.

National Water Well Association (NWWA). 1984. NWWA/EPA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (San Antonio, TX). NWWA, Dublin, OH.

National Water Well Association (NWWA). 1985. NWWA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations (Fort Worth, TX). NWWA, Dublin, OH.

National Water Well Association (NWWA). 1986. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition (Denver, CO). NWWA, Dublin, OH.

Nelson, R.A. 1985. Geologic Analysis of Naturally Fractured Reservoirs. Contributions in Petroleum Geology and Engineering, V. 1. Gulf Publishing, Houston, TX, 320 pp.

Nielsen, D.M. 1991. An Update on the ASTM Subcommittee on Ground Water and Vadose Zone Investigations. Ground Water Monitoring Review 11(3):92-96.

Nielsen, D.M. and L. Aller. 1984. Methods for Determining the Mechanical Integrity of Class II Injection Wells. EPA/600/2-84/121 (NTIS PB84-215755), 263 pp. Also published in NWWA/EPA Series by the National Water Well Association, Dublin, OH. [Temperature, noise log, EM thickness, flowmeter, radioactive tracers, cement bond]

Nofziger, D.L. 1978. Errors in Gamma-Ray Measurement of Water Content and Bulk Density in Nonuniform Soils. Soil Sci. Soc. Am. J. 42:845-850.

Nofziger, D.L. and D. Swartzendruber. 1974. Material Content of Binary Physical Mixtures as Measured with a Dual-Energy Beam of Gamma Rays. J. Appl. Physics 45:5443-5449.

Olgaard, P.L. 1965. On the Theory of the Neutronic Method for Measuring the Water Content of Soil. Riso Rep. 97. Danish Atomic Energy Commission, Roskilde, Denmark, 74 pp.

Olgaard, P.L. and V. Haahr. 1968. On the Sensitivity of Subsurface Neutron Moisture Gauges to Variations in Bulk Density. Soil Science 105:62-64.

Paillet, F.L. and C.H. Cheng. 1991. Acoustic Waves in Boreholes. CRC Press, Boca Raton, FL, 264 pp.

Parks, M. and N. Siam. 1979. Error Associated with Measurement of Soil Moisture Change by Neutron Probe. J. Agric. Eng. Res. 24:87-93.

Patten, Jr., E.P. and G.D. Bennett. 1963. Application of Electrical and Radioactive Well Logging to Groundwater Hydrology. U.S. Geological Survey Water-Supply Paper 1544-D, 60 pp. [Resistivity, SP, fluid conductivity, gamma]

Phillips, R.E., C.R. Jensen, and D. Kirkham. 1960. Use of Radiation Equipment for Plow-Layer Density and Moisture. Soil Science 89:2-7. [Surface neutron probe]

Pierpoint, G. 1966. Measuring Surface Soil Moisture with the Neutron Depth Probe and Surface Shield. Soil Science 101:189-192.

Pirson, S.J. 1963. Handbook of Well Log Analysis for Oil and Gas Formation Evaluation. Prentice-Hall, Englewood Cliffs, NJ, 326 pp.

Pirson, S.J. 1983. Geologic Well Log Analysis, 3rd edition. Gulf Publishing Co., Houston, TX. (Earlier editions 1970, 1977.) [SP, Eh, dipmeter]

Poeter, E.P. 1988. Perched Water Identification with Nuclear Logs. Ground Water 26(1):15-21. [Gamma-gamma, neutron probe]

Prensky, S.E. Various Dates. Log Analyst Geologic Applications Bibliographies. Geological Applications of Well Logs--An Introductory Bibliography and Survey of Well Logging Literature through September 1986, Arranged by Subject and First Author (Log Analyst, 1987: Parts A and B 28(1):71-107; Part C 28(2):219-248); Annual Update, October 1986 through September 1987 (Log Analyst, 1987: 28(6):558-575); Bibliographic Update for October 1987 through September 1988 (Log Analyst, 1988: 29(6):426-443); Bibliography of Well Log Applications: October 1988-September 1989 Annual Update (Log Analyst, 1989: 30(6):448-470); October 1989-September 1990 Annual Update (Log Analyst, 1990:31(6):395-424).

Rawitz, E. 1969. Installation and Field Calibration of Neutron-Scatter Equipment for Hydrologic Research in Heterogeneous and Stony Soils. Water Resources Research 5:519-523.

Rawls, W.J. and L.E. Asmussen. 1973. Neutron Probe Field Calibration for Soils in the Georgia Coastal Plain. Soil Science 116:262-265.

Redwine, J. et al. 1985. Groundwater Manual for the Electric Utility Industry, Volume 3: Groundwater Investigations and Mitigation Techniques. EPRI CS-3901. Electric Power Research Institute, Palo Alto, CA. [Section 3 covers surface and borehole geophysical methods]

Reginato, R.J. 1974. Gamma Radiation Measurements of Bulk Density Changes in a Soil Pedon Following Irrigation. Soil Sci. Soc. Am. Proc. 38:24-29.

Reginato, R.J. and R.D. Jackson. 1971. Field Measurement of Soil Water Content by Gamma-Ray Transmission Compensated for Temperature Fluctuations. Soil Sci. Soc. Am. Proc. 35:529-533.

Reginato, R.J. and F.S. Nakayama. 1988. Neutron Probe Calibration Based on Plastic Transfer Standards. Soil Science 145:381-384.

Reginato, R.J. and K. Stout. 1970. Temperature Stabilization of Gamma Ray Transmission Equipment. Soil Sci. Soc. Am. Proc. 34:152-153.

Reginato, R.J. and C.H.M. van Bavel. 1964. Soil Water Measurement with Gamma Attenuation. Soil Sci. Soc. Am. Proc. 28:721-

724.

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature. EPRI EA-4301. Electric Power Research Institute, Palo Alto, CA. [Section 5 covers electrical, nuclear, acoustic and flow logs]

Repsold, H. 1989. Well Logging in Groundwater Development. International Contributions to Hydrogeology, Vol. 9. International Association of Hydrogeologists, Verlag Heinz Heise, Hannover, West Germany, 147 pp.

Richardson, B.Z. 1966. Installation of Soil Moisture Access Tubes in Rocky Soils. J. Soil and Water Conservation 21:143-145. [Neutron probe]

Rider, M.H. 1986. The Geological Interpretation of Well Logs. Halstead Press, New York, NY, 175 pp. [SP, resistivity, induction, gamma, spectral gamma, gamma-gamma, neutron, acoustic]

Robbins, S.L. 1986. The Use of Borehole Gravimetry in Water Well and Waste Disposal Site Evaluations. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 474-496.

Robbins, G.A. and J.M. Hayden. 1988. Application of Cross-Well Voltage Measurement for Assessing Fracture Flow Hydrology. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford, CT), National Water Well Association, Dublin, OH, pp. 28-38.

Robertson, P.K., R.G. Campanella, D. Gillespie, and A. Rice. 1986. Seismic CPT to Measure In-Situ Shear Wave Velocity. J. Geotech. Eng. Div. ASCE 112(8):791-803.

Ross, H.P. and S.H. Ward. 1984. Borehole Electrical Geophysical Methods: A Review of the State-of-the-Art and Preliminary Evaluation of the Application to Fracture Mapping in Geothermal Systems. Earth Science Laboratory, Univ. of Utah Res. Inst. Rep. 12196-2.

Roy, A. 1982. Focused Resistivity Logs. Developments in Geophysical Exploration Methods 3:61-94.

Ryhiner, A. and J. Pankow. 1969. Soil Measurement by the Gamma Transmission Method. J. Hydrology 9:194-205.

Schimschal, U. 1981. The Relationship of Geophysical to Hydraulic Conductivity at the Brantley Dam Site, New Mexico. Geoexploration 19:115-125. [Neutron probe]

Schlichter, C. 1963. Principles of Magnetic Resonance. Harper and Row, New York, 397 pp.

Schlumberger Limited. 1972. Log Interpretation. Vol. I: Principles. Schlumberger Limited, New York, NY.

Schlumberger Limited. 1974. Log Interpretation. Vol. II: Applications. Schlumberger Limited, New York, NY.

Schlumberger Limited. 1989a. Log Interpretation Principles/Applications. Schlumberger Educational Services, Houston, TX. (Earlier edition published in 1987.) [SP, resistivity, induction, dielectric, gamma, gamma-gamma, neutron, acoustic-velocity, VSP]

Schlumberger Limited. 1989b. Cased Hole Log Interpretation Principles/Applications. Schlumberger Educational Services, Houston, TX. [Gamma, spectral gamma, neutron, neutron lifetime, acoustic velocity, spinner flowmeter, temperature, various well construction logs]

Schlumberger Limited. 1991. Log Interpretation Charts. Schlumberger Limited, New York, NY. (Earlier charts published in 1972, 1976, 1979, 1984.)

Schmugge, T.J., T.J. Jackson, and H.L. McKim. 1980. Survey of Methods for Soil Moisture Determination. Water Resources Research 16(6):961-979. [Gamma-gamma, neutron]

Schneider, G.J. 1982. In Situ Neutron Activation Analysis. In: Premining Investigations for Hardrock Mining, U.S. Bureau of Mines Information Circular 8891, pp. 46-54. [Neutron activation, spectral-gamma]

Scholl, D.G. and W.E. Honey. 1983. An Automatic Instrument for Recording the Count Rate of a Moving Neutron Moisture Probe. In: Proc. NWWA/EPA Conf. on Characterization and Monitoring in the Vadose (Unsaturated) Zone (1st, Las Vegas, NV), National Water Well Association, Dublin, OH, pp. 602-608.

Schonstedt Instrument Company. Undated. MG-220 Magnetic Gradiometer. Schonstedt Instrument Company, Reston, VA.

Scott, J.H. and B.L. Tibbets. 1974. Well Log Techniques for Mineral Deposit Evaluation: A Review. U.S. Bureau of Mines Information Circular 3627, 45 pp.

Scott, J.H., R.L. Seeley, and J.J. Barth. 1981. A Magnetic Susceptibility Well Logging System for Mineral Exploration. Trans. 22nd Annual SPWLA Logging Symposium, Society of Professional Well Log Analysts, Houston, TX.

Senger, J.A. 1985. Defining Glacial Stratigraphy with the Neutron Log. In: NWWA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations (2nd, Fort Worth, TX), National Water Well Association, Dublin, OH, pp. 355-370.

Serra, O. 1984a. Fundamentals of Well-Log Interpretation, 1: The Acquisition of Logging Data. Developments in Petroleum Science, Vol. 15A. Elsevier, New York, NY, 423 pp. [SP, resistivity, gamma, gamma spectrometry, gamma-gamma, neutron, neutron activation/lifetime, acoustic, dielectric, caliper, temperature, dipmeter, acoustic televiewer, VSP, nuclear magnetic resonance]

Serra, O. 1984b. Fundamentals of Well-Log Interpretation, 2: The Interpretation of Logging Data. Developments in Petroleum Science, Vol. 15B. Elsevier, New York, NY, 684 pp. [Chapters focus on log interpretation for specific applications--sedimentary structure, fractures, etc].

Shirazi, G. and M. Isobe. 1976. Calibration of Neutron Probe in Some Selected Hawaiian Soils. Soil Science 122:165-170.

Sinclair, D.F. and J. Williams. 1979. Components of Variance Involved in Estimating Soil Water Content and Water Content Changes Using a Neutron Moisture Meter. Aust. J. Soil Res. 17:237-247.

Smith, E.M., T.H. Taylor, and S.W. Smith. 1967. Soil Moisture Measurement Using Gamma Transmission Techniques. Trans. Am. Soc. Agric. Eng. 10:205-208.

Soane, B.D. 1967. Dual Energy Gamma-Ray Transmission for Coincident Measurement of Water Content and Dry Bulk Density of Soil. Nature 214:1273-1274.

Soane, B.D. and J. Henshall. 1979. Spatial Resolution and Calibration Characteristics of Two Narrow Probe Gamma-Ray Transmission Systems for the Measurement of Soil Bulk Density In Situ. J. Soil Science 30:517-528.

Society of Professional Well Log Analysts (SPWLA). 1960 to present. Annual Logging Symposium Transactions. SPWLA, Houston, TX. (32nd was held in 1991; recent costs have been $75 for two volume set)

Society of Professional Well Log Analysts (SPWLA). 1978a. Gamma Ray, Neutron, and Density Logging. Reprint Volume Series, SPWLA, Houston, TX.

Society of Professional Well Log Analysts (SPWLA). 1978b. Acoustic Logging. Reprint Volume Series, SPWLA, Houston, TX.

Society of Professional Well Log Analysts. 1985. Glossary of Terms and Expressions Used in Well Logging, Revised. SPWLA, Houston, TX. (1st edition 1975.)

Society of Professional Well Log Analysts (SPWLA). 1990. Borehole Imaging. Reprint Volume Series, SPWLA, Houston, TX. [Optical, acoustic, electrical]

Stevens, Jr., H.H., J.F. Ficke, and G.F. Smoot. 1975. Water Temperature--Influential Factors, Field Measurement and Data Presentation. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 1-D1, 65 pp.

Stewart, R.R. 1991. Seismic Tomography. Course Notes No. 3. Society of Exploration Geophysicists, Tulsa, OK, 190 pp.

Stewart, G.L. and W.H. Gardner. 1969. Water Content Measurement by Neutron Attenuation for Application in the Study of the Unsaturated Flow of Soil Water. AEC Report No. RLO-1543-5. Atomic Energy Commission, Washington, DC.

Stewart, G.L. and S.A. Taylor. 1957. Field Experiments with the Neutron Scattering Method of Measuring Soil Moisture. Soil Science 83:151-158.

Stolzy, L.H. and G.A. Cahoon. 1957. A Field-Calibrated Portable Neutron Rate Meter for Measuring Soil Moisture in Citrus Orchards. Soil Sci. Soc. Am. Proc. 21:571-575.

Stone, J., D. Kirkham, and A. Read. 1955. Soil Moisture Determination by a Portable Neutron Scattering Moisture Meter. Soil Sci. Soc. Am. Proc. 19:419-423.

Stone, J.R., R.H. Shaw, and D. Kirkham. 1960. Statistical Parameters and Reproducibility of the Neutron Method of Measuring Soil Moisture. Soil Sci. Soc. Am. Proc. 24:435-438.

Stowell, J.R. 1989. An Overview of Borehole Geophysical Methods for Solving Engineering and Environmental Problems. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 871-890.

Taylor, K. 1989. Review of Borehole Methods for Characterizing the Heterogeneity of Aquifer Hydraulic Properties. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 121-132.

Taylor, T.A. and J.A. Dey. 1985. Bibliography of Borehole Geophysics as Applied to Ground-Water Hydrology. U.S. Geological Survey Circular 926, 62 pp.

Taylor, K., J. Hess, and S. Wheatcraft. 1990. Evaluation of Selected Borehole Geophysical Methods for Hazardous Waste Site Investigations and Monitoring. EPA/600/4-90/029. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, 82 pp. [Acoustic velocity, thermal flowmeter, borehole dilution, induction logs]

Tearpock, D. and R.E. Bischke. 1991. Applied Subsurface Geological Mapping. Prentice Hall, Englewood Cliffs, NJ, 648 pp. [Focusses on construction of geological maps from various sources, including geophysical measurements]

Teasdale, W.E. and A.I. Johnson. 1970. Evaluation of Installation Methods for Neutron-Meter Access Tubes. U.S. Geological Survey Professional Paper 700-C, pp. 237-241.

Technos, Inc. 1992. Application Guide to Borehole Geophysical Logging. Technos, Miami, FL, 15 pp.

Telford, W.M.N., L.P. Geldart, R.E. Sheriff, and D.A. Keys. 1990. Applied Geophysics, 2nd ed. Cambridge University Press, New York, NY, 770 pp. (1st edition, 1976, reprinted 1982.) [Chapter 11 covers borehole geophysics: SP, resistivity, dipmeter, induction, IP, acoustic, nuclear, gravity, magnetic, temperature]

Tellam, J.H. 1992. Reversed Flow Test: A Borehole Logging Method for Estimating Pore Water Quality and Inflow Rates Along an Uncased Borehole Profile. Ground Water Monitoring Review 12(2):146-154. [Fluid conductivity log]

Theys, P.P. 1991. Log Data Acquisition and Quality Control. Editions Technip, Paris, 326 pp.

Thompson, C.M., L.J. Holcombe, D.H. Gancarz, A.E. Behl, J.R. Erikson, I. Star, R.K. Waddell, and J.S. Fruchter. 1989. Techniques to Develop Data for Hydrogeochemical Models. EPRI EN-6637. Electric Power Research Institute, Palo Alto, CA. [Gamma-gamma, neutron probe]

Thornhill, J.T. and B.G. Benefield. 1990. Injection-Well Mechanical Integrity. EPA/625/9-89/007. Available from CERI.*

Tittle, C.S. 1961. Theory of Neutron Logging I. Geophysics 26(1):27-39.

Tittman, J. 1986. Geophysical Well Logging. Academic Press, New York, NY, 192 pp. [Electrical, nuclear, sonic]

Toksoz, M.N. and R.R. Stewart. 1984. Vertical Seismic Profiling, Part B: Advanced Concepts. Seismic Exploration Volume 14b, Geophysical Press, London, 419 pp.

Troxler, W.F. 1964. Calibration of Nuclear Meters for Measuring Moisture Density. In: Symposium on Soil Exploration, ASTM STP 351, American Society for Testing and Materials, Philadelphia, PA, pp. 29-43. [Neutron probe]

Tweeton, D.R. 1988. A Tomographic Computer Program with Constraints to Improve Reconstruction for Monitoring In Situ Mining Leachate. U.S. Bureau of Mines Report of Investigation 9159.

Tyler, S.W. 1985. Moisture Monitoring in Large Diameter Boreholes. In: Proc. Conf. on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Dublin, OH, pp. 97-106. [Neutron probe]

Tyler, S.W. 1988. Neutron Moisture Meter Calibration in Large Diameter Borehole. Soil Sci. Soc. Am. J. 52:890-893.

Unruh, M.E., C. Corey, and J.M. Robertson. 1990. Vadose Zone Monitoring by Fast Neutron Thermalization (Neutron Probe)-a 2-Year Case Study. Ground Water Management 2:431-445 (4th NOAC).

Ursic, S. 1967. Improved Standards for Neutron Soil Water Meters. Soil Science 104:323-325.

U.S. Army Corps of Engineers. 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Department of the Army, Washington, DC, 313 pp. [Section II of Chapter 3 covers borehole seismic, SP, resistivity, acoustic, gamma, gamma-gamma, neutron, temperature, caliper and fluid resistivity]

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14) (NTIS PB88-181557/AS). [Section 8.3.4 covers borehole methods]

U.S. Environmental Protection Agency (EPA). 1993. Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide. EPA/625/R-92/007. Available from CERI.*

U.S. Nuclear Regulatory Commission. 1985. Rules and Regulations, Title 10, Chap. 1, Code of Federal Regulations, Part 20, Standards for Protection Against Radiation.

Vachaud, G., J.M. Royer, and J.D. Cooper. 1977. Comparison of Methods of Calibration of a Neutron Probe by Gravimetry or Neutron-Capture Model. J. Hydrology 34:343-356.

van Bavel, C.H.M. 1958. Measurement of Soil Moisture Content by the Neutron Method. U.S. Department of Agriculture Agricultural Research Service Report ARS41-24, 29 pp.

van Bavel, C.H.M. 1961. Neutron Measurement of Surface Soil Moisture. J. Geophys. Res. 66:1493-1498.

van Bavel, C.H.M. 1962. Accuracy and Source Strength of Soil Moisture Neutron Probes. Soil Sci. Soc. Am. Proc. 26:405.

van Bavel, C.H.M. 1963a. Soil Moisture Measurement with the Neutron Method. U.S. Department of Agriculture Agricultural Research Service Report ARS-41-70.

van Bavel, C.H.M. 1963b. Neutron Scattering of Soil Moisture: Development and Current Status. In: Proc. Int. Symp. on Humidity and Moisture (Washington, DC), pp. 171-184.

van Bavel, C.H.M. and G. Stirk. 1967. Soil Water Measurement with an AM^{241}-Be Neutron Source and an Application to Evaporimetry. J. Hydrology 5:40-60.

van Bavel, C. and N. Underwood. 1956. Neutron and Gamma Radiation as Applied to Measuring Physical Properties of Soil in Its Natural State. Trans. Int. Cong. of Soil Sci (6th Cong., Paris), B:355-360.

van Bavel, C.H.M., N. Underwood, and R.W. Swanson. 1956. Soil Moisture Measurement by Neutron Moderation. Soil Science 82:29-41.

van Bavel, C.H.M., N. Underwood, and S. Ragar. 1957. Transmission of Gamma Radiation by Soils and Soil Densitometry. Soil Sci. Soc. Am. Proc. 21:588-591

van Bavel, C.H.M., D.R. Nielsen, and J.M. Davidson. 1961. Calibration and Characteristics of Two Neutron Moisture Probes. Soil Sci. Soc. Am. Proc. 25:329-334.

van der Leeden, F. 1991. Geraghty & Miller's Groundwater Bibliography, 5th edition. Water Information Center, Plainview, NY, 507 pp. (4th edition 1987.)

Visvalingam, M. and J.D. Tandy. 1972. The Neutron Method for Measuring Soil Moisture Content--A Review. J. Soil Science 23:499-511.

Vomocil, J. 1954. In Situ Measurement of Soil Bulk Density. Agric. Eng. 35:651-654. [Gamma-gamma]

Weinberg, A.M. and E.P. Wignor. 1958. The Physical Theory of Neutron Chain Reactors. University of Chicago Press, Chicago, IL, 800 pp.

West, R.C. and S.H. Ward. 1988. The Borehole Controlled-Source Audiomagnetotelluric Response of a Three-Dimensional Fracture Zone. Geophysics 53(2):215-230.

Wheatcraft, S.W., K.C. Taylor, J.W. Hess, and T.M. Morris. 1986. Borehole Sensing Methods for Ground-Water Investigations at Hazardous Waste Sites. EPA/600/2-86/111 (NTIS PB87-132783).

Williams, J.H. and R.W. Conger. 1990. Preliminary Delineation of Contaminated Water-Bearing Fractures Intersected by Open-Hole Bedrock Wells. Ground Water Monitoring Review 10(4):118-126. [Gamma, SP resistance, caliper, fluid-resistivity, temperature, acoustic televiewer, thermal flowmeter]

Wilson, L.G. 1971. Observations of Water Content Changes in Stratified Sediments During Pit Recharge. Ground Water 9(3):29-40. [Neutron probe]

Wilson, L.G. 1980. Monitoring in the Vadose Zone: A Review of Technical Elements. EPA/600/7-80/134 (NTIS PB81-125817). [Neutron probe]

Wilson, L.G. 1981. Monitoring in the Vadose Zone Part I: Storage Changes. Ground Water Monitoring Review 1(3):32-41. [Gamma-gamma, neutron probe]

Wilson, L.G. and K.J. DeCook. 1968. Field Observations on Changes in the Subsurface Water Regime During Influent Seepage in the Santa Cruz River. Water Resources Research 4(6):1219-1234. [Neutron probe]

Wood, B. and N. Collis-George. 1980. Moisture Content and Bulk Density Measurements Using Dual-Energy Beam of Gamma Radiation. Soil Sci. Soc. Am. J. 44:662-663.

Wyllie, M.R.J. 1963. The Fundamentals of Well Log Interpretation, 3rd edition. Academic Press, New York, NY, 238 pp. (Earlier editions 1954, 1957.) [SP, resistivity, neutron, gamma-gamma, acoustic velocity, gamma, gamma-spectrometry, nuclear magnetic resonance, cement bond]

Yearsley, E.N., R.E. Crowder, and L.A. Irons. 1991. Monitoring Well Completion Evaluation with Borehole Geophysical Density Logging. Ground Water Monitoring Review 11(1):103-118. [Acoustic cement bond, gamma-gamma]

Young, S.C. and J.S. Pearson. 1990. Characterization of Three-Dimensional Hydraulic Conductivity Field with an Electromagnetic Borehole Flowmeter. In: Proc. Fourth Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. Ground Water Management 2:83-97.

Young, S.C. and W.R. Waldrop. 1989. An Electromagnetic Borehole Flowmeter for Measuring Hydraulic Conductivity Variability. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers (Dallas, TX), National Water Well Association, Dublin, OH, pp. 463-475.

Zuber, A. and J.F. Cameron. 1966. Neutron Soil Moisture Gauges. Atomic Energy Rev. 4:143-167.

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH 45268-0963 (513-569-7562).

SECTION 4

AQUIFER TEST METHODS

When ground water is contaminated, the needs for aquifer characterization can be boiled down to four basic questions. How deep is it? What direction is it flowing? How much is flowing through the system? How fast is it flowing? Remedial actions requiring hydrodynamic controls to contain a contaminant plume or requiring pump-and-treat activities, also require an understanding of the **storage** properties of the aquifer in order to evaluate how flow patterns will respond to pumping from or injection into the aquifer.

Basic Characteristics of Ground Water

Water state in the subsurface is measured in terms of **hydraulic head** in the saturated zone, and **negative pressure potential** or **suction** in the vadose zone (covered in Section 6.1). The term ground water usually is applied to subsurface water occurring in a **saturated** zone, where water fills the pore space and moves as a result of differences in hydraulic head. The hydraulic head at a particular location is the elevation to which water rises in an open borehole (or the elevation to which a flowing well would rise if the casing were extended above the ground surface). The hydraulic **gradient** is measured as the change in water level per unit of distance along the direction of maximum head decrease. The gradient can be determined from a **water-table** map of an unconfined aquifer, or a **piezometric** (pressure) surface map showing the elevation to which water would rise in a well tapping a confined or artesian aquifer. Either type of map is called a **potentiometric** map. Table 4-1 summarizes information on seven techniques for measuring water levels in open or cased boreholes and three methods for measuring pressure head in flowing (artesian) wells. The **steel-tape** and **electric probe** methods are used most commonly for routine measurement of water levels. **Transducers** are used most commonly in aquifer tests where accurate measurement of changes in multiple wells is required in relatively short time periods. Pressure potential in the saturated zone also can be measured by burying **in situ** piezometers that sense pore pressure (Section 4.1.10). Table 5-3 in Section 5 provides information on possible sources for commercially available ground-water level measuring devices.

The **hydraulic conductivity** (K, often expressed in terms of centimeters or meters per second) is a basic aquifer parameter used to calculate the amount of ground-water flow using Darcy's Law ($Q = -KiA$, where Q = discharge, i = the hydraulic gradient, and A = the area through which the ground-water is flowing). Ground water **flux** (q) is the flow of water through a specified area ($q = Q/A = Ki$). The average flow **velocity** (v) can also be calculated if K, i, and the effective porosity (n) is known: $v = qn = Kin$. **Transmissivity** (T), or transmissibility, is a measure of the amount of water moving through an entire aquifer and is calculated by multiplying the **thickness** of the aquifer (b) by K ($T = Kb$). Storage properties of aquifers are measured in terms of the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (**specific storage S_s**). **Storativity** (or **storage coefficient**) (S) is the specific storage or yield multiplied by the aquifer thickness ($S = S_s b$). Characterization of aquifer **heterogeneity** (K varies depending on the location within the aquifer) and **anisotropy** (K varies at a given point in an aquifer depending on the direction of measurement) is essential for accurate prediction of ground-water flow direction. Ground-water flow in **porous** media, such as unconsolidated deposits and sandstone, has very different characteristics than flow in which **fractures** (typically igneous and metamorphic rocks) and **conduits** (karst limestone) are present. **Dispersion** (the net effect of a variety of microscopic, macroscopic, and regional conditions that influence the spread of a solute concentration front through an aquifer) is another important aquifer parameter that requires some evaluation. Dispersion allows contaminants to move more rapidly through an aquifer than would be predicted by the average hydraulic conductivity as measured by a pumping test, for example.

This section classifies aquifer characterization methods into four categories: (1) Shallow water table tests, (2) well tests, (3) tracer tests, and (4) other methods. Table 4-2 summarizes information on the types of aquifer parameters that can be measured using specific techniques.

Table 4-1 Summary Information on Ground Water Level/Pressure Measurement

Method	Property Measured	Accuracy[a]	Chapter Sections
Monitoring Well Water Level Measurement			
Steel Tape	Water surface	0.01'	4.1.1
Electric Probe	Water surface	0.02-0.1'	4.1.2
Air Line	Pressure head	0.25'	4.1.3
Pressure Transducers	Pressure head	0.01-0.1'	4.1.4
Popper/Acoustic Probe	Water surface	0.1'	4.1.5
Ultrasonic	Water surface	0.02-0.1'	4.1.6
Mechanical Float	Water surface	0.02-0.5'	4.1.7
Potentiometer Float	Water surface	0.01-0.1'[b]	4.1.7
Electromechanical	Water surface	0.02-0.5'	4.1.8
Flowing Well Head Measurement			
Casing Extensions	Water surface	0.1'	4.1.9
Manometer/Pressure Gage	Pressure head	0.1-0.5'	4.1.9
Transducers	Pressure head	0.02'	4.1.9
In Situ Piezometers	Pressure head	0.02-0.5'[c]	4.1.10

[a]Water level measurement accuracy in wells taken from Dalton et al. (1991).
[b]Reported by Rosenberry (1990) as having accuracy similar to pressure transducers.
[c]Lower range for measurements with transducers and upper range for pressure gage.

Table 4-2 Summary Information on Aquifer Test Methods

Technique	Confined/ Unconfined	Porous/ Fractured	Aquifer Properties Measured	Chapter Section	Table
Shallow Water Table					
Auger Hole	Unconfined	Porous	K (horizontal)[a]	4.2.1	4-5, 7-2
Pit-Baling	Unconfined	Porous[b]	K (undefined)	4.2.1	4-5
Pumped Borehole	Unconfined	Porous	K (undefined)	4.2.1	4-5
Piezometer	Unconfined	Porous	K (undefined)	4.2.2	4-5, 7-2
Tube	Unconfined	Porous[b]	K (vertical)	4.2.2	4-5
Well Point	Unconfined	Porous	K (undefined)	4.2.2	4-5
Two-Hole	Unconfined	Porous	K (undefined)	4.2.3	4-5
Four-Hole	Unconfined	Porous	K (undefined)	4.2.3	4-5, 7-2
Multiple-Hole	Unconfined	Porous	K (undefined)	4.2.3	4-5
Drainage Outflow	Unconfined	Porous	K (undefined)	4.2.3	4-5
Well Tests					
Slug (Injection/Withdrawal)	Both	Porous	K, H, T	4.3.1	4-5
Slug (Displacement)	Both	Porous	K, H, T	4.3.1	4-5
Single-Well Pump	Both	Porous	K, S, T	4.3.2	4-5
Multiple-Well Pump	Both	Porous	A, K, S, T	4.3.2	4-5
Single-Packer	Both	Both	K, H, T	4.3.3	4-5
Two-Packer[c]	Both	Both	K, H, T	4.3.3	4-5
Tracers					
Ions	Both	Both	D, F, V	4.4.1	4-3
Dyes	Unconfined	Both	D, F, V	4.4.2	4-3, 4-6
Gases	Unconfined	Both	D, F, R, V	4.4.3	4-3
Stable Isotopes	Both	Both	D, F, R, V	4.4.4	4-3, 4-6
Radioactive Isotopes	Both	Both	D, F, R, V, T[d]	4.4.5	4-3, 4-6
Water Temperature	Unconfined	Both	D, F, V	4.4.6	4-3
Particulates/Microorganisms	Unconfined	Both	D, F, V	4.4.7	4-3, 4-6
Other Techniques					
Water Balance	Unconfined	Both	R	4.5.1	4-5
Moisture Profile	Unconfined	Porous	S	4.5.2	
Shallow Geothermal	Unconfined	Porous	F, R	1.6.2	
Fluid Conductivity Log	Both	Both	F	3.1.3	
Neutron Activation	Both	Both	F, H, V	3.3.5	
Differential Temperature Log	Both	Both	F	3.5.2	
Flow Meters	Both	Both	F, H, V	3.5.3-3.5.5	
Single-Well Tracer Methods	Both	Both	F, H, V	3.5.6	
Other borehole methods	Both	Both	H	Section 3	
Piezometric Map	Both	Both	F, H	4.1	

Boldface = most commonly used methods.
A = anisotropy; D = dispersivity; F = flow direction; H = heterogeneity; K = hydraulic conductivity; R = recharge/age; S = specific storage/yield; T = Transmissivity; V = Velocity.

[a]Directional ratings are qualitative in nature. Different references may give different ratings depending on site conditions and criteria used to define directionality. For example, U.S. EPA (1981) and Hendrickx (1990) note that this method often measures primarily horizontal conductivity, whereas Bouma (1983) indicates that the direction is undefined (see Figure 7-2).
[b]Can be used in rocky soils; other methods generally require fine-grained soils.
[c]Can be used to measure saturated hydraulic conductivity both above and below the water table in open holes in consolidated rock.
[d]Actual uses are much more restricted due to health concerns.

Shallow Water Table Tests

A number of relatively simple techniques have been developed for measuring hydraulic conductivity where a shallow water table is present (see Table 4-2). The **auger hole** method (Section 4.2.1) is the most widely used of these methods, but others can be appropriate for special applications. Sections 7.3 and 7.4 of this guide cover techniques for measuring saturated hydraulic conductivity above a water table. These shallow tests only provide information on hydraulic conductivity.

Well Test Methods

Test methods involving wells that have been placed in an aquifer fall into three main categories: (1) Single-well **slug** tests (Section 4.3.1), (2) **pumping** tests (Section 4.3.2), and (3) **packer** tests (Section 4.3.3). Table 4-2 indicates the types of aquifer parameters that can be obtained from these tests. Slug and packer tests provide information on relatively small portions of an aquifer, but are relatively easy to carry out and consequently are well-suited for characterizing aquifer heterogeneity. Pumping tests are more complex and difficult to carry out, but provide information on a larger portion of the aquifer and provide more information on aquifer storage properties (see also, Section 4.5.2). Well test methods are best suited for porous media, and most methods tend to give misleading results where fracture or conduit flow is an important component of ground-water flow. ASTM (1991a) provides guidance on the selection of aquifer well test methods.

Tracer Test Techniques

Ground-water tracers primarily are used to identify the source, direction, and velocity of ground-water flow, and the dispersion of contaminants. Depending on the type of test and the hydrogeologic conditions, other parameters, such as hydraulic conductivity, porosity, chemical distribution coefficients, source of recharge, and age of ground water also can be measured. Any detectable substance that can be injected into the subsurface and travel in the vadose or saturated zone can serve as a tracer. Table 4-3 identifies over 60 substances that have been reported or suggested as tracers in ground-water studies. Any contaminant that is detected in ground water functions as a tracer, provided the original source is known. The large number of tracers and many different ways in which they have been used precludes detailed coverage of this topic. For the purposes of this guide, tracers are grouped in seven major categories: (1) Ions and other water soluble compounds; (2) dyes, (3) gases, (4) stable isotopes, (5) radioactive isotopes, (6) water temperature, and (7) particulates (including spores, bacteria, and viruses). Table 4-1 provides some summary information on uses of these groups of tracers for aquifer characterization. Dyes and ions probably are the most commonly used tracers at contaminated sites. Dye tracer tests are especially valuable for characterizing fracture flow, and flow in karst limestone systems where conventional well tests can yield misleading results, and ground-water flow directions tend to be unpredictable. Tracers, especially gases and dyes, also are widely used for vadose zone characterization.

Other Aquifer Characterization Methods

Water balance methods (Section 4.5.1) have a wide variety of applications, and are used most commonly at contaminated sites for evaluating transport of contaminants from the vadose zone to ground water, and for design of waste disposal facilities to minimize flow through the vadose zone. In an unconfined aquifer, specific yield can be calculated by measuring changes in soil moisture profiles in response to changes in water table (Section 4.5.2) as an alternative to pumping tests.

Sources of Additional Information on Aquifer Test Methods

The detailed literature on ground-water hydraulics and pumping tests is too large to include in any comprehensive way in this guide. Consequently, only major text references and reports on these two topics are included in the references at the end of this section (see Table 4-5, at the end of this section, for index). Table 4-5 includes a reasonably comprehensive index to the literature on shallow water table tests, slug tests, and packer tests. The detailed literature on use of tracers in ground-water and contaminated site investigations also is too large for inclusion here. Table 4-6 (also at the end of this section) provides an index of major texts and review papers covering major types of tracers (dyes, microorganisms, stable isotopes and radioactive isotopes) and also identifies major texts and reports that focus on tracing karst hydrologic systems.

Table 4-3 List of Major Ground-Water Tracers

NATURAL TRACERS	INJECTED TRACERS		
	Radioactive	Activable	Inactive
Stable Isotopes			Ionized Substances
Deuterium (^2H)	Tritium	Bromine-35	$Na^+ Cl^-$
Oxygen-18	Sodium-24	Indium-39	$K^+ Cl^-$
Carbon-12	Chromium-51	Manganese-25	$Li^+ Cl^-$
Carbon-13	Cobalt-58	Lanthanum-57	$Na^+ I^-$
Nitrogen-14	Cobalt-60	Dysprosium-68	$K^+ Br^-$
Nitrogen-15	Gold-198		
Strontium-88	Iodine-131		Drift Material
Sulfur-32	Phosphorus-32		
Sulfur-34			Lycopodium Spores
Sulfur-36			Bacteria
			Viruses
Radioactive Isotopes			Fungi
			Sawdust
Tritium (^3H)			
Carbon-14			Fluorescent Dyes
Silicon-32			
Chlorine-36			Optical Brighteners
Argon-37			Tinopal 5Bm6x(FDA 22)
Argon-39			Direct Yellow 96
Krypton-81			Fluorescein
Krypton-85			Acid Yellow 7
Bromine-32			Rhodamine WT
Radon-222			Eosin (Acid Red 87)
			Amidorhodamine 6 (Acid Red 50)
Gases			Physical Characteristics
Fluorocarbons			Water Temperature
			Flood Pulse
			Gases
			Helium
			Argon
			Neon
			Krypton
			Xenon

Source: Modified from Jones (1984)

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.1 Steel Tape

Other Names Used to Describe Method: Wetted tape.

Uses at Contaminated Sites: Manually measuring water levels in wells.

Method Description: A lead weight is attached to a standard surveyor's steel tape and the bottom two or three feet coated with carpenter's chalk. The tape usually is lowered into the water a sufficient depth to place the tape at an even foot mark at a reference point of known elevation on the casing (Figure 4.1.1). The water-level in the well is calculated by subtracting the submerged distance, as indicated by the point at which the chalk is still dry, from the reference point at the top of the well.

Method Selection Considerations: **Advantages:** (1) Most precise method (accuracy 0.01 feet); (2) equipment is inexpensive, portable, durable, and does not require a power source; (3) calibration can be easily checked. **Disadvantages:** (1) The method is slow, particularly in wells where depth to water is unknown, where too short a length of chalked tape can require several tries to obtain a reading (slowness also limits usefulness for pumping tests where measurements must be made a close time intervals); (2) continuous measurements of water-level changes are not possible; (3) errors in measurement might result from water condensation on the casing or cascading water wetting the tape above the actual water level; (4) displacement of water level by the weighted end of the tape might significantly affect readings in small diameter wells in low permeability materials; and (5) measurement in wells where the temperature is high or at depth greater than 1,000 feet require corrections for stretch and expansion.

Frequency of Use: Common.

Standard Methods/Guidelines: ASTM (1987).

Sources for Additional Information: Dalton et al. (1991), Driscoll (1986), Garber and Koopman (1968), Thompson et al. (1989), Thornhill (1989), U.S. EPA (1987), U.S. Geological Survey (1980).

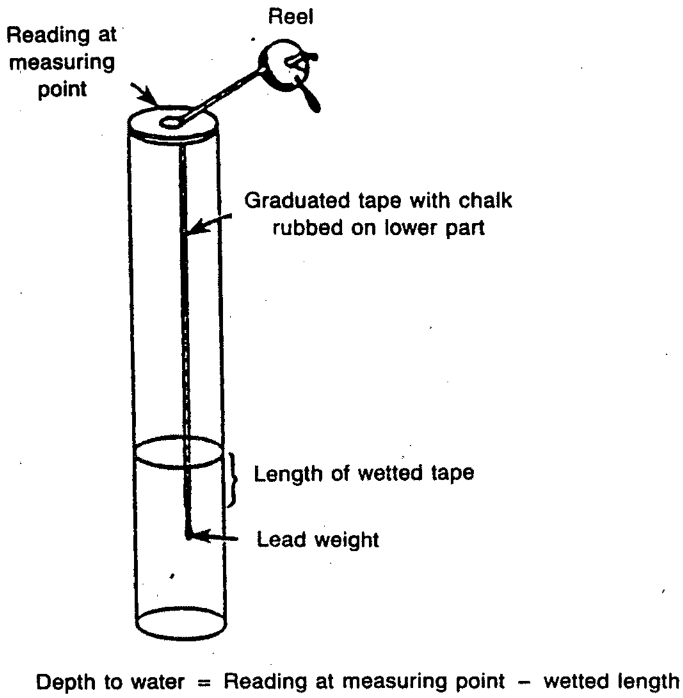


Figure 4.1.1 Steel tape method for measuring water levels (Thompson et al., 1989, after Davis and DeWiest, 1966, Copyright © 1989, Electric Power Research Institute, EPRI EN-6637, *Techniques to Develop Data for Hydrogeochemical Models*, reprinted with permission).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.2 Electric Probe

Other Names Used to Describe Method: Electric cable, conductive probe, water level indicators.

Uses at Contaminated Sites: Manually measuring water levels in wells; performing water level-measurement for aquifer tests.

Method Description: Various types of instruments have been developed, all have some kind of electrode sensor attached to a cable that is lowered down the well. When the probe comes into contact with the water surface, the fluid conducts a current that activates a meter, light, or buzzer at the surface. Figure 4.1.2 illustrates five different types of electric probes. The cable usually is marked at 1- or 5-foot intervals and distance is measured from the nearest marking to a known reference point on the casing at the surface to obtain the water-level depth. Some newer instruments use coated steel tapes as an insulated electrode. The most common type of instrument uses an open circuit of two electrodes attached to a batter, which is completed when they come in contact with water. Other instruments use resistance, capacitance, or self-potential to generate a signal. Henszey (1991) provides detailed plans for a simple, inexpensive electrical device for measuring shallow ground-water levels.

Method Selection Considerations: **Advantages:** (1) Rugged, simple, and relatively inexpensive; (2) good precision if properly calibrated (0.02 to 0.1 feet); (3) multiple measurements can be taken in quick succession without raising the probe to the surface; and (4) protective casing around the probe prevents false readings from cascading water or splashing during a pumping test. **Disadvantages:** (1) Continuous measurements of water-level changes are not possible; (2) hydrocarbons on water surface might interfere with measurements; (3) changes in cable length and markings as a result of use, depth, and temperature might reduce accuracy of readings; and (4) lower accuracy and periodic calibration required when used in deep wells.

Frequency of Use: Probably the most commonly used method.

Standard Methods/Guidelines: ASTM (1987).

Sources for Additional Information: Dalton et al. (1991), Driscoll (1986), Garber and Koopman (1968), Thompson et al. (1989), U.S. EPA (1987), U.S. Geological Survey (1980). See also, Table 4-4.

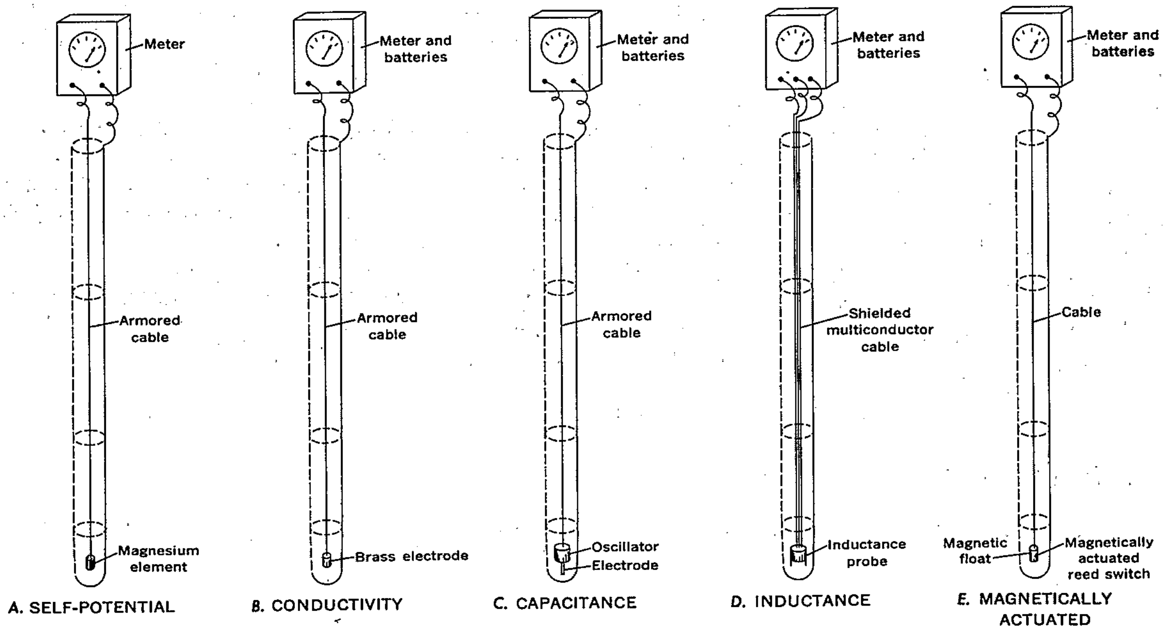


Figure 4.1.2 Types of electric probes for measuring water levels (Garber and Koopman, 1968).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.3 Air Line

Other Names Used to Describe Method: Air-line submergence.

Uses at Contaminated Sites: Measuring water levels in wells; performing water level-measurement for pumping tests.

Method Description: An air-tight tube, usually 0.375 inch or less in diameter and made of plastic, copper, or steel, is extended a measured distance from the surface to a depth below the lowest water level that is anticipated during pumping. A hand air pump (for shallow wells) or a compressor is used to pump air into the tube as pressure is monitored by a gage attached to the system (Figure 4.1.3). Air pressure increases until all water is expelled from the line. When the pressure gage stabilizes, the reading indicates the height of water in the tube (directly in feet, if calibrated, or the pressure reading is converted). Subtracting the calculated height of water in the air line from the line's length gives the actual level in the well.

Method Selection Considerations: **Advantages:** (1) Fast and simple, but air compressor required; and (2) well suited for taking continuous measurements in wells that are being pumped. **Disadvantages:** (1) Relatively low accuracy (0.25 feet with gages accurate to 0.1 psi) and lacks precision for hydraulic tests with small fluid level changes; (2) leaks in air line or fittings will cause errors in readings; and (3) measurements in deep wells require corrections for thermal expansion, hysteresis, fluid density, and barometric pressure.

Frequency of Use: Commonly used for pumping tests where water turbulence precludes using more precise methods.

Standard Methods/Guidelines: --

Sources for Additional Information: Dalton et al. (1991), Driscoll (1986), Garber and Koopman (1968), U.S. EPA (1987), U.S. Geological Survey (1980). See also, Table 4-4.

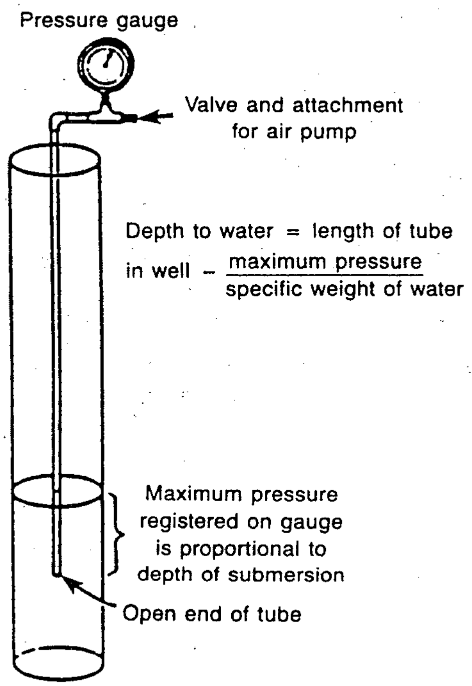


Figure 4.1.3 Air line method for measuring water levels (Thompson et al., 1989, after Davis and DeWiest, 1966, Copyright © 1989, Electric Power Research Institute, EPRI EN-6637, *Techniques to Develop Data for Hydrogeochemical Models*, reprinted with permission).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.4 Pressure Transducers

Other Names Used to Describe Method: Submersible differential pressure transducer.

Uses at Contaminated Sites: Measuring water levels in wells; performing continuous water level-measurement for aquifer tests.

Method Description: A **pressure transducer** contains a current transmitter (which prevents measurement sensitivity from being affected by cable length) and a strain gage sensor. The strain gage sensor generates an electrical signal, proportional to pressure, which is transmitted by cables to a surface recording station (Figure 4.1.4). The pressure measured allows calculation of the depth of the transducer below the water surface, and calculation of the water level if the length of the cable to a reference point at the surface is known. **Vented** pressure transducers have a small capillary tube that is open to the atmosphere and allows automatic compensation for barometric pressure. Nonvented transducers require measurement of barometric pressure, which is subtracted from the total pressure to obtain the pressure of the column of water over the transducer. Continuous monitoring of changes in water level during aquifer tests or natural ground-water fluctuations is possible provided the transducer remains below the lowest anticipated water level and data loggers are used.

Method Selection Considerations: **Advantages:** (1) Good precision (0.01 to 0.1 feet); (2) respond quickly to changing water levels; (3) continuous monitoring of water levels is possible; and (4) a permanent record is provided, and data can be recorded for automatic data processing. **Disadvantages:** (1) Probe and recording devices are expensive; (2) instruments are sensitive and require care in handling and storage and periodic recalibration is required; (3) a continuous, stable power source is required; and (4) measurement errors can result from temperature changes, instrument drift, and blocked capillary.

Frequency of Use: Most commonly used for complex pumping tests involving monitoring of multiple wells, and for slug tests in permeable material.

Standard Methods/Guidelines: --

Sources for Additional Information: Dalton et al. (1991), Driscoll (1986), Thompson et al. (1989).

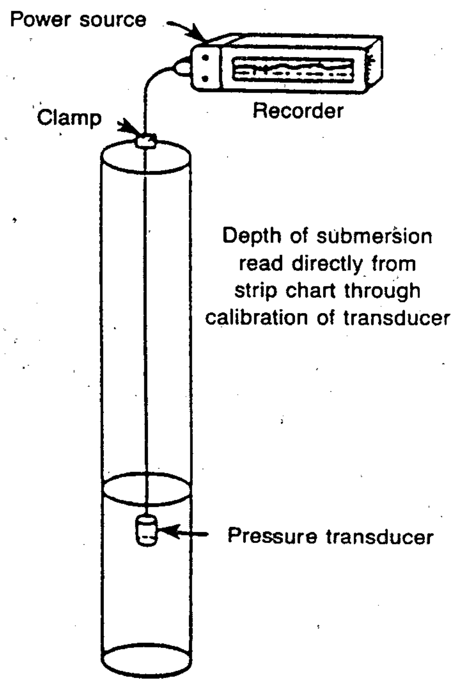


Figure 4.1.4 Pressure transducer method for measuring water levels (Thompson et al., 1989, after Davis and DeWiest, 1966, Copyright © 1989, Electric Power Research Institute, EPRI EN-6637, *Techniques to Develop Data for Hydrogeochemical Models*, reprinted with permission).

4.1.5 Audible Methods

Other Names Used to Describe Method: Popper, acoustic probe, "rock and bong" techniques.

Uses at Contaminated Sites: Measuring water levels in wells.

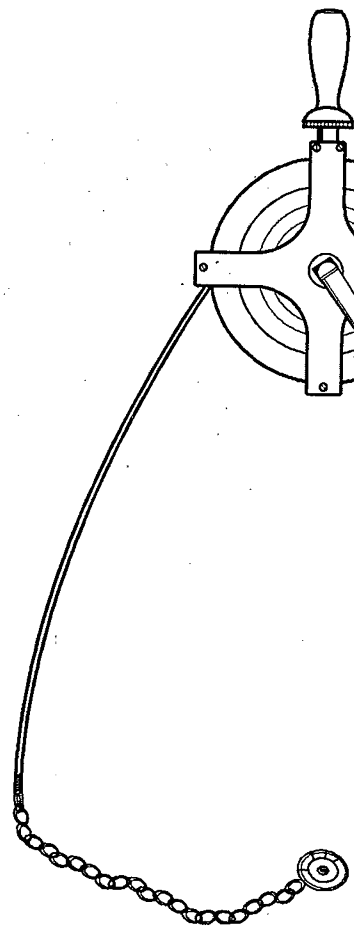
Method Description: Various methods involve attachment of devices that create an audible sound when they come in contact with water in the well. **Popper:** A concave-bottomed metal cylinder 1 to 1.5 inches in diameter and 2 to 3 inches long is attached to a steel tape (Figure 4.1.5) and lowered to within a few inches of the water surface in the well. Depth to water is determined by repeatedly dropping the popper onto the water surface and noting the tape reading at which a distinctive "pop" is heard. **Acoustic probe:** An electronic device that emits an audible sound generated by a battery powered transducer in the probe when two electrodes come in contact with water. Unlike electric cables, the probe is self-contained and attached to a steel tape that is used for measuring the depth at which the sound is heard. The **rock and bong** method involves dropping a BB (air rifle shot) or glass marble and recording the time of the return sound of impact.

Method Selection Considerations: **Popper/Acoustic Probe Advantages:** (1) Simple and inexpensive; and (2) moderately accurate (0.1 feet for popper; 0.02 for acoustic probe). **Popper/Acoustic Probe Disadvantages:** (1) Generally not suitable for use with pumping wells because of noise and lack of clearance; and (2) hydrocarbons on well water surface will affect acoustic probe. **Rock and Bong Advantages:** Very simple and inexpensive. **Rock and Bong Disadvantages:** (1) Inaccurate (within 5 feet); (2) introduces foreign objects into the well.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: **Popper:** Bureau of Reclamation (1981); **Acoustic probe:** Schrale and Brandwyck (1979); **Rock and bong:** Stewart (1970).

Sources for Additional Information: Dalton et al. (1991), U.S. EPA (1987).



Popper. PX-D-25996

Figure 4.1.5 Popper for measuring depth to water in a well (Bureau of Reclamation, 1981).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.6 Ultrasonic

Other Names Used to Describe Method: Sonic transducers, acoustic sounder.

Uses at Contaminated Sites: Measuring water levels in wells.

Method Description: Instrument emits a sonic or ultrasonic wave pulse and measures the arrival time of the reflected sound (Figure 4.1.6). Typically, the instrument has a microprocessor that allows the signal to be transmitted, received, and averaged many times a second, allowing rapid measurement. The microprocessor automatically calculates the depth to water and displays it in various units. Some instruments are designed to rest on top of the well casing, whereas others can require lowering into the well.

Method Selection Considerations: **Advantages:** (1) Reasonably accurate (0.1 feet) and high accuracy is possible with specialized installations (0.02 feet); (2) automatic data collection is possible; (3) rapid determination of water level in deep wells is possible; and (4) presence of hydrocarbons usually does not affect measurements. **Disadvantages:** (1) Accuracy can be limited by change of temperature in the path of the sound wave or by reflective surfaces in the well such as pipes, casing burrs, pumps, and samplers; and (2) care must be taken in reading wave charts because discontinuities in the casing or in other well construction components might generate anomalous wave forms resulting in inaccurate determination of water level depth.

Frequency of Use: Relatively new method that is becoming more common.

Standard Methods/Guidelines: --

Sources for Additional Information: Dalton et al. (1991), U.S. EPA (1987). See also, Table 4-4.

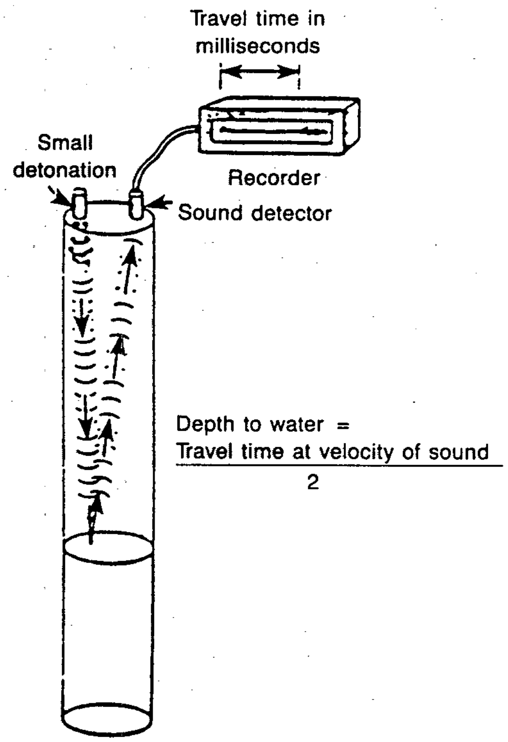


Figure 4.1.6 Ultrasonic method (Thompson et al., 1989, after Davis and DeWiest, 1966, Copyright © 1989, Electric Power Research Institute, EPRI EN-6637, *Techniques to Develop Data for Hydrogeochemical Models*, reprinted with permission).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.7 Float Methods

Other Names Used to Describe Method: Mechanical float recorder, flotation device, potentiometer float.

Uses at Contaminated Sites: Continuously measuring water level fluctuations.

Method Description: **Mechanical float:** A flotation device is attached to a length of steel tape and suspended over a pulley into the well. A counterweight at the other end of the tape keeps the tape taught as the float moves up and down in response to changes in water level. The depth to water can be read directly from the steel tape at a known reference point on the casing, but more commonly the pulley is attached to a recording-chart drum that rotates in response to changes in the level of the float (Figure 4.1.7). A pen records fluctuations by moving across the chart at a constant rate by a clock-driven motor, or alternatively electronic or punch-tape recorders can be used. **Potentiometer float:** Similar to the mechanical float except that a variable resistor or potentiometer is attached to the float allowing digital datalogging.

Method Selection Considerations: **Mechanical Float Advantages:** (1) Provides continuous measurements of water-level changes for up to several months; (2) relatively simple; and (3) moderately accurate (0.02 to 0.5 feet). **Mechanical Float Disadvantages:** (1) Protective housing is required to protect recording-chart drum from unfavorable weather; (2) float lag, line shift, submergence of counterweight, temperature, and humidity can affect accuracy of measurements; (3) as depth to water increases, potential for drag between the float and well casing increases, which might reduce or delay pen response to water level changes; and (4) problems might be encountered when used in small wells (Shuter and Johnson, 1961). **Potentiometer Float Advantages and Disadvantages:** Generally similar to mechanical float except that they are generally more accurate (0.01 to 0.1 feet).

Frequency of Use: Commonly used when continuous measurement of natural ground-water fluctuations are required.

Standard Methods/Guidelines: --

Sources for Additional Information: Dalton et al. (1991), Leupold and Stevens (1991), Shuter and Johnson (1961), U.S. Geological Survey (1980). See also, Table 4-4.

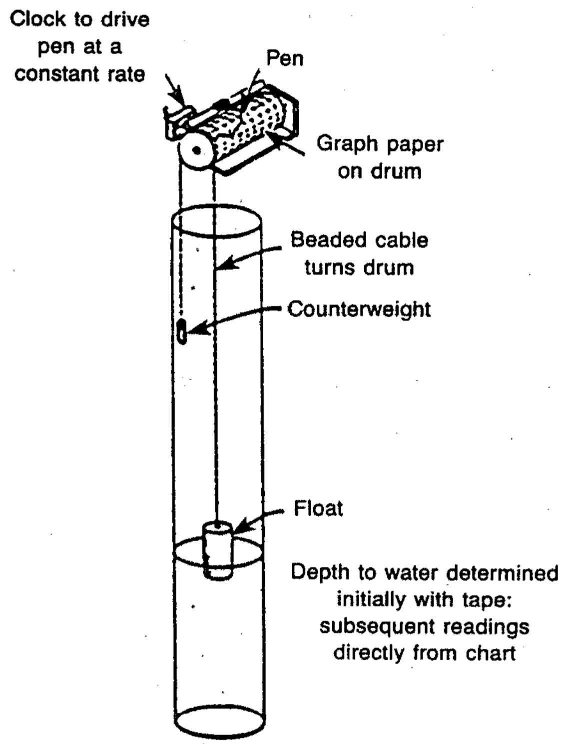


Figure 4.1.7 Mechanical float recorder (Thompson et al., 1989, after Davis and DeWiest, 1966, Copyright © 1989, Electric Power Research Institute, EPRI EN-6637, *Techniques to Develop Data for Hydrogeochemical Models*, reprinted with permission).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.8 Electromechanical

Other Names Used to Describe Method: Iterative conductance probes, dipping probes, dippers.

Uses at Contaminated Sites: Continuously measuring water level fluctuations.

Method Description: Dipping probes are motor-driven devices that use an electronic feedback circuit to measure water level in a well. The probe is lowered on a wire by a stepping motor until it makes contact with the water, at which time an electrical signal causes the motor to reverse and retract the probe a short distance. After a set period of time, the motor lowers the probe until it touches the water, and retracts again. The wire cable is connected to either a chart-recording drum or a potentiometer with an output signal proportional to the water level, and water levels are recorded at whatever time increments the motor is set to repeat its cycle.

Method Selection Considerations: **Advantages:** (1) Provide automatic, periodic measurement of water level changes; (2) work well in small diameter wells and can accommodate some tortuosity in the well casing; and (3) greater depths can be monitored without mechanical losses associated with float recorders. **Disadvantages:** Instrumentation is more complex than mechanical float recorder.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Dalton et al. (1991).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.9 Artesian Aquifer Measurement

Other Names Used to Describe Method: Manometers/pressure gages, transducers, casing extension.

Uses at Contaminated Sites: Measuring head in flowing wells (artesian aquifers).

Method Description: Flowing wells (confined aquifers where the pressure head is above the ground surface) can be measured in several ways. Capping off the well allows measuring pressure with **manometers, pressure gages,** or **pressure transducers** (see Section 4.1.4). Figure 4.1.9 shows a schematic of a mercury manometer for measuring artesian heads. Another method is to extend the casing above the ground surface until water ceases to flow, and measuring the height of above the ground-surface that water has risen in the casing.

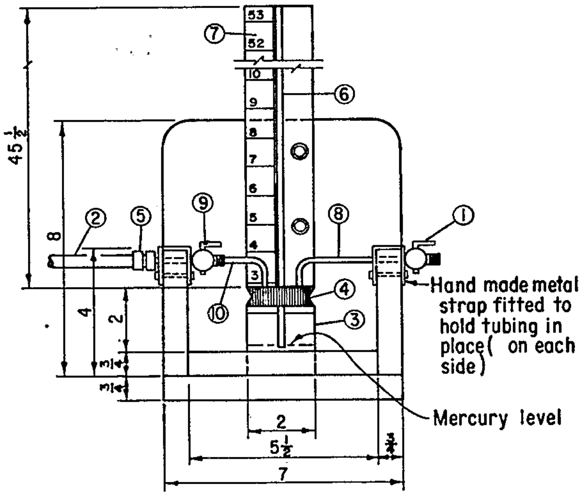
Method Selection Considerations: **Manometers/Pressure Gage Advantages:** A properly installed mercury manometer provides the greatest accuracy (0.005 to 0.1 feet) and pressure gages are accurate to 0.2 to 0.5 feet. **Manometers/Pressure Gage Disadvantages:** Both types requires periodic calibration. **Transducers:** See advantages and disadvantages discussed in Section 4.1.4. **Casing Extension Advantages:** No calibration of gages or instruments is required (assuming steel tape or electric probe is used to measure distance from top of casing). **Casing Extension Disadvantages:** Limited range and awkward to implement.

Frequency of Use: Manometers or pressure gages are most commonly used when flowing artesian aquifers are present.

Standard Methods/Guidelines: --

Sources for Additional Information: Bureau of Reclamation (1981), Dalton et al. (1991), U.S. Geological Survey (1980).

① 1- $\frac{1}{4}$" Stainless steel stop cock.
② 4' Length of $\frac{5}{8}$" i.d. rubber hose.
③ 1- 2" Dia. ink bottle.
④ 1- 3 Holed No. 8 rubber stop.
⑤ 1- $\frac{3}{4}$" Hose coupling.
⑥ 48" Length of 2 mm i.d. glass tubing.
⑦ 45" Length of stainless steel strip with graduations which give readings in feet of water.
⑧ 1- 4" Length of $\frac{1}{4}$" o.d. stainless steel tubing with fittings.
⑨ 1- $\frac{5}{16}$" Stainless steel stop cock.
⑩ 1 - 4" Length of $\frac{5}{16}$" o.d. stainless steel or plastic tubing with fitting.
Assorted lumber (marine plywood)
Assorted $\frac{1}{8}$" bolts with nuts.



(After S.W. Lohman)

Figure 4.1.9 Mercury manometer for measuring artesian heads (Bureau of Reclamation, 1981).

4. AQUIFER TEST METHODS

4.1 GROUND-WATER LEVEL/PRESSURE MEASUREMENT

4.1.10 In Situ Piezometers

Other Names Used to Describe Method: Pore pressure piezometer, pneumatic piezometer, hydraulic piezometer.

Uses at Contaminated Sites: Measuring ground-water levels.

Method Description: In situ piezometers are permanently installed devices intended primarily for measurement of changes in pore pressure, from which ground-water levels can be calculated. In some cases, units are designed so that both pressure measurements and water samples can be obtained (a cone penetration rig using the BAT system can do this, see Sections 2.2.2 and 5.5.2). There are three major types of pore pressure piezometers: (1) **Vibrating wire** piezometers generate electrical signals at the surface as the tension in a wire that is connected to a diaphragm situated behind a filter stone changes in response to higher or lower pore pressure (Figure 4.1.10a); (2) **pneumatic** piezometers use a pressure transducer to measure changes that water pressure has exerted against a diaphragm into which air has been forced (Figures 4.1.10a and b); and (3) **hydraulic** piezometers consist of one or two water-filled tubes that run from the surface to a ceramic or porous stone tip and pressure changes are read from a gage at the surface (mercury manometer, transducer, or Bourdon gage, see Figure 4.1.10c). There are three main types of installations for in situ piezometers: (1) **Driven**, in which the piezometer tip is attached to steel standpipe and driven to the depth of interest (Figure 4.1.10c), (2) jetting to install open-ended tubes (see Section 2.1.8), and (3) **capsule** installations in a borehole in which a filter pack is placed around the unit and bentonite seals are used, if required to isolate it from other units (see Figure 4.1.10d).

Method Selection Considerations: **Advantages:** (1) Generally easier to install and less expensive than monitoring well installations; (2) multilevel installation is relatively easy; (3) most types operate well with automatic data acquisition systems, allowing rapid hydraulic head measurements in a large area; and (4) more responsive to instantaneous changes in head than open standpipes, and consequently are especially useful for monitoring fast water level changes during pumping tests and in very low permeability materials where open standpipes might have a long lag time in response to water level changes. **Disadvantages:** (1) Clogging of tubes and corrosion of transducers can be a problem for pneumatic piezometers; (2) calibration is required for electric wire and pneumatic piezometers and might cause difficulties when additional cable or tubing is required; (3) hydraulic piezometers require occasional flushing to remove air which has entered the porous tip through diffusion; and (4) most installations do not allow sampling of ground water.

Frequency of Use: Relatively uncommon, but more extensive use at contaminated sites for preliminary characterization shallow ground-water systems might be merited.

Standard Methods/Guidelines: Reeve (1986).

Sources for Additional Information: Morrison (1983), U.S. EPA (1987). See also, Table 4-4.

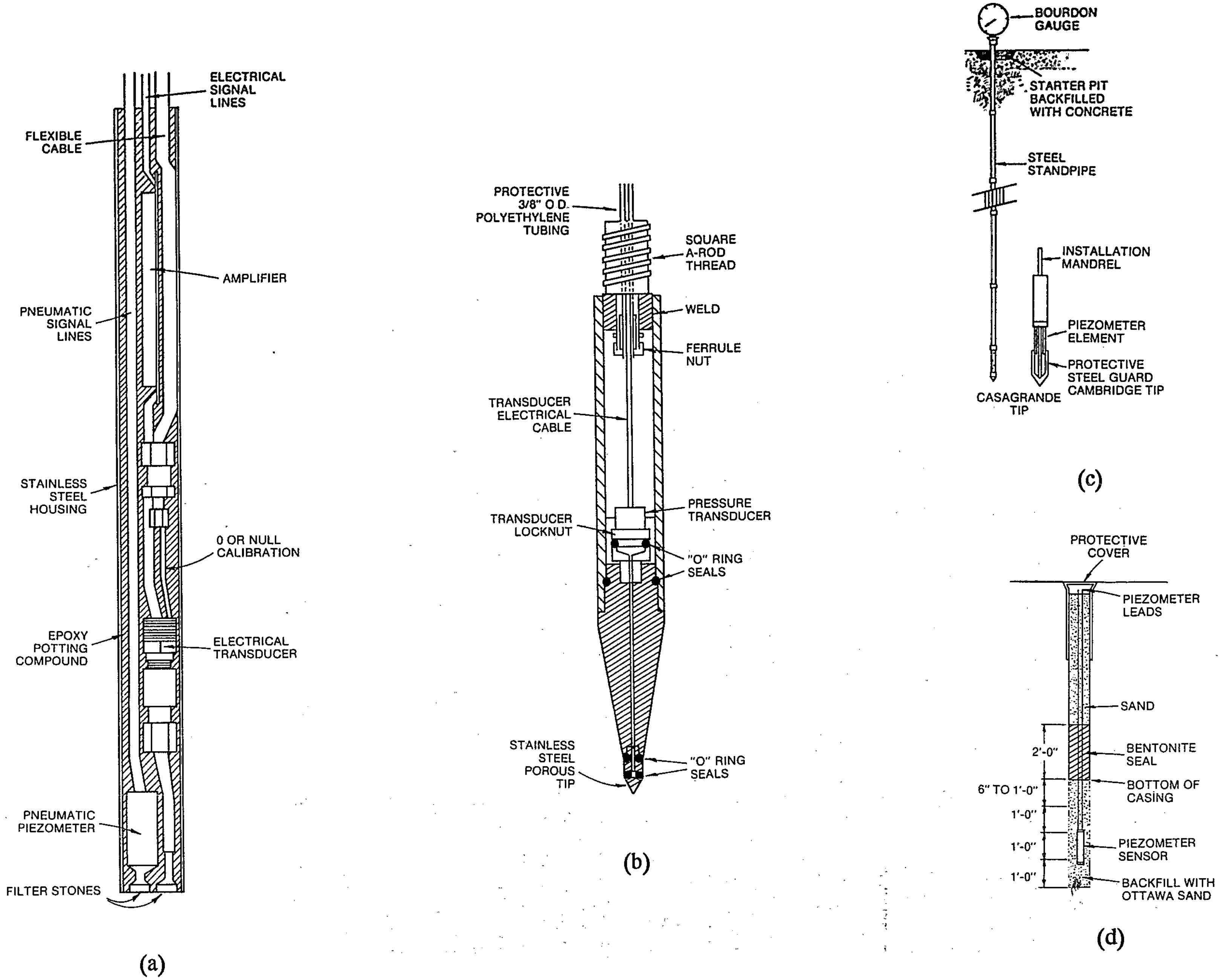


Figure 4.1.10 Pore pressure piezometers: (a) Combined vibrating wire and pneumatic types (Morrison, 1983, by permission); (b) Pneumatic type (Morrison, 1983, after Wissa et al., 1975, by permission); (c) Driven installation of hydraulic type (Morrison, 1983, by permission); (d) Borehole installation (Morrison, 1983, after Hemond, 1982, by permission).

4. AQUIFER TEST METHODS

4.2 HYDRAULIC CONDUCTIVITY (SHALLOW WATER TABLE)

4.2.1 Auger Hole Method

Other Names Used to Describe Method: Variants: Pit-baling method, pumped borehole method.

Uses at Contaminated Sites: Measuring saturated hydraulic conductivity where there is a shallow water table.

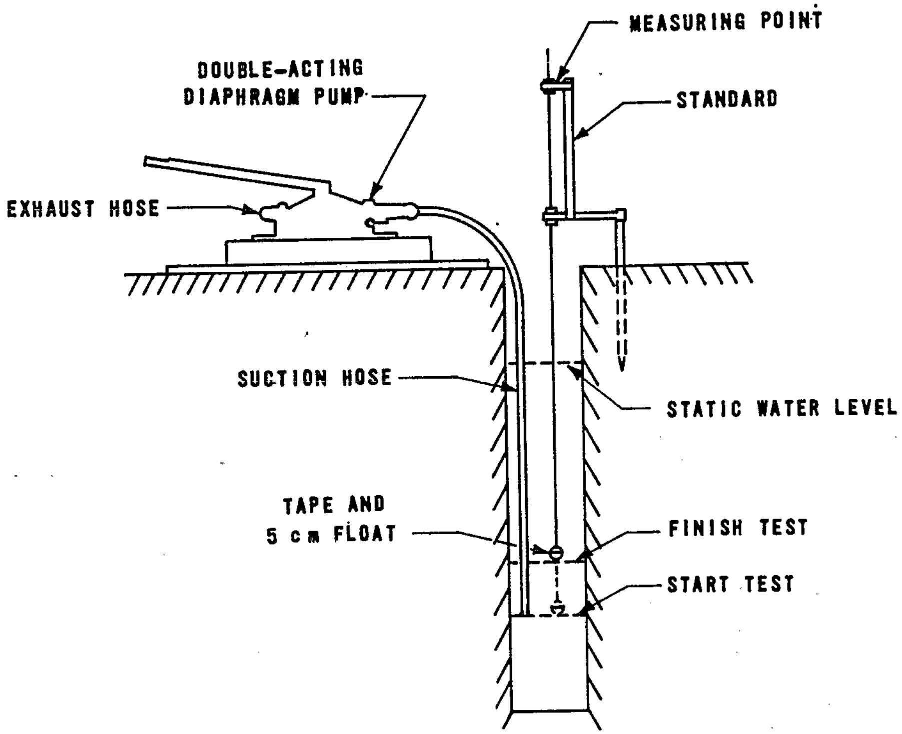
Method Description: A hole is bored to a depth at least 30 centimeters below the water level, taking care to minimize disturbance of the sidewalls. Several borehole volumes are removed to eliminate puddling effects. When the water level has stabilized, water is removed again from the hole and the rise in water level measured at intervals until equilibrium is reached (Figure 4.2.1a). In moderately permeable soils the rise in water level can be measured with a tape and float; in highly permeable soils a pressure transducer should be used (Hendrickx, 1990). The hydraulic conductivity can be calculated based on the geometry of the borehole, depth from the bottom of the hole to an impermeable layer, and the rate of rise of water in the borehole (Figure 4.2.1b). The **pit-baling** method is a variant of the auger hole method in which a large hole extending below the water table is dug. The water level is rapidly lowered and the rise of the water level is measured. Shape factors based on piezometer theory or hole geometry are required for the hydraulic conductivity calculations. The **pumped borehole** method is a variant that can be used in highly permeable soils where the water level rises too quickly for accurate measurement when the hole is baled. With this method water is pumped at a constant rate from a hole until the water level reaches equilibrium. Saturated conductivity is calculated with Zanger's analytical solution for holes that penetrate less than 20 percent into a deep homogenous unconfined aquifer (Kessler and Oosterbaan, 1974).

Method Selection Considerations: **Auger Hole Advantages:** (1) Method is simple and inexpensive; and (2) yields reliable information on horizontal conductivity for many conditions, provided an impermeable layer is present not too far below the bottom of the hole. **Auger Hole Disadvantages:** (1) Alternative methods might be required if the soil is layered or thin layers of high permeability occur; (2) unreliable when water level is above the soil surface or artesian conditions exist; and (3) unreliable if hole walls have been smeared or measurements are made after the hole is more than one-half full. **Pit-Baling Method:** Particularly useful for stony soils where the auger-hole and other techniques are not practical. **Pumped Borehole Method:** Used for very permeable soils when available instrumentation is not available to accurately measure rapid rises in water level when the hole is baled (use of pressure transducers is easier and cheaper).

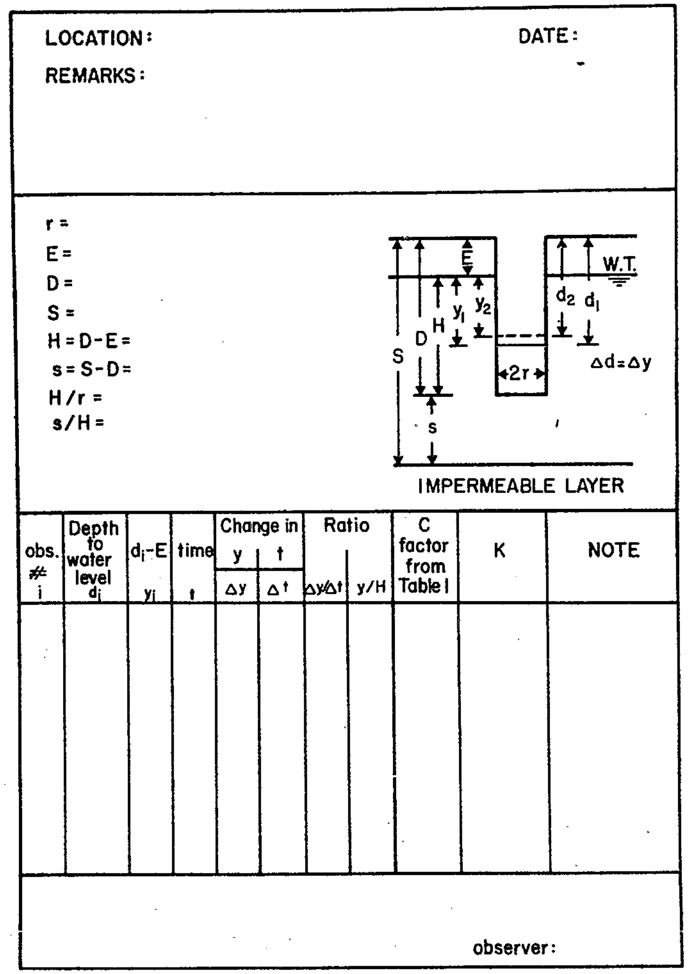
Frequency of Use: Most widely used method where there is a shallow water-table.

Standard Methods/Guidelines: Amoozegar and Warrick (1986).

Sources for Additional Information: See Table 4-5.



(a)



(b)

Figure 4.2.1 Auger hole method: (a) Equipment setup (U.S. EPA, 1981)); (b) Geometry of auger hole and data sheet recording measurements (Amoozegar and Warrick, 1986, by permission).

4. AQUIFER TEST METHODS

4.2 HYDRAULIC CONDUCTIVITY (SHALLOW WATER TABLE)

4.2.2 Piezometer Method

Other Names Used to Describe Method: Tube technique, well-point technique.

Uses at Contaminated Sites: Measuring saturated hydraulic conductivity where there is a shallow water table.

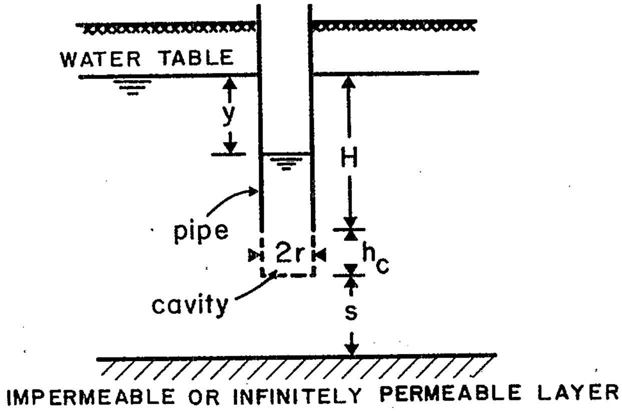
Method Description: A piezometer tube or pipe is placed in an auger hole as big as the tube's diameter without disturbing the soil to a depth below the water table. A cavity then is bored below the bottom of the piezometer (Figure 4.2.2a). To measure horizontal hydraulic conductivity, the length of the cavity should exceed its diameter; for vertical hydraulic conductivity the length should be less than the radius of the cavity. Several volumes of water are bailed or pumped from the cavity to eliminate the puddling effect. When the water level recovers, water again is removed and the rise in water level recorded at time intervals until equilibrium is reached again. The hydraulic conductivity can be calculated based on the geometry of the cavity and the rate of the rise of water and the determination of a "shape factor" can be estimated from tables or nomographs that are related to the depth from the bottom of the hole to an impermeable or infinitely permeable layer. The **tube** technique is a variant of the piezometer method in which there is no cavity below the piezometer tube and primarily vertical hydraulic is measured. The well-point technique is another variant of the piezometer method in which a screened well-point of a specified geometry (Figure 4.2.2b) is driven below the water table and is pumped until an equilibrium flow rate is determined. Graphs are available relating K to the pumping rate at several depths of the suction tube below the water table (Donnan and Aronovici, 1961), or from equations (Bouwer and Jackson, 1974).

Method Selection Considerations: **Piezometer Advantages:** (1) Simple and inexpensive; (2) in stratified soils this method can be used to determine conductivity of each individual layer; and (3) an impermeable layer below the bottom of the hole is not required. **Piezometer Disadvantages:** (1) Generally not suitable for rocky and gravelly soils unless a good seal can be obtained between soil and tube; and (2) in unstable soils the geometry of the cavity might be difficult to define precisely. The **tube** and **well-point** methods have similar advantages and do not have potential problems associated with defining cavity geometry. The tube method measures primarily vertical hydraulic conductivity. A disadvantage of the well-point method is that the requirement for continuous pumping makes the procedure more complicated.

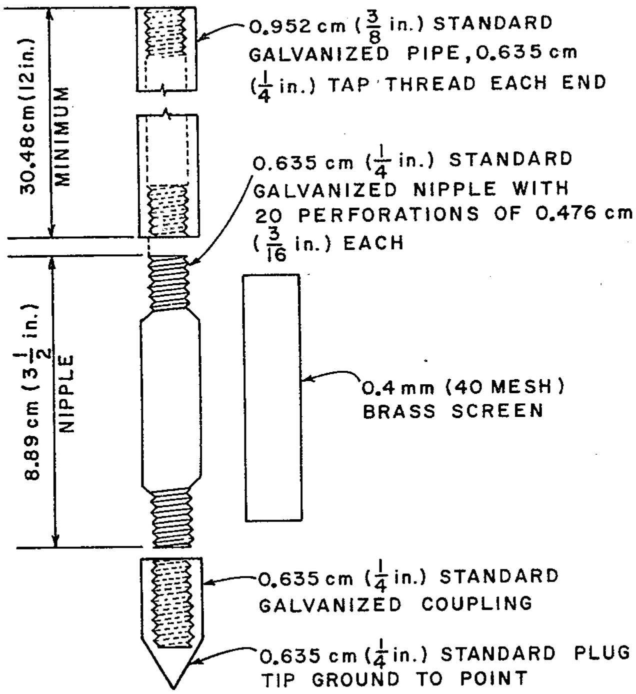
Frequency of Use: **Piezometer and tubes methods:** Relatively uncommon; **Well-point method:** Uncommon.

Standard Methods/Guidelines: Amoozegar and Warrick (1986).

Sources for Additional Information: See Table 4-5.



(a)



(b)

Figure 4.2.2 Piezometer techniques: (a) Diagram of piezometer hole (Amoozegar and Warrick, 1986, by permission); (b) Construction details for wellpoint method (Bouwer and Jackson, 1974, by permission).

4.2 HYDRAULIC CONDUCTIVITY (SHALLOW WATER TABLE)

4.2.3 Multiple-Hole Methods

Other Names Used to Describe Method: Two-well, four-well, multiple-well, drainage outflow method.

Uses at Contaminated Sites: Measuring saturated hydraulic conductivity where there is a shallow water table.

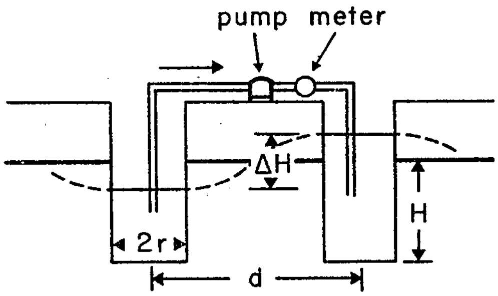
Method Description: In the **two-well** method, two holes of equal diameter and depth, about a meter apart, are augered below the water table. Water is pumped from one hole into the other hole at a constant rate until equilibrium in the water levels in both holes is attained (Figure 4.2.3a). Hydraulic conductivity is calculated from the geometry of the holes and the difference in head. The **four-well** method is similar, except that two center wells of smaller diameter are placed between the pumping and receiving wells, and calculation is based on the difference in head between the inner wells to avoid possible bias resulting from clogging in the receiving well (Figure 4.2.3b). The **multiple-well** method involves an even-numbered array of wells spaced equally on the circumference of a circle (Figure 4.2.3c). Adjacent wells are paired and water is pumped from one to the other as in the two-well method. Hydraulic conductivity is calculated with an equation using the average hydraulic head difference for each pair of wells. The **drainage outflow** method involves the installation of shallow piezometers in the vicinity of drainage tiles. Saturated hydraulic conductivity can be determined from simultaneous measurements of drain discharge and water table depths using drainage spacing equations (Smedema and Rycroft, 1983).

Method Selection Considerations: Multiple well methods are more complex and time-consuming to carry out in the field, with expense increasing as the number of wells in the test increases. The two-well method works best if the auger holes penetrate to the top of an impermeable layer. Clogging in the walls and bottom in the receiving well might be a problem with the two-well method and the multiple-well methods. The four-well method overcomes the problems of clogging. The multiple-well method has the advantage of measuring hydraulic conductivity for a larger volume of soil. The drainage outflow method requires drainage tile outlets at which discharge can be accurately measured at the same time water levels are measured.

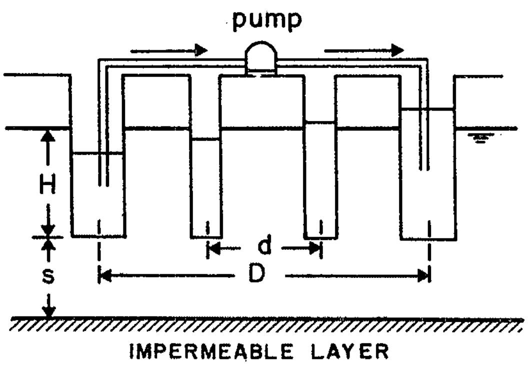
Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

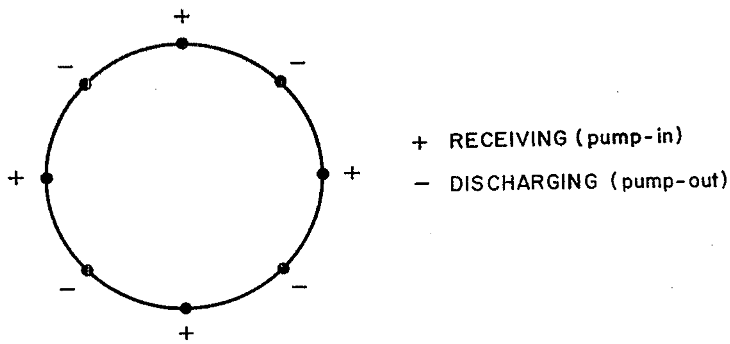
Sources for Additional Information: Amoozegar and Warrick (1986), Bouwer and Jackson (1974). See also, Table 4-5.



(a)



(b)



(c)

Figure 4.2.3 Multiple-hole techniques: (a) Geometry of two-hole technique; (b) Geometry of four-hole technique; (c) Geometry of multiple-hole technique (Amoozegar and Warrick, 1986, by permission).

4. AQUIFER TEST METHODS

4.3 WELL TEST METHODS

4.3.1 Slug Tests

Other Names Used to Describe Method: Instantaneous head change test, Bailer test, rising/falling head test. Slug tests vary somewhat in procedures and formulas used for calculations. Different methods are usually identified by the names of the developers: Hvorslev, Ferris-Knowles, Cooper-Bredehoeft-Papadopulos, Bouwer-Rice, and Nguyen-Pinder methods.

Uses at Contaminated Sites: Measuring hydraulic conductivity (all methods), storativity and transmissivity (some methods).

Method Description: Slug testing involves measuring the rate at which water in a well returns to its initial level after: (1) A sudden injection or withdrawal of a known volume of water from a well, or (2) instantaneous displacement by a weight or change in pressure. Changes in water level over time are recorded and formulas used to calculate hydraulic conductivity are plotted and matched against type curves. Rising-head (withdrawal) and falling-head (injection) methods often yield different results and the best estimate might be an average of the two values. Figure 4.3.1a shows an apparatus for a water injection test and Figure 4.3.1b illustrates an equipment setup for a pneumatic rising head test.

Method Selection Considerations: **Advantages:** (1) Can be used in hydrogeologic units with a wide range of permeabilities; and (2) relatively inexpensive in terms of manpower, equipment, and site set-up, allowing multiple tests for characterization of aquifer heterogeneity. **Disadvantages:** (1) Very high or very low permeabilities might require sophisticated electronic monitoring equipment, such as transducers and data loggers, and with high hydraulic conductivity even transducers might not work very well; (2) permeability values are only applicable to a small volume of the aquifer; (3) most tests do not provide information on aquifer storage properties; (4) injection-type tests should not be done in wells from which water quality samples will be collected; and (5) mechanical slug tests might not displace enough water for meaningful results. Different methods are applicable to different well and hydrologic conditions. Hvorslev method can be used for both unconfined and confined aquifers with gully or partially penetrating wells below the water table. The Bouwer-Rice method applies to unconfined aquifers. The Cooper-Bredehoeft-Papadopulos method is for confined conditions with fully penetrating wells. The Nguyen-Pinder method can be used for partially penetrating wells in confined aquifers.

Frequency of Use: Common.

Standard Methods/Guidelines: ASTM (1991b, 1991c).

Sources for Additional Information: See Table 4-5.

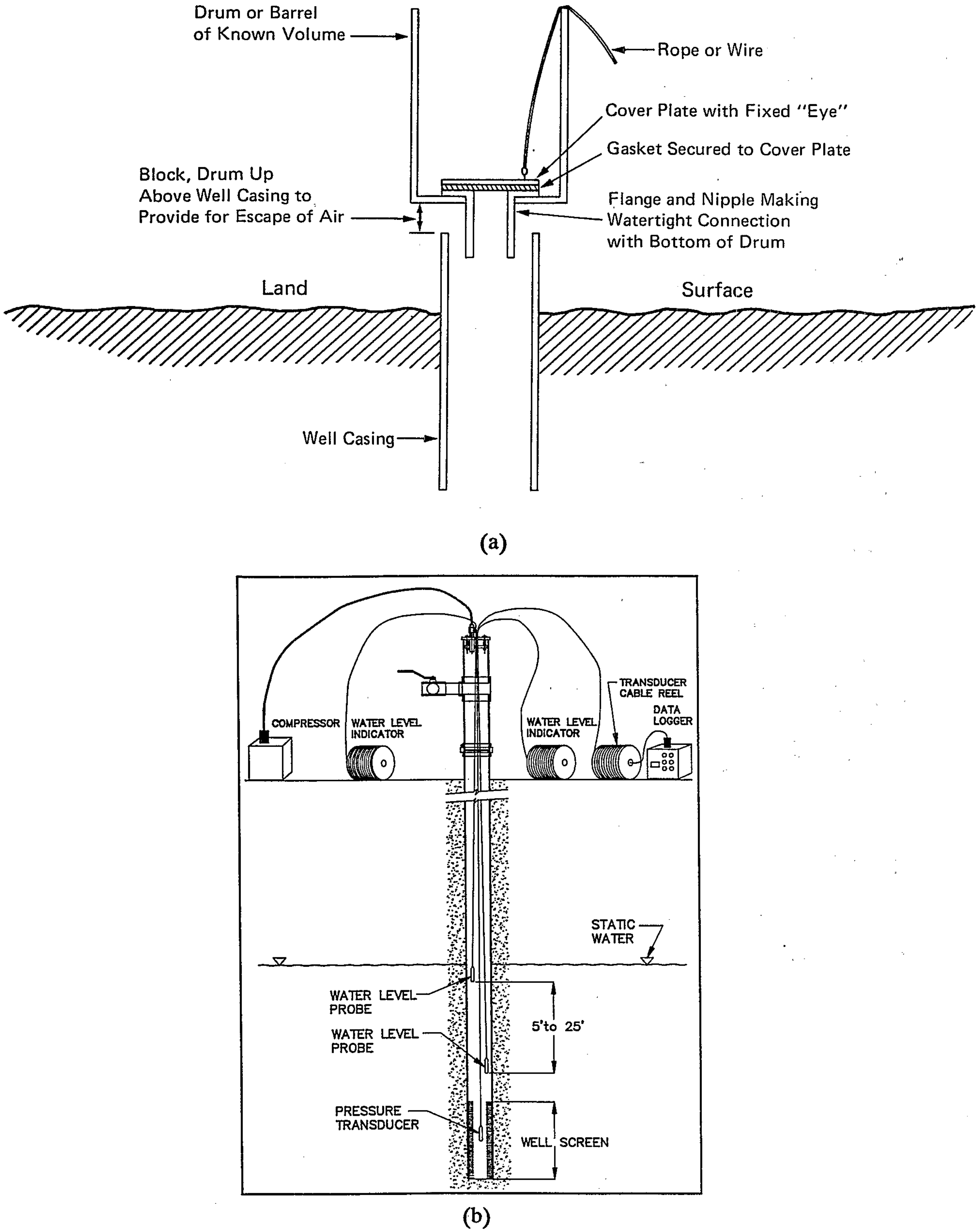


Figure 4.3.1 Slugs tests: (a) Apparatus for performing water injection slug test (Brakensiek et al., 1979); (b) Equipment setup for conducting a pneumatic rising head slug test (McLane et al., 1990, by permission).

4. AQUIFER TEST METHODS

4.3 WELL TEST METHODS

4.3.2 Pumping Tests

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Measuring aquifer hydraulic conductivity, transmissivity, and storage properties (specific storage, specific yield, storativity). Properly designed multiple-well tests also can measure anisotropy.

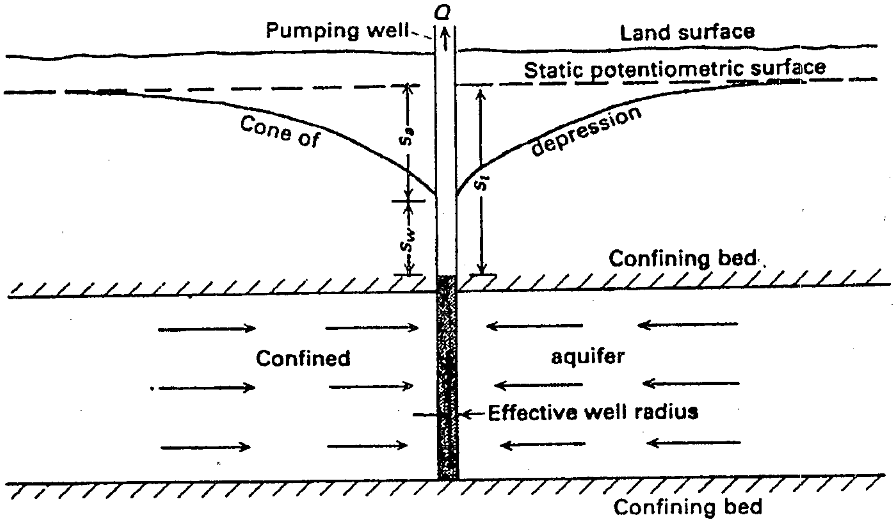
Method Description: **Single-well** pumping tests (Figure 4.3.2a) differ from withdrawal slug tests in that water is removed at a constant rate over a period of time from hours to days. Thirty minutes to four hours is a common length for domestic wells. **Multiple-well** pumping tests usually involve placing observation wells at different distances from a pumping well (Figure 4.3.2b) or in a circle around the pumping well. Pumping rates can be measured volumetrically, commonly using an orifice weir (see Section 10.6.2), or using a commercial water meter. Water levels in the pumping and observation wells are measured at specified intervals, closely spaced at the beginning of the test and more widely spaced as time goes on. The use of pressure transducers and automatic dataloggers facilitates data collection and analysis. Numerous analytical methods are available for analyzing pump test data, which usually are presented as a series of types curves against which the time-drawdown test data plots are matched to obtain transmissivity and storage parameters. The Thiem equilibrium equation and the Theis nonequilibrium equation are two of the most commonly used basic analytical solutions for pump tests. A variety of solutions to the Theis nonequilibrium equation have been derived for special aquifer and pumping conditions. Important considerations in selection of an analytical solution for a pump test include: (1) Type of aquifer (confined, leaky, or unconfined), (2) how much of the aquifer is intersected by the well(s) (fully or partially penetrating), and (3) the degree of heterogeneity and anisotropy in the aquifer.

Method Selection Considerations: **Advantages:** (1) Analytical solutions are available for almost any aquifer and well-type; (2) average hydraulic properties are measured for a relatively large volume of the aquifer; (3) can be used over a wide range of permeabilities; and (4) test wells also can be used for water quality sampling after completion of the test. **Disadvantages:** (1) Expensive due to manpower and equipment requirements, and length of test (several days is not uncommon); (2) large volumes of pumped water require appropriate handling and disposal; and (3) are inaccurate in rock with fractures or high secondary porosity (karst limestone). **Multiple-well** configurations generally provide better results than single-well tests because they: (1) Are more accurate for measuring storage values; (2) pumping well measurements are more affected by construction methods than measurements from observation wells; (3) observation wells allow detection and characterization of aquifer heterogeneity and anisotropy; and (4) observation wells are less affected by changes in pumping rate, which might occur in longer tests.

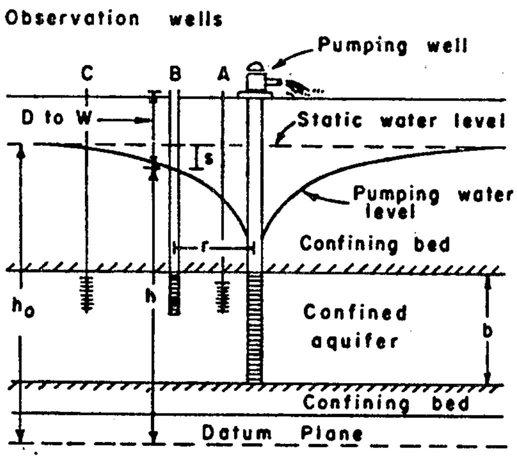
Frequency of Use: Common.

Standard Methods/Guidelines: ASTM (1991d, 1991e, 1991f, 1992a, 1992b).

Sources for Additional Information: See Table 4-5.



(a)



(b)

Figure 4.3.2 Pumping tests: (a) Single-well test; (b) Multiple-well test (U.S. EPA, 1991).

4.3 WELL TEST METHODS

4.3.3 Packer Testing

Other Names Used to Describe Method: Injection test, pressure or pulse test, pressure permeability test, falling head packer test, Lugeon/step-pressure test.

Uses at Contaminated Sites: Packers have a variety of applications in boreholes. Packer tests using water injection or pressure monitoring measure hydraulic conductivity and storage coefficient above or below the water table; packers might be used in combination with tracers to identify zones of high permeability and connectivity of fractures between holes. Packers can also be used to isolate zones for multi-level water quality sampling in a single well, and to improve well purging efficiency.

Method Description: Packers are inflatable devices that are inserted at a selected depth and inflated using water or a gas to seal off a portion of a borehole. Packers can be used for a variety of applications. A **single packer** is used to test a section of borehole, typically a section to 5- or 10-feet, between the hole bottom and the packer location. After the packer is inflated, water is injected until steady-state conditions are achieved, or for a specified period of time (typically 15 minutes to 2 hours), whichever comes first. The amount of water and pressure changes is monitored during the test. By removing the packer after each test, hydraulic conductivity can be measured in different sections of the borehole as drilling progresses. **Two-packer** tests usually are performed after a borehole has been completed. Usually progressing from bottom to top, sections of the borehole are isolated by top and bottom packers, and water injected as with single packer tests. Figure 4.3.3a illustrates a typical two-packer installation. Figure 4.3.3b shows geometry and equations for single- and two-packer tests. **Pressure** or **pulse** tests usually are used in formation with very low hydraulic conductivity (i.e., $< 1 \times 10^{-7}$ cm/sec). After the packer is inflated, an increment of pressure is applied to the zone isolated by the packer(s) and the decay of pressure is monitored using pressure transducers, and plotted versus time. The rate of decay is related to the storage coefficient and the hydraulic conductivity. The **Lugeon method** of packer testing uses a series of five tests (three at increasing pressures and two at decreasing pressures.* The pattern **tracer tests** (see Section 4.4) can use packers to isolate zones of interest in a single borehole, or they can be used to determine interconnection of fractures between two uncased boreholes. Multi-level samplers can use packers to allow collection of water quality samples from different levels in a single borehole.

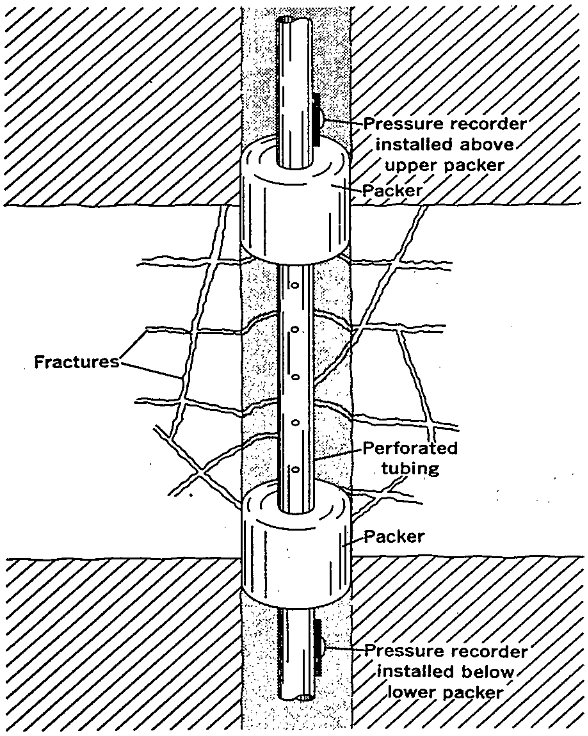
Method Selection Considerations: **Advantages:** (1) Simple and relatively inexpensive and should be considered any time boreholes are in consolidated rock; (2) can be used in both saturated or unsaturated unconsolidated rock; and (3) two-packer tests have the advantage of not requiring an interruption in drilling. **Disadvantages:** (1) Failure to obtain a good packer seal will overstate hydraulic conductivity (more likely with two-packer than single-packer tests); (2) skin effects caused by drilling mud, or closing of fractures due to stress changes from core removal, will cause underestimation of hydraulic conductivity; (3) pressure tests require more complicated instrumentation and electronic data loggers or strip-chart recorders, and some understanding of the presence and orientation of fractures is necessary to select the appropriate type curve to analyze test results; and (4) not suitable for use in unconsolidated rock.

Frequency of Use: Fairly common in consolidated rock.

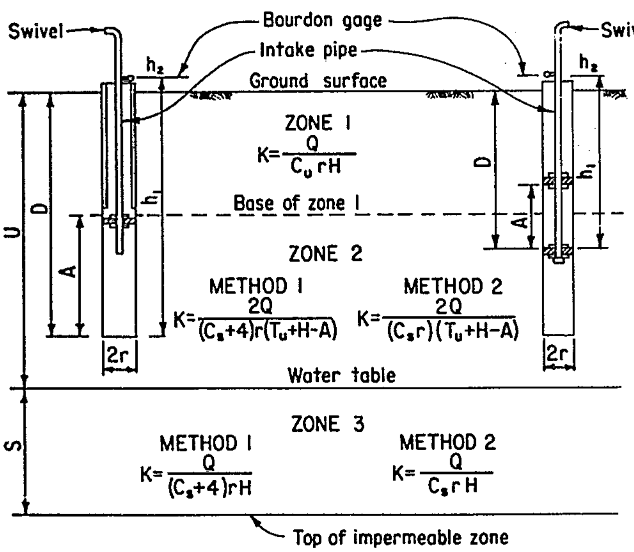
Standard Methods/Guidelines: Bureau of Reclamation (1981).

Sources for Additional Information: See Table 4-5.

*The Lugeon method was originally designed to assess the need for foundation grouting at dam sites. Roeper et al. (1992) concluded that the method it not very good for hydrogeologic investigations because it takes longer than conventional packer tests and could artificially increase hydraulic conductivity because of the higher pressures used.



(a)



K = coefficient of permeability, feet per second under a unit gradient
Q = steady flow into well, ft^3/s
$H = h_1 + h_2 - L$ = effective head, ft
h_1 (above water table) = distance between Bourdon gage and bottom of hole for method 1 or distance between gage and upper surface of lower packer for method 2, ft
h_1 (below water table) = distance between gage and water table, ft
h_2 = applied pressure at gage, 1 lb/in² = 2.307 ft of water
L = head loss in pipe due to friction, ft; ignore head loss for Q<4 gal/min in $1\frac{1}{4}$-inch pipe; use length of pipe between gage and top of test section for computations
$X = \frac{H}{T_u}(100)$ = percent of unsaturated stratum
A = length of test section, ft
r = radius of test hole, ft
C_u = conductivity coefficient for unsaturated materials with partially penetrating cylindrical test wells
C_s = conductivity coefficient for semi-spherical flow in saturated materials through partially penetrating cylindrical test wells
U = thickness of unsaturated material, ft
S = thickness of saturated material, ft
$T_u = U - D + H$ = distance from water surface in well to water table, ft
D = distance from ground surface to bottom of test section, ft
a = surface area of test section, ft²; area of wall plus area of bottom for method 1; area of wall for method 2
Limitations:
$Q/a \leq 0.10$, $S \geq 5A$, $A \geq 10r$, thickness of each packer must be $\geq 10r$ in method 2

(b)

Figure 4.3.3 Packer tests: (a) Typical straddle-packer installation (Garber and Koopman, 1968); (b) Single- and double-packer permeability tests for use in saturated or unsaturated consolidated rock (Bureau of Reclamation, 1981).

4.4 GROUND-WATER TRACERS

4.4.1 Ions

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Measuring ground-water flow paths and velocity; monitoring sanitary landfill leachate migration and dilution by receiving waters; evaluating solute transport mechanisms in fractures; separating baseflow and stormflow components of karst aquifers; estimating flux of liquid pollutants in vadose zone.

Method Description: **Tracing:** Soluble salts (such as NaCl, LiBr) are dissolved in water and injected into a well and monitoring wells downgradient are sampled at time intervals (see Figure 4.4.7a). Concentrations of the ion of interest are analyzed in the laboratory. Neutron activation (see Sections 3.3.5 and 10.6.1 for description of neutron activation) can be used to detect bromide tracers. Fluorinated benzoic acid derivatives, which are anions at pHs greater than 5.0, also have been shown to be conservative in a variety of aquifer materials (Bowman, 1984; Bowman and Gibbons, 1992). Less commonly nonionic substances are used as tracers. For example, fluorescent polylcyclic aromatic hydrocarbons have been used as tracers to study the transport of contaminants on colloids in ground water (Backhus and Gschwend, 1990). Figure 4.4.1 illustrates use of an injected tracer and multilevel sampling installations to measure hydrodynamic dispersion. **Monitoring:** Measurement of natural variation in Ca and Mg concentrations in karst aquifers can be used to separate baseflow (where concentrations are higher) and stormwater flow (which dilutes the concentration). Potassium (K^+) can serve as an indicator of leachate migration from sanitary landfills which receive a large amount of vegetable waste, because it is less susceptible to immobilization by cation exchange.

Method Selection Considerations: A major advantage of ionic tracers is that they do not decompose, so are not lost from the system. Anionic tracers such as nitrate, chloride, and bromide, generally do not interact with aquifer material so serve as conservative tracers (i.e., travel at the same velocity as ground-water). Bromide is often the anion of choice because natural background levels usually are low. Where natural background concentrations of chloride and nitrate exist, injection of larger amounts as a tracer can have unacceptable impacts on water quality. In fissured and fracture formations, soluble chemical tracers (NaCL, $CaCl_2$, LiCl, NH_4Cl) have to be diluted or used in large volumes to prevent them from sinking and escaping from circulation because of their high density. Where density effects are a concern, potassium bichromate is a good tracer because of dilution of 1 to 2×10^{-9} can be detected by diphenylcarbazide reagent. Cations have more severe limitations as tracers because they tend to interact with aquifer material through cation exchange, but can be useful for monitoring applications (see method description above).

Frequency of Use: Common

Standard Methods/Guidelines: --

Sources for Additional Information: U.S. EPA (1991-Chapter 4).

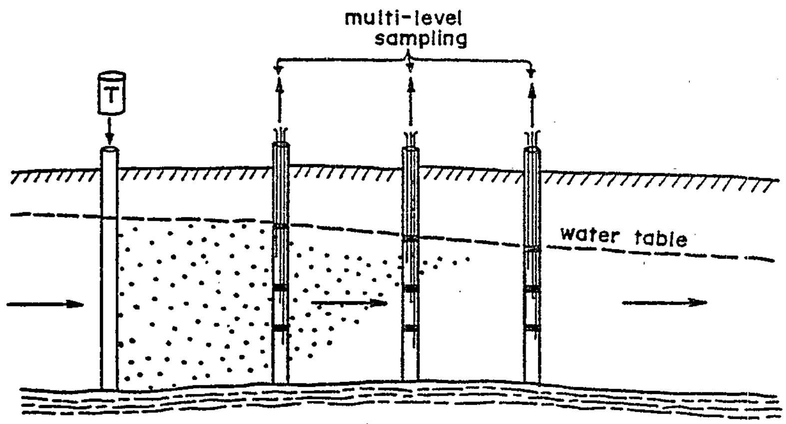


Figure 4.4.1 Use of ionic or other type of tracers to test hydrodynamic dispersion under natural ground-water gradients (Davis et al., 1985).

4. AQUIFER TEST METHODS

4.4 GROUND-WATER TRACERS

4.4.2 Dyes

Other Names Used to Describe Method: Dye tracing, dye injection.

Uses at Contaminated Sites: Identifying zones of preferential water flow in the vadose zone. In karst limestone, other fractured rock and porous media, dyes can be used to measure the speed and directions of ground-water flow. Identifying sources, velocity, and direction of movement of contaminants.

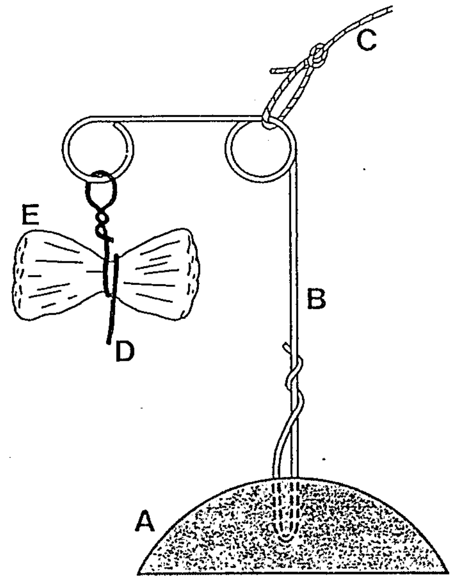
Method Description: Dye is poured on the ground surface, down a drain, or injected into a well. Suspected points of discharge (well, spring, stream, or lake) are monitored visually or sampled. The presence of dye at a discharge point indicates a hydrologic connection and the time it appears after injection allows estimation of the speed of travel. Dye can be recovered by taking periodic water samples or using detectors (called bugs) and using cotton or charcoal to absorb the dye, depending on the type of dye used (Figure 4.4.2a). A fluorometer or spectrofluorometer can be used to detect concentrations that might not be discernible to the eye. A spectrofluorometer also allows differentiation of different dyes in the same sample. Quantitative tests require precise measurement of dye concentrations in grab samples of water and monitoring of flow rates for mass balance analysis. Figure 4.4.2b shows a continuous recording fluorimeter that can be used for quantitative tests. See also, Section 3.5.6 (Single-Borehole Tracer Methods).

Method/Device Selection Considerations: Dyes are relatively inexpensive and simple to use. Either fluorescent or nonfluorescent dyes can be used for visual inspection of flow patterns in soil. Fluorescent dyes are better for ground-water tracer studies because they are easier to detect and are non-toxic in the concentrations typically used in tracer tests (Field et al., in press). Many dyes are available but nomenclature can be confusing. Available methods for estimating the optimum amount of dye to inject result in greatly varying estimates. Adsorption of dye on subsurface geologic materials can be a problem.

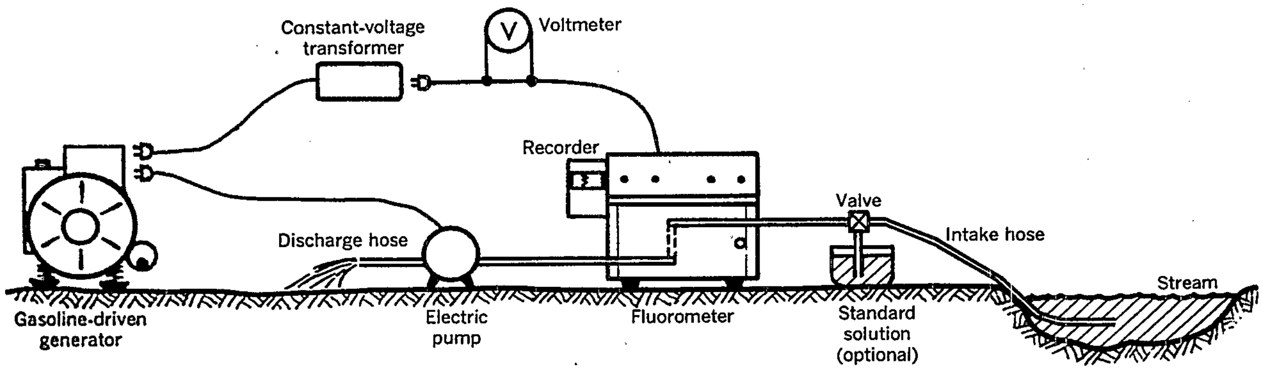
Frequency of Use: Fluorescent dyes are the main method used in this country for mapping ground-water flow patterns in karst systems. Dyes are commonly used to identify contamination of wells or surface water bodies from septic-tank absorption fields. Use for vadose zone and porous media aquifer characterization has been limited mostly to research applications in the past, and more widespread use in those settings would probably be beneficial.

Standard Methods/Guidelines: Quinlan (1989) for karst areas. No standard reference for uses in porous media. Aley et al. (in preparation) will be a good source when it is published.

Sources for Additional Information: U.S. EPA (1991-Chapter 4). See also, Table 4-5.



(a)



(b)

Figure 4.4.2 Tracer tests using dyes: (a) Gumdrop used to suspend dye-detectors (bugs) above stream beds for karst tracing: A--concrete weight, B--galvanized steel wire, C--nylon cord, D--vinyl-clad electrical wire, E--surgical cotton or charcoal packets (Aley et al., in press); (b) Use of continuous recording fluorometer (Wilson et al., 1986).

4.4 GROUND-WATER TRACERS

4.4.3 Gases

<u>Other Names Used to Describe Method</u>: --

<u>Uses at Contaminated Sites</u>: Similar to ions in porous media; detecting fracture connectivity in the unsaturated zone; estimating ground-water age (see also, Sections 4.4.6 and 4.4.7); detecting natural gas leaks (isotopic differentiation, see Section 4.4.6); detecting pipeline leaks (helium).

<u>Method Description</u>: Gas tracers can be grouped into three major groups: (1) **Inert natural gases** include the noble gases, which are argon, neon, helium, krypton, and xenon; (2) **anthropogenic gases** of which fluorocarbons are of the most interest as tracers; and (3) **gas isotopes** in which the atomic weight of the gas is of interest (covered in Sections 4.4.4 and 4.3.5). These groups are not mutually exclusive. For example Krypton 85 has been used as a radioactive tracer, and tritium (a radioactive isotope of hydrogen) in recently recharged ground-water has its origin in nuclear weapons testing. In ground water, injection and sampling procedures generally are similar to those for ions. In the unsaturated zone, fracture-connectivity can be characterized using packers to isolate different sections of adjacent open boreholes. Gas is injected into the space between the packers in one hole, and air pumped out of the area between the packers in the other hole, with sampling to detect presence of the injected gas (Figure 4.4.3). The natural concentration of inert natural gases (such as argon and krypton) in infiltrating water is a function of temperature, and measurement of variations in the concentrations of these gases in aquifers can be used to reconstruct paleoclimatic trends. The presence of fluorocarbons in ground water (unless a point source is suspected) indicates that the water has infiltrated within the past 40 years or so, since large amounts of flourocarbons were not released into the atmosphere before the late 1940's.

<u>Method Selection Considerations</u>: Noble gases (such as helium, argon, and krypton) have the advantage of being nonreactive, nontoxic, and low natural background concentrations. Problems with gases as active tracers include: (1) Difficulties in maintaining a constant recharge rate, (2) time required to develop equilibrium in unconfined aquifers, and (3) possible loss to the atmosphere in unconfined aquifers.

<u>Frequency of Use</u>: Uncommon as an active tracer. Volatile gases are commonly monitored in the vadose zone to detect subsurface contamination by volatile organics (see Section 9.4).

<u>Standard Methods/Guidelines</u>: --

<u>Sources for Additional Information</u>: U.S. EPA (1991-Chapter 4).

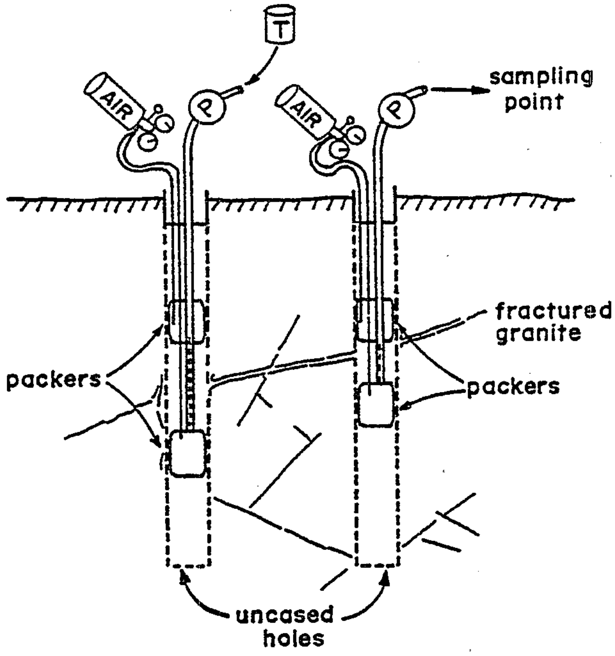


Figure 4.4.3 Test using packers and gas tracer to determine interconnection of fractures in open boreholes (Davis et al., 1985).

4.4.4 Stable Isotopes

Other Names Used to Describe Method: Environmental isotopes.

Uses at Contaminated Sites: Differentiating contaminant-derived and naturally occurring chemical constituents in ground water (for example, nitrates from fertilizer/sewage contribution, sulfates from a sulfuric acid spill, methane from gas leaks); tracing large-scale movement of ground water and locating areas of recharge (^{2}H and ^{18}O).

Method Description: Ground-water samples are collected and analyzed for isotopic composition. The average isotopic composition of deuterium (^{2}H) and ^{18}O in precipitation reaches the ground water through infiltration changes with elevation latitude, distance from the coast, and temperature, and these variations allow interpretations to be made concerning the origin or recharge and large-scale movement of ground water. Alternatively, naturally occurring chemical constituents in ground water, such as nitrate, sulfate, and methane, are sampled and analyzed to determine ratios of stable isotopes of nitrogen, sulfur, and carbon. For example, methane (CH_4) originating from deep geologic deposits is isotopically heavier than methane originating from near-surface sources, allowing identification of methane contamination from pipelines or subsurface storage tanks (Figure 4.4.4). Stable isotopes rarely are artificially injected in the field because: (1) It is difficult to detect small variations of most isotopes against the natural background; (2) their analysis is costly; and (3) preparing isotopically enriched tracers is expensive.

Method Selection Considerations: **Advantages:** Isotopic ratios might be the only way to differentiate between natural and contaminant sources where nitrates, sulfates, and methane can result from either source. **Disadvantages:** (1) Require laboratory analyses, which are relatively expensive; (2) generally are not suitable for injection tests for reasons discussed above.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: U.S. EPA (1991-Chapter 4). See also, Table 4-5.

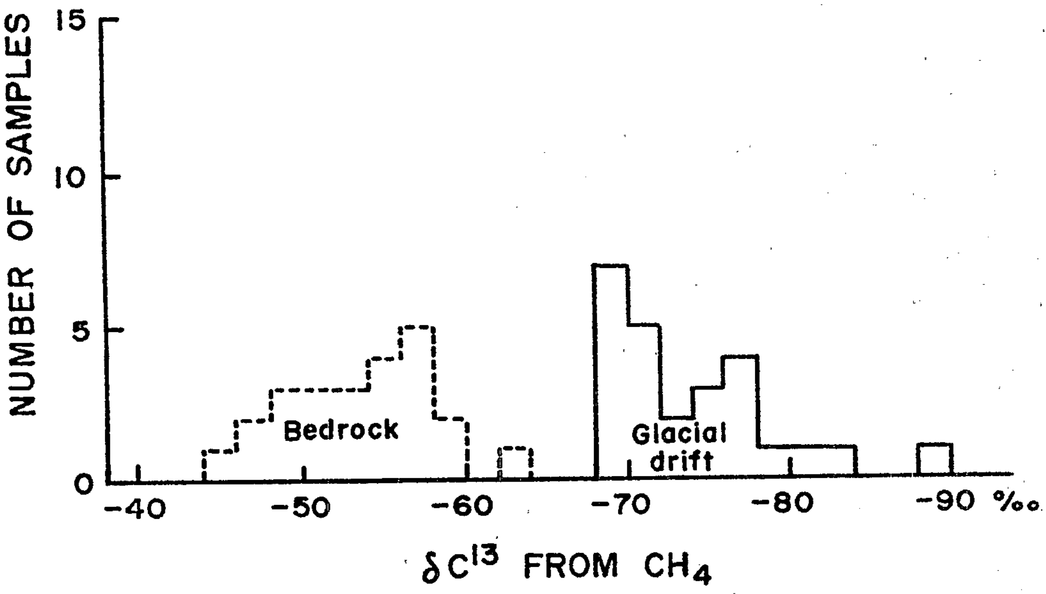


Figure 4.4.4 Carbon isotope percentages allow differentiation of bedrock-derived methane leaking from pipelines or tanks from natural methane generated in shallow aquifers in glacial drift (Davis et al., 1985, after Coleman et al., 1977).

4.4 GROUND-WATER TRACERS

4.4.5 Radioactive Isotopes

Other Names Used to Describe Method: Radionuclides.

Uses at Contaminated Sites: Estimating ground-water age (tritium, carbon-14); infiltrating and discharging ground water to surface waters (Radon-222); testing deep-well mechanical integrity. Injected radioactive tracers can be used to measure a wide range of aquifer properties, but in recent years, health concerns have generally limited their use for near-surface applications.

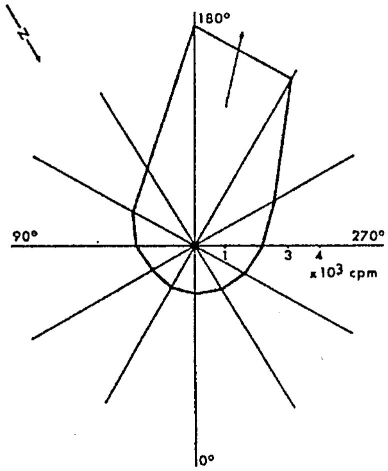
Method Description: In the early 1950s, there was extensive experimentation using radionuclides as natural "environmental" tracers and as injected artificial tracers for a wide variety of applications (see Table 4-3). For example, Figure 4.4.5a illustrates identification of ground-water flow direction in a borehole using a radioactive tracer. However, the use of artificially injected radioactive tracers has been greatly restricted as a result of concerns about possible adverse health effects. The use of "natural" environmental radioisotopes, such as anthropogenic tritium, carbon-14, and radon-222, can be used in estimating how long it has been since ground water infiltrated from the surface. In all applications of this kind, ground- or surface-water samples are collected and analyzed to the radionuclide of interest. **Tritium:** Since the 1950s, atmospheric tritium, the radioactive isotope of hydrogen with a half-life of 12.3 years, has been dominated by tritium from the detonation of thermonuclear devices. Consequently, ground water in the northern hemisphere with more than about 5 tritium units generally is less than 30 years old. Figure 4.4.5b illustrates age estimates and flow directions in a ground-water basin using tritium as a tracer. **Carbon-14,** with a half-life of 5,730 years, can be used to identify ground water that infiltrated in the range of 500 to 30,000 years ago. **Radon-222,** a daughter product from the spontaneous fission of Uranium-238, is present in the subsurface, but due to its short half-life of 3.8 days, is virtually absent in surface water that has reached equilibrium with the atmosphere. Consequently, reduced levels in ground water are an indication of recent infiltration of precipitation and increased levels in surface water are an indication of ground-water discharge.

Method Selection Considerations: **Environmental Radioisotope Advantages:** (1) Normal ground-water sampling procedures can be followed with no health concerns; (2) analysis for tritium or Radon-222 is a relatively easy way to test for recent recharge. **Environmental Radioisotope Disadvantages:** (1) Tests for radioisotopes are not standard laboratory procedures and could require some effort to find a suitable laboratory; (2) interpretation of carbon-14 "ages" is very complex due to possible sources of old carbon from the dissolution of limestone and fractionation of isotopes by formation of gases and precipitation reactions. **Injected Radioisotopes:** As noted above, health concerns have largely stopped the use of radionuclides as active tracers, except where is not a likely threat to quality for drinking water, such as in deep petroleum production zones or testing the mechanical integrity of deep underground waste injection wells (see for example, Thornhill and Benefield [1990]).

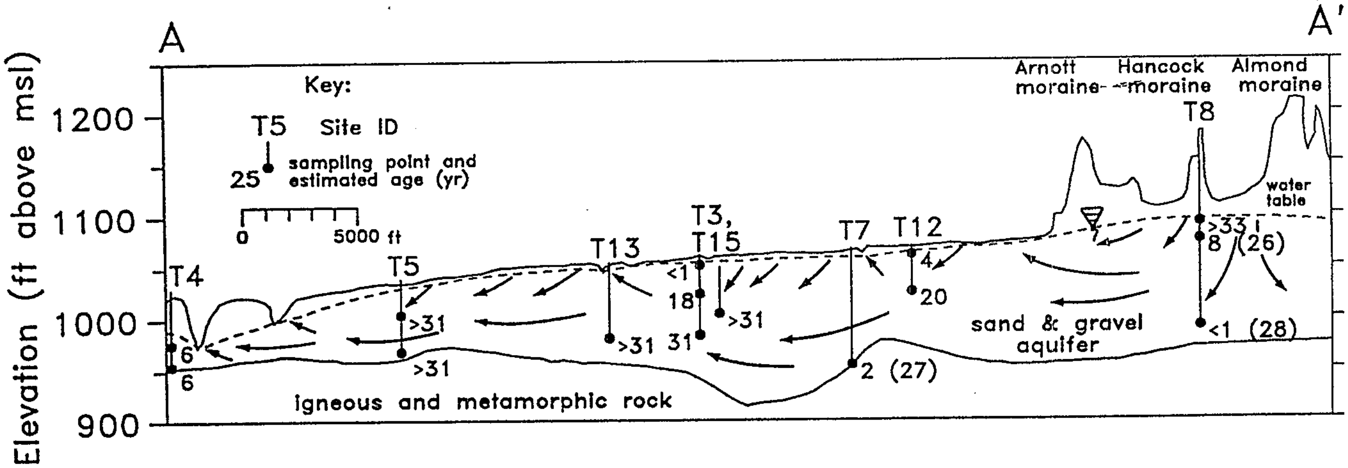
Frequency of Use: Uncommon. Environmental radioisotopes could probably be beneficially used more frequently than they are.

Standard Methods/Guidelines: --

Sources for Additional Information: Bradbury (1991-tritium), U.S. EPA (1991-Chapter 4). See also, Table 4-6.



(a)



(b)

Figure 4.4.5 Radioactive Tracers: (a) Flow direction in an uncased borehole determined from an uncased borehole (Halevy et al., 1967); (b) Estimated minimum ground-water age in Buena Vista ground-water basin (Bradbury, 1991, by permission).

4. AQUIFER TEST METHODS

4.4 GROUND-WATER TRACERS

4.4.6 Water Temperature

Other Names Used to Describe Method: See also, Sections 1.6.2 (Shallow Geothermal), 3.5.2 (Temperature Log), and 3.5.4 (Thermal Flowmeter).

Uses at Contaminated Sites: Measuring ground-water travel time between two wells; detecting temperature anomalies associated with transport of radioactive wastes in the subsurface; detecting temperature anomalies associated with subsurface microbial degradation of contaminants (see Section 1.6.2); detecting river recharge in an aquifer.

Method Description: A pulse of hot water is injected into a well and temperature in one or more observations wells down-gradient is measured at intervals to identify the initial arrival time and time of peak temperature after injection (Figure 4.4.6). One or more wells outside the travel path also are monitored for baseline comparison. Surface-water recharge of an aquifer adjacent to a river can be observed by measuring temperatures in observation wells near the river. Most rivers have large seasonal water temperature fluctuations, whereas ground-water temperature remain relatively constant through the year. Consequently, seasonal fluctuations in ground-water temperature near a river serve as an indicator that recharge from the surface is occurring. At a regional level, ground water in areas of active recharge will generally be warmer than areas of ground-water discharge.

Method Selection Considerations: Simple, inexpensive and applicable in granular media, fractured rock, or karst. Very precise temperature measurement instruments should be used if the distance between observation points is very large (for example, a temperature drop from 40°C to 27°C has been observed over the space of 0.6 meters [2 feet] with the peak temperature measured about 2 hours after injection). Temperature-induced changes in water density and viscosity can alter the velocity and direction of flow. For this reason, measurements might be less accurate than other tracers, but can serve as a useful complement to other tracers: (1) For selecting wells for more accurate tracer tests (i.e., allow focussing of sampling on only those wells that receive flow from the injection well where multiple wells have been installed); and (2) as a guide for developing the sampling schedule for other tracers.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Davis et al. (1985), U.S. EPA (1991).

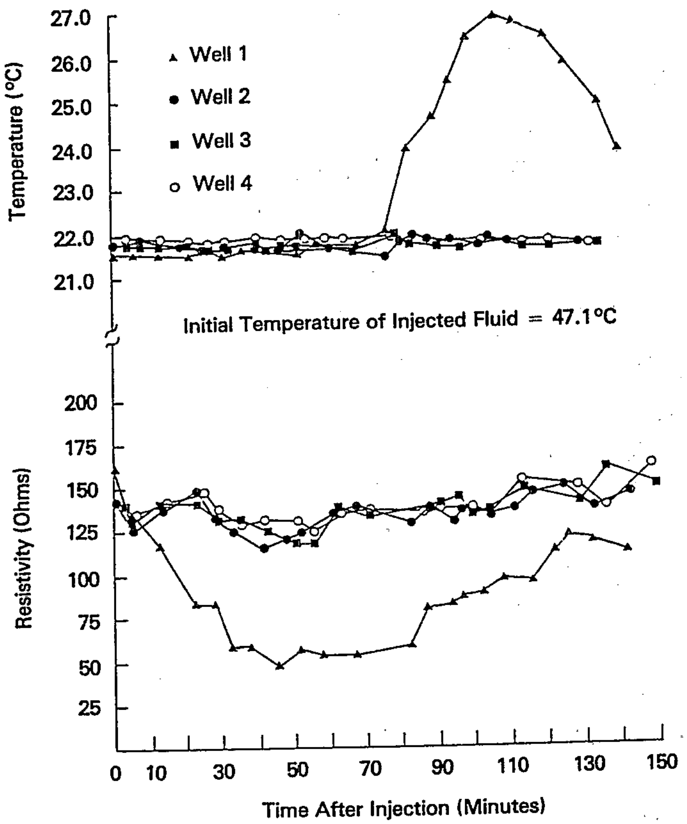


Figure 4.4.6 Results of a field tracer test using hot water (Davis et al., 1985).

4.4 GROUND-WATER TRACERS

4.4.7 Particulates

Other Names Used to Describe Method: Microbial tracers (yeast, bacteria, viruses), lycopodium spores.

Uses at Contaminated Sites: Tracing the velocity and direction of flow in areas where water flows in large conduits (some basalt, karst limestone); detecting actual or potential ground-water contamination from subsurface seepage of sewage.

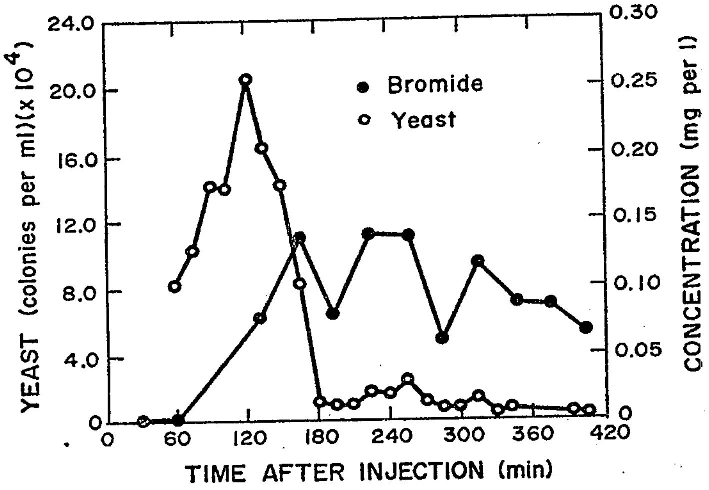
Method Description: **Microbes:** A selected microbe (typically baker's yeast or nonpathogenic bacteria) are injected in a well and monitoring wells downgradient are sampled at time intervals (Figure 4.4.7a). Samples are incubated and identified in the laboratory. If pollution is suspected, ground water is sampled at one or more points downgradient from the source and the samples are analyzed. **Spores:** A few kilograms of dyed spores are added to a cave or sinking stream. Movement of the tracer is monitored by sampling downstream in the cave at a spring with plankton nets (Figure 4.4.7b). Sediment caught in the net is concentrated, treated to remove organic matter, and the presence or absence spore determined using a microscope.

Method Selection Considerations: **Microbes:** Can be used in any porous media where the pore size is larger than the size of the microorganism. In fine-grained material, sorption effects can slow travel time compared to actual ground-water flow. The fecal coliform E. coli usually is used as an indicator of fecal pollution. Yeast and bacteria commonly are used due to ease of growth and detection, but care must be taken to ensure that types used are nonpathogenic (not a concern with baker's yeast). Viruses are smaller, but create greater health concerns. **Spore Advantages:** (1) High injection concentration is possible; (2) pose no health threat; (3) are easily detectable under a microscope; (4) use of multiple dye color (at least five) allows injection of multiple sites at the same time (however dyes used to color spores tend to be toxic); and (5) can be a good alternative to dyes for use in large-scale water resource reconnaissance studies in karst areas. **Spore Disadvantages:** (1) Spore tracers do not perform well without turbulent flow to keep spores in suspension or in water with high sediment concentrations; (2) sample collection is very labor intensive; and (3) if multiple simultaneous traces are required, use of fluorescent dyes and a scanning spectrofluorophotometer are easier and cheaper (see Section 4.4.2).

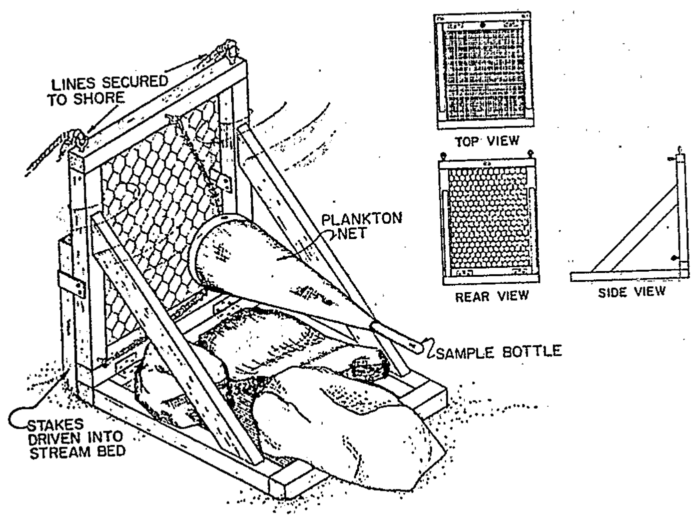
Frequency of Use: Testing of ground water for actual microbial contamination is very commonly used method to evaluate the effectiveness of surface and subsurface disposal of sewage wastes. The use of injected microbial tracers is uncommon. Lycopodium spores occasionally have been used as tracers in karst areas in Europe, but rarely in the United States.

Standard Methods/Guidelines: --

Sources for Additional Information: **Microbial Tracers:** Keswick et al. (1982), See also, Table 4-6; **Spore Tracers:** Drew and Smith (1969), Gardner and Gray (1976).



(a)



(b)

Figure 4.4.7 Particulate tracers: (a) Results of a two-well tracer test in an alluvial aquifer using yeast and bromide (Davis et al., 1985, after Wood and Ehrlich, 1978); (b) Diagram of operating dyed-spore trap for karst tracer tests (Gardner and Gray, 1976).

4.5 OTHER AQUIFER CHARACTERIZATION METHODS

4.5.1 Unconfined Ground-Water Balance

Other Names Used to Describe Method: Water/hydrologic budget.

Uses at Contaminated Sites: Predicting the response of near-surface ground-water levels to other parameters in the hydrologic system.

Method Description: A water budget requires quantification of all aspects of the hydrologic system that add or remove water from the component of interest. The water balance equation can be solved for any individual component, and there are numerous forms of the water balance equation. In the case of ground water, it usually is applied to unconfined aquifers to determine changes in the amount of water stored in an aquifer and/or ground-water levels with time. Positive elements in the balance include: (1) Infiltration reaching the capillary fringe, (2) unconfined ground-water inflow in a horizontal direction, and (3) confined water leakage from underlying aquifers. The negative elements of the balance include: (1) Evapotranspiration from the top of the capillary fringe above the water table, (2) unconfined ground-water outflow in a horizontal direction, and (3) unconfined ground-water outflow downwards as leakage to underlying semi-confined aquifers. Figure 4.5.1 illustrates the way the water table responds to the interaction of the different components of the water balance. Most vadose zone computer models either are based on, or contain modules using, water budget principles (see Section 7.5.1), and often can be used without field measurement of all the input parameters of concern to estimate the infiltration/evapotranspiration balance in relation to ground water. The well test methods discussed in this section, and Section 8 (Vadose Zone Water Budget Characterization Methods) cover ways in which specific components of the water balance equation can be measured, if required. Other methods using water balance calculations are covered in Sections 7.1.1 (Infiltration Impoundment Methods), 7.5.1 (Unsaturated Zone Water Flux), and 8.3 (Evapotranspiration Water Balance Methods).

Method Selection Considerations: **Advantages:** (1) Most useful at early stage of site characterization for using estimated values for various components to develop a conceptual model of the site and to identify critical components that might require more detailed field measurement; and (2) also useful in evaluating different approaches and designs for remediation of contaminated sites. **Disadvantages:** (1) Field measurement of parameters required for a water balance is very time-consuming and expensive; and (2) use of estimated values in place of field measurement might reduce the accuracy of calculations.

Frequency of Use: Water balance approach is more commonly used to evaluate leaching potential of contaminants from the vadose to the saturated zone (Sections 7.5.1 and 9.5.1) than for determining ground-water balance at a site-specific level. Commonly used for analysis of ground-water storage changes for larger areas.

Standard Methods/Guidelines: --

Sources for Additional Information: See Table 4-3.

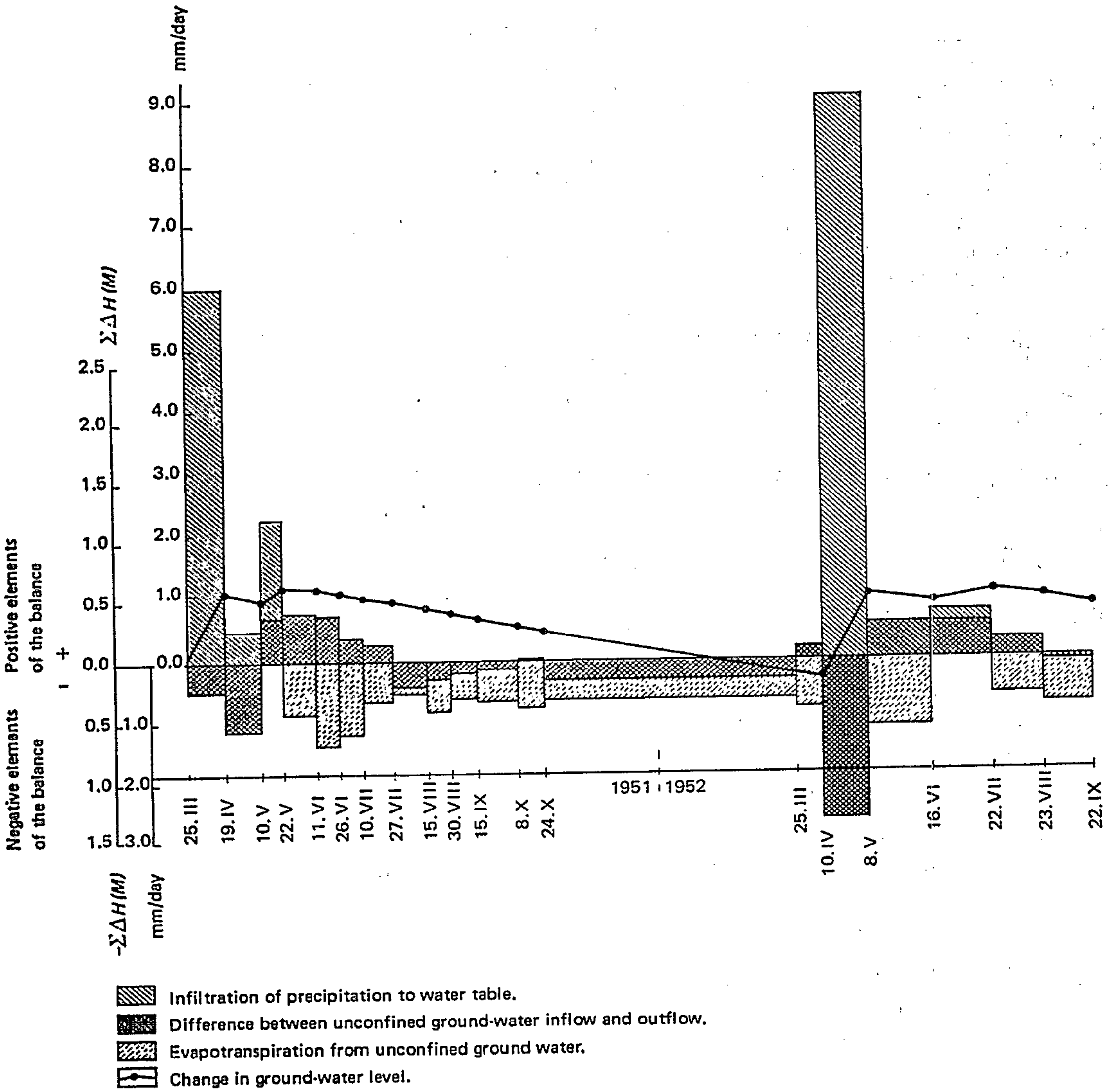


Figure 4.5.1 Elements of unconfined ground-water balance observations (Brown et al., 1983).

4.5 OTHER AQUIFER CHARACTERIZATION METHODS

4.5.2 Moisture Profiles for Specific Yield

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Measuring specific yield (drainable pore space) in shallow, unconfined aquifers.

Method Description: The initial level in a shallow well (up to 5 to 6 meters) is measured, and moisture content is determined at intervals of 0.1 meters in the capillary fringe above the water table, either by sampling and gravimetric analysis (Section 6.2.1), a neutron probe (Sections 3.3.3 and 6.2.2), or some other in situ measurement method (see Table 6-1). When the ground-water level has risen by the value delta H (Figure 4.5.2), the moisture profile above the water table is determined again at the same location. The difference in area between the two moisture profiles in Figure 4.5.1 represents the increment of gravity water reserves for the observed water level rise. Brown et al. (1983) provide equations for accurate calculation of specific yield from the moisture profile data.

Method Selection Considerations: **Advantages:** Most useful when specific yield needs to be determined at a site where it is desirable to avoid a pumping test that brings contaminated water to the surface. **Disadvantages:** (1) Can only be used with a shallow, unconfined aquifer; and (2) provides less information about the aquifer than a pumping test.

Frequency of Use: Uncommon. The advantage cited above might merit more widespread use at contaminated sites.

Standard Methods/Guidelines: Brown et al. (1983).

Sources for Additional Information: Bouwer and Jackson (1974).

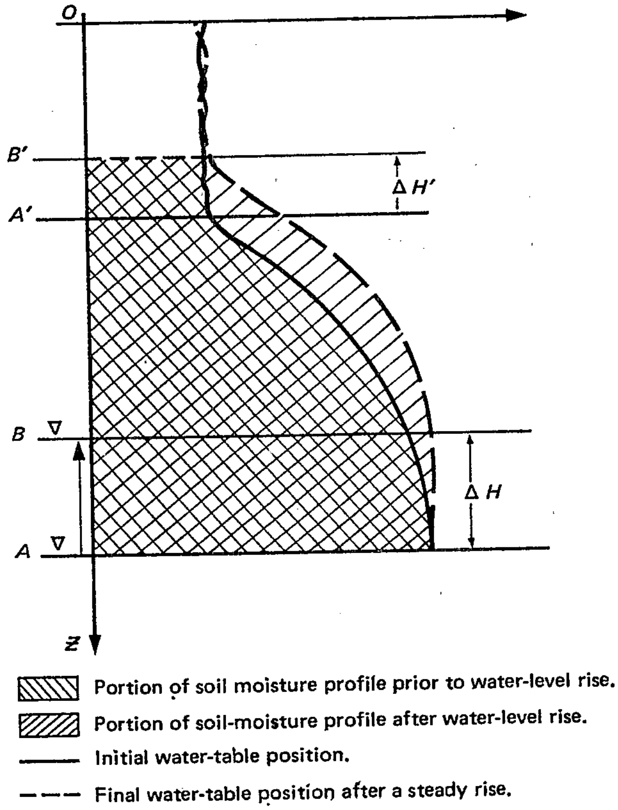


Figure 4.5.2 Soil-moisture profile changes in response to unconfined ground-water level rise for determination of specific yield (Brown et al., 1983).

Table 4-4 Reference Index for Ground-Water Level/Pressure Measurement Methods

Topic	References
Reviews of Methods	Brown et al. (1983), Bureau of Reclamation (1981, 1984), Cordes (1984), Dalton et al. (1991), Driscoll (1986), Garber and Koopman (1968), Sophocleous and Perry (1984), Sweet et al. (1990), Thompson et al. (1989), Thornhill (1989), U.S. EPA (1987), U.S. Geological Survey (1980)
Accuracy/Precision	Gibbons (1990), Sweet et al. (1990); U.S. Geological Survey Testing Program: Holland and Rapp (1988), Olive (1989), Rapp et al. (1985a, 1985b)
Water Level Fluctuations	Andreason and Brookhart (1963-reverse fluctuations), Freeze and Cherry (1979), Kohout (1960-effects of salt water), Languth and Treskatis (1989), Moench (1971), Rockaway (1970), Sayko et al. (1990), Weeks (1979-barometric effects), Weiss-Jennemann (1991-offsite effects), Winograd (1970)
Data Interpretation	Chapus (1988), Davis and DeWiest (1966), Fetter (1981), Frimpter (1992), Henning (1990), Hoeksma et al. (1989), Rockaway (1970), Rosenberry (1990), Saines (1981), Struckmeier et al. (1986)
Air Line	Fournier and Truesdell (1971), Franzoy and Busch (1966), Peake and Mioduszewski (1989)
Electric	Henszey (1991), Luthin (1949), Ritchey (1986), Sanders (1984), Weir and Nelson (1976)
Sonic Methods	Andersen (1986), Ritchey (1986)
Transducers	Durham and Bumala (1992)
Float Methods	Mechanical Float: Walton (1963); Potentiometer Float: Buchanan and Somers (1968), Rosenberry (1990)
In Situ Piezometers	Hemond (1982), Massarsch et al. (1975), Reeve (1986), Reeve and Jensen (1949), Rice (1967), Russel (1981), Talsma (1960), Wissa et al. (1975), Wolf et al. (1991), Wolff and Olsen (1968)

Table 4-5 Sources of Information on Aquifer Tests and Analysis of Test Data

Topic	Reference
Ground-Water Hydraulics	Bear (1972,1979), Bear and Corapciuglu (1987), Bennett (1976), Brooks and Corey (1964-unsaturated flow), Bureau of Reclamation (1981), Campbell and Lehr (1973), Cedergren (1989), Collins (1961), Colt Industries (1974), Corey (1977), Daly (1984), DeWiest (1966, 1969), Dodge and Thompson (1937), Driscoll (1986), Dullien (1979), Edelman (1983), Glover (1966), Hantush (1964), Hubbert (1969), IAHR (1972), Lohman (1972), Marsily (1986), McWhorter and Sunada (1981), Muskat (1937), Peterson et al. (1952), Rosenshein and Bennett (1984), Scheidegger (1974), Simon (1976), Stallman (1967-unsaturated flow), Strack (1989), U.S. EPA (1986)
Shallow Water Table Tests	
Reviews	Amoozegar and Warrick (1986), Boersma (1965), Bouma (1979, 1983), Bouwer and Jackson (1974), Johnson and Richter (1967), Kessler and Oosterbaan (1974), Kirkham (1965), Luthin (1957), Schmid (1967), U.S. EPA (1986), Youngs (1991)
Auger-Hole Method	Boast and Kirkham (1971), Bouma (1983), Bouma et al. (1976, 1979a,b, 1981), Bouwer (1978), Bouwer and Jackson (1974), Bouwer et al. (1955-stony soils), Bureau of Reclamation (1978), Ernst (1950), Hendrickx (1990), Hoffman and Scwab (1964), Johnson et al. (1952), Kirkham (1958, 1965), Kirkham and van Bavel (1948), Luthin (1957-layered soils), Maasland (1955, 1957-anisotropic soils), Roberts (1984), Topp and Sattlecker (1983), Topp and Zebchuk (1986), U.S. EPA (1981), van Bavel and Kirkham (1948), van Beers (1958), Youngs (1991)
Pit-Baling Method	Boast and Langebartel (1984), Bouwer and Rice (1983), Healy and Laak (1973), Hendrickx (1990)
Pumped Borehole Method	Hendrickx (1990), Kessler and Oosterbaan (1974)
Piezometer Methods	Piezometer Method: Bouwer (1978), Bureau of Reclamation (1978), Hendrickx (1990), Johnson et al. (1952), Kessler and Oosterbaan (1974), King and Franzmeier (1981), Kirkham (1946), Luthin and Kirkham (1949), Youngs (1968, 1991); Tube Method: Frevert and Kirkham (1948), Kirkham (1946), Luthin (1973); Well Point Method: Bouwer and Jackson (1974), Donnan and Aronovici (1961)
Multiple-Hole Methods	Overviews: Amoozegar and Warrick (1986), Bouwer and Jackson (1974), Luthin (1957), Youngs (1991); Two-Well: Childs (1952), Childs et al. (1953); Four-Well: Bouwer and Jackson (1974), Kirkham (1954), Snell and van Schilfgaarde (1964), Thomas and Snell (1967); Multiple-Well: Smiles and Youngs (1963); Drainage Outflow Method: Hendrickx (1990), Smedema and Rycroft (1983), Youngs (1991)
Slug Tests	
Texts/Reviews	Bentall (1963a), Bouwer (1978), Campbell et al. (1990), Chapus (1989), Chirlin (1990), Dagan (1978), Dawson and Istok (1991), Herzog and Morse (1986, 1990), Kraemer et al. (1990), Lohman (1972), Olson and Daniel (1981), Sevee (1991), Thompson et al. (1989), Wynne (1992)
Pressure Displacement	Leap (1984), Levy and Pannell (1991), McLane et al. (1990), Orient et al. (1987)

Table 4-5 (cont.)

Topic	Reference
Slug Tests (cont.)	
Multilevel Tests	Mastrolonardo and Thomsen (1992), Melville et al. (1991), Molz et al. (1990a, b), Widdowson et al. (1989, 1990)
Hvorslev Method	Cedergren (1989), Chirlin (1989), Freeze and Cherry (1979), Hvorslev (1951), Leap (1984)
Ferris-Knowles Method	Ferris and Knowles (1954, 1963), Ferris et al. (1962), Leap (1984)
Cooper-Bredehoeft-Papadopulos Method	Cooper et al. (1967), Leap (1984), Papadopulos et al. (1973),
Bouwer-Rice Method	Bouwer (1989), Bouwer and Rice (1976)
Data Analysis Procedures	Dax (1987), Faust and Mercer (1984), Keller and van der Kamp (1992), Marschall and Barczewski (1989), Moench and Hsieh (1985), Nguyen and Pinder (1984), Palmer and Paul (1987), Peres et al. (1989), Widdowson et al. (1990)
Pumping Tests	Bentall (1963a,b), Bouwer (1978), Brown et al. (1983), Bureau of Reclamation (1981), Clarke (1988), Dawson and Istok (1991), Driscoll (1986), Earlougher (1977), Ferris et al. (1962), Johnson and Richter (1967), Kruseman and de Ridder (1990), Lang (1967), Lohman (1972), Schicht (1972), Stallman (1971), Streltsova (1989), U.S. EPA (1986, 1991), U.S. Geological Survey (1980), Walton (1962, 1979, 1987), Wenzel (1942)
Packer Tests	Braester and Thunvik (1984), Brassington and Walthall (1985), Bureau of Reclamation (1981), Dagan (1978), Koopman et al. (1962), Sevee (1991), Shuter and Pemberton (1978), Sutcliffe and Joyner (1966); Lugeon Test: Houlsby (1976), Roeper et al. (1992); see also, references for multilevel slug tests
Water Balance Methods	
Texts/Reviews	ASCE (1952), Brown et al. (1983), Bureau of Reclamation (1981), Chapman (1964), Childs (1969), Downes (1964), Hagan et al. (1967), Meinzer (1932), Phillips (1964, 1969), Rijtema and Wassink (1969), Skeat (1969), Sokolow and Chapman (1974), Thornthwaite and Mather (1955), Walton (1970)
Case Studies	Dennehy and McMahon (1989), Holmes (1960), Kohler (1964), Meinzer and Stearns (1929), Rasmussen and Andreason (1959), Schicht and Walton (1961), Turner and Halpenny (1941), Ubell (1965), White (1990), Williams and Lohman (1947)
Other Aquifer Properties	
Effective Porosity	Horton et al. (1988)

Table 4-6 Sources of Information on Tracer Tests

Topic	Reference
Other Aquifer Properties (cont.)	
General Reviews	Atkinson and Smart (1981), Davis et al. (1980, 1985), Drew and Smith (1969), Gaspar (1987), Grisak et al. (1983), Kaufman and Orlob (1956), Knuttson (1968), Molz et al. (1986, 1987), U.S. EPA (1991-Chapter 4)
Bibliographies	Edwards and Smart (1988a,b), LaMoreaux et al. (1984, 1989), Smart et al. (1988), Taylor and Dey (1985), van der Leeden (1991)
Specific Tracers	
Dyes	Drew and Smith (1969), Field et al. (in press), McLaughlin (1982), Mull et al. (1988), Quinlin (1989), Smart and Laidlaw (1977), Thrailkill et al. (1983), Wilson et al. (1986); see also, Karst Tracing
Microorganisms	Crane and Moore (1984), Gerba (1983, 1985, 1987), Gerba and Bitton (1984), Keswick and Gerba (1980), Keswick et al. (1982), Matthess and Pekdeger (1985), Romero (1970), Sobsey and Shields (1987), Vaughn and Landry (1983), Wood and Ehrlich (1978)
Stable Isotopes	Back and Cherry (1976), Bowen (1980-Chapter 3), Coleman et al. (1977), Davis and Bentley (1982), Ferronsky and Polyakov (1982), Fritz and Fontes (1980, 1986), Halevy et al. (1967), IAEA (1967a, 1967c, 1970, 1974a, 1974b, 1978), Lamoreaux et al. (1984), Moser and Rauert (1985), Payne (1972)
Radioactive Isotopes	Csallany (1966), Gaspar and Oncescu (1972), Hoefs (1980), IAEA (1963, 1967b, 1967c, 1974b), Jäeger and Hunziker (1979), Kaufman and Orlob (1956), Thornhill and Benefield (1990), Wiebenga et al. (1967)
Karst Tracing	Aley and Fletcher (1976), Aley et al. (in press), Back and Zoetl (1975), Bögli (1980), Brown (1972), Ford and Williams (1989), Gospodaric and Habic (1976), Gunn (1982), Jones (1984), LaMoreaux (1984, 1989), Milanovic (1981), Mull et al. (1988), Quinlan (1989), Sweeting (1973), SUWT (1966, 1970, 1976, 1981, 1986), Thrailkill et al. (1983)

SECTION 4 REFERENCES

Aley, T. and M.W. Fletcher. 1976. The Water Tracer's Cookbook. Missouri Speleology 16(3):1-32.

Aley, T. J.F. Quinlan, E.C. Alexander, and H. Behrens. In press. The Joy of Dyeing: A Compendium of Practical Techniques for Tracing Groundwater, Especially in Karst Terranes. National Ground Water Association, Dublin, OH.

American Society of Civil Engineers (ASCE). 1952. Hydrology Handbook. ASCE Manual of Engineering Practice No. 28. ASCE, New York, NY.

American Society for Testing and Materials (ASTM). 1986a. Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In-Situ Measurements Using the Constant Head Injection Test. D4630-86, (Vol. 4.08), ASTM, Philadelphia, PA. [Packer test]

American Society for Testing and Materials (ASTM). 1986b. Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In-Situ Measurements Using the Pressure Pulse Technique. D4631-86, (Vol. 4.08), ASTM, Philadelphia, PA. [Packer test]

American Society for Testing and Materials (ASTM). 1987. Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well). D4750-87, (Vol. 4.08), ASTM, Philadelphia, PA. [Measuring tape, electrical]

American Society for Testing and Materials (ASTM). 1991a. Standard Guide for Selection of Aquifer-Test Field and Analytical Procedures in Determination of Hydraulic Properties by Well Techniques. D4043-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991b. Standard Test Method (Field Procedures) for Instantaneous Change in Head (Slug Tests) for Determining Hydraulic Properties of Aquifers. D4044-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991c. Standard Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Test). D4104-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991d. Standard Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems. D4050-91, (Vol. 4.08), ASTM, Philadelphia, PA. [Pumping tests]

American Society for Testing and Materials (ASTM). 1991e. Standard Test Method for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method. D4105-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991f. Standard Test Method for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method. D4106-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992a. Standard Test Method for (Analytical Procedure) Determining Transmissivity of Non-Leaky Confined Aquifers by the Theis Recovery Method. D5269-92, (Vol 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992b. Standard Test Method for (Analytical Procedure) Determining Transmissivity and Storage Coefficient of Bounded, Non-Leaky Confined Aquifers. D5270-92, (Vol 4.08), ASTM, Philadelphia, PA.

Amoozegar, A. and A. W. Warrick. 1986. Hydraulic Conductivity of Saturated Soils: Field Methods. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 735-770.

Andersen, S.G. 1986. Water Level Measurements Using Sound Waves. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 18-27.

Andreason, G.E. and J.W. Brookhart. 1963. Reverse Water Level Fluctuations. U.S. Geological Survey Water Supply Paper 1544 H, pp. H30-H35.

Atkinson, T.C. and P.L. Smart. 1981. Artificial Tracers in Hydrology. In: A Survey of British Hydrology, The Royal Society, London, pp.173-190.

Back, W. and J.A. Cherry. 1976. Chemical Aspects of Present and Future Hydrogeologic Problems. Advances in Groundwater Hydrology September:153-172.

Back, W. and J. Zoetl. 1975. Application of Geochemical Principles, Isotopic Methodology, and Artificial Tracers to Karst Hydrology. In: Hydrogeology of Karstic Terrains, A. Burger and L. Dubertret (eds.), Int. Ass. Hydrogeologists, Paris, pp. 105-121.

Backhus, D.A. and P.M. Gschwend. 1990. Fluorescent Polycyclic Aromatic Hydrocarbons as Probes for Studying the Impacts of Colloids on Pollutant Transport in Groundwater. Environ. Sci. Technol. 24:1214-1223.

Bear, J. 1972. Dynamics of Flow in Porous Media. Elsevier, New York, NY. (Reissued in paperback in 1988 by Dover Publications, Mineola, NY.)

Bear, J. 1979. Hydraulics of Groundwater. McGraw-Hill, New York, NY, 567 pp.

Bear, J. and M.Y. Corapciuglu (eds.). 1987. Advances in Transport Phenomena in Porous Media. NATO Advanced Studies Institutes Series E, Vol. 128. Martinus Nijhoft Publishers, Dordrecht, The Netherlands.

Bennett, G.D. 1976. Introduction to Ground-Water Hydraulics: A Programmed Text for Self-Instruction. U.S. Geological Survey Techniques of Water Resources Investigations TWRI 3-B2, 172 pp.

Bentall, R. (ed.). 1963a. Methods of Determining Permeability, Transmissibility, and Drawdown. U.S. Geological Survey Water Supply Paper 1536-I.

Bentall, R. (compiler). 1963b. Shortcuts and Special Problems in Aquifer Tests. U.S. Geological Survey Water-Supply Paper 1545-C.

Boast, C.W. and D. Kirkham. 1971. Auger Hole Seepage Theory. Soil Sci. Soc. Am. Proc. 35:365-374.

Boast, C.W. and R.G. Langebartel. 1984. Shape Factors for Seepage into Pits. Soil Sci. Soc. Am. J. 48:10-15.

Boersma, L. 1965. Field Measurement of Hydraulic Conductivity Below a Water Table. In: Method of Soil Analysis, Part 1, 1st edition, ASA Agronomy Monograph 9, American Society of Agronomy, Madison, WI, pp. 222-233.

Bögli, A. 1980. Karst Hydrology and Physical Speleology. Springer-Verlag, New York, NY.

Bouma, J. 1979. Field Measurement of Soil Hydraulic Properties Characterizing Water Movement Through Swelling Clay Soils. J. Hydrology 45:149-158.

Bouma, J. 1983. Use of Soil Survey Data to Select Measurement Techniques for Hydraulic Conductivity. Agric. Water Manage. 6:177-190.

Bouma, J. and L.W. Dekker. 1981. A Method of Measuring the Vertical and Horizontal Ksat of Clay Soils with Macropores. Soil Sci. Soc. Am. J. 45:662-663.

Bouma, J., L.W. Dekker, and H.L. Verlinden. 1976. Drainage and Vertical Hydraulic Conductivity of Some Dutch "Knik" Clay Soils. Agric. Water Manage. 1:67-78.

Bouma, J., L.W. Dekker, and J.C.F. Haans. 1979a. Drainability of Some Dutch Clay Soils: A Case Study of Soil Survey Interpretation. Geoderma 22:193-203.

Bouma, J., A. Jongerius, and D. Schoonderbeek. 1979b. Calculation of Saturated Hydraulic Conductivity of Some Pedal Clay Soils Using Micromorphometric Data. Soil Sci. Soc. Am. J. 43:261-264.

Bouma, J., J.W. Van Hoorn, and G.H. Stoffelsen. 1981. Measuring the Hydraulic Conductivity of Soil Adjacent to Tile Drains in a Heavy Clay Soil in The Netherlands. J. Hydrology 50:371-381.

Bouwer, H. 1978. Groundwater Hydrology. McGraw-Hill, New York, NY. [Chapter 5 covers pump test methods; also includes auger hole and piezometer methods]

Bouwer, H. 1989. The Bouwer and Rice Slug Test--An Update. Ground Water 27(3):304-309.

Bouwer, H. and R.D. Jackson. 1974. Determining Soil Properties. In: Drainage for Agriculture, J. van Schilfgaarde (ed.), ASA Agronomy Monograph No. 17, American Society for Agronomy, Madison, WI, pp. 611-672.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. Water Resources Research 12(3):423-428.

Bouwer, J. and R.C. Rice. 1983. The Pit Baling Method for Hydraulic Conductivity Measurement of Isotropic or Anisotropic Soils. Am. Soc. Agric. Eng. Trans. 26:1435-1439.

Bouwer, H., P.J. Zwerman, H.E. Gray, and G. Levine. 1955. Drainage Research Methods on Stony Soils. Agr. Eng. 36:591-592.

Bowen, R. 1980. Ground Water. Applied Science Publishers, London. [Chapter 3 covers isotope tracing techniques]

Bowman, R.S. 1984. Evaluation of Some New Tracers for Soil Water Studies. Soil Sci. Soc. Am. J. 48:987-993. [Ionic tracers]

Bowman, R.S. and J.F. Gibbons. 1992. Difluorobezoates as Nonreactive Tracers in Soil and Ground Water. Ground Water 30:8-14.

Bradbury, K.R. 1991. Tritium as an Indicator of Ground-Water Age in Central Wisconsin. Ground Water 29:398-404.

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls (eds.). 1979. Field Manual for Research in Agricultural Hydrology. Agricultural Handbook No. 224, U.S. Department of Agriculture, Washington, DC.

Braester, C. and R. Thunvik. 1984. Determination of Formation Permeability by Double Packer Tests. J. Hydrology 72:375-389.

Brassington, F.C. and S. Walthall. 1985. Field Techniques Using Borehole Packers in Hydrogeological Investigations. Quart. J. Eng. Geol. 18:181-193.

Brooks, R.H. and A.T. Corey. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Colorado State University, Fort Collins, CO.

Brown, M.C. 1972. Karst Hydrology of the Lower Maligne Basin, Jasper, Alberta. Cave Studies No. 13. Cave Research Associates, Castro Valley, CA.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7. UNESCO, Paris. (Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983.)

Buchanan, T.J. and W.P. Somers. 1968. Stage Measurement at Gaging Stations. U.S. Geological Survey Techniques of Water Resource Investigations TWRI 3-A7, 28 pp. [Potentiometer float]

Bureau of Reclamation. 1978. Drainage Manual, 1st edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 286 pp. [Piezometer method]

Bureau of Reclamation. 1981. Ground Water Manual--A Water Resources Technical Publication, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 480 pp. (1st edition 1977.)

Bureau of Reclamation. 1984. Water Measurement Manual, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 327 pp. (1st edition 1967.)

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill Book Company, New York, NY.

Campbell, M.D., M.S. Sterrett, S.F. Fowler, and J.J. Klein. 1990. Slug Tests and Hydraulic Conductivity. Ground Water Management 4:85-99 (7th NWWA/API Conf.).

Cedergren, H.R. 1989. Seepage, Drainage, and Flow Nets, 3rd edition. John Wiley & Sons, New York, NY. (1st edition 1967.)

Chapman, T.G. 1964. Effects of Ground-Water Storage and Flow on Water Balance. In: Water Resources Use and Management (1963 Canberra Symp.), Melbourne Univ. Press, Melbourne, pp. 290-301.

Chapus, R.P. 1988. Determining Whether Wells and Piezometers Give Water Levels or Piezometric Levels. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 162-171.

Chapus, R.P. 1989. Shape Factors for Permeability Tests in Boreholes and Piezometers. Ground Water 27(5):647-654).

Childs, E.C. 1952. The Measurement of the Hydraulic Permeability of Saturated Soil in Situ. I: Principles of a Proposed Method. Proc. Royal Soc. (London) A. 215:525-535.

Childs, E.C. 1969. An Introduction to the Physical Basis of Soil Water Phenomena. Wiley Interscience, New York, NY, 493 pp.

Childs, E.C., A.H. Cole, and D.H. Edwards. 1953. The Measurement of the Hydraulic Permeability of Saturated Soil in Situ. II. Proc. Royal Soc. (London) 216:72-89.

Chirlin, G.R. 1989. A Critique of the Hvorslev Method for Slug Test Analysis: The Fully Penetrating Well. Ground Water Monitoring Review 9(2):130-138.

Chirlin, G.R. 1990. The Slug Test: The First Forty Years. In: Proceedings of the Cluster Conferences: Ground Water Management and Wellhead Protection. Ground Water Management 1:365-381.

Clarke, D. 1988. Groundwater Discharge Tests: Simulation and Analysis. Dev. in Water Science 37. Elsevier, New York, NY.

Coleman, D.D., W.F. Meents, C.L. Liu, and R.A. Keogh. 1977. Isotopic Identification of Leakage Gas from Underground Storage Reservoirs--a Progress Report. Petroleum Report No. 111. Illinois State Geological Survey, Urbana, IL.

Collins, R.E. 1961. Flow of Fluids in Porous Media. Reinhold Publishing Corp., New York, NY.

Colt Industries. 1974. Hydraulic Handbook. Fairbanks Morse Pump Division, Colt Industries, Kansas City, KS, 246 pp.

Cooper, Jr., H.H., J.D. Bredehoeft, and I.S. Papadopoulos. 1967. Response of a Finite-Diameter Well to an Instantaneous Charge of Water. Water Resources Research 3(1):263-270.

Cordes, E.H. 1984. Ground Water Instrumentation Program of the U.S. Geological Survey. Ground Water Monitoring Review 4(4):103-114.

Corey, A.T. 1977. Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Fort Collins, CO.

Crane, S.R. and J.A. Moore. 1984. Bacterial Pollution of Groundwater: A Review. Water, Air, and Soil Pollution 22:67-83.

Csallany, S.C. 1966. Application of Radioisotopes in Water Resources Research. In: Proc. 2nd Annual American Water Resource Conference, American Water Resource Association, Champaign, IL, pp. 365-373.

Dagan, G. 1978. A Note on Packer, Slug and Recovery Tests in Unconfined Aquifers. Water Resources Research 14(5):929-934.

Dalton, M.G., B.E. Huntsman, and K. Bradbury. 1991. Acquisition and Interpretation of Water-Level Data. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 367-395.

Daly, C.J. 1984. A Procedure for Calculating Ground Water Flow Lines. CRREL Special Report 84-9. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, NH.

Davis, S.N. 1986. Reply to the Discussion by James F. Quinlan of Ground Water Tracers. Ground Water 24(3):398-399.

Davis, S.N. and H.W. Bentley. 1982. Dating Groundwater, a Short Review. In: Nuclear and Chemical Dating Techniques, L. Currie (ed.), ACS Symposium Series 176, pp. 187-222.

Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogeology. John Wiley & Sons, New York, NY, 366 pp.

Davis, S.N., G.M. Thompson, H.W. Bentley, and G. Stiles. 1980. Ground Water Tracers--A Short Review. Ground Water 18:14-23.

Davis, S.N., D.J. Campbell, H.W. Bentley, and T.J. Flynn. 1985. Introduction to Ground-Water Tracers. EPA/600/2-85/022 (NTIS PB86-100591). Also published under the title Ground Water Tracers in NWWA/EPA Series, National Water Well Association, Dublin, OH, 200 pp. (See also, discussion by Quinlan [1986] and reply by Davis [1986].)

Dawson, K.J. and J.D. Istok. 1991. Aquifer Testing: Design and Analysis of Pumping and Slug Tests. Lewis Publishers, Chelsea, MI, 280 pp.

Dax, A. 1987. A Note on the Analysis of Slug Tests. J. Hydrology 91:153-177.

Dennehy, K.F. and P.B. McMahon. 1989. Water Movement in the Unsaturated Zone at a Low-Level Radioactive-Waste Burial Site Near Barnwell, South Carolina. U.S. Geological Survey Water Supply Paper 2345, 40 pp. [Ground-water balance]

DeWiest, R.J.M. 1966. Geohydrology. John Wiley & Sons, New York, NY.

DeWiest, R.J.M. (ed.). 1969. Flow Through Porous Media. Academic Press, New York, NY.

Dodge, R.A. and M.J. Thompson. 1937. Fluid Mechanics. McGraw-Hill, New York, NY.

Donnan, W.W. and V.S. Aronovici. 1961. Field Measurement of Hydraulic Conductivity. J. Irrig. Drain. Div. (ASCE) 87(IR2):1-13.

Downes, R.G. 1964. The Water Balance and Land-Use. In: Water Resources Use and Management (1963 Canberra Symp.), Melbourne Univ. Press, Melbourne, pp. 329-341.

Drew, D.P. and D.I. Smith. 1969. Techniques for the Tracing of Subterranean Drainage. British Geomorphological Research Group Tech. Bulletin 2:1-36.

Driscoll, F.G. 1986. Groundwater and Wells, 2nd edition. Johnson Division, UOP Inc., St. Paul, MN, 1089 pp. (1st edition by Johnson UOP, 1966.) [Chapter 16 covers water level measurement methods: steel tape, electric probe, air line, pressure transducer]

Dullien, F.A.L. 1979. Porous Media: Fluid Transport and Structure. Academic Press, New York, NY.

Durham, G.N. and T.G. Bumala. 1992. Using Vibration Strip Transducers for Measuring Water Levels in Monitoring Wells. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 273-280.

Earlougher, Jr., R.C. 1977. Advances in Well Test Analysis. Soc. Petrol. Eng. of AIME, New York, NY, 264 pp.

Edelman, J.H. 1983. Groundwater Hydraulics of Extensive Aquifers, 2nd edition. ILRI Bulletin No. 13. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 216 pp.

Edwards, A.J. and P.L. Smart. 1988a. Solute Interaction Processes: An Annotated Bibliography. Turner Designs, Sunnyvale, CA. [61 references]

Edwards, A.J. and P.L. Smart. 1988b. Contaminant Transport Modeling: An Annotated Bibliography. Turner Designs, Sunnyvale, CA. [58 references]

Ernst, L.F. 1950. A New Formula for the Calculation of the Permeability Factor with the Auger Hole Method. TNO, Groningnen. (Translated from the Dutch by H. Bouwer, Cornell University, Ithaca, NY.)

Faust, C.R. and J.W. Mercer. 1984. Evaluation of Slug Tests in Wells Containing a Finite Thickness Skin. Water Resources Research 20(4):504-506.

Ferris, J.G. and D.B. Knowles. 1954. The Slug Test for Estimating Transmissibility. U.S. Geological Survey Ground Water Note 26.

Ferris, J.G. and D.B. Knowles. 1963. The Slug-Injection Test for Estimating the Coefficient of Transmissibility of an Aquifer. In: U.S. Geological Survey Water Supply Paper 1536-I.

Ferris, J.G., D.B. Knowles, R.H. Brown, and R.W. Stallman. 1962. Theory of Aquifer Tests. U.S. Geological Survey Water-Supply Paper 1536-E.

Ferronsky, V.I. and V.A. Polyakov. 1982. Environmental Isotopes in the Hydrosphere. Wiley-Interscience, New York, NY.

Fetter, Jr., C.W. 1981. Determination of the Direction of Groundwater Flow. Ground Water Monitoring Review 1(3):28-31.

Field, M.S., R.G. Wilhelm, and J.F. Quinlan. In press. Selection, Toxicity, and Use of Fluorescent Dyes for Tracing Ground Water in Karst and Fractured Rock Aquifers: 1. What Is Safe, Why, Where, and When? Ground Water.

Ford, D.C. and P.W. Williams. 1989. Karst Geomorphology and Hydrology. Unwin Hyman, Boston, MA, 601 pp.

Fournier, R.D. and A.H. Truesdell. 1971. A Device for Measuring Down-Hole Pressures and for Sampling Fluids in Geothermal Wells. U.S. Geological Survey Professional Paper 750-C, pp. C146-C150. [Air line]

Franzoy, C.E and C.D. Busch. 1966. A Portable Airline to Measure Water Level. Agric. Eng. 47:86-87.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pp.

Frevert, R.K. and D. Kirkham. 1948. A Field Method for Measuring the Permeability of Soil Below the Water Table. Highway Research Board Proc. 28:433-442.

Frimpter, M.H. 1992. Use of Long-Term Observation Well Data to Estimate Ground-Water Levels for Site Investigations. Ground Water Management 13:279-291 ([8th] Focus Conf. Eastern GW Issues).

Fritz, P. and J.C. Fontes (eds.). 1980. Handbook of Environmental Isotope Geochemistry, Vol 1: The Terrestrial Environment. Elsevier, New York, NY, 545 pp.

Fritz, P. and J.C. Fontes (eds.). 1986. Handbook of Environmental Isotope Geochemistry, Vol 2: The Terrestrial Environment, Part B. Elsevier, New York, NY.

Garber, M.S. and F.C. Koopman. 1968. Methods of Measuring Water Levels in Deep Wells. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 8-A1, 23 pp. [Steel tape, electric, air line, float recorder, transducers]

Gardner, G.D. and R.E. Gray. 1976. Tracing Subsurface Flow in Karst Regions Using Artificially Colored Spores. Association of Engineering Geologists Bulletin 13:177-197.

Gaspar, E. (ed.). 1987. Modern Trends in Tracer Hydrology. CRC Press, Boca Raton, FL, Vol. I, 145 pp.; Vol. II, 137 pp.

Gaspar, E. and M. Oncescu. 1972. Radioactive Tracers in Hydrology. Elsevier, New York, NY.

Gerba, C.P. 1983. Virus Survival and Transport in Groundwater. Dev. Ind. Microbiol. 24:247-251.

Gerba, C.P. 1985. Microbial Contamination of the Subsurface. In: Ground Water Quality, C.H. Ward, W. Giger, and P.L. McCarty (eds.), Wiley and Sons, New York, NY, pp. 53-67.

Gerba, C.P. 1987. Transport and Fate of Viruses in Soils: Field Studies. In: Human Viruses in Sediments, Sludges, and Soil, V.C. Rao and J.L. Melnick (eds.), CRC Press, Boca Raton, FL.

Gerba, C.P. and G. Bitton. 1984. Microbial Pollutants: Their Survival and Transport Pattern to Groundwater. In: Groundwater Pollution Microbiology, G. Bitton and C.P. Gerba (eds.), Wiley-Interscience, New York, NY, pp. 66-88.

Gibbons, R.D. 1990. Estimating the Precision of Ground-Water Elevation Data. Ground Water 28:357-360.

Glover, R.E. 1966. Ground-Water Movement. Tech. Eng. Monograph No. 31. U.S. Bureau of Reclamation, Denver, CO, 76 pp.

Gospordaric, R. and P. Habic (eds.). 1976. Underground Water Tracing: Investigations in Slovenia 1972-1975. Institute Karst Research, Ljubljana, Jugoslavia.

Grisak, G.E., J.F. Pickens, F.J. Pearson, and J.M. Bahr. 1983. Evaluation of Ground Water Tracers for Nuclear Fuel Waste Management Studies. Report Prepared by Geologic Testing Consultants, Ltd. for Atomic Energy of Canada, Ltd., Whiteshell Nuclear Research Establishment, Pinawa, Manitoba.

Gunn, J. 1982. Water Tracing in Ireland: A Review with Special References to the Cuillcagh Karst. Irish Geography 15:94-106.

Hagan, R.M., H.R. Haise, and T.W. Edminster (eds.). 1967. Irrigation of Agricultural Lands, ASA Monograph 11, American Society of Agronomy, Madison, WI.

Halevy, E., H. Moser, O. Zellhoffer, and A. Zuber. 1967. Borehole Dilution Techniques: A Critical Review. In: Isotopes in Hydrology, International Atomic Energy Agency, Vienna, pp. 531-564.

Hantush, M.S. 1964. Hydraulics of Wells. Advances in Hydroscience 1:281-432.

Healy, K.A. and R. Laak. 1973. Sanitary Seepage Pits--Site Evaluation and Design. Civil Eng. Dept., Univ. of Connecticut, Storrs, CT.

Hemond, H. 1982. A Low-Cost Multichannel Recording Piezometer for Wetland Research. Water Resources Research 18:182-186.

Hendrickx, J.M.H. 1990. Determination of Hydraulic Soil Properties. In: Process Studies in Hillslope Hydrology, M.G. Anderson and T.P. Burt (eds.), John Wiley & Sons, New York, NY, pp. 43-92. [Auger-hole, piezometer, pumped borehole, pit bailing, drainage outflow methods]

Henning, R.J. 1990. Presentation of Water Level Data. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 193-209.

Henszey, R. 1991. A Simple, Inexpensive, Device for Measuring Shallow Groundwater Levels. J. Soil and Water Conservation 46(4):304-306.

Herzog, B.L. and W.J. Morse. 1986. Hydraulic Conductivity at a Hazardous Waste Disposal Site: Comparison of Laboratory and Field Measured Values. Waste Management and Research 4:177-187.

Herzog, B.L. and W.J. Morse. 1990. Comparison of Slug Test Methodologies for Determination of Hydraulic Conductivity in Fine-Grained Sediments. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053. American Society for Testing and Materials, Philadelphia, PA, pp. 152-164.

Hoefs, J. 1980. Stable Isotope Geochemistry, 2nd edition. Springer-Verlag, New York, NY, 208 pp.

Hoeksma, R.J., Clapp, R.B., A.L. Thomas, A.E. Hunley, N.D. Farrow, and K.C. Dearstone. 1989. Cokriging Model for Estimation of Water Table Elevation. Water Resources Research 25(3):429-438.

Hoffman, G.J. and G.O. Schwab. 1964. Tile Spacing Prediction Based on Drain Outflow. Trans. Am. Soc. Agric. Eng. 7:444-447. [Auger hole method]

Holland, R.R. and D.H. Rapp. 1988. Results of Qualification Tests on Water-Level Sensing Instruments, 1986. U.S. Geological Survey Open-File Report 88-193, 34 pp.

Holmes, J.W. 1960. Water Balance and the Water-Table in Deep Sandy Soils of the Upper Southeast, South Australia. Aust. J. Agric. Res. II:970-988.

Horton, R., M.L. Thompson, and J.F. McBride. 1988. Determination of Effective Porosity of Soil Materials. EPA/600/2-88/045 (NTIS PB88-242391), 130 pp.

Houlsby, A.C. 1976. Routine Interpretation of the Lugeon Water-Test. Quart. J. Engineering Geology 9:303-313. [Step-pressure packer test]

Hubbert, M.K. 1969. The Theory of Ground-Water Motion and Related Papers. Hafner Publishing Co., 311 pp.

Hvorslev, M.J. 1951. Time Lag and Soil Permeability in Groundwater Observations. U.S. Army Corps of Engineers Waterways Experiment Station, Bull. 36, Vicksburg, MS.

International Association for Hydraulic Research (IAHR). 1972. Fundamentals of Transport Phenomena in Porous Media. Elsevier, New York, NY.

International Atomic Energy Agency (IAEA). 1963. Proceedings of the Symposium on Radioisotopes in Hydrology (Tokyo). IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1967a. Isotopes in Hydrology. Proceedings of the Symposium on Isotopes in Hydrology (Vienna), IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1967b. Radioisotopes in Industry and Geophysics--A Symposium (Prague). IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1967c. Isotopes and Radiation Techniques, (Proc. of Symp. Techniques in Soil Physics and Irrigation Studies, Istanbul), IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1970. Isotope Hydrology (1970). Proceedings of a Symposium on Use of Isotopes in Hydrology (Vienna). IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1974a. Isotope Techniques in Groundwater Hydrology (1970), 2 Volumes. Proceedings Vienna Symposium, IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1974b. Isotope Techniques in Soil Physics and Irrigation Studies. IAEA, Vienna.

International Atomic Energy Agency (IAEA). 1978. Isotope Hydrology (1978), 2 Volumes. Proceedings of an International Symposium on Isotope Hydrology (Neuherberg). IAEA, Vienna.

Jäeger, E. and J.C. Hunziker (ed.). 1979. Lectures in Isotope Geology. Springer-Verlag, Berlin, 312 pp.

Johnson, A.I. and R.C. Richter. 1967. Selected Bibliography on Permeability and Capillarity Testing of Rock and Soil Materials. In: Permeability and Capillarity of Soils, ASTM STP 417, American Society for Testing and Materials, Philadelphia, PA, pp. 167-210.

Johnson, H.P., R.K. Frevert, and D.D. Evans. 1952. Simplified Procedure for the Measurement and Computation of Soil Permeability Below the Water Table. Agric. Eng. 33:283-286.

Jones, W.K. 1984. Dye Tracers in Karst Areas. National Speleological Society Bulletin 36:3-9.

Kaufman, W.J., and G.T. Orlob. 1956. Measuring Ground-Water Movements with Radioactive and Chemical Tracers. Am. Water Works Ass. J. 48:559-572.

Keller, C.K. and G. van der Kamp. 1992. Slug Tests with Storage Due to Entrapped Air. Ground Water 30:3-7.

Kessler, J. and R.J. Oosterbaan. 1974. Determining Hydraulic Conductivity of Soils. In: Drainage Principles and Applications, Vol. III, International Institute for Land Reclamation and Improvement/ILRI, Wageningen, pp. 254-296. [Auger hole, piezometer, pumped borehole methods]

Keswick, B.H. and C.P. Gerba. 1980. Viruses in Groundwater. Environ. Sci. Technol. 14:1290-1297.

Keswick, B.H., D. Wang, and C.P. Gerba. 1982. The Use of Microorganisms as Ground-Water Tracers: A Review. Ground Water 20(2):142-149.

King, J.J. and D.P. Franzmeier. 1981. Estimation of Saturated Hydraulic Conductivity from Soil Morphological and Genetic Information. Soil Sci. Soc. Am. J. 45:1153-1156.

Kirkham, D. 1946. Proposed Method for Field Measurement of Permeability of Soil Below the Water Table. Soil Sci. Soc. Am. Proc. 10:58-68.

Kirkham, D. 1954. Measurement of the Hydraulic Conductivity in Place. In: Symp. on Permeability of Soil, ASTM STP 163. American Society for Testing and Materials, Philadelphia, PA, pp. 80-97.

Kirkham, D. 1958. Theory of Seepage into an Auger Hole Above an Impermeable Layer. Soil Sci. Soc. Am. Proc. 18:204-208.

Kirkham, D. 1965. Saturated Conductivity as a Characterizer of Soil for Drainage Design. In: Drainage for Efficient Crop Production Conference, American Society of Agricultural Engineers, St. Joseph, MI, pp. 24-31.

Kirkham, D. and C.H.M. van Bavel. 1948. Theory of Seepage into Auger Holes. Soil Sci. Soc. Am. Proc. 13:75-82.

Knuttson, G. 1968. Tracers for Ground-Water Investigations. In: Ground Water Problems, E. Eriksson, Y. Gustafsson, and K. Nilsson (eds.), Pergamon Press, London.

Kohler, M.A. 1964. Simulation of Daily Catchment Water Balance. In: Water Resources Use and Management (1963 Canberra Symp.), Melbourne Univ. Press, Melbourne, pp. 312-328.

Kohout, F.A. 1960. Cyclic Flow of Salt Water in Biscayne Aquifer of South Eastern Florida. J. Geophys. Research 65:2133-2141. [Effects on water level measurements]

Koopman, F.C., et al. 1962. Use of Inflatable Packers in Multiple-Zone Testing in Water Wells. U.S. Geological Survey Professional Paper 450-B, pp. B108-B109.

Kraemer, C.A., J.B. Hankins, and C.J. Mohrbacher. 1990. Selection of Single-Well Hydraulic Test Methods for Monitoring Wells. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 125-137.

Kruseman, G.P. and N.A. de Ridder. 1990. Analysis and Evaluation of Pumping Test Data. ILRI Publication No. 47. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 345 pp. (Completely revised edition of the 1979 english version of Bulletin 11.)

LaMoreaux, P.E., B.M. Wilson, and B.A. Mermon (eds.). 1984. Guide to the Hydrology of Carbonate Rocks. UNESCO Studies and Reports in Hydrology, No. 41.

LaMoreaux, P.E., E. Prohic, J. Zoetl, J.M. Tanner, and B.N. Roche (eds.). 1989. Hydrology of Limestone Terranes: Annotated Bibliography of Carbonate Rocks, Volume 4. International Association of Hydrogeologists Int. Cont. to Hydrogeology Volume 10. Verlag Heinz Heise GmbH., Hannover, West Germany.

Lang, S.M. 1967. Pumping Test Methods for Determining Aquifer Characteristics. In: Permeability and Capillarity of Soils. In: ASTM STP 417, American Society for Testing and Materials, Philadelphia, PA, pp. 35-55.

Languth, H.R. and C. Treskatis. 1989. Reverse Water Level Fluctuations in Semiconfined Aquifer Systems--"Rhade Effect". J. Hydrology 109:79-93.

Leap, D.I. 1984. A Simple Pneumatic Device and Techniques for Performing Rising Water Level Slug Tests. Ground Water Monitoring Review 4(4):141-146.

Leupold & Stevens, Inc. 1991. Stevens Water Resources Data Book, 5th edition. Leupold & Stevens, Inc., Beaverton, OR. (3rd edition 1978; 4th edition 1987.) [Float recording devices covered in Chapter 2]

Levy, B.S. and L. Pannell. 1991. Evaluation of a Pressure System for Estimating In-Situ Hydraulic Conductivity. Ground Water Management 5:31-45 (5th NOAC).

Lohman, S.W. 1972. Ground-Water Hydraulics. U.S. Geological Survey Professional Paper 708.

Luthin, J.N. 1949. A Reel-Type Probe for Measuring Water Table Elevations. Agronomy J. 41:584. [Electric probe]

Luthin, J.N. 1957. Measurement of Hydraulic Conductivity In Situ. In: Drainage of Agricultural Lands, J.H. Luthin (ed.), ASA Agronomy Monograph 7, American Society of Agronomy, Madison, WI, pp. 420-431.

Luthin, J.N. 1973. Drainage Engineering. R.E. Krieger Publ. Co., Huntington, NY. [Tube method]

Luthin, J.H. and D. Kirkham. 1949. A Piezometer Method for Measuring Permeability of Soil In Situ Below a Water Table. Soil Science 68:349-358.

Maasland, M. 1955. Measurement of Hydraulic Conductivity by the Auger Hole Method in Anisotropic Soil. Soil Science 81:379-388.

Maasland, M. 1957. Soil Anisotropy and Land Drainage. In: Drainage of Agricultural Lands, J.H. Luthin (ed.), ASA Agronomy Monograph 7, American Society of Agronomy, Madison, WI, pp. 216-287.

Marschall, P. and B. Barczewski. 1989. The Analysis of Slug Tests in the Frequency Domain. Water Resources Research 25(11):2388-2396

Marsily, G. 1986. Quantitative Hydrogeology: Groundwater Hydrology for Engineers. Academic Press, New York, NY.

Massarsch, K., B. Broms, and O. Sundquist. 1975. Pore Pressure Determination with Multiple Piezometer. In: Proc. In Situ Measurement of Soil Properties, North Carolina State University, Raleigh, NC, 1:260-265.

Mastrolonardo, R.M. and K.O. Thomsen. 1992. Determination of the Vertical Distribution of Horizontal Hydraulic Conductivity-A Simple Method. Ground Water Management 11:205-216 (6th NOAC). [Slug test with packers]

Matthess, G. and A. Pekdeger. 1985. Survival and Transport of Pathogenic Bacteria and Viruses in Ground Water. In: Ground Water Quality, C.H. Ward, W. Giger, and P.L. McCarty (eds.), Wiley and Sons, New York, NY, pp. 474-482.

McLane, G.A., D.A. Harrity, and K.O. Thomsen. 1990. A Pneumatic Method for Conducting Rising and Falling Head Tests in High Permeability Aquifers. Ground Water Management 2:1219-1231 (4th NOAC).

McLaughlin, M.J. 1982. A Review of the Use of Dyes as Soil Water Tracers. Water S.A., Water Research Commission, Pretoria, South Africa 8(4):196-201.

McWhorter, D.B. and D.K. Sunada. 1981. Ground-Water Hydrology and Hydraulics. Water Resources Publications, Littleton, CO, 492 pp. (Earlier edition published 1977.)

Meinzer, O.E. 1932. Outline of Methods for Estimating Ground-Water Supplies. U.S. Geological Survey Water-Supply Paper 638-C.

Meinzer, O.E. and N.D. Stearns. 1929. A Study of Ground Water in the Pomperaug Basin, Connecticut. U.S. Geological Survey Water-Supply Paper 597-B.

Melville, J.G., F.J. Molz, O. Güven, and M.A. Widdowson. 1991. Multilevel Slug Tests with Comparisons to Tracer Data. Ground Water 29:897-907.

Milanovic, P.T. 1981. Karst Hydrogeology. Water Resource Publications, Littleton, CO.

Moench, A. 1971. Ground-Water Fluctuations in Response to Arbitrary Pumpage. Ground Water 9(2):4-8.

Moench, A.F. and P.A. Hsieh. 1985. Analysis of Slug Test Data in A Well with Finite Thickness Skin. Int. Congr. Int. Ass. Hydrogeol 17(1):17-29.

Molz, F.J., O. Güven, J.G. Melville, and J.F. Keely. 1986. Performance and Analysis of Aquifer Tracer Tests with Implications for Contaminant Transport Modeling. EPA/600/2-86/062 (NTIS PB86-219086).

Molz, F.J., O. Güven, J.G. Melville, and J.F. Keely. 1987. Performance and Analysis of Aquifer Tracer Tests with Implications for Contaminant Transport Modeling--A Project Summary. Ground Water 25:337-341.

Molz, F.J., O. Güven, and J.G. Melville. 1990a. A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers. EPA/600/2-90/002 (NTIS PB90-187063). [Multilevel slug tests, tracers]

Molz, F.J., O. Güven, and J.G. Melville. 1990b. Measurement of Hydraulic Conductivity Distribution: A Manual of Practice. EPA/600/8-90/046 (NTIS PB91-211938), 71 pp.

Morrison, R.D. 1983. Groundwater Monitoring Technology. Timco Mfg., Inc., Prairie du Sac, WI, 105 pp. (Sections on use of Teflon for suction lysimeters and casing for monitoring wells are out of date. See Sections 9.2.1 and A.1 in this guide for more current information.)

Moser, H. and W. Rauert. 1985. Determination of Groundwater Movement by Means of Environmental Isotopes: State of the Art. In: Relation of Groundwater Quantity and Quality, F.X. Dunin, G. Matthess, and R.A. Gras (eds.), Int. Ass. Hydrological Sciences Pub. No. 146, pp. 241-257.

Mull, D.S., T.D. Lieberman, J.L. Smoot, and L.H. Woosely, Jr. 1988. Application of Dye-Tracing Techniques for Determining Solute-Transport Characteristics of Ground Water in Karst Terranes. EPA/904/6-88/001, Region 4, Atlanta, GA.

Muskat, M. 1937. The Flow of Homogenous Fluids Through Porous Media. McGraw-Hill, New York, NY, 763 pp.

Nguyen, V. and G.F. Pinder. 1984. Direct Calculation of Aquifer Parameters in Slug Test Analysis. In: Groundwater Hydraulics, J. Rosenshein and G. Bennett (eds.), American Geophysical Union Water Resources Monograph 9, Washington, DC, pp. 222-239.

Nielsen, D.M. 1991. An Update on the ASTM Subcommittee on Ground Water and Vadose Zone Investigations. Ground Water Monitoring Review 11(3):92-96.

Nielsen, D.M. and R. Schalla. 1991. Monitoring Wells. In: Practical Handbook of Ground-Water Monitoring. Lewis Publishers, Chelsea, MI, pp. 239-331.

Olive, T.E. 1989. Results of Qualification Tests on Water-Level Sensing Instruments, 1987. U.S. Geological Survey Open-File Report 89-397, 37 pp.

Olson, R.E. and D.E. Daniel. 1981. Measurement of the Hydraulic Conductivity of Fine-Grained Soils. In: Permeability and Groundwater Contaminant Transport, T.F. Zimmie and C.O. Riggs (eds.), ASTM STP 746, American Society for Testing and Materials, Philadelphia, PA, pp. 18-64.

Orient, J.P., A. Nazar, and R.C. Rice. 1987. Vacuum and Pressure Test Methods for Estimating Hydraulic Conductivity. Ground Water Monitoring Review 7(1):49-50.

Palmer, C.D. and D.G. Paul. 1987. Problems in the Interpretation of Slug Test Data from Fine-Grained Glacial Tills. In: Proc. Focus Conf. on Northwestern Ground Water Issues, National Water Well Association, Dublin, OH, pp. 99-123.

Papadopulos, S.S., J.D. Bredehoeft, and H.C. Cooper, Jr. 1973. On the Analysis of "Slug Test" Data. Water Resources Research 9(4):1087-1089.

Payne, B.R. 1972. Isotope Hydrology. Advances in Hydroscience 8:95-138.

Peake, B.R. and D. Mioduszewski. 1989. A Versatile New Method of Water Level Measurement for Improve Precision, Speed and Well Integrity. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 289-303.

Peres, A.M.M., M. Onur, and A.C. Reynolds. 1989. A New Analysis Procedure for Determining Aquifer Properties from Slug Test Data. Water Resources Research 25(7):1591-1602.

Peterson, D.F. et al. 1952. Hydraulics of Wells. Agric. Exp. Sta. Bull. 351, Utah State College, Logan, UT.

Phillips, J.R. 1964. The Gain, Transfer, and Loss of Soil-Water. In: Water Resources Use and Management (1963 Canberra Symp.), Melbourne Univ. Press, Melbourne, pp. 257-275.

Phillips, J.R. 1969. Theory of Infiltration. Advances in Hydroscience 5:215-296.

Quinlan, J.F. 1986. Discussion of "Ground Water Tracers" by Davis et al. (1985) with Emphasis on Dye Tracing, Especially in Karst Terranes. Ground Water 24(2):253-259 and 24(3):396-397. [References]

Quinlan, J.F. 1989. Ground-Water Monitoring in Karst Terranes: Recommended Protocols and Implicit Assumptions. EPA/600/X-89/050, U.S. Environmental Protection Agency Environmental Monitoring Systems Laboratory, Las Vegas, NV, 79 pp.

Rapp, D.H., B.L. McDonald, and R.M. Hughes. 1985a. Results of Qualification Tests on Water-Level Sensing Instruments. U.S. Geological Survey Open-File Report 85-199, 47 pp.

Rapp, D.H., B.L. McDonald, and R.M. Hughes. 1985b. Results of Qualification Tests on Water-Level Sensing Instruments, 1984-85. U.S. Geological Survey Open-File Report 85-489, 18 pp.

Rasmussen, W.C. and G.E. Andreason. 1959. Hydrologic Budget of the Beaverdam Creek Basin, Maryland. U.S. Geological Survey Water-Supply Paper 1472, 106 pp.

Reeve, R.C. 1986. Water Potential: Piezometry. In: Methods of Soil Analysis, Part 1, 2nd edition, A. Klute (ed.), Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI, pp. 545-561.

Reeve, R.C. and M.C. Jensen. 1949. Piezometers for Ground-Water Flow Studies and Measurements of Subsoil Permeability. Agric. Eng. 30:435-438.

Rice, R.C. 1967. Dynamic Response of Small Piezometers. Trans. Am. Soc. Agric. Eng. 10:80-83.

Rijtema, P.E. and H. Wassink (eds.). 1969. Water in the Unsaturated Zone (Proc. Wageningen Symp), 2 Vols. IASH-UNESCO Studies and Reports in Hydrology 2. UNESCO, Paris.

Ritchey, J.D., 1986. Electronic Sensing Devices Used for In Situ Ground Water Monitoring. Ground Water Monitoring Review 6(2):108-113. [Electric probe and sonic method]

Roberts, D.W. 1984. Soil Properties, Classification, and Hydraulic Conductivity Testing. EPA/SW-925 (NTIS PB87-155784), U.S. Environmental Protection Agency [Auger hole method]

Rockaway, J.D. 1970. Trend-Surface Analysis of Ground-Water Fluctuations. Ground Water 8(3):29-36.

Roeper, T.R., W.G. Soukup and R.L. O'Neill. 1992. The Applicability of the Lugeon Method of Packer Test Analysis to Hydrogeologic Investigations. Ground Water Management 13:661-671 ([8th] Focus Conf. Eastern GW Issues). [Not recommended]

Romero, J.C. 1970. The Movement of Bacteria and Viruses through Porous Media. Ground Water 8(2):37-48.

Rosenberry, D.O. 1990. Effect of Sensor Error on Interpretation of Long-Term Water-Level Data. Ground Water 28:927-936. [Pressure transducer, potentiometer float]

Rosenshein, J., and G. Bennett (eds.). 1984. Groundwater Hydraulics. American Geophysical Union Water Resources Monograph 9.

Russel, H. 1981. Instrumentation and Monitoring of Excavations. Bull. Ass. Eng. Geol. 18:91-99.

Saines, M. 1981. Errors in Interpretation of Ground-Water Level Data. Ground Water Monitoring Review 1(1):56-61

Sanders, P.J. 1984. New Tape for Ground-Water Measurements. Ground Water Monitoring Review 4(1):39-42. [Steel tape with electric sensor]

Sayko, S.P., K.L. Ekstrom, and R.M. Schuller. 1990. Methods for Evaluating Short-Term Fluctuations in Ground Water Levels. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 165-177.

Scheidegger, A.E. 1974. The Physics of Flow through Porous Media, 353 pp. University of Toronto Press, Toronto, Ontario. (1st edition published by MacMillan in 1957; 2nd edition 1960.)

Schicht, R.J. 1972. Selected Methods of Aquifer Test Analysis. Water Resources Bulletin 8(1):175-187.

Schicht, R.J. and W.C. Walton. 1961. Hydrologic Budgets for Three Small Water Sheds in Illinois. ISWS Rept. of Invest. No. 46, Illinois State Water Survey, Urbana, IL.

Schmid, W.E. 1967. Field Determination of Permeability by the Infiltration Test. In: Permeability and Capillarity of Soils. ASTM STP 417. American Society for Testing and Materials, Philadelphia, PA, pp. 142-159.

Schrale, G. and J.F. Brandwyk. 1979. An Acoustic Probe for Precise Determination of Deep Water Levels in Boreholes. Ground Water 17(1):110-111.

Sevee, J. 1991. Methods and Procedures for Defining Aquifer Parameters. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 397-447.

Shuter, E. and A.I. Johnson. 1961. Evaluation of Equipment for Measurement of Water Levels in Wells of Small Diameter. U.S. Geological Survey Circular 453, 12 pp. [Float recorders]

Shuter, E. and R.R. Pemberton. 1978. Inflatable Straddle Packers and Associated Equipment for Hydraulic Fracturing and Hydrologic Tests. U.S. Geological Survey Water Resources-Investigations Report 78-55, 16 pp.

Simon, A.L. 1976. Practical Hydraulics. John Wiley & Sons, New York, NY.

Skeat, W.O. (edition). 1969. Manual of British Water Engineering Practice, Vol. II: Engineering Practice, 4th edition. W. Heffer and Sons, Cambridge.

Smart, P.L. and I.M.S. Laidlaw. 1977. An Evaluation of Some Fluorescent Dyes for Water Tracing. Water Resources Research 13(1):15-33.

Smart, P.L., F. Whitaker, and J.F. Quinlan. 1988. Ground Water Tracing: An Annotated Bibliography. Turner Designs, Sunnyvale, CA.

Smedema, L.K. and D.W. Rycroft. 1983. Land Drainage: Planning and Design of Agricultural Drainage Systems. Batsford, London. [Drainage outflow method]

Smiles, D.E. and E.G. Youngs. 1963. A Multiple-Well Method for Determining the Hydraulic Conductivity of a Saturated Soil In Situ. J. Hydrology 1:279-287.

Snell, A.W and J. van Schilfgaarde. 1964. Four-Well Method of Measuring Hydraulic Conductivity in Saturated Soils. Am. Soc. Agric. Eng. Trans. 7:83-87.

Sobsey, M.D. and P.A. Shields. 1987. Survival and Transport of Viruses in Soils: Model Studies. In: Human Viruses in Sediments, Sludges, and Soil, V.C. Rao and J.L. Melnick (eds.), CRC Press, Boca Raton, FL.

Sokolow, A.A. and T.G. Chapman (eds.). 1974. Methods for Water Balance Computations: An International Guide for Research and Practice. The Unesco Press, Paris.

Sophocleous, M. and C.A. Perry. 1984. Experimental Studies in Natural Groundwater Recharge Dynamics: Assessment of Recent Advances in Instrumentation. J. Hydrology 70:369-382.

Stallman, R.W. 1967. Flow in the Zone of Aeration. Advances in Hydroscience 4:151-195.

Stallman, R.W. 1971. Aquifer-Test Design, Observation and Data Analysis. U.S. Geological Survey Techniques of Water Resources Investigations, TWRI 3-B1, 26 pp.

Stewart, D.M. 1970. The Rock and Bong Techniques of Measuring Water Levels in Wells. Ground Water 8(6):14-18.

Stibbe, E., T.J. Thiel, and G.S. Taylor. 1970. Soil Hydraulic Conductivity Measurement by Field Monolith. Soil Sci. Soc. Am. Proc. 34:952-954.

Strack, O.D.L. 1989. Ground Water Mechanics. Prentice-Hall, Englewood Cliffs, NJ.

Streltsova, T.D. 1989. Well Testing in Heterogeneous Formations. John Wiley & Sons, New York, NY. [Focuses on testing in deep oil-bearing formations]

Struckmeier, W., G.B. Engelen, M.S. Galitzin, and R.K. Shakchnova. 1986. Methods of Representation of Water Data. In: Developments in the Analysis of Groundwater Flow Systems, G.B. Engelen and G.P. Jones (eds.), Int. Ass. of Hydrological Sciences Pub. No. 163, pp. 45-63.

Sutcliffe, Jr., H. and B.F. Joyner. 1966. Packer Testing in Water Wells Near Sarasota, Florida. Ground Water 4(2):23-27.

Sweet, H.R., G. Rosenthal, and D.F. Atwood. 1990. Water Level Monitoring--Achievable Accuracy and Precision. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 178-192.

Sweeting, M.M. 1973. Karst Landforms. Columbia University Press, New York, NY.

Symposium on Underground Water Tracing (SUWT). 1966. 1st SUWT (Graz, Austria). Published in: Steirisches Beitraege zur Hydrogeologie Jg. 1966/67.

Symposium on Underground Water Tracing (SUWT). 1970. 2nd SUWT (Freiburg/Br., West Germany). Published in: Steirisches Beitraege zur Hydrogeologie 22(1970):5-165, and Geologisches Jahrbuch, Reihe C. 2(1972):1-382.

Symposium on Underground Water Tracing (SUWT). 1976. 3rd SUWT (Ljubljana-Bled, Yugoslavia). Published by Ljubljana Institute for Karst Research: Volume 1 (1976), 213 pp., Volume 2 (1977) 182 pp. See also, Gospodaric and Habic (1976).

Symposium on Underground Water Tracing (SUWT). 1981. 4th SUWT (Bern, Switzerland). Published in: Steirisches Beitraege zur Hydrogeologie 32(1980):5-100; 33(1981):1-264; and Beitraege zur Geologie der Schweiz--Hydrologie 28 pt.1(1982):1-236; 28 pt.2(1982):1-213.

Symposium on Underground Water Tracing (SUWT). 1986. 5th SUWT (Athens, Greece). Published by Institute of Geology and Mineral Exploration, Athens.

Talsma, T. 1960. Measurement of Soil Anisotropy with Piezometers. J. Soil Science 11:159-171.

Taylor, T.A. and J.A. Dey. 1985. Bibliography of Borehole Geophysics as Applied to Ground-Water Hydrology. U.S. Geological Survey Circular 926.

Thomas, A.W. and A.W. Snell. 1967. Measuring Hydraulic Conductivity by the Four-Well Method. Am. Soc. Agric. Eng. Trans. 10:672-674.

Thompson, C.M. et al. 1989. Techniques to Develop Data for Hydrogeochemical Models. EPRI EN-6637. Electric Power Research Institute, Palo Alto, CA.

Thornhill, J.T. 1989. Accuracy of Depth to Water Measurements. EPA Superfund Ground Water Issue Paper. EPA/540/4-89/002 (NTIS PB90-149840). [Steel tape, electric probe, air line]

Thornhill, J.T. and B.G. Benefield. 1990. Injection-Well Mechanical Integrity. EPA/625/9-89/007, 123 pp. Available from CERI.*

Thornthwaite, C.W. and J.R. Mather. 1955. The Water Balance. Publications in Climatology, Vol. 8, No. 1, Laboratory of Climatology, Centerton, NJ, 104 pp.

Thrailkill, J., et al. 1983. Studies in Dye-Tracing Techniques and Karst Hydrogeology. Univ. of Kentucky, Water Resources Research Center Research Report No. 140.

Topp, G.C. and S. Sattlecker. 1983. A Rapid Measurement of Horizontal and Vertical Components of Saturated Hydraulic Conductivity. Can. Agric. Eng. 25:193-197.

Topp, G.C. and W.D. Zebchuk. 1986. The Effect of Auger Hole Diameter Changes on Hydraulic Conductivity Measurements. Can. Agric. Eng. 28:15-17.

Turner, S.F. and L.C. Halpenny. 1941. Ground-Water Inventory in the Upper Gila River Valley, New Mexico and Arizona. Trans. Am. Geophysical Union 22(III):738-744.

Ubell, K. 1965. Investigations into Ground-Water Balance in Experimental Areas. In: Representative and Experimental Areas (Budapest Symposium), IASH Publ. 66, pp. 388-398.

U.S. Environmental Protection Agency (EPA). 1981. Process Design Manual for Land Treatment of Municipal Wastewater. EPA/625/1-81/013. U.S. Army Corps of Engineers, U.S. Department of the Interior, and the U.S. Department of Agriculture also are authors of this report. [Auger hole method; replaces design manual with same title published in 1977 as EPA/625/1-77/008]

U.S. Environmental Protection Agency (EPA). 1986. Criteria for Identifying Areas of Vulnerable Hydrogeology Under RCRA: A RCRA Interpretive Guidance. EPA/530/SW-86/022 (Complete set: NTIS PB86-224946). (Individual Appendices [EPA/530/SW-86/022A to D]: Technical Methods for Evaluating Hydrogeologic Parameters [A, NTIS PB86-224961m 48 pp.]; Groundwater Flow Net/Flow Line Construction and Analysis [B, NTIS PB86-224979]; Technical Methods for Calculating Time of Travel in the Unsaturated Zone [C, NTIS PB86-224987]; Development of Vulnerability Criteria Based on Risk Assessments and Theoretical Modeling [D, NTIS PB86-224995]). [Appendix A covers single and multiple well tests]

U.S. Environmental Protection Agency (EPA). 1987. A Compendium of Superfund Field Operations Methods, Part 2. EPA/540/P-87/001 (OSWER Directive 9355.0-14), (NTIS PB88-181557), 644 pp. [Section 8.5.6.5 covers water level measurement: steel tape, electric probes, poppers/floats, air line, in situ piezometers, ultrasonic]

U.S. Environmental Protection Agency (EPA). 1991. Handbook Ground Water. Volume II: Methodology. EPA/625/6-90/16b, 141 pp. Available from CERI.* [Chapter 4 covers ground water tracers and chapter 5 covers aquifer test analysis]

U.S. Geological Survey. 1980. Ground Water. In: National Handbook of Recommended Methods for Water Data Acquisition, Office of Water Data Coordination, Reston, VA, Chapter 2. [Water level measurement, pp. 2-1 to 2-20: steel tape, electrical, air line, recording, flowing wells; aquifer tests, pp. 2-115 to 2-149]

van Bavel, C.H.M. and D. Kirkham. 1948. Field Measurement of Soil Permeability Using Auger Holes. Soil Sci. Soc. Am. Proc. 13:90-96.

van Beers, W.F.J. 1958. The Auger Hole Method. ILRI Bulletin No. 1. International Institute for Land Reclamation and Improvement, Wageningnen, The Netherlands, 23 pp. (Now available in 6th edition.)

van der Leeden, F. 1991. Geraghty & Miller's Groundwater Bibliography, 5th edition. Water Information Center, Plainview, New York, NY, 507 pp.

Vaughn, J.M. and E.F. Landry. 1983. Viruses in Soils and Groundwaters. In: Viral Pollution of the Environment, G. Berg (ed.), CRC Press, Boca Raton, FL, pp. 163-210.

Walton, W.C. 1962. Selected Analytical Methods for Well and Aquifer Evaluation. ISWS Bulletin No. 49, Illinois State Water Survey, Champaign, IL.

Walton, W.C. 1963. Microtime Measurements of Ground-Water Fluctuations. Ground Water 1(2):18-19. [Recording gage]

Walton, W.C. 1970. Ground Water Resources Evaluation. McGraw-Hill, New York, NY.

Walton, W.C. 1979. Progress in Analytical Groundwater Modeling. In: Contemporary Hydrogeology, W. Back and D.A. Stephenson (eds.), Elsevier, New York, NY.

Walton, W.C. 1987. Groundwater Pumping Tests: Design and Analysis. Lewis Publishers, Chelsea, MI.

Weeks, E.P. 1979. Barometric Fluctuations in Wells Tapping Deep Unconfined Aquifers. Water Resources Research 19:1167-1176.

Weir, Jr., J.E. and J.W. Nelson. 1976. Operation and Maintenance of a Deep-Well Water-Level Measurement Device, the "Iron Horse." U.S. Geological Survey Water Resource Investigations Report 76-27, 28 pp. [Electrical method]

Weiss-Jennemann, L.N. 1991. The Affect of Off-Site Influences on Water Levels at Hazardous Waste Sites. Ground Water Management 5:221-237 (5th NOAC).

Wenzel, L.K. 1942. Methods for Determining Permeability of Water-Bearing Materials with Special Reference to Discharging Well Methods. U.S. Geological Survey Water Supply Paper 887.

White, W.B. 1988. Geomorphology and Hydrology of Karst Terranes. Oxford University Press, New York, NY, 432 pp.

White, E.M. 1990. Estimates of Natural Soil-Drainage Volumes in South Dakota. Soil Science 149:235-238. [Thornthwaite water balance]

Widdowson, M.A., F.J. Molz, and J.G. Melville. 1989. Analysis of Multi-Level Slug Test Data to Determine Hydraulic Conductivity Distribution. In: Proc. 4th Int. Conf. on Solving Ground Water Problems with Models (Indianapolis, IN), National Water Well Association, Dublin, OH, pp. 699-714.

Widdowson, M.A., F.J. Molz, and J.G. Melville. 1990. An Analysis Technique for Multilevel and Partially Penetrating Slug Test Data. Ground Water 28:937-945.

Wiebenga, W.A., W.R. Ellis, B.W. Seatonberry, and J.T.G. Andrew. 1967. Radioisotopes as Ground-Water Tracers. J. Geophysical Research 72:4081-4091.

Williams, C.C. and S.W. Lohman. 1947. Methods Used in Estimating Groundwater Supply in the Wichita, Kansas, Well-Field Area. Trans. Am. Geophysical Union 28(1):120-131.

Wilson, Jr., J.F., E.D. Cobb, and F.A. Kilpatrick. 1986. Fluorometric Procedures for Dye Tracing (Revised). U.S. Geological Survey Techniques of Water Resources Investigations TWRI 3-A12, 41 pp. (Updates report with the same title by J.F. Wilson, Jr. published in 1968.)

Winograd, I.H. 1970. Noninstrumental Factors Affecting Measurement of State Water Levels in Deeply Buried Aquifers and Aquitards, Nevada Test Site. Ground Water 8(2):19-28

Wissa, A., R. Martin, and J. Garlanger. 1975. The Piezometer Probe. In: Proc. In Situ Measurement of Soil Properties, North Carolina State University, Raleigh, NC, 1:536-545.

Wolf, S.H., J.C. LaChance, and L.J. Wolf. 1991. Techniques for Monitoring Flux and Transport Between Ground Water and Surface Water Systems. Ground Water Management 5:179-192 (5th NOAC).

Wolff, R. and H. Olsen. 1968. Piezometer for Monitoring Rapidly Changing Pore Pressures in Saturated Clays. Water Resources Research 4:839-843.

Wood, W.W. and G.G. Ehrlich. 1978. Use of Baker's Yeast to Trace Microbial Movement in Ground Water. Ground Water 16(6):398-403.

Wynne, D.B. 1992. Specific Capacity and Slug Testing: An Overview and Empirical Comparison of Their Uses in Preliminary Estimating Hydraulic Conductivity. Ground Water Management 11:217-230 (6th NOAC).

Youngs, E.G. 1968. Shape Factors for Kirkham's Piezometer Method for Determining the Hydraulic Conductivity of Soil In Situ for Soils Overlying an Impermeable Floor or Infinitely Permeable Stratum. Soil Science 106:235-237.

Youngs, E.G. 1991. Hydraulic Conductivity of Saturated Soils. In: Soil Analysis: Physical Methods, K.A. Smith and C.E. Mullins (eds.), Marcel Dekker, New York, NY, pp. 161-207. [Laboratory, below water table (auger-hole method, piezometer, multiple-well methods, tile drains); above water table (borehole permeameter, air-entry permeameter, ring infiltrometers)]

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH 45268-0963 (513-569-7562).

SECTION 5

GROUND-WATER SAMPLING DEVICES AND INSTALLATIONS

A wide variety of devices and installations are available for the sampling of ground water. Sampling devices can be broadly classified as: (1) **Portable samplers,** which are used in permanently installed and screened monitoring wells, and (2) **portable in situ** samplers, which do not require monitoring wells.

Portable Samplers

Table 5-1 provides the following information on 20 portable sampling devices, which can be used to collect ground-water samples from wells: (1) Maximum depth, (2) minimum well diameter, (3) typical ranges of sampling rates, and (4) sections and tables in the handbook where additional information can be found. Portable well samplers are divided into three main groups: (1) **Positive displacement** samplers, (2) other sampling pumps, (3) **grab/depth specific** samplers.

Positive displacement pumps are placed below the static water level of the well and pump the sample to the surface. These pumps include: **Bladder** pumps (also called gas-operated squeeze pumps [Section 5.1.1]); **gear-drive** (Section 5.1.2); **helical rotor** pumps (Section 5.1.3); **gas-drive/displacement** pumps, where gas displaces water in the subsurface to force it to surface without mixing with the sample (Section 5.1.4); and **gas-drive piston** and **mechanical piston** pumps (Sections 5.1.5 and 5.1.6).

Other types of portable sampling pumps include: **Suction-lift** pumps (**peristaltic** pumps being the most common, but surface centrifugal and any other type of surface pump that operates using suction or a vacuum fall in this category [Section 5.2.1]); **submersible centrifugal** pumps (note that **surface** centrifugal pumps are classified as suction-lift pumps); **inertial-lift** pumps, which are simple mechanisms using foot-valves and inertia to bring water to the surface (Section 5.2.3); **gas-lift** pumps, where air or gas mixes with the water to bring ground water to the surface (Section 5.2.4); and **jet** or **venturi** pumps (Section 5.2.5). **Packer** pumps isolate a portion of the well using inflatable packers (Section 5.2.6).

Grab samplers include: **Bailers** (open and point-source [Section 5.3.1]); **mechanical** or **thief** depth specific samplers (Kemmerer, Coliwasa, stratified sample thief [Section 5.3.3]); and **pneumatic** depth specific samplers, which use vacuum or pressure to activate the sampling mechanism (syringe, Westbay [Section 5.3.2]).

Terminology, especially the use of the terms "air-lift" and "pneumatic" has not been used consistently in the literature, so it might be necessary to examine the basic operating principles of any specific sampling device in order to find the appropriate section that discusses its relative advantages and disadvantages. Sampling devices vary greatly in their suitability for sampling different chemical constituents. Table 5-2 summarizes the suitability of the 12 most commonly used sampling devices for 14 ground-water parameters. Bladder and helical rotor pumps are rated as suitable for the largest number of parameters, followed by point-source bailers. The **inertial** pump, which is not included in Table 5-2, is a quite new device, which probably would rate favorably for sampling many of the parameters on the table. Table 5-3 provides information on sampling devices available from 60 commercial sources.

Portable In Situ Samplers

A relatively new development in ground-water sampling technology has been the design of in situ sampling probes, which allow rapid collection of samples without the installation of permanent wells. The **Hydropunch®** (Section 5.5.1) and **BAT** systems (Section 5.5.2) both operate in conjunction with conventional cone penetrometer rigs. This category also includes a variety of driven probes (Section 5.5.3), which can be retrieved after sampling, or left in place as permanent sampling points. These devices often are best used during the preliminary site characterization stage, or where only a shallow water table is to be sampled. Portable in situ samplers can be valuable in deciding the best location of permanent monitoring wells. **Chemical sensors,** such as Eh and pH probes (Section 5.5.4), and ion-selective electrodes (Section 5.5.5) usually are used in boreholes.

Table 5-1 Summary Information on Ground-Water Sampling Devices (Information is for general guidance only)

Sampling Device	Max. Sample Depth	Min. Well Diameter	Sample Delivery Rate/Vol.[a]	Section	Tables
Portable Positive Displacement Samplers					
Bladder Pumps	1,000'	1.5"	0-3.0 gpm	5.1.1	5-2, 5-3
Gear Pumps	200'	2.0"	0-1.5 gpm	5.1.2	5-2, 5-3
Helical Rotor Pumps	160'	2.0"	0-1.5 gpm	5.1.3	5-2, 5-3
Gas-Drive/Displacement	300'	1.0"	0.1-10 gpm	5.1.4	5-2, 5-3
Gas-Drive Piston Pumps	900'	1.5"	0-1.5 gpm	5.1.5	5-2, 5-3
Mechanical Piston-Pumps	Variable	1.0 to 4.0"	Variable	5.1.6	
Other Portable Ground-Water Sampling Pumps					
Peristaltic Suction Lift	25'	0.5"	0.01-8 gpm	5.2.1	5-2, 5-3
Centrifugal Suction Lift	15'	1.0"	1.0-25 gpm	5.2.1	
Variable-Speed Submersible Centrifugal Pump	290'	1.75"	0.026-8 gpm	5.2.2	5-2, 5-3
Other Submersible Centrifugal Pumps	2,000'	4.0+"	5.0-60 gpm	5.2.2	5-2, 5-3
Inertial-Lift Pump	200'	1.5"	0-2.0 gpm	5.2.3	
Gas-Lift	Variable	1.0"	Variable	5.2.4	5-2
Jet (Venturi) Pump	200'	<1.0"	25-30 gpm	5.2.5	
Packer Pumps[b]	Variable	2.0"	Variable	5.2.6	
Portable Grab/Depth Specific Samplers					
Open Bailer[c]	No limit	0.5"	Variable	5.3.1	5-2, 5-3
Point-Source Bailer[c]	No limit	0.5"	Variable	5.3.1	5-2, 5-3
Syringe Sampler	No limit	1.5"	0.01-0.2 gal	5.3.2	5-2, 5-3
Westbay Sampler	No limit	1.5"	40 mL	5.3.2	
Kemmerer/Van Dorn	No limit	1.0"	Variable	5.3.3	
Coliwasa	5'	2.0"	Variable	5.3.3	
Stratified Sample Thief	No limit	1.5"	Variable	5.3.3	
Swabbing	No limit	6.0"	Variable	5.3.3	
Portable/Permanent In Situ Samplers/Sensors					
Hydropunch	150'[d]	NA	500-1,250 mL	5.5.1	
BAT Sampler	100'[d]	NA	150 mL	5.5.2	
Other CPT Samplers[e]	25'	NA	0.01-0.3 gpm	5.5.2	
Other In Situ Probes[e]	25'	NA	0.01-0.3 gpm	5.5.3	
Eh, pH Probes	No limit	1.0"	NA	5.5.4	
Ion-Selective Electrodes	No limit	1.0"	NA	5.5.5	
Fiber Optic Sensors	No limit	±2.0"	NA	5.5.6	
Other Chemical Sensors	No limit	2.0-6.0"	NA	10.6.5	

Boldface = most commonly used devices.

[a]Sample delivery rates and volumes are averages based on typical field conditions. Actual rates are a function of diameter of monitoring well installation, size and capacity of sampling device, hydrogeologic conditions, and depth to sampling point.
[b]Depends on type of pump used (submersible, gas lift, suction)--see appropriate device for ratings.
[c]Not recommended for use with sensitive chemical constituents (see text discussion).
[d]Unlimited depth if hole is bored to desired depth before using sampler. Otherwise, actual depth of penetration is highly dependent on type of soil material.
[e]Depth and pumping rate depends on type of suction-lift device used. Values shown are for peristaltic pump.

Table 5-2 Suitability of Major Ground-Water Sampling Devices for Different Ground-Water Parameters

	Inorganic							Organic				Other		
Sampling Device	EC	pH	Re-dox	Major Ions	Tr. Met.	NO3 F	Diss. Gases	Non Vol.	Vol.	TOC	TOX	Ra-dium	Alpha Beta	Coli-form
<u>Portable Grab/Depth Specific Samplers</u>														
Open Bailer	x			x	x	x		x				x		x
Point-Source Bailer	x	x	x	x	x	x		x	x	x	x	x		x
Syringe Sampler	x	x	x	x	x	x		x				x	x	x
<u>Portable Positive Displacement (Submersible) Pumps</u>														
Bladder	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Centrifugal	x			x		x						x	x	
Helical Rotor	x	x	x	x	x	x	x	x	x	x	x	x	x	
Gas-Drive Piston	x			x	x	x		x				x	x	
Gear-Drive									x					
<u>Other Portable Samplers</u>														
Peristaltic	x			x		x		x				x		x
Gas-Drive/Displacement	x			x		x		x				x		
Gas-Lift														
<u>Portable In Situ Samplers</u>														
Pneumatic	x	x	x	x	x	x		x				x	x	x

TOC = Total Organic Carbon.
TOX = Total Organic Halogen.

Source: Adapted from Pohlmann and Hess (1988)

Table 5-3 Characteristics of Some Commercially Available Ground-Water Sampling Devices

MANUFACTURER	TYPE	MTL	WELL SAMPLERS: WELL DIAM. (IN)	WELL SAMPLERS: VOL. (CC)	WELL SAMPLERS: BODY LENGTH (IN)	LIFT (FT)	POWER SOURCE	PORTABILITY	GROUND CONDUCT.: DEPTH (FT)	GROUND CONDUCT.: TEMP RANGE (°F)	LEVEL INSTRUMENTS: DEPTH (FT)	LEVEL INSTRUMENTS: POWER SOURCE	LEVEL INSTRUMENTS: REC.	LEVEL INSTRUMENTS: SENSOR DIAM (IN)
AMERICAN SIGMA 716/798-5580, 800/635-4567	BA,SL AL,GS	AV,SS TE	2+	250	14	400	CG,CA	PO,FX			300	BT	Y	⅝
AMETEK, P M T 215/355-6000											690	DC		1¼
ARTS MANUFACTURING & SUPPLY 208/226-2017, 800/635-7330	X													
ATLANTIC SCREEN & MANUFACTURING 302/684-3197	BA,SU AL	AB,PV,SS TE,PE	1.315-4.50	1.49-84.48	12-120	300	AC,DC CA	PO,FX			2000	BT	&	.59-1.5
BENNETT SAMPLE PUMPS 806/352-0264	GP	SS	1.5+			1000	CA,CG	PO,FX						
BRAINARD KILMAN 404/469-2720, 800/241-9468	BA,GR SL	AY,PV SS	2-4		2,3 5	100	MA,CA	PO,FX			500	BT	Y	
CAMBRIDGE SCIENTIFIC 410/228-5111, 800/638-9566									X					
CAPITAL CONTROLS 215/822-2901, 800/523-2553									X					
DIVERSIFIED REMEDIATION CONTROLS 612/424-2421, 800/644-1372	GR													
DIVERSIFIED WELL PRODUCTS 714/637-2383, 800/637-9355	BA,AL	PV,SS	2		12	300	CA	PO						
DREXELBROOK ENGINEERING 215/674-1234											3000	AC,DC		⅛
DYNAMIC PROCESS INDUSTRIES 214/556-0010	GR													
E L E INTERNATIONAL/SOILTEST PRODUCTS 708/295-9400, 800/323-1242											X			
EJECTOR SYSTEMS 708/543-2214, 800/645-5325	GR										X			
ENVIRO PRODUCTS 517/887-1222, 800/368-4764	BA,SU	PE,AY,PV SS,TE	1+		12-36	250	AC	PO						
ENVIRONMENTAL INSTRUMENTS 510/686-4474, 800/648-9355	BA, SL SU,AL	AY,PV SS,TE	2+		36	280	CG	PO,FX	150	212	200	BT		½
ENVIRONMENTAL MONITORING 206/486-8687, 800/468-3106											150	AC	Y	2½-12
ENVIRONMENTAL SYSTEMS ENGINEERING 215/538-7000	GR													
FULZ PUMPS 717/248-2300	SU	PE,SS,TE	2-3			150	DC	PO,FX						
GENERAL OCEANICS/ENVIRONMENTAL 305/621-2882	X								X		X			
GEOTECH ENVIRONMENTAL EQUIPMENT 303/433-7101, 800/833-7958	BA,SL SU,AL	PP,SR,SS PV,TE VY,PE				400	CG,AC DC,BT CA	PO,FX	330	23-122	3000	BT,DC	Y	⅜-⅝
GEOTECHNICAL SERVICES 714/832-5610	X								X		X			
GODWIN PUMPS 609/467-3636	GR													
GRUNDFOS PUMPS 209/292-8000	SU													
HAZCO SERVICES 513/293-2700, 800/332-0435	BA													
HYDROLAB 512/255-8841	X								600	23-122	33	BT	PO	3½
IN-SITU 307/742-8213, 800/446-7488									920		X	BT	PO	.69-1.0
INDUSTRIAL & CHEMICAL MEASUREMENTS 503/648-2014, 800/262-3668									X					
INSTRUMENTATION NORTHWEST 206/885-3729, 800/776-9355	SU	SS,TE	2+			500	DC,CA	PO,FX			231	BT	Y	0.84
INVENTRON 313/473-9250											400	AC,BT DC	Y	2-5

MANUFACTURER	TYPE	MTL	WELL SAMPLERS						GROUND CONDUCT.		LEVEL INSTRUMENTS			
			WELL DIAM. (IN)	VOL. (CC)	BODY LENGTH (IN)	LIFT (FT)	POWER SOURCE	PORTABILITY	DEPTH (FT)	TEMP RANGE (°F)	DEPTH (FT)	POWER SOURCE	REC.	SENSOR DIAM (IN)
ISCO ENVIRONMENTAL 402/474-2233, 800/228-4373	BA,SL GS	TE,PE SR,SS	1½+	1050	12, 36	250	BT,CA CG	PO,FX						
JENSEN INERT PRODUCTS 305/871-8339, 800/446-3781	BA	TE	2,4	350 700 1050	13 23 35									
KECK INSTRUMENTS 517/655-5616, 800/542-5681	BA,SU	PV,TE SS,VI	1 2/3	1065	36	150	DC,BT	PO			200	BT,DC		½
KELLER PSI 619/697-6066, 800/328-3665											X			
LEUPOLD & STEVENS 503/646-9171, 800/452-5272											1500	BT	Y	1.3
M M C INTERNATIONAL 516/239-7339, 800/645-7339	BA	SS	1⅝								1651	BT		1⅜
MARSCHALK 919/781-8788, 800/722-8200	GS	SS	1.5+			300	CA	PO,FX						
MARTEK INSTRUMENTS 714/250-4738	X								1000	212	1000	BT	Y	1¾
METRITAPE 508/369-7500											X			
NATIONAL ENVIRONMENTAL SYSTEMS 508/761-6611	GR													
NEPCCO EQUIPMENT 904/867-7482, 800/277-3279	BA,GR													
NORTON PERFORMANCE PLASTICS 201/696-4700, 800/526-7844	BA	TE,PP	1,2 3,4	60-1050	36									
OMNIDATA INTERNATIONAL 801/753-7760									100	23-178	300	BT		.84
ONTEK 310/510-0434, 800/356-5872	BA													
PETRO VEND 708/485-4200											12	AC	Y	.4
PROTEC 918/493-6101	GR													
Q E D GROUNDWATER SPECIALISTS 313/995-2547, 800/624-2026	GS,BA GR	AY,PV SS,TE	1¼+	3.5	30	1000	DC,CA CG	PO	X		1200	BT		½
REMEDIAL SYSTEMS 508/543-1512											500	AC,DC	Y	1½
SEEPEX 513/233-9904, 800/695-3659														
SOIL MOISTURE EQUIPMENT 805/964-3525	X													
SOLINST CANADA 416/873-2255	BA,AL GS	SS,TE	½+	35-240	12-60	2000	CA,CG	PO,FX			2500	BT	Y	½
SOLOMAT 203/849-3111, 800/765-6628									X	32-122	340	BT		
TELOG 716/359-1110											500	BT,DC	Y	≤1
TIMCO 608/643-8534, 800/236-8534	AL,GS BA,GR	AY,PV SS,TE	0.84-4.5		12-72		BT,CA CG	PO,FX						
UNIDATA AMERICA 503/697-3570											150	BT	Y	
VEEDER ROOT 203/651-2700											11	AC	Y	
XITECH INSTRUMENTS 707/425-9283	GR													
Y S I 513/767-7241, 800/765-4974									150	23-122	150	BT		1

KEY FOR GROUNDWATER SAMPLING

AB ABS
AC AC
AL AIR LIFT SAMPLERS
AY ACRYLIC
BA BAILERS
BT BATTERY
CA COMPRESSED AIR
CG COMPRESSED GAS
DC DC
FX FIXED
GP GAS-OPERATED PISTON PUMPS
GR GROUNDWATER RECOVERY PUMPING SYSTEMS
GS GAS-OPERATED SQUEEZE PUMPS
MA MANUAL
PE POLYETHYLENE
PO PORTABLE
PP POLYPROPYLENE
PV PVC
SL SUCTION LIFT PUMPS
SR SILICONE RUBBER
SS STAINLESS STEEL
SU SUBMERSIBLE PUMPS
TE TEFLON
VI VITON
VY VINYL
X PRODUCT PRODUCED

Source: April 1993 issue of Pollution Equipment News

Use of **fiber optic** (Section 5.5.6), electrochemical piezoelectric,and other chemical sensors (Section 10.6.5) for subsurface chemical characterization is the subject of considerable research, and might become more widespread for routine investigations with further refinements in instrumentation. Strictly speaking, the term **in situ** (from Latin, meaning in its original position) only should be applied to chemical sensors that measure ground-water quality in place without bringing the sample to the surface. In common usage, however, the term is applied to methods that allow collection of samples without the installation of a permanent monitoring well, or permanent installations that do not require use of portable sampling equipment.

Sampling Installations

Permanent well installations for portable samplers include: (1) **Single-riser/limited interval** wells, in which only a small section of an aquifer is sampled (Section 5.4.1); (2) **single-riser/long screen** wells, in which the entire thickness of the aquifer is sampled (Section 5.4.2); (3) **nested wells** in a **single** borehole, in which different portions of the aquifers are sampled from isolated screen intervals installed in one hole (Section 5.4.3); and (4) **nested wells in separate** boreholes (often called **clusters**), in which single-riser/limited interval wells are installed in a cluster to different levels in an aquifer (Section 5.4.4). Permanent in situ installations include: (1) **Capsule multilevel** installations (Section 5.6.1), and (2) **multiple-port casings** (Section 5.6.2).

This section also covers **destructive** ground-water sampling methods (Section 5.7). An overview of general aspects of ground-water sampling procedures is contained in Appendix B.

5. GROUND-WATER SAMPLING METHODS

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.1 Bladder Pumps

Other Names Used to Describe Method: Gas-operated bladder pump, gas-squeeze pump, diaphragm pump, Middelburg-type bladder pump, gas-operated squeeze pump.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: A flexible bladder within the device has check valves at each end (Figure 5.1.1a). The pump mechanism is placed in the well. Gas from ground surface is cycled between the bladder and sampler wall, forcing the sample to enter the bladder and then be driven up the discharge line. Figure 5.1.1b shows an operational bladder pump unit.

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using bladder pumps. **Advantages:** (1) Most bladder pumps have been designed specifically to sample for low levels of contaminants, so most are, or can be, made of inert or nearly inert materials; (2) the driving gas does not contact the sample directly, minimizing problems of aeration or gas stripping; (3) are portable, although accessory equipment can be cumbersome; (4) relatively high pumping rate in comparison to other sampling devices allows well purging and large sample volumes to be collected; (5) pumping rate of most models can be controlled easily to allow for both well purging at high flow rates and collection of volatile samples at low flow rates; (6) most models are capable of pumping lifts in excess of 200 feet; (7) are easy to disassemble for cleaning and repair; (8) most models are designed for use in small-diameter wells (1.5 to 2 inches), while large diameter pumps (3.25 inch outer diameter) are available for larger diameter wells; (9) are relatively durable, allowing dedication of pumps to individual wells to eliminate cross contamination and speed sample collection; and (10) in-line filtration is possible. **Disadvantages:** (1) Deep sampling requires large volumes of gas and longer cycles, increasing operating time and expense, and reducing portability; (2) check valves in some pump models can fail in water with high suspended solids; (3) relatively expensive; (4) minimum rates of discharge for some models can be higher than ideal for sampling volatile compounds; (5) require large but portable power source (compressed gas); and (6) intermittent but adjustable flow.

Frequency of Use: Second most common sampling device, and the most widely used device when samplers are dedicated to a single well. One of the best devices for sampling both trace inorganics and volatile organics.

Standard Methods/Guidelines: --

Sources for Additional Information: Gillham et al. (1983), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985), Scalf et al. (1981). See also, Table 5-4.

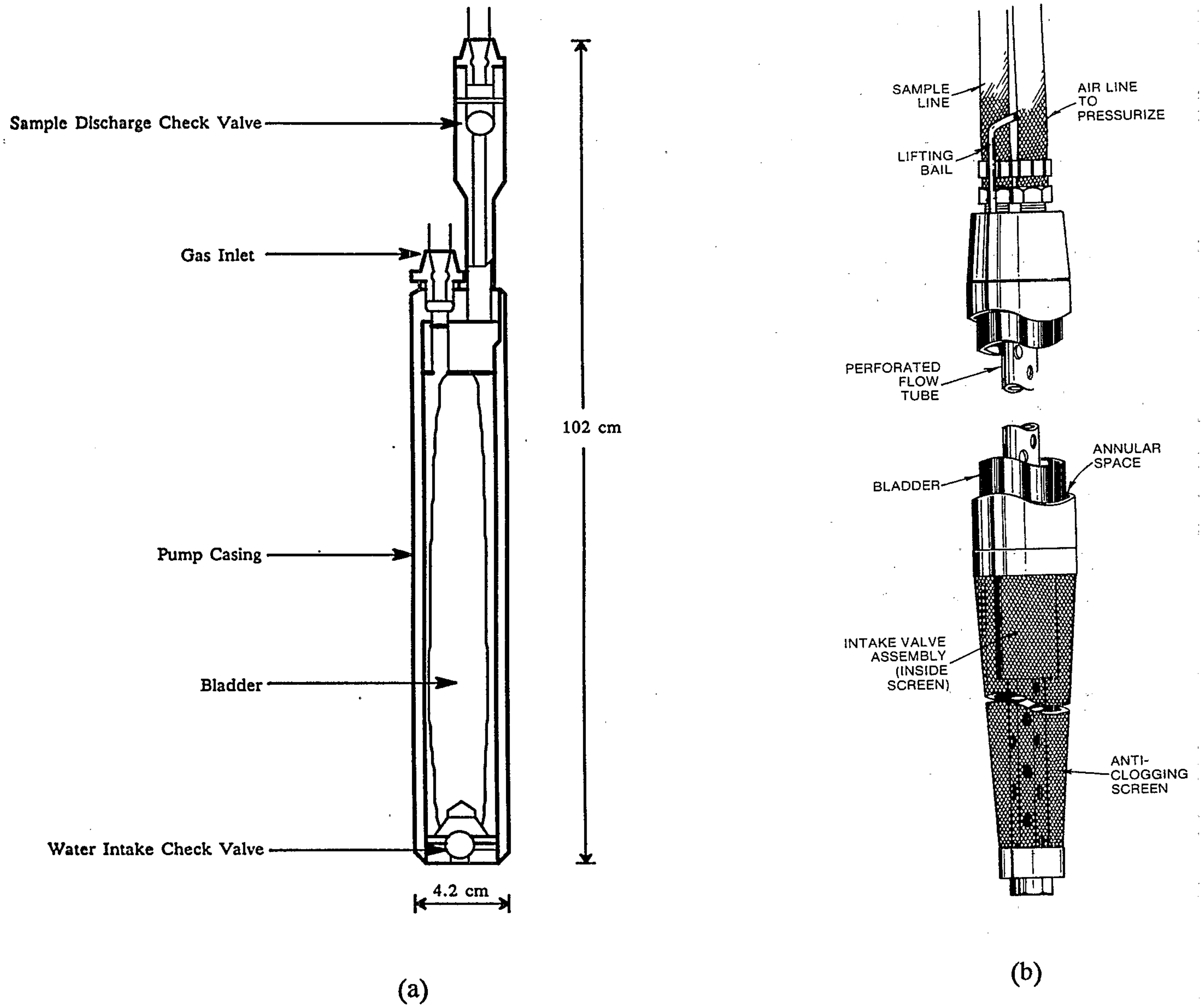


Figure 5.1.1 Bladder pump: (a) Schematic (Pohlmann et al., 1990); (b) Operational unit (Morrison, 1983, by permission).

5. GROUND-WATER SAMPLING METHODS

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.2 Gear Pump

Other Names Used to Describe Method: Gear-drive electric submersible pump.

Uses at Contaminated Sites: Well development and purging; collecting ground-water samples for non-sensitive parameters.

Method Description: Electric motor rotates a set of gears, which drives the sample up the discharge line (Figure 5.1.2). Pumps designed for ground-water sampling use Teflon gears.

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using a gear-drive pump. **Advantages:** (1) Constructed of inert or nearly inert materials, making it suitable for sampling organics when optionally available Teflon discharge line is used; (2) highly portable and totally self-contained, except when auxiliary power sources are used; (3) able to provide a continuous sample over extended periods of time; (4) models available for both 2-inch and 3-inch or larger wells; (5) high pumping rates are possible, making it feasible to use the pump for both well purging and sampling; (6) reasonably high pumping rates can be achieved to depths of 150 feet, and depth range can be extended through the use of an auxiliary power source; (7) easy to operate, clean, and maintain in the field, and replacement parts are inexpensive; and (8) in comparison to other pumps offering the same performance, these pumps are inexpensive to purchase and operate. **Disadvantages:** (1) No control over flow rates, so it is not possible to adjust from a high pumping rate for well purging to a lower rate required for sampling volatiles; (2) sampling of wells with high levels of suspended solids might require frequent replacement of gears; and (3) potential for pressure changes (cavitation) exists at the drive mechanism (this has not be adequately evaluated).

Frequency of Use: Units designed for ground-water sampling are relatively new (6 to 7 years old). Pohlmann and Hess (1988) rate this pump as suitable for volatiles sampling (Figure 5-2), but their use has not be widely reported in the ground-water literature.

Standard Methods/Guidelines: --

Sources for Additional Information: Imbrigiotta et al. (1988), Nielsen and Yeates (1985), Pohlmann and Hess (1988).

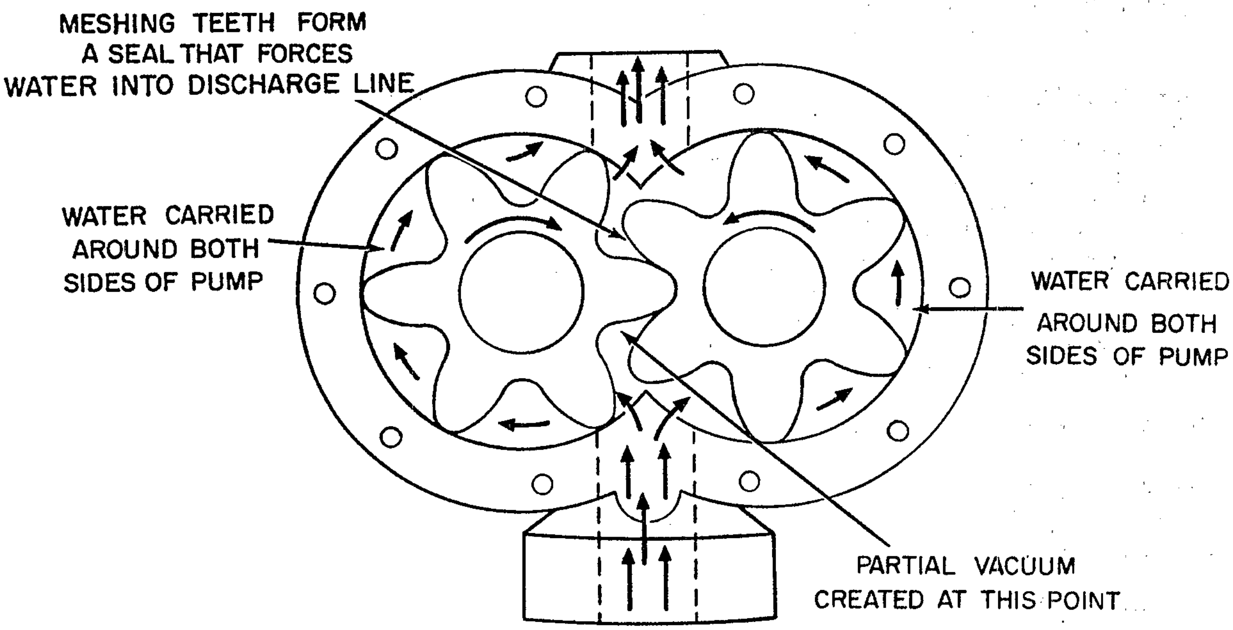


Figure 5.1.2 Rotary gear pump (U.S. Army, 1981).

5. GROUND-WATER SAMPLING METHODS

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.3 Helical-Rotor Pump

Other Names Used to Describe Method: Helical rotor electric submersible pump, helical submersible electric pump (HSEP), progressive cavity pump.

Uses at Contaminated Sites: Well development and purging; collecting ground-water samples for non-sensitive parameters.

Method Description: Water sample is forced up discharge line by electrically driven rotor-stator assembly that moves water through a progression of cavities to the discharge line (Figure 5.1.3).

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using a helical rotor pump. **Advantages:** (1) Portable and relatively easy to transport in the field to remote locations; (2) well-suited for use in 2-inch wells; (3) relatively high pumping rates are possible with currently available units, allowing well purging, while low pumping rates are possible for sampling; (4) Keck pump has been specifically designed for monitoring ground-water contamination, and so is constructed of inert or nearly inert materials (stainless steel and Teflon); and (5) no priming necessary. **Disadvantages:** (1) Currently available pump unit is limited to 160 feet of pumping lift; (2) high pumping rates with this pump lead to creation of turbulence, which can alter sample chemistry; (3) thorough cleaning and repair in the field can be difficult because the pump is moderately difficult to dissemble; (4) water with high suspended solids content can cause aeration problems; (5) the currently available model is expensive in comparison to other devices offering comparable performance; (6) the pump must be cycled on and off approximately every 20 minutes to avoid overheating the motor; (7) the flow rate cannot be controlled, so the pump might not be suitable to taking samples for analysis of chemically sensitive parameters; and (8) sample might be contaminated by coming in contact with the pumping mechanism.

Frequency of Use: Large-diameter progressive cavity pumps are used in the petroleum industry and in water wells; small-diameter helical rotor pumps designed for ground-water sampling are becoming more commonly used.

Standard Methods/Guidelines: --

Sources for Additional Information: Koopman (1979), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985). See also, Table 5-4.

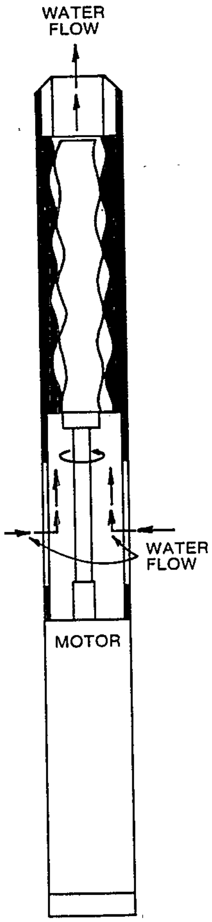


Figure 5.1.3 Submersible helical rotor pump (Morrison, 1983, by permission).

5. GROUND-WATER SAMPLING METHODS

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.4 Gas-Drive (Displacement) Pumps.*

Other Names Used to Describe Method: Pressure displacement pumps, single/double/triple tube gas-drive sampler; gas-drive continuous flow pump, nitrogen-powered continuous-delivery pump, pneumatic sampler (not to be confused with depth-specific pneumatic samplers in Section 5.3.2).

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: Positive gas pressure applied to the surface of water within the device's sample chamber forces the sample to surface through an open tube. Most available devices function on a filling-emptying two-step cycle, in which no water is obtained at the surface during the filling step (Figure 5.1.4a). A continuous-flow device consisting of two separate, in-line gas-drive devices has been developed that eliminates this problem (Figure 5.1.4b). Materials can include polyethylene, brass, nylon, aluminum oxide, PVC, and polypropylene. A simpler, **annulus-type** sampling method involves pressurizing the annulus space to drive water up a tube in which the intake is placed below the maximum depression of the water level in the well (Figure 5.1.4c).

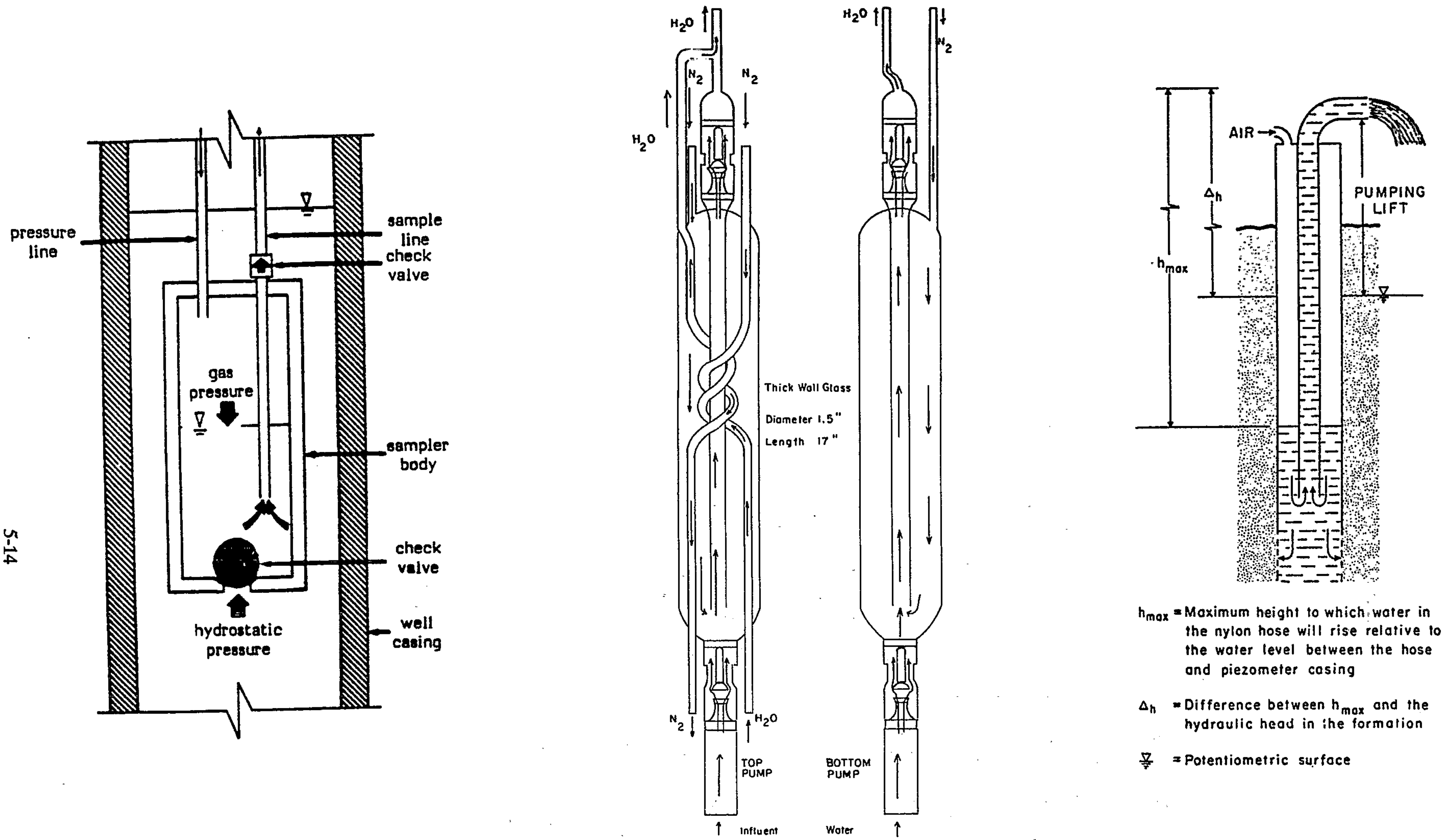
Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using gas drive devices. **Advantages:** (1) Can be used in wells as small as 1.25 inches; (2) inexpensive, allowing dedication to individual wells to eliminate possible cross-contamination; (3) highly portable for most sampling applications; (4) discrete depth sampling possible; (5) deliver sample at a controlled, nearly continuous flow rate; (6) use of an inert gas, such as nitrogen, minimizes sample oxidation and other chemical alteration; (7) can be installed permanently in boreholes without casing; (8) permanent and multiple installations in a single borehole are possible (see Section 5.6.2), avoiding possible cross-contamination; (9) can be constructed entirely of inert materials; (10) depth of sampling limited only by the burst strength of the materials from which the device and tubing are made (typically 300 feet); (11) good potential for preserving sample integrity because there is minimal contact between the driving gas and the sample, and because the sample is driven by a positive pressure gradient; and (12) triple-tube sampler is well-suited for installations of very narrow diameter (as low as 3/8 of an inch). **Disadvantages:** (1) Might not be appropriate for chemically sensitive parameters if air or oxygen is used as the driving gas due to oxidation (causing possible precipitation of meals), and gas stripping of volatiles or carbon dioxide (with consequent shift in pH); (2) deep sampling locations require an air compressor or large compressed-air tanks, reducing portability; (3) application of excessive pressure can rupture the gas entry or discharge tubing; (4) permanent installations in boreholes without casing are difficult or impossible to retrieve for repair and proper installation and operation might not be assured; (5) not very efficient for purging wells larger than about 1-inch diameter; (6) can be difficult to clean between sampling sessions; (7) driving gas comes in contact with the water, which contaminates the beginning and the end of the slug of water obtained as the surface; and (8) pump intermittently and at a variable flow-rate.

Frequency of Use: Most commonly used for purging rather than sampling.

Standard Methods/Guidelines: **Purging:** Ford et al. (1984).

Sources for Additional Information: Gillham et al. (1983), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985). See also, Table 5-4.

*There is some inconsistency in the published literature in the use of the term "gas" or "air" lift, which has been applied to two distinctly different types of samplers. In this handbook the term **gas lift** (Section 5.2.4) refers to methods where gas mixes with water to provide the buoyant force to bring it to the surface, and **gas drive** (this section) refers to methods in which gas is used to push water up a tube without the gas becoming mixed with the water that is brought to the surface. Morrison (1983) and Scalf et al. (1981) have applied the term "lift" to samplers that are classified as gas-drive samplers in this guide.



(a) (b) (c)

Figure 5.1.4 Gas-drive (displacement) pumps: (a) Operating principles of two-step cycle pump (Unwin, 1982); (b) Continuous flow pump (Scalf et al., 1981); (c) Annulus-type pump (Gillham et al., 1983, after Trescott and Pinder, 1970, by permission).

5. GROUND-WATER SAMPLING METHODS

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.5 Gas-Drive Piston Pumps

Other Names Used to Describe Method: Gas-drive piston pump, gas-operated double-acting piston pump, rod pump, stationary barrel piston pump, air activated piston pump (AAPP).

Uses at Contaminated Sites: Collecting ground-water samples.

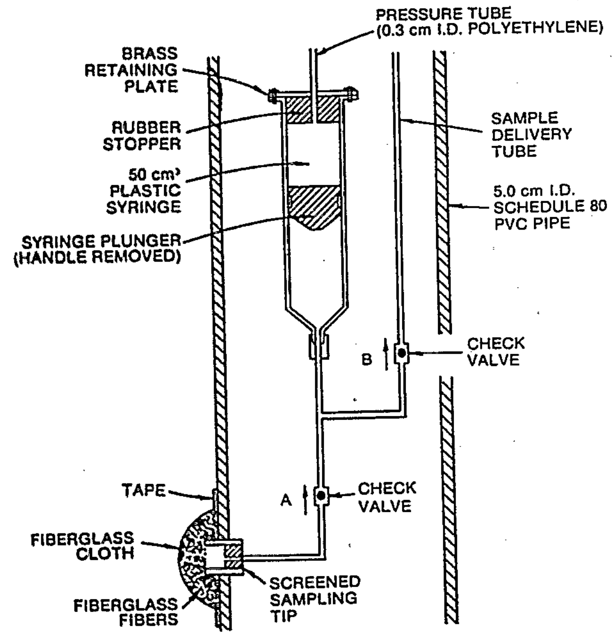
Method Description: Piston pumps consist of one or more plungers (pistons) moving inside a submerged cylinder or barrel. When the piston moves up and down, one-way check valves direct water moved by the pistons to the surface. **Gas-drive** pumps use gas pressure controlled from the surface to drive the piston up and down. Figure 5.1.5a illustrates an in-situ single-piston syringe pump for a multi-level sampling installation. Figure 5.1.5b shows a schematic of a dual-piston pump. Section 5.1.6 discusses mechanically-driven piston pumps.

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using a gas-drive piston pump. **Advantages:** (1) Sample is isolated from the driving gas, avoiding aeration; (2) provide a continuous sample over extended periods of time; (3) relatively easy to operate and easy to disassemble for cleaning and maintenance, although some problems, such as with the pump motor or valving mechanism, cannot usually be solved in the field; (4) models available for small diameter wells (1.25 to 2 inches or greater); (5) pump uses gas economically; (6) pumping lifts of more than 500 feet can be overcome; (7) double-acting pumps have continuous adjustable flow rate by varying the driving gas pressure on the pump; (8) can be made of inert or nearly inert materials, although most commercially available pumps are not; and (9) moderately high pumping rates at great depths allow collection of large volumes of sample in a relatively short time. **Disadvantages:** (1) Relatively expensive in comparison to other sampling devices; (2) not highly portable, must be mounted on a vehicle; (3) unless pump intake is filtered, particulate matter can damage the pump's intricate valving mechanism; (4) the pump's valving mechanism might cause a series of pressure drops in the sample resulting in sample degassing and pH changes; (5) fixed-length tubing bundles can be inconvenient for shallow, low-yield monitoring wells; (6) the tubing bundles can be difficult to clean adequately to avoid cross-contamination; and (7) single acting pumps have intermittent flow.

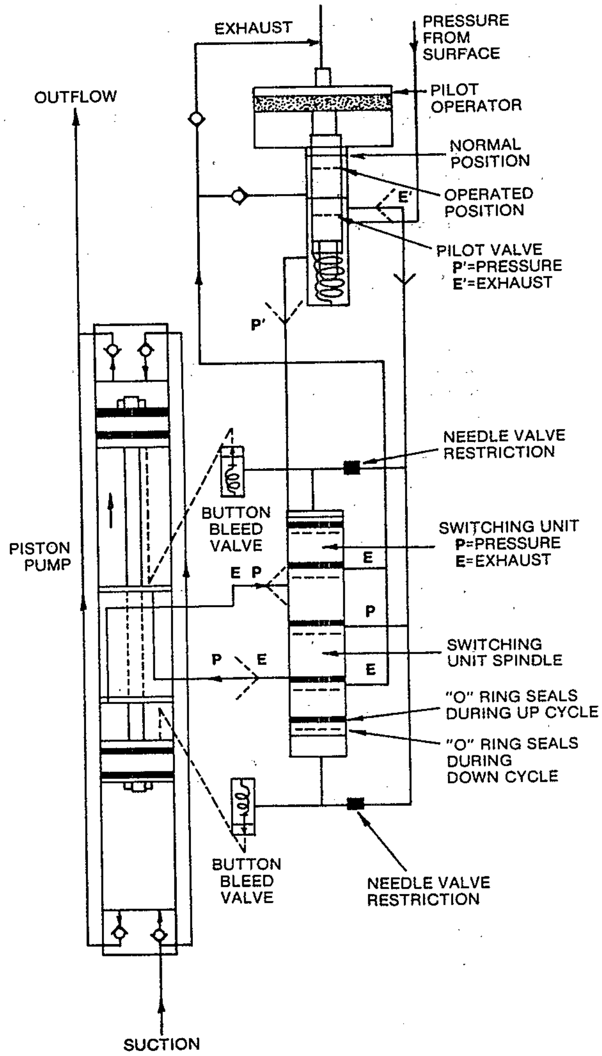
Frequency of Use: Gas-drive piston pumps are designed specifically for ground-water sampling; moderately common.

Standard Methods/Guidelines: **Sampling:** Ford et al. (1984).

Sources for Additional Information: Gillham et al. (1983), Koopman (1979), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985), Scalf et al. (1981). See also, Table 5-4.



(a)



(b)

Figure 5.1.5 Gas-drive piston pumps: (a) In situ single-piston syringe pump (Morrison, 1983, after Gillham and Johnson, 1981, by permission); (b) Schematic of dual-piston pump (Morrison, 1983, after Signor, 1978, by permission).

5.1 PORTABLE POSITIVE DISPLACEMENT GROUND-WATER SAMPLERS

5.1.6 Mechanical Piston Pumps

Other Names Used to Describe Method: Rod pump, stationary barrel piston pump, sucker rod pump, piston pump.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: Piston pumps consist of one or more plungers (pistons) moving inside a submerged cylinder or barrel. When the piston moves up and down, one-way check valves direct water moved by the pistons to the surface (Figure 5.1.6). **Rod** pumps use steel or wooden rods that are attached to the piston and run to the surface, where they are connected to a mechanical driving mechanism, which can be powered by hand, electric motor, gasoline engine, or windmill. Figure 5.1.6 illustrates wind-mill and hand pump assemblies for moving the rod up and down.

Method Selection Considerations: **Rod-Pumps:** Generally not suited for ground-water sampling because: (1) Require large power sources and are permanently mounted; (2) are difficult to clean; (3) require large diameter wells (4 inches or greater); and (4) contact with pumping mechanism can cause contamination. Unwin (1982) has noted the development of a prototype rod pump small enough to fit down a 1-inch casing.

Frequency of Use: Mechanical piston pumps commonly are used for water and petroleum production; use for ground-water is fairly common.

Standard Methods/Guidelines: --

Sources for Additional Information: Gillham et al. (1983), Unwin (1982), U.S. Army (1981).

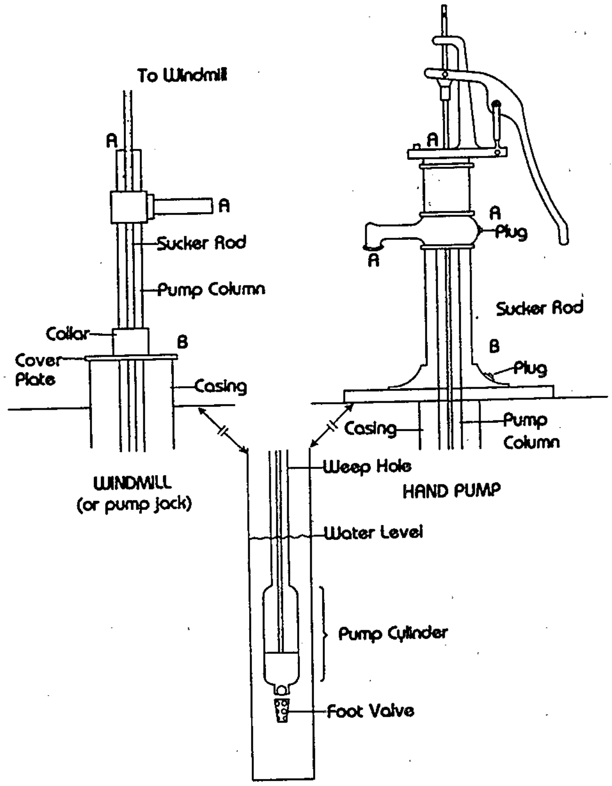


Figure 5.1.6 Windmill and hand-operated rod pumps (U.S. Geological Survey, 1980).

5. GROUND-WATER SAMPLING METHODS

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.1 Suction-Lift Pumps

Other Names Used to Describe Method: Peristaltic suction/tubing pump, direct line vacuum pump, surface centrifugal pump, manual diaphragm-type pump, pitcher pump, surface adsorption/thermal desorption (ATD) sampler, subsurface ATD sampler.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: A large variety of surface pumps that apply a vacuum to the well casing, or to tubing running from the pump to the desired sampling depth, can be used for ground-water sampling. The most commonly used is the **peristaltic** pump, which is a self priming manual or power operated vacuum pump (Figure 5.2.1a). Other types of manual vacuum or diaphragm-type pumps or portable gasoline-powered or electric surface centrifugal pumps can be attached to tubing for sample retrieval. Another device that can be used as a permanent sampling installation for ground-water sampling where sensitive parameters are not involved is the conventional manual **pitcher pump**, which is commonly used on shallow water supply wells (Figure 5.2.1b). Ground-water samples containing volatile organic compounds require use of sample tubing and containers that can be used for gas headspace/vacuum extraction (Section 10.2.1) or purge and trap extraction (Section 10.2.2), or adsorption/thermal desorption (ADT) samplers (Section 10.2.4). ADT samplers can be placed at the surface (Figure 5.2.1c) or in the well (Figure 5.2.1d).

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using a peristaltic pump. **Advantages:** (1) Most suction lift pumps are easily controlled to provide a continuous and variable flow rate; (2) simple, convenient to operate, highly portable, and readily available; (3) most are relatively inexpensive to purchase and operate; (4) sample does not come in contact with the pump, so only the tubing must be cleaned (peristaltic pump only); (5) can be used in wells of any diameter and can be used in nonplumb wells; (6) easily cleaned; (7) components can be made of inert materials; and (8) in-line filtration is possible. **Disadvantages:** (1) Sampling is limited to wells where the water level is less than 25 feet below the surface; (2) the drop in pressure caused by the suction causes degassing of the sample and loss of volatiles, especially if the sample is taken from an in-line vacuum flask; (3) the gasoline motor power source used for most centrifugal pumps creates potential for hydrocarbon contamination of samples; (4) pumping with centrifugal pumps causes aeration and turbulence, which might disturb sample integrity; (5) centrifugal pumps might have to be primed, providing a possible source of sample contamination; (6) low pumping rates of peristaltic pumps make it difficult to purge the well in a reasonable amount of time; (7) can cause contamination if sample is allowed to touch pump components; and (8) where the sample comes in contact with the pump mechanism or tubing, the choice of appropriate materials for impellers (centrifugal pump) or flexible pump-head tubing (peristaltic pump) might be restrictive.

Frequency of Use: Surface centrifugal pump is commonly used for well development. Peristaltic pumps are commonly used for shallow ground-water sampling.

Standard Methods/Guidelines: **Peristaltic** (purging and sampling): Ford et al. (1984).

Sources for Additional Information: Gillham et al. (1983), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985), Scalf et al. (1981), Unwin (1982). See also, Table 5-4.

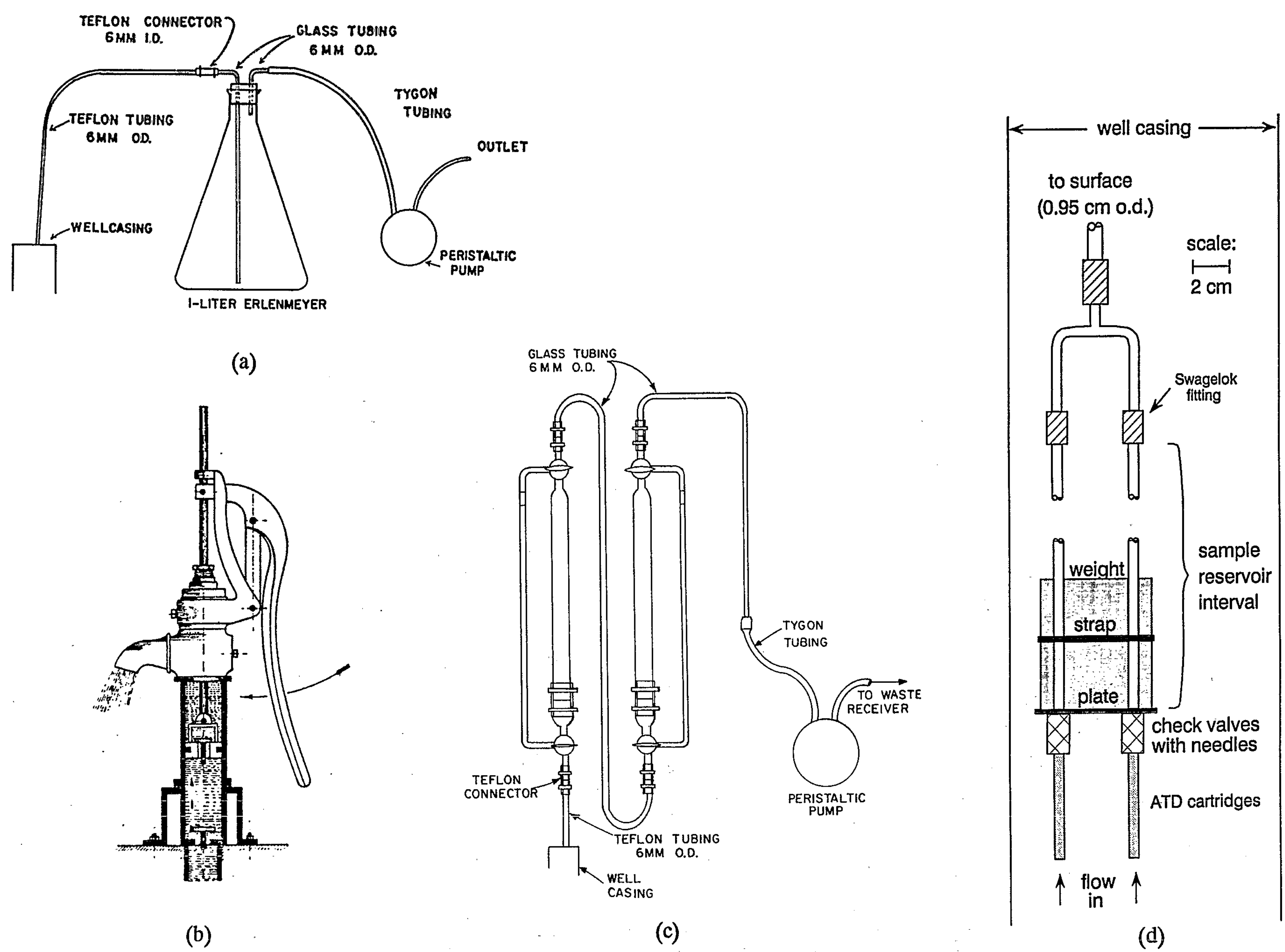


Figure 5.2.1 Suction-lift pumps: (a) Grab sampling with peristaltic pump (Scalf et al., 1981); (b) Pitcher pump (Unwin, 1982); (c) Organics adsorption column surface sampler with peristaltic pump (Scalf et al., 1981); (d) Downhole adsorption/thermal desorption (ATD) sampler (Rosen et al., 1992, by permission).

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.2. Submersible Centrifugal Pumps

Other Names Used to Describe Method: Rotary submersible pump, impeller submersible electric pump (ISEP); small-diameter submersible centrifugal: Johnson-Keck, Grundfos.

Uses at Contaminated Sites: Well purging and collecting ground-water samples.

Method Description: Electrically driven rotating impeller accelerates water within the pump body, building up pressure and forcing the sample up the discharge line (Figure 5.2.2). Commonly constructed of stainless steel, teflon, rubber, and brass.

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using centrifugal pumps. **Advantages:** (1) Can pump at large and variable flow rates, which makes them good for purging; (2) small-diameter units are available that can be used in 2-inch diameter wells and can be operated at both high flow rates for purging and low flow rates for sampling; (3) clay, silt, and fine sand have relatively little effect on small-diameter units; and (4) relatively limited test data indicates that small-diameter units yield comparable results to bladder pumps and helical rotor pumps when VOCs are sampled. **Disadvantages:** (1) Conventional units are subject to excessive wear in abrasive or corrosive waters; (2) relatively expensive in comparison to other devices offering comparable performance; (3) conventional pumps cannot be used in installations of diameter less than about 4 inches; and (4) potential for sample contamination from lubricants in motors in both small- diameter and conventional pumps.

Frequency of Use: Conventional, large-diameter pumps are common in water wells; small-diameter units for ground-water sampling are becoming more commonly used.

Standard Methods/Guidelines: **Sampling:** Ford et al. (1984).

Sources for Additional Information: Gillham et al. (1983), Koopman (1979), McMillion and Keeley (1968), Morrison (1983), Pohlmann and Hess (1988), Rehm et al. (1985). See also, Table 5-4.

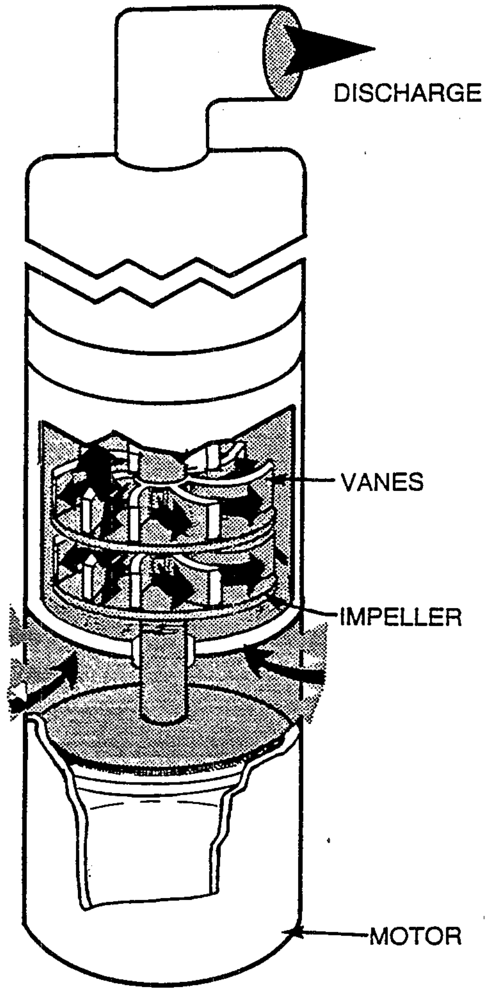


Figure 5.2.2 Submersible centrifugal pump (GRUNDFOS Pumps Corporation, Clovis, CA).

5. GROUND-WATER SAMPLING METHODS

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.3 Inertial-Lift Pumps

Other Names Used to Describe Method: Inertial pump.

Uses at Contaminated Sites: Well purging and ground-water sampling.

Method Description: The pump consists of a foot valve at the end of a flexible tube, which runs to the surface. At the beginning of sampling, the water column in the sampling tube is equal to that in the well. A levered handle or gasoline motor drive provides a continuous up-and-down movement of the tubing. An initial rapid upstroke lifts the water column in the tubing a distance equal to the stroke length. At the end of the upstroke, the water continues to move slightly upward by inertia. On the downstroke, the foot valve opens allowing fresh water to enter the tube. Figure 5.2.3 shows an installation with a levered handle for pumping.

Method Selection Considerations: **Advantages:** (1) Design is simple, easy to operate, and requires little or no maintenance; (2) inexpensive in comparison to other pumps, allowing dedication of pumps to individual wells; (3) can be used in monitoring wells as small as 0.5 inches in diameter and are capable of controlled flow rates between 0 and 2 gallons per minute; (4) are suitable for sampling volatile organics; (5) operate in silty and sandy environments without difficulty; (6) can be used to develop, purge, sample, and test monitoring wells; (7) can be operated manually as deep as 40 meters (130 feet), and as deep as 60 meters (200 feet); (8) the manual pump is lightweight and portable; and (9) drive mechanisms and pump construction materials can be selected to suit a variety of technical and budgetary requirements. **Disadvantages:** (1) Manual pump is difficult to operate in deep, large diameter wells (motor drive can overcome this); (2) cannot operate manually as deep as bladder or gas-drive pumps; (3) manual pumping is labor-intensive and requires some exertion for deeper wells; (4) some skill is necessary for most effective manual operation; (5) gasoline motor drive is heavy and not very portable; (6) plastic foot valves wear with heavy use, especially in metal casing; and (7) tubing coils are stiff and awkward to transfer between monitoring wells.

Frequency of Use: Relatively new method.

Standard Methods/Guidelines: Rannie and Nadon (1988).

Sources for Additional Information: Baerg et al. (1992), Barker and Dickhout (1988), Iles et al. (1992).

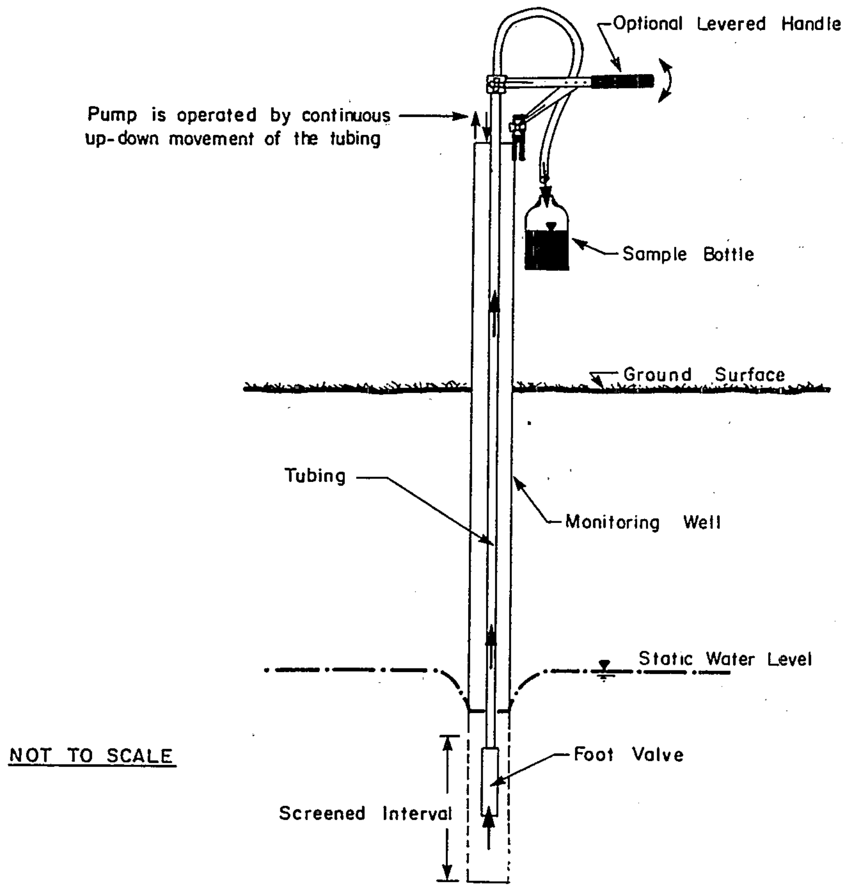


Figure 5.2.3 Typical manual installation of an inertial pump (Rannie and Nadon, 1988, by permission).

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.4 Gas-Lift Pumps*

Other Names Used to Describe Method: Air lift pump, hydrogen/nitrogen lift pump.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: Gas emitted from a gas line at the desired depth forces the sample to surface, either by the gas bubbles mixing with the water to reduce its overall specific gravity (annulus type [Figure 5.2.4a]), or the bubbles completely block the riser tube while ascending, thus pushing the water ahead (riser type [Figure 5.2.4b]).

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using gas lift devices. **Advantages:** (1) Simple to construct, or are available commercially at relatively low cost; (2) can be used in any diameter wells; (3) usually are easily portable or can be permanently installed; and (4) are easily cleaned. **Disadvantages:** (1) Only efficient when roughly 1/3 of the underground portion of the device is submerged; (2) contamination of the sample by the driving gas, atmosphere, and degassing all are unavoidable; (3) large power source (compressed gas) is required; and (4) does not work well in deep wells.

Frequency of Use: Very commonly used for well development (Section B.5); not recommended by Pohlmann and Hess (1988) due to potential for alteration of most chemical parameters of interest.

Standard Methods/Guidelines: --

Sources for Additional Information: Gillham et al. (1983), Morrison (1983), Pohlmann and Hess (1988), Rehm et al. (1985), Scalf et al. (1981), Unwin (1982). See also, Table 5-4.

*There is some inconsistency in the published literature in the use of the term "gas" or "air" lift, which has been applied to two distinctly different types of samplers. In this handbook the term **gas lift** (this section) refers only to methods where gas mixes with water to provide the buoyant force to bring the water to the surface, and **gas drive** (Section 5.1.4) refers to methods in which gas is used push water up a tube without the gas becoming mixed with the water that is brought to the surface. Morrison (1983) and Scalf et al. (1981) have applied the term "lift" to samplers that are classified as gas-drive samplers in this guide.

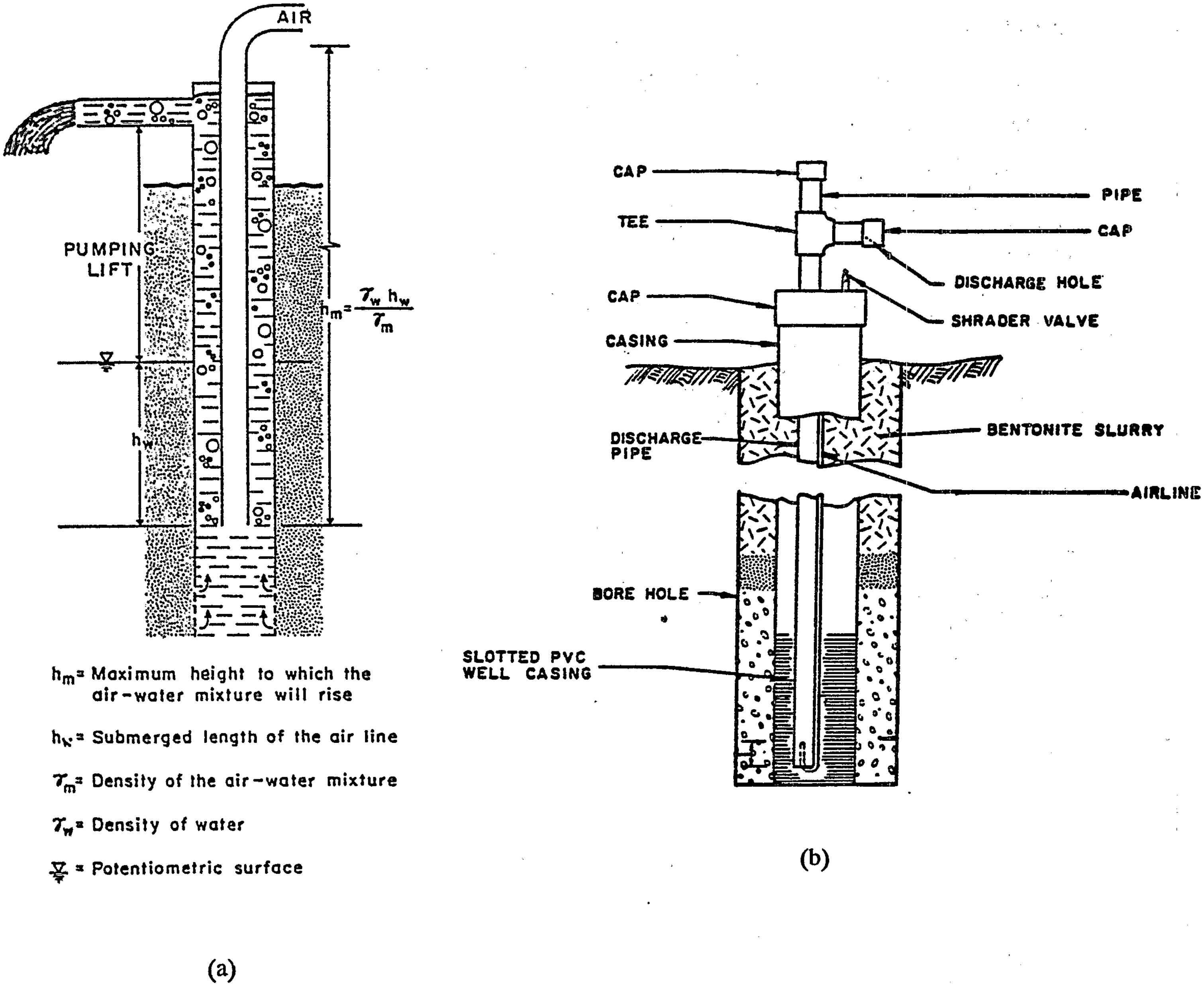


Figure 5.2.4 Gas-lift pumps: (a) Annulus type (Gillham et al., 1983, after Trescott and Pinder, 1970, by permission); (b) Riser type (Gillham et al., 1983, after Walker, 1974, by permission).

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.5 Jet Pumps

Other Names Used to Describe Method: Venturi/eductor pump.

Uses at Contaminated Sites: Developing or purging of monitoring wells.

Method Description: A circulating pump at the surface is attached to two tubes extending down the well. The submerged end of the tubes is connected by an ejector-venturi assembly and the pump maintains positive pressure in the tube that injects water and negative pressure on the tube that draws both water from the formation and circulates water to the surface (Figure 5.2.5). At the surface, water can be drawn off at the input end of the pump.

Method Selection Considerations: **Advantages:** (1) Can be used at great depths; (2) useful for well development or possibly purging; (3) high capacity at low heads; and (4) simple to operate and has no moving parts in the well. **Disadvantages:** (1) Use circulating water, which mixes with the formation water, requiring pumping a large amount of water before the circulating water has similar composition to the formation water; (2) water entering the venturi assembly is subject to a potentially large pressure drop, causing degassing and/or volatilization of the sample; (3) water circulating through the pump at the surface can be contaminated by materials and lubricants; and (4) air in suction or return line will stop pumping.

Frequency of Use: Uncommon, though a new down-well design does exist. Sometimes used for well development. Not recommended for sampling.

Standard Methods/Guidelines: --

Sources for Additional Information: Gillham et al. (1983), Iles et al. (1992), Koopman (1979), Unwin (1982), U.S. Geological Survey (1980).

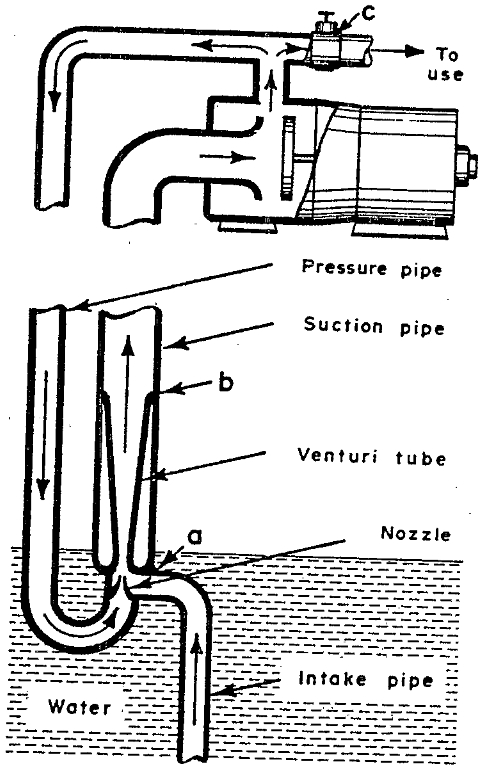


Figure 5.2.5 Jet (venturi) pump (Unwin, 1982).

5.2 OTHER PORTABLE GROUND-WATER SAMPLING PUMPS

5.2.6 Packer Pumps

Other Names Used to Describe Method: Packer-equipped pump.

Uses at Contaminated Sites: Collecting depth specific ground-water samples; performing borehole dilution tests to measure ground-water velocity.

Method Description: Hydraulically or pneumatically inflated packers are wedged against the wall of an open borehole, perforated casing, or screen to isolate a section of the well for sampling. The packers are deflated for vertical movement in the well and inflated when the desired depth is reached. Ground water is pumped to the surface using a submersible pump (Figure 5.2.6a), gas lift, suction pump (Figure 5.2.6b), or bladder pump.

Method Selection Considerations: **Advantages:** Discrete, vertically spaced samples can be collected in a single well. **Disadvantages:** (1) Vertical movement of water outside the well might result in samples that are not representative of the sampling interval (can be minimized by low pumping rates); and (2) failure to obtain a tight seal with the packers, because of an irregular open borehole or because of deterioration in the expandable material, might affect representativeness of the sample.

Frequency of Use: Very common in dedicated systems; occasionally used for portable applications.

Standard Methods/Guidelines: --

Sources for Additional Information: Bureau of Reclamation (1981), Morrison (1983). See also, Table 5-4.

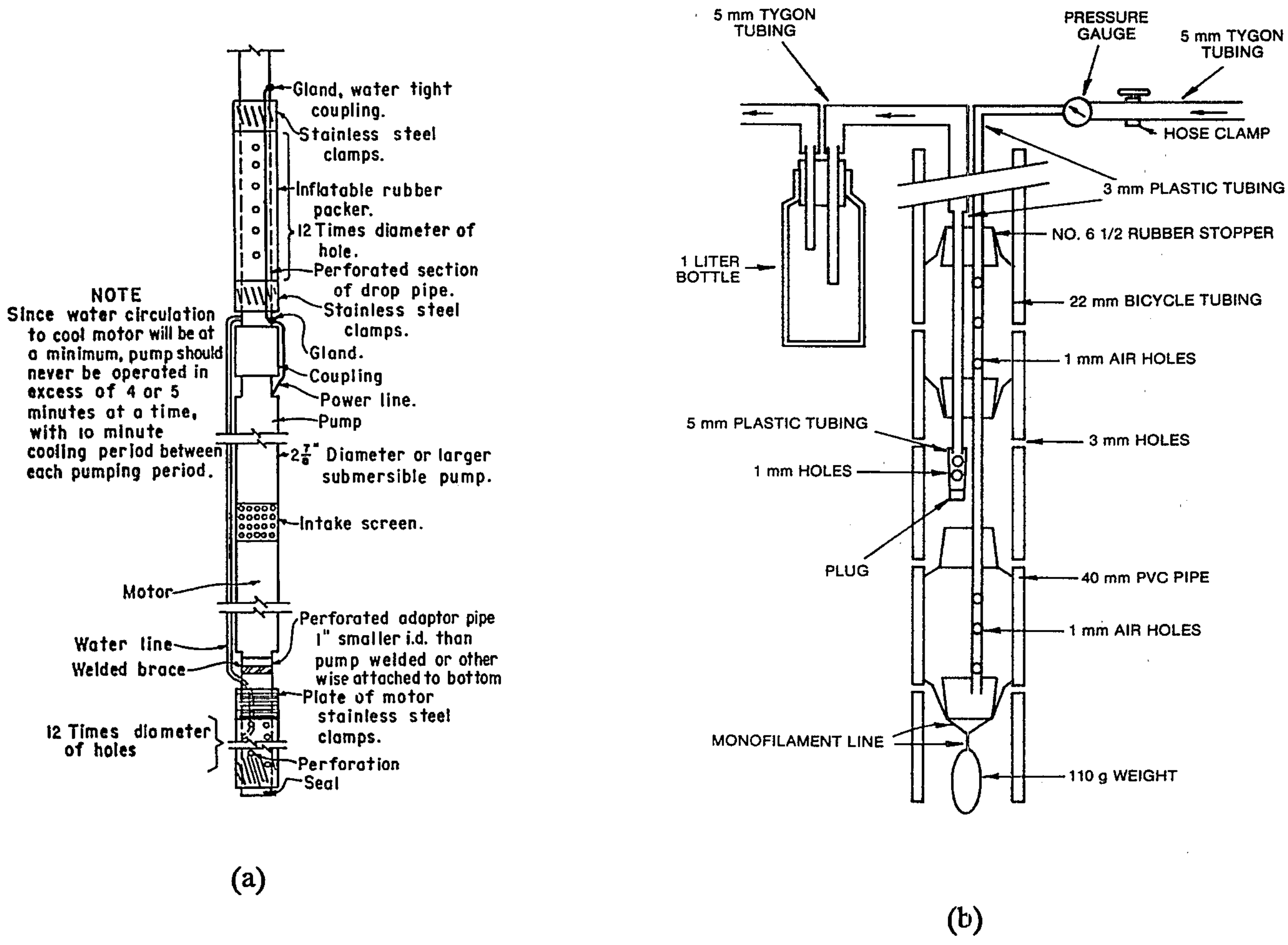


Figure 5.2.6 Packer pumps: (a) With submersible pump (Bureau of Reclamation, 1981); (b) With vacuum pump (Morrison, 1983, by permission).

5. GROUND-WATER SAMPLING METHODS

5.3 PORTABLE GRAB GROUND-WATER SAMPLERS

5.3.1 Bailers

Other Names Used to Describe Method: Open bailer, point-source bailer.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: A bailer is a hollow tube with a check valve at the base (open bailer) or a double check valve (point-source bailer). The bailer is attached to a line (polypropylene or nylon rope, or stainless steel or Teflon-coated wire) and lowered into the water column, with the check valve allowing water to flow through the bailer. When the desired depth is reached, the bailer is pulled up, with the weight of the water closing the check valve. At the surface, the sample in decanted into a sample container. Open bailers provide an integrated sample of the column of water through which it has descended (Figure 5.3.1a). Point-source bailers can use balls that serve as checks to prevent additional water from entering the bailer when it is pulled to the surface (Figure 5.3.1b), or can have valves that are opened and closed from a cable operated from the surface, allowing collection of a sample at a specific point. The first type allows water to flow through the bailer as it is being lowered, whereas the latter type allows water to enter only when the sampling depth has been reached. The check valves of depth-specific bailers can also be operated pneumatically (Section 5.3.2).

Method Selection Considerations: See Table 5-2 for suitability ratings of open and point-source bailers for different ground-water parameters. **Advantages:** (1) Low cost can allow dedication of one bailer per well, avoiding potential for cross contamination; (2) simple to operate; (3) easily cleaned, although cleaning of ropes and/or cables can be more difficult; (4) can be constructed of almost any rigid or flexible material, including those materials that are inert to chemical contaminants and can be made to fit any diameter well and to almost any length to obtain desired sample volume; (5) no limit to depth of sampling; (6) bailers made of flexible material can pass through nonplumb wells; (7) very portable and require no power source; and (8) good for sampling nonaqueous phase liquids at the water table surface. **Disadvantages:** (1) Time consuming and physically demanding (if device is lowered and raised by hand) when used for purging, especially in deep wells; (2) lines used with bailer can be difficult to decontaminate and cause cross contamination if not dedicated to a sample well; (3) can cause chemical alterations due to aeration, degassing, volatilization, turbulence, or atmospheric invasion while lowering the bailer through the water column and/or when transferring the sample to the storage container; (4) the person sampling might be exposed to contaminants in the sample; (5) does not supply a continuous flow of water to the surface; (6) with open bailers, it might be difficult to determine the point within the water column that the sample represents; (7) bailer check valves might not operate properly with high suspended solids content or freezing temperatures; and (8) the swabbing effect of tightly fitting bailers might cause fines to enter the well, especially if it has been poorly developed.

Frequency of Use: Bailers have been the most widely used sampling method because they are inexpensive, but other devices, such as the bladder pump, helical rotor, and gear-drive pump, provide better results when sensitive constituents, such as volatile organics, are present.

Standard Methods/Guidelines: Berg (1982), deVera (1980), Ford et al. (1984).

Sources for Additional Information: Dunlap et al. (1977), Gillham et al. (1983), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985), Scalf et al. (1981). See also, Table 5-4.

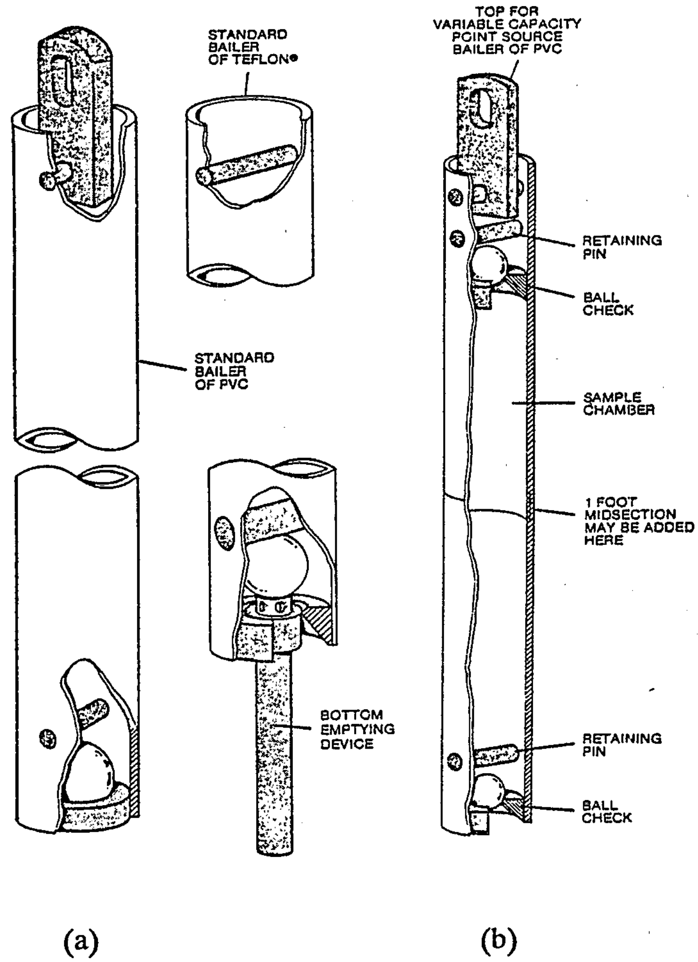


Figure 5.3.1 Bailers: (a) Standard type; (b) Point-source type (Gillham et al., 1983, by permission).

5.3 PORTABLE GRAB GROUND-WATER SAMPLERS

5.3.2 Pneumatic Depth-Specific Samplers

Other Names Used to Describe Method: Syringe sampler, syringe bailer, discrete point sampler, pressurized bailer, Chismar (surface bomb/pressurized bailer) samplers, Westbay sampler, VOA trap sampler.

Uses at Contaminated Sites: Collecting depth-specific ground-water samples.

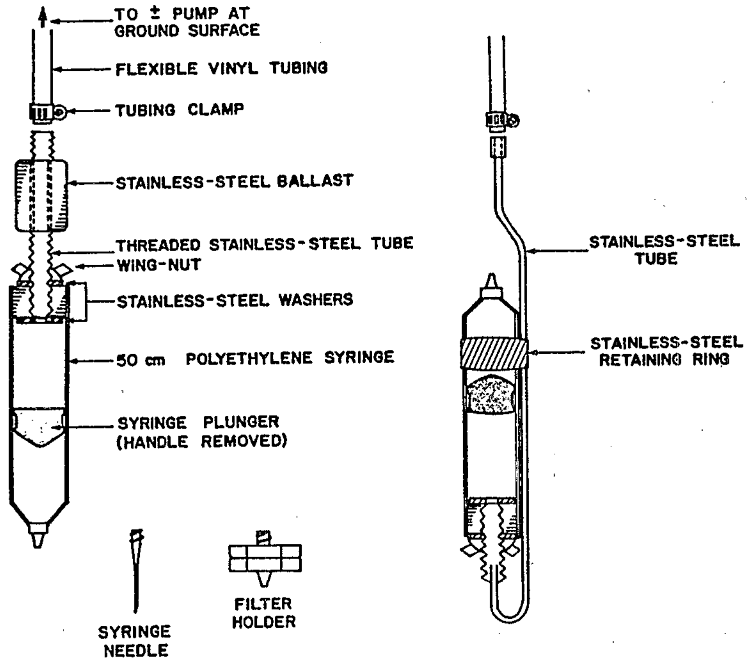
Method Description: Various types of samplers have been developed in which the sample container is pressurized or evacuated before being lowered into the sampling installation. Opening the container and/or releasing the pressure allows sample to enter the device. Figure 5.3.2a illustrates a syringe sampler constructed from a hospital syringe. Figure 5.3.2b illustrates the operation of the sampling device used with a Westbay multilevel sampling installation (see Section 5.6.2). The BAT sampler (Section 5.5.2) is another example of this type of sampler.

Method Selection Considerations: See Table 5-2 for suitability ratings for different ground-water parameters using syringe samplers. **Syringe Advantages:** (1) Sample does not come into contact with any atmospheric gases; very slight negative pressure during sampling should minimize aeration or degassing; (2) samples can be collected at discrete intervals and at any depth; (3) syringes can be made out of inert or nearly inert materials; (4) the syringe can be used as the sample container, eliminating the possibility of cross-contamination between wells; (5) syringes are inexpensive, highly portable, and simple to operate, requiring only a hand pump; (6) can be used in small diameter wells (as small as 1.2 inches); and (7) syringe can be flushed downhole with the water to be sampled. **Syringe Disadvantages:** (1) Inefficient for collecting large volume samples; (2) cannot be used to purge well; (3) might not be as readily available as other, more established, sampling devices; (4) sample contamination by components of "homemade" sampling devices is possible unless materials are carefully selected; (5) use limited to water with low suspended solids because particulates might damage plunger or check valve; (6) possible gas diffusion through polyethylene barrel wall; (7) requires compressed gas; and (8) failure of the seal between the piston and the syringe barrel can result of loss of volatile organics. **Other Samplers Disadvantages:** (1) Commercially available pneumatic samplers are moderately expensive; (2) Westbay sampler is only compatible with the Westbay casing system (Section 5.6.2); (3) might be difficult to clean.

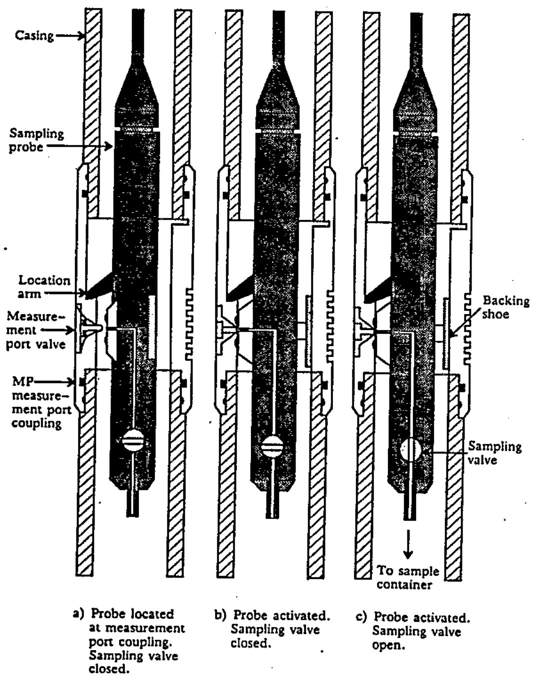
Frequency of Use: Most commonly used in research projects.

Standard Methods/Guidelines: --

Sources for Additional Information: Gillham et al. (1983), Morrison (1983), Nielsen and Yeates (1985), Pohlmann and Hess (1988), Rehm et al. (1985). See also, Table 5-4.



(a)



(b)

Figure 5.3.2 Pneumatic Depth-Specific Samplers: (a) Syringe sampler (Gillham et al., 1983, after Gillham, 1982, by permission); (b) Westbay sampling probe operation (Pohlmann et al., 1990, after Black et al., 1986).

5.3 PORTABLE GRAB GROUND-WATER SAMPLERS

5.3.3 Mechanical Depth-Specific Samplers

Other Names Used to Describe Method: Kemmerer sampler, Van Dorn sampler, composite liquid waste samplers (coliwasa), stratified sample thief, swabbing.*

Uses at Contaminated Sites: Collecting depth-specific ground-water samples; sampling thickness of nonaqueous phase liquids (NAPLs) floating on the water table, or at the bottom of a well (stratified sample thief).

Method Description: **Kemmerer** (Figure 5.3.3a) and **Van Dorn** samplers are tube samplers with end caps that close when triggered by a "messenger" sent down the line, allowing collection of a water sample at the desired depth. The **Coliwasa** is a tube with neoprene stoppers at each end, which are controlled by a rod running through the tube and a locking mechanism, and is used for sampling fluids in tank (Figure 5.3.3b). The **stratified sample thief** was developed by the petroleum industry to sample stratified immiscible fluids. It consists of a rod passing through the center of a series of disks spaced at the interval for which sampling is desired (Figure 5.3.3c). The assembly is lowered into the fluid to the depth of interest and a tube with an inside diameter slightly larger than the diameter of the disks is slipped over the assembly, entrapping fluid between the adjacent disks. The entire assembly is brought to the surface and fluid sample obtained for each chamber as the tube is withdrawn from the disks. **Swabbing** involves pushing a leather swabbing cup, which is attached to a rod that extends from the surface, down into the well. As the cup is lowered to the desired depth, water flow past it. As the cup is drawn out of the well, it opens, lifting water to the surface.

Method Selection Considerations: **Depth-Specific Sampler Advantages:** (1) Coliwasa is inexpensive to construct and can be made of inert materials; (2) are very portable and require no power source; (3) the stratified sampler is well-suited for sampling hydrocarbon contaminated ground water where distinct layers have developed between immiscible fluids; and (4) are easily cleaned. **Depth-Specific Sampler Disadvantages:** (1) Activating mechanism of Kemmerer and Van Dorn samplers can be prone to malfunctions; (2) Kemmerer sampler is difficult to clean thoroughly, as are rubber stoppers used with other samplers, causing the potential for cross-contamination; (3) operation might be difficult at depth; (4) problems with potential chemical alteration of sample similar to bailers; and (5) can be difficult to transfer sample to storage container. **Swapping Advantages:** Sampling to great depths is possible (limited only by the length of rod attached to the swabbing cup). **Swabbing Disadvantages:** (1) Difficult to use with large diameter wells; (2) volumes of water obtained and discharge rates cannot be regulated; (3) contamination is common when oil-field equipment is used for deep sampling; (4) technique is difficult to use, requiring a crew of about four people; (5) might cause plugging of well screens in small diameter wells; and (6) consistent water quality sample collection is difficult due to vertical mixing of water during extraction.

Frequency of Use: Kemmerer and Van Dorn samplers are most commonly used for surface water sampling. The Coliwasa is primarily used for sampling containerized waste. The stratified sample thief has good potential for use at hydrocarbon contaminated sites, although actual use has been infrequent. Swabbing is commonly used in oil field operations, but is not recommended for ground water sampling (Everett et al. [1983]).

Standard Methods/Guidelines: **Kemmerer and Coliwasa samplers:** Ford et al. (1984); **Stratified sample thief:** Johnson (1981).

Sources for Additional Information: Fenn et al. (1977), Gillham et al. (1983), Houghton and Berger (1984), Rehm et al. (1985), Spaulding et al. (1976), Tate (1973), Wood (1976).

*Swabbing in only roughly depth-specific in that it provides integrated samples of the depth below the water table to which the swabber is placed.

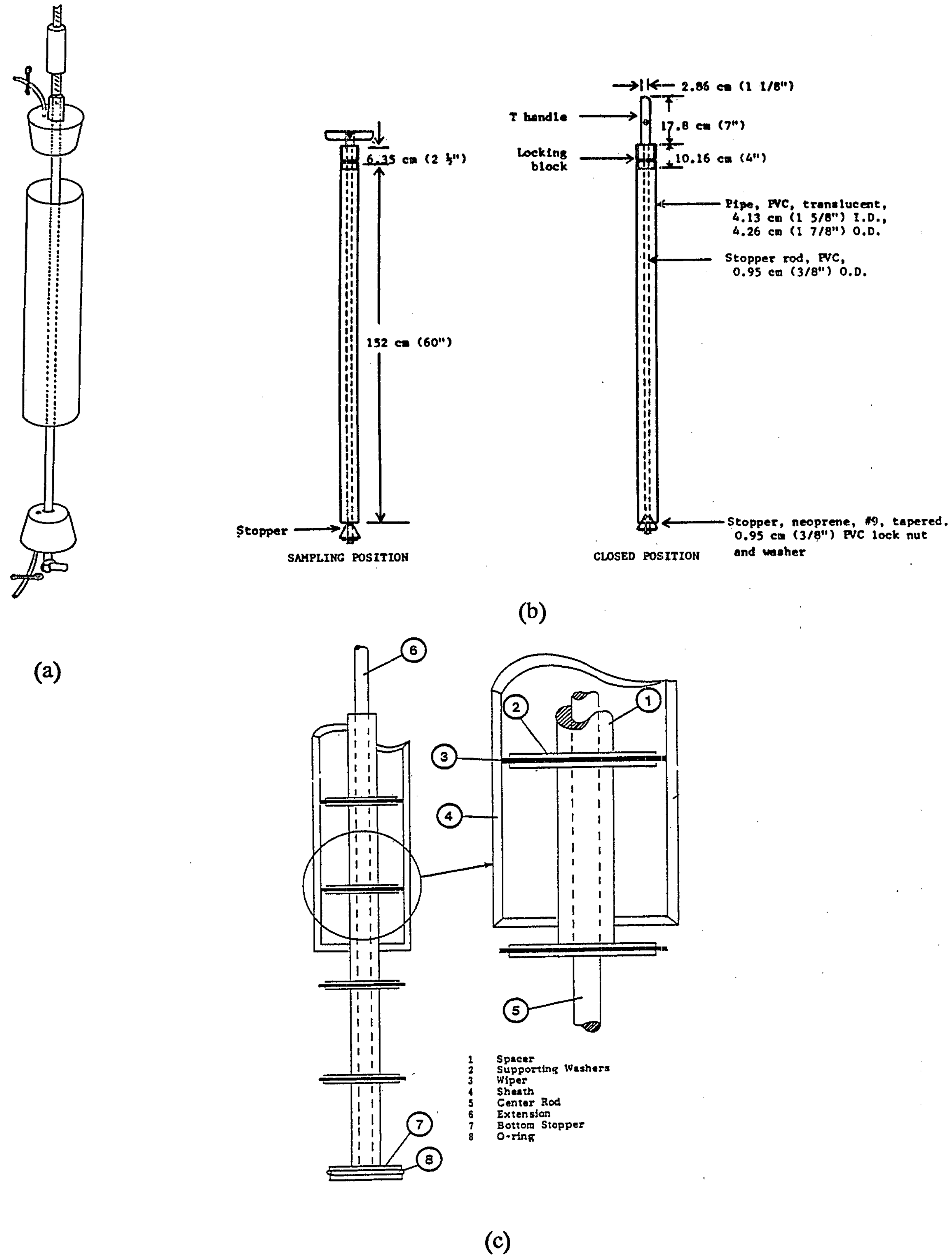


Figure 5.3.3 Mechanical depth-specific samplers: (a) Modified Kemmerer sampler (Scalf et al., 1981); (b) Coliwasa (Ford et al., 1984); (c) Stratified Sample Thief (Gillham et al., 1983, after Johnson, 1981, by permission).

5.4 SAMPLING INSTALLATIONS FOR PORTABLE SAMPLERS

5.4.1 Single-Riser/Limited Interval Wells

Other Names Used to Describe Method: Single-level or short-screened installations/well completions/piezometers.

Uses at Contaminated Sites: Providing access for ground-water sampling of specific subsurface intervals.

Method Description: A borehole is drilled to the desired depth in an aquifer and a short to moderate length screen (usually 3 to 10 feet) is installed (Figure 5.4.1). See Appendix B for additional information on well installation, and Figure B.1a for a more detailed schematic of elements of a monitoring well.

Method Selection Considerations: **Advantages:** (1) Simple and suitable for any type of formation; (2) easier to install, pack, and seal than multilevel installations; (3) no potential for vertical cross-contamination between sampling points due to leaky seals; (4) maximum flexibility in selection of well diameter (up to diameter of borehole); and (5) most common well diameters (2 to 4 inches) do not restrict the choice of sample collection methods. **Disadvantages:** (1) Provide no information on the vertical distribution of contaminants; (2) high cost per sampling point compared to multilevel installations, especially at great depth; and (3) contaminant plume might bypass wells with short screened intervals.

Frequency of Use: Common.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Gillham et al. (1983), Morrison (1983), Scalf et al. (1981).

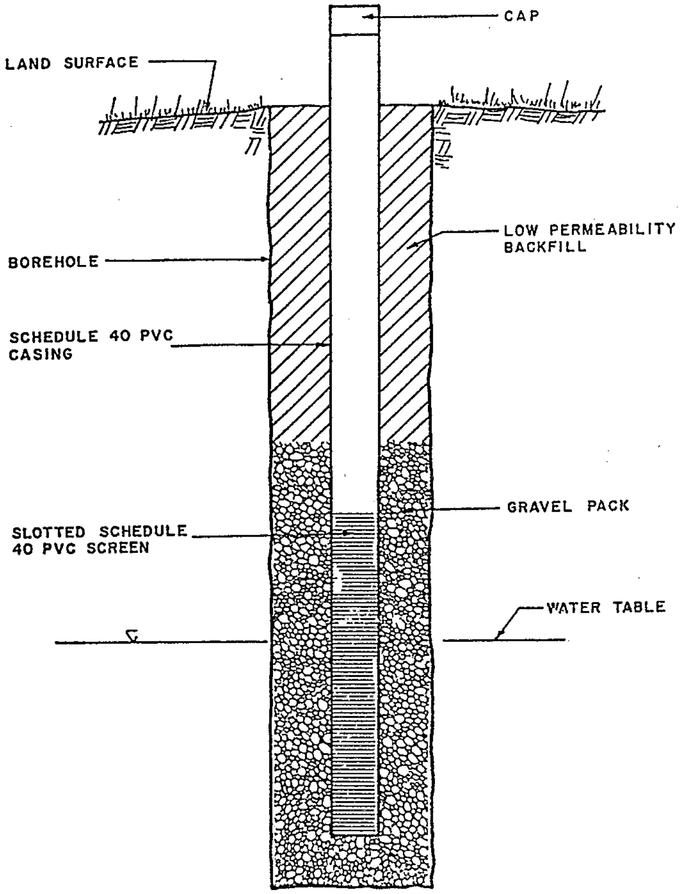


Figure 5.4.1 Typical monitoring well screened over a single vertical interval (Gillham et al., 1983, after Fenn et al., 1977, by permission).

5.4 SAMPLING INSTALLATIONS FOR PORTABLE SAMPLERS

5.4.2 Single-Riser/Long-Screened Wells

Other Names Used to Describe Method: Flow-through installations/completion/piezometers.

Uses at Contaminated Sites: Detection monitoring; collecting ground-water samples at different levels in an aquifer (if flow-through assumptions apply).

Method Description: A borehole is drilled to the bottom of the aquifer of interest and the full thickness of the aquifer is screened (unconsolidated material [Figure 5.4.2]), or left open (bedrock aquifers). Sampling such a well after purging yields a composite sample of the aquifer. Gillham et al. (1983) restrict use of the term "flow through" wells to small diameter wells (2 inches or less) in hydraulically homogeneous formations with no vertical gradient, where ground water flows through the well without having its course altered. In this special situation, purging in not necessary. Minimally disturbed water samples can be obtained at different levels in the well by either taking a series of grab samples, or a series of samples at very low pumping rates.

Method Selection Considerations: **Advantages:** (1) Simple and suitable for any type of formation; (2) easier to install, pack, and seal than multilevel installations; (3) maximum flexibility in selection of well diameter (up to diameter of borehole); (4) most common well diameters (2 to 4 inches) do not restrict the choice of sample collection methods; and (5) where flow-through assumptions apply, there is no need to purge the well before sampling and the number of vertical sampling points is not limited by the diameter of the well. **Disadvantages:** (1) Contaminant plume might bypass wells with short-screened intervals; (2) long-screened intervals might not give accurate measurement of maximum concentrations because concentration and hydraulic-head values tend to be averaged over the length of the screen; (3) because of disadvantage #4, long-screened installations can be used to confirm the presence, but not the absence of a contaminant; (4) long-screened installations can cause cross-contamination in an aquifer by connecting contaminated zones to uncontaminated zones; and (5) the underlying assumption for flow-through wells that the well screen will not alter the flow of ground water cannot be support for most natural systems.

Frequency of Use: Relatively common at older sites; uncommon at new sites.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Gillham et al. (1983), Reynolds et al. (1991).

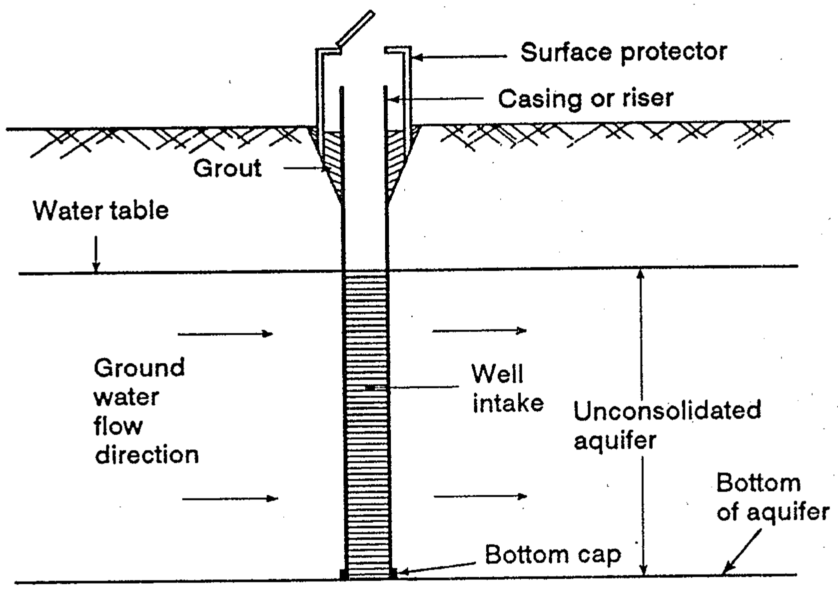


Figure 5.4.2 Diagram of single-riser/flow-through well (Aller et al., 1991).

5.4 SAMPLING INSTALLATIONS FOR PORTABLE SAMPLERS

5.4.3 Nested Wells/Single Borehole

Other Names Used to Describe Method: Multiple wells/single borehole installation, multiple well-single borehole installation/completion, well clusters, hybrid.

Uses at Contaminated Sites: Delineating contaminant plumes; detection monitoring.

Method Description: A cluster of single-riser/limited interval wells is installed at different depths in a single borehole (Figure 5.4.3a). Each screened interval is separated by a grout seal. In cohesionless deposits, **bundle** piezometers can be installed, which consist of a bundle of narrow-diameter standpipe piezometers, each of different length. At the bottom of each pipe is a short (6-8 inch) slotted interval wrapped with fine nylon screen. A cluster of nine piezometers can be placed down a hollow-stem auger, and the formation is allowed to cave in around the bundles as the auger is withdrawn from the hole (Figure 5.4.3b). Well casings can be eliminated by installing in situ samplers (well screens with submersible pumps) or individual gas-drive/suction-lift samplers (Section 5.6.1) at different levels in single borehole. **Hybrid** well installations can involve a variety of combinations of permanently placed in situ vadose zone and ground-water monitoring devices and/or small diameter monitoring wells (Figure 5.4.3c).

Method Selection Considerations: **Advantages:** (1) Allow sampling for vertical distribution of ground-water constituents; (2) lower cost per sampling point than separate single-riser wells; and (3) the generally smaller diameters of individual wells in a nest compared to single-riser installations means that smaller volumes of water must be removed for purging. **Disadvantages:** (1) Installation, packing, and sealing is more difficult than for single-level installations and increases greatly as the number of wells in the boreholes increases; (2) the short-screened intervals must be separated by a grout seal with the possibility that small zones of contaminated water might be missed in heterogeneous materials (reconnaissance methods such as destructive sampling [see Sections 5.7.1 and 5.7.2] can reduce the this likelihood); (3) cross-contamination of sampling points might occur as a result of leaky seals (this can be checked using tracer tests); (4) number of sampling points per borehole is restricted by the diameter of the borehole and the diameter of the individual piezometers; (5) bundle piezometers are suitable only where cohesionless sands will collapse around the tips; (6) the small diameter of individual piezometers might restrict choice of sampling methods; and (7) in fine-grained material with low hydraulic conductivity, the small storage volume of individual piezometers might make it difficult to collect samples of sufficient volume.

Frequency of Use: Relatively uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Fenn et al. (1977), Gillham et al. (1983), Morrison (1983), Scalf et al. (1981). See also, Table 5-4.

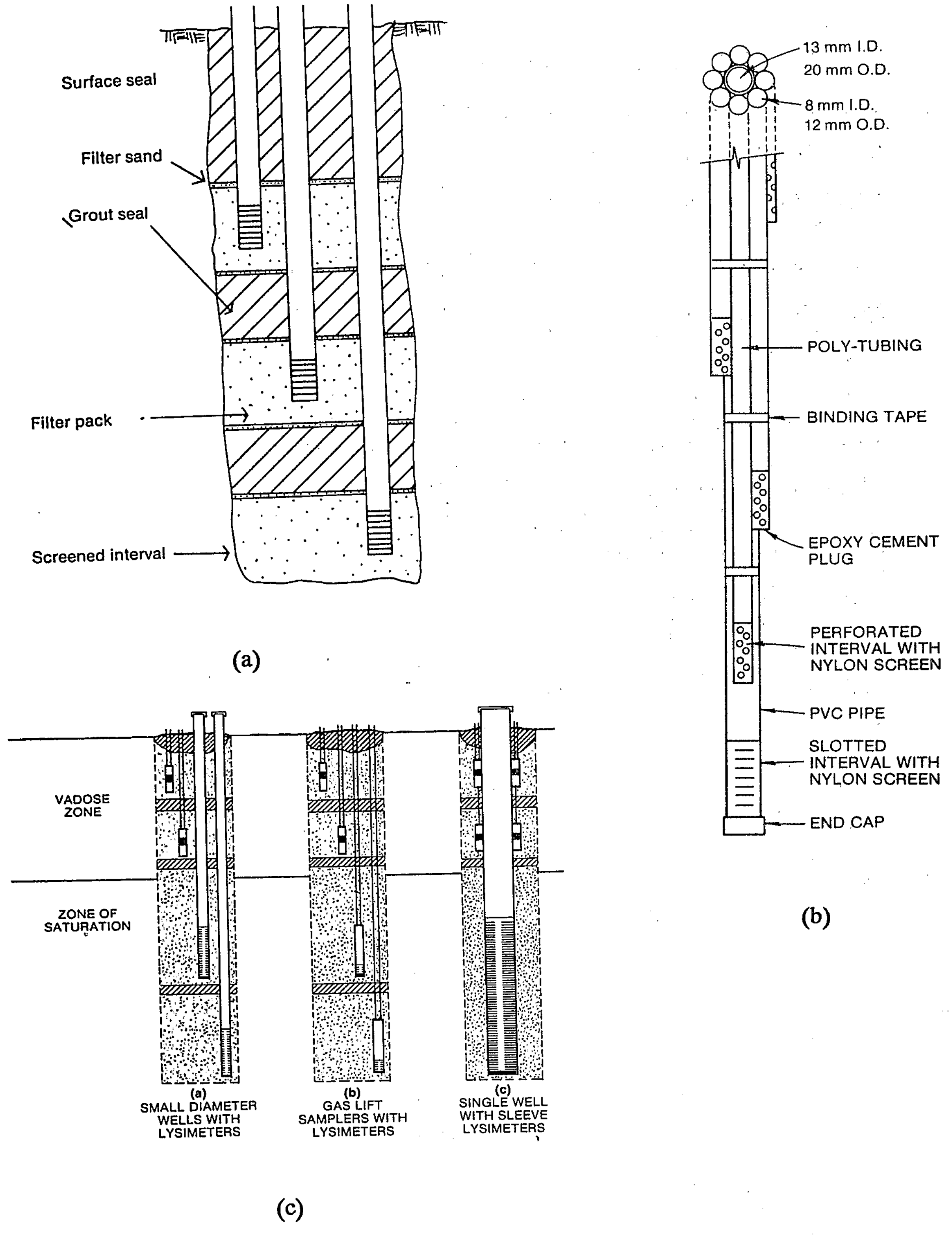


Figure 5.4.3 Multiple wells in a single borehole: (a) Conventional completion (Aller et al., 1991, after Johnson, 1983); (b) Bundle piezometers (Morrison, 1983, by permission); (c) Hybrid well systems (Morrison, 1983, by permission).

5.4 SAMPLING INSTALLATIONS FOR PORTABLE SAMPLERS

5.4.4 Nested Wells/Multiple Boreholes

Other Names Used to Describe Method: Multi-level wells/multiple borehole installation, multi-level wells/multiple borehole completion.

Uses at Contaminated Sites: Delineating contaminant plumes; detection monitoring.

Method Description: A series of single-riser/limited interval wells is installed at different depths in an aquifer in separate, but closely spaced or clustered boreholes (Figure 5.4.4). See Appendix B for additional information on well installation.

Method Selection Considerations: **Advantages:** (1) Allow sampling for vertical distribution of ground-water constituents; (2) somewhat lower cost per sampling point than widely spaced single-riser wells; (3) simple design and operation; (4) potential for cross-contamination between different levels in the aquifer is eliminated; (5) only the drilling method limits well diameter; and (6) if desired, screened intervals can be placed to provide complete vertical coverage of the aquifer. **Disadvantages:** (1) More expensive than nested wells in a single borehole; and (2) small zones of contaminated water might be missed in heterogeneous materials if the screened intervals do not provide complete vertical coverage of the aquifer (reconnaissance methods such as destructive sampling [see Sections 5.7.1 and 5.7.2] can reduce the this likelihood).

Frequency of Use: Common.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Gillham et al. (1983), Reynolds (1991).

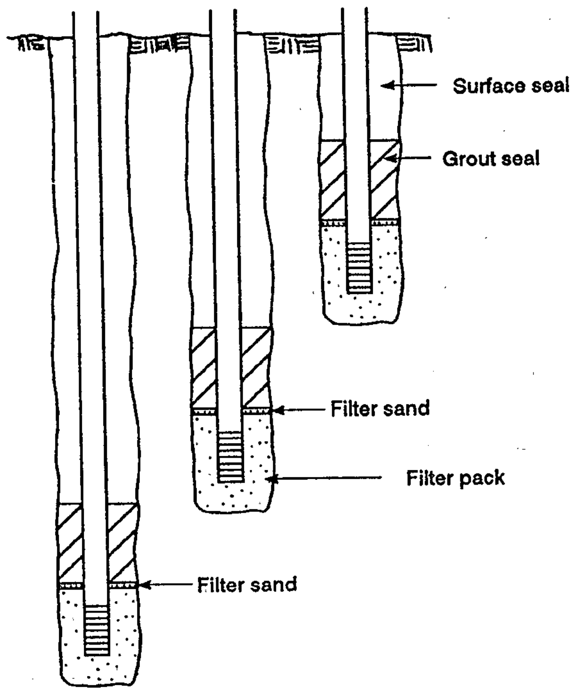


Figure 5.4.4 Nested wells with multiple boreholes (Aller et al., 1991, after Johnson, 1983).

5.5 PORTABLE IN SITU GROUND-WATER SAMPLERS/SENSORS

5.5.1 Hydropunch®

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Collecting representative ground-water samples without installation of permanent ground-water monitoring wells.

Method Description: The Hydropunch® is a device that collects one-time ground-water samples in unconsolidated material (Figure 5.5.1a). It is attached to cone penetrometer rods (see Section 2.2.2) and driven into the soil with hydraulic rams (Figure 5.5.1b). When the bottom of the probe is at least 5 feet below the water table, the outer cylinder is pulled back, exposing a perforated stainless steel sample entry barrel covered with either a nylon or polyethylene filter material (Figure 5.5.1c). Hydrostatic pressure forces ground water that is relatively free of turbidity into the sample compartment, and the probe is pulled to the surface to retrieve the sample. Depending on the soil materials, depths up to 150 feet can be achieved by direct penetration. If deeper depths are desired, boreholes can be drilled to the desired depth before using the sampler.

Method Selection Considerations: **Advantages:** (1) Allows relatively rapid collection of ground-water samples with minimal disturbance of the ground surface (6 to 10 samples of between 500 and 1,000 mL a day if no major problems occur); (2) cost-effective method for preliminary contaminant plume delineation based on actual ground-water sampling; and (3) can be used in most materials that can be augered or sampled with a split spoon. **Disadvantages:** (1) Provides one-time sample only; (2) cannot be used in very gravelly or consolidated formations; (3) samples must be taken 3 to 5 feet below the water table surface, meaning the light nonaqueous phase liquid floating at the ground-water surface might be missed in sampling; (4) collection of samples in clayey zones requires excessive fill times (up to 2 hours) and filter mesh might allow significant uptake of fines in the sample; and (5) problems in penetrating well-sorted coarse sand might result in a zone of significant contamination being bypassed during sampling.

Frequency of Use: Relatively new method that has gained rapid acceptance as a preliminary reconnaissance method.

Standard Methods/Guidelines: --

Sources for Additional Information: See Table 5-5.

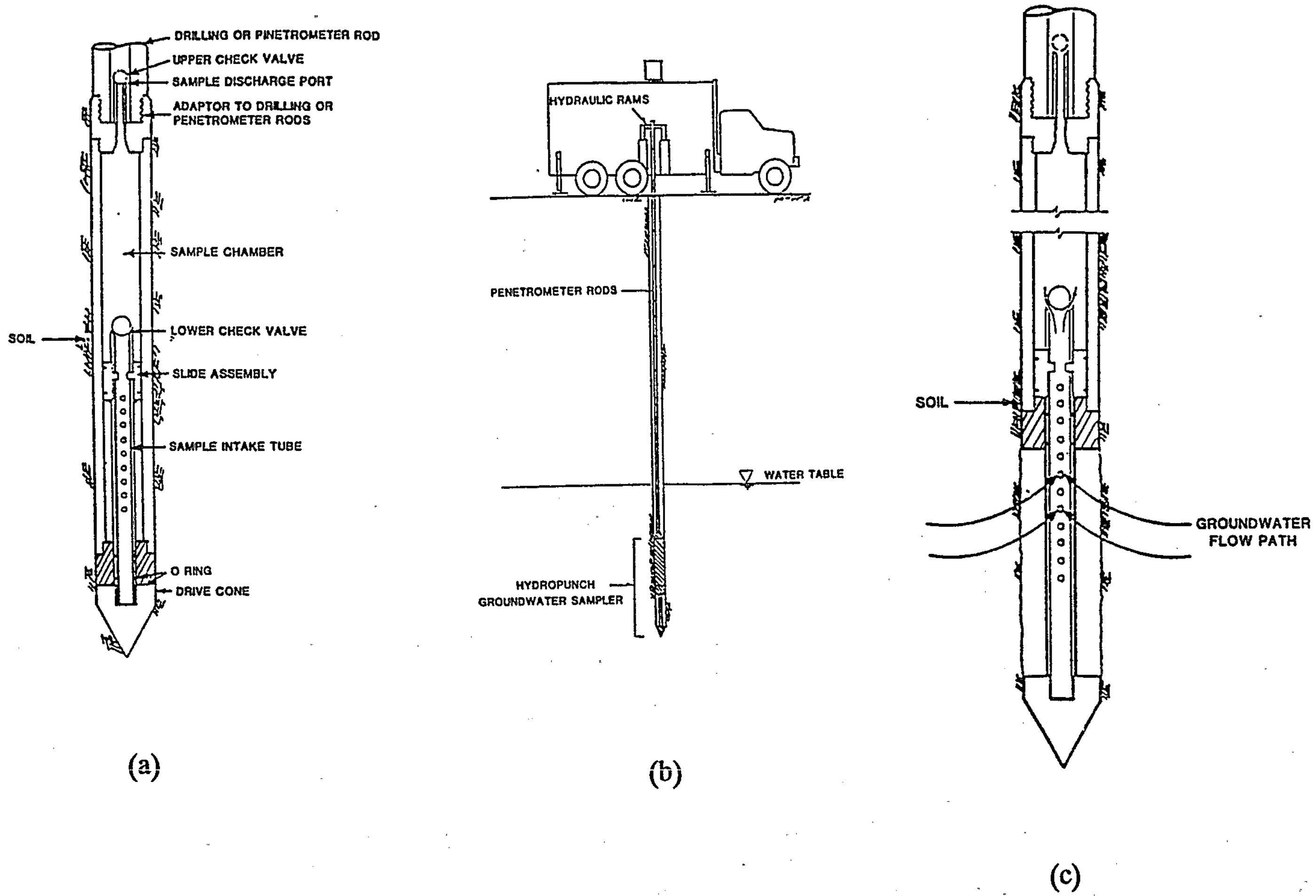


Figure 5.5.1 **Hydropunch: (a) Schematic; (b) Operation; (c) Sample collection (Edge and Cordry, 1989, by permission).**

5.5.2 Other Cone Penetrometer Samplers

Other Names Used to Describe Method: CPT/porous probe, BAT system; CPT samplers (radial filter element, retractable tip, expendable tip, slotted probe); TerraTrog (soil-gas sampler).

Uses at Contaminated Sites: Collecting in situ ground-water samples; measuring pore-water pressure and hydraulic conductivity.

Method Description: **BAT system:** A special ground-water/soil-gas sampling cone, with a filter mounted inside its stainless steel shaft, either is placed in the subsurface as a permanent installation or attached to cone penetration rods and pushed into the ground (Figure 5.5.2a). A specially developed septum keeps the top of the filter sealed. A pre-sterilized evacuated sample vial sealed with a similar septum and a disposable double-ended hypodermic needle are lowered down the cone penetration rods. The sample vial connects with the porous probe when the hypodermic needle penetrates both devices and the vacuum in the vial pulls a sample into the vial (Figure 5.5.2b). The septum on the probe reseals when the vial and needle are pulled to the surface, allowing collection of multiple samples from the same point. The BAT system can be used for ground-water sampling, as a vacuum-type porous cup suction lysimeter (Section 9.2.1), and for soil gas sampling (Section 9.4.2). Figure 5.5.2c illustrates several types of permanent installations of the filter tip probe. With the appropriate additional equipment, the probe also is able to measure pore-water pressure, and to measure hydraulic conductivity. **Other CPT samplers:** Various other types of tips (radial filter element, retractable tip, expendable tip, slotted probe) have been developed that can be attached to a cone penetration rig for ground-water and soil-gas sampling. Unlike the BAT and Hydropunch® probes, ground-water samples are drawn to the surface using a suction-lift device, commonly a peristaltic pump (Section 5.2.1).

Method Selection Considerations: **BAT Advantages:** (1) Allows relatively rapid collection of ground-water samples with minimal disturbance of the ground surface; (2) cost-effective method for preliminary contaminant plume delineation based on actual ground-water sampling; (3) can be used in most materials that can be augered or sampled with a split spoon; (4) permanent installation for ongoing sampling is possible; and (5) also can be used to sample soil gases and soil water in the vadose zone. **BAT Disadvantages:** (1) Provides one-time sample only (unless permanent installation is used); (2) cannot be used in very gravelly or consolidated formations; (3) one-time sample volumes are smaller that Hydropunch® (150 mL vs. 500 to 1,000 mL); (4) with permanent installations, depth of ground-water sampling is limited to the suction capacity of the suction-lift device that is used (around 15 to 25 feet); and (5) problems in penetrating well-sorted coarse sand might result in a zone of significant contamination being bypassed during sampling. **Other CPT Samplers:** Different probes vary in the suitability for use in fine-grained and coarse-grained soil materials. All require suction-lift devices for ground-water sampling, limiting sampling depth to around 15 to 25 feet.

Frequency of Use: Relatively new method that has potential for wide applications.

Standard Methods/Guidelines: --

Sources for Additional Information: See Table 5-5.

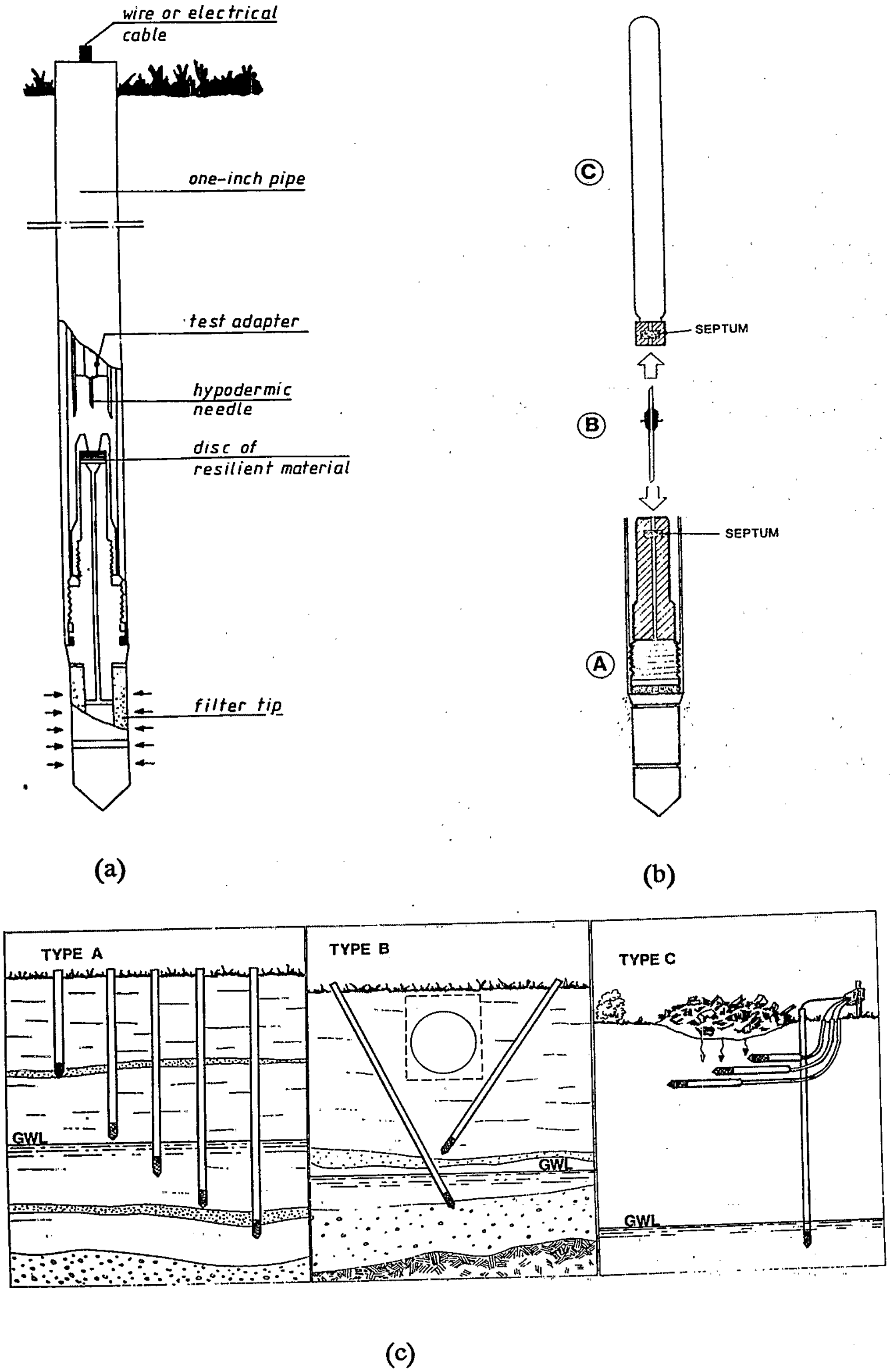


Figure 5.5.2 **BAT system: (a) Schematic of test adaptor for sampling of ground water and gas; (b) Filter tip attachment for cone penetration rig (A) with double-ended hypodermic needle (B) and sample vial (C) (Torstensson and Petsonk, 1988, Copyright ASTM, reprinted with permission); (c) Example permanent installations of filter tip probe (Torstensson, 1984, by permission).**

5.5.3 Other Driven Samplers

Other Names Used to Describe Method: Well point sampler, driven multilevel sampler (DMLS), hydraulic probe sampler, hollow steel drive probe, miniature multi-level sampler.

Uses at Contaminated Sites: Collecting in situ ground-water samples; performing tracer studies of ground-water flow (multi-level).

Method Description: **Well point samplers:** A well point (Figure 5.5.3a), which usually is fabricated from metal and includes a screen, casing, and hardened point, is jetted (see Section 2.1.8) or driven (see Section 2.2.1) into the soil. The well point is left in place to function as a monitoring well. **Multiple port well point sampler:** A driveable well point, with multiple sampling ports separated by a sand matrix and caulking, is driven into the soil and a suction device is used to collect samples from the different ports (Figure 5.5.3b). **DMLS:** This sampler consists of a 4.4-centimeter OD screwed, flush-joint steel casing, with sampling tubes on the inside of the casing, which are attached by pressure fittings to screened sampling ports at 25- to 38-centimeter intervals (Figure 5.5.3c). The lower end of the casing is attached to a drive point. It is installed by augering to the top of the desired depth of placement and driving the sampler to the final depth. Water is pumped into the sampling tubes to keep the sampling ports from being clogged while the casing is being driven. Once in place, the auger hole is backfilled and sealed at the surface. **Hydraulic probe sampler:** This sampler uses a modification of soil-gas sampling methods (Section 9.4.2) to collect ground-water samples. A 0.75 to 1-inch outer diameter hollow probe with detachable drive points is hydraulically driven 2 feet below the water table (as determined by an electronic water level indicator). Ground-water samples are taken using tubing placed down the probe and a peristaltic pump (Section 5.2.1). **Miniature multilevel sampler:** This sampler is like a cross between the hydraulic probe sampler and the simpler types of multiple port-casings (Section 5.6.2). It is constructed of steel conduit with a drive point so that sampler can be driven into the ground. **Hydrocarbon thickness probe:** A hollow steel rod, with a circuit at the tip to sense the top of the water table, is driven into the soil until it is to the top of the water table. A replaceable insert, which contains a coating of product indicator chemicals, is placed down the tube. A horizontal slot above the tip allows petroleum products floating on the surface of the water table to enter the tube and react with the chemicals on the insert. The insert is removed and the thickness of product measured.

Method Selection Considerations: **Advantages:** Most devices offer a portable, quick, and efficient method for monitoring at shallow depths in bogs, muds, unconsolidated sands, and permafrost. **Disadvantages:** (1) Most devices are limited to relatively shallow depths; (2) forcing probes into the soils affects the soil density immediately adjacent to the well, which might influence some downhole monitoring instruments; and (3) except for well points, off-the-shelf availability of most types generally is limited.

Frequency of Use: Well points are commonly used for shallow monitoring; other methods are used less commonly due to relativeness newness of methods, but more widespread use is likely.

Standard Methods/Guidelines: --

Sources for Additional Information: **Well point samplers:** Morrison (1983), see also, Table 5-5; **Multiple port well point probe:** Hansen and Harris (1974, 1980); **DMLS:** Boggs and Hemond (1988); **Hydraulic probes:** Mastrolonardo and Thomsen (1990), Patton (1990); **Miniature multilevel samplers:** Stites and Chambers (1991); **Hydrocarbon thickness probe:** Wagner et al. (1989).

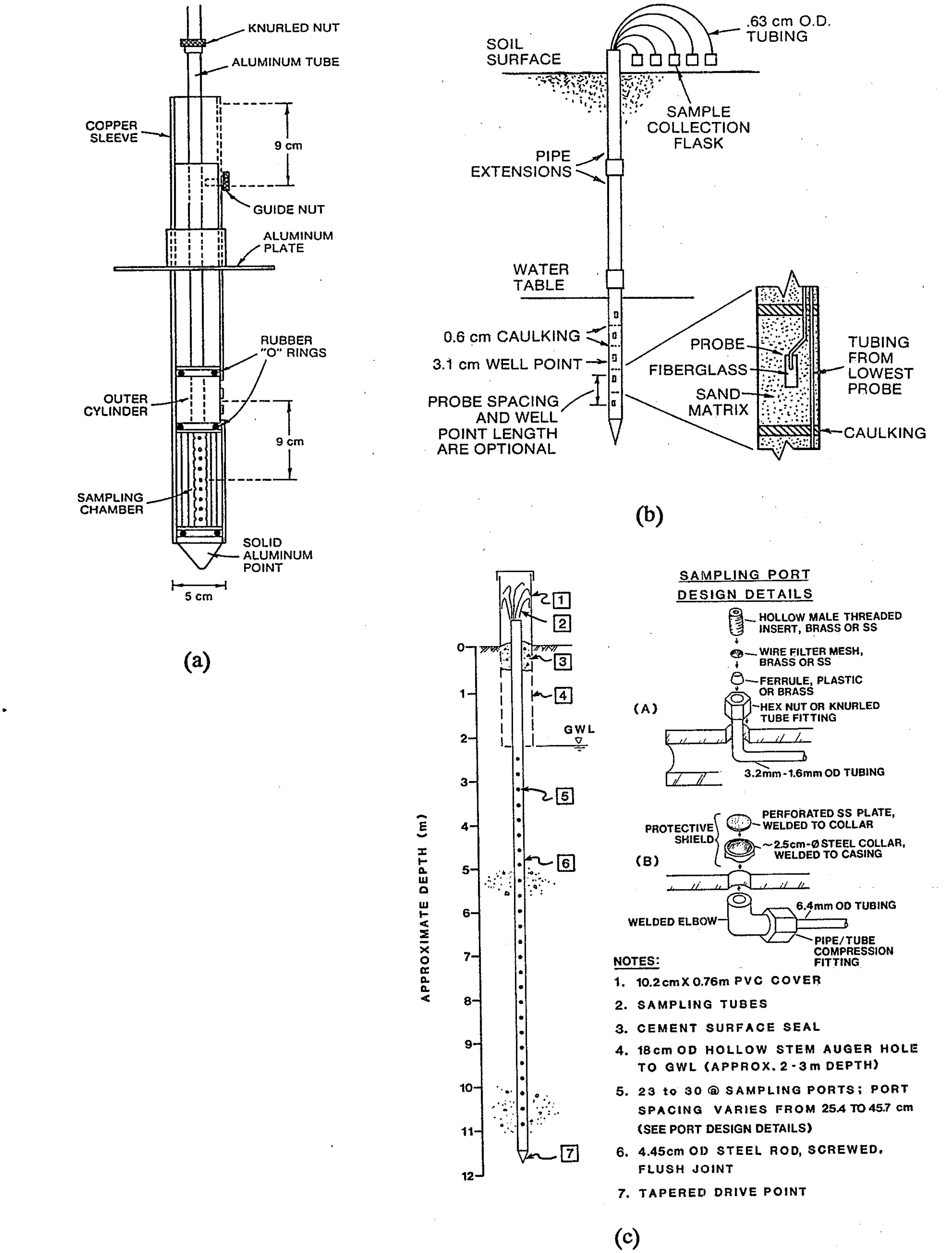


Figure 5.5.3 Driven samplers: (a) Well point sampler (Morrison, 1983, after Summerfield, 1973); (b) Multiple port well point sampler (Morrison, 1983, after Hansen and Harris, 1974); (c) Driven multi-level sampler (Boggs and Hemond, 1988, Copyright © 1988, Electric Power Research Institute, EPRI EA-5816, *Evaluation of Tracer Sampling Devices for the Macrodispersion Experiment*, reprinted with permission).

5.5 PORTABLE IN SITU GROUND-WATER SAMPLERS/SENSORS

5.5.4 Dissolved Oxygen, Eh, and pH Probes

Other Names Used to Describe Method: Continuous pH log, continuous redox (ORP) log.

Uses at Contaminated Sites: Detecting contaminant plumes; obtaining information on the vertical distribution and temporal variations in the pH and redox status of ground-water/borehole fluid.

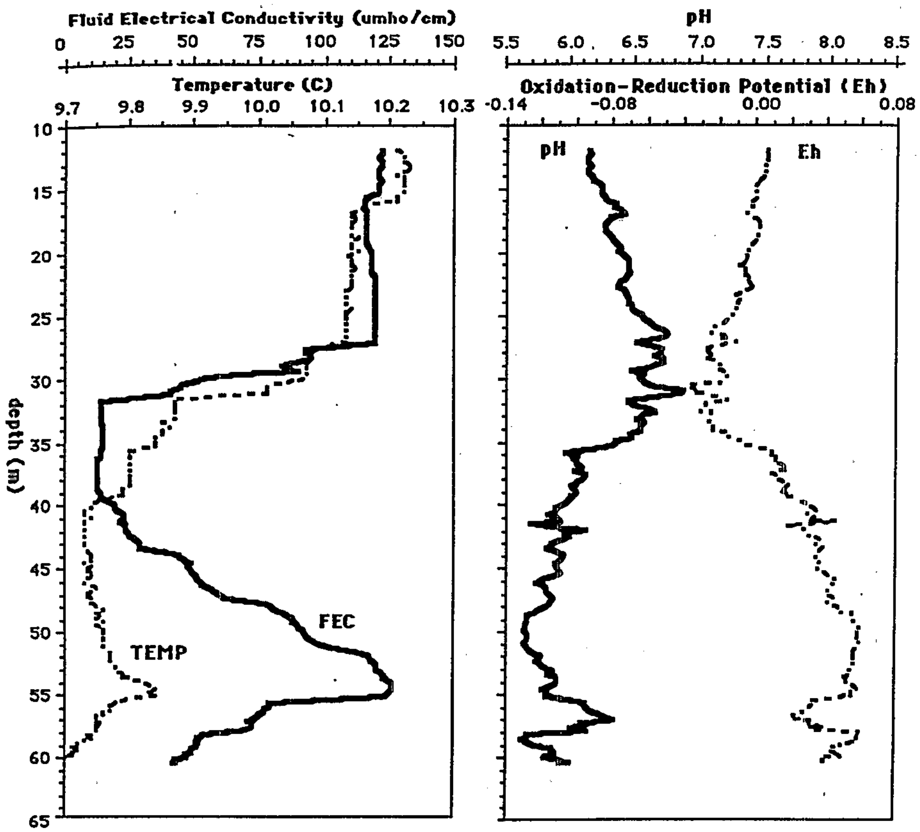
Method Description: Various probes are available that measure dissolved oxygen, oxidation-reduction potential (Eh), and hydrogen ion concentration (pH) in borehole fluids, individually or in combination. Pedlar et al. (1990) describe a technique for defining the relative contribution of fractures to the specific capacity of a well and characterizing hydrochemistry using a new logging tool, which simultaneously measures fluid electrical conductivity (see also, Section 3.1.3), temperature (see also, Section 3.5.2), pH, and Eh. Figure 5.5.4 shows example logs from such a device. Section 10.1 discusses in more detail field the measurement of pH and Eh in ground-water samples.

Method Selection Considerations: **Advantages:** (1) In situ measurements are less likely to reflect chemical alteration due to pressure changes than measurements taken of a water sample brought to the surface; and (2) combination probes that measure several hydrochemical parameters simultaneously greatly simplify collection. **Disadvantages:** The general disadvantages that are associated with a new method: (1) Limited operational and field experience; and (2) limited equipment availability.

Frequency of Use: Good potential for wider use for aquifer characterization as the instrumentation is refined and becomes more widely available.

Standard Methods/Guidelines: --

Sources for Additional Information: Pedlar et al. (1990).



LEGEND	LOG NO.	PARAMETER
——	PA01623	FEC
- - - - - -	PA01623	temp

LEGEND	LOG NO.	PARAMETER
——	PA01623	pH
- - - - - -	PA01623	Eh

Figure 5.5.4 Example fluid electrical conductivity, temperature, pII, and Eh logs from a single borehole (Pedlar et al., 1990, by permission).

5.5 PORTABLE IN SITU GROUND-WATER SAMPLERS/SENSORS

5.5.5 Ion-Selective Electrodes

Other Names Used to Describe Method: Specific-ion electrodes.

Uses at Contaminated Sites: Detecting presence and concentration of specific ions. Ion-selective electrodes have been developed for ammonia, bromide, calcium, chloride, fluoride, hydrogen sulfide, and nitrate.

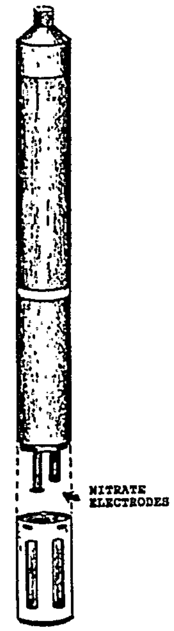
Method Description: Electrodes are designed to detect the presence and concentration of specific ions using a reference electrode. Figure 5.5.5a shows a nitrate-specific electrode, which consists of a solvent-polymer membrane containing a nitrate ion exchanger in an inert polyvinyl chloride plastic matrix. The electrode has an internal silver/silver chloride element, which establishes a fixed potential in contact with the internal filling solution. The membrane undergoes ion exchange, which varies inversely with the activity of the nitrate ion. Signals are recorded on a strip chart recorder that presents readings in parts per million or millivolts on a logarithmic or linear scale. Readings in millivolts require use of a calibration curve to convert readings to parts per million (Figure 5.5.5b).

Method Selection Considerations: **Advantages:** Relatively new method with good potential for detection monitoring and preliminary water quality characterization. **Disadvantages:** (1) Proper calibration is difficult due to interference from different constituents present in many ground waters; (2) some parameters might inhibit the electrode's output; and (3) constituents for which specific electrodes have been developed are limited.

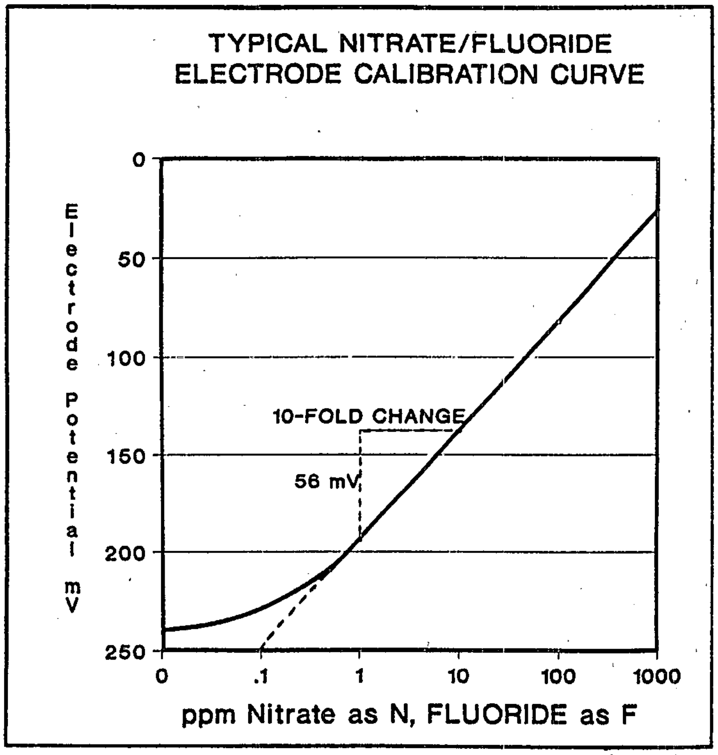
Frequency of Use: Use for contaminated-site investigations relatively new.

Standard Methods/Guidelines: ASTM (1982) describes standard terminology, measurement technique, and conditions affecting measurements.

Sources for Additional Information: Jeffers et al. (1982), Newman and Corbell (1990), Ritchey (1986).



(a)



(b)

Figure 5.5.5 **Nitrate specific ion electrode: (a) Probe; (b) Calibration curve (Newman and Corbell, 1990, by permission).**

5.5 PORTABLE IN SITU GROUND-WATER SAMPLERS/SENSORS

5.5.6 Fiber-Optic Chemical Sensors (FOCS)

Other Names Used to Describe Method: Remote laser-induced fluorescence (RLIF), remote fiber spectroscopy with fiber optic chemical sensors (RFS-FOCS), immunochemical fiber optic sensors.

Uses at Contaminated Sites: Detecting the presence of specific organic compounds in water or vapor phase. **Solid fiber:** BTEX, DCE, TCE, carbon tetrachloride, chloroform, diesel fuel, JP-5, gasoline, and phenols; **Porous fiber:** Humidity, pH, ammonia, ethylene, CO, hydrazines, and BTX.

Method Description: A variety of chemical sensors using fiber optic technology are in developmental stages. **FOCS** are made of a reagent phase, which is physically confined or chemically immobilized at the end of an optical fiber. The reagent phase contains a chemical or immunochemical indicator that changes its optical properties, usually absorbance or fluorescence, when it interacts with the analyte (immunochemical techniques are discussed further in Section 10.5.2). The optical fiber is a strand of glass or plastic, ranging from two to several hundred microns in diameter, and acts as a conduit to propagate light to and from the FOCS. The FOCS is placed in the subsurface using a cone penetration rig (Figure 5.5.6a) or into a ground-water monitoring well. The fiber optic cable is attached to a **spectrophotometer** (Section 10.4.3) or a **fluorometer** (Section 10.4.2), which contains a light source (light bulb or laser) and a detector. An excitation signal from the light source is transmitted down the cable to the FOCS, and the sensor fluoresces and provides a constant-intensity light source that is transmitted back up the cable and detected as the return signal (Figure 5.5.6b). If the target contaminant is present, the intensity of the return signal is reduced, and the intensity of light that is recorded by the detector is inversely proportional to the concentration (Figure 5.5.6c). Fiber optic sensors also are used with the colorimetric borehole dilution techniques (Section 3.5.6).

Method Selection Considerations: **Advantages:** (1) Provide selective in situ real-time measurements in the field; (2) eliminate sample handling and chain-of-custody concerns; (3) potential for specific detection of a large number of specific organic compounds (theoretically over half the organics on EPA's priority pollutant list); (4) sensors can be placed in small boreholes (0.5-inch diameter), reducing drilling and monitoring well installation costs, or can be used with cone penetration rigs (Section 5.5.2) for rapid field screening; (5) field instrumentation is potentially very portable (small enough to fit in a coat pocket); and (6) potential for greatly reduced costs compared to conventional sampling and analytical methods for organic contaminants. **Disadvantages:** (1) New technique with limited operational and field experience; (2) equipment not yet readily available; (3) field performance of RLIF has been poorer than laboratory results, perhaps due to temperature fluctuations and affect of increased vibration on optics; (4) numerous separate sensors are required for discrimination between specific compounds; and (5) turbidity might interfere with readings.

Frequency of Use: Relatively new development with excellent potential.

Standard Methods/Guidelines: --

Sources for Additional Information: See Table 5-5.

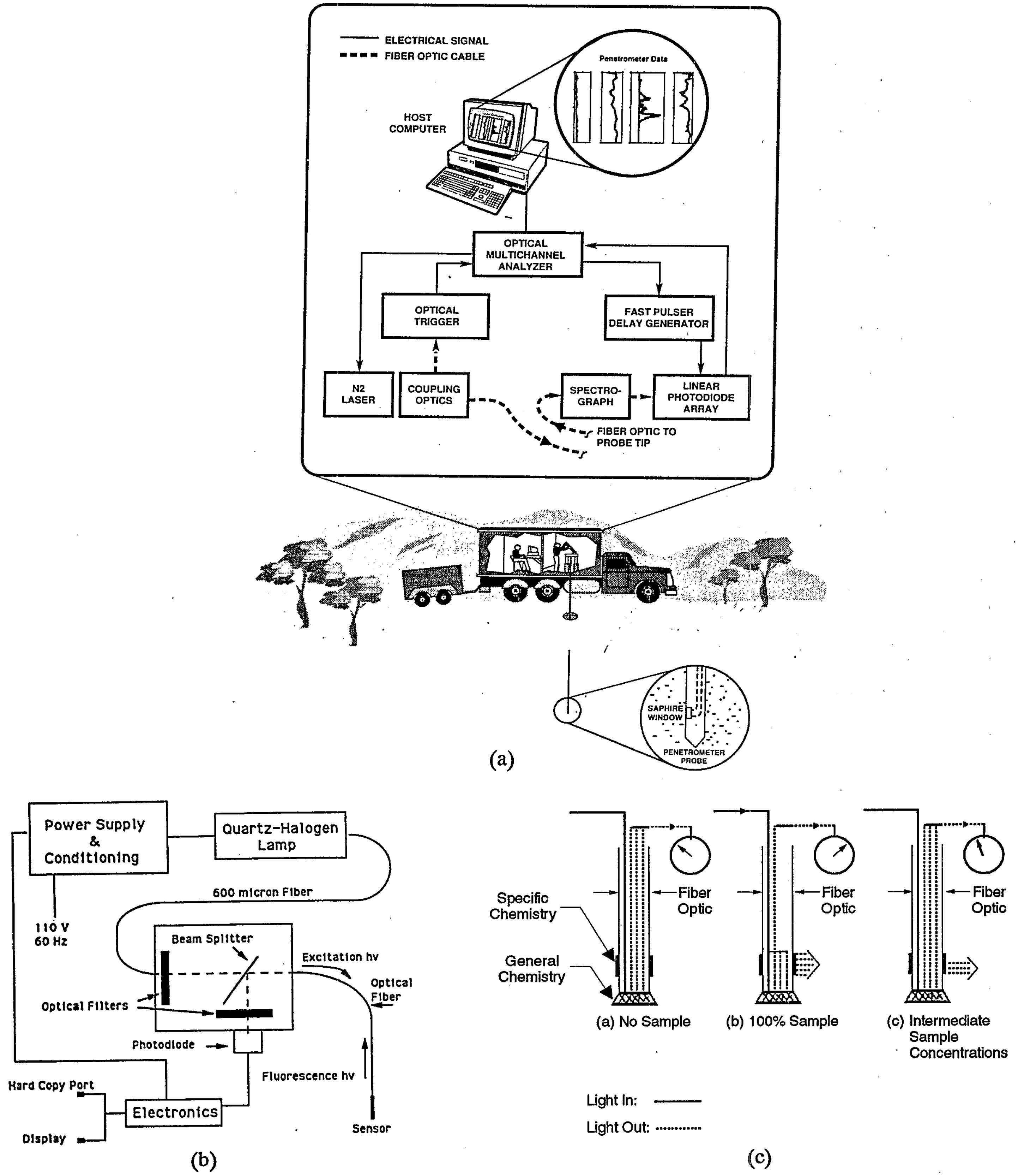


Figure 5.5.6 Fiber optic sensors: (a) Schematic of laser induced fiber optic fluorometer system (Lieberman et al., 1991); (b) Block diagram of field-portable fluorometer with fiber optic sensor (Barnard and Walt, 1991); (c) Principle of operation of a fiber optic sensor (Morlock, 1989, by permission).

5.6 FIXED IN SITU GROUND-WATER SAMPLERS

5.6.1 Multilevel Capsule Samplers

Other Names Used to Describe Method: Gas-drive/suction-lift multilevel sampling device installation.

Uses at Contaminated Sites: Delineating contaminant plumes; detection monitoring; ground-water quality monitoring.

Method Description: A variety of gas-drive (see Section 5.1.4) or suction-lift (see Section 5.2.1) sampling devices have been developed for permanent installation in a single borehole to allow multi-level sampling. Individual gas-drive (Figure 5.6.1a) or suction-lift samplers are placed at different levels in a borehole and separated by grout in a manner similar to nested wells in a single borehole (Figure 5.6.1b). Samples are collected using tubing that runs from the surface to each individual sampling device.

Method Selection Considerations: **Advantages:** (1) Allow sampling for vertical distribution of ground-water constituents; (2) relatively easy to operate and safer than most other installation types where hazardous contaminants are involved; and (3) minimal purging is required because there is little mixing between incoming water from the formation and stagnant water. **Disadvantages:** (1) Proper installation is difficult; (2) cost per sampling point is moderately high; (3) depending on the type of sampler, number of sampling points might be limited by the diameter of the borehole (commonly three to four sampling points for 6-inch borehole); (4) permanent nature of installation means that devices at individual sampling points cannot be retrieved for servicing or repairs, and malfunction means the sampling point is lost; (5) cross contamination is a potential concern with multi-level installations requiring grout to isolate sampling points; and (6) the choice of sample collection method is restricted to gas-drive or suction-lift devices (for shallow water table). See Sections 5.1.4 and 5.2.1 for advantages and disadvantages of these sampling methods.

Frequency of Use: Relatively uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Gillham et al. (1983), Morrison (1983). See also, Table 5-5.

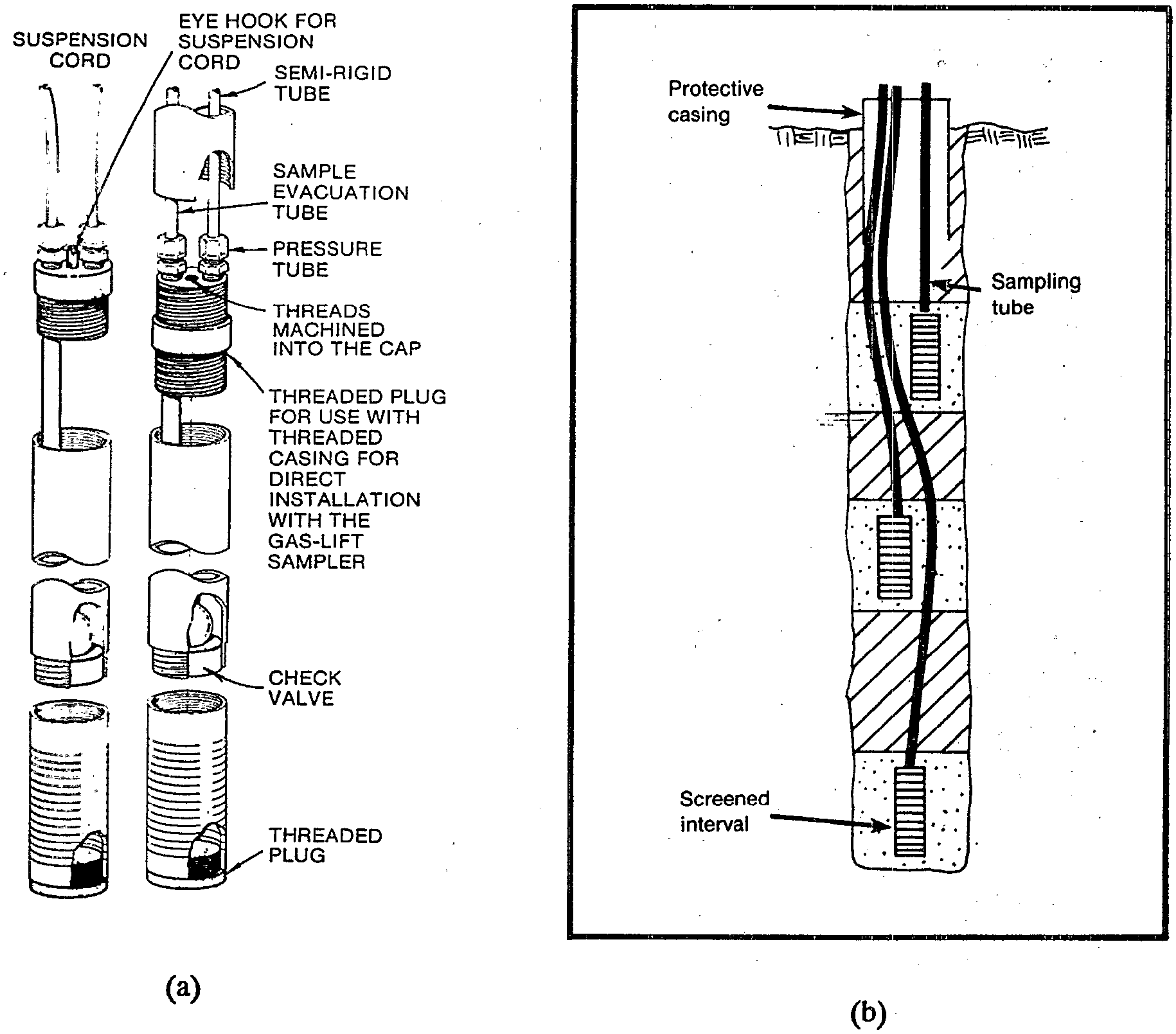


Figure 5.6.1 Capsule multilevel installation: (a) Gas-drive capsule sampling device (Morrison, 1983, by permission); (b) Multilevel installation (Aller et al., 1991, after Johnson, 1983).

5.6 FIXED IN SITU GROUND-WATER SAMPLERS

5.6.2 Multiple-Port Casings

Other Names Used to Describe Method: Vacuum-lift multiple port devices, pneumatic in-situ sampler, dialysis cell method.

Uses at Contaminated Sites: Delineating contaminant plumes; detection monitoring; ground-water quality monitoring.

Method Description: A variety of multiple port casings have been developed that allow collection of samples from different levels, using a casing that has been installed in a single borehole. In cohesionless sands, the formation collapses around the casing as a hollow-stem auger or drill casing is withdrawn from the borehole. In other formations, grout or inflatable packers can be used to isolate sampling ports. The simplest type involves field-fabricated multilevel samplers, in which individual sampling points are screen rubber stoppers placed at intervals along PVC pipe with flexible tubing that runs to the surface from each sampling point (Figure 5.6.2a). A suction-lift pump is used to obtain samples where the water table is shallow or a gas-driven piston pump can be installed by each port for deeper installations. The **Westbay** system (Figure 5.6.2b) is probably the most complex example of this type. This system has specially designed ports that allow measurement of pressure and sampling with a pneumatic device, which generally uses the same operating principles as syringe samplers (i.e., a pressurized or evacuated sample container is lowered to the sampling port and opened, allowing the sample to enter). The **Waterloo** system uses chemical packer assemblies to isolate ports (Figure 5.6.2b). The **dialysis cell** methods uses polyethylene vials with replaceable dialysis membranes at both ends placed at intervals in a perforated casing (Ronen et al., 1987). Vials are filled with distilled water and allowed to equilibrate with ground water for around 4 weeks before being removed for sample analysis.

Method Selection Considerations: **Advantages:** (1) Allow sampling for vertical distribution of ground-water constituents; (2) cost per sampling point is relatively small (except for Westbay system); (3) generally smaller diameters of individual wells in a nest compared to single-riser installations means that smaller volumes of water must be removed for purging; and (4) seals between sampling points can be obtained using permanent packers or traditional back-filled seals. **Disadvantages:** (1) Assembly and placement can be difficult; (2) cross-contamination of sampling points might occur as a result of leaky seals; (3) the number of sampling points is limited by the diameter of the borehole (does not apply to Westbay system); (4) permanent nature of installation means that devices at individual sampling points cannot be retrieved for servicing or repairs, and malfunction means the sampling point is lost; (5) the Westbay system is very expensive, but can be cost-effective if a large number of sampling points at great depth is required; (6) operation of the Westbay system requires special operator skills and can be time consuming; and (7) the down-hole complexity of the Westbay system might result in mechanical difficulties.

Frequency of Use: Vacuum-lift multiple-port casings are relatively common for monitoring of shallow aquifers in unconsolidated sediments. The dialysis cell method is uncommon.

Standard Methods/Guidelines: --

Sources for Additional Information: Aller et al. (1991), Gillham et al. (1983), Morrison (1983). See also, Table 5-5.

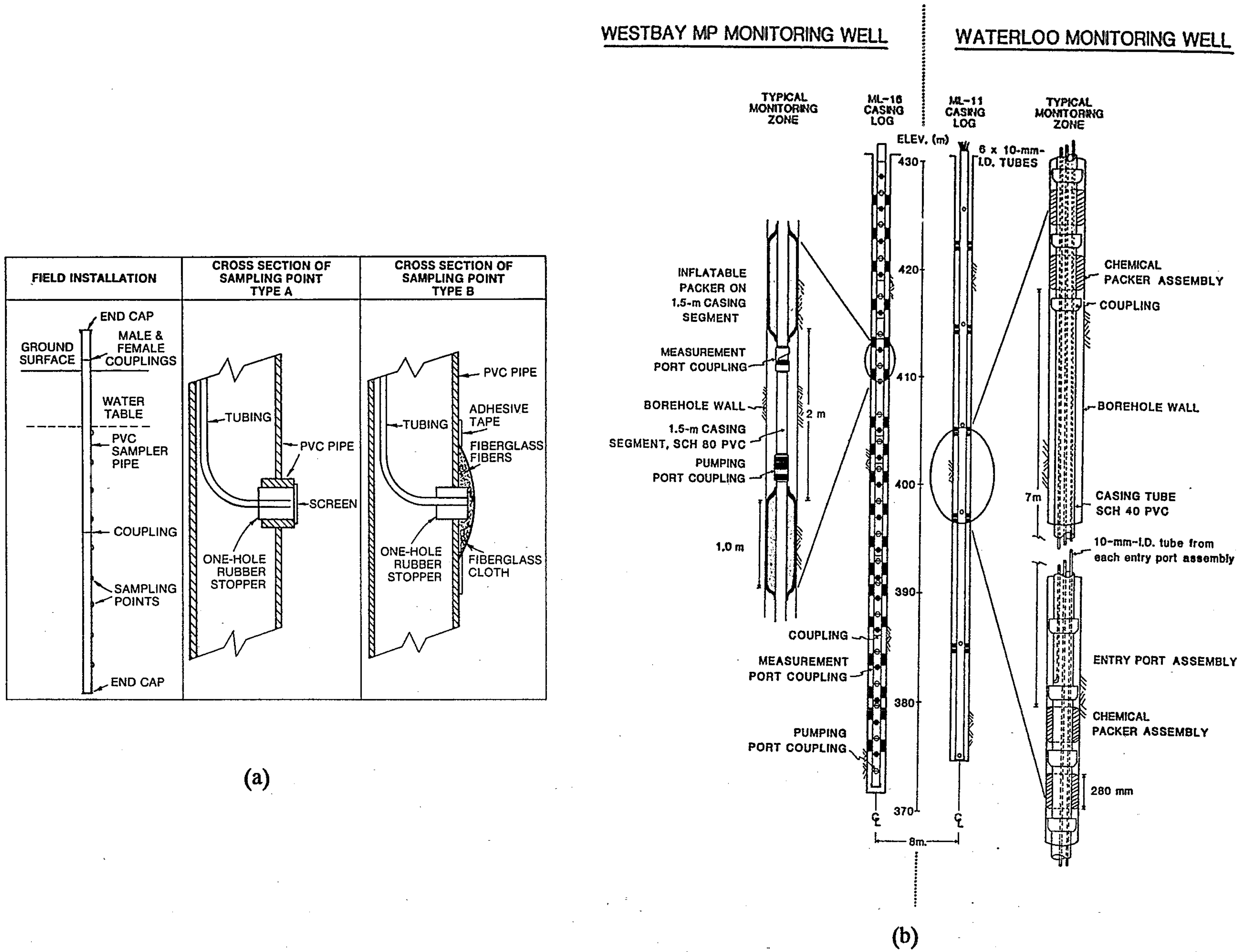


Figure 5.6.2 Multiple-port casings: (a) Field fabricated PVC multilevel sampler (Morrison, 1983, after Pickens et al., 1978); (b) Westbay and Waterloo systems (Ridgeway and Larssen, 1990, Copyright ASTM, reprinted with permission).

5.7 DESTRUCTIVE GROUND-WATER SAMPLING METHODS

5.7.1 Coring and Extraction

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Collecting ground-water samples during initial site characterization to assist in vertical placement of permanent monitoring well installations.

Method Description: Cores are collected, usually with a power-driven sampling device (see Section 2.4), which is driven ahead of the cutting head of a drill bit. Various methods are available for extracting water samples from cores (see Methods/Guidelines below).

Method Selection Considerations: **Advantages:** (1) Can provide useful information in preliminary site characterization for selection of drillhole placement and vertical placement of permanent monitoring wells; (2) use during the drilling operation keeps the option open for installing a permanent monitoring well; and (3) coring-extraction methods provide information on parameters related to both the solid and liquid phase, and might be the best way to obtain unbiased water quality samples in fine-grained formations. **Disadvantages:** (1) Cannot be used to monitor long-term trends in ground-water quality (although installation of a permanent monitoring well in the borehole from which cores have been extracted makes this possible); (2) collection of cores increases drilling costs; (3) water extracted from cores can be contaminated with drilling fluids and might undergo degassing and volatilization at the ground surface or during extraction; and (4) relatively small water samples are obtained from cores.

Frequency of Use: Uncommon.

Standard Methods/Guidelines: **Coring:** See Section 2.4; **Extraction:** See Section 9.3.4.

Sources for Additional Information: Fenn et al. (1977), Gillham et al. (1983); **Case studies:** Roberts et al. (1982), Schwartz et al. (1982). See also, references in Table 9-5.

5. GROUND-WATER SAMPLING METHODS

5.7 DESTRUCTIVE GROUND-WATER SAMPLING METHODS

5.7.2 Temporary Installations

Other Names Used to Describe Method: Multiple-completion well, screened auger.

Uses at Contaminated Sites: Collecting ground-water samples.

Method Description: Ground-water samples can be collected during drilling with a hollow-stem auger by using a **screened** auger section (Figure 5.7.2a). Various types of screens near or above the cutting head can be used, and samples can be collected using a portable sampler (suction-lift or positive-displacement), which is lowered down the hollow stem. Another type of temporary installation is the **multiple-completion well.** Multiple-completion wells can be done from the bottom up (casing is gun-perforated at the bottom, samples taken, grouted to seal perforations, perforated at the next level, sampled, grouted, etc. [see Figure 5.7.2b]), or from the top down (drilled to a certain depth, a temporary well installed and sampled, and casing removed and drilled deeper to the next sampling point [see Figure 5.7.2c]).

Method Selection Considerations: **Advantages:** In some situations temporary installations can be the most cost-effective way of obtaining preliminary and/or reconnaissance data. **Disadvantages:** (1) Cannot be used to monitor long-term trends in ground-water quality; (2) additional expense required for drilling and installation of permanent monitoring wells; (3) can be time-consuming; (4) cement grout used in multiple completion wells can affect quality of samples, but use might be justified in a deep hole where detailed vertical sampling is desired; (5) top-down multiple completion wells are very time consuming; and (6) screened-auger sampling can be expensive in very fine-grained sediments because of the time required to obtain samples from low-yielding formations, and depth of sampling might be limited by the type of sampling device that is used (suction-lift or submersible-pump).

Frequency of Use: Uncommon.

Standard Methods/Guidelines: **Multiple completion wells:** Bottom-up (Scalf et al., 1981), top-down (Yare, 1975); **Screened augers:** Scalf et al. (1981).

Sources for Additional Information: Anderson (1977), Cherry et al. (1992), Gillham et al. (1983), Karwoski et al. (1992), Tuttle and Chapman (1989); **Screened augers:** Durrett et al. (1992), Reynolds et al. (1991), Taylor and Serfini (1988).

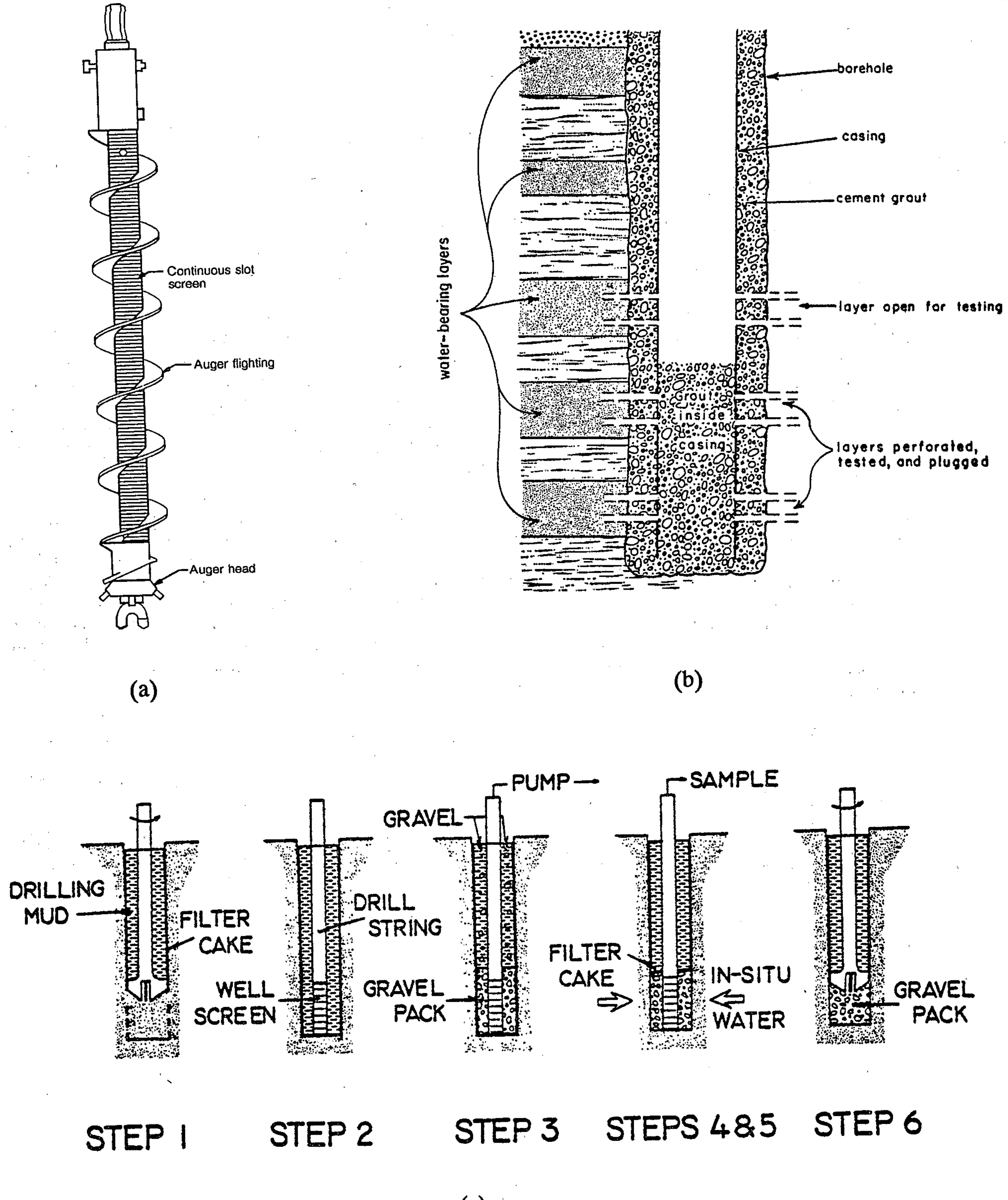


Figure 5.7.2 **Temporary installations: (a) Screened hollow-stem auger (Aller et al., 1991); (b) Bottom-up multiple completion well (Scalf et al., 1981) (c) Top-down temporary sampling wells (Gillham et al., 1983, after Yare, 1975, by permission).**

Table 5-4 Reference Index for Portable Ground-Water Sampling Devices and Installations

Topic	References
General	
Text Reviews	See Appendix C, Table C-1
Review Papers	Barcelona et al. (1984, 1988), Barker and Dickhout (1988), Blegen et al. (1987-bibliography), Bryden et al. (1986), Cherry et al. (1983), Herzog et al. (1991), Koopman (1979), Nielsen and Yeates (1985), Pohlmann and Hess (1988)
Chemical Effects	Barcelona et al. (1984, 1985b-tubing), Clark et al. (1992), Gibb and Schuller (1981), Gibb et al. (1981), Holm et al. (1988-tubing), Houghton and Berger (1984), Iles et al. (1992), Junk et al. (1974), Parker (1992-material recommendations), Pennino (1988), Rose and Long (1988-sampling for dissolved oxygen), Schuller et al. (1981), Small (1953), Stolzenburg and Nichols (1985, 1986); see also, Volatile Sample Comparisons below
Volatiles Sampling	Baerg et al. (1992), Barcelona et al. (1984), Barker and Dickhout (1988), Barker et al. (1987), Ho (1983), Imbrigiotta et al. (1987, 1988), Knobel and Mann (1993), Laney and Enberg (1992), Luhdorff and Scalmanini (1982), Mines et al. (1993), Muska et al. (1986), Pankow et al. (1985), Pearsall and Eckhardt (1987), Pohlmann et al. (1990), Reynolds et al. (1991), Rosen et al. (1992), Schalla et al. (1988), Seanor and Brannaka (1981), Sonntag (1987), Unwin (1984), Unwin and Maltby (1988), Yeskis et al. (1988)
NAPL Sampling/Detection	Abdul et al. (1989), API (1989), Blake and Hall (1984), Borst (1987), Cohen et al. (1992), Collins et al. (1991), Durnford et al. (1991), Farr et al. (1990), Feenstra et al. (1991), Hall et al. (1984), Hampton and Miller (1988), Hughes et al. (1988), Kemblowski and Chiang (1990), Korte and Kearl (1991), Kram (1990), Lenhard and Parker (1990), Lundy and Gogel (1988), McElroy et al. (1992), Preslo (1989), Sullivan et al. (1988), Testa and Paczkowski (1989), Viallaune (1985), Wagner et al. (1989), Wallace and Huntley (1992), Wilson et al. (1988), Yaniga (1984), Yaniga and Warburton (1984)
Positive Displacement (Submersible) Pumps	
Bladder	Baerg et al. (1992), Barcelona et al. (1984), Barker and Dickhout (1988), Bryden et al. (1986), Clark et al. (1992), Durrett et al. (1992), Houghton and Berger (1984), Iles et al. (1992), Imbrigiotta et al. (1988), Meyer (1990-dedicated sampler), Middleburg (1976), Muska et al. (1986), Parker et al. (1992), Paul and Puls (1992), Pohlmann et al. (1990), Ross et al. (1992), Schalla et al. (1988), Snow et al. (1992), Stolzenburg and Nichols (1985, 1986), Tai et al. (1991), Unwin (1982, 1984), Yeskis et al. (1988)
Electrical Submersible	Bryden et al. (1986), McMillion and Keeley (1968), Meyer (1990-dedicated sampler), Ring and Sale (1987); Helical-Rotor: Barcelona et al. (1984), Imbrigiotta et al. (1988), Pearsall and Eckhardt (1987), Rosen et al. (1992), Tai et al. (1991), Yeskis et al. (1988)
Gas-Drive (Displacement)	Barcelona et al. (1984), Bianchi et al. (1962), Buss and Bandt (1981), Cadwgan and Barvenick (1980), Gibb and Schuller (1981), Gibb et al. (1981), Houghton and Berger (1984), Idler (1980), Norman (1986), Parker et al. (1992), Robin et al. (1982), Scalf et al. (1981-continuous flow), Schalla et al. (1988), Timmons (1981), Tomson et al. (1980, 1981-continuous flow), Sommerfeldt and Campbell (1975), Trescott and Pinder (1970)

Topic	References
Positive Displacement (Submersible) Pumps (cont.)	
Gas-Drive (Piston)	Cadwgan et al. (1983), Cherry et al. (1983), Knobel and Mann (1993), Koopman (1979), Schalla et al. (1988), Tai et al. (1991), Yeskis et al. (1988); Single-Acting: Bianchi et al. (1962), Gillham and Johnson (1981), Hillerich (1977); Double-Acting: Signor (1978), Syringe Pump: Gillham (1982)
Other Portable Pumps	
Suction-Lift	Peristaltic: Baerg et al. (1992), Barker and Dickhout (1988), Bryden et al. (1986), Gibb and Schuller (1981), Gibb et al. (1981), Houghton and Berger (1984), Imbrigiotta et al. (1988), Paul and Puls (1992), Pearsall and Eckhardt (1987), Pettyjohn et al. (1981), Schuller et al. (1981), Tai et al. (1991); Centrifugal: Pearsall and Eckhardt (1987), Wilson (1980); Vacuum: Allison (1971), Hitchman (1988), Stolzenburg and Nichols (1985, 1986), Willardson et al. (1972); Adsorption Column Sampler: Dunlap et al. (1977), Pettyjohn et al. (1981), Rosen et al. (1992), Scalf et al. (1981)
Submersible Centrifugal	Small Diameter: Clark et al. (1992), Gass et al. (1991), Harju (1992), Iles et al. (1992), Knobel and Mann (1993), Muska et al. (1986), Parker et al. (1992), Paul and Puls (1992), Snow et al. (1992), Tai (1992), Unwin (1984), Yeskis et al. (1988); Large Diameter: Houghton and Berger (1984), Stolzenburg and Nichols (1985, 1986)
Gas-Lift	Fenn et al. (1977), Gronowski (1979), Sommerfeldt and Campbell (1975), Trescott and Pinder (1970); Chemical Effects: Gibb and Schuller (1981), Gibb et al. (1981), Houghton and Berger (1984), Iles et al. (1992), Schuller et al. (1981), Stolzenburg and Nichols (1985)
Packer	Cadwgan et al. (1983), Cherry (1965), Cherry and Johnson (1982), Galgowski and Wright (1980), Grisak et al. (1977), Truettner et al. (1986), Welch and Lee (1987)
Portable Grab/Depth-Specific Samplers	
Bailers	Bryden et al. (1986), Buss and Bandt (1981), Laney and Enberg (1992), Parker et al. (1992), Tai et al. (1991); Chemical Effects: Baerg et al. (1992), Barcelona et al. (1984), Gibb and Schuller (1981), Gibb et al. (1981), Gillham (1982), Iles et al. (1992), Imbrigiotta et al. (1988), Muska et al. (1986), Pearsall and Eckhardt (1987), Pohlmann et al. (1990), Schalla et al. (1988), Schuller et al. (1981), Seanor and Brannaka (1981), Snow et al. (1992), Stolzenburg and Nichols (1985, 1986), Thomey et al. (1991), Unwin (1984), Yeskis et al. (1988)
Pneumatic Depth-Specific	Baerg et al. (1992-syringe), Barcelona et al. (1984), Bryden et al. (1986), Gillham (1982-syringe), Ficken (1988), Imbrigiotta et al. (1988), Johnson et al. (1987), MacPherson and Pankow (1988), Muska et al. (1986), Pankow et al. (1984, 1985), Pohlmann et al. (1990-Westbay), Rosen et al. (1992-dowhole ATD sampler)
Sampling Installations for Portable Samplers	
Nested Wells/Single Borehole	Cadwgan et al. (1983), Korte and Kearl (1991), Nakamoto et al. (1986), Patton and Smith (1988); Bundle Piezometers: Cherry et al. (1980), Cherry et al. (1983), Hitchman (1988), Jackson et al. (1985), Lee and Cherry (1979), Stites and Chambers (1991)

Table 5-5 Reference Index for In-Place and In Situ Samplers/Installations

Topic	References
<u>In Situ Samplers</u>	
Hydropunch®	Bergren et al. (1990), Cordry (1986, 1991), Edge and Cordry (1989), Ehrenzeller et al. (1991), Kaback et al. (1990), Klabanow et al. (1992), Kuhlmeier and Sturdivant (1992), Lammons et al. (1989), Smolley and Kappmeyer (1989, 1991), Strutynsky and Sainey (1992), Taylor and Berzins (1988), Zemo et al. (1992a, 1992b)
Other Cone Penetrometer Samplers	Berzins (1992), Chiang et al. (1989a, 1989b, 1992), Christy and Spradlin (1992), Cooper et al. (1989, 1990, 1991), Haldorsen et al. (1985), Karwoski et al. (1992), Klopp et al. (1989), Lang et al. (1991), Litherland et al. (1985), Lucero (1989, 1990), Mines et al. (1993), Pohlmann et al. (1990), Smolley and Kappmeyer (1989, 1991), Smythe et al. (1988), Strutynksy and Sainey (1990, 1992), Strutynksy et al. (1992), Taylor and Berzins (1988), Torstensson (1984), Torstensson and Petsonk (1988), Zemo et al. (1992a, 1992b)
Well Point Samplers	Cherry et al. (1992-temporary, multilevel), Harrison and Ostercamp (1981), Harrison et al. (1981), John et al. (1977), Patton (1990), Reeve and Doering (1965), Rutter and Webster (1962), Summerfield (1973)
Fiber optics	<u>Texts/Reports</u>: Eccles and Simon (1987), Eccles et al. (1987), Hirschfield et al. (1984), Murphy and Hostetler (1989), U.S. EPA (1988a,b), Wilson and Hawks (1983); <u>Papers</u>: Arendale and Hatcher (1991-calibration), Barnard and Walt (1991), Beemster and Schlager (1992), Carrabba et al. (1988, 1991-spectroelectrochemical), Chudyk et al. (1988, 1990, 1991), Ferrel et al. (1988), Finger et al. (1988-porous), Griffin and Olsen (1992), Kenny et al. (1988), Klainer et al. (1988a,b), Knuth (1991-TNT), Lieberman et al. (1991), Milanovich et al. (1991-TCE), Morlock (1989), Morlock et al. (1992-VOCs), Nielsen et al. (1991), Olsen et al. (1988), Shahriari et al. (1988-porous), Smith et al. (1988), St. Germain and Gillislpie (1991), Tabacco et al. (1991-porous); <u>UV Fluorescence</u>: Gillispie and St. Germain (1988), Haas et al. (1988, 1991), Taylor et al. (1991); <u>UV Absorption Spectroscopy</u>: Beemster and Schlager (1991); <u>Immunochemical</u>: Bolts et al. (1988), Lin et al. (1988)
<u>In Situ Multilevel Installations</u>	
Gas-Drive/Suction Lift	Boyle (1992); <u>Individual Gas Drive Samplers</u>: Barker et al. (1987), Barvenik and Cadwgan (1983), Cherry et al. (1983), Lofy et al. (1977), Morrison and Brewer (1981), Morrison and Ross (1978); <u>Suction</u>: Cherry et al. (1983), Eleuterius (1980), John et al. (1977)
Multiple Port Casings	Morrison and Brewer (1981), Ronen et al. (1987-dialysis cells), Welch and Lee (1987); <u>Multiple Port Well Casing</u>: Cherry et al. (1983), Gillham and Johnson (1981), Hyman and McLaughlin (1991), Pickens et al. (1978, 1981), Wells (1988); <u>Packer/Waterloo System</u>: Cherry and Johnson (1982), Rehtlane and Patton (1982), Ridgeway and Larssen (1990); <u>Westbay System</u>: Black et al. (1986), Dreier et al. (1991), Gilmore (1990), Pohlmann et al. (1990), Ridgeway and Larssen (1990), Vispi (1980); <u>Auger Installed Multilevel Sampler</u>: Boggs and Hemond (1988)

SECTION 5 REFERENCES

Abdul, A.S., S.F. Kia, and T.L. Gibson. 1989. Limitations of Monitoring Wells for the Detection and Quantification of Petroleum Products in Soils and Aquifers. Ground Water Monitoring Review 9(2):90-99. (Also in: 3rd NOAC, pp. 357-272.)

Aller, L., et al. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. EPA/600/4-89/034, 221 pp. Available from CERI.* (Also published in 1989 by the National Water Well Association, Dublin, OH, in its NWWA/EPA series, 398 pp.)

Allison, L. 1971. A Simple Device for Sampling Ground Waters in Auger Holes. Soil Sci. Soc. Am. Proc. 35:844-845.

American Petroleum Institute (API). 1989. A Guide to the Assessment and Remediation of Underground Petroleum Releases. API Publication 1628, Washington, DC.

American Society for Testing and Materials (ASTM). 1982. Standard Terminology Used with Ion-Selective Electrodes. D4127-82, (Vol. 11.01), ASTM, Philadelphia, PA. [Revisions in preparation]

Anderson, E.G. 1977. New Groundwater Contaminant Sampler for Contaminant Plume Mapping. Canadian Water Well, p. 36. (As cited in Gillham et al., 1983.)

Arendale, W.F. and R. Hatcher. 1991. Calibration of Fiber Optic Chemical Sensors. In: U.S. EPA (1991), Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals EPA/600/9-91/028 (NTIS PB 92-125764), pp. 597-598.

Baerg, D.F., R.C. Starr, J.A. Cherry, and D.J.A. Smyth. 1992. Performance Testing of Conventional and Innovative Downhole Samplers and Pumps for VOCs in a Laboratory Monitoring Well. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 71-75. [Bailer, syringe sampler, bladder pump, peristaltic pump, inertial pump]

Barcelona, M.J. and J.P. Gibb. 1988. Development of Effective Ground-Water Sampling Protocols. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 17-26.

Barcelona, M.J., J.P. Gibb, and R.A. Miller. 1983. A Guide to the Selection of Materials for Monitoring Well Construction and Ground-Water Sampling. ISWS Contract Report 327, Illinois State Water Survey, Champaign, IL, 78 pp.

Barcelona, M.J., J.A. Helfrich, E.E. Garske, and J.P. Gibb. 1984. A Laboratory Evaluation of Ground Water Sampling Mechanisms. Ground Water Monitoring Review 4(2):32-41. [Bailer, syringe, bladder pump, helical rotor, gas-drive (displacement), peristaltic pump]

Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske. 1985a. Practical Guide for Ground-Water Sampling. EPA/600/2-85/104 (NTIS PB86-137304). (Also published as ISWS Contract Report 374, Illinois State Water Survey, Champaign, IL.)

Barcelona, M.J., J.A. Helfrich, and E.E. Garske. 1985b. Sampling Tubing Effects on Groundwater Samples. Anal. Chem. 57:460-464.

Barcelona, M.J., J.A. Helfrich, and E.E. Garske. 1988. Verification of Sampling Methods and Selection of Materials for Ground-Water Contamination Studies. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 221-231.

Barker, J.F. and R. Dickhout. 1988. An Evaluation of Some Systems for Sampling Gas-Charged Ground Water for Volatile Organic Analysis. Ground Water Monitoring Review 8(4):112-119. [Inertial-lift pump, bladder pump, peristaltic pump]

Barker, J.F., G.L. Patrick, L. Lehman, and G.M. Travis. 1987. Some Biases in Sampling Multilevel Piezometers for Volatile Organics. Ground Water Monitoring Review 7(2):48-54. [Suction lift, gas drive]

Barnard, S.M. and D.R. Walt. 1991. Fiber-Optic Organic Vapor Sensor. Environ. Sci. Technol. 25:1301-1304.

Barvenik, M.J. and D.R.M. Cadwgan. 1983. Multi-Level Gas-Drive Sampling of Deep Fracture Rock Aquifers in Virginia. Ground Water Monitoring Review 3(4):34-40.

Beemster, B.J. and K. Schlager. 1991. In-Situ Ultraviolet-Visible Absorption Spectroscopy: A New Tool for Groundwater Monitoring. In: Ground Water Management 5:3-16 (5th NOAC). [Fiber optics]

Beemster, B.J., K.J. Schlager, C.A. Bergstrom, and K.A. Rusch. 1992. In-Situ Fiber-Optic Absorptions and Emission Spectrometry for Simultaneous Multiple Component Analysis in Groundwater. Ground Water Management 11:357-368 (6th NOAC).

Berg, E.L. 1982. Handbook for Sampling and Sample Preservation of Water and Wastewater, 2nd edition. EPA/600/4-82/029 (NTIS PB83-124503), 414 pp. (Replaces report with same title by Huibregste and Mover, EPA/600/4-76/049.)

Bergren, C.L., R.C. Tuckfield, and N.M. Park. 1990. Suitability of the Hydropunch® for Assessing Groundwater Contaminated by Volatile Organics. In: Proc. 4th Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 387-401.

Berzins, N.A. 1992. Use of the Cone Penetration Test and BAT Groundwater Monitoring System to Assess Deficiencies in Monitoring Well Data. Ground Water Management 11:327-340 (6th NOAC).

Bianchi, W., C. Johnson, and E. Haskell. 1962. A Positive Action Pump for Sampling Small Bore Holes. Soil Sci. Soc. Am. Proc. 26:86-87.

Black, W.H., H.R. Smith, and F.D. Patton. 1986. Multiple-Level Ground Water Monitoring with the MP System. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 41-61.

Blake, S.B. and R.A. Hall. 1984. Monitoring Petroleum Spills with Wells: Some Problems and Solutions. In: Proc. 4th Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 305-310.

Blegen, R.P., K.F. Pohlmann, and J.W. Hess. 1987. Bibliography of Ground-Water Sampling Methods. EPA/600/X-87/325, U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, 43 pp.

Boggs, J.M. and H.F. Hemond. 1988. Evaluation of Tracer Sampling Devices for the Macrodispersion Experiment. EPRI EA-5816, Electric Power Research Institute, Palo Alto, CA, 80 pp. [Comparison of auger-installed multi-level sampler, driveable multi-level sampler, and driveable in situ membrane probe]

Bolts, J.M., et al. 1988. Integrated Immunochemical Systems for Environmental Monitoring. In: U.S. EPA (1988b), pp. 243-248. [Fiber optics]

Borst, M. 1987. Sampling Oil-Water Mixtures at OHMSETT. EPA/600/2-87/073 (NTIS PB88-102892).

Boyle, D.R. 1992. A Multilevel Ground Water Monitoring System for Casing Advance and Bedrock Drilling Methods. Ground Water Monitoring Review 12(2):105-115.

Bryden, G.W., W.R. Mabey, and K.M. Robine. 1986. Sampling for Toxic Contaminants in Ground Water. Ground Water Monitoring Review 6(2):67-72. [Bladder, suction, submersible pumps, bailer]

Bureau of Reclamation. 1981. Ground Water Manual--A Water Resources Technical Publication, 2nd edition. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO. [Packer pump]

Buss, D.F. and K.E. Bandt. 1981. An All-Teflon Bailer and an Air-Driven Pump for Evacuating Small-Diameter Ground-Water Wells. Ground Water 19:429-431.

Cadwgan, R. and M. Barvenik. 1980. Monitoring Device Simplifies Sample Collection. Water Well Journal 34:48-50.

Cadwgan, R.M., M.J. Barvenik, and A.D. Ehrenfreid, and D. Ulllinsky. 1983. Improving Monitoring Efficiency at Deep Wells. Ground Water Monitoring Review 3(1):110-118. [Gas-drive piston, packer samplers]

Carrabba, M.M., R.B. Edmonds, P.J. Marren, and R.D. Rauh. 1988. The Suitability of Surface Enhanced Raman Spectroscopy (SERS) to Fiber Optic Sensing of Aromatic Hydrocarbon Contamination in Groundwater. In: U.S. EPA (1988b), pp. 31-40.

Carrabba, M.M., R.B. Edmonds, R.D. Rauh, and J.W. Haas, III. 1991. Spectroelectrochemical Sensing of Chlorinated Hydrocarbons for Field Screening and In Situ Monitoring Applications. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 67-72. [Fiber optic, carbon tetrachloride, DCE, chloroform, TCE]

Cherry, J. 1965. A Portable Sampler for Collecting Water Samples from Specific Zones in Uncased or Screened Wells. U.S. Geological Survey Professional Paper 25-C, pp. C214-C216.

Cherry, J. and P. Johnson. 1982. A Multilevel Device for Monitoring in Fractured Rock. Ground Water Monitoring Review 2(3):41-44.

Cherry, J., R. Gillham, G. Anderson, and P. Johnson. 1980. CFB Borden Landfill Study, Vol. 2: Groundwater Monitoring Devices. Final Report Submitted to the Canadian Dept. of Supply and Services, OSU 78-00195, 34 pp.

Cherry, J.A., R.W. Gillham, E.G. Anderson, and P.E. Johnson. 1983. Migration of Contaminants in Groundwater at a Landfill: A Case Study 2. Groundwater Monitoring Devices. J. Hydrology 63:31-49. [Hollow-stem auger suction sampler, multi-level installation and bundle piezometers with suction and gas-drive piston samplers]

Cherry, J.A., R.A. Ingleton, and D.K. Solomon, and N.D. Farrow. 1992. Low Technology Approaches for Drive Point Profiling of Contaminant Distributions. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 109-111. [Temporary, multi-level sampling installations]

Chiang, C.Y., C.C. Stanley, L. Hekma, and G.F. Boehm. 1989a. Characterization of Ground Water and Soil Conditions by Cone Penetrometry. In: Proc. 6th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 141-157.

Chiang, C.Y., K.R. Loos, R.A. Klopp, and M.C. Beltz. 1989b. A Real-Time Determination of Geological/Chemical Properties of an Aquifer by Penetration Testing. In: Proc. 6th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, , pp. 175-189.

Chiang, C.Y., K.R. Loos, and R.A. Klopp. 1992. Field Determination of Geological/Chemical Properties of an Aquifer by Cone Penetrometry and Headspace Analysis. Ground Water 30:428-436.

Christy, T.M. and S.C. Spradlin. 1992. The Use of Small Diameter Probing Equipment for Contaminated Site Investigations. Ground Water Management 11:87-101 (6th NOAC). [Geoprobe: soil vapor, solids, ground-water sampling]

Chudyk, W., K. Pohlig, N. Rico, and G. Johnson. 1988. Field Screening for Aromatic Organics Using Laser-Induced Fluorescence and Fiber Optics. In: U.S. EPA (1988b), pp. 99-104.

Chudyk, W., K. Pohlig. K. Exarhoulakos, J. Holsinger, and N. Rico. 1990. In Situ Analysis of Benzene, Ethylbenzene, Toluene, and Xylenes (BTEX) Using Fiber Optics. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 266-272.

Chudyk, W., K. Pohlig, C. Botteron, and R. Najjar. 1991. Practical Limits in Field Determination of Fluorescence Using Fiber Optic Sensors. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 629-630.

Clark, S.B., N.M. Park, and R.C. Tuckfield. 1992. Effects of Sample Collection Device and Filter Pore Size On Concentrations of Metals in Groundwater Samples (U). In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 13-19. [Bladder pump, submersible centrifugal pump]

Cohen, R.M., A.P. Bryda, S.T. Shaw and C.P. Spalding. 1992. Evaluation of Visual Methods to Detect NAPL in Soil and Water. Ground Water Monitoring Review 12(4):132-141.

Collins, M., K.D. Drake, and W.R. Rohrman. 1991. Monitoring Well Design and Sampling Techniques at NAPL Sites. Ground Water Management 5:749-758 (5th NOAC).

Cooper, S.S., P.G. Malone, R.S. Olsen, and G.B. Morhman. 1988. Use of an Instrumented Cone Penetrometer in Monitoring Land Disposal Sites. In: HWHM '88 (Proc. 5th Nat. Conf. on Hazardous Wastes and Hazardous Materials), Hazardous Material Control and Research Institute, Silver Spring, MD, pp. 424-427.

Cooper, S.S., P.G. Malone, P.W. Lurk, and S.H. Lieberman. 1990. Development of Innovative Penetrometer Technology for the Detection and Delineation of Contaminated Soils. In: Proc. 14th Annual Army Environmental R&D Symp. (1989), CETHA-TE-TR-90055, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 577-588.

Cooper, S.S., P.G. Maline, G. Comes, W. Sisk, and S.H. Lieberman. 1991. Progress in the Development of Innovative Penetrometer Technology for the Detection and Delineation of Contaminated Soil. In: Proc. 15th Annual Army Environmental R&D Symp. (1990), CETHA-TS-CR-91077, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 711-722.

Cordry, K.E. 1986. Ground Water Sampling Without Wells. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 262-271. [Hydropunch]

Cordry, K. 1991. Hydropunch II--The Second Generation: A New In Situ Ground Water Sampling Tool. Ground Water Management 5:749-758 (Proc. of the 5th Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods).

deVera, E.R. 1980. Samplers and Sampling Procedures for Hazardous Waste Streams. EPA/600/2-80/018 (NTIS PB80-135353).

Dreier, R.B., T.O. Early, and J.L. King. 1991. Groundwater Studies at the Oak Ridge Y-12 Plant Using Multiport Monitoring Systems Installed in Coreholes. Ground Water Management 7:239-253 (8th Eastern Ground Water Issues Conf.). [Westbay system]

Driscoll, F.G. 1986. Groundwater and Wells, 2nd edition. Johnson Filtration Systems, Inc., St. Paul, MN, 1089 pp.

Dunlap, W.J., J.F. McNabb, M.R. Scalf, and R.L. Cosby. 1977. Sampling for Organic Chemicals and Microorganisms in the Subsurface. EPA/600/2-77/176 (NTIS PB-272679).

Durnford, D., J. Brookman, J. Billica, and J. Milligan. 1991. LNAPL Distribution in Cohesionless Soil: A Field Investigations and Cryogenic Sampler. Ground Water Monitoring Review 11(3):115-122.

Durrett, C., J. Kubiczki, J. Hamel, and D.W. Folan. 1992. An Innovative Field Method to Determine the Presence and Extent of Volatile Organic Compounds in Water. Ground Water Management 13:293-303 (8th Focus Conf. Eastern GW Issues). [Screened hollow-stem auger with packer and bladder pump]

Eccles, L.A. and S.J. Simon. 1987. In Situ Monitoring at Superfund Sites with Fiber Optics, II. Plan for Development. EPA/600/X-87/415. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Eccles, L.A., S.J. Simon, and S.M. Kaliner. 1987. In Situ Monitoring at Superfund Sites with Fiber Optics, I. Rationale. EPA/600/X-87/156. U.S. EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Edge, R.W. and K. Cordry. 1989. The Hydropunch: An In Situ Sampling Tool for Collection of Ground Water from Unconsolidated Sediments. Ground Water Monitoring Review 9(3):177-183.

Ehrenzeller, J.L., F.G. Baker, and V.E. Keys. 1991. Using the Cone Penetrometer and Hydropunch Method to Collect Reconnaissance Ground Water Samples. Ground Water Management 5:733-746 (5th NOAC).

Eleuterius, L. 1980. A Rapid In Situ Method of Extracting Water From Tidal Marsh Soils. Soil Sci. Soc. Am. J. 44:884-886.

Everett, L.G., L.G. Wilson, and E.W. Hoylman. 1983. Vadose Zone Monitoring for Hazardous Waste Sites. EPA/600/X-83/064 (NTIS PB84-212752). (Also published in 1984 by Noyes Data Corporation, Park Ridge, NJ.)

Farr, A.M., R.J. Houghtalen, and D.B. McWhorter. 1990. Volume Estimation of Light Nonaqueous Phase Liquids in Porous Media. Ground Water 28(11):48-56.

Feenstra, S., D.M. Mackay, and J.A. Cherry. 1991. A Method for Assessing Residual NAPL Based on Organic Chemical Concentration in Soil Samples. Ground Water Monitoring Review 11(2):128-136.

Fenn, D., E. Cocozza, J. Isbister, O. Braids, B. Yare, and P. Roux. 1977. Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities. EPA/530/SW-611 (NTIS PB84-174820).

Ferrell, T.L., et al. 1988. Fiber-Optic Surface-Enhanced Raman System for Field Screening of Hazardous Compounds. In: U.S. EPA (1988b), pp. 41-42.

Ficken, J.H. 1988. Recent Development of Downhole Water Samplers for Trace Organics. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 253-257. [Pneumatic depth-specific samplers]

Finger, S.M. et al. 1988. Porous Glass Fiber Optic Sensors for Field Screening of Hazardous Waste Sites. In: U.S. EPA (1988b), pp. 127-132.

Ford, P.J., P.J. Turina, and D.E. Seely. 1984. Characterization of Hazardous Waste Sites--A Methods Manual: Vol. II: Available Sampling Methods, 2nd edition. EPA/600/4-84/076 (NTIS PB85-521596).

Galgowski, C. and W. Wright. 1980. A Variable-Depth Ground-Water Sampler. Soil Sci. Soc. Am. J. 44:1120-1121.

Gass, T.E., J.F. Barker, R. Dickhout, and J.S. Fyle. 1991. Test Results of the Grundfos Ground-Water Sampling Pump. Ground Water Management 5:553-565. [Submersible centrifugal pump]

Gibb, J.P. and R.M. Schuller. 1981. Collection of Representative Water Quality Data from Monitoring Wells. In: Proc. 7th Annual Research Symp. Land Disposal: Municipal Solid Waste, EPA/600/9-81/002a (NTIS PB81-173874), pp. 126-137. [Peristaltic pump, air-lift, gas-drive (nitrogen displacement), bailer]

Gibb, J.P., R.M. Schuller, and R.A. Griffin. 1981. Procedures for the Collection of Representative Water Quality Data from Monitoring Wells. ISWS/ISGS Cooperative Groundwater Report 7, Illinois State Water Survey and Illinois State Geological Survey, Urbana, IL. [Peristaltic pump, air-lift, gas-drive (nitrogen displacement), bailer]

Gillham, R. 1982. Syringe Devices for Ground Water Sampling. Ground Water Monitoring Review 2(2):36-39.

Gillham, R.W. and P.E. Johnson. 1981. A Positive-Displacement Groundwater Sampling Device. Ground Water Monitoring Review 1(3):33-35.

Gillham, R.W., M.J.L. Robin, J.F. Barker, and J.A. Cherry. 1983. Groundwater Monitoring and Sample Bias. API Publication 4367. American Petroleum Institute, Washington, DC, 206 pp.

Gillispie, G.D. and R. St. Germain. 1988. Wavelength Tunable Portable Laser for Remote Fluorescence Analysis. In: U.S. EPA (1988b), pp. 94-98. [UV fiber optic]

Gilmore, T.J. 1990. Installations of Two Westbay Multiport Ground-Water Monitoring Systems Using a Backfilling Technique. Ground Water Management 2:177-191 (4th NOAC).

Griffin, J.W. and K.B. Olsen. 1992. A Review of Fiber Optic and Related Technologies for Environmental Sensing Applications. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 311-328.

Grisak, G., W. Merritt, and D. Williams. 1977. A Fluoride Borehole Dilution Apparatus for Ground-Water Velocity Measurements. Can. Geotech. J. 14:554-561.

Gronowski, R. 1979. Innovations Simplify Shallow Well Monitoring. Water Well Journal 33:57.

Haas, III, J.W., E.Y. Lee, C.L. Thomas, and R.B. Gammage. 1988. Second-Derivative Ultraviolet Absorption Monitoring or Aromatic Contaminants in Groundwaters. In: U.S. EPA (1988b), pp. 105-110. [UV fiber optic]

Haas, III, J.W., T.G. Matthews, and R.B. Gammage. 1991. In Situ Detection of Toxic Aromatic Compounds in Groundwater Using Fiberoptic UV Spectroscopy. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 677-681.

Haldorsen, S., A.M. Petsonk, and B.A. Torstensson. 1985. An Instrument for In Situ Monitoring of Water Quality and Movement in the Vadose Zone. In: Proc. NWWA Conf. on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Worthington, OH, pp. 158-172. [Cone penetrometer/BAT system]

Hall, R.A., S.B. Blake, and S.C. Champlin, Jr. 1984. Determination of Hydrocarbon Thickness in Sediments Using Borehole Data. In: Proc. 4th Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 300-303.

Hampton, D.R. and P.D.G. Miller. 1988. Laboratory Investigations of the Relationship Between Actual and Apparent Product Thickness in Sands. In: Proc. [5th] NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 157-182.

Hansen, E.A. and A. Harris. 1974. A Groundwater Profile Sampler. Water Resources Research 10(2):375.

Hansen, E.A. and A. Harris. 1980. An Improved Technique for Spatial Sampling of Solutes in Shallow Groundwater Systems. Water Resources Research 16:827-829.

Harju, J.A. 1992. Hydrologic Investigations of Contaminants at Ultra-Trace Concentrations Utilized Dedicated Sampling Pumps. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 7-10. [Submersible centrifugal pump]

Harrison, W. and T. Osterkamp. 1981. A Probe Method for Soil Water Sampling and Subsurface Measurements. Water Resources Research 17:1731-1736.

Harrison, W., T. Osterkamp, and M. Inoue. 1981. Details of a Probe Method for Interstitial Soil Water Sampling and Hydraulic Conductivity and Temperature Measurement. Geophysics Institute Report. No. UAG R-280. University of Alaska/Fairbanks.

Herzog, B.L., J.D. Pennino, and G.L. Nielsen. 1991. Ground-Water Sampling. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 449-499. [Bailers, syringe, suction-lift, gas-drive, bladder pump, submersible (gear-drive, helical rotor), gas-drive piston]

Hillerich, M.S. 1977. Air-Driven Piston Pump for Sampling Small Diameter Wells. U.S. Geological Survey, Water Resources Division Bulletin Oct-Dec:46-47.

Hirschfield, T., T. Deaton, F.M. Ionovish, and S.M. Klainer. 1984. Feasibility of Using Fiber Optics for Monitoring Groundwater Contaminants. EPA/600/7-84/067 (NTIS PB84-201607), 92 pp.

Hitchman, S. 1988. A Collection Manifold for Multilevel Ground-Water Sampling Devices. Ground Water 26:348-349.

Ho, J.S.-Y. 1983. Effect of Sampling Variables on Recovery of Volatile Organics in Water. J. Am. Water Works Ass. 75(12):583-586.

Holm, T.R., G.K. George, and M.J. Barcelona. 1988. Oxygen Transfer through Flexible Tubing and Its Effects on Ground Water Sampling Results. Ground Water Monitoring Review 8(3):83-89.

Houghton, R.L. and M.E. Berger. 1984. Effects of Well Casing Composition and Sampling Method on Apparent Quality of Ground Water. In: Proc. 4th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Association, Worthington, OH, pp. 203-213. [Bladder, gas-drive, peristaltic, submersible centrifugal, gas-lift, mechanical depth-specific samplers]

Hughes, J.P., C.R. Sullivan, and R.E. Zinner. 1988. Two Techniques for Determining the True Hydrocarbon Thickness in an Unconfined Aquifer. In: Proc. 5th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, Volume 1, pp. 291-314.

Hyman, J.A. and D.B. McLaughlin. 1991. Multi-Level Sampling for Naphthalene in a Shallow, Sandy Aquifer. Ground Water Management 5:777-785 (5th NOAC).

Idler, G. 1980. Modification of an Electronic Downhole Water Sampler. Ground Water 18:532-535.

Iles, D.L., P.D. Hammond, and L.D. Schulz. 1992. Effects of Sampling Methods on Inorganic Water Chemistry Results. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 41-68. [Bladder, submersible centrifugal, jet, air lift, and inertial pumps, bailer]

Imbrigiotta, T.E., J. Gibs, J.F. Pankow, and M.R. Rosen. 1987. Field Comparison of Downhole and Surface Sampling Devices for Purgeable Organic Compounds. In: Proc. 3rd Tech. Meeting, U.S. Geological Survey Program on Toxic Waste-Ground Water Contamination, U.S. Geological Survey Open File Report 87-109, pp. E5-E9. [Downhole isobaric samplers, downhole ATD, helical rotor pump, submersible pump, surface ATD, point source bailer]

Imbrigiotta, T.E., J. Gibs, T.V. Fusillo, G.R. Kish, and J.J. Hochreiter. 1988. Field Evaluation of Seven Sampling Devices for Purgeable Organic Compounds in Ground Water. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 258-273. [Bladder pump, helical-rotor, gear-drive submersible, open bailer, point-source bailer, syringe sampler, peristaltic pump]

Jackson, R.E., R.J. Patterson, B.W. Graham, J. Bahr, D. Belanger, J. Lockwood, and M. Priddle. 1985. Contaminant Hydrogeology of Toxic Organic Chemicals at a Disposal Site, Gloucester, Ontario, 1. Chemical Concepts and Site Assessment. Inland

Waters Directorate Scientific Series No. 141. Environment Canada, Ottawa, Ontario, 114 pp.

Jeffers, E.L., et al. 1982. Water Reclamation and Automated Water Quality Monitoring. EPA/600/2-82/043 (NTIS PB82-227497), 216 pp.

John, P., M. Lock, and M. Gibbs. 1977. Two New Methods for Obtaining Water Samples from Shallow Aquifers and Littoral Sediments. J. Environ. Qual. 6:322-324.

Johnson, M.G. 1981. The Stratified Sample Thief--A Device for Sampling Unknown Fluids. In: Proc. Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 154-157.

Johnson, T.L. 1983. A Comparison of Well Nests Versus Single-Well Completions. Ground Water Monitoring Review 3(1):76-78.

Johnson, R.L., J.F. Pankow, and J.A. Cherry. 1987. Design of a Ground Water Sampler for Collecting Volatile Organics and Dissolved Gases in Small-Diameter Wells. Ground Water 25:448-454.

Junk, G.A., H.J. Svec, R.D. Vick, and M.J. Avery. 1974. Contamination of Water by Synthetic Polymer Tubes. Environ. Sci. Technol. 8:1100-1106.

Kaback, D.S., C.L. Bergren, C.A. Carlson, and C.L. Carlson. 1990. Testing a Ground Water Sampling Tool: Are the Samples Representative? Ground Water Management 2:403-417 (4th NOAC). [Hydropunch]

Karwoski, T.J., J.E. Moser, K.J. Quinn, and D.E. Penniman. 1992. Vertical Groundwater Quality Screening: A Cost-Effective Approach to 3-D Investigations. Ground Water Management 11:385-400 (6th NOAC). [Temporary installations, cone penetrometer samplers]

Kaufman, R.F., T.A. Gleason, R.B. Ellwood, and G.P. Lindsey. 1981. Ground-Water Monitoring Techniques for Arid Zone Hazardous Waste Disposal Sites. Ground Water Monitoring Review 1(3):47-54. [Submersible pumps, bailers]

Kemblowski, M.W. and C.Y. Chiang. 1990. Hydrocarbon Thickness Fluctuations in Monitoring Wells. Ground Water 28(2):244-252.

Kenny, J.E., G.B. Jarvis, and H. Xu. 1988. Instrumentation and Methodology for Multicomponent Analysis Using In Situ Laser-Induced Fluorescence. In: U.S. EPA (1988b), pp. 133-139.

Klabanow II, R.I., K.A. Andersson, and T.J. McDonald. 1992. Hydropunch Sampling Techniques for Multi-Level Sampling of an Unconfined Alluvial Aquifer--Central Valley, California: A Case Study. Ground Water Management 11:315-325 (6th NOAC).

Klainer, S.M., et al. 1988a. Monitoring Gasoline Vapor and Liquid by Fiber Optic Chemical Sensor (FOCS) Technology. In: U.S. EPA (1988b), pp. 25-30.

Klainer, S.M., J.D. Koutsandreas, and L. Eccles. 1988b. Monitoring Ground-Water and Soil Contamination by Remote Fiber Spectroscopy. In: Ground-Water Contamination: Field Methods, ASTM STP 963, A.G. Collins and A.I. Johnson (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 370-380.

Klopp, R.A., A. M. Petsonk, and B.-A. Torstensson. 1989. In-Situ Penetration Testing for Delineation of Ground Water Contaminant Plumes. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 329-343.

Knobel, L.L. and L.J. Mann. 1993. Sampling for Purgeable Organic Compounds Using Positive-Displacement Piston and Centrifugal Submersible Pumps: A Comparative Study. Ground Water Monitoring and Remediation 13(2):142-148.

Knuth, K.V. 1991. Portable Dual Wavelength Analyzer for Detection of TNT in Ground Water Using Fiber Optics. In: Proc. 15th Annual Army Environmental R&D Symp. (1990), CETHA-TS-CR-91077, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 147-152.

Koopman, F. 1979. Downhole Pumps for Water Sampling in Small Diameter Wells. U.S. Geological Survey Open File Report 79-1264. [Gas-drive piston, submersible centrifugal pump, helical rotor pump, jet pump]

Korte, N.E. and P.M. Kearl. 1991. The Utility of Multiple-Completion Monitoring Wells for Describing a Solvent Plume. Ground Water Monitoring Review 11(2):153-156.

Kram, M. 1990. Measurement of Floating Petroleum Product Thickness and Determination of Hydrostatic Head in Monitoring Wells. NEESA Energy and Environmental News Inf. Bull. No. IB-107 (November), Naval Energy and Environmental Support Activity, Port Hueneme, CA.

Kuhlmeier, P.D. and T.E. Sturdivant. 1992. Delineation of Lithology and Groundwater Quality in a Complex Fluvial Estuarine Depositional Zone. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 183-198. [Hydropunch]

Lammons, T.L., T.A. Mann, and A.M. Pelletier. 1989. An Assessment Tool for Sampling Ground Water in the Undisturbed Saturated Zone. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 345-356. [Hydropunch]

Laney, S.E. and C.A. Enberg. 1992. Progressive Packer/Zone Sampling Method for VOC Plume Delineation in Consolidated Aquifers. Ground Water Monitoring Review 12(3):108-111. [Bailer]

Lang, K.T., D.T. Scarborough, M. Glover, and D.P. Lucero. 1991. Quantitative Soil Gas Sampler Implant for Monitoring Dump Site Subsurface Hazardous Fluids. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Wastes and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 423-432. [Terratrog sampler with cone penetrometer]

Lee, D.R. and J.A. Cherry. 1979. A Field Exercise on Groundwater Flow Using Seepage Meters and Minipiezometers. Journal of Geological Education 27(1):6-10.

Lenhard, R.J., and J.C. Parker. 1990. Estimation of Free Hydrocarbon Volume from Fluid Levels in Monitoring Wells. Ground Water 28:57-67.

Lieberman, S.H., G.A. Theriault, S.S. Cooper, P.G. Malone, R.S. Olsen, and P.W. Lurk. 1991. Rapid, Subsurface, In Situ Field Screening of Petroleum Hydrocarbon Contamination Using Laser Induced Fluorescence over Optical Fibers. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 57-65. [Diesel fuel, JP-5]

Lin, J.-N., et al. 1988. Remote Continuous Multichannel Biochemical Sensors Based on Fluoroimmunoassay Technologies. In: U.S. EPA (1988b), pp. 251-252. [Fiber optics]

Litherland, S.T., T.W. Hoskings, and R.L. Boggess. 1985. A New Ground Water Survey Tool: The Combined Cone Penetrometer/Vadose Zone Vapor Probe. In: Proc. [2nd] NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 322-330.

Lofy, R., H. Phung, R. Stearns, and J. Walsh. 1977. Investigation of Groundwater Contamination From Subsurface Sewage Sludge Disposal, Vol. I: Project Description and Findings. U.S. EPA Contract 68-01-4166, pp. 301-304.

Lucero, D.P. 1989. Soil Gas Sampler Implant for Monitoring Dump Site Subsurface Hazardous Fluids. In: Proc. 6th Nat. Conf. on Hazardous Wastes and Hazardous Materials, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 548-553. [TerraTrog soil-gas sampler with cone penetrometer]

Lucero, D.P. 1990. A Soil Gas Sampler Implant for Monitoring Dump Site Subsurface Hazardous Fluids. Hazardous Materials Control 3(5):36-44. [TerraTrog soil-gas sampler with cone penetrometer]

Luhdorff, Jr., E.E. and J.C. Scalmanini. 1982. Selection of Drilling Method, Well Design and Sampling Equipment for Wells to Monitor Organic Contamination. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 359-365.

Lundy, D. and T. Gogel. 1988. Capabilities and Limitations of Wells for Detecting and Monitoring Liquid Phase Hydrocarbons. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 343-362.

MacPherson, Jr., J.R. and J.F. Pankow. 1988. A Discrete Point Sampler for Ground Water Monitoring Wells. Ground Water Monitoring Review 8(3):160-164.

Mastrolonardo, R.M. and K.O. Thomsen. 1990. Ground-Water Contaminant Plume and Source Location Surveys Using Hydraulic Probe Sampling in Shallow Aquifers. Ground Water Management 3:189-197 (Proc. FOCUS Conf. on Eastern Regional Groundwater Issues).

McElroy, W.J., L.A. Drinkwater, and B.A. Kanzler. 1992. Impact of Water Table Fluctuations on Assessment and Remediation of Non-Aqueous Phase Liquids. Ground Water Management 13:95-109 (8th Focus Conf. Eastern GW Issues).

McMillion, L. and J. Keeley. 1968. Sampling Equipment for Ground-Water Investigations. Ground Water 6(2):9-11. [Submersible pump]

Meyer, Jr., K.A. 1990. Dedicated Ground Water Sampling Systems--A Technical and Economic Evaluation. Ground Water Management 2:341-346 (4th NOAC). [Bladder pump, submersible pump]

Middleburg, R.F. 1976. Air Operated Pump for Sampling Small Diameter Wells. U.S. Geological Survey Water Resources Division Bulletin April-June.

Milanovich, F.P., P.F. Daley, K. Langry, B.W. Colston, Jr., S.B. Brown, and S.M. Angel. 1991. A Fiber Optic Sensor for the Continuous Monitoring of Chlorinated Hydrocarbons. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 43-47.

Mines, B.S., J.L. Davidson, D. Bloomqyuist, and T.B. Stauffer. 1993. Sampling VOCs with the BAT Ground Water Sampling System. Ground Water Monitoring and Remediation 13(1):115-120.

Morlock, C.R. 1989. In Situ Monitoring of Gasoline Concentrations with Fiber Optic Chemical Sensors. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 31-41.

Morlock, C.R., N. Moschella, and A. Sundelin. 1992. Long-Term Remedial Action Monitoring. Ground Water Management 13:411-425 (8th Focus Conf. Eastern GW Issues). [VOC fiber-optic sensors]

Morrison, R.D. 1983. Ground Water Monitoring Technology: Procedures, Equipment and Applications. Timco Mfg., Prairie Du Sac, WI, 111 pp. [Bailers, syringe, suction-lift (direct-line, centrifugal, peristaltic), submersible helical rotor, gas-lift, bladder pump, gas displacement, gas-drive piston, packer pump, in-situ gas-drive displacement (called gas-lift), multi-level installations]

Morrison, R. and P. Brewer. 1981. Air-Lift Samplers for Zone-of-Saturation Monitoring. Ground Water Monitoring Review 1(1):52-54.

Morrison, R. and D. Ross. 1978. Monitoring for Ground-Water Contamination From a Hazardous Waste Disposal Site. In: Proc. 1978 Nat. Conf. on Control of Hazardous Material Spills, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 281-286.

Murphy, E.M. and D.D. Hostetler. 1989. Evaluation of Chemical Sensors for In-Situ Ground-Water Monitoring at the Hanford Site. PNL-6854, UC-403, Pacific Northwest Laboratory, Richland, WA (prepared for U.S. Department of Energy).

Muska, C.F., W.P. Colven, V.D. Jones, J.T. Scogin, B.B. Looney, and V. Price. 1986. Field Evaluation of Ground Water Sampling Devices for Volatile Organic Compounds. In: Proc. 6th Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 235-246. [Bladder pump, small-diameter submersible centrifugal pump, dual-check valve bailer, pneumatic depth-specific samplers (syringe, pressurized bailer, surface bomb)]

Nakamoto, D.B., F.R. McLaren, and P.J. Phillips. 1986. Multiple Completion Monitor Wells. Ground Water Monitoring Review 6(2):50-55.

Newman, J.L. and G.W. Corbell. 1990. Continuous In Situ Measurements of Nitrates and Other Contaminants Utilizing Specialized Geophysical Logging Devices. Ground Water Management 2:953-967 (4th NOAC).

Nielsen, D.M. and G.L. Yeates. 1985. A Comparison of Sampling Mechanisms Available for Small-Diameter Ground Water Monitoring Wells. Ground Water Monitoring Review 5(2):83-99. [Bailers, syringe, suction-lift, gas-drive, bladder pump, submersible (gear-drive, helical rotor), gas-drive piston]

Norman, W.R. 1986. An Effective and Inexpensive Gas-Drive Ground-Water Sampling Device. Ground Water Monitoring Review 6(2):56-60.

Olsen, K.B., J.W. Griffin, D.A. Nelson, and B.S. Matson. 1988. Prototype Design and Testing of Two Fiber-Optic Spectrochemical Emission Sensors. In U.S. EPA (1988b), pp. 111-116.

Pankow, J.R., L.M. Isabelle, J.P. Hewetson, and J.A. Cherry. 1984. A Syringe and Cartridge Method for Down-Hole Sampling for Trace Organics in Ground Water. Ground Water 22:330-339.

Pankow, J.F., L.M. Isabelle, J.P. Hewetson, and J.A. Cherry. 1985. A Tube and Cartridge Method for Down-Hole Samples of Trace Organic in Ground Water. Ground Water 23:775-782.

Parker, L.V. 1992. Suggested Guidelines for the Use of PTFE, PVC and Stainless Steel in Samplers and Well Casings. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 217-229.

Parker, T.K., M.F. Eisen, A.A. Kopania, A. Robertson, R.L. Eades, and G. Thomas. 1992. Selection, Design, Installation, and Evaluation of Dedicated Groundwater Sampling Systems: A Case Study. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 89-106. [Bailer, bladder pump, combined gas-drive/bladder, submersible centrifugal pump]

Patton, K.R. 1990. A Cost-Effective Screening Technique Used in the Characterization of Agricultural Compounds in Ground Water. Ground Water Management 1:831-839 (Proc. of the 1990 Cluster of Conferences). [Well-point sampler]

Patton, F.D. and H.R. Smith. 1988. Design Considerations and the Quality of Data from Multiple-Level Ground-Water Monitoring Wells. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 206-218.

Paul, C.J. and R.W. Puls. 1992. Comparison of Ground-Water Sampling Devices Based on Equilibration of Water Quality Indicator Parameters. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 21-39. [Bladder pump, submersible centrifugal pump, peristaltic pump]

Pearsall, K.A. and D.A.V. Eckhardt. 1987. Effects of Selected Sampling Equipment and Procedures on the Concentrations of Trichloroethylene and Related Compounds in Ground Water Samples. Ground Water Monitoring Review 7(2):64-73. [Helical rotor, surface centrifugal pump, peristaltic pump, bailer]

Pedlar, W.H., M.J. Barvenik, C.F. Tsang, and F.V. Hale. 1990. Determination of Bedrock Hydraulic Conductivity and Hydrochemistry Using a Wellbore Fluid Logging Method. Ground Water Management 2:39-53 (4th NOAC).

Pennino, J.D. 1988. There's No Such Things as a Representative Ground Water Sample. Ground Water Monitoring Review 8(3):4-9.

Pettyjohn, W.A., W.J. Dunlap, R. Cosby, and J.W. Keeley. 1981. Sampling Ground Water for Organic Contaminants. Ground Water 19(2):180-188.

Pickens, J.F., J.A. Cherry, G.E. Grisak, W.F. Merritt, and B.A. Risto. 1978. A Multilevel Device for Groundwater Sampling and Piezometric Monitoring. Ground Water 16(5):322-327. (See also, 1979 discussion by Vonhof et al. in Ground Water 14(4):391-393, and reply by Pickens and Grisak, pp. 393-397.)

Pickens, J.F., J.A. Cherry, R. Coupland, and G.E. Grisak. 1981. A Multi-Level Device for Groundwater Sampling. Ground Water Monitoring Review 1(1):48-51.

Pohlmann, K.F. and J.W. Hess. 1988. Generalized Ground Water Sampling Device Matrix. Ground Water Monitoring Review 8(4):82-84.

Pohlmann, K.F., R.P. Blegen, and J.W. Hess. 1990. Field Comparisons of Ground-Water Sampling Devices for Hazardous Waste Sites: An Evaluation Using Volatile Organic Compounds. EPA/600/4-90/028 (NTIS PB91-181776), 102 pp. [Bailer, bladder pump, BAT sampler, Westbay sampler]

Preslo, L.M. 1989. The Subsurface Behavior of Light and Dense Non-Aqueous Phase Liquids in Underground Storage Tank Investigations. In: Proc. of the 5th Annual Hazardous Materials Management Conference/West, pp. 418-427.

Rannie, E.H. and R.L. Nadon. 1988. An Inexpensive, Multi-Use, Dedicated Pump for Ground Water Monitoring Wells. Ground Water Monitoring Review 8(4):100-107.

Reeve, R.C. and E.J. Doering. 1965. Sampling the Soil Solution for Salinity Appraisals. Soil Science 99:339-344. [Point sampler]

Rehm, B.W., T.R. Stolzenburg, and D.G. Nichols. 1985. Field Measurement Methods for Hydrogeologic Investigations: A Critical

Review of the Literature. EPRI EA-4301, Electric Power Research Institute, Palo Alto, CA.

Reynolds, M., E. Sandin, and J. Urquhart. 1991. Evolution of Techniques for Characterizing VOC Plumes: A Case Study. In: Ground Water Management 7:583-596 (8th Eastern GW Issues Focus Conf.). [Long-screen, multi-level wells, auger screen with field GC]

Rehtlane, E.A. and F.D. Patton. 1982. Multiple Port Piezometers vs. Standpipe Piezometers: An Economic Comparison. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground-Water Monitoring, National Water Well Association, Worthington, OH, pp. 287-295.

Ridgeway, W.R. and D. Larssen. 1990. A Comparison of Two Multiple-Level Ground-Water Monitoring Systems. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 213-237.

Rinaldo-Lee, M.B. 1983. Small- vs. Large-Diameter Monitoring Wells. Ground Water Monitoring Review 1(1):72-75.

Ring, G.T. and T.C. Sale. 1987. Evaluation of Well Field Contamination Using Downhole Geophysical Logs and Depth-Specific Samples. In: Superfund '87, Proceedings of the 8th Annual Conference, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 320-325. [Submersible pump at different levels]

Ritchey, J.D. 1986. Electronic Sensing Devices Used for In Situ Ground Water Monitoring. Ground Water Monitoring Review 6(2):108-113.

Roberts, J.R., J.A. Cherry, and F.W. Schwartz. 1982. A Case Study of a Chemical Spill: Polychlorinated Biphenyls (PCBs), 1. History, Distribution, and Surface Translocation. Water Resources Research 18(3):525-534.

Robin, M., D. Dytynyhyn, and S. Sweeney. 1982. Two Gas-Drive Sampling Devices. Ground Water Monitoring Review 2(1):63-66.

Ronen, D., M. Margaritz, and I. Levy. 1987. In Situ Multi-Level Sampler for Preventive Monitoring and Study of Hydrochemical Profiles in Aquifers. Ground Water Monitoring Review 7(4):69-74. [Dialysis cell (method modified polyethylene vials with replaceable dialysis membranes at both ends are filled with distilled water and placed in a specially-designed multilevel sampling installation; sample left about 30 days to allow vials to equilibrate with ground water and then retrieved for sampling)]

Rose, S.R. and A. Long. 1988. Monitoring Dissolved Oxygen in Ground Water: Some Basic Considerations. Ground Water Monitoring Review 8(1):93-97.

Rosen, M.E., J.R. Pankow, J. Gobs, and T.E. Imbrigiotta. 1992. Comparison of Downhole and Surface Sampling for the Determination of Volatile Organic Compounds (VOCs) in Ground Water. Ground Water Monitoring Review 12(1):126-133. [Downhole ATD, helical rotor]

Ross, C.G.A., R.A. Niemeyer, and T.D. Blackman. 1992. A Method for Reducing Purge Volumes in Deep Monitoring Wells, A Purging Experiment. Ground Water Management 11:45-58 (6th NOAC). [Dual submersible purge/bladder pump sample system]

Rutter, A. and J. Webster. 1962. Probes for Sampling Ground Water for Gas Analysis. J. Ecology 50:615-618.

Scalf, M.R., J.F. McNabb, W.J. Dunlap, R.L. Cosby, and J. Fryberger. 1981. Manual of Ground-Water Quality Sampling Procedures. EPA/600/2-81/160, (NTIS PB82-103045). (Also published in NWWA/EPA Series, National Water Well Association, Dublin OH.)

Schalla, R., D.A. Myers, M.A. Simmons, J.M. Thomas, and A.P. Toste. 1988. The Sensitivity of Four Monitoring Well Sampling Systems to Low Concentrations of Three Volatile Organics. Ground Water Monitoring Review 8(3):90-96. [Gas-drive piston pump, bailer, bladder pump, gas-drive (displacement)]

Schmidt, K.D. 1982. How Representative are Water Samples Collected from Wells? In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 117-128.

Schuller, R.M., J.P. Gibb, and R.A. Griffin. 1981. Recommended Sampling Procedures for Monitoring Wells. Ground Water Monitoring Review 1(1):42-46. [Peristaltic, gas-lift (air and nitrogen), bailer]

Schwartz, F.W., J.A. Cherry, and J.R. Roberts. 1982. A Case Study of a Chemical Spill: Polychlorinated Biphenyls (PCBs), 2.

Hydrogeological Conditions and Contaminant Migration. Water Resources Research 18(3):525-534.

Scanor, A.M. and L.K. Brannaka. 1981. Influence of Sampling Techniques on Organic Water Quality Analyses. In: Management of Uncontrolled Hazardous Waste Sites, Hazardous Material Control Research Institute, Silver Spring, MD, pp. 143-148. [Electric submersible, gas-drive piston samplers]

Shahriari, M.R., Q. Zhou, and G.H. Sigel, Jr. 1988. Porous Fiber Optic for Chemical Sensors. In: U.S. EPA (1988b), pp. 43-50.

Signor, D. 1978. Gas-Driven Pump for Ground-Water Samples. U.S. Geological Survey Water Resources Investigation Report 78-72.

Small, P.A. 1953. Some Factors Affecting the Solubility of Polymers. J. Applied Chemistry 3:71-80.

Smith, Jr., J.E., T.M. Bond, J.A. Gilbert, and K.M. Leonard. 1988. A Remote Fiber Optic Ground Water Monitoring System Based on Surface Enhanced Raman Spectroscopy. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 3-16.

Smolley, M. and J.C. Kappmeyer. 1989. Cone Penetrometer Tests and Hydropunch® Sampling: An Alternative to Monitoring Wells for Plume Definition. In: Proc. Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, Dublin, OH, pp. 717-724.

Smolley, M. and J.C. Kappmeyer. 1991. Cone Penetrometer Tests and HydroPunch® Sampling: A Screening Technique for Plume Definition. Ground Water Monitoring Review 11(2):101-106.

Smythe, J.M., P.B. Bedient, and R.A. Klopp. 1988. Cone Penetrometer Technology for Hazardous Waste Site Investigations. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 71-94.

Snow, D.D., M.E. Burbach, and R.F. Spalding. 1992. Ground Water Sampler Comparison: Pesticide and Nitrate Concentrations. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 77-87. [Submersible centrifugal pump, bladder pump, bailer]

Sommerfeldt, T. and D. Campbell. 1975. A Pneumatic System to Pump Water from Piezometers. Ground Water 13:293.

Sonntag, W.H. 1987. Comparative Test of Two Sampling Devices for Obtaining Purgeable Organic Compounds from Ground Water Wells. In: Proc. 3rd USGS Toxic Waste Technical Meeting (Pensacola, FL), U.S. Geological Survey Open-File Report 87-109, pp. E7-E9. [Flow-through depth-specific sampler]

Spaulding, R.F., M.E. Exner, and J.R. Gomly. 1976. A Note on an In Situ Ground Water Sampling Procedure. Water Resources Research 12:1319-1321

St. Germain, R.W. and G.D. Gillispie. 1991. Transportable Tunable Dye Laser for Field analysis of Aromatic Hydrocarbons in Groundwater. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 789-792. [Fiber optics]

Stites, W. and L.W. Chambers. 1991. A Method for Installing Miniature Multilevel Sampling Wells. Ground Water 29(3):430-432.

Stolzenburg, T.R. and D.G. Nichols. 1985. Evaluation of Chemical Changes in Ground Water Samples Due to Sampling Mechanism. EPRI EA-4118. Electric Power Research Institute, Palo Alto, CA. [Peristaltic pump, bailer, bladder pump, vacuum pump, gas drive, nitrogen lift, large-diameter submersible centrifugal, air lift, surface centrifugal]

Stolzenburg, T.R. and D.G. Nichols. 1986. Effects of Filtration Method and Sampling Devices on Inorganic Chemistry of Sampled Well Water. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 216-234. [Peristaltic pump, bailer, bladder pump, vacuum pump, gas-drive, nitrogen lift, large-diameter submersible centrifugal, air-lift, surface centrifugal]

Strutynsky, A.I. and T.J. Sainey. 1990. Use of Piezometric Cone Penetration Testing and Penetrometer Groundwater Sampling for Volatile Organic Contaminant Plume Detection. Ground Water Management 4:71-84 (7th NWWA/API Conf.).

Strutynsky, A.I. and T.J. Sainey. 1992. Use of Piezometric Cone Penetration Testing and Penetrometry Ground Water Sampling for Volatile Organic Contaminant Plume Detection. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp.

199-214. [Hydropunch, BAT samplers]

Strutynsky, A.I., R.E. Sandiford, and D. Cavaliere. 1992. Use of Piezometric Cone Penetration Testing with Electrical Conductivity Measurements (CPTU-EC) for the Detection of Hydrocarbon Contamination in Saturated Granular Soils. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 169-182.

Sullivan, R.R., R.E. Zinner, and J.P. Hughes. 1988. The Occurrence of Hydrocarbon on an Unconfined Aquifer and Implications for Liquid Recovery. In: Proc. 5th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, Volume 1, pp. 135-156

Summerfield, R. 1973. A Probe for Sampling Mire Waters for Chemical and Gas Analysis. Plant and Soil 38:469-472.

Tabacco, M.B., Q. Zhou, K. Rosenblum, and M.R. Shahriari. 1991. Chemical Sensors for Hazardous Waste Monitoring. In Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 49-56. [Porous fiber optics]

Tai, D.Y. 1992. Ground-Water Sampler Testing in a Standpipe System. In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 3-4. [Submersible centrifugal pump, VOA trap]

Tai, D.Y., K.S. Turner, and L.A. Garcia. 1991. The Use of a Standpipe to Evaluate Ground Water Samplers. Ground Water Monitoring Review 11(1):125-132. [Bailer, manual/motor piston sampler, helical rotor pump, peristaltic pump, bladder pump]

Tate, T.K. 1973. Variations in the Design of Depth Samplers for Use in Ground Water Studies. Water and Water Engineering 77:223.

Taylor, L.R. and N. Berzins. 1988. Subsurface Contamination Screening by Combined Soil Gas/Groundwater Survey Procedure. In Superfund '88, Proceeding of the 9th National Conference, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 158-163. [Hydropunch, BAT, other CPT samplers]

Taylor, T.W. and M.C. Serfini. 1988. Screened Auger Sampling: The Techniques and Two Case Studies. Ground Water Monitoring Review 8(3):145-152.

Taylor, T.A., H. Xu, and J.E. Kenny. 1991. Laser Fluorescence EEM Instrument for In-Situ Groundwater Screening. In: Proc. 2nd Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 797-803. [Fiber optics]

Testa, S.M. and M.T. Paczkowski. 1989. Volume Determination and Recoverability of Free Hydrocarbon. Ground Water Monitoring Review 9(1):120-128.

Thomey, N., R. Ogle, and J. Jackson. 1991. A Comparison of Results for Samples Collected with Bailers Constructed of Different Materials. Ground Water Management 5:577-582.

Timmons, R. 1981. Discussion of "An All Teflon Bailer and an Air-Driven Pump for Evacuating Small-Diameter Ground-Water Wells" by D. Buss and K. Bandt. Ground Water 19:666-667.

Tomson, M.B., S. Hutchins, J.M. King, and C.H. Ward. 1980. A Nitrogen Powered Continuous Delivery All-Glass-Teflon Pumping System for Ground-Water Sampling from Below 10 Meters. Ground Water 18(5):444-446. [Gas-drive/displacement sampler]

Tomson, M.B., J. Dauchy, S. Hutchins, C. Curran, C. Cook, and C. Ward. 1981. Groundwater Contamination by Trace Level Organics from a Rapid Infiltration Site. Water Research 15:1109-1115.

Torstensson, B.-A. 1984. A New System for Ground Water Monitoring. Ground Water Monitoring Review 4(4):131-138.

Torstensson, B.-A. and A.M. Petsonk. 1988. A Hermetically Isolated Sampling Method for Ground-Water Investigations. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 274-289. [CPT/BAT system]

Trescott, P. and G. Pinder. 1970. Air Pump for Small-Diameter Piezometers. Ground Water 8(3):10-15.

Truettner, L.E., T.J. Morahan, and B.E. Mackie. 1986. Downhole Packer Assembly for Bedrock Ground Water Sampling. In: Proc. Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conf. and Exp., National Water Well Association, Dublin, OH, pp. 29-40.

Tuttle, J.C. and G.H. Chapman. 1989. Field Analytical Screening, Reconnaissance Geophysical and Temporary Monitoring Well Techniques--An Integrated Approach to Pre-Remedial Site Characterization. In: Proc. 6th Nat. Conf. on Hazardous Waste and Hazardous Materials, Hazardous Materials Control Research Institute, Silver Spring, MD, pp. 530-537.

Unwin, J. 1982. A Guide to Groundwater Sampling. Tech. Bull No. 362, National Council of the Paper Industry for Air and Stream Improvement, New York, NY, 67+ pp.

Unwin, J.P. 1984. Sampling Ground Water for Volatile Organic Compounds: The Effect of Sampling Method, Compound Volatility and Concentration. In: In: Proc. 4th Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 214-220. [Bailer, bladder pump, submersible centrifugal]

Unwin, J. and V. Maltby. 1988. Investigations of Techniques for Purging Ground-Water Monitoring Wells and Sampling Ground Water for Volatile Organic Compounds. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 240-252. [Bailer, bladder pump, centrifugal submersible, pneumatic grab]

U.S. Army. 1981. Well Drilling Operations. Department of Army Technical Manual FM5-1161/AFR 85-23. Reprinted by National Water Well Association, Dublin, OH, 249 pp. (Supersedes TM 5-297/AFR 85-23, published in 1965).

U.S. Environmental Protection Agency (EPA). 1988a. Field Screening Methods Catalog: User's Guide. EPA/540/2-88/005. FSMC System Coordinator, OERR, Analytical Operations Branch (WH-548-A), U.S. EPA, Washington, DC 20460. [FM-D5 covers fiber optics]

U.S. Environmental Protection Agency (EPA). 1988b First International Symposium, Field Screening Methods for Hazardous Waste Site Investigations. EPA/600/D-89/189 (NTIS PB90-132572). [Contains 13 papers on uses of fiber optics and chemical sensors]

U.S. Geological Survey (USGS). 1980. Ground Water. In: National Handbook of Recommended Methods for Water Data Acquisition, Office of Water Data Coordination, Reston, VA, Chapter 2.

Viallaune, J.F. 1985. Investigations of Sites Contaminated with Dense Non-Aqueous Phase Liquids (NAPLs). Ground Water Monitoring Review 5(2):60-70.

Vispi, M.A. 1980. Multiple-Port Piezometer Installation at Rocky Mountain Arsenal. Report NO. WES/MP/GL-80-12.

Wagner, R.B., D.R. Hampton and J.A. Howell. 1989. A New Tool to Determine the Actual Thickness of Free Product in a Shallow Aquifer. In: Proc. 6th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water--Prevention, Detection and Restoration, National Water Well Association, Dublin, OH, pp. 45-59.

Walker, W. 1974. Field Verification of Industrial Hazardous Material Migration from Land Disposal Sites in Humid Region. U.S. Environmental Protection Agency. (As cited in Gillham et al., 1983.)

Wallace, J.W. and D. Huntley. 1992. Effect of Local Sediment Variability on the Estimation of Hydrocarbon Volumes. Ground Water Management 11:273-285 (6th NOAC).

Welch, S.J. and D.R. Lee. 1987. A Multiple-Packer/Standpipe System for Ground Water Monitoring in Consolidated Media. Ground Water Monitoring Review 7(3):83-87.

Wells, C.E. 1988. Design and Installation of a Simple, Cost Effective Multi-Level Monitoring Well System. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 415-433.

Willardson, L., B. Meek, and M. Huber. 1972. A Flow Path Ground Water Samplers. Soil Sci. Soc. Am. Proc. 36:965-966.

Wilson, L.G. 1980. Monitoring in the Vadose Zone: A Review of Technical Elements. EPA/600/7-80/134 (NTIS PB81-125817).

Wilson, J. and J.F.B. Hawkes. 1983. Optoelectronics: An Introduction. Prentice-Hall, Englewood Cliffs, NJ.

Wilson, J.L., S.H. Conrad, E. Hagan, W.R. Mason, and W. Pelinkski. 1988. The Pore Level Spatial Distribution of Saturation of Organic Liquids in Porous Media. In: Proc. 5th NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 107-134.

Wood, W.W. 1976. Guidelines for Collection and Field Analysis of Groundwater Samples for Selected Unstable Constituents. U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 1-D2.

Yaniga, P.M. 1984. Hydrocarbon Retrieval and Apparent Hydrocarbon Thickness: Interrelationships to Recharging/Discharging Aquifer Conditions. Proc. 1st NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 299-329.

Yaniga, P.M. and J.G. Warburton. 1984. Discrimination Between Real and Apparent Accumulation of Immiscible Hydrocarbons on the Water Table: A Theoretical and Empirical Analysis. In: Proc. 4th Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 311-335.

Yare, B.S. 1975. The Use of a Specialized Drilling and Groundwater Sampling Technique for Delineation of Hexavalent Chromium Contamination in an Unconfined Aquifer, Southern New Jersey Coastal Plain. Ground Water 13(2):151-154.

Yeskis, D., K. Chiu, S. Meyers, J. Weiss, and T. Bloom. 1988. A Field Study of Various Sampling Devices and Their Effects on Volatile Organic Contaminants. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 471-479. [Bailer, bladder pump, gas-drive piston pump, helical rotor pump, and small-diameter submersible centrifugal pump]

Zemo, D.A., Y.G. Pierce, and J.D. Gallinatti. 1992a. Cone Penetrometer Testing and Discrete-Depth Groundwater Sampling Techniques: A Cost-Effective Method of Site Characterization in a Multiple-Aquifer Setting. Ground Water Management 11:299-313 (6th NOAC). [BAT, Hydropunch]

Zemo, D.A., T.A. Delfino, J.D. Gallinatti, V.A. Baker, and L.R. Hilpert. 1992b. Field Comparison of Analytical Results from Discrete-Depth Groundwater Samplers: BAT Enviroprobe and QED Hydropunch. Ground Water Management 11:341-355 (6th NOAC).

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH, 45268-0963 (513-659-7562).

APPENDIX A

DESIGN AND CONSTRUCTION OF MONITORING WELLS

This appendix provides an overview of basic elements of the design and construction of permanent ground-water monitoring wells in which portable sampling devices can be used. Section 2 covers well drilling methods and Section 5.4 should be referred to for a discussion of basic types of monitoring well installations. ASTM (1992c) and U.S. EPA (1992) identify the minimum set of data elements necessary for documenting the location and construction of monitoring wells.

Figures A-1a and A-1b show the basic design components of properly and constructed single- and multi-cased monitoring wells. Nielsen and Schalla (1991) have identified six common monitoring well design flaws and installation problems that should be avoided:

1. Use of **well casing** or **well screen materials** that are not compatible with the hydrogeologic environment, known or suspected contaminants, or the requirements of the ground-water sampling program. The result is chemical alteration of samples or failure of the well. See Section A.1.

2. Incorrect **screen slot-sizing** practices or use of nonstandard types of well screen, such as field-slotted, drilled, or perforated casing. The result is well sedimentation and turbid samples throughout the monitoring program. See Section A.2.

3. Improper **length** and **placement** of **well screens** so that discrete zones of the aquifer are missed or cannot be differentiated. In this situation, water level measurements and water quality samples might provide misleading results. See Section 5.4.

4. Improper selection and placement of **filter pack** materials. Consequences can include well sedimentation, well screen plugging, ground-water sample alteration, or potential well failure. See Section A.3.

5. Improper selection and placement of **annular seal** materials. The results can include alteration of chemistry of water samples, plugging of the filter pack and/or well screen, and cross-contamination between water-bearing units that have not be adequately isolated. See Section A.4.

6. Inadequate **surface protection measures**, such as surface seals that are susceptible to frost heave. The results can include surface water entering the well, chemical alteration of water quality samples, and well damage to destruction. See Section A.4.

Another common installation problem that can be added to this list occurs after installation has been completed:

7. Use of improper **well development** techniques. The results can include continuing turbidity in water quality samples due to failure to remove fines for the well screen and filter pack, chemical alteration of water quality samples due to the introduction of air or foreign water into the aquifer, and possible damage to the well screen by stresses caused by excessive surging. See Section A.5.

Once a well has been installed, ongoing **maintenance** is required to ensure proper functioning and **rehabilitation** might be required if routine maintenance is not able to prevent impairment of well efficiency or if modifications are required for a change in purpose of the well (see Section A.6). Finally, when a well is no longer required for its original or modified purpose, it must be properly **abandoned** (see Section A.7).

Table A-1, located at the beginning of the reference section, provides an index of general references which cover monitoring well design and installation, as well as references that cover more specific topics.

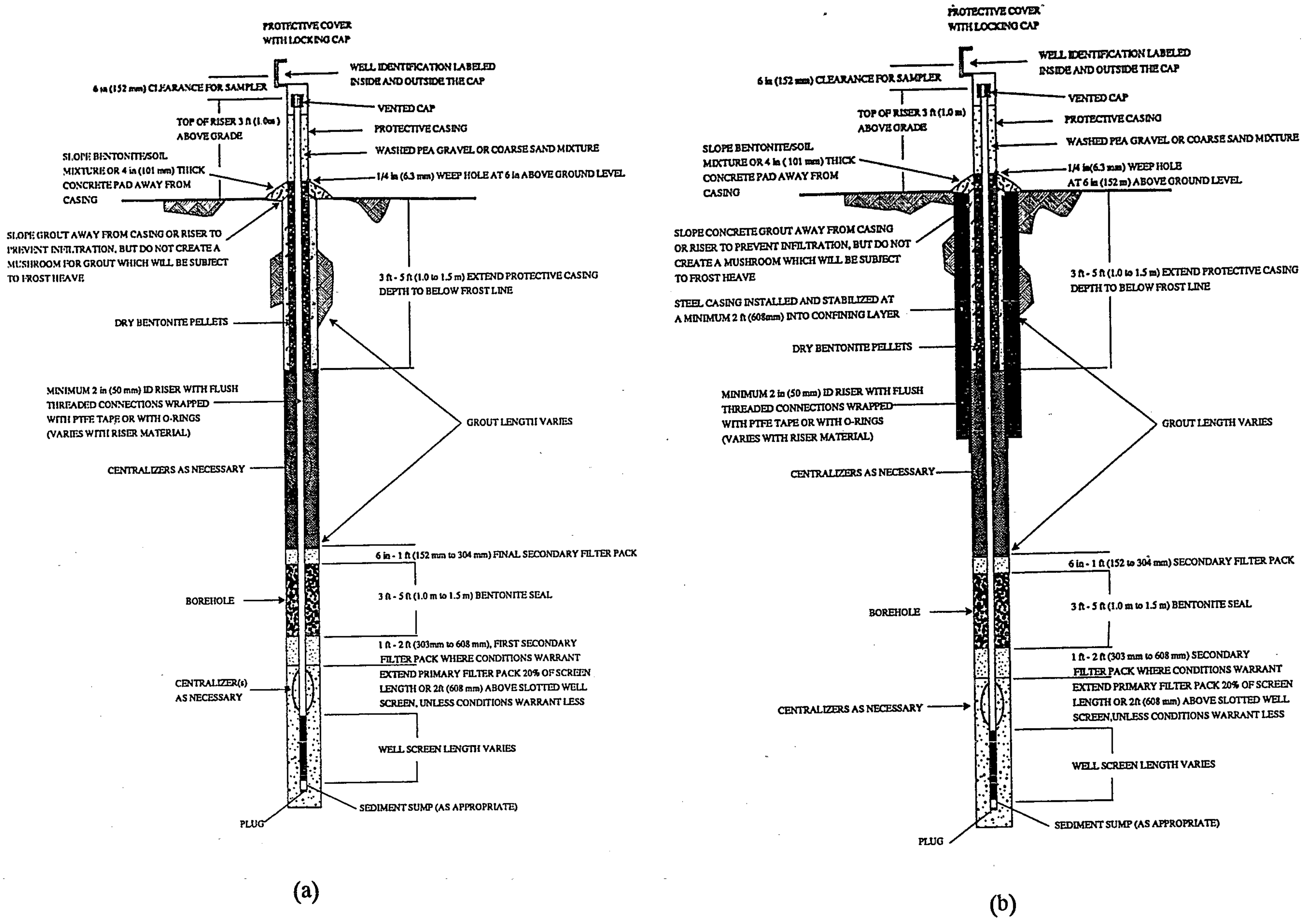


Figure A-1 Monitoring well design and construction: (a) Single-cased monitoring well design (b) Multi-cased monitoring well design (ASTM, 1990a, Copyright ASTM, reprinted with permission).

A.1 WELL CASING MATERIALS

Other Names Used to Describe Materials: **Thermoplastics:** Polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS). **Fluoropolymers:** Polytetrafluoroethylene/tetrafluoroethylene (PTFE/TFE, Teflon, Halon, Fluon, Hostaflon, Polyflon, Algoflon, Soriflon), fluorinated ethylene propylene (FEP, Neflon, Teflon), perfluoroalkoxy (PFA, Neoflon, Teflon), polyvinylidine fluoride (PVDF, Kynar), chlorotrifluoroethylene (CTFE, Kel-F, Diaflon). **Metallic:** Cast iron, mild/soft steel, carbon steel, low carbon steel, galvanized steel, and stainless steel (particularly types 304 and 316). **Fiber-glass reinforced:** Fiberglass-reinforced epoxy (FRE), fiberglass-reinforced plastic (FRP).

Uses at Contaminated Sites: Casing materials for monitoring wells.

Materials Description: **Thermoplastics** include varying formulations of plastics, which are molded or extruded to form rigid well casing (PVC and ABS) or tubing (polyethylene and polypropylene). **Fluoropolymers** are plastics with high chemical resistance consisting of different formulations of fluoromonomers, which can be either molded by powder metallurgy methods or extruded with heat. **Metals:** Various types of steel tubing. **Fiberglass reinforced** plastic or epoxy forms casing of higher strength than thermoplastic or fluoropolymer materials.

Materials Selection Considerations: **Plastic Casing Advantages:** (1) Is lightweight; (2) PVC is inexpensive; and (3) generally good to excellent chemical resistance (fluoropolymers have the best chemical resistance, except for fluorinated solvents; PVC has poor resistance to high concentrations of aromatic hydrocarbons [toluene, xylene, trichlorethylene] esters, and ketones). **Plastic Casing Disadvantages:** (1) Weaker, less rigid, and more temperature sensitive than metallic materials (PTFE/TFE is especially low, PVDF is stronger; ABS has low strength and less heat resistance compared to PVC); (2) PVC might adsorb some constituents from ground water; (3) PVC might react with and leach some constituents into ground water and PTFE is prone to sorption of selected organic compounds (proper purging and sampling procedures can minimize these problems); (4) fluoropolymers are expensive (PVDF is less expensive than PTFE/TFE); (5) some materials are not commonly available (ABS, PVDF); (6) tensile strength of wear resistance of PTFE/TFE is low compared to other plastics, and screen slot opening might decrease in size over time; and (7) antistick properties of fluoropolymer materials make it difficult to achieve an annular seal with neat cement grout, creating potential for alteration of ground-water chemistry by percolating surface water (see Figure A.4a). **Metallic Casing Advantages:** (1) Stainless steel has least adsorption of halogenated and aromatic hydrocarbons; (2) all steel casings have high strength and generally are not temperature sensitive; (3) stainless steel has excellent resistance to corrosion and oxidation; (4) stainless steel is readily available in all diameters and screen slot sizes; and (5) mild steel is readily available and less expensive than stainless steel for casing. **Metallic Casing Disadvantages:** (1) Heavier than plastics; (2) stainless steel might corrode and leach some chromium in highly acidic water, and might act as a catalyst in some organic reactions; (3) stainless steel screens are more expensive than plastic screens; (4) mild steel might react with and leach some constituents into ground water and is not as chemically resistant as stainless steel; (5) under saturated conditions carbon and low carbon steel rust easily, providing highly sorptive surface for many metals, and they deteriorate in corrosive environments; and (6) zinc might leach from galvanized steel, and if the coating is scratched, will rust, providing a highly sorptive surface for metals. **Fiberglass Reinforced Advantages:** (1) High-strength (almost as strong as stainless steel); (2) light (weighs about the same as PVC); and (3) limited available data indicate that it is relatively inert in most monitoring well environments. **Fiberglass Reinforced Disadvantages:** (1) Some adsorption of volatile organics (can be overcome by proper purging and sampling procedures; and (2) not readily available and little data available on its performance in the field.

Frequency of Use: PVC in the most commonly used casing material, followed by stainless steel. PTFE is uncommon due to expense and low strength (best application where concentrations of organic solvents are high [parts-per-thousand levels] and highly corrosive conditions preclude use of metallic casing).

Standard Guidelines: ASTM (1990a,b).

Sources for Additional Information: Aller et al. (1991), Devinny et al. (1990), Driscoll (1986), Nielsen and Schalla (1991). See also, Table A-1.

A.2 WELL SCREEN TYPES AND MATERIALS

Other Names Used to Describe Method: **Monitoring wells:** Wire-wound (plastic) continuous-slot, verticle or horizontal machine slotted casing, factory slotted perforated pipe, bridge-slot, shutter-type (louvre-type). **Other well screens:** Field slotted pipe (torch cut or perforated), wire-wound perforated pipe (pipe-based screen).

Uses at Contaminated Sites: Allowing ground water to enter monitoring wells for sampling.

Method Description: Well screens of the appropriate length and slot size are attached to solid casing and placed at the depth in the aquifer where sampling is desired. This method usually is used in unconsolidated formations in combination with a filter pack (see Section A.3) to minimize entry of fine particles from the aquifer into the well during development (Section A.5), purging (Section B.2), and sampling (Section B.3). The slot size is selected to: (1) Maximize open area for water to flow through, and (2) minimize entry of fines into the well during pumping. The major types of well intake screens are: (1) **Factory slotted** (Figure A.2a), (2) **continuous slot** (Figure A.2b), (3) **bridge slot** (Figure A.2c), and (4) **shutter type** (Figure A.2d). Other types include **field-slotted pipe,** in which slots are manually cut, and **wire-wound perforated pipe.**

Method Selection Considerations: **Factory Slotted Casing Advantages:** (1) Has good slot control; (2) is readily available; and (3) is inexpensive. **Factory Slotted Casing Disadvantages:** (1) Low amount of open area makes development difficult; (2) rough, jagged edges might be present, forming surface for sorption of chemicals, (3) lighter stock metal screens (less than 8 gage) not strong enough for depths greater than 100 to 150 feet, and plastic screens much weaker (one-sixth to one-tenth as strong as stainless steel screens) are used. **Continuous Slot Advantages:** (1) Very good slot control is possible, allowing custom made slot sizes for specific aquifer gradations; (2) wide range of slot sizes are available; (3) is the most efficient screen available because of high amount of open area, facilitating development and ensuring good flow for sampling; (4) wire-wound is made in both telescoping and pipe sizes; and (5) plastic is less expensive than wire-wound. **Continuous Slot Disadvantages:** (1) Wire-wound is more expensive than slotted pipe, but still moderately priced; and (2) plastic screens have much lower strength than metal screens. **Bridge and Shutter Type Advantages:** (1) Slots are accurately sized; (2) are wire-brushed to remove roughness and irregularities; (3) have reasonably high intake area (up to 20%); and (4) are relatively inexpensive. **Bridge and Shutter Type Disadvantages:** (1) Clog relatively easily; (2) have relatively low collapse strength; (3) have a minimum diameter of 6 inches. **Field-slotted** pipe is not recommended due to low amount of open area, poor slot control, and the development of rough jagged edges, which are vulnerable to corrosion (metal pipe). **Wire-wound perforated pipe** screens have good tensile and collapse strength, but have relatively low open area and are easily clogged with fines.

Frequency of Use: Wire-wound continuous-slot (or continuous plastic slotted) screens and machine slotted casing are the most commonly used types of screens, because they are the most readily available for 2-inch monitoring wells.

Standard Methods/Guidelines: ASTM (1990a).

Sources for Additional Information: Aller et al. (1991), Bureau of Reclamation (1981), Devinny et al. (1990). See also, Table A-1.

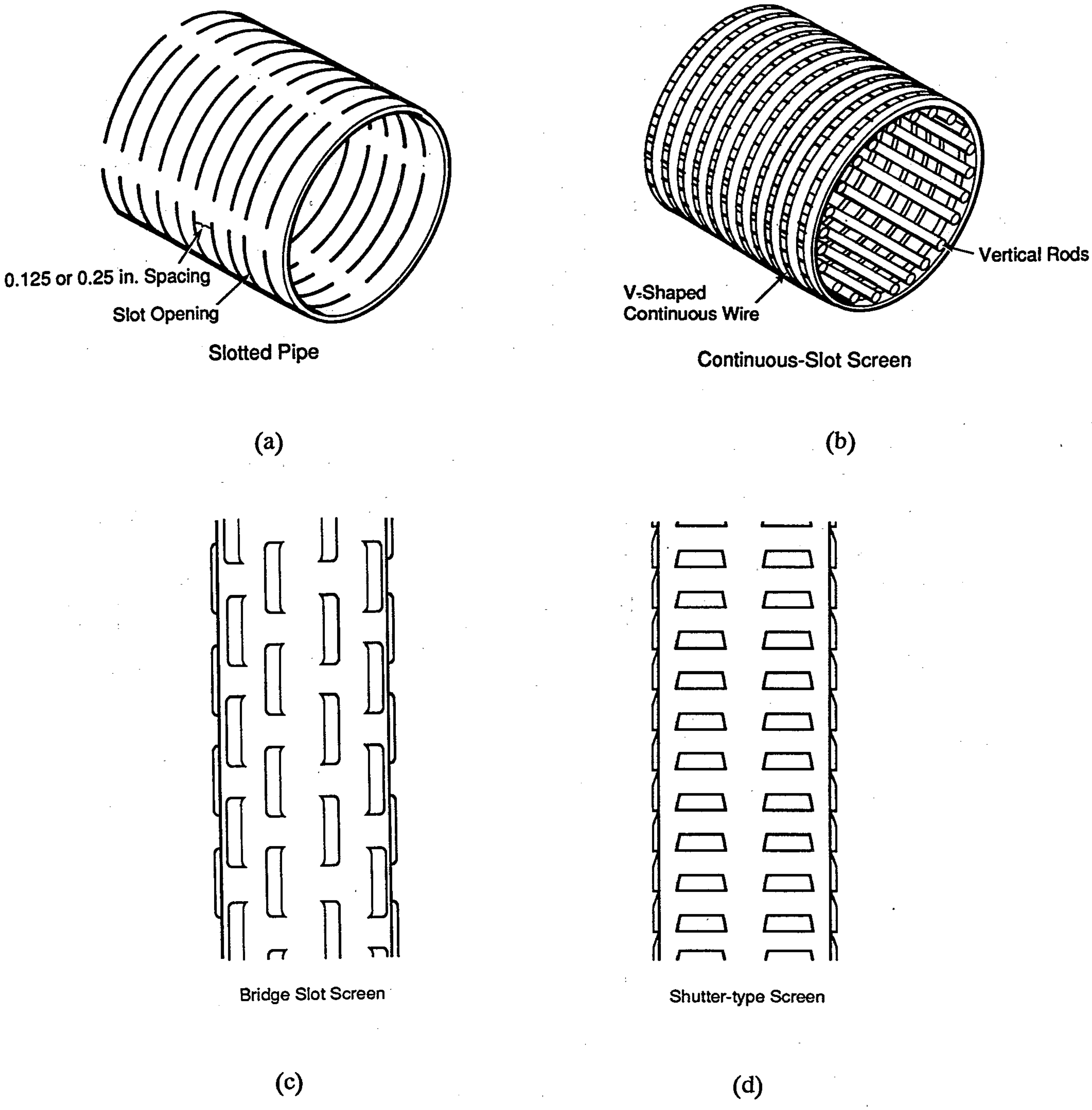


Figure A.2 Major types of well screens: (a) Slotted (Nielsen and Schalla, 1991, by permission); (b) Continuous slot (Nielsen and Schalla, 1991); (c) Bridge slot (Aller et al., 1991, by permission); (d) Shutter type (Aller et al., 1991).

A.3 FILTER PACK

Other Names Used to Describe Method: Natural and artificial "gravel" pack/sand pack.

Uses at Contaminated Sites: Increasing hydraulic conductivity around the well screen and keeping fine particles from entering the well screen during ground-water sampling.

Method Description: An artificial filter pack is placed around the well screen. The filter pack must: (1) Be clean (to minimize loss of material during development and development time [Section A.5]), (2) have well-rounded grains (to increase hydraulic conductivity, porosity, yield, and effectiveness of well development), (3) have 90 to 95% quartz grains (to minimize changes to ground-water chemistry and to eliminate loss of volume by dissolution of minerals), and (4) have a uniformity coefficient of 2.5 or less (to minimize separation during installation and lower head loss). Alternatively, well screen slot size is determined based on the particle-size distribution in the aquifer materials and the fines are removed during the development process. In relatively shallow wells, the filter pack can be placed by simply dumping sand down the annulus (provided the annular space is more than 2 inches). More typically, the filter pack is placed by pouring the sand into a **tremie pipe**, a rigid or partially flexible tube of pipe that allows funneling of the material directly to the interval around the well screen (Figure A.3a). Other methods include the **reverse circulation** method, where a sand and water mixture is fed into the annulus around the well screen and the water entering the screen is pumped up to the surface (Figure A.3b), and **backwashing**, where water is pumped down the well and allowed to rise up around the annular area as filter-pack material filters down through the rising water (Figure A.3c).

Method Selection Considerations: **Artificial Filter Pack Advantages:** Characteristics of the filter-pack material can be selected for optimum efficiency of well operation. **Artificial Filter Pack Disadvantages:** (1) Procedure is relatively time consuming and expensive; (2) bridging might prevent complete filling around the well screen; (3) extension of filter pack above or below the screen area might allow contaminants to move to uncontaminated areas; (4) filter pack material might introduce contaminants into the aquifer (a leaching test can be used to determine whether this might be a problem); and (5) use of reverse circulation and backwashing emplacement methods might alter ground-water chemistry. **Natural Filter Pack Advantages:** (1) Simpler and can be less expensive (depending on time requirements for well development); and (2) potential for alteration of ground-water chemistry is minimized. **Natural Filter Pack Disadvantages:** (1) Well development is more difficult, and success is less assured; (2) selection of optimum screen slot size is more difficult.

Frequency of Use: Filter packs are a standard feature of monitoring wells. Artificial filter packs are usually used in finer and very coarse grained material.

Standard Methods/Guidelines: ASTM (1990a).

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986), U.S. EPA (1975, 1986). See also, Table A-1.

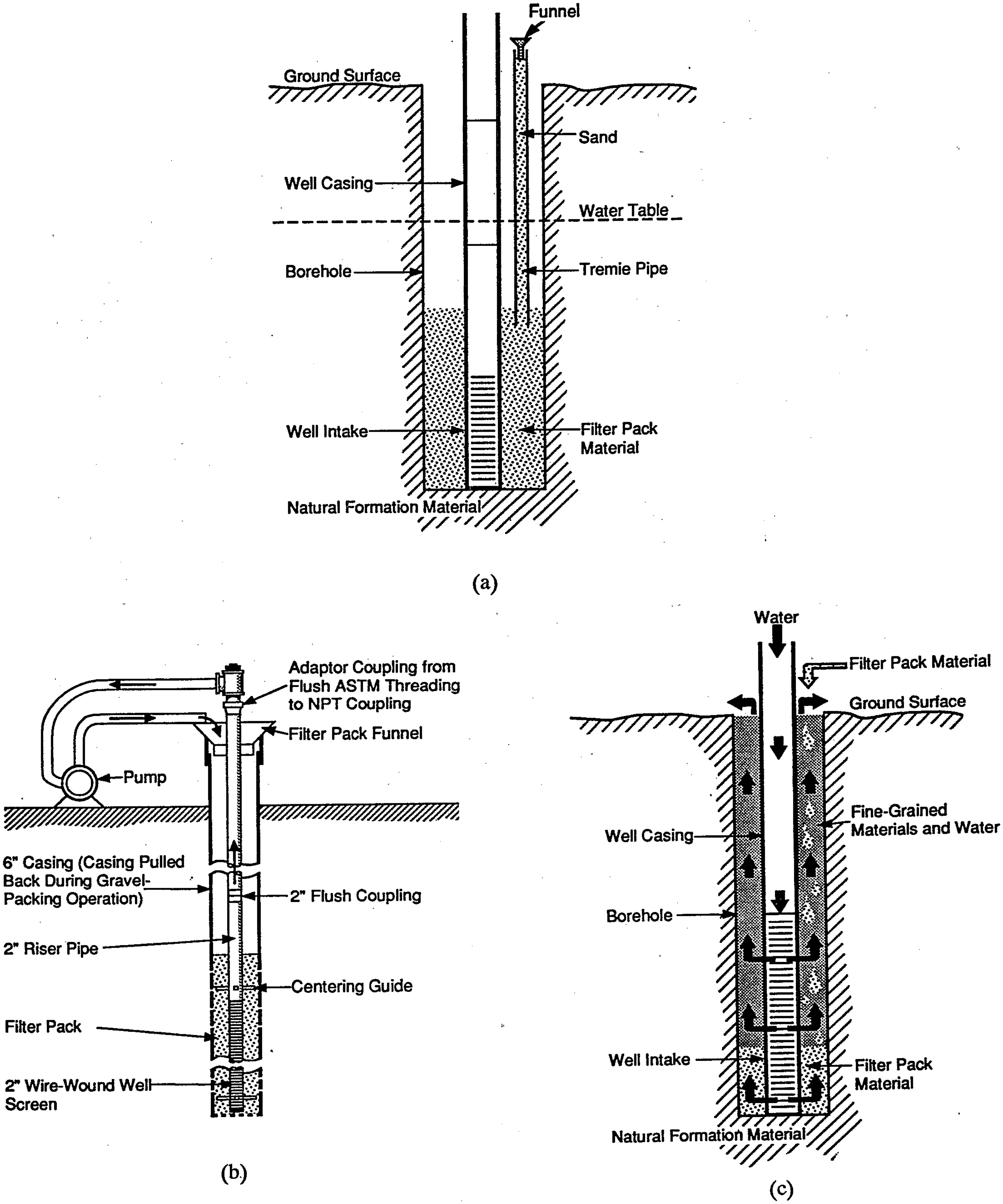


Figure A.3 Artificial filter pack placement methods: (a) Tremie-pipe emplacement; (b) Reverse circulation emplacement; (c) Backwashing (Nielsen and Schalla, 1991, by permission).

A.4 GROUTS AND SEALS

Other Names Used to Describe Method: Bentonite, cement, neat cement.

Uses at Contaminated Sites: Sealing the annular space between the well casing and the formation to prevent contaminants from moving upward or downward to uncontaminated areas (Figure A.4).

Method Description: After the filter pack is placed, grout (usually either bentonite or neat cement) is used to provide the optimum seal in the annual space between the casing and borehole walls. **Bentonite** can be placed either as unhydrated pellets or chips with water added later, or pumped down through a tremie pipe as a slurry. **Neat cement** (a mixture of 5 to 6 gallons of clean water per 1 cubic foot bag of Portland Cement, usually Type I) is mixed manually or with a mechanical mixture and pumped into the annulus. A variety of additives can be mixed with the cement slurry to change the properties of the cement (Table A.4). The more common additives include: (1) Bentonite (to improve workability, and to reduce weight and shrinkage), (2) calcium chloride (to accelerate setting time and create higher early strength, especially useful in cold climates), (3) gypsum (quick setting, expanding cement, but expensive), (4) aluminum powder (which produces a strong, quick-setting cement than expands on setting), (5) fly ash (to increase sulfate resistance and early compressive strength), (6) hydroxylated carboxylic acid (to retard setting time and improve workability without compromising set strength), and (7) diatomaceous earth (to reduce slurry density and thickening time, but increase water demand and reduce set strength). Table A.4 summarizes information on the effect of 15 additives commonly used with cement. Major **surface sealing** measures include: (1) Placement of a sturdy protective outer casing with cover and lock to a depth below the frost line and a drainage hole to prevent moisture buildup between the protective casing and the well casing, and (2) placement of a concrete pad sloping away from the casing to prevent infiltration of surface water and shaped so as to prevent frost heaving. See Figure A-1a for typical surface protection measures.

Method Selection Considerations: **Bentonite Advantages:** (1) Is readily available; (2) is inexpensive; and (3) pellets or slurry can be used. **Bentonite Disadvantages:** (1) Might cause constituent interference due to ion exchange; (2) might not give complete seal and complete bond to casing cannot be assured; (3) pellets might bridge or wet and swell, sticking to the formation or casing before filling the annular space; and (4) pump might clog if slurry gets too dense. **Cement Advantages:** (1) Is readily available; (2) is inexpensive; (3) can use sand and/or gravel filler; and (4) is possible to determine how well the cement has been placed by means of temperature logs (see Figure 2.6.2a) or sonic bond logs (Section 3.6.2). **Cement Disadvantages:** (1) Might cause constituent interferences (high pH with attendant change in ground-water chemistry); (2) mixer, pump, and tremie lines are required and more cleanup generally is required compared to bentonite; (3) can have problems getting the material to set up; (4) channeling between the casing and seal might develop because of temperature changes during the curing process, swelling and shrinkage of the grout while the mixture cures, and poor bonding between the grout and the casing surface; and (5) heat from setting can compromise structural integrity of some well casing materials (i.e., thermoplastic).

Frequency of Use: Both bentonite and neat cement are used widely.

Standard Methods/Guidelines: API (1990, 1991a), ASTM (1990a, 1992b).

Sources for Additional Information: Aller et al. (1991), Driscoll (1986). See also, Table A-1.

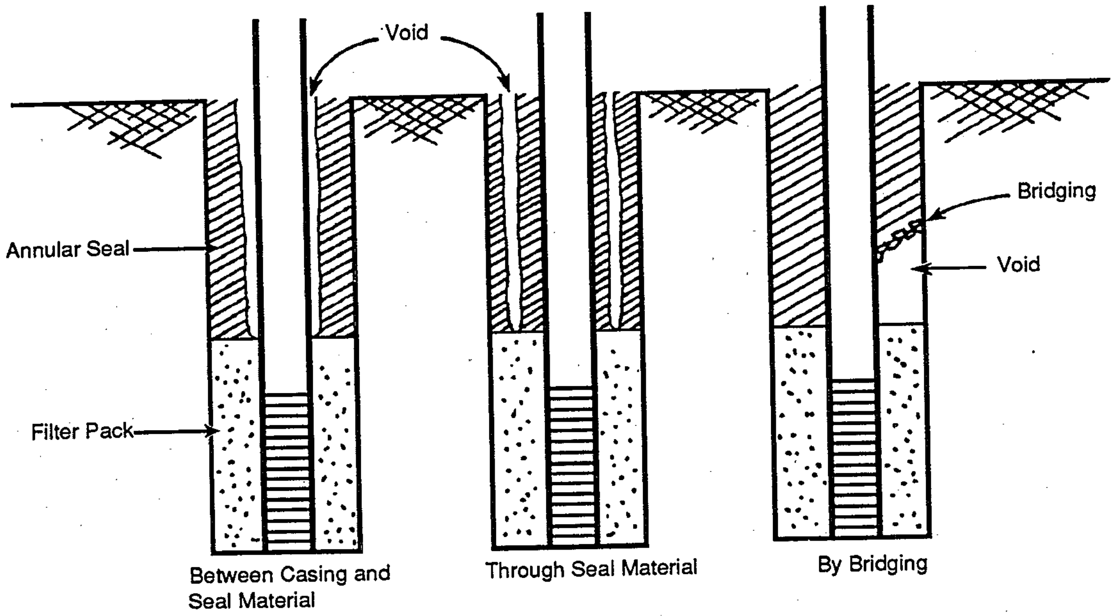


Figure A.4 Potential pathways for fluid movement in the casing-borehole annulus (Aller et al., 1991).

Table A.4 Some Additives Commonly Used with Cement

EFFECTS OF SOME ADDITIVES ON THE PHYSICAL PROPERTIES OF CEMENT		BENTONITE	PERLITE	DIATOMACEOUS EARTH	POZZOLAN	SAND	BARITE	ARSENOFERRITE	CALCIUM CHLORIDE	SODIUM CHLORIDE*	LIGNOSULFONATES	CMHEC†	DIESEL OIL	LOW-WATER-LOSS MATERIALS	LOST-CIRCULATION MATERIALS	ACTIVATED CHARCOAL
DENSITY	DECREASE	⊗	⊗	⊗	x											
	INCREASE					⊗	⊗	⊗	x	x	x					
WATER REQUIRED	LESS										⊗					
	MORE	⊗	x	⊗	x	x	x	x							x	x
VISCOSITY	DECREASE								x		⊗					
	INCREASE	x	x	x	x	x	x	x							x	x
THICKENING TIME	ACCELERATED	x					x	x	⊗	⊗						
	RETARDED			x						x	⊗	⊗	x	⊗		
SETTING TIME	ACCELERATED						x	x	⊗	⊗						
	RETARDED	x	x	x	x						⊗	⊗		x		
EARLY STRENGTH	DECREASED	x	x	x	x		x	x			⊗	⊗		x	x	x
	INCREASED								⊗	⊗						
FINAL STRENGTH	DECREASED	x	x	⊗	x		x					⊗		x	x	x
	INCREASED										x					
DURABILITY	DECREASED	x	x	x									x		x	
	INCREASED				⊗											x
WATER LOSS	DECREASED	⊗									x	⊗	x	⊗	x	
	INCREASED		x	x												

x DENOTES MINOR EFFECT.

⊗ DENOTES MAJOR EFFECT AND/OR PRINCIPAL PURPOSE FOR WHICH USED.

* SMALL PERCENTAGES OF SODIUM CHLORIDE ACCELERATE THICKENING. LARGE PERCENTAGES MAY RETARD API CLASS A CEMENT.

† CARBOXYMETHYL HYDROXYETHYL CELLULOSE.

Source: API, (1959)

A.5 WELL DEVELOPMENT

Other Names Used to Describe Method: Over-pumping, backwashing, surge-plunger, surge block, mechanical surging, bailer, compressed air, airlift pumping, air surging, high velocity (water/hydraulic) jetting, blasting, acidizing.

Uses at Contaminated Sites: Removing fines from filter pack around monitoring wells to improve hydraulic performance and eliminate or reduce collection of sediment in water quality samples; rectifying damage done during drilling to borehole wall and adjacent formation.

Method Description: In **overpumping** the well is pumped at a rate that substantially exceeds the ability of the formation to deliver water. **Backwashing** often is used in conjunction with overpumping. If the pump does not have a backflow prevention valve, alternately starting and stopping the pump creates a surging effect where water is driven back into the formation during the off cycle. Alternatively, water can be added to the well (Figure A.5a). In **bailing**, a bailer (Section 5.3.1) is allowed to fall freely through the borehole until it strikes the surface of the water. The impact of the bailer produces an outward surge of water through the well screen and filter pack. As the bailer fills, the flow of water reverses and fines migrate into the well and are brought to the surface in the bailer. Sediment in the bottom of the well can be mobilized by short rapid strokes of the bailer near the bottom before retrieving the bailer. **Mechanical surging** forces water into and out of the well screen by operating a plunger, called a **surge block**, which is attached to a drill rod or a wireline (Figure A.5b). The surge block is lowered to the top of the well intake and operated in a pumping action with strokes typically around 3 feet and is gradually worked downward through the screened interval. At regular intervals, the surge block is removed and fines that have entered the well are removed by pumping or with a bailer. **Compressed air** can be used to alternately surge and air-lift pump a well to remove sediment. In **air surging**, injected air lifts the water column until it reaches the top of the casing and the air supply is shut off, causing an outward surging action in the well intake. **Air lift** pumping using compressed air (Figure A.5c) brings water to the surface as described in Section 5.2.4. **High velocity jetting** uses a single- or multiple-nozzle device, which directs a horizontal stream of water against the well screen opening (Figure A.5d). The jetting tool is placed near the bottom of the screen and slowly rotated while being pulled upward. Material that enters the screen in the backwash of the jet stream is removed by pumping or bailing. **Jetting/pumping**, which combines jetting with simultaneous pumping, provides for maximum development efficiency. Two development methods that are used for water wells but are not recommended for monitoring well development because they introduce contaminants into the aquifer are: (1) **Blasting** (used only in solid rock wells), and (2) **acidizing** (used only in limestone aquifers).

Method Selection Considerations: **Overpumping Advantages:** (1) Is convenient for small wells or poor aquifers; (2) minimal time and effort are required; (3) no new fluids are introduced; and (4) removes fluids introduced during drilling and fine sediments. **Overpumping Disadvantages:** (1) Not adequate for large wells; (2) will not develop maximum efficiency in a well because does not effectively remove fine-grained sediment; (3) tends to cause sand to bridge in the formations (can be reduced by alternating pump on and pump off); (4) requires the use of high capacity pumping equipment; (5) can result in a large volume of water to be contained and disposed; (6) can leave the lower portion of large screen intervals undeveloped; (7) excessive pumping rates can caused well collapse, especially in deep wells; and (8) equipment for effective overpumping might not fit in small diameter wells. **Backwashing Advantages:** (1) Effectively rearranges filter pack; (2) effective in breaking down bridging; and (3) no new fluids introduced with on-off overpumping. **Backwashing Disadvantages:** (1) Fine sand, mud, silt, or clay can be washed into the well or filter pack from the formation; (2) not fully effective unless combined with surging, bailing, or pumping; (3) large quantities of water are required; (4) unless combined with pumping or bailing, does not remove drilling fluids; and (5) backwashing with added water introduces fluid into the well that might alter formation chemistry. **Bailing Advantages:** (1) No new fluids are introduced into the aquifer; (2) removes fluids introduced during drilling; (3) removes fines from well; and (4) bailers are easily obtained and can double as sampling devices. **Bailing Disadvantages:** (1) Is time-consuming and tiring if done manually; (2) not as effective as surge blocks; and (3) is not effective in unproductive wells. **Mechanical Surging Advantages:** (1) Is low cost; (2) effectively rearranges filter pack; (3) has greater suction action and surging than backwashing; (4) breaks down bridging in filter pack; (5) no new fluids are introduced; and (6) convenient to use for cable-tool rigs. **Mechanical Surging Disadvantages:** (1) Can produce unsatisfactory results when an aquifer contains clay because the casing or screen can collapse if it becomes plugged with fines; (2) tends to push fine-grained sediments into the filter pack; (3) unless combined with pumping or bailing, does not remove drilling

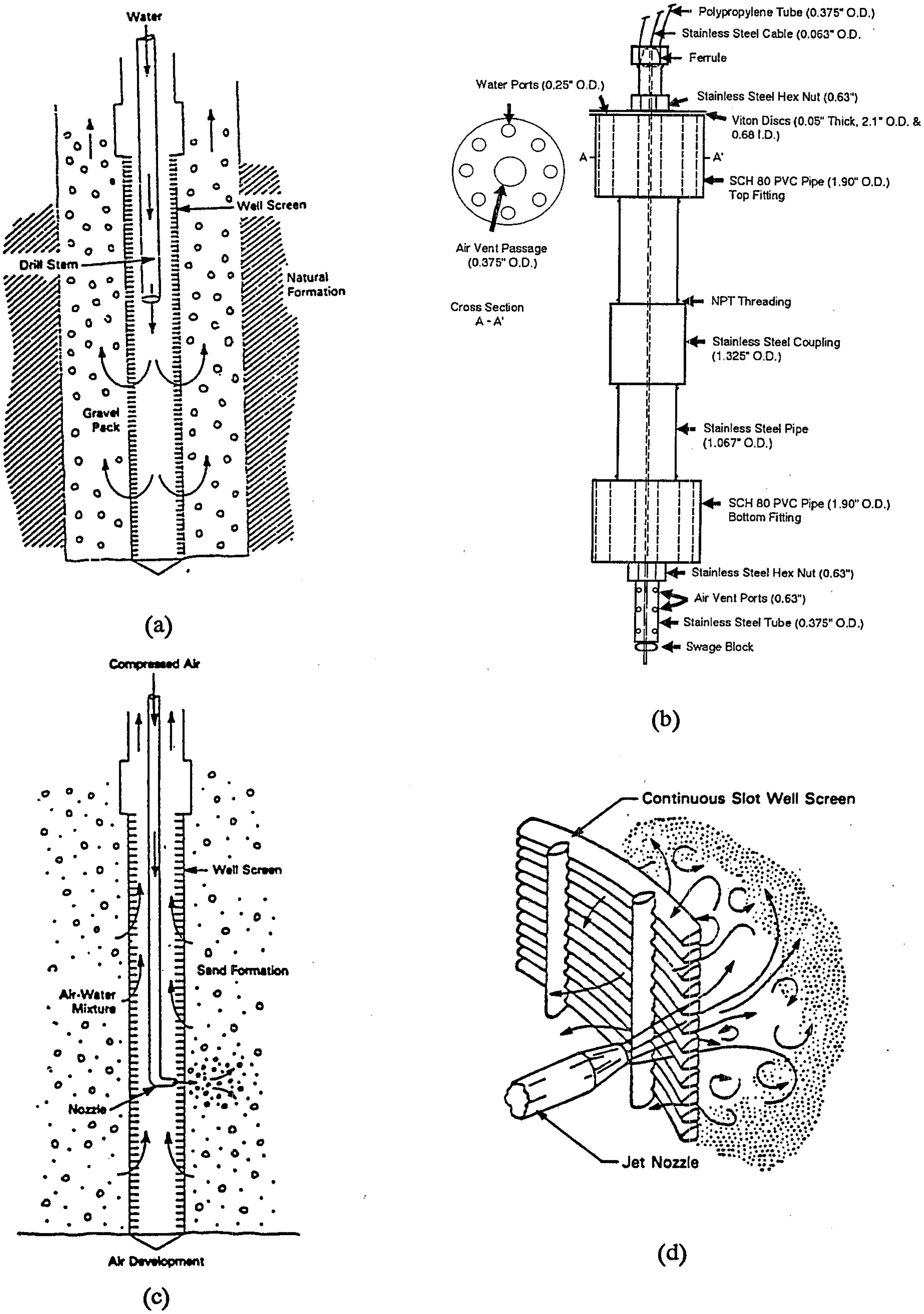


Figure A.5 Well development methods: (a) backwashing (U.S. EPA, 1991); (b) specialized surge block (Schalla and Landick, 1986); (c) compressed air (U.S. EPA, 1991); (d) high-velocity jetting (U.S. EPA, 1991).

fluids; (4) sometimes the well seal can be disturbed when surging; and (5) excessive sand can result in sand-locking of the surge block. **Compressed Air Advantages:** It is a rapid method. **Compressed Air Disadvantages:** Not recommended for monitoring wells because: (1) Air can become entrained in the filter pack and reduce permeability; (2) where yield is very weak and drawdown rapid, or submergence is low, other methods will be more satisfactory; and (3) introduction of air into aquifer can alter chemistry. **Jetting Advantages:** (1) Simple to use; (2) effectively rearranges and breaks down bridging in filter pack; (3) effectively removes mud cake around screen; (4) jetting with simultaneous pumping is particularly successful for wells in unconsolidated sands and gravels; and (5) jetting/pumping removes sediment from the well before it can settle in the screen and jetting waters can be recirculated after sediment has been removed at the surface. **Jetting Disadvantages:** Generally not recommended because: (1) Foreign water and possible contaminants are introduced to the aquifer; (2) air blockage can develop with air jetting; (3) air jetting can change water chemistry and biology (iron bacteria) near well; (4) unless combined with pumping or bailing, does not remove drilling fluids; and (5) jetting with simultaneous pumping is not always practicable.

Frequency of Use: Well development in some form should be performed on any monitoring well. Overpumping and backwashing are probably the most commonly used forms of well development. These methods or bailing combined with mechanical surging will be the most effective methods for most situations.

Standard Methods/Guidelines: Draft ASTM guide (ASTM, 1993).

Sources for Additional Information: Aller et al. (1991), Barcelona et al. (1983), Barrett et al. (1980), Campbell and Lehr (1973), Driscoll (1986), GeoTrans (1989), Scalf et al. (1981), Unwin (1982), U.S. EPA (1986). See also, Table A-1.

A.6 WELL MAINTENANCE AND REHABILITATION

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Maintaining monitoring well integrity; restoring monitoring well functions or changes in the purpose of a well.

Method Description: **Maintenance** involves the routine, ongoing tasks that ensure a well is a representative sampling point. This involves full **documentation** of design and installation of the well and of all subsequent sampling and other activities involving the well. Routine maintenance activities include: (1) Periodic bail testing of the well to determine specific capacity (can be done during normal purging for sampling or more frequently if sampling is infrequent); (2) measurement of depth before purging; (3) repair of protective casing, covers, hinges, and any other exposed parts of the well; and (4) occasional redevelopment by bailing, surging or bottom pumping (see Section A.5). **Rehabilitation** involves efforts beyond normal maintenance that are intended to restore the well's original performance or to alter the well to serve other purposes. Common rehabilitation techniques include: (1) Deepening because the water table has been lowered; (2) installation of sleeving to repair a physical problem; (3) treatment of screens to reduce plugging or encrustation; and (4) use of aggressive development techniques, such as high-velocity jetting (Section A.5), to improve well performance. In traditional well rehabilitation, three categories of chemicals are used for rehabilitation: (1) **Acids**, to dissolve incrustation on the well intake or in the surrounding formation; (2) **biocides**, to kill bacteria in the well or surrounding formation that contribute to clogging; and (3) **surfactants**, to disperse clay and fine materials for easier removal.

Method Selection Considerations: The main consideration in selection of maintenance and rehabilitation techniques is to avoid or minimize practices that might alter the integrity of water quality samples from the well. In general, this means avoiding use of development techniques, such as compressed air, non-native water for jetting, and traditional well rehabilitation chemical treatment methods, which introduce chemicals or alter the chemical environment of the formation.

Frequency of Use: All wells requiring maintenance procedures should be clearly defined in the site sampling plan. Rehabilitation procedures are used on an as-needed basis.

Standard Methods/Guidelines: ASTM Draft Standard Guide for Maintenance and Rehabilitation of Monitoring Wells (Nielsen, 1991).

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986), U.S. EPA (1975, 1986). See also, Table A-1.

A.7 WELL ABANDONMENT

Other Names Used to Describe Method: Decommissioning.

Uses at Contaminated Sites: Eliminating physical hazards; preventing ground-water contamination; conserving aquifer yield and hydrostatic head; preventing intermixing of subsurface water.

Method Description: Well abandonment involves the combination of full or partial casing/screen removal and plugging. **Casing/screen removal techniques:** The two main casing removal techniques are: (1) **Pulling**, using hydraulic jacks or by pumping the casing with a rig, and (2) **overdrilling**, in which a large-diameter hollow stem auger is used to drill around the casing. In shallow, sandy aquifers, casing can be removed by **jetting** (see Section 2.1.8). **Sandlocking** can be used to remove telescoped well screens, where the diameter is smaller than the casing. A pulling pipe wrapped with burlap strips is lowered to penetrate about 2/3 of the length of the screen. Sand is added to create a locking effect and the screen is pulled to the surface. **Latch-type** tools can be used to remove telescoped well screens that are 2 to 6 inches in diameter. **Partial casing removal** involves cutting the casing off below ground level. **Plugging techniques:** The simplest technique for plugging an uncased borehole is to fill the entire hole with grout material, commonly a **cement/bentonite** mixture (Section A.4), which is chemically compatible with the formation. Where casing is left in place, the interval adjacent to water-bearing zones is ripped or perforated with **casing rippers, gun-perforators,** or **jet perforators,** and grouted under pressure to allow penetration outside the casing. **Partial grouting** requires the use of **bridge plugs,** which allow sealing of selected portions of a borehole. A **permanent bridge seal** is the most deeply located plug that forms a bridge upon which fill material can be placed and is used to prevent cross contamination between lower and upper aquifers. If more than two water-bearing zones are intersected by the wells, **intermediate** seals are placed adjacent to intermediate zones and the remaining permeable zones are filled with clean disinfected sand, gravel, or other material. **Uppermost aquifer** seals keep out surface water and keep artesian aquifers from flowing to the surface. In artesian aquifers, special procedures might be required for plugging such as: (1) Pumping nearby wells to lower hydrostatic head, (2) placing fluids of high specific gravity in the borehole, or (3) elevating the casing high enough to stop the flow.

Method Selection Considerations: **Casing Removal Advantages:** Preferred method for abandonment because complete removal of casing provides greatest assurance that the hole is completely sealed. **Casing Removal Disadvantages:** (1) Pulling method generally is not feasible if casing has been sealed and grouted; (2) overdrilling requires hollow stem at least 2 inches larger than the casing being removed, which might not be available; (3) overdrilling will not work in consolidated formations and might be difficult if the well casing is not plumb; (4) sandlocking and latch-type tools can only be used when screen diameter is smaller than the inner diameter of casing; and (5) unstable boreholes require placement of grout at the same time the casing is pulled. **Plugging Advantages:** (1) Full plugging provides the greatest assurance that there will be no contamination or cross contamination of aquifers; and (2) partial plugging is less expensive than full plugging. **Plugging Disadvantages:** (1) Full plugging is more expensive than partial plugging, especially in deep boreholes; and (2) partial plugging procedures are more complex and do not provide as great assurance that the effective seals have been developed.

Frequency of Use: All wells should be properly abandoned when they are no longer needed for their original or a modified purpose.

Standard Methods/Guidelines: ASTM (1992c). Most states have well abandonment laws (see Kraemer et al., 1991 for summary of status of state well abandonment requirements). AWWA (1984), also reproduced as Appendix C in Aller et al. (1991), provides general guidelines for well abandonment.

Sources for Additional Information: Aller et al. (1991), Campbell and Lehr (1973), Driscoll (1986), U.S. EPA (1975, 1986). See also, Table A-1.

Table A-1 Index to References on Design and Installation of Monitoring Wells[a]

Topic	References
<u>General</u>	
Texts/Symposia	Aller et al. (1991), Anderson (1971), Barcelona et al. (1985a), Campbell and Lehr (1973), Driscoll (1986), Gaitlin (1960), GeoTrans (1989), Gibson and Singer (1969, 1971), Gillham et al. (1983), Howsam (1990), Johnson (1966), Korte and Kearl (1985), Lehr et al. (1988), Oregon Well Contractors Association (1968), Scott and Scalamini (1978), U.S. EPA (1975, 1986, 1993); <u>Bibliographies</u>: Campbell and Lehr (1973), Giefer (1963), Hix (1992a)
Federal/State Guidelines	CDHS (1986), CEPA (1983), Clark and Sabel (1980), NDEC (1984), U.S. Army Corps of Engineers (1990), USATHAMA (1982), WDNR (1985, 1991)
<u>Specific Topics</u>	
Case Studies	Fetter and Griffin (1988), Gordon and Powell (1989), Hunkin et al. (1984), Keely and Boateng (1987b), Laney (1988), Last and Bjornstand (1990), Macfarlane et al. (1988), Moore et al. (1990), Petermann et al. (1989), Reaber and Stein (1990), Schalla and Landick (1986), Seikan and Deyling (1989), Smith (1988), Smith et al. (1989), Spruill (1988), White (1990)
Well Costs	Ackermann (1969), Everett et al. (1976), Gibb (1971), Gibb and Sanderson (1969)
Chemical Effects	Barcelona et al. (1983, 1985b, 1988a), Boettner et al. (1981), Brobst and Buszka (1986-drilling fluids), Clarke (1966), Dunbar et al. (1985), Evans and Ellingson (1988), Gibb (1987), Gillham et al. (1983), Hamm (1971), Junk et al. (1974), Lewis (1982), Liikala et al. (1988), Lolcama (1988), Martin and Lee (1989), Massee et al. (1990), Nielsen (1988), Reynolds and Gillham (1985), Reynolds et al. (1990), Richter and Callentine (1983), Robertson (1968), Schmidt (1983), Struempler (1973), Walker (1983); see also, references on chemical effects listed under "Well Casing," and references on "water quality effects of well drilling" and "mud toxicity/water chemistry effects" in Table 2-4
Cross Contamination Prevention	Fetter and Griffin (1988), Hamm (1971), Millison et al. (1989)
Decontamination	Hix (1992b); see also, Section B.4 and Table B-5
Design/Installation	Ahrens (1957, 1958, 1970), ASTM (1990a), Beard (1992), Beck (1983), Cohen and Rabold (1988), Dablow et al. (1988-Teflon casing), Diefendorf and Ausburn (1977), Fetter and Griffin (1988), Gass (1984), Healy (1990), Keely and Boateng (1987a,b), Kelly (1982), Kerfoot (1988), Lewis (1982), Luhdorff and Scalmanini (1982), McCullom and Cronin (1992-permafrost areas), Minning (1982), Nielsen (1991), Paul et al. (1988), Reynolds and Zemo (1992-fine-grained formations), Richter and Collentine (1983), Riggs and Hatheway (1988), Rinaldo-Lee (1983), Robbins (1989), Schaff (1950), Smith et al. (1989), Swanson (1988), Treadway (1990), Walker (1983), Wehrmann (1983), Williams (1981), Voytek (1983); <u>Horizontal Wells</u>: See Section 2.1.11 and Table 2-4

Topic	References
Network Design	Andricevic and Foufoula-Georgiou (1991), Barcelona et al. (1989), Brown et al. (1983), Carerra et al. (1984), Cleveland and Yeh (1991), Cohen and Rabold (1988), Collins et al. (1991), Gordon and Powell (1989), Grisak et al. (1978), Haug et al. (1989), Hsueh and Rajagopal (1988), Huber (1989), Hudak and Laoiciga (1992), Hughes and Lettenmaier (1981), Knopman and Voss (1989), Loaiciga (1989), Loftis and Ward (1978), McKinney and Loucks (1992), McLaughlin and Graham (1986), McNichols and Davis (1988), Meyer and Brill (1988), Moore et al. (1990), Nightingale and Bianchi (1979), Robbins (1989), Schalla et al. (1989), Slawson (1980), Sophocleous et al. (1982), Spruill and Candela (1990), Wood and McLaughlin (1984), Young and Boggs (1990)
Well Casing	API (1976), ASTM (1986, 1990), Barcelona and Gibb (1988), Barcelona et al. (1983), Boettner et al. (1981), Brice (1990), Committee of Steel Pipe Producers (1979), Dablow et al. (1988), Foster (1989), Gross (1970), Kurt (1979), Nass (1976), National Association of Steel Pipe Distributors (1979), Nielsen (1988), NWWA/PPI (1980), Parker (1992-guidelines), Purdin (1980), Royce (1991), Uni-Bell Plastic Pipe Association (1979), Yu (1989); Casing Chemical Effects (see also, references listed under "Chemical Effects"): Barcelona and Helfrich (1986), Barcelona et al. (1988b), Bianchi-Mosquera and Mackay (1992), Boettner et al. (1981), Cowgill (1988), Curran and Tomson (1983), Dowd (1987), Gillham and O'Hannesin (1990), Hewitt (1989a,b, 1991, 1992), Hewitt et al. (1989), Houghton and Berger (1984), Jones and Miller (1988), Lang et al. (1989), Miller (1982), Parker and Jenkins (1986), Parker et al. (1989a, 1989b, 1990), Raber et al. (1983), Sosebee et al. (1983), Sykes et al. (1986); Diameter: Rinaldo-Lee (1983), Schalla and Myers (1988), Schalla and Oberlander (1983), Schmidt (1982)
Well Screens	Ahmad et al. (1983), Bikis (1979), Blair (1970), Burger (1989), Clark and Turner (1983), Gass (1988), Giddings and Shosky (1987), Gillespie (1992), Jackson (1983), McIlvride and Rector (1988), Meredith and Bryce (1992), Peterson et al. (1955), Rich and Beck (1990), Schalla and Walters (1990), Schmidt (1987), Smith (1963)
Filter Pack	Blair (1970), Boyle (1992), Bureau of Reclamation (1986), Fawcett (1963), Gass (1988), Hampton and Heuvelhorst (1990), Hampton et al. (1991), Mader (1989), Palmer et al. (1987), Schalla and Walters (1990), Smith (1954), Svitana (1989)
Sealing/Grouting	API (1959, 1990, 1991a, 1991b), Baker (1992), Bertane (1986), Bodocsi et al. (1988-reactivity with waste/leachate), Bowen (1981), Boyle (1992), Calhoun (1988), Campbell and Lehr (1975), CEMBUREAU (1967), Colangelo (1988), Coleman and Corrigan (1941), Edil et al. (1992), Fetzer (1982), Gaber and Fisher (1988), Gibb (1987-chemical effects), Halliburton (1968, 1969), Johnson et al. (1980), Kosmatka and Panarese (1988), Kurt (1983), Kurt and Johnson (1982), Leonard (1985), Lerch and Ford (1948), McCandless et al. (1988), McEllhiney (1955), Moerhl (1964), Molz and Kurt (1979), Senger and Perpich (1983), Smith (1976), Smith et al. (1990), Troxell et al. (1968), Williams and Evans (1987)

Table A-1 (cont.)

Topic	References
Well Development	Ault and Bethart (1970), Clarke (1966), Dougherty and Paczkowski (1988), Gass (1986), Giddings (1983), Gordon (1959), Hall and Luttrell (1990), Helweg et al. (1983), Johnson (1968), Keely and Boateng (1987a,b), Kelly (1982), Kill (1990), Lorenz and Price (1988), Mogg (1966), Nuckols (1990), Paul et al. (1988), Sevee and Maher (1990), Walker (1974), Whitesides (1970), Winegardner (1990); Hydraulic Fracturing: Howard and Fast (1970)
Maintenance/Rehabilitation	Texts: Gass et al. (1980); Papers: Bennison (1953), Gates (1989), Grubb and Martin (1963), Kraemer et al. (1991), Leach et al. (1991), McCullom and Cronin (1992-permafrost areas), Sevee and Maher (1990), Strumel (1965), Upp (1966), Winegardner (1990); Mechanical Integrity Testing: Aller and Nielsen (1984), Thornhill and Benefield (1990, 1992); see also, Section 3.6 on well construction logs (3.6)
Abandonment	AWWA (1984), Bergren et al. (1988), Herndon and Smith (1976, 1984), Hix (1990), Kraemer et al. (1991), Lamb and Kinney (1989), Perazzo et al. (1984), Renz (1989), Smith et al. (1990), U.S. EPA (1968), Van Eck (1978), Winegardner (1990); Old Abandoned Wells: Aller (1984), Fairchild and Canter (1984), Frischknecht et al. (1983), Gass et al. (1977), Hamm (1971)

[a]Other related reference index tables:

Table 2-4 (drilling methods).
Table 5-4 (well installations for NAPL sampling/detection).
Table 5-5 (well installations for portable samplers and in situ multilevel installations).

APPENDIX A REFERENCES

Ackermann, W.C. 1969. Costs of Wells and Pumps. Ground Water 7(1):35-37.

Ahmad, M.U., E.B. Williams, and L. Hamdan. 1983. Commentaries on Experiments to Assess the Hydraulic Efficiency of Well Screens. Ground Water 21(3):282-286.

Ahrens, T.P. 1957. Well Design Criteria: Part One. Water Well Journal 11(9):13-15; 11(11):9,18,20,22,26,28,30.

Ahrens, T.P. 1958. Water Well Engineering: More on Well Design Criteria. Water Well Journal 12(9):14,20,24,26; 12(11):16,26.

Ahrens, T.P. 1970. Basic Considerations of Well Design: Part III. Water Well Journal 24(4):45-50; 24(5):49-51; 24(6):47-51; 24(8):35-37.

Aller, L. 1984. Methods for Determining the Location of Abandoned Wells. EPA/600/2-83/123 (NTIS PB84-141530). (Also published in NWWA/EPA Series, National Water Well Association, Dublin, OH, 130 pp.) [Air photos, color/thermal IR, ER, EMI, GPR, MD, MAG, combustible gas detectors]

Aller, L. and D.M. Nielsen. 1984. Methods for Determining the Mechanical Integrity of Class II Injection Wells. EPA/600/20-84/121 (NTIS PB84-215755), 281 pp. Also published in NWWA/EPA series by National Water Well Association, Dublin, OH.

Aller, L., et al. 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells. EPA/600/4-89/034, 221 pp. Available from CERI.* (Also published in 1989 by National Water Well Association, Dublin, OH in its NWWA/EPA series, 398 pp. Nielsen and Schalla [1991] contain a more updated version of material in this handbook that is related to design and installation of ground-water monitoring wells.)

American Petroleum Institute (API). 1959. Oil-Well Cementing Practices in the United States. API, New York, NY, 297 pp.

American Petroleum Institute (API). 1976. API Specification for Casing, Tubing, and Drill Pipe. API Spec 5A, API, Dallas, TX.

American Petroleum Institute (API). 1990. Specification for Materials and Testing for Well Cements. API Spec 10, API, Washington, DC.

American Petroleum Institute (API). 1991a. Specification for Well Cements. API Spec 10A, API, Washington, DC.

American Petroleum Institute (API). 1991b. Worldwide Cementing Practices, 1st edition API, Washington, DC, 465 pp.

American Society for Testing and Materials (ASTM). 1986. Standard Specifications for Polyvinyl Chloride (PVC) Plastic Pipe Schedules 40, 80 and 120. D1785-86, (Vol. 8.02), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1990a. Recommended Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers. D5092-90, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1990b. Standard Specifications for Thermoplastic Water Well Casing Pipe and Couplings Made in Standard Dimension Ratios (SDR). F480-90, (Vol. 08.03), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1991. Standard Guide for the Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes and Other Devices for Environmental Activities. D5299-91, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992a. Standard Practice for the Minimum Set of Data Elements to Identify a Groundwater Site. D5254-92, (Vol 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992b. Specification for Portland Cement. C150-92, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992c. Standard Guide for the Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes and Other Devices for Environmental Activities. D5299-92, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993. Draft Standard Guide for Development of Ground-Water Monitoring Wells in Granular Aquifers. D18 Ballot 93-01, April 8, ASTM, Philadelphia, PA.

American Water Works Association (AWWA). 1984. AWWA Standards for Water Wells. AWWA A100-84. AWWA, Denver, CO, 74 pp. [Appendix I: Abandonment of Test Holes, Partially Completed Wells and Completed Wells, pp. 45-47]

Anderson, K.E. 1971. Water Well Handbook, 3rd edition Missouri Water Well and Pump Contractors Association, Inc., Rolla, MO. (2nd edition published in 1967 by Scholin Brothers Printing Corp, St. Louis, MO, 281 pp.)

Andricevic, R. and E. Foufoula-Georgiou. 1991. A Transfer Function Approach to Sampling Network Design for Groundwater Contamination. Water Resources Research 27(10):2759-2769.

Ault, D.C. and H.R. Bethart. 1970. Tools for Well Development. Water Well Journal 24(3):45-47.

Baker, P. 1992. Cement vs. Bentonite Grout for Construction of Monitoring Wells. Water Well Journal 46(12):30-31.

Barcelona, M.J. and J.P. Gibb. 1988. Development of Effective Ground-Water Sampling Protocols Ground-Water Contamination: Field Methods. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 17-26.

Barcelona, M.J. and J.A. Helfrich. 1986. Well Construction and Purging Effects on Ground-Water Samples. Environ. Sci. Technol. 20(11):1179-1184.

Barcelona, M.J. and J.A. Helfrich. 1988. Laboratory and Field Studies of Well-Casing Material Effects. In: Proc. of the Ground Water Geochemistry Conference, National Water Well Association, Dublin, OH, pp. 363-375.

Barcelona, M.J., J.P. Gibb, and R.A. Miller. 1983. A Guide to the Selection of Materials for Monitoring Well Construction and Ground-Water Sampling. ISWS Contract Report 327, Illinois State Water Survey, Champaign, IL., 78 pp.

Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske. 1985a. Practical Guide for Ground-Water Sampling. EPA/600/2-85/104 (NTIS PB86-137304). (Also published as ISWS Contract Report 374, Illinois State Water Survey, Champaign, IL.)

Barcelona, M.H., J.A. Helfrich, and E.E. Garske. 1985b. Sampling Tubing Effects on Ground-Water Samples. Analytical Chemistry 57(2):460-464.

Barcelona, M.J., J.A. Helfrich, and E.E. Garske. 1988a. Verification of Sampling Methods and Selection of Materials for Ground-Water Contamination Studies. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 221-231.

Barcelona, M.J., G.K. George, and M.R. Schock. 1988b. Comparison of Water Samples from PTFE, PVC and SS Monitoring Wells. EPA/600/X-88/091. U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Barcelona, M.J., D.P. Lettenmaier, and M.R. Schock. 1989. Network Design Factors for Assessing Temporal Variability in Ground-Water Quality. Environmental Monitoring and Assessment 12:149-179.

Barrett, J., et al. 1980. Procedures Recommended for Overburden and Hydrologic Studies of Surface Mines. GTR-INT-71, U.S. Forest Service, Intermountain Forest and Experiment Station, Ogden, UT, 106 pp.

Beard, L.D. 1992. Design and Construction of Deep Groundwater Monitoring Wells. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 256-269.

Beck, B.F. 1983. A Common Pitfall in the Design of RCRA Ground-Water Monitoring Programs. Ground Water 21(4):488-489.

Bennsion, G.W. 1953. Fundamentals of Water Well Operation and Maintenance. Am. Water Works Ass. J. 45(3):252-258.

Bergren, C.L., J.L. Janssen, and J.D. Heffner. 1988. Abandonment of Groundwater Monitoring Wells at the Savannah River Plant, Aiken, South Carolina. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues, National Water Well Association, Dublin, OH, pp. 215-220.

Bertane, M. 1986. The Use of Grout for the Sealing of Monitoring Wells. American Colloid Company, Skokie, IL.

Bianchi-Mosquera, G.C. and D.M. Mackay. 1992. Comparison of Stainless Steel vs. PTFE Miniwells for Monitoring Halogenated Organic Solute Transport. Ground Water Monitoring Review 12(4):126-131.

Bikis, E.A. 1979. A Laboratory and Field Study of Fiberglass and Continuous-Slot Screens (Abstract). Ground Water 17(1):111.

Blair, A.H. 1970. Well Screens and Gravel Packs. Ground Water 8(1):10-21.

Bodocsi, A., M.T. Bowers, and R. Sherer. 1988. Reactivity of Various Grouts to Hazardous Wastes and Leachates. EPA/600/2-88/021 (NTIS PB88-182936).

Boettner, E.A., G.L. Ball, Z. Hollingsworth, and R. Aquino. 1981. Organics and Organotin Compounds Leached from PVC and CPVC Pipes. EPA/600/1-81/062, 102 pp.

Bowen, R. 1981. Grouting in Engineering Practice, 2nd edition, Applied Science Publishers, Halstad Press, New York, NY, 285 pp.

Boyle, D.R. 1992. A Dry Injection System for the Emplacement of Filter Packs and Seals in Ground Water Monitoring Wells. Ground Water Monitoring Review 12(1):120-125.

Brice, D.A. 1990. Design of Hybrid Monitor Wells for Cost Efficiency While Meeting Technical and Quality Assurance Requirements. Ground Water Management 5:209-218 (4th NOAC).

Brobst, R.D. and P.M. Buszka. 1986. The Effect of Three Drilling Fluids on Ground-Water Sample Chemistry. Ground Water Monitoring Review 6(1):62-70.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalensky. 1983. Ground-Water Studies: An International Guide for Research and Practice. Studies and Reports in Hydrology No. 7, UNESCO, Paris. Originally published in 1972, with supplements added in 1973, 1975, 1977, and 1983.) [Section 7 covers considerations for location of monitoring wells in different hydrogeologic settings]

Bureau of Reclamation. 1981. Ground Water Manual--A Water Resources Technical Publication, 2nd edition, U.S. Department of the Interior, Denver, CO, 480 pp.

Bureau of Reclamation. 1986. Gravel Pack Thickness for Ground-Water Wells. REC-ERC-86-7, U.S. Department of the Interior, Denver, CO, 70 pp.

Burger, R.M. 1989. Pre-Screening for Vertical Extent of Contamination with Long Well Screens in a Homogeneous Aquifer. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 167-177.

Calhoun, D.E. 1988. Sealing Well Casings: An Idea Whose Time Has Come. Water Well Journal 42(2):25-29.

California Department of Health Services (CDHS). 1986. The California Site Mitigation Decision Tree Manual. CDHS, Sacramento, CA, 375 pp.

Campbell, M.D. and J.H. Lehr. 1973. Water Well Technology. McGraw-Hill, New York, NY, 681 pp. [Annotated bibliography contains over 600 references]

Campbell, M.D. and J.H. Lehr. 1975. Well Cementing. Water Well Journal 29(7):39-42.

Carrera, J., E. Usunoff, and F. Szidarovszky. 1984. A Method for Optimal Observation Network Design for Groundwater Management. J. Hydrology 73:147-163.

CEMBUREAU. 1967. Cement Standards of the World--Portland Cement and Its Derivatives. CEMBUREAU, Paris.

Clark, T.P. and G.V. Sable. 1980. Requirements of State Regulatory Agencies for Monitoring Ground-Water Quality at Waste Disposal Sites. Ground Water 18(2):168-174.

Clark, L. and P.A. Turner. 1983. Experiments to Assess the Hydraulic Efficiency of Wells. Ground Water 21(3):270-281.

Clarke, F.E. 1966. The Chemistry of Water Well Development. Industrial Water Eng. 3(9):19-25.

Cleveland, T.G. and W.W.-G. Yeh. 1991. Sampling Network Design for Transport Parameter Identification. J. Water Resour.

Plann. Manage. Div. ASCE 117(1):764-783.

Cohen, R.M. and R.R. Rabold. 1988. Simulation of Sampling and Hydraulic Tests to Assess a Hybrid Monitoring Well Design. Ground Water Monitoring Review 8(1):51-59. [Partial vs. fully penetrating screens and sand pack]

Colangelo, R.V. 1988. Inert Annular Space Materials, The Acid Test. Ground Water Monitoring Review 8(2):57-58.

Coleman, R.J. and G.L. Corrigan. 1941. Fineness and Water-to-Cement Ration in Relation to Volume and Permeability of Cement. Petroleum Technology Techn. Pub. No. 1266, pp. 1-11.

Collins, M., K.D. Drake, and W.R. Rohrman. 1991. Monitoring Well Design and Sampling Techniques at NAPL Sites. Ground Water Management 5:749-758 (5th NOAC).

Committee of Steel Pipe Producers. 1979. Handbook of Steel Pipe. American Iron and Steel Institute, Washington, DC, 48 pp.

Connecticut Environmental Protection Agency (CEPA). 1983. Ground-Water Monitoring Guidelines for Hazardous Waste Management Facilities. CEPA Hazardous Material Management Unit and Water Compliance Unit, Hartford, CT, 20 pp.

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 Casing. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 172-184.

Curran, C.M. and M.B. Tomson. 1983. Leaching of Trace Organics Into Water From Five Common Plastics. Ground Water Monitoring Review 3(3):68-71.

Dablow, III, J.F., D. Persico, and G.R. Walker. 1988. Design Considerations and Installation Techniques for Monitoring Wells Cased with Teflon PTFE. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 199-205.

Diefendorf., A.F. and R. Ausburn. 1977. Ground Monitoring Wells. Public Works 108(7):48-50.

Devinny, J.S., L.G. Everett, J.C.S. Lu, and R.L. Stollar. 1990. Subsurface Migration of Hazardous Wastes. Van Nostrand Reinhold, New York, NY. [Chapter 6 Groundwater Monitoring]

Dougherty, P.J. and M.T. Paczkowski. 1988. A Technique to Minimize Contaminated Fluid Produced During Well Development. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 303-317.

Dowd, R.M. 1987. Review of Studies Concerning Effects of Well Casing Materials on Trace Measurements of Organic Compounds. Presented at ASTM/NWWA/API Joint Workshop on Ground-Water Monitoring Standards Development, Tampa, FL, January 22-23.

Driscoll, F.G. 1986. Groundwater and Wells, 2nd edition, Johnson Filtration Systems, Inc., St. Paul, MN, 1089 pp.

Dunbar, D., H. Tuchfeld, R. Siegel, and R. Sterbentz. 1985. Ground Water Quality Anomalies Encountered During Well Construction, Sampling and Analysis in the Environs of a Hazardous Waste Management Facility. Ground Water Monitoring Review 5(3):70-74.

Edil, T.B., M.M.K. Chang, L.T. Lan, and T.V. Riewe. 1992. Sealing Characteristics of Selected Grouts for Water Wells. Ground Water 30:351-361.

Evans, L.G. and S.B. Ellingson. 1988. The Formation of Cement Slurry Bleed-Water and Minimizing its Effects on Water Quality Samples. In: Proc. of the Groundwater Geochemistry Conference, National Water Well Association, Dublin, OH, pp. 377-389.

Everett, L.G., K.D. Schmidt, R.M. Tinlin, and D.K. Todd. 1976. Monitoring Groundwater Quality: Methods and Costs. EPA/600/4-76/023 (NTIS PB257-133).

Fairchild, D.M. and L.W. Canter. 1984. Abandoned Wells and Ground Water. Ground Water Age 19(3):33-39.

Fawcett, A.E. 1963. Hydraulic Gravel Packing for Deep Water Wells. Ground Water 1(1):16-24.

Fetter, C.W. and R.A. Griffin. 1988. Field Verification of Noncontaminating Methodology for Installation of Monitoring Wells and Collection of Ground Water Samples. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 437-444.

Fetzer, C.A. 1982. Pumped Bentonite Mixture Used to Seal Piezometers. J. Geotech. Eng. 108:295-299.

Foster, S. 1989. Flush-Joint Threads Find a Home. Ground Water Monitoring Review 9(2):55-58.

Frischknecht, F.C., L. Muth, R. Grette, T. Buckley, and B. Kornegay. 1983. Geophysical Methods for Locating Abandoned Wells. U.S. Geological Survey Open-File Report 83-702, 211 pp. (Also published as EPA/600/4-84/065 [NTIS PB84-212711].)

Gaber, M.S. and B.O. Fisher. 1988. Michigan Water Well Grouting Manual. Ground Water Control Section, Michigan Department of Public Health, Lansing, MI, 83 pp.

Gaitlin, C.G. 1960. Petroleum Engineering, Drilling and Well Completions. Prentice-Hall, Engelwood Cliffs, NJ, 341 pp.

Gass, T.E. 1984. Methodology for Monitoring Wells. Water Well J. 38(6):30-31.

Gass, T.E. 1986. Monitoring Well Development. Water Well Journal 40(1):52-55.

Gass, T.E. 1988. Monitoring Well Filter Pack and Screen Slot Selection: A Reassessment of Design Parameters. Water Well Journal 42(6):30-32.

Gass, T.E., J.H. Lehr, and H.W. Heiss, Jr. 1977. Impact of Abandoned Wells on Ground Water. EPA/600/3-77/095 (NTIS PB-272665), 62 pp.

Gass, T.E., T.W. Bennett, J. Miller, and R. Miller. 1980. Manual of Water Well Maintenance and Rehabilitation Technology. National Water Well Association, Worthington, OH, 247 pp.

Gates, W.C.B. 1989. Protection of Ground-Water Monitoring Wells Against Frost Heave. Bull. Ass. Eng. Geologists 26(2):241-251.

GeoTrans. 1989. Groundwater Monitoring Manual for the Electric Utility Industry. Edison Electric Institute, Washington, DC.

Gibb, J.P. 1971. Cost of Domestic Wells and Water Treatment in Illinois. Illinois State Water Survey Circular 104, Champaign, IL, 23 pp.

Gibb, J.P. 1987. How Fluids and Grouting Materials Affect the Integrity of Ground Water Samples from Monitoring Wells. Ground Water Monitoring Review 7(1):33-42.

Gibb, J.P. and E.W. Sanderson. 1969. Cost of Municipal and Industrial Wells in Illinois, 1964-1968. Illinois State Water Survey Circular 98, Champaign, IL.

Gibson, U.P. and R.D. Singer. 1969. Small Wells Manual. U.S. Agency for International Development, Washington, DC.

Gibson, U.P. and R.D. Singer. 1971. Water Well Manual. Premier Press, 156 pp. (Reprint of Gibson and Singer [1969].)

Giddings, T. 1983. Bore-Volume Purging to Improve Monitoring Well Performance: An Often Mandated Myth. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 253-256

Giddings, T. and D.J. Shosky, Jr. 1987. What Is an Adequate Screen Length for Monitoring Wells? Ground Water Monitoring Review 7(2):96-103.

Giefer, G.J. 1963. Water Wells-An Annotated Bibliography. Water Resources Center Archives Series Rept. No. 13, Univ. of Calif. Berkeley, Berkeley, CA, 141 pp.

Gillespie, G.A. 1992. An Effective Monitoring Screen for Fine Sand Aquifers. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 241-255.

Gillham, R.W. and S.F. O'Hannesin. 1990. Sorption of Aromatic Hydrocarbons by Materials Used in Construction of Ground-Water Sampling Wells. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM

STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 108-124.

Gillham, R.W., M.J.L. Robin, J.F. Barker, and J.A. Cherry. 1983. Groundwater Monitoring and Sample Bias. API Publication 4367, American Petroleum Institute, Washington, DC, 206 pp.

Gordon, R.W. 1959. Development of Wells with Cable Tools. Water Well Journal 13(2):15-16, 31-34; 13(12):18-19, 28, 30, 32. [Surge, compressed air]

Gordon, M.J. and R.L. Powell. 1989. Identification of Aquifer Interconnection and Continuity in a Coastal Plain Geologic Environment. In: Proc. of the Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, pp. 33-52. [Monitoring network for RCRA facility]

Grisak, G.E., R.E. Jackson, and J.F. Pickens. 1978. Monitoring Ground Water Quality: The Technical Difficulties. In: Establishment of Water Quality Monitoring Programs, L.G. Everett and K.D. Schmidt (eds.), American Water Resources Association, Minneapolis, MN, pp. 210-232.

Gross, S. 1970. Modern Plastics Encyclopedia, Vol. 46. McGraw-Hill, New York, NY, 1050 pp.

Grubb, W.E. and F.G. Martin. 1963. A Guide to Chemical Well Treatments, Parts 1 to 7. Petrol. Eng. Vol. 21 (June to November), Nos. 5, 6, 7, 8, 9, 10, and 11.

Hall, S.H. and S.P. Luttrell. 1990. Geochemical Criteria for Developing and Purging Ground-Water Monitoring Wells. Ground Water Management 2:363-371 (4th NOAC).

Halliburton Services. 1968. Oil Well Cement Manual. Halliburton Services, Oklahoma City, OK.

Halliburton Services. 1969. Halliburton Cementing Tables. Halliburton Services, Oklahoma City, OK, 75 pp.

Hamm, H.H. 1971. Water Wells and Ground-Water Contamination. Bull. Ass. Eng. Geol. 8(1):79-90.

Hampton, D.R. and H.G. Heuvelhorst. 1990. Designing Gravel Packs to Improve Separate-Phase Hydrocarbon Recovery: Laboratory Experiments. Ground Water Management 4:195-209 (7th NWWA/API Conf.).

Hampton, D.R., M.M. Smith, and S.J. Shank. 1991. Further Laboratory Investigations of Gravel Pack Design for Hydrocarbon Recover Wells. Ground Water Management 8:615-629 (8th NWWA/API Conf.).

Haug, A., R.H. Petrini, G.E. Grisak, and K. Klahsen. 1989. Application of Geostatistical Methods to Assess Positions and Spacing of Ground-Water Monitoring Wells. In: 6th NWWA/API Conf., In: Proc. (6th) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Waters, National Water Well Association, Dublin, OH, pp. 159-173.

Healy B.E. 1990. Regulating Monitoring Well Construction. National Drillers Buyers Guide 11(10):24.

Helweg, O.J., V.H. Scott, and J.C. Scalmanini. 1983. Improving Well and Pump Efficiency. American Water Works Association, Denver, CO, 168 pp.

Herndon, J. and D.K. Smith. 1976. Plugging Wells for Abandonment. Union Carbide Corp., Nuclear Division, Office of Waste Isolation, Oak Ridge, TN.

Herndon, J. and D.K. Smith. 1984. Setting Down-Hole Plugs: A State-of-the-Art. In: Proc. of the 1st Nat. Conf. on Abandoned Wells: Problems and Solutions, Environmental and Ground-Water Institute, University of Oklahoma, Norman, OK, pp. 227-250.

Hewitt, A.D. 1989a. Influence of Well Casing Composition on Trace Metals in Ground Water. CRREL Special Report 89-9. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 18 pp.

Hewitt, A.D. 1989b. Leaching of Metal Pollutants from Four Well Casings Used for Ground-Water Monitoring. CRREL Special Report 89-32. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, NH, 11 pp.

Hewitt, A.D. 1991. Potential Influences of Common Well Casings on Metal Concentrations in Low Dissolved Oxygen Well Water. CRREL Report 91-13, U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, NH, 17 pp.

Hewitt, A.D. 1992. Potential of Common Well Casing Materials to Influence Aqueous Metal Concentrations. Ground Water Monitoring Review 12(2):131-136.

Hewitt, A.D., L.V. Parker, T.F. Jenkins, C.M. Reynolds, K.T. Lang, and M.H. Stutz. 1989. Influence of Ground Water Monitoring Well Casing on Metals and Organic Compounds in Well Water. Proc. of the 1989 Haztech Conference.

Hix, G.L. 1990. Decomissioning Monitoring Wells. Ground Water Monitoring Review 10(2):63-65.

Hix, G.L. 1992a. Ground Water Remediation as a Business Opportunity. Water Well Journal 46(5):61-65. [Includes bibliography of monitoring articles that have appeared in WWJ since 1965]

Hix, G.L. 1992b. Squeaky Clean Drill Rigs. Ground Water Monitoring Review 12(3):94-97.

Houghton, R.L. and M.E. Berger. 1984. Effects of Well Casing Composition and Sampling Methods on Apparent Quality of Ground Water. In: Proc. 4th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 203-213.

Howard, G.C. and C.R. Fast. 1970. Hydraulic Fracturing. American Institute of Mining, Metallurgical and Petroleum Engineers, Dallas, TX, 203 pp.

Howsam, P. (ed.). 1990. Proceedings of International Groundwater Engineering Conference on Water Wells Monitoring, Maintenance, and Rehabilitation. Chapman and Hall, London, 422 pp.

Hsueh, Y-W. and R. Rajagopal. 1988. Modeling Ground Water Quality Sampling Decisions. Ground Water Monitoring Review 8(4):121-133.

Huber, W.A. 1989. Well Placement and Well Elimination. In: Proc. 4th Int. Conf. on Solving Ground Water Problems with Models, National Water Well Association, pp. 187-207.

Hudak, P.F. and H.A. Laoiciga. 1992. A Location Modeling Approach for Groundwater Monitoring Network Augmentation. Water Resources Research 28(3):643-649.

Hughes, J.P. and D.P. Lettenmaier. 1981. Data Requirements for Kriging: Estimation and Network Design. Water Resources Research 17:1641-1650.

Hunkin, G.G., T.A. Reed, and G.N. Brand. 1984. Some Observations on Field Experiences with Monitoring Wells. Ground Water Monitoring Review 4(1):43-45

Jackson, P.A. 1983. A Laboratory and Field Study of Well Screen Performance and Design (Abstract). Ground Water 12(6):771-772.

Johnson, UOP. 1966. Ground Water and Wells, 1st edition, Edward E. Johnson, Inc., St. Paul, MN, 440 pp. (See Driscoll [1986] for 2nd edition.)

Johnson, UOP. 1968. Principles and Practical Methods of Developing Water Wells. Johnson UOP Bulletin 1033 (Revised), Johnson UOP, St. Paul, MN, 24 pp.

Johnson, Jr., R.C., C.E. Kurt, and G.F. Dunham, Jr. 1980. Well Grouting and Casing Temperature Increases. Ground Water 18(1):7-13.

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

Junk, G.A., H.J. Svec, R.D. Vick, and M.J. Avery. 1974. Contamination of Water by Synthetic Polymer Tubes. Environ. Sci. Technol. 8(13):1100-1106.

Keely, J.F. and K. Boateng. 1987a. Monitoring Well Installation, Purging, and Sampling Techniques--Part 1: Conceptualization. Ground Water 25(3):300-313.

Keely, J.F. and K. Boateng. 1987b. Monitoring Well Installation, Purging, and Sampling Techniques--Part 2: Case Histories. Ground Water 25(4):427-39.

Kelly, K.D. 1982. Bailing and Construction Considerations for Deep Aquifer Monitoring Wells on Western Oil Shale Leases. Ground Water 20(2):179-185.

Kerfoot, W.B. 1988. Monitoring Well Construction, and Recommended Procedures for Direct Ground-Water Flow Measurements Using a Heat-Pulsing Flowmeter. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 146-161.

Kill, D.L. 1990. Monitoring Well Development--Why and How. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 82-90.

Knopman, D.S. and C.I. Voss. 1989. Multiobjective Sampling Design for Parameter Estimation and Model Discrimination in Groundwater Solute Transport. Water Resources Research 25(10):2245-2258

Korte, N.W. and P.M. Kearl. 1985. Procedures for the Collection and Preservation of Ground Water and Surface Water Samples and for the Installation of Monitoring Wells, 2nd edition, U.S. Department of Energy Technical Measurements Center Report GJ/TMC-08 (NTIS DE86-006184), 68 pp.

Kosmatka, S.H. and W.C. Panarese. 1988. Design and Control of Concrete Mixtures. Portland Cement Association, Skokie, IL, 205 pp.

Kraemer, C.A., J.A. Shultz, and J.W. Ashley. 1991. Monitoring Well Post-Installation Considerations. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 333-365.

Kurt, C.E. 1979. Collapse Pressure of Thermoplastic Water Well Casing. Ground Water 17(6):550-555.

Kurt, C.E. 1983. Cement-Based Seals for Thermoplastic Water Well Casings. Water Well Journal 37(1):38-40.

Kurt, C.E. and R.C. Johnson, Jr. 1982. Permeability of Grout Seals Surrounding Thermoplastic Well Casing. Ground Water 20(4):415-419.

Lamb, B. and T. Kinney. 1989. Decommissioning Wells--Techniques and Pitfalls. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 217-228.

Laney D.F. 1988. Hydrocarbon Recovery as Remediation for Vadose Zone Soil/Gas Contamination. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 1147-1172.

Lang, K.T., M.H. Stutz, L.V. Parker, A.D. Hewitt, and T.F. Jenkins. 1989. Influence of Well Casing Materials on Chemical Species in Ground Water. In: Proc. of the 5th Annual Waste Testing and Quality Assurance Symp. (Washington).

Last, G.V. and B.N. Bjornstad. 1990. Monitoring Well Construction and Documentation at the Hanford Site, Washington. Ground Water Management 2:219-231 (4th NOAC).

Leach, R., A. Mikell, C. Richardson, and G. Alford. 1991. Rehabilitation of Monitoring, Production and Recharge Wells. In: Proc. 15th Annual Army Environmental R&D Symp. (1990), CETHA-TS-CR-91077, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 623-646.

Lehr, J., S. Hurlburt, B. Gallacher, and J. Voyteck. 1988. Design and Construction of Water Wells: A Guide for Engineers. Van Nostrand Reinhold, New York, NY, 224 pp.

Leonard, R. 1985. Dry Grout Driven Method: New Approach to Grouting. Ground Water Age 19(7):19-23.

Lerch, W. and C.L. Ford. 1948. Long-Time Study of Cement Performance in Concrete, Chapter 3--Chemical and Physical Tests of the Cements. Journal of the American Concrete Institute 19(8):745-796.

Lewis, R.W. 1982. Custom Designing of Monitoring Wells for Specific Pollutants and Hydrogeologic Conditions. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 187-193

Liikala, T.L., D.S. Daly, and A.P. Toste. 1988. An Evaluation of the Effects of Well Construction Materials and Ground-Water Sampling Equipment on Concentrations of Volatile Organic Compounds. PNL-6585, Pacific Northwest Laboratory, Richland, WA.

Loaiciga, H.A. 1989. An Optimization Approach for Groundwater Quality Monitoring Network Design. Water Resources Research 25(8):1771-1782.

Loftis, J.C. and R.C. Ward. 1978. Statistical Tradeoffs in Monitoring Network Design. In: Establishment of Water Quality Monitoring Programs, L.G. Everett and K.D. Schmidt (eds.), American Water Resources Association, Minneapolis, MN, pp. 36-48.

Lolcama, J.L. 1988. Reconciliation of Hydrochemistry of Ground Water Affected by Drilling and Sampling in Deep Boreholes. In: Proc. of the Groundwater Geochemistry Conference, National Water Well Association, Dublin, OH, pp. 405-426.

Lorenz, R. and V. Price, Jr. 1988. Well Volume Evacuation Versus pH, Conductivity, Volatile Organic Chlorocarbon and Metal Concentrations for Selected Monitoring Wells on the Savannah River Plant. In: Proc. of the Groundwater Geochemistry Conference, National Water Well Association, Dublin, OH, pp. 391-404.

Luhdorff, Jr., E.E. and J.C. Scalmanini. 1982. Selection of Drilling Method, Well Design and Sampling Equipment for Wells to Monitor Organic Contamination. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 359-365.

Macfarlane, P.A., M.A. Townsend, and D.L. Evans. 1988. Construction and Use of Multiple Completion Monitoring Wells in Hydrogeologic Studies of Deep Aquifer Systems: A Case Study from the Dakota Aquifer of Central Kansas. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 391-413.

Mader, D. 1989. Hydraulic Fracturing and Gravel Packing. Elsevier, New York, NY, 1239 pp.

Martin, W.H. and C.-C. Lee. 1989. Persistent pH and Tetrahydrofuran Anomalies Attributable to Well Construction. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 201-215.

Massee, R., F.J.M.J. Maessen, and J.J.M. DeGoeij. 1981. Losses of Silver, Arsenic, Cadmium, Selenium and Zinc Traces from Distilled Water and Artificial Sea-Water by Sorption on Various Container Surfaces. Analytica Chimica Acta 127:181-193.

McCandless, R.M., A. Bodocsi, and H.K. Howard. 1988. Quick Indicator Tests to Characterize Bentonite Type. EPA/600/2-88/049 (NTIS PB88244033).

McCullom, K.M. and J.E. Cronin. 1992. Installation and Maintenance of Groundwater Monitoring Wells Located in Permafrost Soils. Ground Water Management 11:31-44 (6th NOAC).

McEllhiney, W.A. 1955. Cementing Small Wells. Water Well Journal 9(1):12-13, 39-46.

McIlvride, W.A. and B.M. Rector. 1988. Comparison of Short- and Long-Screen Monitoring Wells in Alluvial Sediments. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 375-390.

McKinney, D.C. and D.P. Loucks. 1992. Network Design for Predicting Groundwater Contamination. Water Resources Research 28(1):133-147.

McLaughlin, D.B. and W.D. Graham. 1986. Design of Cost-Effective Programs for Monitoring Groundwater Contamination. In: Integrated Design of Hydrologic Networks, M.E. Mass (ed.), IAHS Publ. No. 158, pp. 231-245.

McNichols, R.J. and C.B. Davis. 1988. Statistical Issues and Problems in Ground Water Detection Monitoring at Hazardous Waste Facilities. Ground Water Monitoring Review 8(4):135-150.

Meredith, D.V. and D.A. Brice. 1992. Limitations on the Collection of Representative Samples from Small Diameter Monitoring Wells. Ground Water Management 11:429-439 (6th NOAC). [Screen design, purge/sample rates]

Meyer, P.D. and E.D. Brill. 1988. A Method for Locating Wells in a Groundwater Monitoring Network Under Conditions of Uncertainty. Water Resources Research 24(8):1277-1282.

Mickam, J.T., R. Bellandi, and E.C. Tifft, Jr. 1989. Equipment Decontamination Procedures for Ground Water and Vadose Zone

Monitoring Programs: Status and Prospects. Ground Water Monitoring Review 9(2):100-121.

Miller, G.D. 1982. Uptake and Release of Lead, Chromium and Trace Level Volatile Organics Exposed to Synthetic Well Casings. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 236-245.

Millison, D., T. Eckard, J. Muller, and E. Vander Velde. 1989. Use of a Continuous Sampling Wireline System and Telescopic Casing to Optimize Well Construction and Prevent Cross-Contamination In Deep Monitor Well Installations. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 273-287.

Minning, R.C. 1982. Monitoring Well Design and Installation. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 194-197.

Moehrle, K.E. 1964. Well Grouting and Well Protection. J. Am. Water Works Ass. 56(4):423-431.

Mogg, J.L. 1966. Maximum Yield from Minimum Aquifers. Ground Water 4(2):11-12. [Well development]

Molz, F.J. and C.E. Kurt. 1979. Grout-Induced Temperature Rises Surrounding Wells. Ground Water 17(3):264-269.

Moore, B.A., J.T. Witherspoon, L.L. Bullard, T.J. Aley, and J.K. Rosenfeld. 1990. Strategy for Delineation and Detection Monitoring of the Fulbright Springhead Protection Area, Springfield, Missouri. Ground Water Management 1:447-461 (Proc. of the 1990 Cluster of Conferences).

Nass, L.I. 1976. Encylopedia of PVC, Vols. I and II. Marcel Dekker, New York, NY, 1249 pp.

National Association of Steel Pipe Distributors. 1979. Tubular Products Manual. San Antonio, TX, 135 pp.

National Water Well Association and Plastic Pipe Institute (NWWA/PPI). 1980. Manual on the Selection and Installation of Thermoplastic Water Well Casing. NWWA, Worthington, OH, 64 pp.

Nebraska Department of Environmental Control (NDEC). 1984. Guidelines for Design and Construction of Water-Quality Monitoring Wells. NDEC Program Plans Division, Waster and Waste Management Division, Lincoln, NE, 11 pp.

Nielsen, D. 1988. Much Ado About Nothing: The Monitor Well Construction Material Controversy. Ground Water Monitoring Review 8(1):4.

Nielsen, D.M. 1991. An Update on ASTM Subcommittee on Ground Water and Vadose Zone Investigations. Ground Water Monitoring Review 11(3):92-96.

Nielsen, D.M. and R. Schalla. 1991. Design and Installation of Ground-Water Monitoring Wells. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 239-331.

Nightingale, H.I. and W.C. Bianchi. 1979. Influence of Well Water Quality Variability on Sampling Decisions and Monitoring. Water Resources Bulletin 15(5):1394-1407.

Nuckols, T.E. 1990. Development of Small Diameter Wells. Ground Water Management 2:193-207 (4th NOAC).

Oregon Well Contractors Association. 1968. Manual of Water Well Construction Practices. Oregon Well Contractors Association, Portland, OR, 85 pp.

Palmer, C.D., J.F. Keely, and W. Fish. 1987. Potential for Solute Retardation on Monitoring Well Sand Packs and Its Effect on Purging Requirements for Ground Water Sampling. Ground Water Monitoring Review 7(2):40-47.

Parker, L.V. 1992. Suggested Guidelines for the Use of PTFE, PVC and Stainless Steel in Samplers and Well Casings. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 217-229.

Parker, L.V. and T.F. Jenkins. 1986. Suitability of Polyvinyl Chloride Well Casings for Monitoring Munitions in Ground Water. Ground Water Monitoring Review 6(3):92-98.

Parker, L.V., T.F. Jenkins, and P.B. Black. 1989a. Evaluation of Four Well Casing Materials for Monitoring Selected Trace-Level

Organics in Ground Water. CRREL Report 89-18, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 29 pp.

Parker, L.V., A.D. Hewitt, and T.F. Jenkins. 1989b. Influence of Well Casing Materials on Chemical Species in Groundwater. In: Proc. 13th Annual Environmental Quality R&D Symp. (1988), CETHA-TE-CR-89005, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, pp. 450-461.

Parker, L.V., A.D. Hewitt, and T.F. Jenkins. 1990. Influence of Casing Materials on Trace-Level Chemicals in Well Water. Ground Water Monitoring Review 10(2):146-156.

Paul, D.G., C.D. Palmer, and D.S. Cherkauer. 1988. The Effect of Construction, Installation, and Development on the Turbidity of Water in Monitoring Wells in Fine-Grained Glacial Till. Ground Water Monitoring Review 7(1):73-82.

Perazzo, J.A., R.C. Dorrier, and J.P. Mack. 1984. Long-Term Confidence in Ground Water Monitoring Systems. Ground Water Monitoring Review 4(4):119-123.

Petermann, M.A., S.W. Webb, L.D. Schutts, and J.E. Clemmer. 1989. Assessment and Restoration of VOC-Impacted Ground Water and Soils in the Appalachian Piedmont Physiographic Province. In: Proc. (6th) NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Dublin, OH, pp. 655-672.

Peterson, J.S., et al. 1955. Effects of Well Screens on Flow into Wells. ASCE Trans. 120:562-584.

Purdin, W. 1980. Using Nonmetallic Casing for Geothermal Wells. Water Well Journal 34(4):90-91.

Raber, E., J. Garrison, and V. Oversby. 1983. Sorption of Selected Radionuclides on Various Metal and Polymeric Materials. Radioactive Waste Management and the Nuclear Cycle 4(1):41-52.

Reaber, D.W. and T.L. Stein. 1990. Design and Installation of a Detection Monitoring Network at a Class I Facility in an Arid Environment. Ground Water Management 2:299-311 (4th NOAC).

Renz, M.E. 1989. In-Situ Decommissioning of Monitor Wells. Water Well Journal 43(5):58-60.

Reynolds, G.W. and R.W. Gillham. 1985. Adsorption of Halogenated Organic Compounds by Polymer Materials Commonly Used in Ground Water Monitoring. In: Proc. 2nd Canadian/American Conference on Hydrogeology, National Water Well Association, Dublin, OH, pp. 125-132.

Reynolds, S.D. and D.A. Zemo. 1992. Methodology for the In-Field Design of Monitoring Wells in Heterogeneous Fine-Grained Formations. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 230-240.

Reynolds, G.W., J.T. Hoff, and R.W. Gillham. 1990. Sampling Bias Caused by Materials Used to Monitor Halocarbons in Ground Water. Environ. Sci. Technol. 24(1):135-142.

Rich, C.A. and B.M. Beck. 1990. Experimental Screen Design for More Sediment-Free Sampling. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 76-81.

Richter, H.R. and M.G. Collentine. 1983. Will My Monitoring Wells Survive Down There? Installation Techniques for Hazardous Waste Studies. In: Proc. 3rd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 223-229.

Riggs, C.O. and A.W. Hatheway. 1988. Groundwater Monitoring Field Practice--An Overview. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 121-136.

Rinaldo-Lee, M.B. 1983. Small vs. Large Diameter Monitoring Wells. Ground Water Monitoring Review 3(1):72-75.

Robbins, G.A. 1989. Influence of Using Purged and Partially Penetrating Monitoring Wells on Contaminant Detection, Mapping, and Modeling. Ground Water 27(2):155-162.

Robertson, D.E. 1968. The Adsorption of Trace Elements in Sea Water on Various Container Surfaces. Analytica Chimica Acta 42:533-536.

Royce, K.L. 1991. Selection of Well Construction Materials. Water Well Journal 45(8):30-32.

Scalf, M.R., J.F. McNabb, W.J. Dunlap, R.L. Cosby, and J. Fryberger. 1981. Manual of Ground-Water Quality Sampling Procedures. EPA/600/2-81/160, (NTIS PB82-103045). (Also published in NWWA/EPA Series, National Water Well Association, Dublin OH.)

Schaff, S.L. 1950. Geology and Water Well Construction. J. Am. Water Works. Ass. 42(4):475-478.

Schalla, R. and R.W. Lankick. 1986. A New Valved and Air-Vented Surge Plunger for Developing Small-Diameter Monitor Wells. Ground Water Monitoring Review 6(2):77-80.

Schalla, R. and D.A. Myers. 1988. Small-Diameter Casing for Standpipe Monitoring Wells: A Comparison of Current Alternatives. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 365-373.

Schalla, R. and P.L. Oberlander. 1983. Variation in the Diameter of Monitoring Wells. Water Well Journal 37(5):56-67.

Schalla, R. and W.H. Walters. 1990. Rationale for the Design of Monitoring Well Screens and Filter Packs. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 64-75.

Schalla, R., S.P. Luttrell, and R.M. Smith. 1989. Hydrochemical Monitoring and Hydrogeologic Characterization: Conflict and Resolution. In: Proc. of the Conf. on New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, National Water Well Association, pp. 355-367.

Schmidt, K.D. 1982. The Case for Large-Diameter Monitor Wells. Water Well Journal 36(12):28-29.

Schmidt, K.D. 1983. How Representative Are Water Samples Collected from Wells? In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 117-128.

Schmidt, G.W. 1987. The Use of PVC Casing and Screen in the Presence of Gasoline on the Ground Water Table. Ground Water Monitoring Review 7(2):94.

Scott, V.H. and J.C. Scalmanini. 1978. Water Wells and Pumps: Their Design, Construction, Operation and Maintenance. Div. of Agric. Science Bulletin 1889, Univ. of California.

Seikan, D.I. and M.A. Deyling. 1989. Ground Water Monitoring Network Installation at the Fall River, Massachusetts Municipal Landfill. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 179-189.

Senger, J.A. and W.M. Perpich. 1983. An Alternative Well Seal in Highly Mineralized Ground Water. In: Proc. 3rd Nat. Conf. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 230-234.

Sevee, J.E. and P.M. Maher. 1990. Monitoring Well Rehabilitation Using the Surge Block Technique. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 91-97.

Slawson, G.C. (ed.). 1980. Groundwater Quality Monitoring of Western Oil Shale Development: Monitoring Program Development. EPA/600/7-80/089 (NTIS PB80-203219), 200 pp.

Smith, H.F. 1954. Gravel Packing Water Wells. Water Well J. 8(1):31-34.

Smith, R.C. 1963. Relation of Screen Design to the Design of Mechanically Efficient Wells. J. Am. Water Works Ass. 55(5):609-614.

Smith, D.K. 1976. Cementing. SPEM Monograph Series. Society of Petroleum Engineers of AIME, Dallas, TX, 184 pp.

Smith, R.M. 1988. Resource Conservation and Recovery Act Ground-Water Monitoring Project for Hanford Facilities: Progress Report for the Period April 1 to June 31, 1988. PNL-6675/UC-11, 41, Pacific Northwest Laboratory, Richland, WA.

Smith, R.M., D.J. Bates, and R.E. Lundgren. 1989. Resource Conservation and Recovery Act Ground-Water Monitoring Project for Hanford Facilities: Progress Report for the Period January 1 to March 31, 1989. PNL-6957/UC-11, 41. Pacific Northwest

Laboratory, Richland, WA.

Smith, M.D., R.L. Perry, G.F. Stewart, W.A. Holloway, and F.R. Jones. 1990. A Feasibility Study of the Effectiveness of Drilling Mud as a Plugging Agent in Abandoned Wells. EPA/600/2-90/022 (NTIS PB90-227232).

Sophocleous, M., J.E. Paschetto, and R.A. Olea. 1982. Ground-Water Network Design for Northwest Kansas, Using the Theory of Regionalized Variables. Ground Water 20:48-58.

Sosobee, J.B., P.C. Geiszler, D.L. Winegardner, and C. Fisher. 1983. Contamination of Ground Water Samples With Poly(Vinyl Chloride) Adhesive and Poly(Vinyl Chloride) Primer from Monitor Wells. In: Second Symposium of Hazardous and Industrial Solid Waste Testing, ASTM STP 805, American Society for Testing and Materials, Philadelphia, PA, pp. 38-49.

Spruill, T.B. 1988. Use of Total Organic Carbon as an Indicator of Contamination From an Oil Refinery, South-Central Kansas. Ground Water Monitoring Review 8(3):76-82.

Spruill, T.B. and L. Candela. 1990. Two Approaches to Design of Monitoring Networks. Ground Water 28(3):430-442.

Struempler, A.W. 1973. Adsorption Characteristics of Silver, Lead, Cadmium, Zinc and Nickel on Borasilicate Glass, Polyethylene, and Polypropylene Container Surfaces. Analytical Chemistry 45(13):2251-2254.

Strumel, G.H. 1965. Maintenance of Well Efficiency. J. Am. Water Works. Ass. 57(8):996-1010.

Svitana, K.D. 1989. Geofabrics: An Effective Alternative to Gravel Packed Wells. In: Proc. 3rd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 191-199.

Swanson, G.J. 1988. Mastering the Fundamentals. Water Well Journal 42(5):55-57.

Sykes, A.L., R.A. McAllister, and J.B. Homolya. 1986. Sorption of Organics by Monitoring Well Construction Materials. Ground Water Monitoring Review 6(4):44-47.

Thornhill, J.T. and B.G. Benefield. 1990. Injection-Well Mechanical Integrity. EPA/625/9-89/007, 123 pp. Available from CERI.*

Thornhill, J.T. and B.G. Benefield. 1992. Detecting Water Flow Behind Pipe in Injection Wells. EPA/600/R-92/041, U.S. Environmental Protection Agency R.S. Kerr Environmental Laboratory, Ada, OK, 82 pp.

Treadway, C. 1990. High Water Level Installation of Monitoring Wells for Underground Storage Tanks. Ground Water Monitoring Review 10(3):82-83.

Troxell, G.E., H.E. Davis, and J.W. Kelly. 1968. Composition and Properties of Concrete. McGraw-Hill, New York, NY.

Uni-Bell Plastic Pipe Association. 1979. Handbook of PVC Pipe. Dallas, TX, 306 pp.

Unwin, J. 1982. A Guide to Groundwater Sampling. NCPASI Technical Bulletin 362. National Council of the Paper Industry for Air and Stream Improvement, New York, NY.

Upp, J.E. 1966. The Use of the Cement Bond Log in Well Rehabilitation. In: Trans. SPWLA 7th Annual Logging Symp., Society of Professional Well Log Analysts, Tulsa, OK, pp. X1-X11.

U.S. Army Corps of Engineers. 1990. Draft Monitor Well Installation at Hazardous and Toxic Waste Sites. Engineer Circular EC 1110-7-XX(FR). (Interim guidance pending development of final engineering circular.)

U.S. Army Toxic and Hazardous Materials Agency (USATHAMA). 1982. Minimum Requirement for Boring Logs, Drilling Procedures, Monitoring Installation, and Associated Data Management System Entries. USTHAMA, Aberdeen Proving Ground, MD.

U.S. Environmental Protection Agency (EPA). 1968. Technical Manual: Injection Well Abandonment. U.S. EPA Office of Drinking Water Contract No. 68-01-5971.

U.S. Environmental Protection Agency (EPA). 1975. Manual of Water Well Construction Practices. EPA/570/9-75/001 (NTIS PB267-371), 156 pp.

U.S. Environmental Protection Agency (EPA). 1986. RCRA Ground Water Monitoring Technical Enforcement Guidance Document. EPA/530/SW-86/055 (OSWER-9950.1), (NTIS PB87-107751), 332 pp. (Also published in NWWA/EPA Series, National Water Well Association, Dublin, OH.) Final OSWER Directive 9950.2 (NTIS PB91-140194). Executive Summary: OSWER 9950.1a (NTIS PB91-140186), 17 pp. (See also, U.S. EPA [1993].)

U.S. Environmental Protection Agency (EPA). 1991. Ground Water Handbook, Vol. II: Methodology. EPA/625/6-90/016b, 141 pp. Available from CERI.*

U.S. Environmental Protection Agency (EPA). 1992. Definitions for the Minimum Set of Data Elements for Ground Water Quality. EPA/813/B-92/002, 98 pp. Available from Safe Drinking Water Hotline, 800-426-4791.

U.S. Environmental Protection Agency (EPA). 1993. RCRA Ground Water Monitoring: Draft Technical Guidance. EPA/530/R-93/001 (NTIS PB93-139350).

Van Eck, O.J. 1978. Plugging Procedures for Domestic Wells. Public Information Circular No. 11. Iowa Geological Survey, Des Moines, IA, 7 pp. (Supersedes Circular No. 1 by same author titled "Optimal Well Plugging Procedures.")

Voytek, J.E., Jr. 1983. Considerations in the Design and Installation of Monitoring Wells. Ground Water Monitoring Review 3(1):70-71.

Walker, W.H. 1974. Tube Wells, Open Wells, and Optimum Ground-Water Resource Development. Ground Water 12(1):10-15.

Walker, S.E. 1983. Background Ground-Water Quality Monitoring: Well Installation Trauma. In: Proc. 3rd Nat. Symp. on Aquifer Restoration and Ground-Water Monitoring, National Water Well Association, Worthington, OH, pp. 235-246.

Wehrmann, H.A. 1983. Monitoring Well Design and Construction. Ground Water Age 17(8):35-38.

White, A.E. 1990. Design/Installation of Deep Groundwater Monitoring Wells in an Arid Region. Ground Water Management 4:101-109 (7th NWWA/API Conf.).

Whitesides, D.W. 1970. Common Errors in Developing a Ground Water Aquifer. Ground Water 8(4):25-28.

Williams, E.B. 1981. Fundamental Concepts of Well Design. Ground Water 19(5):527-542.

Williams, C. and L.G. Evans. 1987. Guide to the Selection of Cement, Bentonite and Other Additives for Use in Monitor Well Construction. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 325-343.

Winegardner, D.L. 1990. Monitoring Wells: Maintenance, Rehabilitation, and Abandonment. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 98-107.

Wisconsin Department of Natural Resources (WDNR). 1985. Guidelines for Monitoring Well Installation. WDNR Bureau of Solid Waste Management, Madison, WI, 35 pp.

Wisconsin Department of Natural Resources (WDNR). 1991. Groundwater Monitoring Well Requirements. Wisconsin Administrative Code Chapter NR 141. (See also, Monitoring Well Construction Form 4400-113A, rev. 4-90.)

Wood, E.F. and D. McLaughlin. 1984. Ground Water Monitoring Well Network Redesign. In: Proc. NWWA/API Conf. on Petroleum Hydrocarbons and Organic Chemicals in Ground Water-Prevention, Detection and Restoration, National Water Well Association, Worthington, OH, pp. 198-209.

Young, S.C. and J.M. Boggs. 1990. Observed Migration of a Tracer Plume at the MADE Site. In: Proc. Environmental Research Conference on Groundwater Quality and Waste Disposal. EPRI EN-6749, Electric Power Research Institute, Palo Alto, CA, pp. 11-1 to 11-18.

Yu, J.K. 1989. Should We Use a Well Foot (Sediment Trap) in Monitoring Wells? Ground Water Monitoring Review 9(2):59-61.

*ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH 45268-0963 (513-569-7562).

APPENDIX B

GENERAL GROUND-WATER SAMPLING AND HANDLING PROCEDURES

This appendix provides an overview of ground-water sampling and handling procedures, which generally are applicable to any ground-water monitoring program. This information should be considered in combination with Section 5 (Ground-Water Sampling Devices and Installations, and Appendix A (Design and Construction of Monitoring Wells). This appendix is not intended to provide specific guidance on sampling for a specific situation, but provides information on the major activities that are required for sample collection and handling. The appropriate guidance documents and other reference sources identified in Table B-1 (at the end of this appendix) should be used in consultation with the appropriate regulatory agency to determine procedures appropriate to a specific site.

The starting point for any ground-water sampling program is the **quality assurance/quality control (QA/QC) plan** (Section B.1). Ground-water sampling protocols appropriate to the data quality objectives and the site conditions will define the specific procedures that will be followed for individual sampling events. **Well purging** (Section B.2) typically has been an important element of sampling procedures, the specific procedures of which will vary with site conditions. As discussed in Section B.2, well purging should no longer be assumed to be required for all well sampling situations. Specific **sample handling and preservation** procedures (Section B.3) are likely to vary somewhat, depending on the analyte of interest at a site, as will **decontamination** procedures (Section B.4). U.S. EPA (1992) and ASTM (1992a) identify the minimum information that is required for documenting a ground-water sampling event. ASTM is nearing completion of a series of guides that cover additional descriptors for documenting a ground-water sampling events (ASTM 1992b, 1992c, 1992d, 1993).

B.1 QUALITY ASSURANCE/QUALITY CONTROL

Other Names Used to Describe Method: QA/QC, sampling protocol.

Uses at Contaminated Sites: Minimizing the sources of error in ground-water (and soil) sampling results.

Method Description: A QA/QC plan involves the establishment of a sampling protocol, which is designed to minimize sources of error in each stage of the sampling process, from sample collection to analysis and reporting of analytical data. Key elements include: (1) Development of a statistically sound sampling plan for spatial and temporal characterization of ground water (U.S. EPA, 1989b); (2) installation of a vertical and horizontal sampling network, which allows collection of samples that are representative of the subsurface; (3) use of sampling devices that minimize disturbance of the chemistry of the formation water; (4) use of decontamination procedures for all sampling equipment to minimize cross-contamination between sampling points (see Section B.4); (5) collection of QA/QC samples (see Table B.1 for types of samples); and (6) bottling, preservation, and transport of samples to maximize the integrity of the samples (Section B.3). Additional QA/QC procedures must be followed in the laboratory. Figure B.1 shows a generalized flow diagram for ground-water soil sampling protocol.

Method Selection Considerations: As requirements for precision and accuracy increase, the type and number of QA/QC samples will increase. Field rinsate blanks should be collected any time there is a possibility of cross-contamination from sampling equipment.

Frequency of Use: Required standard procedure for all ground-water sampling.

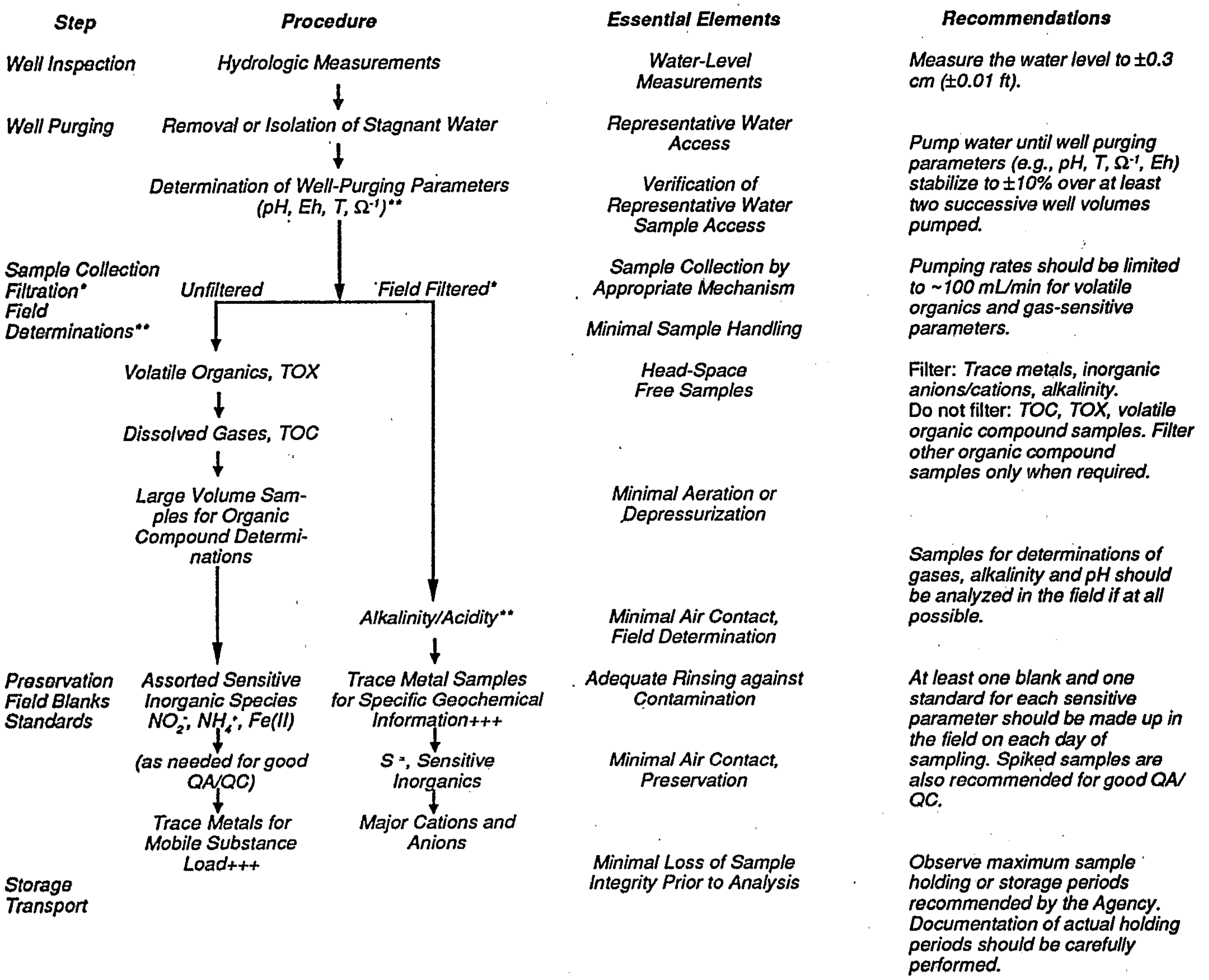
Standard Methods/Guidelines: --

Sources for Additional Information: See Table B-1.

Table B.1 Types of QA/QC Samples

Double-Blind Samples
Field evaluation samples (FES)
Low-level field evaluation samples (LLFES)
External laboratory evaluation samples (ELES)
Low-level external laboratory evaluation samples (LLELES)
Field matrix spike (FMS)
Field duplicate (FD)
Preparation split (PS)
Single-Blind Samples
Field rinsate blanks (FRB)--also called field blanks, decontamination blanks, equipment blanks, and dynamic blanks
Preparation rinsate blank (PRB)--also called sample bank blanks
Trip blank (TB)--also called field blank

Source: van Ee et al. (1990)



* Denotes samples that should be filtered to determine dissolved constituents. Filtration should be accomplished preferably with in-line filters and pump pressure or by N_2 pressure methods. Samples for dissolved gases or volatile organics should not be filtered. In instances where well development procedures do not allow for turbidity free samples and may bias analytical results. split samples should be spiked with standards before filtration. Both spiked samples and regular samples should be analyzed to determine recoveries from both types of handling.

** Denotes analytical determinations that should be made in the field.

+++ See Puls and Barcelona (1989).

Figure B.1 Generalized flow diagram of ground-water sampling protocol (U.S. EPA, 1991a).

B.2 WELL PURGING

Other Names Used to Describe Method: Well flushing.

Uses at Contaminated Sites: Removing stagnant water from a well before sample collection.

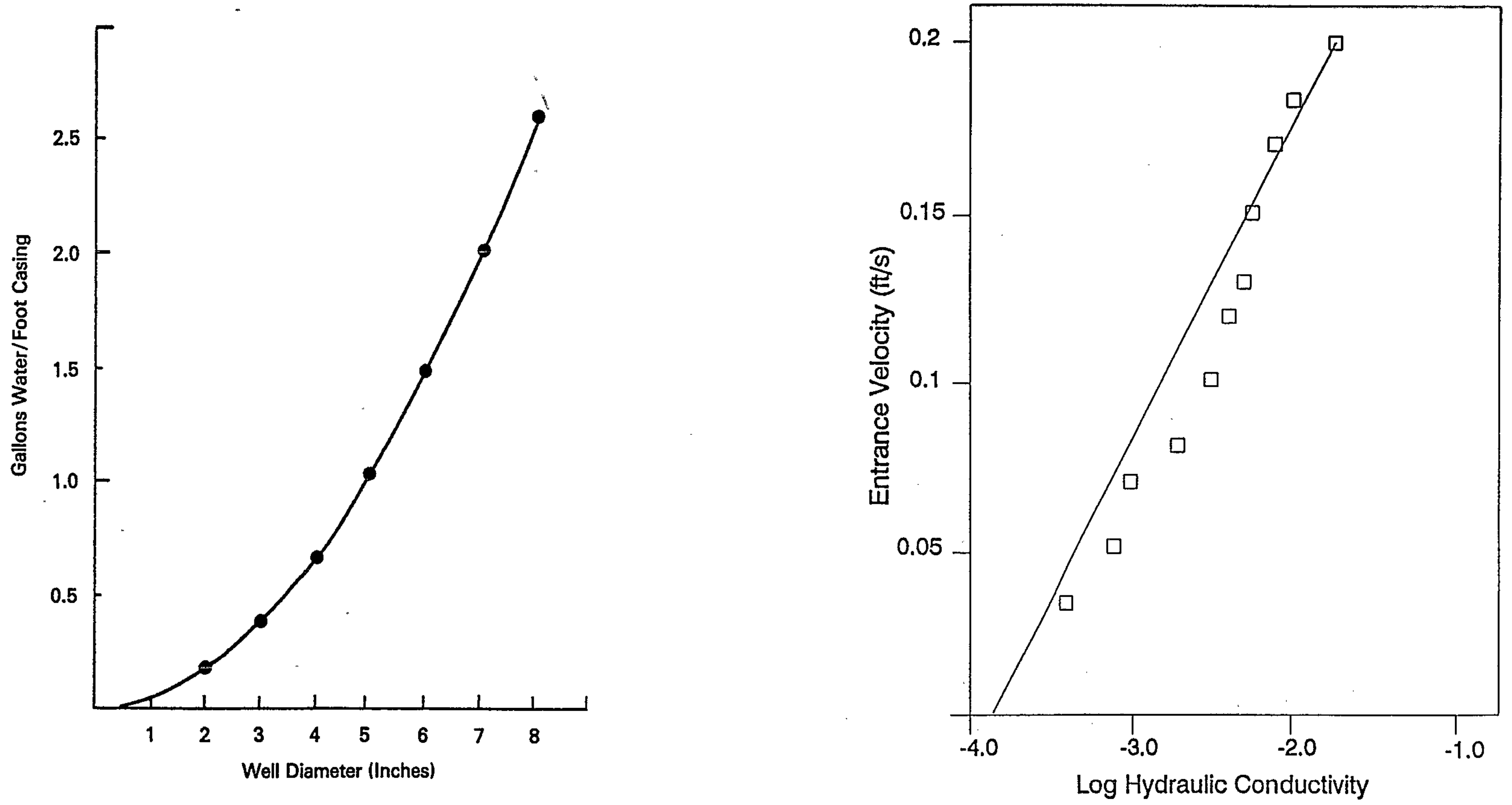
Method Description: Well purging involves the pumping of stagnant water from a well before sample collection. A monitoring well is pumped (generally at a rate from 1 to 5 gallons per minute) until a certain number of well volumes have been removed and until water quality indicators, such as pH, conductance, and/ or temperature, have stabilized, indicating that fresh formation water fills the well. Sampling takes place after purging in completed. Recent research (Kearl et al., 1992) has suggested that purging is not desirable because it can mobilize colloidal particles upon which contaminants are sorbed. The alternative to purging is to use a dedicated sampling device set at the level of the well screen capable of low pumping rates (around 100 mL/minute), which will not increase colloid density in the ground-water sample compared to natural colloidal flow through the well screen.

Method Selection Considerations: Recommended rules of thumb, such as purging three to five volumes (Fenn et al., 1977) should be treated only as a starting point. Accurate estimation of purge volume requires knowing: (1) Well yield, determined from a slug or pumping test, and (2) the stagnant volumes of both the well casing, and the sand pack. Figure B.2a shows the volume of water stored per foot of well casing at different diameters. In slowly recovering wells, extra care is required when purging to ensure that water levels do not drop below the level of the well screen because aeration might allow loss of volatile or redox sensitive contaminants. After stagnant water has been removed or isolated, chemical indicators (pH, conductance, and temperature) should continue to be monitored until they reach a consistent end point (no upward or downward trend). Another important consideration in purging is that the pumping rate should not exceed levels that will cause turbulent flow. Turbulent flow in the well might cause pressure changes, which could result in loss of carbon dioxide and other volatile gases, subsequently changing pH and dissolved solids content (Meredith and Brice, 1992). The maximum discharge rate during pumping that avoids turbulent flow is a function of hydraulic conductivity, the length of the well screen, width of the screen openings, and the total open area of the screen. Figure B.2b shows the optimum screen entrance velocity related to the hydraulic conductivity of an aquifer. Table B.2 provides guidelines for maximum purging rate based on screen type, diameter, slot size, open area, and entrance velocity (from Figure B.2b).

Frequency of Use: Has been a standard procedure for all ground-water sampling, although, as noted above, the practice has been called into question.

Standard Methods/Guidelines: Barcelona et al. (1985) provide a detailed procedure for estimating well purging volume.

Sources for Additional Information: All standard guides on ground-water sampling discuss purging (see general texts/reports and additional references listed under "purging" in Table B-1). Herzog et al. (1991) provide a good review of the literature on well purging.



(a)

(b)

Figure B.2 **Well purging: (a) Volume of water stored per foot of well casing for different diameter casings (Rinaldo-Lee, 1983, by permission); (b) Optimum screen entrance velocity related to hydraulic conductivity of aquifer (Meredith and Brice, 1992, by permission).**

Table B.2 Maximum Recommended Purging Rate for Monitoring Well Screens

Screen Type	Diameter (in)	Slot (in)	Open Area (ft²/ft)	Open Area (%)	Recommended Pumping Rate gpm/ft@ 0.1 ft/s	gpm/ft@ 0.07 ft/s	gpm/ft@ 0.03 ft/s
PVC (machine slot)	2	0.01	0.018	3.4	0.804	0.563	0.241
	2	0.02	0.033	6.4	1.496	1.047	0.449
	2	0.025	0.042	8.0	1.870	1.309	0.561
	2	0.04	0.060	11.5	2.693	1.885	0.808
	2	0.051	0.075	14.4	3.385	2.369	1.015
	4	0.01	0.036	3.4	1.608	1.126	0.482
	4	0.02	0.067	6.4	2.992	2.094	0.898
	4	0.025	0.083	8.0	3.740	2.618	1.122
	4	0.04	0.120	11.5	5.386	3.770	1.616
	4	0.051	0.151	14.4	6.773	4.741	2.032
PVC (wound)	2	0.01	0.047	9.0	2.119	1.484	0.636
	2	0.02	0.089	17.0	3.989	2.793	1.197
	2	0.03	0.124	23.7	5.579	3.905	1.674
	2	0.04	0.156	29.7	6.981	4.887	2.094
	2	0.05	0.183	34.9	8.197	5.738	2.459
	4	0.01	0.078	7.5	3.522	2.465	1.057
	4	0.02	0.147	14.1	6.607	4.625	1.982
	4	0.03	0.208	19.9	9.350	6.545	2.805
	4	0.04	0.262	25.0	11.750	8.225	3.525
	4	0.05	0.309	29.5	13.869	9.708	4.161
Stainless Steel (wire-wound)	2	0.01	0.090	17.1	4.021	2.814	1.206
	2	0.02	0.157	30.0	7.044	4.931	2.113
	2	0.03	0.210	40.2	9.444	6.610	2.833
	2	0.04	0.253	48.4	11.376	7.963	3.413
	2	0.05	0.287	54.8	12.872	9.010	3.862
	4	0.01	0.177	16.9	7.948	5.563	2.384
	4	0.02	0.307	29.3	13.776	9.643	4.133
	4	0.03	0.410	39.1	18.388	12.872	5.517
	4	0.04	0.492	47.0	22.097	15.468	6.629
	4	0.05	0.560	53.4	25.120	17.584	7.536

Source: Meredith and Brice (1992), by permission

B.3 SAMPLE HANDLING AND PRESERVATION

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Minimizing chemical changes to samples from the time they are collected to the time they are analyzed.

Method Description: Figure B.1 gives a generalized flow diagram of ground-water sampling steps. Ground-water samples are collected using a device that is appropriate for the type of well installation and for the constituents of concern (see Table 5-1 and 5-2 for guidance on selection of devices). Other considerations in sample collection include: (1) The required volume, (2) the type of container, (3) method of preservation, and (4) the maximum holding period before the sample should be analyzed. Depending on the constituents to be analyzed, these can vary considerably. Sample volume can range from 10 to 1,000 mL. Containers can be Teflon, stainless steel, plastic (PVC, polypropylene, or polyethylene), or borosilicate glass. In most instances preservation involves cooling to 4° Centigrade. Some types of samples (such as for major ions and phenols) require field acidification to a specified pH. Required holding times can range from hours (for highly sensitive parameters) to days. Samples for some constituents, such as major cations require filtration before being sealed in the sample container. The question of **filtration** of samples being analyzed for contaminants has received considerable attention in the last few years because contaminants can be sorbed to colloidal particles moving through an aquifer. Analysis of filtered ground-water samples might underestimate the amount of a contaminant that is actively moving through an aquifer if colloidal transport of occurring. Given the changing status of regulatory thinking on this issue, it is probably best to consult with the appropriate regulatory agency to determine whether samples should be filtered before being placed in the sampling container. Table B-1 identifies a number of references that address the issue of filtration.

Method Selection Considerations: Depends on the constituents to be analyzed. Table B.3 provides guidance for a detective monitoring program. Devinny et al. (1990-Chapter 6) contains an expanded list for 60 specific types of contaminants and ground-water chemical parameters.

Frequency of Use: Required standard procedure for all ground-water sampling.

Standard Methods/Guidelines: **General sampling procedures:** U.S. EPA (1986b-Chapter 11), ASTM (1985).

Sources for Additional Information: All standard guides on ground-water sampling discuss sample collection, handling, and preservation. See generally, Table B-1.

Table B.3 Recommended Sample Handling and Preservation Procedures for a Detective-Monitoring Program

Parameters (Type)	Volume Required(mL) 1 Sample[a]	Containers (Material)	Preservation Method	Maximum Holding Period
Well purging				
pH (grab)	50	T,S,P,G	None; field det.	<1 hr[b]
Ω^{-1} (grab)	100	T,S,P,G	None; field det.	<1 hr[b]
T (grab)	1,000	T,S,P,G	None; field det.	None
Eh (grab)	1,000	T,S,P,G	None; field det.	None
Contamination indicators				
pH, Ω^{-1} (grab)	As above	As above	As above	As above
TOC	40	G,T	Dark, 4°C	24 hr[d]
TOX	500	G,T	Dark, 4°C	5 days
Water quality				
Dissolved gases (O_2,CH_4,CO_2)	10 mL minimum	G,S	Dark, 4°C	<24 hr
Alkalinity/acidity	100	T,G,P	4°C/None	<6 hr[b] <24 hr
	Filtered under pressure with appropriate media			
(Fe, Mn, Na^+, K^+, Ca^{++}, Mg^{++})	All filtered 1,000 mL[f]	T,P	Field acidified to pH <2 with HNO_3	6 months[c]
(PO_4^-, Cl^-, Silicate)	@50	(T,P,G glass only)	4°C	24 hr/ 7 days[e]; 7 days
NO_3^-	100	T,P,G	4°C	24 hr[d]
SO_4^-	50	T,P,G	4°C	7 days[e]
OH_4^+	400	T,P,G	4°C/H_2SO_4 to pH <2	24 hr/ 7 days

Table B.3 (cont.)

Parameters (Type)	Volume Required(mL) 1 Sample[a]	Containers (Material)	Preservation Method	Maximum Holding Period
Phenols	500	T,G	4°C/H_2PO_4 to pH <4	24 hours
Drinking Water suitability As, Ba, Cd, Cr, Pb, Hg, Se, Ag	Same as above for water quality cations (Fe, Mn, etc.)[f]	Same as above	Same as above	6 months
F⁻	Same as chloride above	Same as above	Same as above	7 days
Remaining organic	As for TOX/ TOC, except where analytical parameters method calls for acidification of sample			24 hours

T = Teflon; S = stainless steel; P = PVC, polypropylene, polyethylene; G = borosilicate glass.

[a]It is assumed that at each site, for each sampling date, replicates, a field blank, and standards must be taken at equal volume to those of the samples.
[b]Temperature correction must be made for reliable reporting. Variations greater than ± 10% can result from a longer holding period.
[c]In the event that HNO_3 cannot be used because of shipping restrictions, the sample should be refrigerated to 4°C, shipped immediately, and acidified on receipt at the laboratory. Container should be rinsed with 1:1 HNO_3 and included with sample.
[d]28-day holding time if samples are preserved (acidified).
[e]Longer holding times in U.S. EPA (1986b).
[f]Filtration is <u>not</u> recommended for samples intended to indicate the mobile substance lead. See Puls and Barcelona (1989a) for more specific recommendations for filtration procedures involving samples for dissolved species.

Source: U.S. EPA, 1991b, adapted from Scalf et al. (1981) and U.S. EPA (1986b)

B.4 DECONTAMINATION

Other Names Used to Describe Method: --

Uses at Contaminated Sites: Preventing cross-contamination between sampling sites.

Method Description: Any equipment that has come in contact with potentially contaminated soil or water is cleaned prior to and after each use. Decontamination methods can be broadly classified as physical and chemical. **Physical decontamination** techniques include: (1) Physical removal/scrubbing, (2) air blasting, (3) wet blasting (high pressure steam cleaning/hot-water power wash/hydrolazer), (4) dry ice blasting, (5) high pressure Freon cleaning, (6) ultrasonic cleaning, and (7) vacuum cleaning. **Chemical decontamination** techniques can involve use of one or more cleaning solutions (see Table B.4). A typical minimum decontamination sequence would include: (1) Scraping or brushing to remove any soil or residue from the device; (2) washing with potable water, deionized water, and/or one or more or a variety of detergents and cleaning fluids, such as acetone; and (3) pressure cleaning (high pressure steam cleaner or water blaster/hydrolazer).

Method Selection Considerations: See discussion of standard methods below.

Frequency of Use: Required standard procedure for all ground-water sampling.

Standard Methods/Guidelines: ASTM (1990). Mickam et al. (1989) summarize recommended procedures and materials in U.S. EPA guidance documents. Specific procedures for state agencies vary greatly from state to state and also are summarized in Mickam et al. (1989). The appropriate regional EPA office or state agency should be contacted to identify recommended or required procedures for site of interest. Table B.4 identifies potential cleaning solutions. The selection of solvents depends on the nature of the contaminant and weighing characteristics of the solvent, such as flash point, threshold limit value, and toxicity factors.

Sources for Additional Information: See Table B-1.

Table B.4 Decontamination Solutions

Type of Hazard	Name of Solution	Remarks
Amphoteric-acids and bases	Sodium bicarbonate	5-15% aqueous solution
Inorganic acids, metal processing wastes, heavy metals	Sodium carbonate	Good water softener, 10-20% aqueous solution
Solvents and organic compounds, oily, greasy unspecified wastes	Trisodium phosphate	Good rinsing solution or detergent, 10% aqueous solution
Pesticides, fungicides, cyanides, ammonia, and other non-acidic inorganic wastes	Calcium hypochlorite	Excellent disinfectant, bleaching and oxidizing agent, 10% aqueous solution

Other Types of Decontamination Solutions

Other Detergents and Aqueous Surfactants

Phosphate-free laboratory detergent (Alconox, Liquinox), Pennsalt 91, Oakite, Gunk, Clorox

Solvents

1,1,2-trichloroethane, H2-ethyl-hexyl acetate, pesticide-grade isopropanol/acetone/methanol/hexane, heptane (non-hydrogen bonding), alcohol, diesel fuel, naptha, beta-propiolactone, carbon tetrachloride, 8% formalinethylene, 8% hexachloromelamine, 1,2-dichlorethane (in solution), Quadcoat

Other Solutions

10% nitric acid, 0.1 N/10%/20% hydrochloric acid

Water

Potable/tap water (demonstrated to be analyte-free), distilled water, deionized water, reagent grade distilled and deionized water

Source: Adapted from Devinny et al. (1990) and Mickam et al. (1989)

Table B-1 Reference Index for Ground-Water Sampling Procedures

Topic	References
<u>General</u>	
Texts/Reports[a]	Barcelona et al. (1983, 1985), Classen (1982), Fenn et al. (1977), Gibb et al. (1981), Korte and Kearl (1985), Lindorff et al. (1987), Lloyd and Walters (1985), Mooij and Rovers (1976), Nash and Leslie (1991), NJDEP (1988), Rainwater and Thatcher (1960), Santa Clara County Water District (1985), Scalf (1984), Scalf et al. (1981), Starks (1989), U.S. EPA (1986a, 1986b, 1993)
Review Papers	Barcelona (1988), Barcelona and Gibb (1988), Bone (1986), Bryden et al. (1986), Cullen et al. (1992), Herzog et al. (1991), Keith (1990), Nelson and Ward (1981), Parsons and Davis (1992), Schuller et al. (1981), Sgambat and Stedinger (1981), Smith et al. (1988), Summers and Gherini (1987), Unwin (1982)
Minimum Data Elements	ASTM (1992a, 1992b, 1992c, 1992d, 1993), U.S. EPA (1992)
<u>Specific Topics</u>	
Sampling Frequency	Barcelona et al. (1989), Casey et al. (1983), Loftis and Ward (1979), Rajagopal (1986), Sgambat and Stedinger (1981)
Sample Preservation	Berg (1982), Maskarinec and Moody (1988), Parr et al. (1988), Prentice and Bender (1987)
Metals/Colloids/Filtration	Backhus and Gschwend (1990), Backhus et al. (1993), Braids (1986, 1987), Burger (1986, 1987), Clark et al. (1992), Kearl et al. (1992), Kennedy et al. (1974, 1976), Laxen and Chandler (1982), McCarthy and Zachara (1989), Pennino (1990), Puls (1990), Puls and Barcelona (1989a,b), Puls and Eychaner (1990), Puls and Powell (1992), Puls et al. (1990, 1991), Ryan and Gscwhend (1990), Skougstad and Scarbro (1968), Stolzenburg and Nichols (1986), Trela (1986), Wagemann and Brunskill (1975), West (1990)
Sampling Volatiles/Gases	Barker and Dickhout (1988), Brice and Kelley (1991), Dunlap et al. (1977), Gibb and Barcelona (1984), Holden (1984), Pettyjohn et al. (1981), Schaal (1992), Schalla et al. (1988), Unwin and Maltby (1988); see also, references in Table 5-4 on effect of sampling devices and materials on volatiles
Sampling in Karst	Beck (1986), Field (1988), Quinlan (1989), Quinlan and Alexander (1987), Quinlan and Ewars (1985), Quinlan et al. (1988)
Microbiological	Britton and Greeson (1989), Dunlap et al. (1977), Gerba (1988), Greeson et al. (1977)

Table B-1 (cont.)

Topic	References
Purging	Backhus et al. (1993), Barber and Davis (1987), Barcelona and Helrich (1986), Gibb et al. (1981), Gibs and Imbrigiotta (1990), Giddings (1983), Gillham et al. (1985), Herzog et al. (1988), Kearl et al. (1992), Keely and Boateng (1987a,b), MacFarlane et al. (1992), Maltby and Unwin (1992), Oliveros et al. (1988), Palmer et al. (1987), Panko and Barth (1988), Pennino (1988), Robbins (1989), Robin and Gillham (1987), Ross et al. (1992), Ryan and Gschwend (1990), Schaal (1992), Schalla (1992), Smith et al. (1988), Unwin and Maltby (1988); Water Quality Changes with Pumping: Gibb et al. (1981), Keith et al. (1982), Marsh and Lloyd (1980), Nightingale and Bianchi (1979, 1980), Pettyjohn (1976, 1982), Slawson et al. (1982), Summers and Brandvold (1967)
Quality Assurance and Quality Control	Barcelona et al. (1985), Barth et al. (1989), Campbell and Mabey (1985), Evans (1986), Evans et al. (1987), Friedman and Erdman (1982), Kent and Payne (1988), Lewis (1988), Mateo et al. (1991), Mitchell-Hall et al. (1989), Paulson et al. (1988), Provost and Elder (1985), Simes (1989), Stanley and Verner (1983), Starks and Flatman (1991), Taylor (1987), U.S. Army Corps of Engineers (1990), U.S. EPA (1986a, 1986b, 1987, 1989a, 1989b, 1990, 1991b), van Ee and McMillion (1986), van Ee et al. (1990).
Decontamination	Brice and Kelley (1991), Esposito et al. (1985), Fetter (1983), Fetter and Griffin (1988), Lewis (1988), Matteoli and Noonan (1987), Meade and Ellis (1985), Mickam et al. (1989), Moberly (1985), Nielsen (1991), Richter and Collentine (1983)

[a]Reports focussing on ground-water sampling procedures are identified here. Many other references identified in Appendix A also cover ground-water sampling procedures.

APPENDIX B REFERENCES

American Society for Testing and Materials (ASTM). 1990. Standard Practice for Decontamination of Field Equipment Used at Nonradioactive Waste Sites. D5088-90, (Vol. 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1985. Guide for Sampling Groundwater Monitoring Wells. D4448-85, (Vol. 11.04), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992a. Standard Practice for the Minimum Set of Data Elements to Identify a Groundwater Site. D5254-92, (Vol 4.08), ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992b. Draft Standard Guide for the Set of Data Elements to Describe a Ground-Water Site; Part 1--Additional Identification Descriptors. D18 Committee Ballot, December, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992c. Draft Standard Guide for the Set of Data Elements to Describe a Ground-Water Site; Part 2--Physical Descriptors. D18 Committee Ballot, December, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1992d. Draft Standard Guide for the Set of Data Elements to Describe a Ground-Water Site; Part 3--Usage Descriptors. D18 Committee Ballot, December, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 1993. Draft Standard Guide for Selection of Data Elements for Ground-Water Investigations. D18 Committee Ballot, April, ASTM, Philadelphia, PA.

Backhus, D.A. and P.M. Gswchend. 1990. Fluorescent Polycyclic Aromatic Hydrocarbons as Probes for Studying the Impacts of Colloids on Pollutant Transport in Groundwater. Environ. Sci. Technol. 24:1214-1223.

Backhus, D.A., J.N. Ryan, D.M. Groher, J.K. MacFarlane, and P.M. Gschwend. 1993. Sampling Colloids and Colloid-Associated Contaminants in Ground Water. Ground Water 31:466-479.

Barber, C. and G.B. Davis. 1987. Representative Sampling of Ground Water from Short-Screened Boreholes. Ground Water 25(5):581-587. [Purging]

Barcelona, M.J. 1988. Overview of the Sampling Process. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 3-23.

Barcelona, M.J. and J.P. Gibb. 1988. Development of Effective Ground-Water Sampling Protocols. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 17-26.

Barcelona, M.J. and J.A. Helfrich. 1986. Well Construction and Purging Effects on Ground-Water Samples. Environ. Sci. Technol. 20:1179-1184.

Barcelona, M.J. and J.A. Helfrich. 1992. Realistic Expectations for Ground-Water Investigations in the 1990's. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 3-23.

Barcelona, M.J., J.P. Gibb, and R.A. Miller. 1983. A Guide to the Selection of Materials for Monitoring Well Construction and Ground-Water Sampling. ISWS Contract Report 327, Illinois State Water Survey, Champaign, IL, 78 pp.

Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske. 1985. Practical Guide for Ground-Water Sampling. EPA/600/2-85/104 (NTIS PB86-137304), 184 pp. (Also published as ISWS Contract Report 374, Illinois State Water Survey, Champaign, IL, 94 pp.)

Barcelona, M.J., H.A. Wehrmann, M.R. Schock, M.E. Sievers, and J.R. Karny. 1989. Sampling Frequency for Ground-Water Quality Monitoring. EPA/600/4-89/032 (NTIS PB89-233522), 203 pp.

Barker, J.F. and R. Dickhout. 1988. An Evaluation of Some Systems for Sampling Gas-Charged Ground Water for Volatile Organic Analysis. Ground Water Monitoring Review 8(4):112-119.

Barth, D.S., B.J. Mason, T.H. Starks, and K.W. Brown. 1989. Soil Sampling Quality Assurance User's Guide, 2nd edition. EPA/600/8-89/046 (NTIS PB89-189864), U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, NV, 225+ pp.

Beck, B.F. 1986. Ground-Water Monitoring Considerations in Karst on Young Limestones. In: Proc. Conf. on Environmental Problems In Karst and Their Solutions, National Water Well Association, Dublin, OH, pp. 229-248.

Berg, E.L. 1982. Handbook for Sampling and Sample Preservation of Water and Wastewater, 2nd edition. EPA/600/4-82/029 (NTIS PB83-124503). (Replaces report with the same title by Huibregste and Mover, EPA/600/4-76/049).

Bone, L.I. 1986. Developing Guides for Sampling and Analysis of Ground Water. In: Hazardous and Industrial Solid Waste Testing and Disposal: 6th Volume, Lorenzen, D. et al. (eds.), ASTM STP 933, American Society for Testing and Materials, Philadelphia, PA, pp. 337-342.

Braids, O.C. 1986. The Rationale for Filtration of Ground Water Samples. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 292-294.

Braids, O.C. 1987. Should Ground Water Samples from Monitor Wells Be Filtered Before Laboratory Analysis? Opinion I. Ground Water Monitoring Review 7(3):58-59.

Brice, D.A. and M.E. Kelley. 1991. Evaluation of EPA Region IV Standard Operating Procedures for Decontamination of Field Equipment When Sampling for Volatile Organic Compounds. Ground Water Management 5:601-609 (5th NOAC).

Britton, L.J. and P.E. Greeson (eds.). 1989. Methods for Collection and Analysis of Aquatic Biological and Microbiological Samples. U.S. Geological Survey TWRI 5-A4, 363 pp. (Supersedes Greeson et al., [1977].)

Bryden, G.W., W.R. Mabey, and K.M. Robine. 1986. Sampling for Toxic Contaminants in Ground Water. Ground Water Monitoring Review 6(2):67-72.

Burger, R.M. 1986. Positive Aspects of Sample Filtration. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 301-314.

Burger, R.M. 1987. Should Ground Water Samples from Monitor Wells Be Filtered Before Laboratory Analysis? Opinion II. Ground Water Monitoring Review 7(3):59-63.

Campbell, J.A. and W.R. Mabey. 1985. A Systematic Approach for Evaluating the Quality of Ground Water Monitoring Data. Ground Water Monitoring Review 5(4):58-62.

Casey, D., P.N. Nemetz, and D.H. Uyeno. 1983. Sampling Frequency for Water Quality Monitoring: Measures of Effectiveness. Water Resources Research 19(5):1107-1110.

Clark, S.B., N.M. Park, and R.C. Tuckfield. 1992. Effects of Sample Collection Device and Filter Pore Size on Concentrations of Metals in Groundwater Samples (U). In: National Groundwater Sampling Symposium Proceedings (Washington, DC), Grundfos Pumps Corporation, Clovis, CA, pp. 13-19. [Bladder pump, submersible centrifugal pump]

Classen, H.C. 1982. Guidelines and Techniques for Obtaining Water Samples that Accurately Represent the Water Chemistry of the Aquifer. U.S. Geological Survey Open File Report 82-1024, 49 pp.

Cullen, S.J., J.H. Kramer, L.G. Everett, and L.A. Eccles. 1992. Is Our Ground Water Monitoring Strategy Illogical? Ground Water Monitoring Review 12(3):103-107.

Devinny, J.S., L.G. Everett, J.C.S. Lu, and R.L. Stollar. 1990. Subsurface Migration of Hazardous Wastes. Van Nostrand Reinhold, New York, NY.

Dunlap, W.J., J.F. McNabb, M.R. Scalf, and R.L. Cosby. 1977. Sampling for Organic Chemicals and Microorganisms in the Subsurface. EPA/600/2-77/176 (NTIS PB272 679).

Esposito, M.P. et al. 1985. Guide for Decontaminating Buildings, Structures, and Equipment at Superfund Sites. EPA/600/2-85/028 (NTIS PB85-201234). [9 authors]

Evans, R.B. 1986. Ground-Water Monitoring Data Quality Objectives for Remedial Site Investigations. In: Quality Control in Remedial Site Investigation: Hazardous and Industrial Solid Waste Testing, 5th Volume, C.L. Perket (ed.), ASTM STP 925, American Society for Testing and Materials, Philadelphia, PA, pp. 21-33.

Evans, R.B., E.N. Koglin, and K.W. Brown. 1987. Ground-Water Monitoring: Quality Assurance for RCRA. EPA/600/X-87/415, U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Fenn, D., E. Cocozza, J. Isbister, O. Braids, B. Yare, and P. Roux. 1977. Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities. EPA/530/SW611 (NTIS PB84-174820), 283 pp.

Fetter, C.W. 1983. Potential Sources of Contamination in Ground Water Monitoring. Ground Water Monitoring Review 3(2):60-64.

Fetter, C.W. and R.A. Griffin. 1988. Field Verification of Noncontaminating Methodology for Installation of Monitoring Wells and Collection of Ground Water Samples. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 437-444.

Field, M.S. 1988. U.S. Environmental Protection Agency's Strategy for Ground-Water Quality Monitoring at Hazardous Waste Land Disposal Facilities in Karst Terranes. In: Karst Hydrogeology and Karst Environmental Protection, Int. Ass. Sci. Hydrol. Pub. No. 176, pp. 1006-1011.

Friedman, L.C. and D.E. Erdmann. 1982. Quality Assurance Practices for the Chemical and Biological Analyses of Water and Fluvial Sediments. U.S. Geological Survey TWRI 5-A6, 181 pp.

Gerba, C.P. 1988. Methods for Virus Sampling and Analysis of Ground Water. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 343-346.

Gibb, J.P. and M. Barcelona. 1984. Sampling for Organic Contaminants in Ground Water. J. Am. Water Works Ass. 76(5):48-51.

Gibb, J.P, R.M. Schuller, and R.A. Griffin. 1981. Procedures for the Collection of Representative Water Quality Data from Monitoring Wells. ISWS/ISGS Cooperative Ground Water Report 7, Illinois State Water Survey, Champaign, IL.

Gibs, J. and T.E. Imbrigiotta. 1990. Well-Purging Criteria for Sampling Purgeable Organic Compounds. Ground Water 28(1):68-78.

Giddings, T. 1983. Bore-Volume Purging to Improve Monitoring Well Performance: An Often Mandated Myth. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, pp. 253-256

Gillham, R.W., M.J.L. Robin, J.F. Barker, and J.A. Cherry. 1985. Field Evaluation of Well Flushing Procedures. API Publication No. 4405, American Petroleum Institute, New York, NY, 120 pp.

Greeson, P.E., T.A. Ehlke, G.A. Irwin, B.W. Lium, and K.V. Slack (eds.). 1977. Methods for Collection and Analysis of Aquatic Biological and Microbiological Samples. U.S. Geological Survey TWRI 5-A4, 332 pp. (Updated by Britton an Greeson, 1989.)

Herzog, B.L., S.-F. Chou, J.R. Valkenberg, and R.A. Griffin. 1988. Changes in Volatile Organic Chemical Concentrations After Purging Slowly Recovering Wells. Ground Water Monitoring Review 8(4):93-99.

Herzog, B.L., J.D. Pennino, and G.L. Nielsen. 1991. Ground-Water Sampling. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 449-499.

Holden, P.W. 1984. Primer on Well Water Sampling for Volatile Organic Compounds. Water Resources Research Center, University of Arizona, Tucson, AZ, 44 pp.

Kearl, P.M., N.E. Korte, and T.A. Cronk. 1992. Suggested Modifications to Ground Water Sampling Procedures Based on Observations from the Colloidal Boroscope. Ground Water Monitoring Review 12(2):155-161.

Keely, J.F. and K. Boateng. 1987a. Monitoring Well Installation, Purging, and Sampling Techniques--Part 1: Conceptualization. Ground Water 25(3):300-313.

Keely, J.F. and K. Boateng. 1987b. Monitoring Well Installation, Purging, and Sampling Techniques--Part 2: Case Histories. Ground Water 25(4):427-39.

Keith, L.H. 1990. Environmental Sampling: A Brief Summary. Environ. Sci. Technol. 24(5):610-617.

Keith, S.J., L.G. Wilson, H.R. Fitch, and D.M. Esposito. 1982. Sources of Spatial-Temporal Variability in Ground-Water Quality Data and Methods of Control: Case Study of the Cortaro Monitoring Program, Arizona. In: Proc. 2nd Nat. Symp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 217-227.

Kennedy, V.C., B.W. Zellweger, and B.F. Jones. 1974. Filter Pore Size Effects on the Analysis of Al, Fe, Mn, and Ti in Water. Water Resources Research 10(4):785-790.

Kennedy, V.C., E.A. Jenne, and J.M. Burchard. 1976. Backflushing Filters for Field Processing of Water Samples Prior to Trace-Element Analysis. U.S. Geological Survey Water Resource Investigations Report 76-126.

Kent, R.T. and K.E. Payne. 1988. Sampling Groundwater Monitoring Wells: Special Quality Assurance and Quality Control Considerations. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 231-260.

Korte, N.W. and P.M. Kearl. 1985. Procedures for the Collection and Preservation of Ground Water and Surface Water Samples and for the Installation of Monitoring Wells, 2nd edition. U.S. Department of Energy Technical Measurements Center Report GJ/TMC-08 (NTIS DE86-006184), 68 pp.

Laxen, D.P.H. and I.M. Chandler. 1982. Comparison of Filtration Techniques for Size Distribution in Fresh Waters. Analytical Chem. 54(8):1350-1355.

Lewis, D.L. 1988. Assessing and Controlling Sample Contamination. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 199-143.

Lindorff, D.E., J. Feld, and J. Connelly. 1987. Groundwater Sampling Procedures Guidelines. Wisc. Dept. Nat. Resources (WDNR) Rept. PUBL-WR-153-87, WDNR, Madison, WI, 91 pp.

Lloyd, J.W. and M. Walters. 1985. Sampling of Ground Water with Special Reference to Saline/Freshwater Conditions. Report PECD7/10/60 to Department of the Environment, United Kingdom.

Loftis, J.C. and R.C. Ward. 1979. Water Quality Monitoring-Some Practical Sampling Frequency Considerations. Environmental Management 4(6).

MacFarlane, I.D., J.L. Kocornik, F.T. Barranco, and A.R. Bonas. 1992. The Application of Slow Pumping at a Manufactured Gas Plant. Ground Water Management 11:413-427 (6th NOAC).

Maltby, V. and J.P. Unwin. 1992. A Field Investigation of Ground-Water Monitoring Well Purging Techniques. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 281-299.

Marsh, J.M. and J.W. Lloyd. 1980. Details of Hydrochemical Variations in Flowing Wells. Ground Water 18(4):366-373.

Maskarinec, M.P. and R.L. Moody. 1988. Storage and Preservation of Environmental Samples. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 145-155.

Mateo, J.M., C.M. Andreas, and W. Coakley. 1991. A Quality Assurance Sampling Plan for Emergency Response (QASPAR). In: Proc. Second Int. Symp. Field Screening Methods for Hazardous Waste and Toxic Chemicals, EPA/600/9-91/028 (NTIS PB92-125764), pp. 217-225.

Matteoli, R.J. and J.M. Noonan. 1987. Decontamination of Rubber Hose and "Teflon" Tubing for Ground Water Sampling. In: Proc. 1st Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 159-183.

McCarthy, J.E. and J.M. Zachara. 1989. Subsurface Transport of Contaminants. Environ. Sci. Technol. 23:496-502. [Colloidal transport]

Meade, J.P. and W.D. Ellis. 1985. Decontamination Techniques for Mobile Response Equipment Used at Waste Sites (State-of-the-Art Survey). EPA/600/2-85/105 (NTIS PB85-247021).

Meridith, D.V. and D.A. Brice. 1992. Limitations on the Collection of Representative Samples from Small Diameter Monitoring Wells. Ground Water Management II:429-439 (6th NOAC).

Mickam, J.T., R. Bellandi, and E.C. Tifft, Jr. 1989. Equipment Decontamination Procedures for Ground Water and Vadose Zone Monitoring Programs: Status and Prospects. Ground Water Monitoring Review 9(2):100-121.

Mitchell-Hall, T.E., A.C. Neale, S.G. Paulsen, J.E. Pollard, D.W. Sutton. 1989. Eastern Lake Survey--Phase II Quality Assurance Report. EPA/600/4-89/029 (NTIS PB89-224919).

Moberly, R.L. 1985. Equipment Decontamination. Ground Water Age 19(8):36-39.

Mooij, H. and F.A. Rovers. 1976. Recommended Groundwater and Soil Sampling Procedures. EPS-4-EC, Environmental Protection Service, Canada.

Nash, R.G. and A.R. Leslie (eds.). 1991. Groundwater Residue Sampling. ACS Symposium Series 465, American Chemical Society, Washington, DC, 395 pp.

Nelson, J.D. and R.C. Ward. 1981. Statistical Considerations and Sampling Techniques for Ground-Water Quality Monitoring. Ground Water 19(6):617-625.

New Jersey Department of Environmental Protection (NJDEP). 1988. Field Sampling Procedures Manual. Hazardous Waste Program, NJDEP, Trenton, NJ.

Nielsen, G.L. 1991. Decontamination Program Design for Ground-Water Quality Investigations. In: Practical Handbook of Ground-Water Monitoring, D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, pp. 625-636.

Nightingale, H.I. and W.C. Bianchi. 1979. Influence of Well Water Quality Variability on Sampling Decisions and Monitoring. Water Resources Bulletin 15(5):1394-1407.

Nightingale, H.I. and W.C. Bianchi. 1980. Well Water Quality Changes Correlated with Well Pumping Time and Aquifer Parameters---Fresno, California. Ground Water 18:275-280.

Oliveros, J.P., D.A. Vroblesky, and M.M. Lorah. 1988. Increasing Purging Efficiency Through the Use of Inflatable Packers. In: Proc. 2nd Nat. Outdoor Action Conf. on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 457-469.

Palmer, C.D., J.F. Keely, and W. Fish. 1987. Potential for Solute Retardation on Monitoring Well Sand Packs and Its Effect on Purging Requirements for Ground Water Sampling. Ground Water Monitoring Review 7(2):40-47.

Panko, A.W. and P. Barth. 1988. Chemical Stability Prior to Ground-Water Sampling: A Review of Current Well Purging Methods. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 232-239.

Parr, J., M. Bollinger, O. Callaway, and K. Carlberg. 1988. Preservation Techniques for Organic and Inorganic Compounds in Water Samples. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 221-230.

Parsons, A.M. and P.A. Davis. 1992. A Proposed Strategy for Assessing Compliance with the RCRA Ground-Water Monitoring Regulations. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 39-56.

Paulson, S.G., C.L. Chen, K.J. Stetzenbach, and M.J. Miah. 1988. Guide to Application of Quality Assurance Data to Routine Survey Data Analysis. EPA/600/4-88/010 (NTIS PB88-166863).

Pennino, J.D. 1988. There's No Such Things as a Representative Ground Water Sample. Ground Water Monitoring Review 8(3):4-9.

Pennino, J.D. 1990. Total Versus Dissolved Metals: Implications for Preservation and Filtration. In: Ground Water and Vadose Zone Monitoring, D.M. Nielsen and A.I. Johnson (eds.), ASTM STP 1053, American Society for Testing and Materials, Philadelphia, PA, pp. 238-246.

Pettyjohn, W.A. 1976. Monitoring Cyclic Fluctuations in Ground Water Quality. Ground Water 14(6):472-479.

Pettyjohn, W.A. 1982. Cause and Effect of Cyclic Changes in Ground Water Quality. Ground Water Monitoring Review 2(1):43-49.

Pettyjohn, W.A., W.J. Dunlap, R. Cosby, and J.W. Keeley. 1981. Sampling Ground Water for Organic Contaminants. Ground Water 19(2):180-188.

Prentice, H.S. and D.F. Bender. 1987. Development of Preservation Techniques and Establishment of Maximum Holding Times: Inorganic Constituents of the National Pollutant Discharge Elimination System and Safe Drinking Water Act. EPA/600/4-86/043 (NTIS PB87-132833).

Provost, L.P. and R.S. Elder. 1985. Choosing Cost-Effective QA/QC Programs for Chemical Analysis. EPA/600/4-85/056 (NTIS PB85-241461).

Puls, R.W. 1990. Colloidal Consideration in Ground Water Sampling and Contaminant Transport Predictions. Nuclear Safety 31(1):58-65.

Puls, R.W. and M.J. Barcelona. 1989a. Ground Water Sampling for Metals Analyses. Superfund Ground Water Issue Paper. EPA/540/4-89/001 (NTIS PB91-1333249).

Puls, R.W. and M.J. Barcelona. 1989b. Filtration of Ground Water Samples for Metal Analysis. Hazardous Wastes and Hazardous Materials 6(4):385-393.

Puls, R.W. and J.H. Eychaner. 1990. Sampling of Ground Water for Inorganics--Pumping Rate, Filtration and Oxidation Effects. Ground-Water Management 2:313-327 (4th NOAC).

Puls, R.W. and R.M. Powell. 1992. Acquisition of Representative Ground Water Quality Samples for Metals. Ground Water Monitoring Review 12(3):167-176.

Puls, R.W., R.M. Powell, and J.H. Eychaner. 1990. Colloidal Facilitated Transport of Inorganic Contaminants in Ground Water: Part I. Sampling Considerations. EPA/600/M-90-023 (NTIS PB91-168419), 12 pp.

Puls, R.W., R.M. Powell, D.A. Clark, and C.J. Paul. 1991. Facilitated Transport of Inorganic Contaminants in Ground Water: Part II. Colloidal Transport. Environmental Research Brief EPA/600/M-91/040 (NTIS PB92-114503), 14 pp.

Quinlan, J.F. 1989. Ground-Water Monitoring in Karst Terranes: Recommended Protocols and Implicit Assumptions. EPA/600/X-89/050, U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, NV, 79 pp.

Quinlan, J.F. and E.C. Alexander, Jr. 1987. How Often Should Samples Be Taken at Relevant Locations for Reliable Monitoring of Pollutants from an Agricultural, Waste Disposal, or Spill Site in a Karst Terrane? A First Approximation. In: Proc. 2nd Multidisciplinary Conf. on Sinkholes and the Environmental Impacts of Karst (Orlando), Beck, B.F. and W.L. Wilson (eds.), Balkema, Accord, MA, pp. 277-286.

Quinlan, J.F. and R.O. Ewers. 1985. Ground-Water Flow in Limestone Terranes: Strategy and Rationale and Procedure for Reliable, Efficient Monitoring of Ground-Water Quality in Karst Areas. In: Proc. 5th Nat. Symp. and Exp. on Aquifer Restoration and Ground-Water Monitoring, National Water Well Association, Worthington, OH, pp. 197-234.

Quinlan, J.F., R.O. Ewars, and M.S. Field. 1988. How to Use Ground-Water Tracing to "Prove" that Leakage of Harmful Materials from a Site in Karst Terrane Will not Occur. In: Proc. 2nd Conf. on Environmental Problems in Karst Terranes and Their Solutions (Nashville, TN), National Water Well Association, Dublin, OH, pp. 265-288.

Rainwater, F.H. and L.L. Thatcher. 1960. Methods for Collection and Analysis of Water Samples. U.S. Geological Survey Water-Supply Paper 1454.

Rajagopal, R. 1986. The Effect of Sampling Frequency on Ground Water Quality Characterization. Ground Water Monitoring Review 6(4):65-73.

Richter, H.R. and M.G. Collentine. 1983. Will My Monitoring Wells Survive Down There?: Design and Installation Techniques for Hazardous Waste Studies. In: Proc. 3rd Nat. Symp on Aquifer Restoration and Ground-Water Monitoring, National Water Well Association, Worthington, OH, pp. 223-229.

Rinaldo-Lee, M.B. 1983. Small- vs. Large-Diameter Monitoring Wells. Ground Water Monitoring Review 1(1):72-75.

Robbins, G.A. 1989. Influence of Using Purged and Partially Penetrating Monitoring Wells on Contaminant Detection, Mapping, and Modeling. Ground Water 27(2):155-162.

Robin, M.J.L. and R.W. Gillham. 1987. Field Evaluation of Well Purging Procedures. Ground Water Monitoring Review 7(4):85-93.

Ross, C.G.A., R.A. Niemeyer, and T.D. Blackman. 1992. A Method for Reducing Purge Volumes in Deep Monitoring Wells, A Purging Experiment. Ground Water Management 11:45-58 (6th NOAC). [Dual submersible purge/bladder pump sample system]

Ryan, J.N. and P.M. Gschwend. 1990. Colloid Mobilization in Two Atlantic Coastal Plain Aquifers: Field Studies. Water Resources Research 26(2):307-322. [Purging]

Santa Clara County Water District. 1985. Groundwater Monitoring Guidelines. Santa Clara County, CA, 58 pp.

Scalf, M.R. 1984. Sampling Procedures for Ground Water Quality Investigations. EPA/600/D-84/137 (NTIS PB84-194844), 37 pp.

Scalf, M.R., J.F. McNabb, W.J. Dunlap, R.L. Cosby, and J. Fryberger. 1981. Manual of Ground-Water Quality Sampling Procedures. EPA/600/2-81/160 (NTIS PB82-103045). (Also published in NWWA/EPA Series, National Water Well Association, Dublin OH.)

Schaal, W. 1992. Is Well Purging with Vacuum a Reliable Cost-Saving Technique when Testing for Volatile Organic Compounds? Ground Water Management 11:401-412 (6th NOAC).

Schalla, R. 1992. Deployment and Purging for In Situ Sensors in Monitoring Wells. In: Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, D.M. Nielsen and M.N. Sara (eds.), American Society for Testing and Materials, Philadelphia, PA, pp. 300-310.

Schalla, R., D.A. Myers, M.A. Simmons, J.M. Thomas, and A.P. Toste. 1988. The Sensitivity of Four Monitoring Well Sampling Systems to Low Concentrations of Three Volatile Organics. Ground Water Monitoring Review 8(3):90-96.

Schuller, R.M., J.P. Gibb, and R.A. Griffin. 1981. Recommended Sampling Procedures for Monitoring Wells. Ground Water Monitoring Review 1(1):42-46.

Sgambat, J.D. and R.J. Stedinger. 1981. Confidence in Ground-Water Monitoring. Ground Water Monitoring Review 1(1):62-69.

Simes, G.F. 1989. Preparing Perfect Project Plans: A Pocket Guide for the Preparation of Quality Assurance Project Plans. EPA/600/9-89/087.

Skougstad, M.W. and G.F. Scarbro, Jr. 1968. Water Sample Filtration Unit. Environ. Sci. Techol. 2(4):298-301.

Slawson, Jr., G.C., K.E. Kelly, and L.G. Everett. 1982. Evaluation of Ground Water Pumping and Bailing Methods--Application in the Oil Shale Industry. Ground Water Monitoring Review 2(3):27-32.

Smith, J.S., D.P. Steele, M.J. Malley, and M.A. Bryant. 1988. Groundwater Sampling. In: Principles of Environmental Sampling, L.H. Keith (ed.), ACS Professional Reference Book, American Chemical Society, Washington, DC, pp. 255-262.

Stanley, T.W. and S.S. Verner. 1983. Guidelines and Specification for Preparing Quality Assurance Program Plans. EPA/600/8-83/024 (NTIS PB83-219667), 27 pp.

Starks, T.H. 1989. Evaluation of Control Chart Methodologies for RCRA Waste Sites. EPA/600/4-88/040 (NTIS PB89-138416). [Statistical procedures for ground-water monitoring]

Starks, T.H. and G.T. Flatman. 1991. RCRA Ground-Water Monitoring Decision Procedures Viewed as Quality Control Schemes. Environmental Monitoring and Assessment 16:19-37.

Stolzenburg, T.R. and D.G. Nichols. 1986. Effects of Filtration Method and Sampling Devices on Inorganic Chemistry of Sampled Well Water. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 216-234.

Summers, W.K. and L.A. Brandvold. 1967. Physical and Chemical Variations in the Discharge of a Flowing Well. Ground Water 5(1):9-10.

Summers, K.V. and S.A. Gherini. 1987. Sampling Guidelines for Groundwater Quality. EPRI EA-4952, Electric Power Research Institute, Palo Alto, CA.

Taylor, J.K. 1987. Quality Assurance of Chemical Measurements. Lewis Publishers, Chelsea, MI.

Trela, J.J. 1986. Should Ground Water Samples from Monitoring Wells Be Filtered Before Laboratory Analysis? Yes and No. In: Proc. 6th Nat. Symp. and Exp. on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Dublin, OH, pp. 295-300.

Unwin, J. 1982. A Guide to Groundwater Sampling, NCPASI Technical Bulletin 362. National Council of the Paper Industry for Air and Stream Improvement, New York, NY.

Unwin, J. and V. Maltby. 1988. Investigations of Techniques for Purging Ground-Water Monitoring Wells and Sampling Ground Water for Volatile Organic Compounds. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 240-252.

U.S. Army Corps of Engineers. 1990. Chemical Data Quality Management for Hazardous Waste Remedial Activities. Engineering Regulation ER 1110-1-263 (Supersede ER with the same title and number dated December 30, 1985.)

U.S. Environmental Protection Agency (EPA). 1975. National Interim Primary Drinking Water Regulations. 40 Federal Register 59565, December 24, 1975.

U.S. Environmental Protection Agency (EPA). 1986a. RCRA Ground Water Monitoring Technical Enforcement Guidance Document. EPA/530/SW-86/055 (OSWER-9950.1) (NTIS PB87-107751), 332 pp. (Also published in NWWA/EPA Series, National Water Well Association, Dublin, OH.) Final OSWER Directive 9950.2 (NTIS PB91-140194). Executive Summary: OSWER 9950.1a (NTIS PB91-140186), 17 pp. (See also, U.S. EPA [1993]).

U.S. Environmental Protection Agency (EPA). 1986b. Final RCRA Comprehensive Ground-Water Monitoring Evaluation (CME) Guidance Document. Final OSWER Directive 9950.2 (NTIS PB91-140194), 59 pp. [Contains detailed checklist drawing heavily from U.S. EPA (1986a)]

U.S. Environmental Protection Agency (EPA). 1987. Data Quality Objective for Remedial Response Activities, Development Process. EPA/840/G-87/003.

U.S. Environmental Protection Agency (EPA). 1989a. Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities: Interim Final Guidance. EPA/530/SW-89/026 U.S. EPA Office of Solid Waste (NTIS PB89 151047), (Addendum issued July, 1992.)

U.S. Environmental Protection Agency (EPA). 1989b. Report on Minimum Criteria to Assure Data Quality. EPA/530/SW-90/021, 36 pp. Available from RCRA Information Center, U.S. EPA (OS-305), 401 M. St. SW, Washington, DC 209460.

U.S. Environmental Protection Agency (EPA). 1990. Quality Assurance/Quality Control Guidance for Removal Activities, Sampling QA/QC Plan and Data Validation Procedures, Interim Final. EPA/540/G-90/004 (NTIS PB90-274481), U.S. EPA, 66 pp.

U.S. Environmental Protection Agency (EPA). 1991a. Site Characterization for Subsurface Remediation. EPA/625/4-91/026, 259 pp. Available from CERI.*

U.S. Environmental Protection Agency (EPA). 1991b. Preparation Aids for the Development of Category III Quality Assurance Project Plans. EPA/600/8-91/005.

U.S. Environmental Protection Agency (EPA). 1992. Definitions for the Minimum Set of Data Elements for Ground Water Quality. EPA/813/B-92/002. Available from Safe Drinking Water Hotline (800-426-4791).

U.S. Environmental Protection Agency (EPA). 1993. RCRA Ground Water Monitoring: Draft Technical Guidance. EPA/530/R-93/001 (NTIS PB93-139350).

van Ee, J.J. and L.G. McMillion. 1986. Quality Assurance Guidelines for Ground-Water Investigations: The Requirements. In: Ground-Water Contamination: Field Methods, A.G. Collins and A.I. Johnson (eds.), ASTM STP 963, American Society for Testing and Materials, Philadelphia, PA, pp. 27-34.

van Ee, J.J., L.J. Blume, and T.H. Starks. 1990. A Rationale for the Assessment of Errors in the Sampling of Soils. EPA/600/4-90/013. Environmental Monitoring Systems Laboratory, Las Vegas, NV, 57 pp.

Wagemann, R. and G.J. Brunskill. 1975. The Effect of Filter Pore-Size on Analytical Concentrations of Some Trace Elements in Filtrates of Natural Water. Int. J. Environ. Anal. Chem. 4:75-84.

West, C.C. 1990. Transport of Macromolecules and Humate Colloids through a Sand and Clay Amended Sand Laboratory Column. EPA/600/2-90/020 (NTIS PB90-219205).

*Available from ORD Publications, U.S. EPA Center for Environmental Research Information, P.O. Box 19963, Cincinnati, OH 45268-0963 (513-569-7562).

☆U.S. GOVERNMENT PRINTING OFFICE:1998-650-001/80211

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

EPA/625/R-93/003a

Please make all necessary changes on the below label, detach or copy, and return to the address in the upper left-hand corner.

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner.